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**Sandstone Petrography and Authigenic Tourmaline from Lower to Early Middle
Devonian Units of the Appalachian Basin, New York to West Virginia**

**by
Roland Scal**

**A dissertation submitted to the Graduate Faculty in Earth and Environmental
Sciences in partial fulfillment of the requirements for the degree of Doctor of
Philosophy. The City University of New York**

2002

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This manuscript has been read and accepted for the Graduate Faculty in Earth and Environmental Sciences in satisfaction of the dissertation requirement for the degree of the Doctor of Philosophy.

12/11/01
Date

Gerald E. Friedman
Chair of Examining Committee

12/11/01
Date

Jeffrey Oshl
Executive Officer

Professor John A. Chamberlain Jr.

Professor Robert M. Finks

Professor Kenneth G. Johnson
Supervisory Committee

The City University of New York

Abstract

Sandstone Petrography and Authigenic Tourmaline from Lower to Early Middle Devonian Units of the Appalachian Basin, New York to West Virginia

by

Roland Scal

Adviser: Distinguished Professor Gerald M. Friedman

Detrital tourmaline from the Oriskany Sandstone is overgrown by authigenic tourmaline crystallographically aligned to the detrital core. Petrographic characterization was used to evaluate the origin of tourmaline in the Oriskany Sandstone and younger Middle Devonian units. The Oriskany is lithologically very homogeneous from New York to southern Virginia, suggesting it was derived from similar sources along almost its entire extent. A general paragenesis was derived for the unit. Only quartz overgrowths are intergrown with tourmaline overgrowths, and these composite grains can survive reworking. Abrasion of authigenic tourmaline indicates that it must have formed either very early before reworking or was derived from older Paleozoic sandstones. In New York some overgrowths are euhedral and possibly neoformed, while in Virginia, West Virginia, and Maryland no unabraded tourmaline was found. Samples contained reworked overgrowths that vary from unabraded to strongly abraded, suggesting variable

transport and possible multiple reworking.

The overgrowth tourmaline is syntaxial schorl-dravite $\text{Na(Fe, Mg)}_3\text{Al}_6(\text{BO})_3\text{Si}_6\text{O}_{27}(\text{O,OH, F})$, colorless to pale blue, and exhibits growth zones that vary in hue and refractive index. Overgrowths are up to several hundred microns in length parallel to the c-axis. Vanadium occurs in some of the New York overgrowths, and ranges appreciably from below detection to a few weight percent V_2O_3 in different locations. Patterns of elemental zonation and chemistry are consistently similar in any location, but vary between outcrops, suggesting localized occurrences. These variations indicate that a similar set of environmental and postdepositional conditions is responsible for the many isolated incidents of growth, rather than a localized single event followed by redistribution. A general depletion of Fe and a tendency towards dravitic compositions occurs during growth, particularly in New York samples. Though southern samples and New York samples seem to begin formation with similar compositions, New York samples are chemically distinctive. Evidence, particularly from vanadium, suggests a deep burial formation for overgrowths from New York that could not happen if the overgrowths had formed in the Oriskany Sandstone.

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microscope made available by Dr. Micha Tomkiewicz of the Physics Department, it would have been much more difficult to complete the study. Mr. Louis Tundis, Machinist and Chief Technician, Department of Physics and Mr. Joseph Fedullo, Chief Technician, Department of Chemistry, both helped with obtaining laboratory apparatus and supplies. Mr. Richard Bellgrave, health safety officer, gave advice on laboratory techniques. Dr. Arthur M. Langer of the Graduate School and Environmental Science Laboratory at Brooklyn College was very generous with use of his facility and materials and also helped with mineralogical determinations and discussion. Dr. Robert P. Nolan, also of Environmental Science Laboratory at Brooklyn College, helped with use of facilities and materials.

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CHAPTER 1

INTRODUCTION

SUBJECT OF INVESTIGATION

In 1931 Marcellus H. Stow published a dissertation on the distribution and petrography of the Lower Devonian Oriskany Sandstone. He discovered that detrital tourmaline with crystallographically oriented overgrowths of authigenic tourmaline was extremely abundant in the Oriskany Sandstone along almost its entire exposure belt. Since that discovery authigenic tourmaline has fascinated sedimentary petrologists, but it has seldom been investigated with more than reference to its optical properties (see previous investigation of tourmaline overgrowths, Chapter 4).

In this study tourmaline with detrital overgrowths and the enclosing sandstone have been investigated using the tools of thin section petrography, electron microscopy, and microprobe x-ray elemental analysis to characterize the nature of overgrowth tourmaline in the Oriskany Sandstone and sandstones derived from the reworking of the Oriskany Sandstone. Great care was taken in the preparation of samples so that they could be observed in situ in petrographic thin sections of sandstone and as isolated grain mounts without the introduction of artifacts or breakage (see Chapter 2).

This study presents the first chemical analyses of authigenic tourmaline from the Oriskany Sandstone, the first scanning electron micrographs of tourmaline overgrowths,

and discusses the petrographic and geochemical significance of the overgrowths. Along with a detailed description of the tourmaline overgrowths and the mineralogy and petrogenesis of the sandstone, other aspects such as the timing of tourmaline authigenesis are discussed in light of new discoveries. Among other discoveries it became apparent that the overgrowths (1) are probably formed early in diagenesis or may be reworked from an older sandstone, (2) are zoned optically and chemically, due mainly to variations in iron and magnesium, (3) are predominantly abraded indicating that tourmaline overgrowth predated final Oriskany Sandstone deposition, and (4) are reworked into overlying Middle Devonian strata in the basin. These discoveries have bearing on not only local conditions in the sandstones, but are important in understanding the Oriskany Sandstone interval throughout the Appalachian Basin and may even have some value in interpreting paleogeography.

HISTORY OF INVESTIGATION

The Oriskany Sandstone has been a well-known formation for over 160 years, since it was named by Lardner Vanuxem in 1839 for a "White Sandstone" exposed at Oriskany Falls, New York. In his report Vanuxem (1839) noted the unconformity at the base of the Oriskany Sandstone, considerable variations in thickness along its exposure, the abundance of fossils, and the great geographical extent of the formation, which is "readily traced from east to west by its composition and its numerous characteristic fossils" (From Hodgson, 1970; quotes from Apsouri, 1934).

The Oriskany Sandstone in New York had previously been visited by a number of observers including DeWitt Clinton, later governor of New York, in 1810, while a member of a commission searching for possible routes for the Erie Canal. Although trained as a lawyer, Clinton was competent natural scientist and a keen observer. He wrote a detailed description of his trip to Yawgers Woods, a famous location for the Oriskany Sandstone near Lake Cayuga, New York. He noted the basal limestone, now called the Onondaga Limestone, and a sandstone containing numerous shells (the Oriskany Sandstone) that he classified as both oceanic and littoral (Wells, 1963).

In 1820 the Oriskany Sandstone near Seneca Lake, New York, was visited and described as a "shell grit" by Amos Eaton (Wells, 1963). Like Clinton, Eaton was impressed by "the number and singular association of fossils which are found in it" (Hodgson, 1970).

James Hall (1843), in his report on the Fourth District of the New York Geological Survey, wrote a detailed description of the Oriskany Sandstone outcrop in his district, noting, as had Vanuxem, the unconformity at its base and great variations in appearance and lithology in various localities. In 1846, Ebenezer Emmons discussed faunal extinctions during Oriskany times in his book on agriculture in New York State, and in 1859 he published an exhaustive study of the paleontology of the Lower Helderberg and Oriskany Sandstone (Apsouri, 1934). Another early geologist who reported on the Oriskany Sandstone was William W. Mather, who recognized typical Oriskany Sandstone fossils in rocks of varying lithologies (Apsouri, 1934; Hodgson, 1970; Stow, 1931). In 1859 James Hall published his study of the paleontology of the

Helderberg Group and Oriskany Sandstone for the Geological Survey of New York (Apsouri, 1934).

The Oriskany Sandstone, a widespread formation, received many local names as the character of the formation changes along the exposure belt. H. D. Rogers classified the formation later known as the Oriskany Sandstone in Pennsylvania as Number 7 of twelve divisions of Paleozoic rocks in that state (Hodgson, 1970). In Virginia it was called the Monterey Formation (Darton, 1899), and in other parts of Virginia, in West Virginia, and Maryland it became known as the Ridgeley Sandstone, with fauna and lithology similar to the New York Oriskany, and the Shriver Chert (Stow, 1931). In the Kingston area of New York and in the Green Pond Outlier of New York and New Jersey, the Connelly Conglomerate replaces the Oriskany Sandstone. It was named by Chadwick (1908) for an exposure on a hill above South Rondout, Ulster County, New York, who stated that both the Connelly Conglomerate and Glenerie Limestone were lateral equivalents of the Oriskany Sandstone.

In the twentieth century many petrographic, stratigraphic, and paleontological studies have been carried out. Table 1.1 lists some of the significant studies on the Oriskany Sandstone in the last century in a number of states. Because of its economic and historical geologic importance, the Oriskany Sandstone has received scrutiny from numerous state agencies and students of geology, and many of these studies will be reported on and discussed later in this thesis.

In its history the unit assumed economic importance as a source of building stone (MacQuown, 1940), high-grade glass sand (Fettke, 1918), and especially as a source of

Table 1.1
History of Previous Investigation of the Oriskany Sandstone, Lower Devonian

Location	Investigator and Date	Subject
Ontario	Cowan, 1977	Petrography
New York	Vanuxem, 1839 Hall, 1839, 1843 Merrill, 1898 Grabau, 1900 Schuchert, 1900 Ulrich and Schuchert, 1902 Chadwick, 1908 Eaton, 1921 Jensen, 1932 Apsouri, 1934 Stow, 1931 Cahall, 1956 Rickard, 1962 Hodgson, 1970 Voorhees, 1982 Regan, 1982 Baker, 1983 Douglas, 1984 Maliva, 1992 Oliver and Hecht, 1994	Named unit and gave first description Stratigraphy Stratigraphy Paleontology Sedimentology Phosphorites and phosphatic nodules Petrography and stratigraphy Paleontology Stratigraphy Micropaleontology, petrography Petrography Petrography Petrography (Springvale) Petrography and hydrogeology Quartz authigenesis Paleontology
Ohio	Brown, 1953	Heavy minerals
Pennsylvania	Willard, 1931 and 1952 Hamilton, 1937 Fettke, 1938 Cleaves, 1939 Finn, 1949 Foreman and Anderhalt, 1986	Stratigraphy Petroleum exploration Oil and gas Stratigraphy Gas Carbonate Cement in the sandstone
Maryland	Yochelson and Kriz, 1974,	Paleontology
Tennessee	Dunbar, 1919	Stratigraphy
Virginia	Swartz, 1939	Petrology, paleontology
West Virginia	Martens, 1937 Lafferty, 1938 MacQuown, 1940 Heald et al., 1962	Petrography Petroleum geology Stratigraphy Porosity variation
Appalachian Basin	Diecchio, 1985 Seilacher, 1968	Gas accumulation Petrography

natural gas. The first wells opened in Ashtubula County, Ohio, (Hall, 1952; Diecchio, 1985). In 1923 the Oriskany Sandstone west of Cumbridge, Ohio, yielded economic quantities of gas; in the 1930s, more wells were opened in several states (Fettke, 1938; Diecchio, 1985). From 1930 till 1970 the search for natural gas in the Oriskany Sandstone interval was the most important hydrocarbon play in the Appalachian Basin, production and exploration continue today (Harper, 1993). The Oriskany Sandstone is also used as a gas storage unit throughout the central Appalachians and is expected to continue to be important in this use in the future (Friedman et al., 1995; Diecchio, 1985).

DEPOSITIONAL SETTING AND STRATIGRAPHY

The Lower Devonian Oriskany Sandstone (Ulsterian Series, Deerparkian Stage, European stage = Siegenian [= Pragian]) is a well-sorted quartz arenite of marine origin that overlies older Paleozoic, mostly carbonate, rocks throughout the Appalachian Basin (Figures 1.1 and 1.2) and extends from southwestern Ontario across New York and south along the Appalachians to easternmost Kentucky (Stow, 1931; Oliver and Hecht, 1994).

The Appalachian Basin during the Lower Devonian was a relatively shallow asymmetrical marine trough that accumulated thicker sediments on its eastern side, up to 110 m of Oriskany Sandstone in Maryland and Pennsylvanian, and thinner amounts of sediment on the northern and western sides where the Oriskany Sandstone thins to a peripheral depositional edge in southern Ontario, western New York, western Pennsylvania, eastern Ohio, eastern Kentucky, and southwestern Virginia (Milici and de

Figure 1.1. Sample location map. Locations are marked with a polygon, and a number listed below gives the location name. Details of the locations including references to previous studies that reported on the locations are given in Chapter 3. The generalized line of outcrop of the Oriskany Sandstone is from Stow (1931) and Regan (1982).

1. Crandall Estate Well #1, East Independence Field, NY, 2. Seneca Stone Quarry, NY, 3. Yawgers Woods, NY, 4. Auburn, NY, 5. Austeel Plant, Auburn, NY, 6. Skaneateles, NY, 7. Skaneateles Core, NY, 8. I-81 near Syracuse, NY, 9. Nedrow Exit (I-81 south), NY, 10. Oriskany Falls, NY (the type locality), 11. Cherry Valley, NY, 12. Austin Glen, NY, 13. Pea Hill, Green Pond Outlier, NY, 14. Highland Mills, Green Pond Outlier, NY, 15. Monroe Bowl O Fun, Green Pond Outlier, NY, 16. Stroudsburg, PA, 17. Tonoloway Ridge, MD., 18. Cumberland, MD, 19. Dolly Sods, WV, 20. Greenland Gap, WV, 21. Franklin, WV, 22. Minnehaha Springs, WV, 23. Warm Spring, VA

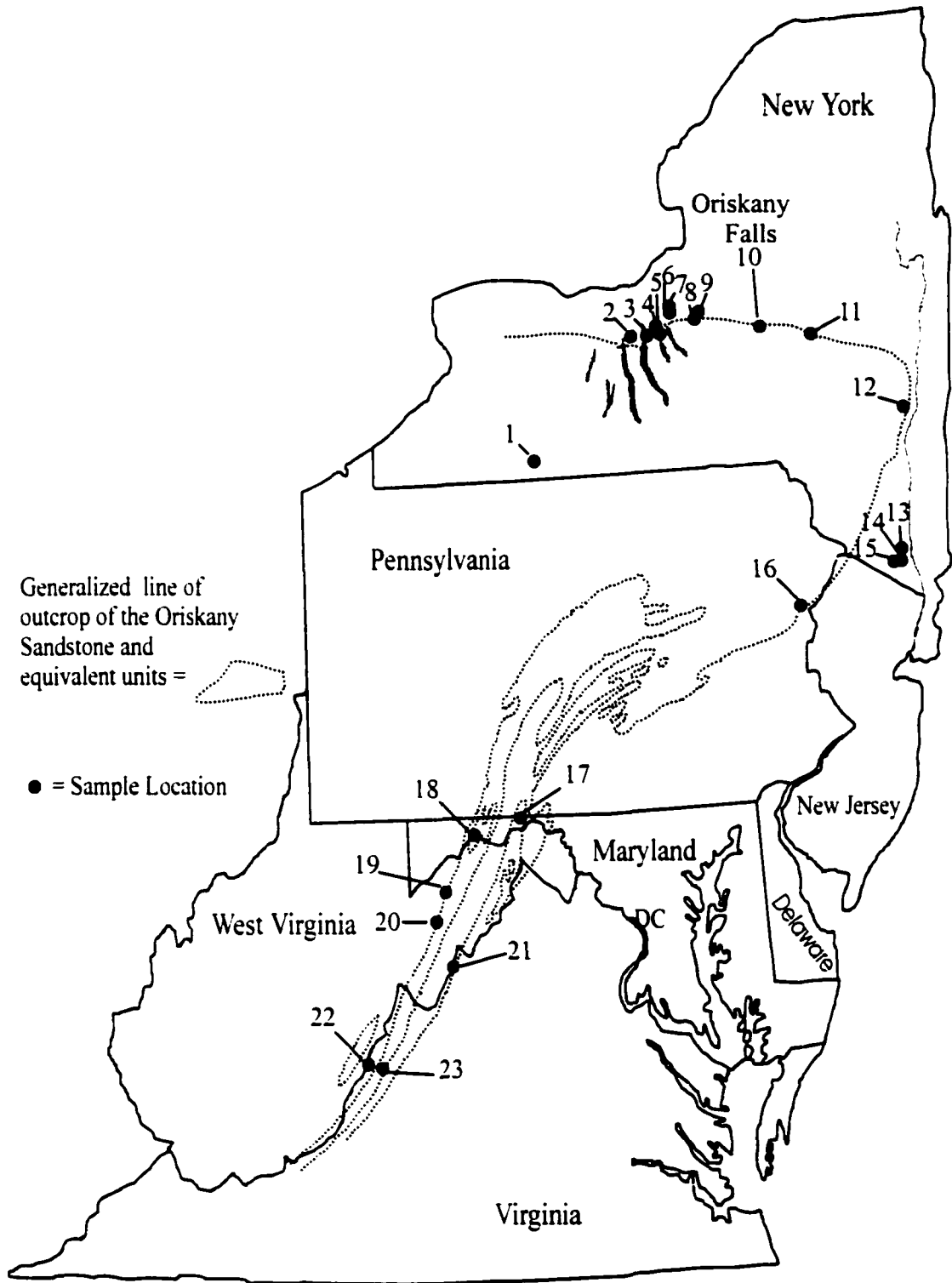
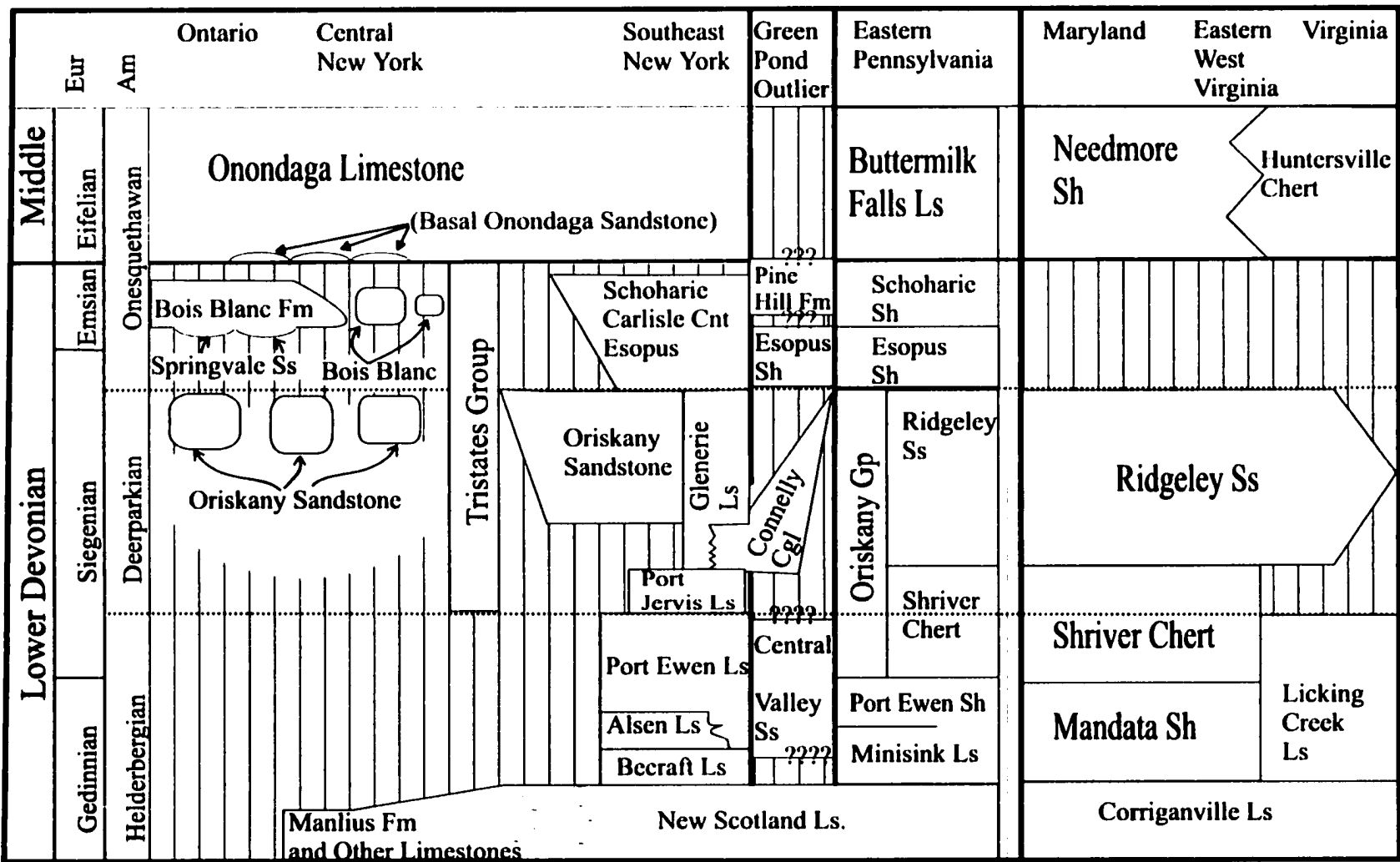


Figure 1.2. Generalized correlation chart for the Oriskany Sandstone. Major stratigraphic units above and below the Oriskany Sandstone interval are shown; locally developed units have been left out. The chart is based on several authors, and where there is disagreement between these sources the newest publication has been chosen (Cooper et al., 1942; Schuchert, 1943; Head, 1974; Dennison and Head, 1975; Rickard, 1975; Berg et al., 1983; Patchen et al., 1985; Milici and Dewitt, 1988; Schwimmer and Frazier, 1987; Harper, 1999). For more localized detailed investigation, the above sources should be consulted. This is because the extent of unconformity between units varies locally and, for instance, Berg et al. (1983) indicate that the contact between the Oriskany Group of Pennsylvania and the Esopus Shale can in places be unconformable.

Unconformities are shown with vertical lines. Where the stratigraphic contact relationship between units is unclear, question marks have been added. Though the Wallbridge Unconformity (underlying the Oriskany Sandstone) is well developed in cratonic areas, western New York, and Ontario, and in the states to the south of New York, within the geosynclinal area of deposition, there appears to have been continuous sedimentation during the interval with only local unconformities.



Witt, 1988; Oliver, 1967; Oliver et al., 1971).

The Oriskany Sandstone has been interpreted as a transgressive sheet sandstone, similar to the St. Peter Sandstone of the Midcontinent, that onlaps a rather gentle topography following a major unconformity (Frazier and Schwimmer, 1987; Stearn et al., 1979). The Oriskany Sandstone is the first-deposited unit of the Kaskaskia Sequence following the Wallbridge Unconformity, which affected the entire craton and eroded sediments along the margin of the Appalachian Basin. The unconformity is the boundary between the Tippecanoe and Kaskaskia cratonic sequences (Sloss, 1963; Brett and Ver Straeten, 1997; Dennison and Head, 1975). Erosion during emergence, for a period of perhaps a few million years, reworked older sandstone units adjacent to the Appalachian Basin that were the source of much of the sand found in the Oriskany Sandstone (Dott and Batten, 1981).

There is a general consensus that the Oriskany Sandstone was deposited in a near-shore or beach environment during the initial Kaskaskia transgression. The robust-shelled brachiopods that dominate its biota and the coarse texture of the sandstone testify to a turbulent environment (Seilacher, 1968). Generally, the Oriskany Sandstone is free of clay minerals, and it was deposited in the basin contemporaneously with carbonate units, suggesting a clear-water sea (Dott and Batten, 1981; Rickard, 1975). It is the first clastic sedimentary unit of any consequence to be deposited in the Appalachian Basin region since the close of the Silurian and covers much of the basin. Younger detrital sediments of the Onesquethawan Stage (Emsian to Eifelian), for example, from oldest to youngest, the Esopus Shale and sandstone, Carlisle Center Shale, and Schoharie

Formation [fine sandstone, siltstone and shale]) of New York, New Jersey, and Pennsylvania, and Needmore Shale of Pennsylvania and Virginia, appear to have a different source that provides more clay; and most likely the influx of these siliciclastic sediments from the east is an early harbinger of the Acadian Orogeny in New England (Eusden et al., 2000), which began with igneous activity in New England more than 400 million years ago. Supporting evidence of this is the newly found bentonite layers in the Esopus Formation and Needmore Shale, which are believed to be from a northern source in Maine where early Acadian tectonism began (Brett et al., 1997; Ver Straeten et al., 1993; Lawrence and Rust, 1988; Solar et al., 1998).

Aside from the main belt of Oriskany Sandstone, some correlative outlier units exist including: Armuchee Chert of northwestern Georgia, which contains sandstones of Oriskany Sandstone or Onondaga Limestone equivalence (Hayes, 1902); the Clear Branch Sandstone of north central Alabama, an Oriskany Sandstone equivalent (Butts, 1927); the Connelly Conglomerate of the Green Pond Outlier of southern New York and northern New Jersey (described below); the Frog Mountain Sandstone of northern and central Alabama and northwestern Georgia, which may include sandstones that correlate with both the Oriskany Sandstone and Onondaga Limestone (Frazier and Schwimmer, 1987); and the Oriskany Member of the Wildcat Valley Sandstone of southwest Virginia and Tennessee (Miller et al., 1964; Dennison and Boucot, 1974). These units, which have only local significance, were mostly named before correlation could be made to the main depositional belt or have a local name because they are lithologically dissimilar to equivalent units in the main depositional belt.

Samples from the Green Pond Outlier were examined in this investigation. No other outlier samples were studied, and because its stratigraphy is a local problem it is discussed further in Chapter 3 under the petrology section of the Green Pond Outlier.

Following deposition of the Deerparkian sediments, another period of erosion occurred along the edges of the Appalachian Basin before deposition of the Limestone units, including the Bois Blanc Formation of Ontario and New York, Onondaga Limestone of New York and Pennsylvania, and the Selinsgrove Limestone of Pennsylvania (Brett, et al., 2000; Milici and de Witt, 1988). This second erosional episode cuts out much or all of the Deerparkian Stage units along the basin margins, which at least partially accounts for the uneven thickness and distribution of the Oriskany Sandstone (Dennison and Head, 1975). As well, it reworks some sand of the Oriskany Sandstone into new discontinuous sandstone units found at the base of the youngest preserved Middle Devonian units.

Sandstones overlying this erosional surface have been studied in New York and Ontario and are often referred to as the Springvale Sandstone (Oliver and Hecht, 1994; Baker, 1983). It is likely that similar, as yet poorly described, units will be found all along the edges of the basin where Middle Devonian rocks unconformably overlie the Oriskany Sandstone (Douglas, 1984).

The extent of the unconformity/hiatus between the Oriskany Sandstone and Middle Devonian Springvale/Onondaga is not well understood, and this may in part be due to the difficulty of distinguishing between true Oriskany Sandstone and reworked Oriskany sand deposited during the Middle Devonian. All of these sandstones grade

upward into carbonate rocks, indicating a reduction in available sand-sized detritus.

Apparently the erosional unconformity and sandstones created by reworking of Oriskany Sandstone are limited to the basin margins, whereas the deeper central portions of the foreland basin had continuous sedimentation throughout this period of erosion. For instance in southeastern New York, Pennsylvania, and West Virginia, Onondaga Limestone (or its equivalent) is deposited on the Oriskany Sandstone without a break in sedimentation (Rickard, 1975; Dennison and Head, 1975). As well, the Huntersville Chert and Needmore Shale are also conformable units on top of the Oriskany Sandstone (Dennison and Head, 1975). These conformable units and the eventual diminishment of coarse detritus marks an end to deposition of mature quartz sandstone deposition in the basin. Though marine sandstones continued to be deposited in the Appalachian Basin during the remainder of the Devonian, they were less mature sediments that reflected a new source formed by the Acadian Orogeny.

PALEOGEOGRAPHY

Preplate tectonic reconstructions of both Siegenian (Oriskany Sandstone time) and general Devonian paleogeography of the Appalachian Basin region, based on lithology and biogeography, generally show a seaway whose entrance is to the south over the present Gulf Coastal region. The basin is bounded by a western land boundary that appears to have coincided with the Cincinnati Arch during the deposition of Oriskany Sandstone (Oliver et al., 1971), a northern land boundary commencing somewhere in

Canada, and an eastern Appalachia-type orogenic boundary (Dunbar; 1960; Schuchert, 1955; Moore, 1949). Later during the Emsian to early Eifelian (late Lower to early Middle Devonian) when transgression onto the craton seems to have been at a peak the transcontinental arch, which was a prominent positive feature during the Devonian, may have been the nearest land to the west (Eardley, 1951). Some reconstructions have an opening continuing out to a continental edge in Newfoundland (Schuchert, 1955). Though these preplate tectonic reconstructions may accurately depict the basin geometry, they do not address paleolatitudes.

More recent paleogeographic maps continue to show a similar basin geometry. It is now understood that the eastern margin orogenic boundary, present since at least the Taconic Orogeny, began to be reactivated in the north, near the St. Lawrence promontory, Canada, about 400 Ma (about the time of Oriskany Sandstone deposition) by plate motions caused by oblique convergence between the Avalon Terrane and North America (Lawrence and Rust, 1988; Solar and Brown, 2001). Igneous activity began in Maine at about this time (Spooner and Fairbairn, 1970; Solar et al., 1998). As the Acadian orogeny continued, its effects were felt farther south along the continental margin for the remainder of the Devonian (Ettensohn, 1985).

Recent reconstructions of the early Devonian paleogeography based on paleomagnetic, paleobiogeographic, and linear magnetic anomalies indicate that North America was part of a larger supercontinent, called Euramerica (Laurussia) that was formed by the merging of Baltica (northwestern and central Europe and parts of Russia) and Avalonia (Newfoundland, England, Wales, southeast Ireland and part of western

Europe) with Laurentia (most of North America, the arctic islands, and Greenland). The Appalachian Basin portion of Euramerica during the lower Devonian appears to have lain somewhere around 35° south latitude (Figure 1.3) (Scotese, 1997 and Scotese, 2001). The orientation and placement of Euramerica is generally supported by Heckel and Witzke (1988) and Witzke (1989) who place, based on paleoclimatic modeling, Euramerica for Lochkovian through Emsian time below the paleoequator in an orientation similar to Scotese's only perhaps 10 degrees farther rotated in a clockwise direction (Figure 1.3b). The reconstruction of Boucot (1988) for the later Early Devonian also shows Euramerica mainly below the equator but has a much larger northern extent to the basin.

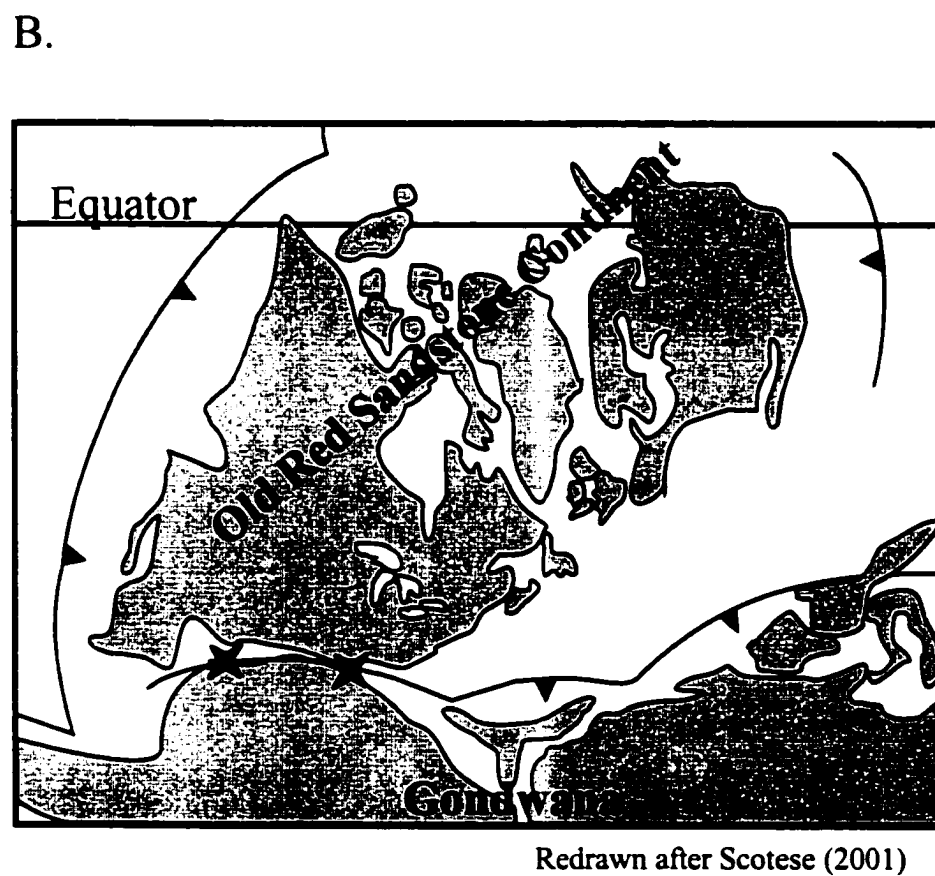
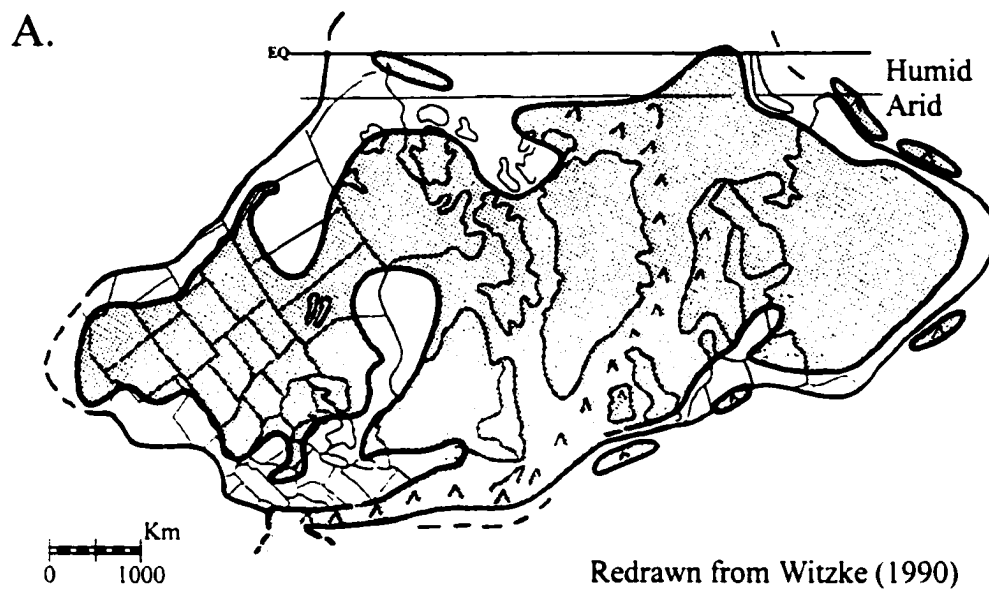
Witzke (1989) shows that the maximum extent of the epeiric sea during the Lower Devonian does not cover nearly as much of the continent as it covered during the middle Devonian (Eifelian-Famennian), and no northern entrance to the Appalachian Basin is indicated. Boucot's reconstruction shows a circulation pattern of southerly derived water entering the basin's east side, continuing northward to the northern reaches of Canada and recirculating down the west side of the basin. Heckel and Witzke's (1980) model shows a cool southwest current in the vicinity of the entrance to the basin, but indicates a probable warm current entering the basin. It is possible that the cooler current could have been deflected into the basin during the Lower Devonian. Koch and Boucot (1982), based on faunal assemblages, suggest that Appalachian Basin waters were cooler at the time of Oriskany Sandstone deposition than they were either before or after when Helderbergian Limestones and Onesquethaw Stage (Onondaga age) limestones were

Figure 1.3. Paleogeographic maps for Laurentia, the Old Red Continent, and Gondwana during the Lower Devonian (~400 Ma).

(A) The map shows a reconstruction of Euramerica for Siegenian through Emsian based on a paleoclimatic model using lithic indicators of climate, modified slightly from Witzke (1989). This map indicates the distribution of land (shaded) and sea at maximum marine inundation (white; the epeiric sea probably extended somewhat farther during deposition of the Onondaga Formation) and gives paleolatitudinal positions based on lithic indicators and a zonal climatic model. The Equator is indicated, along with a lower dashed line that separates proposed humid and arid climates. Witzke and Heckel (1988) suggest that the Appalachian Basin is in southern latitudes below approximately 35° but still within the carbonate belt and not higher than 45° S latitude.

One important aspect of the reconstruction is that a seaway connection is shown between the Appalachian Basin and Michigan Basin through the eastern Great Lakes region and Ontario. This explains the distribution of the Oriskany Sandstone in the Appalachian Basin and southern Ontario and gives a possible explanation of overgrown tourmaline found in Lower Devonian rocks of the Michigan Basin (Alty, 1933; Heinrich, 1965).

(B) Reconstruction of paleogeography of the Old Red Continent and northern Gondwana for the early Devonian, 400 million years ago (redrawn from Scotese, 2001). This map shows major continental boundaries, inferred subduction zones (lines with triangles), and microcontinents. The reconstruction has Euramerica in a similar orientation and latitudinal position as in Witzke (1989), but the data used for the inferred positioning are paleomagnetic data. Avalonia can be seen making first contact with the St. Lawrence promontory. The lower portion of the map shows a brief collision of southern Euramerica with South America (Xs) that closed part of the Rheic Ocean, a prelude to the formation of Pangea. Witzke and Heckel (1988) suggest that an isthmus may have connected Euramerica and southern Gondwana in the early Devonian.



deposited. However, even if waters of the Appalachian Basin were somewhat cooler than at other times, when carbonate sediments and cold intolerant brachiopod communities were more widespread, conditions were sufficient for significant carbonate production since good limestones such as the Port Jervis and Glenora formed in the Deerparkian. This is consistent with paleogeographic reconstructions discussed above that place the basin within the latitudes of the present carbonate belt (Dott and Batten, 1981).

Many recent reconstructions place Euramerica's southern boundary very close to the northern boundary of Gondwana (Figure 1.3) (Scotese, 1997 and 2001; Witzke and Heckel, 1988). Witzke and Heckel (1988) proposed an isthmus extending between northwestern Gondwana in the region of South America that would geographically isolate the Appalachian faunal province and also explains the distribution of the Appalachian Realm fauna in both North and South America and its isolation from the Old World Realm Faunas (Boucot, 1988; Witzke and Heckel, 1988). Rhenish-Bohemian Region (Old World) faunas are excluded from the northern part of the basin by the eastern Appalachia land boundary, but may be able to gain access through the southern entrance (an event that occurs later in the Middle Devonian with a mixing of Appalachian and Old World Realm Faunas).

One important factor for this study is that the sea not only covers most of Appalachian Basin, but also extends one arm into the Ontario and Michigan areas. This suggested connection between the Appalachian and Michigan basins is supported by brachiopod zoogeography (Boucot, et al., 1969; Boucot, 1988) and by the presence of

overgrowth tourmaline grains that are identical to Oriskany Sandstone overgrowths in Monroe County, Michigan (Alty, 1933).

CHAPTER 2

TECHNIQUES OF INVESTIGATION

SAMPLE PREPARATION

Introduction

Interpretation of data obtained on a petrographic sample that has been processed by either physical and chemical means, such as thin sections or heavy mineral separates, could become biased through the inadvertent introduction of artifacts produced by the preparation techniques. A full account of the methods of preparation follows. The analytical techniques are explained with sufficient detail to allow replication in other laboratories.

Every attempt was made to keep the separated heavy minerals in the proportions in which they originally existed in the sedimentary deposit. This ideal state of separation was probably never fully achieved; however, an effort was made to keep the methods of separation consistent, thereby reducing random error so that the results from different samples could be compared.

The heavy mineral suite sought was the nonopaque detrital minerals. In many cases opaque minerals of diagenetic origin, such as pyrite, dolomite, limonite, and hematite, interfered with analysis of the sample by flooding the sample (during the separation procedure) to an extent that they had to be removed to find the minerals of interest. This process of removal, referred to as clarification, may bias the sample by

inadvertently removing less stable minerals such as apatite (Milner, 1962); however, it would be near impossible to obtain information on the mineral population without clarification. The ultrastable suite of minerals found indicates that few unstable minerals are present that would have been destroyed by clarification (Hubert, 1962).

Preparation of Samples for Heavy Mineral Analysis

Disaggregation

Because the amount of induration of samples varied from friable to strongly consolidated, with both siliceous and carbonate cementation, the techniques of disaggregation were varied. The objective was to minimize the amount of breakage of detrital heavy minerals during disaggregation. Thus, for friable samples, crushing in an iron mortar and pestle was sufficient; however, for more indurated samples a mechanical belt-driven jaw crusher was used to comminute samples to approximately 3 mm in longest dimension, and then samples were further crushed using a Bico brand pulverizer yielding a final size approximately that of the detrital framework grains (generally between 0.1 and 0.5 mm in diameter).

To accomplish the crushing, a 0.5 kg to 1 kg sample was tested as to the tenacity of the cementation. If the sample could be fully crushed with a mortar and pestle, it was judged friable. However, most samples were too tough and had to be crushed with the jaw crusher. Small 2.5 to 4 cm diameter fragments, broken in the pestle, were crushed using a jaw crusher with a variable width between the jaws. The jaw width was varied by inserting approximately 1-mm thick shims to close the distance between the jaws from an

initial opening of approximately 10 mm to a final distance of 3 mm at the bottom end of the crusher's jaws. The sample was passed through the crusher 5 times for each setting, and then samples that would not pass through a 1-mm brass sieve were crushed further. The process was repeated after adding a shim until the ultimate setting of 3 mm was attained.

After jaw crushing, a sample that was initially 500 grams typically had only 5 to 10 grams of material remaining that was more than 1 mm in diameter. This coarser material was then used to set the jaws of the pulverizer. The material was passed through the pulverizer, whose steel plates were set approximately 2.5 mm apart. After each pass the plates were brought approximately 0.5 mm closer together until particles produced were of a size approximately equal to that of the original grains. Then the reserved material less than 1 mm in diameter was passed through at this setting.

When the process of crushing was completed, each crushed sample appeared to vary greatly in grain size, from extremely fine, clay-sized particles to approximately the original size of the sand particles composing the rock. This material was then washed to eliminate clays.

Washing

Washing the samples was done to remove clay-sized particles with low settling velocity that fouled the heavy liquid. Fouling means that the clay would be suspended in the heavy liquid, potentially altering the liquid's specific gravity, and clouding the liquid so that it would be difficult to see grains settling through the liquid. The method of washing made use of a large 1-gallon mixing bowl, with a height of 15 cm and room

temperature water (approximately 20°C). The sample was first weighed and then added to the bowl, placed in a flat-bottomed sink, and water was added while the sample was stirred by hand. Then the bowl was filled to within about 5 cm of the top. This meant that the particles after stirring would fall through a maximum height of 10 cm. Since Stoke's Law describes the rate of fall of a spherical particle of given density through a medium of a specific viscosity and density (Krumbein and Sloss, 1963) and is most appropriate for calculating the settling velocity of particles in the size range of 0.2 mm to a lower limit of about 0.0001 mm (Boggs, 1987; Krumbein and Pettijohn, 1938), it can be used to determine an appropriate time for settling that would remove particles smaller than desired for analysis that could potentially foul the heavy liquid. The size of heavy minerals typically analyzed ranges from a maximum of about 0.5 mm to 0.062 mm (mesh 320), the fine sand to silt cutoff point (Mange and Maurer, 1992). A spherical grain of quartz 0.05 mm in diameter (slightly smaller than the desired minimum size) in water of 20°C would settle according to Stoke's Law at a rate of 0.223 cm/sec (or 13.38 cm/minute). Heavy minerals would fall faster because of their higher density. Thus within a minute most heavy minerals of interest should have fallen to the bottom of the basin; however, Stoke's Law is based on many assumptions, including size and shape of particles, viscosity, density, lack of turbulence, etc., that would could negate the accuracy of this calculation. Because what was desired was to remove only very fine particles that would foul the heavy liquid, an empirical time that was sufficiently long to allow heavy minerals to settle and to still have in suspension unwanted clay minerals was found to be 5 minutes of settling. The sediment was allowed to stand for 5 minutes, and then the

supernatant (cloudy water) was decanted. This washing process had to be repeated because no dispersant was used and hand mixing is not completely efficient. It was repeated up to 10 times to remove all fine clay-sized particles. Because it was at first feared that some unpredicted factor such as bubbles in the water would cause particles to float instead of settle, a 230-mesh (0.062-mm) sieve opening was used to pour the supernatant liquid through. It was found that very little sediment of a size larger than the sieve openings was being decanted. Occasionally organic matter, mostly plant root and insect fragments, were found on the sieve, but silicate minerals were not commonly found.

At the same time as mixing, a good quality, capsule-shaped (cow) magnet was introduced into the bowl and forced through the sediments. This magnet picked up iron filings that were generated from the iron plates during crushing. Between decantings, the magnet was removed, rinsed, and then iron filings were removed by wiping the magnet on a foam rubber sponge. The magnetically gathered material was completely wiped off on the foam, and by wringing out, the magnetic material was removed from the sponge into a beaker. The material was then visually inspected to see if detrital magnetic minerals were being removed (detrital minerals were not being removed). In some instances, it was necessary to repeat this step as many as ten times to remove all the iron filings, which may weigh as much as one quarter gram in a five-hundred-gram sample (0.05%).

After washing out of clays and removing iron filings were completed, the samples were decanted completely and then washed and decanted with distilled water. The

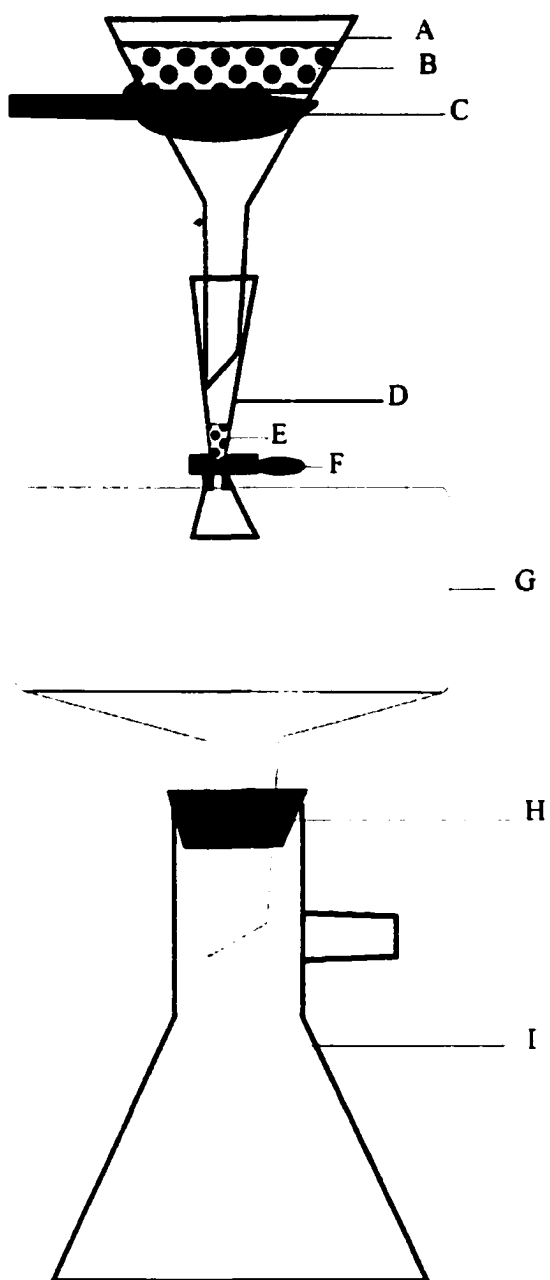
samples were then dried in a 50°C oven for 12 hours.

Separation of Heavy Minerals

Washed samples were initially separated in disposable plastic funnels. Since the entire crushed sample was separated, no splitting was necessary. Initial separation was accomplished in 16-ounce plastic kitchen funnels fitted with latex hosing and a pinch clip (Figure 2.1). A sample of approximately 100 grams was poured into a funnel half filled with sodium polytungstate (Sometu Inc.), with a specific gravity calibrated at 2.89, using a sink float weight (Cargille Inc.). The sample was then stirred and the funnel filled to within 1 centimeter of the top. For the next 2 hours the samples were stirred at 15-minute intervals. Then the samples were stirred once every hour for 4 hours. The samples were then allowed to stand for 1 hour and afterward approximately 50 ml of heavy liquid along with the heavy minerals were siphoned off into a 100-ml polypropylene centrifuge tube. Two funnels' samples filled each tube. Then the tubes were centrifuged for 15 minutes at 2,000 rpm (Mange and Maurer, 1992). The centrifuge tubes were drained by rapidly inverting them over a Buchner type filtering funnel into a coffee filter whose pore size is smaller than that of the heavy minerals. Rapid inversion and maintaining the tubes in an inverted position while using a finger to wipe out any light minerals that clung to the sides of the tube was found to be an efficient means of separating the light fraction from the heavy fraction that clung to the bottom of the tube (a method suggested by Milner [1962]).

The samples were then rinsed from the centrifuge tube, washed in hot distilled water agitated with a magnetic stirrer bar. The water was decanted, and the process was

Figure 2.1. Apparatus used for the separation of heavy minerals. A. plastic funnel, B. mineral grains floating in liquid, C. ring to hold funnel, D. latex tubing over funnel tip, E. heavy minerals, F. pinch clip, G. Büchner funnel holding filter paper, H. rubber cork, I. vacuum flask.



repeated several times. The samples were then transferred to evaporating dishes and dried at 70°C.

Recovery of Heavy Liquid

The sodium polytungstate was recovered from the light fraction of the separate. This was accomplished by draining the sodium polytungstate and light mineral mixture into a coffee filter in a 15 cm Buchner funnel fitted to a vacuum flask. Vacuum filtering was a necessity to speed the rate of recovery of the viscous sodium polytungstate. Further rinsing of the separating funnel and the sediment with distilled water was necessary to recover as much of the heavy liquid as possible. The dilute solution of sodium polytungstate was then allowed to stand in a steep-walled container (Spathe type settling tube) to allow finer particles to settle out. The liquid was then decanted. The solution was evaporated to dryness in a flat-bottom pie plate in a 100°C oven (though the manufacture, Sometu Inc., warns against this, it was found easier to do this than to evaporate the solution back to the correct density). When it had fully dried, the precipitate was loosened from the dish and crushed in a mortar and pestle. The powder then was remixed with water to the proper specific gravity to replenish the dwindling supply of heavy liquid. The remixed and the already mixed sodium polytungstate were carefully filtered to avoid cross contamination of samples.

Clarification of Heavy Mineral Separates

The term clarification refers to the removal of unwanted minerals from the heavy mineral separate. Typically removal is necessary to prevent flooding of the separate with unwanted diagenetic products such as dolomite, hematite, limonite, pyrite, siderite, or

sphalerite, all of which can occur in the sample in variable amounts. These minerals can be present as either grains or surface coatings on the detrital grains and are denser than the heavy liquid used for separation. The adherence of such minerals to quartz can also cause flooding of the sample with quartz.

Two methods of clarification have been advocated: 1) removal by mechanical means and 2) removal by chemical means. Both methods have limitations and drawbacks (Milner, 1962).

Mechanical methods include: 1) magnetic separation, 2) dielectric separation, 3) agitation, 4) vibrational methods for selective shape removal, and 5) flotation methods. In this study only magnetic separation and agitation were used, and only on a few samples; this facilitated the removal of hematite that was present as both a coating and as discrete particles. In some cases these techniques were attempted on limonite with varied, but generally disappointing, results.

Magnetic separation was accomplished using the Frantz Isodynamic Separator. The goal of separation was to isolate as pure a concentrate as possible of the unwanted mineral so that it could be removed from the heavy mineral fraction without removing other minerals of interest. Hematite can be separated using the Frantz Isodynamic Separator at an amperage of 0.6 to 0.7 (Rosenblum, 1958). Typically a setting of slightly less than 0.5 DC amps with a 15-degree side slope and a forward slope of 25 degrees was used to separate black to brown tourmaline from samples with abundant hematite or limonite. This resulted in separate fractions based on magnetic susceptibility, which contained the hematite, limonite, and other minerals not susceptible to low amperages.

Then the amperage was increased so that hematite was susceptible. The less-to-nonsusceptible fraction from the first separation was then further processed, and the susceptible fraction, which typically included the tourmaline without hematite, was put aside. Then the less-to-nonsusceptible-at-low amperage fraction was re-separated in the Frantz Isodynamic Magnetic Separator at 0.6 to 0.7 DC amps using the same slope as above. Hematite was susceptible to these settings (and was in the magnetic portion). The nonmagnetic portion, or not-yet-susceptible fraction from the second magnetic separation run (composed now of minerals other than hematite) was combined with the first magnetic fraction (black and brown tourmaline, etc.); and the fraction from the second run that contained most to all of the hematite was then treated to remove hematite or limonite and recombined with the other two fractions (Milner, 1962; Rosenblum, 1958). The sample after recombination was reduced in size and was re-separated by heavy liquid in a centrifuge tube. This was necessary because with the hematite removed quartz grains that had been coated by hematite were released.

Though some hematite or limonite could be broken down and removed by agitation using a magnetic stirrer bar or ultrasonic cleaning probe, it was found necessary to apply chemical means for complete removal. The method of Leith (1950), using a beaker with a sheet of aluminum wrapped as an outer sleeve, and boiling in oxalic acid, modified slightly by using a magnetic stirrer, was used to remove remaining hematite. This method was found to be very effective. Recombination with the other magnetically separated fractions allowed less stable minerals, such as apatite, to escape this treatment, which could result in its dissolution.

Limonite was not magnetically susceptible except when intimately associated with hematite. Thus a recombination technique could not be used. Limonite was removed using a 3% solution of hot hydrochloric acid. In most cases hydrochloric acid was used after separation of the heavy mineral fraction. A few samples of sandstone with a pervasive limonitic cement or coating were treated before separation.

Pyrite was removed from heavy mineral samples using an 8% solution of hydrogen peroxide. Repeated applications of hydrogen peroxide were needed in some instances. A few samples of mature quartz arenite were boiled with 15% nitric acid to remove pyrite. Removal of pyrite using nitric acid was much more effective than hydrogen peroxide and is less costly, but is more likely to remove apatite and other phosphatic minerals.

The end product of clarification should be a sample of detrital grains composed of nonopaque heavy minerals. However, if a sample was considerably free of interfering opaque minerals, it was sufficiently clarified for study. Therefore small amounts of pyrite, sphalerite, etc., remain in samples, and many samples were considered good enough without any treatment at all.

Thin Section Preparation and Grain Mounts

Impregnation

Thin section blanks were impregnated with blue-dyed epoxy before grinding to help preserve expandable clays (Carrigy and Mellon, 1964). The method used was to mix a batch of epoxy and blue dye resin (Castolite brand CASTOLITE, Inc., 4915 Dean

Street, Woodstock, IL 60098) and place the resin in a polyethylene rectangular plastic mold made in a vacuum desiccator. The previously sawed chip, approximately 22 mm by 50 mm, thoroughly dry from a laboratory oven and still warm was balanced on the lip of the mold. A vacuum of approximately 18 psi was drawn using an electric vacuum pump, and then the entire desiccator was shaken to cause the chip to fall into the epoxy resin. The vacuum was released, and the resin was pulled into the chip's pores by the escape of the vacuum. The chips were then removed and cured in a laboratory oven at 60°C prior to grinding and polishing.

Thin sections were prepared using the Ward-Ingram petrographic saw and grinder. Chips of rock were cut to fit on standard 1 x 2 inch petrographic slides, ground with a succession of carborundum grits, 120, 240, 320, 400, and 600 mesh size, placed on glass plates, and then glued to the slides using epoxide resin. Then the procedures indicated in Ward's manual for saw and grinder were applied, with the exception that final polishing to 30-micron thickness was accomplished on a glass plate using 600 grit.

Feldspar Staining

Thin sections were stained for feldspar. The techniques of staining were by a standard method (Friedman, 1971); to establish that the staining techniques were followed correctly, standards containing plagioclase and potassium feldspar were used; a two-feldspar granite (potassium feldspar and albite) prepared as thin sections was stained, as was a calcium-rich feldspar in thin sections of labradorite. Calcium chloride dip was used to stain sodium-rich albite feldspar red, along with the plagioclase feldspar. During the course of staining, several of these standards were used to insure that the quality of

the reagents remained good throughout the process.

The results of staining of the standards were excellent, and it appears that by analogy should be good for the samples as well. Many of the samples picked up the golden-yellow stain for potassium feldspar, but samples did not show much red stain for calcium. Some of the feldspar appeared to pick up both the red and golden stains from the sodium cobalinitrite and the amaranth, which would suggest sodium-potassium feldspar is present. Since the golden stain dominated, these grains were counted as potassium-rich alkali feldspar.

Carbonate Staining

Because the staining technique for feldspar leaves a red stain that could be confused with the red stain used to identify calcite, only a few thin sections were stained for carbonates. The staining technique was also applied to rock specimens with only moderate success; it was found more difficult to see small areas of stain with reflected light as opposed to transmitted light. The technique used for staining was essentially the one developed by Friedman (1959), though an attempt was made to use the semiquantitative technique of Lindholm and Finkelman (1972). Alizarin red-S and potassium ferricyanide were the stains used. Calcite was stained red by Alizarin red-S, and iron-bearing carbonates were stained blue by potassium ferricyanide. Ferroan calcite stained purple, while ferroan dolomite stained blue. This technique also effectively allows the recognition of nonferroan dolomite because it remains unstained and displays the optical properties and crystal habit of a carbonate mineral. Lindholm and Finkelman's (1972) method, requiring the use of uncoverslipped thin sections, was tried

but abandoned because the resulting stain was subject to damage and did not photograph well without a coverslip. The slides were coverslipped using Canada balsam.

Grain Mounts

Grain mounts for point counting and petrographic examination were prepared by coning and then quartering heavy mineral samples, and requartering when necessary. The samples were then sprinkled on a petrographic slide and a coverslip applied. Then the mounting medium, a thermoplastic (Cargille brand meltmount), with a refractive index of $n_D = 1.704$, was applied. This thermoplastic is viscous at room temperature, and thus the slides are only temporary mounts, due to flow properties of the plastic.

Circular epoxy plugs of selected grains were prepared using one quarter to one half splits of the sample (at least a quarter split was reserved for future study). These mounts, used for microprobe and cathodoluminescence, were prepared using Struer's Caldofix epoxide resin in a 1-inch-diameter polyethylene cylindrical mold. This resin remains liquid until heated to 70°C; thus grains can be aligned in crude rows before curing the resin. Grain mounts were then polished on paper and nylon polishing cloths with 14.5 μm alumina grit until all grains were well exposed, and then polished successively with 5 μm , 3 μm , 0.5 μm , 0.1 μm , and 0.03 μm alumina pastes.

These samples were carbon-coated using standard methods for use in the electron microprobe and scanning electron microscope (Goldstein, et al., 1981).

POINT COUNTING

Petrographic thin sections were point-counted for all framework grains, authigenic

minerals, and porosity, using the Glagolev-Chayes method (Galehouse, 1971).

Heavy mineral modal analysis was carried out, using the methods of Fleet (1926), by counting all grains of interest present when heavy minerals were not abundant. The ribbon method of Van Der Plas (1962) was used when more than 200 nonopaque grains were present on the slide. These methods of point counting allow for the reporting of the number percentage of heavy minerals in the separate. Two hundred grains per sample were considered an adequate number for counting, since at the 95.4 confidence level the probable error is approximately 3 percent (Galehouse, 1971). To minimize the dependence of hydraulic sorting (Morton, 1985) and to appraise the heavy mineral population of the entire sandstone fraction, the 0.062-0.5 mm size fraction was used for analysis, as suggested by Potter and Pryor (1961).

MICROPROBE ANALYSIS

Electron microprobe analysis using wavelength dispersive spectroscopy was carried out using a Cameca SX100 electron microprobe at the Department of Earth and Planetary Sciences, American Museum of Natural History, equipped with a multilayer synthetic crystal for analysis of light elements; assays were carried out down to atomic number 5, boron. A JEOL electron microprobe at the Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, was also used with the same standards as used at the American Museum of Natural History.

In order to facilitate comparison of samples from both the American Museum of

Natural History and Rensselaer Polytechnic Institute, a set of silicate standards and glasses was prepared to use at both on both microprobes (see Appendix 3). At the American Museum of Natural History spot size on samples analyzed for boron was set at 2 microns with an accelerating voltage of 10 kilovolts, a beam current of 100 nanoamps, and counting times of 60 seconds for boron and 30 seconds for background. Fifteen kilovolts and 10 nanoamps with 20 seconds' counting time on the peak and 10 seconds on the background were used to analyze F, Na, Mg, Al, Si, K, Ca, Mn, Ti, Fe, Cr, and V. Some samples were not analyzed for fluorine, and some samples were analyzed for chlorine using 15 kilovolts and 10 nanoamps with 30 seconds' counting time on the peak and 10 seconds on the background.

At Rensselaer Polytechnic Institute, conditions used were the same as for the samples at American Museum of Natural History, but boron, chlorine, and fluorine were not analyzed in order to decrease the spot size to 1 micron and reduce the time needed per analysis.

Detection limits at the American Museum of Natural History were as follows: B 461 ppm, Si 667 ppm, Al 528 ppm, Mg 504 ppm, Fe 1893 ppm, Na 695 ppm, Ca 597 ppm, F 1724 ppm, V 662 ppm, Mn 1663 ppm, K 532 ppm, Cl 277 ppm, Cr 206 ppm, and Ti 2790 ppm, using the following standards available from the American Museum of Natural History, respectively: SRM93a (B) (borosilicate glass), orthoclase 1 (Si), anorthite (Al), Kakanui hornblende (Mg), Rockport fayalite (Fe), albite (Na), Wakefield diopside (Ca), synthetic MgF_2 (F), vanadium grossular (V), rhodonite (Mn), orthoclase 1(K), scapolite (Cl), MgCr_2O_4 (Cr), TiO_2 (Ti). A characterization of the standards is

given in Appendix 3.

These standards were chosen to try to facilitate the best matrix comparable to that of tourmaline; however, because of differences in the matrix the reproduction of the detection limits in the samples of tourmaline is extremely difficult to obtain. For instance, volatilization of sodium, light elements such as boron, fluorine, and chlorine, as well excitation of an area bigger than the predicted volume would tend to increase the amount of error in precision (Goldstein et. al., 1981; Reed, 1995). However, some studies of repeated analysis of single spots have suggested minimal boron loss over time (Henry and Guidotti, 1985; McGee et al., 1991).

Analytical data are given in Appendix 4 and 5; the results are based on a structural formula that was calculated on the basis of 31 oxygen (Selway et al., 1999).

SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy (SEM) was done using a JEOL JSM-6301F scanning electron microscope equipped with a field emission electron gun and energy dispersive spectroscopy.

The samples were prepared by placing them on an SEM sample-holding stub using double-sided sticky vinyl tape. The tape was sliced into thin strips that allowed conductive material to make contact with both the sample and the SEM sample holding stub. The samples were then coated for conductivity using gold.

Images were acquired using Polaroid Type 55 film, and then the images were

scanned using a Hewlett Packard C4200 flat bed scanner with a resolution of 600 dots per inch.

CATHODOLUMINESCENCE

A small amount of cathodoluminescence was done on tourmaline using the JEOL electron microprobe at the Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute. Most cathodoluminescence was done at the Department of Earth and Planetary Sciences, American Museum of Natural History, using a Luminoscope[®] model ELM-3R. The luminoscope follows the basic design described by Marshall (1988) for a cold cathode system. Though conditions varied because of sample differences and machine condition, an attempt was made to use an accelerating voltage of 22 kilovolts and a beam current of around 0.5 milliamps in a vacuum of about 50 millitorr. Spot size was varied using external magnets, and this probably affected the final voltage exciting the specimen.

An attempt was made to analyze tourmaline grains mounted in epoxy resin, but this was abandoned because of excessive beam damage and charring of the epoxy resin. Polished petrographic thin sections were analyzed, and though some beam damage was recognized, it was possible to take color micrographs of features using magnifications of 50 to 100X. Bright luminescence was seen in carbonate cement. Typically, calcite luminesced a yellow-orange, dolomite luminesced orange-red, while ferroan cements had reduced luminescence and some were nonluminescent, particularly ferroan dolomite.

Brachiopod shells unless damaged were mostly nonluminescent, feldspars with both microcline twinning and albite twinning luminesced a bright robin's-egg blue, quartz gave relatively low brown to brownish purple colors to blue-violet colors, and chert luminesced a bright blue in some instances. Phosphatic material luminesces a violet to purple color. Tourmaline did not luminesce under these conditions, while zircon luminesced a lemon yellow and some zoning was visible. Authigenic feldspar luminesced a medium dark blue, while authigenic quartz was nonluminescent. Further discussion of luminescent minerals is found in the petrographic descriptions of selected samples. All luminescent colors reported are from visual examination and could not always be accurately captured in color photographs; as well, both blue-dyed epoxy resin and some glass slides luminesced slightly under the conditions used and may have modified the observed colors.

CHAPTER 3

PETROGRAPHY

GENERAL CHARACTERISTICS OF THE ORISKANY SANDSTONE

The Oriskany Sandstone is an important hydrocarbon reservoir rock from New York to West Virginia (Finn, 1949; Hamilton, 1937; Harper, 1993); because of this, its reservoir characteristics and petrology have been studied by many workers (Douglas, 1984; Heald, 1962, Heald et al., 1962; Lafferty, 1938). Since it is the first well-developed clastic unit deposited in the Devonian of the central and southern Appalachians, it is reasonable to use this unit as a point of comparison for later clastics, particularly for a comparison of changes in detrital mineralogy. Most investigators believe that sand for the Oriskany Sandstone was derived from older sedimentary units and that detrital minerals went through multicycle reworking before their final deposition (Dott and Batten, 1981). Hence, the unit is a baseline for pre-Acadian orogenic source terrains, and any variations in later units reflect new sources that most likely were the result of the Acadian Orogeny. Though many researchers have described the mineralogy of the Oriskany Sandstone (see Table 1.1, Chapter 1), new methodologies such as electron microscopy, cathodoluminescence, whole-rock chemical analysis, and staining techniques have been employed to provide new information and illustrate important aspects of the sandstone's petrology. As well, it would not be appropriate to describe the sandstone's tourmaline overgrowths and other important aspects of the heavy mineral suite from the



various locations and not give an accompanying description of the whole-rock samples.

The Oriskany Sandstone can be characterized as a supermature quartzarenite to conglomerate. In the lower Hudson Valley, in the Green Pond Outlier and near Kingston, New York, sandstones and conglomerates equivalent to the Oriskany are present, but the conglomeratic facies is particularly well displayed in the Connelly Conglomerate (Chadwick, 1908). From near Albany southward to Port Jervis area of New York, the unit equivalent to the Oriskany is the Glenerie Formation, which is a limestone facies. Farther west in Central New York, the Oriskany is typically a clean quartzarenite, varying from a white to light gray color in fresh outcrops to a rusty limonite-stained color in weathered exposures. In eastern Pennsylvania and farther south along the Appalachian trend where tectonic effects have deformed the sandstone into resistant ridges, the Oriskany is equivalent to the Ridgeley Sandstone member (the sandstone facies Oriskany Group in both Pennsylvania and Maryland) and is composed of both clean quartz sandstones and conglomerates. Farther south in Virginia and West Virginia, the sandstone is again referred to as Oriskany Sandstone. Along its entire outcrop, the Oriskany Sandstone and its equivalents remain marine in origin and are characterized by a host of thick-shelled brachiopods referred to as the Big Shell Community by Boucot and Johnson (1967). These thick-shelled brachiopods, an adaption to shallow, agitated water, allow easy recognition of the unit (Cahall, 1956).

Generally the quartz grains of the Oriskany Sandstone are well rounded and highly spherical. Where there is silica cement present in the Oriskany, well-developed quartz overgrowths mask the rounded nature of the grains, but often “ghost” outlines of the

original detrital grains can be found that reveal the predepositional nature of the detrital grains (Figure 3.1).

The cementing agents of the Oriskany are generally quartz or carbonate cements, sometimes occurring together (Figure 3.1). Carbonate cements include calcite, ferroan calcite, dolomite, and ferroan dolomite. These cements were recognized only qualitatively using staining methods (Lindholm and Finkelman, 1972). Douglas (1984) reports ankerite cement as well, but this must be recognized as containing more than 20% iron, which cannot be done with staining. In some instances, leaching of original cements has led to the creation of limonite-cemented sandstone. This limonite could be derived from either iron-rich carbonates or pyrite weathering. In other instances, leaching of cement has left a very clean quartz sandstone that crumbles in hand into individual sand grains.

In the Syracuse area along Interstate 81, hematite and chamosite (both accompanied by ooids of the same material) cement the sandstone (Dossert and Chamberlain, 1983; Brett and Ver Straeten, 1997). The dark color of the chamosite has suggested to some that the outcrop is cemented with phosphate, but whole-rock analysis indicates only traces of phosphorus. Chamosite is the iron end member of the chlorite group (aluminosilicate) (Nesse, 1991). Phosphatic nodules and cement do not seem to occur in the Oriskany Sandstone but have been found in the Springvale Sandstone by Baker (1983), the Onondaga Limestone's Edgecliff member sandstones (Oliver and Hecht, 1994), and the Glenerie Limestone, as discussed below.

Cementation of the Oriskany does not seem to follow any geographical pattern

Figure 3.1. Cementing agents in the Oriskany Sandstone. Oriskany sandstone from Oriskany Falls, Oneida County, New York, Eastern Rock Products Quarry.

(A) Cross-polarized view of sandstone. In most samples quartz is the major cement. Overgrowths of quartz on well-rounded detrital grains show that when originally cemented the sandstone was texturally mature. The “ghosts” of these original grains are preserved as dust lines (D). At the point labeled C, two dust lines meet, forming a straight-line contact.

(B) Cross-polarized view of sandstone. Besides quartz overgrowths (dust lines labeled D), carbonate cement (CO_3) also acts a cement in most samples. The carbonate cement may somewhat embay quartz grains, but acts mainly as an intergranular cement.

(C) Plane-polarized view of sandstone. In this illustration an overthick thin section (approximately $45\text{ }\mu\text{m}$ thick) is used in order to have the blue-dyed pores contrast strongly with the quartz overgrowth. As can be seen in the center of the micrograph, an extremely well-developed overgrowth with a nearly hexagonal outline has formed on a well-rounded sand grain. A dust line (Dl) highlights the original detrital grain outline. Other grains also have well-developed but smaller overgrowths. However, even though there are significant overgrowths, some primary porosity remains. Pyrite (P), present in all thin sections from this locality, has grown into the pore space and seems to have disrupted a quartz overgrowth’s formation. This suggests that pyrite- and quartz-authigenesis were penecontemporaneous.

(A)



(B)

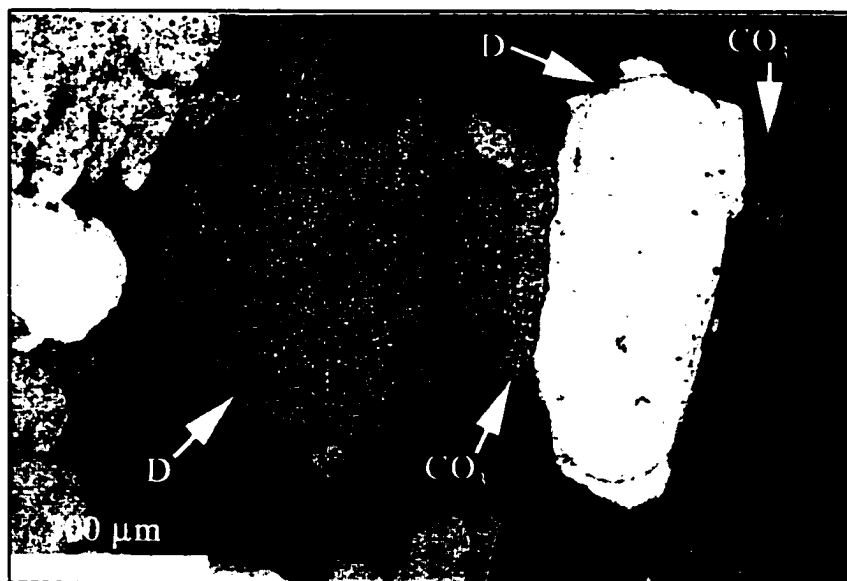
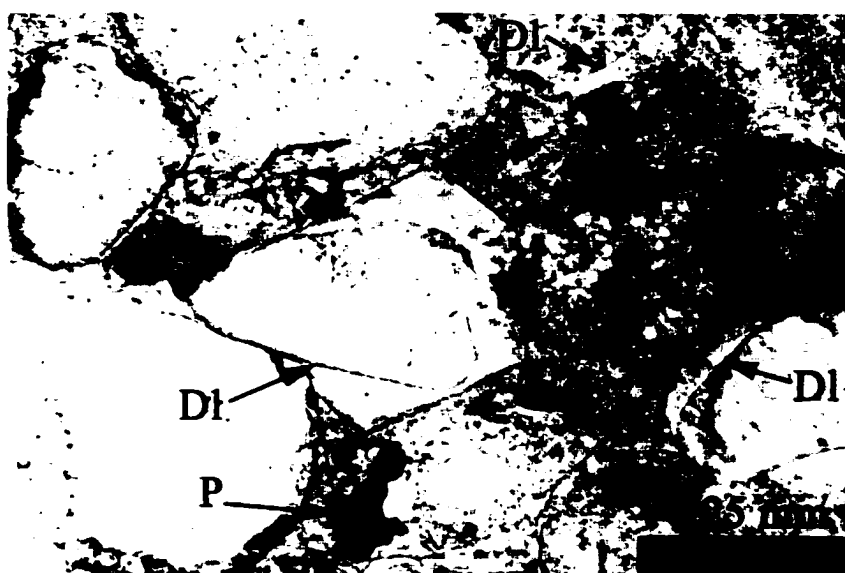


Figure 3.1–Continued

(C)



and varies from pervasive, creating a well-indurated calcite- or silica-cemented quartzite, to only moderately to weakly indurated units. Even in a single exposure, samples of the sandstone can vary from crumbling as described above (for example at Tonoloway Ridge, Maryland) to layers that have a pervasive silica cement and are extremely tenacious. Reported porosities in the Oriskany vary from 0 to 15% (Fettke, 1938; Finn, 1949; Douglas, 1984).

Sandstones Created by Reworking of Oriskany Sandstone

Sands from the Oriskany Sandstone are reworked into the younger, Middle Devonian sandstones that form in a marine environment after a period of emergence. The sandstones present several stratigraphic problems, as discussed below, and are often incorrectly collectively referred to as “Springvale Sandstone” (Apsouri, 1934; Oliver, 1954). Some authors believe that the Oriskany sands had never been lithified before reworking into Middle Devonian units (Apsouri, 1934; Dennison, 1961; Baker, 1983).

The name Springvale Sandstone is derived from Stauffer’s (1913) original designation for a basal sandstone member of the Bois Blanc Formation (Late Emsian) (which he incorrectly called Onondaga Limestone) whose type locality is at Springvale, Ontario (Cowan, 1977). The Springvale Sandstone of Ontario and Western New York is situated at the base of the Bois Blanc Formation (Emsian) and rests unconformably on the Silurian (Bass Island Formation) or the Oriskany Sandstone (Oliver, 1967). The Springvale Sandstone contains fossils similar to those found in the Bois Blanc Formation. In New York, a similar sandstone is located at the base of the Edgecliff member of the

Onondaga Formation (Eifalian, Middle Devonian) and is reworked from either the Oriskany or Springvale Sandstone (Apsouri, 1934; Oliver and Hecht, 1994). It is very difficult to distinguish between the Oriskany Sandstone, Springvale Sandstone (basal Bois Blanc), and basal Edgecliff sandstone, and this has led to confusion in their field relationships (Baker, 1983; personal communication Oliver, 1998). The term Springvale Sandstone seems to be used by most workers by default to describe any sandstone developed from reworking Oriskany Sandstone sand into younger units (younger than Siegenian age). Apsouri (1934) argued correctly that the term Springvale Sandstone is incorrectly used in most examples in New York and that the unit is found at the base of the Onondaga Limestone. He proposed a new name, Syracuse Phosphatic Sandstone, which is not appropriate because it lacks a type area and is not mappable. Fossils are difficult to find in these units, but Oliver and Hecht (1994) propose that most units containing nodular phosphate are basal Edgecliff sandstones. This proposal is somewhat negated by the discovery in this study that some of the nodule-bearing sandstones originally thought to be phosphatic are not phosphatic and that the dark nodules are sandstone cemented with iron silicates (probably chamosite).

In this study several samples of reworked sand from the Oriskany Sandstone were investigated, and they are best described as basal Onondaga Limestone. Reworked authigenic tourmaline was found in these samples.

SAMPLE DESCRIPTIONS

New York Samples

Samples from Western and Central New York are located in the Appalachian (Allegheny) Plateau Province and are flat lying to gently dipping and little deformed (Isachsen et al., 1991). Green Pond Outlier samples are from the Valley and Ridge geographic province.

Auburn

The sample was collected near Auburn, Cayuga County, on the south side of U.S. Route 20 just west of the intersection with Half Acre Road. The exposure is described by Douglas (1984). The Oriskany Sandstone outcrops as a thin ledge just slightly above ground in a wooded area. It is moderately friable, with some more tightly cemented layers, and has abundant brachiopod molds. Some brachiopod fossil fragments retain their calcitic composition. No sedimentary structures are visible. The sandstone is stained brown in many instances by limonite. Some white sandstone can also be found but is spotty within the same layers.

The rock is a fossiliferous, medium-grained quartzarenite with mixed carbonate and quartz cement (Figures 3.2 and 3.3) (Folk, 1968). The detrital component is over 99% monocrystalline quartz; there is almost no feldspar or clay. Small amounts of relatively fresh, sand-sized microcline and untwinned potassium feldspar are present.

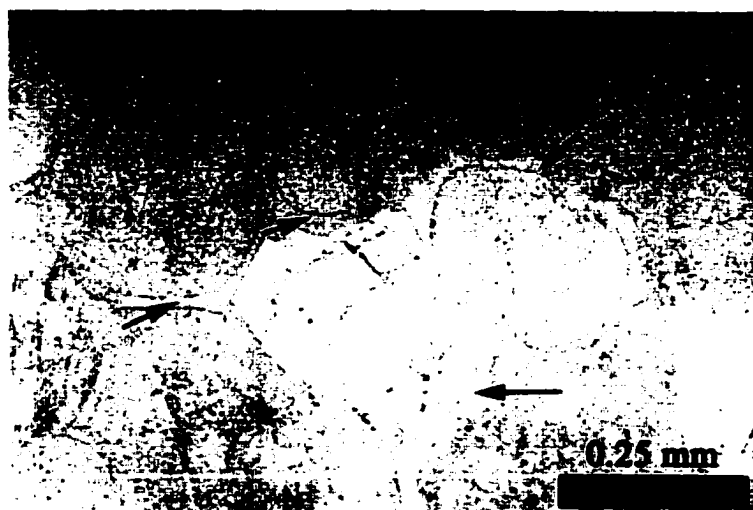
The feldspar has bright blue luminescence, typical of detrital feldspar (Kastner and Siever, 1979). Feldspar overgrowths were found on 62% of the feldspars grains

Figure 3.2. Petrographic thin section of sandstone from Auburn. The sandstone is cemented by quartz overgrowths. Several quartz grains have thin dust lines that reveal the nature of the detrital grains. The grains' detrital cores are subangular to well-rounded in this field of view. The well-developed overgrowths occlude all intergranular porosity. The straight-line contacts between overgrowths indicate that pressure solution/compaction has not been a major factor in porosity loss.

(A) Plane-polarized light micrograph of quartz grains with overgrowths. Arrows (red) point to dust lines that reveal the original detrital grain boundaries.

(B) Same field of view as in A (above). Cross-polarized light micrograph of quartz grains with overgrowths. The overgrowths and detrital cores are in optical/crystallographic continuity (syntaxial overgrowths), and both cores and overgrowths go extinct together. Red arrows point to dust lines that were illustrated in A (above). The dust lines are prominent enough to stand out even in a cross-polarized light micrograph. If the dust lines were not present, it would be possible to interpret this sandstone as strongly polygonized by pressure solution.

(A)



(B)



Figure 3.3. Petrographic thin section of calcite-cemented sandstone from Auburn, New York. Relatively early precipitation of cement has prevented quartz authigenesis. The nature of the detrital grains' original grain outlines is preserved. Other samples of the same sandstone from other areas in the exposure have no carbonate and are cemented by quartz overgrowths.

(A) Cross-polarized light view of sandstone. Detrital quartz is cemented by anhedral calcite. Calcite cement is not pervasive in any of the thin sections and is most abundant in areas around fossil fragments. This strongly suggests that it is derived by local recrystallization of fossils.

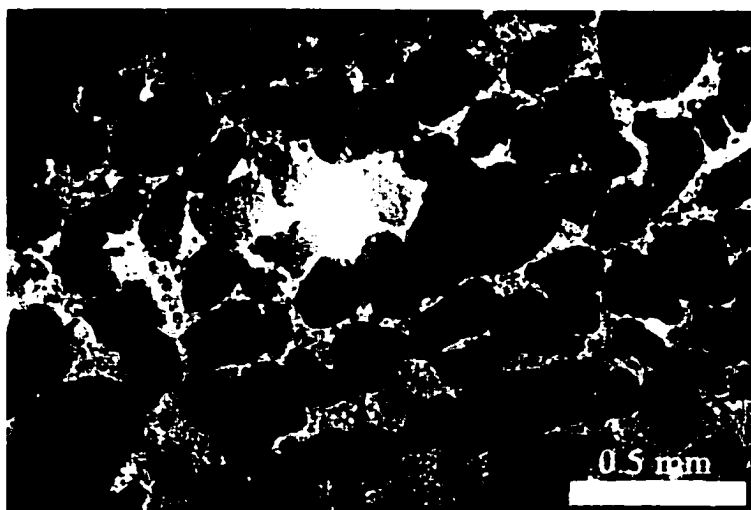
(B) Cathodoluminescent micrograph of the same area shown in A (above). Calcite cement luminesces yellow-orange, and quartz luminesces shades of blue and purple. Note that no overgrowths of quartz are present. This suggests that quartz authigenesis took place after recrystallization and mobilization of calcite in fossil fragments. The original detrital outlines in this sample compare well with those seen in Figure 3.2. Detrital quartz grains were originally moderately well rounded to subrounded in texture.

A bright blue luminescing potassium feldspar grain in the center of the field of view has been overexposed, so that the luminescence of quartz and carbonate would be visible.

(A)



(B)



examined in this sample. However, since feldspar is typically only present in trace amounts, feldspar overgrowths are still quite rare.

Feldspar overgrowths are common in samples from western New York but are mostly absent from other localities. Because similar looking overgrowths occur in several samples, they are described in some detail here (further details can also be found in the section on Discussion of Authigenic Components below). Feldspar overgrowths were found mostly on microcline and untwinned potassium feldspar grains. Plagioclase feldspar is not common in any samples of the Oriskany Sandstone, but one overgrowth on a plagioclase grain was observed (Figure 3.4). The syntaxial overgrowths of mostly untwinned cloudy feldspar filled available pore space around the detrital cores. Occasionally microcline appears to have twinned overgrowths (see discussion below of authigenic components; this is also described by Carozzi [1960]). The overgrowths have distinct dust lines and start with cloudy, brownish rims and then continue as clear overgrowths (Figure 3.5). The overgrowth and core boundary looks similar to that of authigenic quartz overgrowths; however, so far none have been found to be as well developed or as large as the quartz overgrowths. Some grains have feldspar overgrowths on only a portion of the grain, while others seem to have them on all sides. This is presumed to be related to available space for growth.

They have extinction behavior similar to the detrital cores or go extinct at a small angle to the detrital cores (Carrozi, 1960). This same type of overgrowth style, with a slight difference in extinction position between the detrital core and overgrowth, has been observed by the author in Middle Cambrian sandstones from the Midcontinent in

Figure 3.4. Feldspar with authigenic overgrowth, Auburn, New York. The condition of feldspar in the Oriskany Sandstone varies from partially dissolved to relatively fresh. In several localities a few alkali feldspar grains, usually microcline, have overgrowths. In this thin section only two overgrowths on feldspar grains were encountered. The overgrowths are similar to those found in the Midwest in Cambrian sandstones. There is usually a very slight variation in the extinction position of the overgrowths and detrital cores. Typically the overgrowths are clearer than the detrital cores, but in a few instances, the overgrowths seem clouded with bubbles.

(A) Plane-polarized light micrograph of detrital feldspar that has an authigenic feldspar overgrowth (Fo). The condenser aperture has been closed to increase contrast. Both the overgrowth and the detrital core are relatively fresh. The detrital feldspar grain itself appears slightly rounded, while the overgrowth's straight-line contact with surrounding quartz grains suggests that it grew until it made contact with other grains in the sandstone and all pore space was occluded.

(B) Cross-polarized light micrograph of the same area seen in **A** (above). The detrital feldspar displays albite twinning. The overgrowth has no twinning and is a little closer to extinction than the detrital core. A small offset in optical properties was noted. The feldspar grain is abutted on all sides by monocrystalline quartz. A small amount of alteration is evident in the form of high-birefringent clay, but in general the feldspar appears relatively fresh.

(A)



(B)

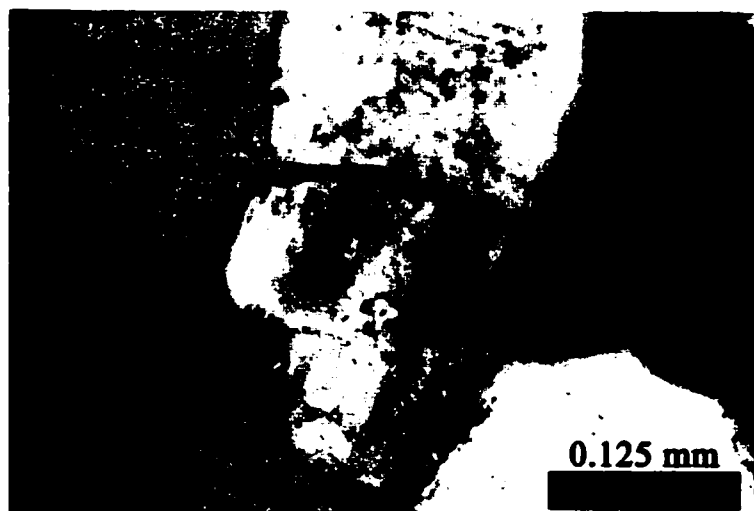
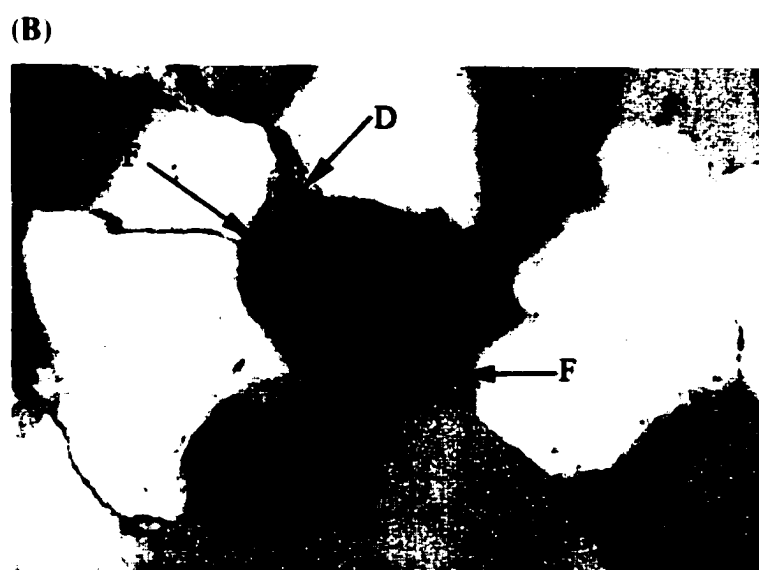
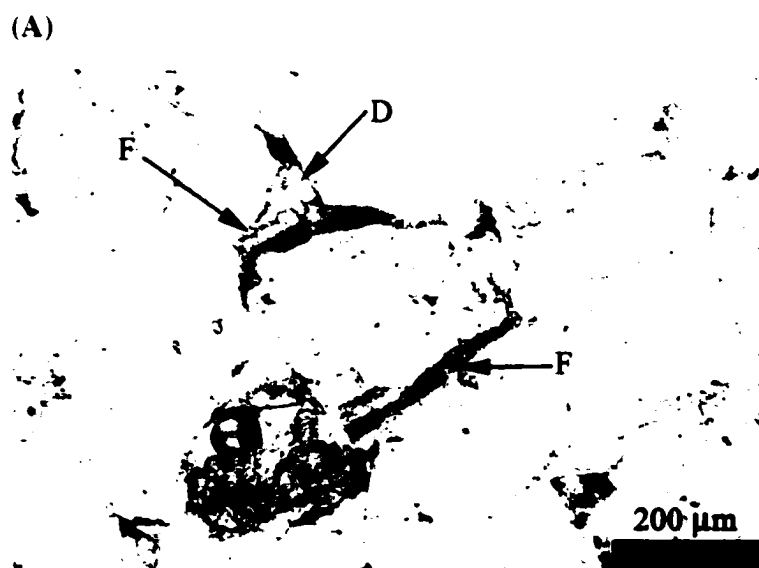


Figure 3.5. Feldspar overgrowth in sandstone. The sandstone was collected near Auburn, New York, Stop 5 of Douglas (1984), and ~62% of the feldspar grains have overgrowths.

(A) Plane-polarized light micrograph of authigenic feldspar overgrowth. The overgrowth (F) is present on two sides of the detrital core. It extends outward perhaps 20 μm , filling intergranular pore space. The overgrowth is very cloudy at first, perhaps due to fluid or other inclusions. Some overgrowths seem to have a reddish brown material (possibly hematite) close to the detrital core. In the upper left hand corner, the overgrowth extends farther, and the cloudy rimming authigenic feldspar is followed by a clearer feldspar. The rest of the pore space is filled with anhedral dolomite (D) that slightly embays the overgrowth.

(B) Cross-polarized light micrograph of the same area seen in A (above). The overgrowth is at extinction, and a small angle can be seen between the overgrowth and the detrital core's extinction position. The detrital core displays spindle twinning typical of microcline. Whatever the inclusions are in the overgrowth, they do not appear to be birefringent. Small amounts of anhedral calcite can be seen on the left side of the feldspar grain and on the top of the grain. The calcite on the top is embaying the feldspar overgrowth slightly, and this suggests that the feldspar overgrowth grew prior to calcite formation. This judgment is based in part on other overgrowths observed in the sample that suggest the paragenetic sequence feldspar overgrowth followed by calcite and quartz overgrowths occur at about the same time as calcite cement.



northeastern Iowa where it grows on detrital rounded cores.

Shell fragments of brachiopods are composed of nonluminescent calcite that in part retains prismatic shell structure. There has been some recrystallization, and glide plane cleavage with twinned appearance is present in some brachiopod shells.

The sandstone appears well cemented, predominantly by silica; some parts of the rock have carbonate cement. But this carbonate cement is spotty and even in a single thin section parts of the sample have differing cements; calcite (stained with Alizarin red S) is found near fossil fragments and appears to form at about the same time as quartz overgrowths (Figures 3.2 and 3.3). In areas of thin sections with fewer fossils, silica or ferroan calcite and dolomite cements are more common. Some void-filling anhedral ferroan calcite (purple staining) and rhombic ferroan dolomite (blue staining) are scattered throughout the sandstone. The ferroan cements are not directly associated with fossil fragments, and do not embay quartz. These cements appear to form after quartz overgrowths.

Quartz grains have well-developed overgrowths that give the sandstone a polygonized appearance in thin section whenever silica is the cementing agent (Figure 3.2). When fossil fragments are nearby, anhedral yellow-luminescing calcite is common. Cathodoluminescence reveals that calcite and dolomite and ferroan dolomite cements slightly embay authigenic quartz (Figure 3.6). Sand grains surrounded by dolomite cements tend to be more strongly embayed, while sand grains surrounded by calcite retain their subrounded to moderately rounded detrital outlines (Figure 3.3). Calcite may interfere with quartz overgrowths' formation. The interference with quartz overgrowths

Figure 3.6. Petrographic thin section of sandstone from Auburn, New York. The sandstone is cemented by a combination of carbonate and silica cement. Quartz overgrowths with dust lines are rather rare in this example, so that cathodoluminescence is needed to reveal the nature of the grain boundaries of the detrital quartz. Using cathodoluminescence, the grains appear to have been originally moderately well rounded to subrounded in texture. Some parts of the sandstone have either pure silica cement or only carbonate cement. This field of view displays a combination of both cement types.

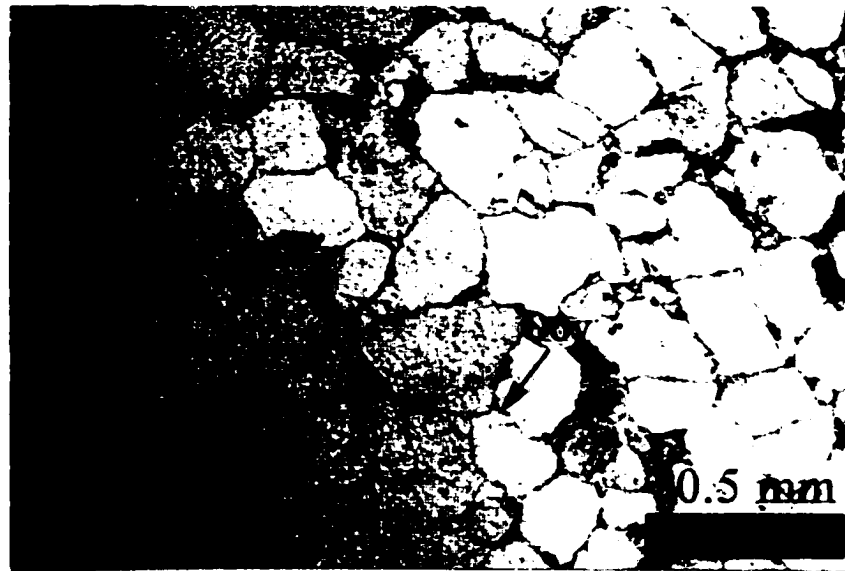
(A) Petrographic thin section using plane-polarized light. Only a couple of quartz grains in this field of view have obvious overgrowths with dust lines (Qov). Many of the grains seem subangular to angular and to have been tightly compacted together.

(B) Same field of view as in **A** viewed with cross-polarized light. The grains that do not show any dust lines appear to be subangular to angular because the overgrowth quartz is in optical continuity with the detrital grains. Arrows labeled Qov point to the same grains pointed to in **A**.

(C) Same field of view as in **A** and **B** viewed using cathodoluminescence. A single rounded feldspar grain can be seen with bright blue luminescence in the middle of the field of view (F). An observation of **A** (above) indicates that the feldspar is relatively fresh and clear without clay alteration. Carbonate cement luminesces a yellow-orange (calcite) to red color (dolomite). Detrital quartz varies from a medium bright blue to a maroon color. The overgrowth quartz is darker in color (less luminescent), and original detrital boundaries can now be observed. Arrows point to areas where considerable overgrowth silica cement can be seen. In this view several of the grains that look subangular to angular would now be considered moderately well rounded, and the overall texture of the sandstone can be interpreted as subrounded to moderately rounded in texture.

Yellow-orange luminescing calcite seems to slightly embay quartz grains, but it is also clear that overgrowths of quartz are much less common in carbonate-cemented areas. This suggests that calcite is preventing some later quartz authigenesis and may be penecontemporaneously forming with quartz overgrowths and perhaps continues to form after quartz overgrowths. Close-up observations of dolomite cements show that ferroan dolomite and dolomite typically form after quartz authigenesis and tend to embay quartz grains to a greater extent than calcite cements.

(A)



(B)

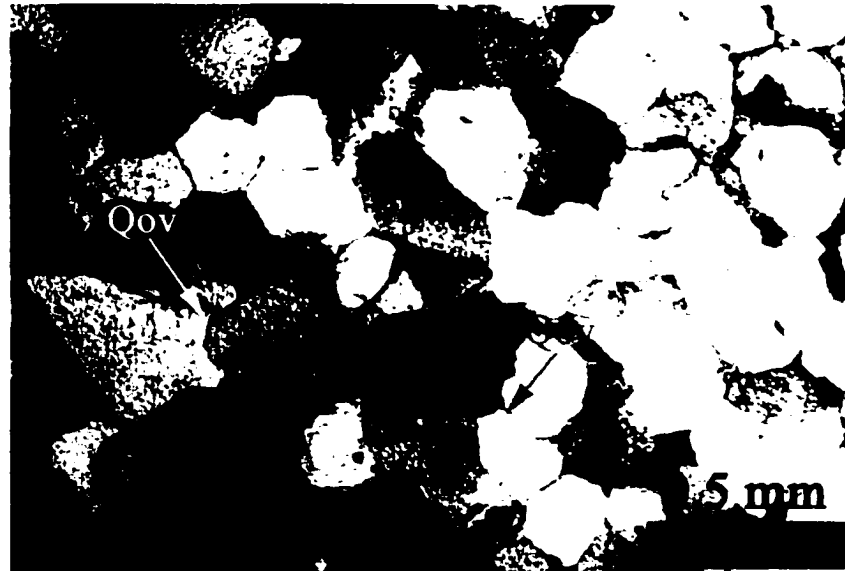
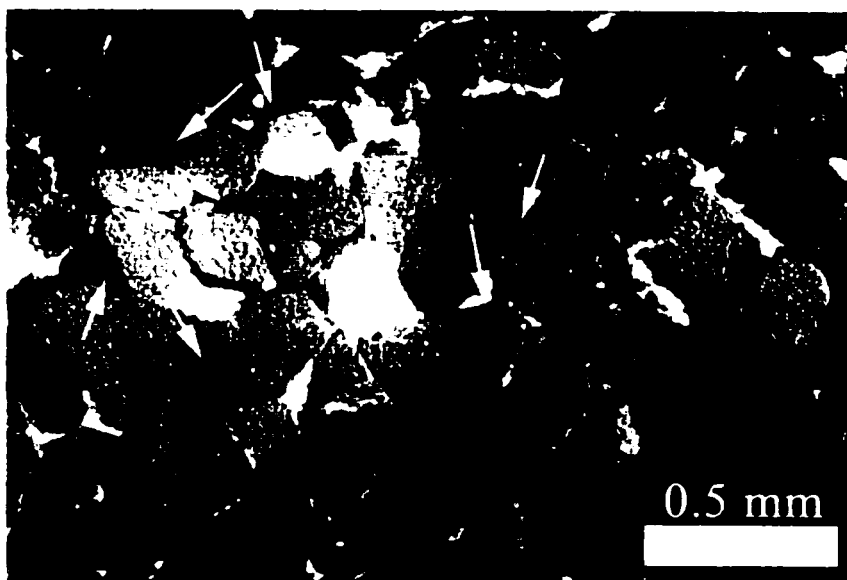


Figure 3.6—Continued

(C)



by calcite along with the absence of quartz overgrowths when calcite surrounds quartz grains as the sole cementing agent suggests that calcite cement formed before or contemporaneously with quartz overgrowths.

Austeel Plant

The sample was collected at the Austeel plant in Auburn, Cayuga County. The locality is described by Baker (1983) as her Section 12, an abandoned quarry just north of Auburn, west of New York Route 34. An extension of the Austeel plant is now located in the quarry. This is an unusual sandstone that may in fact be younger than the Oriskany and could be described as either Springvale Sandstone (according to Baker [1983]) or Onondaga basal sandstone. The sandstone contains large fist-to-head-sized black nodules at first thought to be phosphatic sandstone (they were described as such by Baker [1983]). The nodules occur in layers of both black sandstone and in layers of white sandstone. A sample analyzed from a black sand layer was surprising. Though the hand sample of sandstone appeared black, upon crushing and examination with a low power lens the sand grains are dark gray, almost pure quartz with only partial covering, perhaps 3 to 8% black fine-grained material, that caused the whole rock to appear black. Thinking that it was phosphatic material, an attempt was made to remove it by boiling in 10% hydrochloric acid. However, much of the dark material remained, inviting the speculation that some of it may in fact be carbonaceous material and/or clays. The black material could not be removed when the sample was boiled with 20% nitric acid for an hour. A whole-rock sample was found to contain only 0.08 weight % P_2O_5 .

Chemical analysis gave the following results for a whole-rock sample: SiO_2

85.36%; Al_2O_3 , 3.9%; Fe_2O_3 , 1.49%; MgO , 1.5%; CaO , 1.29%; K_2O , 1.79%; TiO_2 , 0.29%; loss on ignition 3.15%; totaling 98.7 weight % of the sandstone. Compared to a more typical sample of the Oriskany Sandstone, which contains between about 91-100% SiO_2 and 0 to 8% CaCO_3 , this is an unusual occurrence. It is believed that most of the elevated levels of cations are contained in the black intergranular material. Based on the elemental analysis, there could be glauconite, illite, and/or chlorite (chamosite) in some combination. As well, some of the loss on ignition could be from organic carbon compounds that were present in the sandstone and would also be concentrated in this intergranular material.

In thin section the sandstone has moderately rounded to angular quartz grains with an occasional grain of potassium feldspar. Grains do not show quartz overgrowths, and this invites the speculation that cementation was relatively early, preventing quartz authigenesis found in many examples of the Oriskany Sandstone (Figure 3.7).

The cement or matrix material is a fine-grained, tan-brown to dark brown material that is either isotropic or has very low birefringence and occludes most porosity (Figure 3.8). An anomalous green-gray color is seen in this material using cross-polarized light, and it may be either chamosite or glauconite. Glauconite has been reported in the Springvale Sandstone by Cowan (1977). Silt-sized to sand-sized rhombic carbonate material is encased by the brown cement. Pyrite is also present in small quantities as both framboids and irregular masses that coat detrital grains.

Along with the paucity of quartz overgrowths, other evidence suggesting that the intergranular material may be matrix deposited syndepositionally with the sandstone is

Figure 3.7. Sandstone from the Austeel Plant, Auburn, New York. This sample has an unusual iron-rich cement or matrix. The cement/matrix is believed to be either glauconite or a form of the mineral chlorite (chamosite), based on whole rock analysis, but this has not been verified. A small amount carbonate and pyrite are also present. No fossil fragments have been noted. The intergranular material is probably at least in part matrix, because it appears to have prevented quartz authigenesis and shows signs that it was compacted with quartz grains.

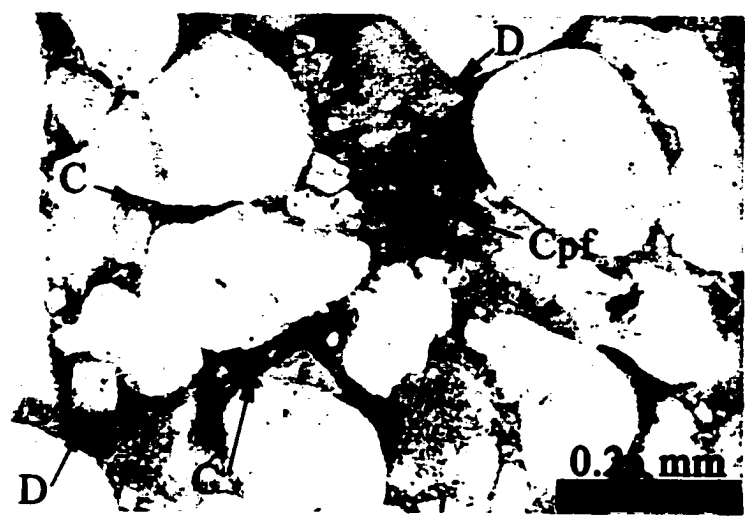
(A) Plane-light image of sandstone. Moderately well-rounded to subangular quartz grains, without authigenic overgrowths, are cemented by a greenish-brown, fine-grained cement. Some of the cement appears to be pore-filling clay (Cpf), while at grain contacts between detrital grains the clay appears to be denser and perhaps has been squeezed into intergranular positions (C). This suggests the clay is depositional in origin, rather than authigenic and is supported by the fact that no quartz overgrowths are present on detrital quartz grains and that quartz grains though in contact with each other have relatively few grain contacts compared to more compacted typical sandstones. Dolomite rhombs (D) are present in intergranular pore spaces and suggest that all pore space was not tightly filled when they developed; since pore spaces are so well filled with clay, it seems reasonable to assume that dolomite formed before the grains and matrix were compacted to their present state.

(B) Polarized-light image of the same view as in **A**. Dolomite rhombs (D) display high birefringence, while clay minerals (Cpf and C) have relatively low birefringence.

(C) Another view in plane light of the sandstone. In this view there appears to have been a little more compaction than in **A** and **B** (above); however, there is still clay separating most grains. Some of the clay-filled areas in this view are suspected of being discrete clay particles or pellets of some kind (Pe). They appear to have discrete boundaries and to have been squeezed as coherent particles. As well, though it is hard to see in this view, their color is a little greener than other parts of the matrix. Some of the clay appears to be pore-filling matrix (Po), as opposed to crushed pellets, but interpretation of the clay's origin is difficult. Pyrite (Py) also is abundant in this sandstone. Dolomite is also present as a pore-filling constituent (D). Detrital grains in this view include well-rounded to subangular quartz and a polycrystalline feldspar and quartz grain (F) that is composed of two distinct microcline crystals with differently oriented microcline twinning. This grain should most likely be interpreted as a crystalline rock fragment. Such grains are rare, and this is the only one found in several thin sections of this sample, though individual microcline grains occur infrequently in trace amounts.

(D) Polarized-light image of the same view as in **C**. Microcline twinning is visible on two crystals (F). Dolomite (D) displays moderate birefringence. Pyrite is opaque (Py), and clay minerals (Po and Pe) have uniformly low birefringence.

(A)

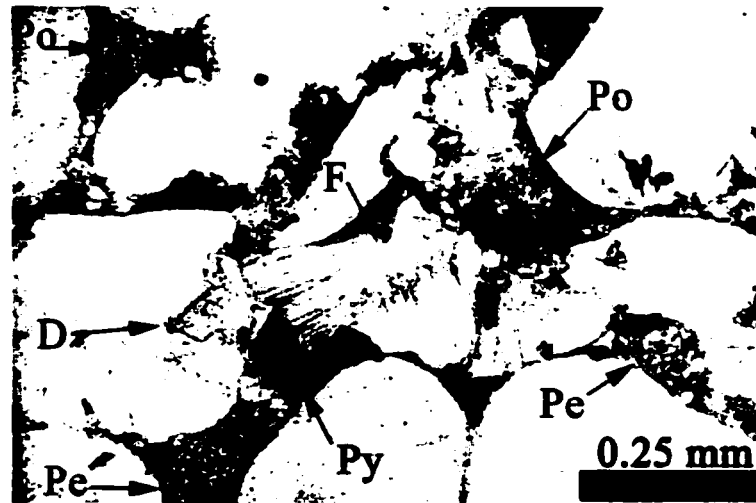


(B)



Figure 3.7—Continued

(C)



(D)

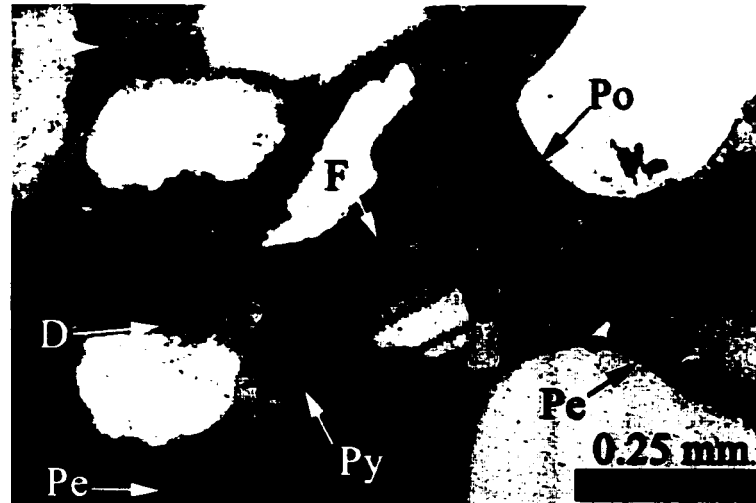


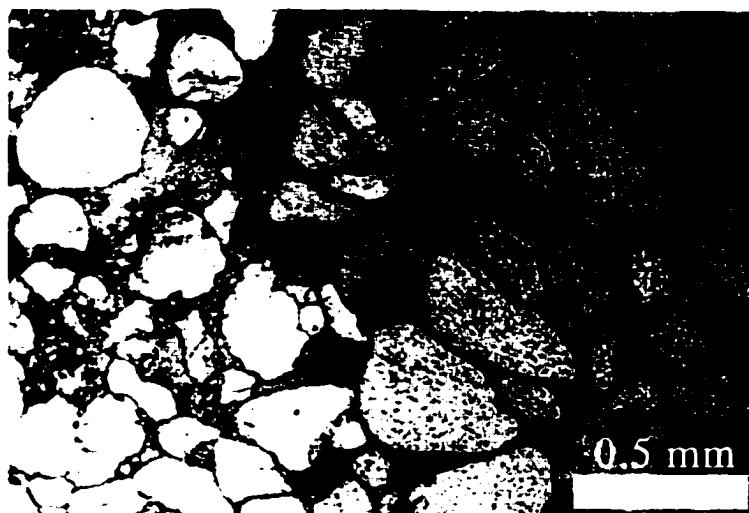
Figure 3.8. Sandstone from the Austeel Plant, Auburn, New York. This sample has an unusual ferroan cement or matrix (referred to here as matrix). The matrix is believed to be either a form of the mineral chlorite (chamosite) or glauconite, based on whole-rock analysis, but this has not been verified. A small amount of dolomite is also present in the matrix. No fossil fragments have been noted.

(A) Plane-light image of sandstone. Moderately well-rounded to angular quartz grains are cemented by a greenish-brown fine-grained matrix. In hand specimens the matrix looks black. The brownish color may be due to limonite formed by oxidation of the matrix. The small, light brown-colored grain towards the center of the field is untwinned feldspar.

(B) Polarized-light image of the same view as in **A**. The cement appears to be isotropic, but may exhibit very low birefringence. Either the material is matrix or an early-formed cement that retarded quartz authigenesis. Though the quartz grains are rather large, most grains in this sandstone are monocrystalline; there is very little polycrystalline quartz in this sandstone.

(C) Cathodoluminescent view of the same field as in **A** and **B**. The very bright grain in the center of the field of view is feldspar. Quartz grains luminesce a darker blue to purple color. No quartz overgrowths are visible. Dolomite cement is orange red, and the major cementing agent, possibly glauconite or chamosite, luminesces a faint greenish color.

(A)



(B)

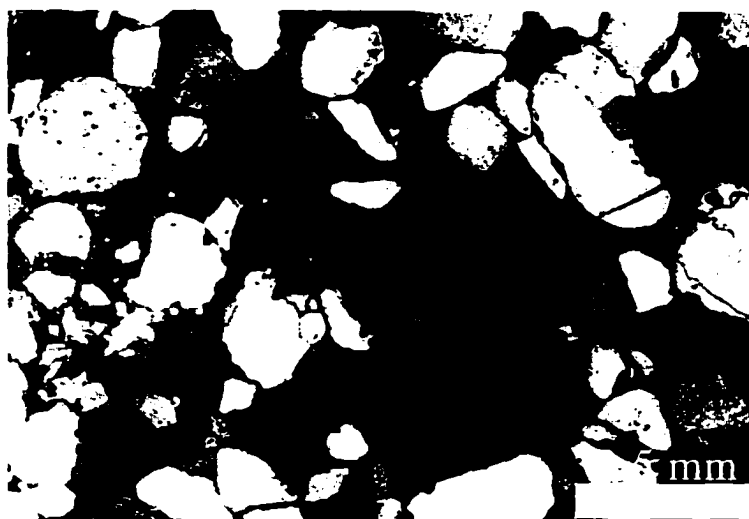
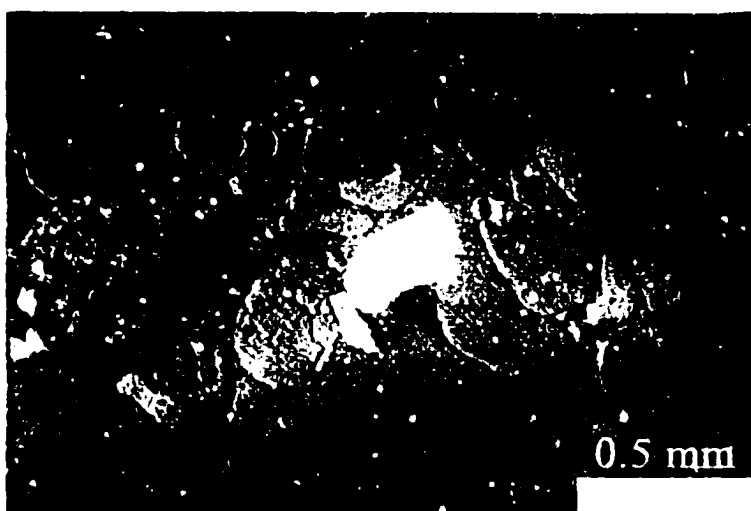


Figure 3.8—Continued

(C)



the presence of pellets that appear to be discrete entities subjected to compaction and made of the same material as the matrix. As well, the lack of tight grain contacts suggests that matrix held quartz grains apart during compaction.

This sandstone with its unusual mineralogy and nodules suggests an unusual depositional setting. Further characterization of the mineralogy, particularly of the matrix, and further investigation of the sandstone's depositional relationship to other units is needed to fully understand the unit's formation. Problems of sparsity of fossils and the lenticular nature of the sandstone will make such investigations difficult. The texture of the sandstone and the tentative assignment of the black matrix material as chamosite, based on optical properties and whole-rock chemical analysis, allow some tentative discussion of how this and other chamosite-bearing sandstones originated as discussed below. The fact that sand in this sandstone is probably reworked from the Oriskany Sandstone and that syndepositional matrix has prevented any authigenic quartz formation may have bearing on the timing of quartz authigenesis in the Oriskany Sandstone.

Austin Glen

A sample of the Glenerie Formation was collected in Catskill Creek, Austin Glen, just down stream from the Route 23 bridge over the creek, Green County, New York. This sample was collected at Stop E-3 of Brett and Ver Straeten (1997), who correlate the unit with the Connelly Conglomerate and consider it to be a sandy phosphatic lag deposit. The sample for this study was taken from the basal bed of the Glenerie Formation and directly overlies the Wallbridge Unconformity (Sloss, 1963). Though the unconformity is

apparent here, farther east near Port Jervis, New York, the Glenerie Formation conformably overlies the Port Jervis Formation (Brett and Ver Straeten, 1997).

Only petrographic analysis was done for this sample, because the unit contains only about 5-8% detrital quartz and not enough sample was collected for heavy mineral analysis. In hand sample, the rock is a gray-brown sandy limestone, with a few unusual rounded black phosphatic grains reaching up to about a centimeter in diameter. No whole-shell fossils were seen, though fragments of brachiopod shells are identifiable.

In the thin section, the rock classifies as a sandy limestone, but it has some unusual features, which could certainly be related to a lag deposit origin. Detrital, or at least transported, materials include in order of abundance: abraded calcitic shell fragments, mainly from brachiopods; well-rounded, phosphatic material including some distinctive nodules with an internal concentric layering; round grains of what appears to be phosphatized limestone with some glauconite included in the grains (one sample was a calcisiltite and another appeared to have calcareous sponge spicules in it); bits of phosphatic or phosphatized shell material from invertebrates; well-rounded monocrystalline quartz; well-rounded grains of polycrystalline quartz; well-rounded chert with polygonal sutures; possible detrital carbonate rock fragments that appear to be mainly recrystallized sparry calcite (some of which have been replaced by zebraic chalcedony [Scholle, 1979]); sporadic grains of feldspar (both plagioclase and microcline); and isolated grains of glauconite.

Authigenic material includes sparry calcite that appears to have formed from recrystallization of carbonate shell and possible rock fragments, some sparry calcite that

replaces silicate minerals, and zebraic chalcedony and chert that replace fossil fragments. The chalcedony that replaces calcitic fossils and a few fossil fragments is replaced by coarser equant-grained microquartz crystals, and some microquartz also has a rhombic shape and probably pseudomorphs, carbonate rhombs. Pyrite is abundant; both stringers and framboidal forms are present. Pyrite is found scattered in the matrix and associated with some skeletal fragments.

All of this material is held in a matrix of micrite. The detrital components seem to float in the matrix, and the sample is not grain supported. There is no evidence of stratification or sorting in the sample, and the abraded fossil fragments and round nodules suggest they were transported and moderately abraded before deposition. This sample certainly appears to have the characteristics of a lag deposit. Aside from the nodules, the phosphatic material is probably all skeletal material. The skeletal material tended to be elongate, homogeneous brown phosphate (Figure 3.9), in places replaced by pyrite. As well, microquartz in drusy fills and rims is often associated with the phosphate.

Cathodoluminescent analysis of the rock (Figure 3.9) revealed that phosphatic material, both nodules and skeletal debris, luminesced shades of purple-lilac. Carbonate skeletal debris had a uniform yellow-orange luminescence. Detrital quartz and some of the silty matrix were nonluminescent, while authigenic microquartz in drusy fillings and replacement chert both luminesced in shades of purple.

Though this sample was not analyzed for heavy minerals, it does have some characteristics in common with other units investigated. This sample has similarities to the phosphatic nodule-bearing, sandy-textured limestone collected at Nedrow, New York.

Figure 3.9. Thin section of Glenerie Limestone from Austin Glen, Greene County, New York. At this location the Glenerie Formation is a sandy limestone with abundant phosphatic material. It directly overlies the Wallbridge Unconformity and has been interpreted as a lag deposit (Brett and Ver Straeten, 1997). Fossil fragments of both calcium carbonate and phosphatic material are common, along with rounded phosphatic nodules. Some chert and microquartz replacement occurs, and there is abundant pyrite.

(A) Plane light image of the limestone. The matrix is micritic calcite with abundant small fossil fragments and quartz silt. This matrix encloses detrital grains of both monocrystalline (Qm) and rare polycrystalline quartz, fossil fragments, and phosphatic and carbonate lithoclasts. Fossil fragments (Ff) include brachiopod debris, but it is relatively finely commuted. Sponge spicules are suspected but not confirmed. Phosphatic material, in part, is probably of skeletal origin (Pf) (based mainly on morphology), but there are also rounded nodules of sand- to pebble-sized silty phosphatic material (Pn). Carbonate lithoclasts (Lc) are relatively common. Some are very similar to the matrix material, while others are dolomitic. Unusual opaque/pyritic grains (Op), which are typically elongate and appear to have elongate internal openings that are often filled with microquartz are common (these might be plant material with vascular structure). Chert partially replaces calcitic and phosphatic material (Ch). Some chert displays a zebraic texture. Notice that a horizontal fracture cuts across the image intersecting one of the monocrystalline quartz (Qm) grains and the phosphatic (Pf) and opaque grains (Op) in the middle of the field of view.

(B) Polarized-light micrograph of the same area shown in **A**. Phosphatic material appears dark, because it is nearly isotropic. One area on the phosphatic fossil fragment shows higher birefringence, and this may be a replacement mineral (possibly Wavellite) or another phosphate mineral with moderate birefringence. The material filling the grain Op can now be seen to be microquartz that forms a drusy filling.

(C) Cathodoluminescent image of the same area shown in **A** and **B**. Notice that the matrix material appears speckled orange and black (darker areas are quartz silt). Several of the grains luminesce a lilac purple. All phosphatic material (Pf and Pn) was noted to luminesce this color, and chert and microquartz (Ch and Mqtz) of suspected authigenic origin also luminesce this color. The grain Op luminesces particularly well where microquartz is present, and is nonluminescent in portions without quartz. It is not clear what the luminescent activator is that causes this purple luminescence, but it is unusual and was only seen at this location. Most likely the activator in this case is an element that was incorporated into porous materials, such as the phosphatic debris, and into authigenic minerals.

(A)



(B)

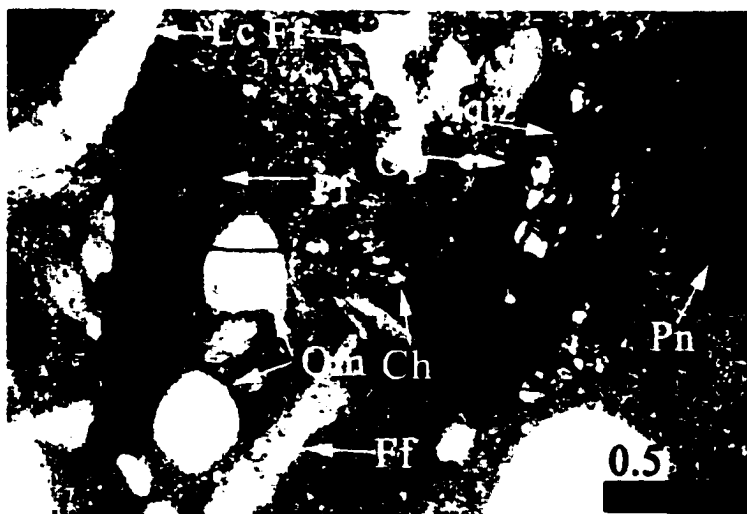
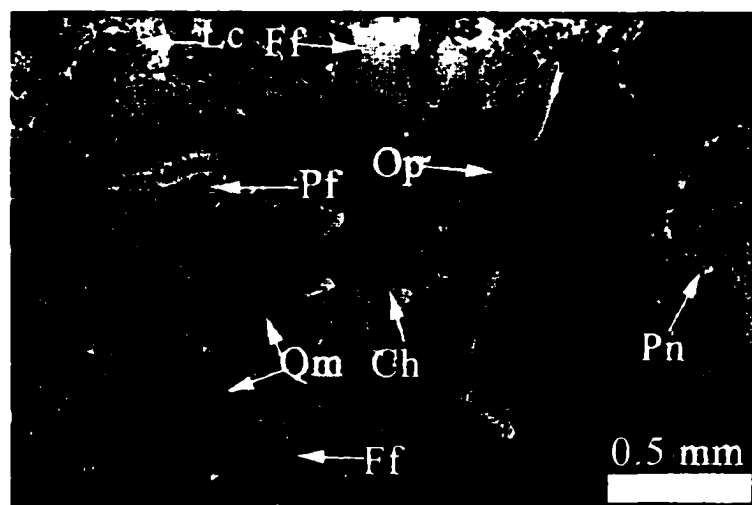


Figure 3.9—Continued

(C)



Though the sample is texturally more complex than at other localities where the Oriskany Sandstone was collected, its detrital component is similar to both the Oriskany Sandstone and the Springvale Sandstone.

Cherry Valley

The sample was collected from the Cherry Valley locality 0.3 m (0.5 km) east from New York route 166 along New York Route 20, Otsego County, New York. This locality is described as stop E by Liebe and Grasso (1990), and a carefully measured stratigraphic section is available from Voorhees (1982). The Oriskany disconformably overlies the Kalkberg Limestone and appears to have been eroded on its upper surface before deposition of the Esopus Formation.

The Oriskany Sandstone is an approximately 0.75 meter thick, massively bedded, medium- to coarse-grained, tan-colored, calcite-cemented quartz sandstone. A small amount of brown clay coats grains and is a minor cementing agent. The outcrop is moderately weathered, and ledges of the sandstone have rounded edges. The sandstone's quartz grains are well rounded and tend to be spherical (Figure 3.10); there is at least a suggestion of bimodality in the quartz sand grains, and this observation was also made by Voorhees (1982). They float in a matrix of smaller grains along with echinoderm skeletal debris (columnals and arm plates) and brachiopod shell fragments that behave as framework grains. The echinoderm and brachiopod debris are strongly modified, abraded and broken, and recrystallized, and grains were modified enough so that they were hard to recognize. The criteria of microporous texture, shape, and unit extinction were applied to identify echinoderm debris. Echinoderm fragments do not have the syntaxial

Figure 3.10. Petrographic thin section of the Oriskany Sandstone, Cherry Valley, New York.

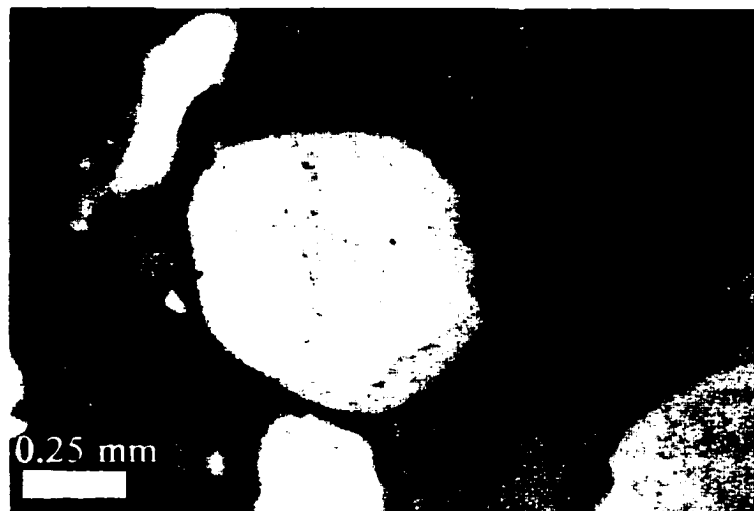
(A) Plane-light image of well-rounded quartz (Q) and abraded echinoderm grain (E). The photograph is given a brown hue by clay minerals that form small discontinuous rims on detrital grains. To the left of grain Q, detrital matrix material is visible. The matrix is angular and is mineralogically less mature than the more rounded larger grain. There appears from qualitative observation to be a bimodal distribution of the quartz grains. In this field of view the largest quartz grain, Q, is typical of the larger sized grains, while the smaller well-rounded grain just above the scale bar is typical in size of the small and yet rounded grains. Very few transition grains between these two sizes have been observed.

(B) Polarized light view of the same area. Quartz grains are light gray. The detrital matrix is mostly low-order colors from quartz and clay minerals that have low birefringence. There is a small amount of anhedral calcite cement to the right of the large quartz grain, and this and the echinoderm grain both display higher birefringence.

A.



B.



overgrowths frequently encountered in encrinites. Though coarser shell material tends to be sparse, some larger brachiopod shell fragments, up to 3 cm, were observed.

Brachiopod debris was identified by shape and parallel fibrous wall structure (parallel to the shells' exteriors, reminiscent of a horse's mane).

The fine sand- to silt-sized matrix has a diverse detrital mineralogy of carbonate shell fragments, mainly brachiopod debris (recognized by shell structure and size); fragments of echinoderm columnals dominate the biogenic component; angular detrital grains of quartz, rare microcline and rare plagioclase feldspar, trace amounts of biotite mica, and some quartz-mica tectonites make up the remainder of the matrix. The feldspars were recognized by twinning and cleavage and are surprisingly fresh in appearance. Cathodoluminescence of the sample also revealed that the blue-luminescing feldspar is present only in the matrix. Because the feldspar grains are irregularly shaped and small, it appears that they have suffered some abrasion. No feldspar overgrowths were found.

The same material that acts as matrix in some examples is present in discrete stringers in the sandstone. However, no clear laminae of finer grained material are visible in hand samples. This suggests bioturbation. This bioturbation may explain in part the bimodality of the sample.

Clearly authigenic components in the sandstone include: calcite cement; chalcedony that can be void filling, but also replaces fossil fragments; both crinoid fragments and brachiopod debris; and pyrite (mostly in framboidal form). Only relatively small quartz overgrowths were observed at this location, and they are very uncommon,

and thus detrital grains retain their original shape. A modal analysis gave the following results: 57% monocrystalline quartz, 28% carbonate cement (and perhaps some recrystallized fossil fragments), 10% echinoderm fragments, 4% brachiopod fragments, and 1% pyrite. These results would classify the sample as a carbonate-cemented sandstone, and this is in agreement with Liebe and Grasso (1990) and Voorhees (1982) who describes the unit as a quartzarenite.

Crandall Estate Well #1, East Independence Field

The sample of the Crandall Estate Well #1 (serial no. 437) core from the East Independence Field in Andover township, Allegany County, New York, drilled by The Sylvania Corporation in 1971, provided by the New York State Geological Survey, was retrieved from a depth of approximately 4,999 feet (1,524 m). The core was described by Van Tyne (1971).

The sandstone is tan to beige, medium grained and has several lenses of brachiopod shells. Several stylolites occur in the sandstone.

Mineralogically, the sandstone is a quartzarenite (99% monocrystalline quartz in the detrital fraction). The framework is made of well-sorted, subangular to subrounded monocrystalline quartz. The subangular texture of detrital grains is somewhat atypical of the Oriskany Sandstone, but appears to be an original detrital texture as investigated by cathodoluminescence (Figure 3.11). There is only a trace amount of potassium feldspar (<1%). Feldspars have minor to moderate alteration to low-birefringent clay. Some intragranular porosity has developed in feldspar grains as a result of minor alteration. The feldspar still displays typical luminescence. No feldspar overgrowths have been found.

Figure 3.11. Petrographic thin section of Oriskany Sandstone from the Crandall Estate Well #1. The core (serial no. 437) from the East Independence Field in Andover township, Allegany County, New York, was taken at a depth of 4,999 ft. (1524 m).

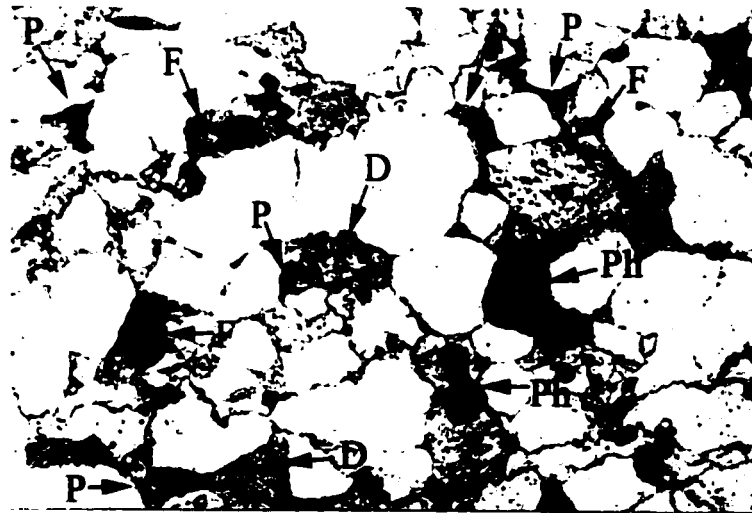
A) Plane-polarized light micrograph of the sandstone. Though the sample is well indurated, it has surprisingly little silica cement. Grain contacts are rather strongly sutured, but a small amount of porosity (P) is still present. Most of this porosity is intergranular and appears to be primary in origin. Potassium feldspar grains are slightly altered, and dissolution has created a small amount of intragranular porosity. Carbonate cement (D), mostly dolomite, varies from anhedral to rhombic. Carbonate slightly embays quartz grains. Brown-colored, rounded grains of phosphatic skeletal debris (Ph), probably fish teeth and bone, are common.

(B) Same field of view as in **A** viewed with cross-polarized light. Dolomite cement (D) displays high order interference colors. Phosphatic debris (Ph) is isotropic as are pores filled with blue-dyed epoxy (P). Feldspar (F) in this field of view is untwinned.

(C) Same field of view as in **A** and **B** viewed using cathodoluminescence. Luminescence reveals that there are at least two types of carbonate present, a nonluminescent rhombic dolomite (D) and a red-orange luminescing anhedral dolomite. It is very likely that nonluminescing dolomite has a higher iron content than the red-orange luminescing variety. Feldspars (F) luminesce a bright blue. Phosphatic debris (Ph) luminesces a bluish-lilac color in this photograph, but yellow luminescing phosphatic grains have also been observed in the sample.

Several quartz grains' original detrital outline are revealed by luminescence to be moderately well rounded. Because authigenic quartz is usually nonluminescent, luminescence typically reveals quartz overgrowths and original detrital grain outlines. However, it appears that this sample has very little authigenic quartz, and that detrital grains were subangular to moderately well rounded when deposited. A small amount of authigenic quartz is present and in combination with carbonate cements the sandstone.

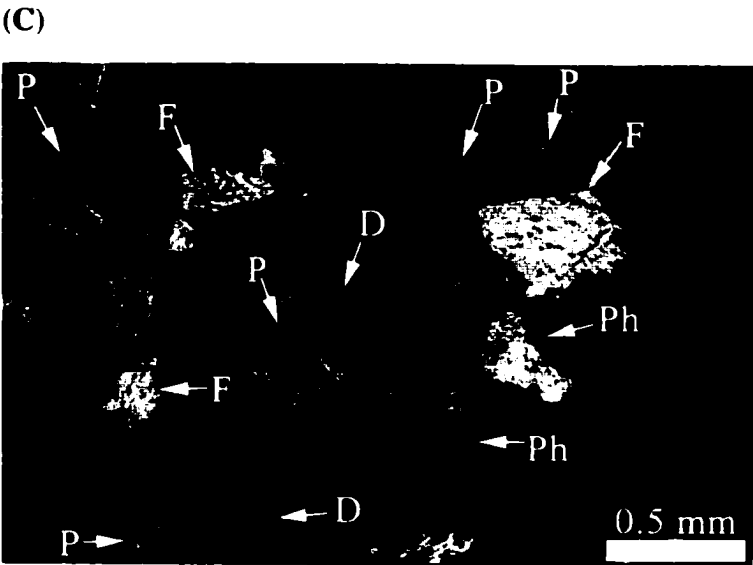
(A)



(B)



Figure 3.11–Continued



A small amount of phosphatic skeletal debris (probably fish bone, recognized because of its shape and because it displays some internal structure) was found in the sample.

Carbonate is present as both abraded skeletal debris (only brachiopod debris was recognizable) and as cement. Pyrite is present in trace amounts as anhedral masses.

Separation of the sandstone for heavy minerals resulted in a residue rich in tourmaline and a little detrital zircon. Authigenic component pyrite and ferroan dolomite (or ankerite) rhombs also occur in the heavy mineral separate.

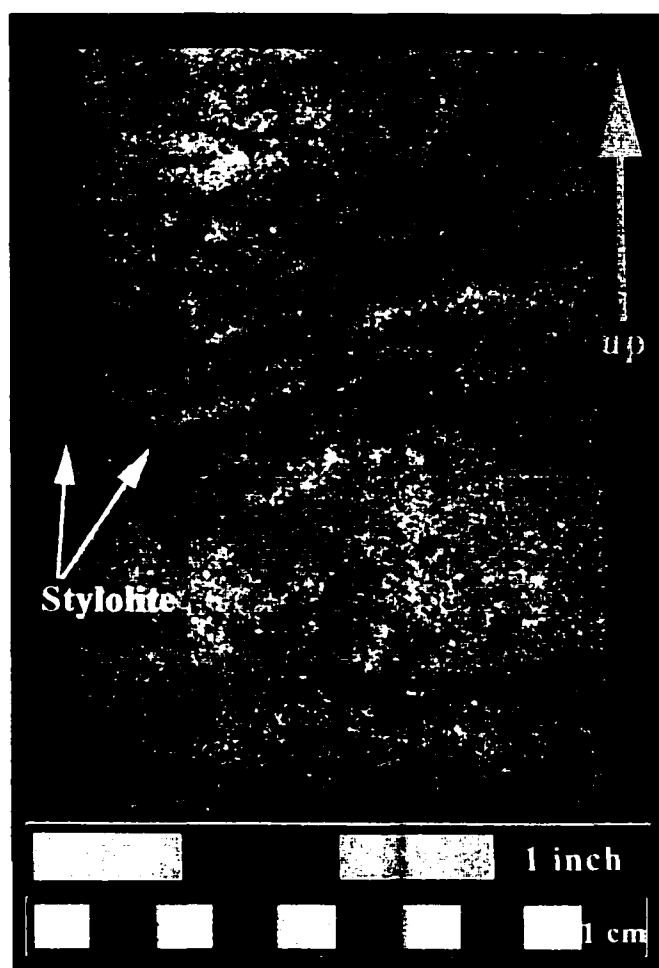
The sandstone is very well indurated and has a cement composed of both carbonate and silica. The silica cement occurs as syntaxial overgrowths, but there are no dust lines. Most of the carbonate is ferroan dolomite that is either nonluminescent or luminesces a dull red. Both ferroan rhombic dolomite (recognized by qualitative EDS analysis) and anhedral pore-filling dolomite are present. The anhedral dolomite luminesces red-orange, while the rhombic dolomite is nonluminescent (probably due to its high iron content). Some framboidal pyrite is engulfed in dolomite. The pyrite is present in both anhedral and rhombic dolomite. Some pyrite is found in intergranular pore spaces as well. Because the rock is well cemented, it is easily sawed and takes a good polish; it was reported to bleed saltwater upon recovery, indicating that the rock has some porosity and permeability (Van Tyne, 1971). Impregnation of thin-sectioned samples with blue-dyed epoxy resin revealed that the 2.2% porosity is mostly intergranular, and it appears to be primary in origin (Figure 3.11). Porosity occurs as small pores that range in shape from very irregular to straight sided when several quartz overgrowths have grown into and reduced the size of the original pores. Many quartz

grains are in contact with their neighbors without any interceding cement, and at times there is suturing at the contacts. Cathodoluminescence did not reveal overgrowths present on these sutured grains, and this suggests that pressure solution is responsible for some of sandstone's cementation.

One thing not readily observed in any of the outcrop samples is stylolites. This sample contains stylolites of relatively low amplitude, less than a centimeter in height, that are most abundant in the quartz-rich sandstone rather than in the shelly portion of the sandstone (Figure 3.12). Pyrite mineralization with possible carbonaceous concentration occurs along the stylolites. Thus it appears there may be two generations of pyrite, one early formed intergranular and the other forming at a relatively late stage. Since there is little quartz cement, detrital grain boundaries and shell fragments are modified and sutured along the stylolites. There is certainly some loss of material at the stylolite; for instance, shell fragments appear to terminate abruptly. However, there does not appear to be a great loss of material along the stylolites, because some carbonate grains though partially dissolved still straddle the stylolite.

A thin section that contained a stylolite, recognizable in hand sample, had quartz grains that were dissolved on opposite sides of the stylolite; different detrital quartz grains had been brought into contact. The thin weld line of the stylolite could be seen, and on opposite sides quartz grains that had clearly been separate detrital grains were fit together. Suturing, best observed in cross-polarized light, fused the separate grains. Over the 2.5 cm width of the thin section, the stylolite had about a 5-mm amplitude. The suture varied from clean with no clay when a quartz grain was in contact with another grain to

Figure 3.12. Slab of Crandall Estate Well #1 Core, Allegany County, New York. This thin slice was taken from a depth of 4990.5–4990.67 ft (~1521 m). The Oriskany Sandstone in this core has stylolites. They are marked by concentrations of dark sulfide minerals and carbonaceous material. The slabbed core is about a half inch thick, and the labeled stylolite can be seen on the edges. This shows that these are not just surface features. Such features were never observed in surface exposures, but microstylolites were seen in some petrographic thin sections.



mineralized when the stylolite skirts around grains and concentrations of mineral material occur. Opaque minerals, probably mostly pyrite and moderate birefringence clay minerals (and some chlorite), followed parts of the stylolite, and a small amount of carbonaceous material is concentrated along it as well.

As mentioned above, there are several lenses of brachiopod shell material. The shells are calcite, and most are fragmental, slightly abraded single valves. They are mostly convex up except in the last half foot (15 cm) of the unit where shells are randomly oriented in a shell hash (Van Tyne, 1971). Shells do not show any grading or size sorting in the core. The brachiopods appear to be the typical big shell fauna found at other locations (Boucot et al., 1970); however, the core is just a thin slice, less than 1.3 cm thick, and thus the brachiopods are not readily identifiable. Along with the shells are small cylindrical (circular outlines), hollow (now spar filled) pieces of calcite, about 2 mm in diameter, that are most likely brachiopod spines. The probable spines are mostly lying parallel to bedding, and some have been intersected at right angles to their long axis while others have been cut so that they appear ovoid. This is the only example of Oriskany Sandstone that the author is familiar with that contains brachiopod spines.

Nedrow

This location on the exit ramp from I-81 onto U.S 11 is described by Brett and Ver Straeten (1997). The locality is an exposure of the Manlius Limestone overlain by the Edgecliff Member of the Onondaga Limestone. At the wavy and unconformable contact (Brett and Ver Straeten, 1997), a sandy limestone with black nodules is developed. Black, fist-sized phosphatic sandy nodules occur scattered in the limestone.

The nodules are not derived from the black and red sandstones described as Schoharie Formation by Brett and Ver Straeten (1997). This can be stated with some confidence because the black sandstones on I-80 (discussed below) do not contain any significant phosphatic material. Phosphatic nodules similar to these are found at many places where the Onondaga Limestone overlies the Oriskany Sandstone/Springvale localities (Apsouri, 1934; Baker, 1983; Oliver and Hecht, 1994). In this instance, there is no underlying sandstone, so this is a case of true basal Onondaga sands (in this case in a limestone).

Sand was extracted from the sandy limestone by acid treatment, and heavy minerals were extracted. The rock is best described as a sandy limestone with about 35% sand. The limestone matrix consists of micritic material and calcite spar and composes about 63% of the rock, with about 2% invertebrate skeletal fragments (total carbonate is about 65%). Though the invertebrate fragments are finely commuted, broken pieces of brachiopod shells and ostracod valve fragments, echinoderm debris, bryozoan fragments, and possible tentaculites are recognizable. Recrystallization of the limestone may have made some of the carbonate skeletal components unrecognizable.

Sand grains in the limestone are predominantly monocrystalline quartz, 34.2%, with a trace of feldspar, and about 1% polycrystalline quartz (Figure 3.13). The polycrystalline quartz is most likely reworked sandstone fragments. Some dust lines can be seen on these fragments, and it appears that authigenic quartz overgrowths are cementing the monocrystalline grains together, rather than the polycrystalline quartz being derived from crystalline (igneous and metamorphic) rocks.

The sandy black nodules also contain the same type and size of moderately well-

Figure 3.13. Sandy limestone at the Nedrow Exit of I-81 south, Nedrow, New York. This locality is described by Brett and Ver Straeten, 1997. Sand grains in this unit are usually moderately well-rounded to subangular. Monocrystalline quartz and a small amount of alkali feldspar (F) are the primary detrital minerals. No overgrowths are developed on the monocrystalline quartz, but some grains appear to be slightly embayed by carbonate.

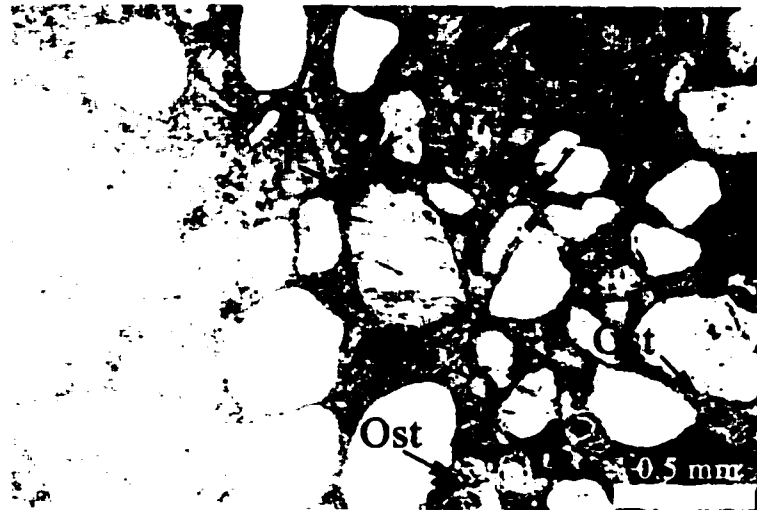
The rock matrix is a micritic carbonate that contains abundant fossil fragments, mostly of ostracods. Whole ostracod fossils filled with calcite spar are common, and an occasional brachiopod shell fragment is found. Some sections have a small amount of purple fluorite that replaces carbonate matrix.

(A) Plane-light image of the limestone. The thin section is very thin on the left hand side. Well-rounded monocrystalline quartz grains dominate the detrital component, but an occasional feldspar (F) is found. The condition of feldspar is moderately fresh, with only a little low-birefringent clay alteration. Fragments of ostracod shells can be seen scattered in the matrix, and two whole shells are obvious (Ost). Carbonate rock fragments with rounded to angular outline can be found (Lc) and are interpreted as intrabasinal lithoclasts.

(B) Same view as in **A** with crossed polarizers. The carbonate grains, such as the fragments and whole shells of ostracods (Ost) and lithoclasts (Lc), now show up better because of their birefringence. The limestone has been slightly recrystallized, and the outline of carbonate fragments can be quite faint.

(C) Same view as in **A** and **B** using cathodoluminescence. The thickness difference in the section is no longer obvious, because luminescence is derived from the surface of the thin section. The feldspar (F) yields a bright robin's-egg blue, and calcite in the matrix (micrite) is orange. Spar in the ostracods (Ost) and other fossil material as well as in the lithoclasts (Lc) is a little bit brighter than the matrix and yields a good contrast. For instance, whole ostracod shells are more easily observed. Because of the overall brightness of the carbonate and feldspar, it was not possible to adequately expose the detrital quartz in this sample

(A)



(B)

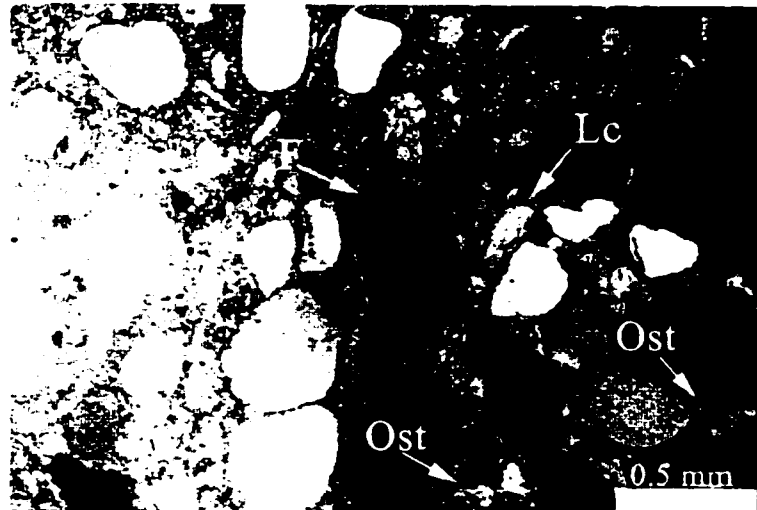
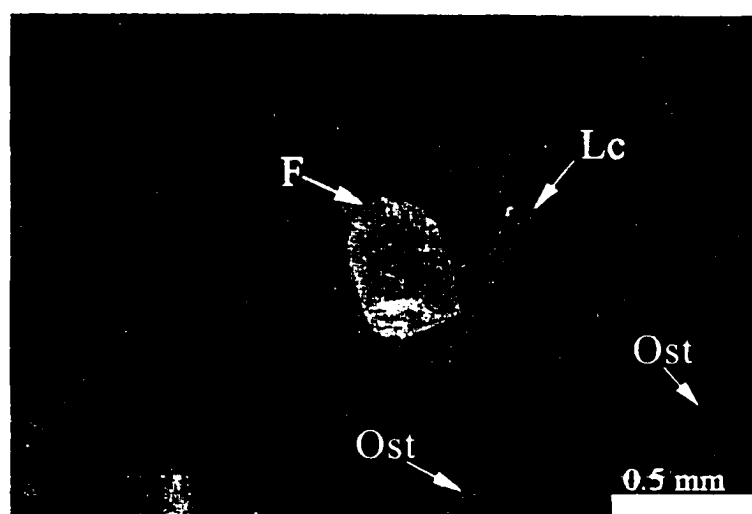


Figure 3.13—Continued

(C)



rounded to angular sand grains. However, there are two distinctive types of nodules. One is devoid of any invertebrate skeletal material and contains about 51.4% monocrystalline quartz grains and 48.2% phosphatic material with 0.4% anhedral carbonate (Figure 3.14), while the other type contains a mixture of skeletal debris including: possible sponge spicules, ostracod valves, and whole gastropod shells (Figure 3.15). Because there is so much carbonate skeletal debris, this at least suggests that some of the phosphate is replacing limestone. A point count of a nodule with invertebrate debris yielded a result of 15% monocrystalline quartz, 17% carbonate invertebrate fossil fragments, and 68% phosphatic matrix. Since the skeletal debris is not phosphatized (that is no obvious replacement of identifiable skeletal debris), it is possible that it was admixed with phosphatic matrix material. As can be seen from the above modal analyses, nodules that lack skeletal debris are very low in carbonate, while nodules with skeletal debris have considerable carbonate in them.

This location yielded euhedral, acicular zircon in addition to the typical well-rounded zircon and tourmaline (and tourmaline with abraded overgrowths). These euhedral zircons make up about 1% of the heavy mineral suite, and this is one of only a few localities locality that yields any of these. Four of these euhedral grains were analyzed by Krueger Laboratories of Cambridge, Massachusetts, for uranium and lead using single crystals for 4 independent dates. The crystals may all be concordant and yielded an age of around 408 million years (personal communication R. Reesman, 1998; see Appendix 5). The dates may be significant in giving a lower age for the source of at least some of the detritus in this unit and will be discussed further below.

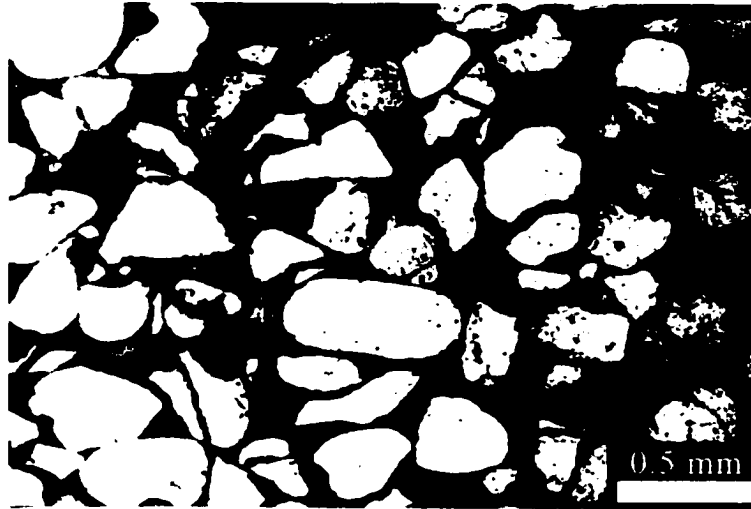
Figure 3.14. Phosphatic nodule. This sample was separated from limestone at the Nedrow Exit of I-81 south, Nedrow, New York (location 9, Figure 1.1). This locality is described by Brett and Ver Straeten, 1997. The phosphatic nodules are loosely compacted sandstone with a brown, isotropic cement of phosphate. There is a small amount of carbonate and a little pyrite dispersed in the phosphate. No fossils were observed. Early cementation and reworking into the limestone is suspected. The mineralogy and texture of the nodules' detrital components are the same as that found in the limestone.

(A) Plane-light image of the nodule. The dark cement/matrix, which looks mahogany brown in strong illumination, encloses angular to subrounded detrital grains. The grains are loosely packed, suggesting a mixing of phosphate matrix and detrital grains, rather than a precipitation of phosphate in intergranular pore spaces of a sandstone body.

(B) Same view as in **A** with crossed polarizers. The detrital grains are visible in the nearly isotropic phosphatic cement. Note that there is no visible carbonate in this view and very rarely is any carbonate present in the nodules, suggesting that they form by primary precipitation of phosphate.

(C) Same view as in **A** and **B** using cathodoluminescence. The phosphatic matrix now luminesces a dull uniform blue. Note that the electron beam is better focused on the upper two thirds of the field of view than on the lower third of the photograph. The lack of orange and red colors indicates there is almost no carbonate. Detrital quartz is luminescing in shades of blue and purple. A few grains in the matrix glow a dark green. These grains, labeled **a**, are low birefringence grains that display some near 90-degree cleavage and are tentatively identified as untwinned feldspar. Note the lack of non-luminescing quartz overgrowths. The lack of quartz authigenesis is tentatively attributed to early lithification in a phosphatic matrix that prevented any syntaxial quartz overgrowths from forming.

(A)



(B)



Figure 3.14—Continued

(C)

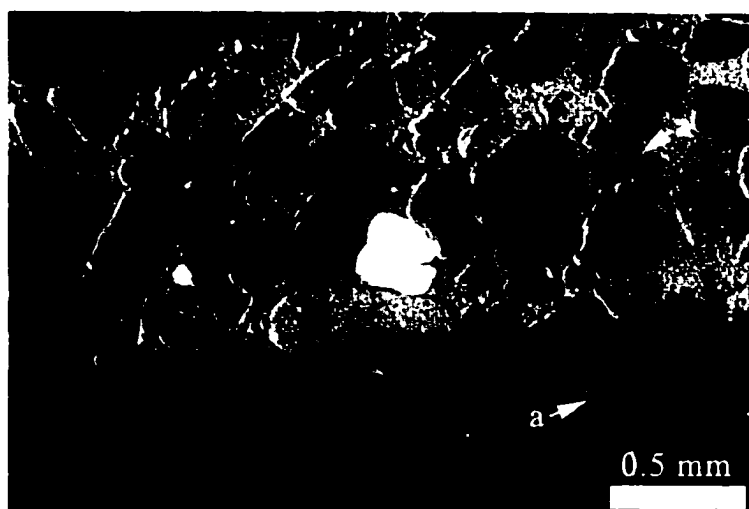


Figure 3.15. Fossiliferous phosphatic nodule separated from limestone at Nedrow. This nodule contained abundant carbonate skeletal material along with detrital minerals. A snail shell, showing the classic “baby bottom” cross section, was partly filled with sparry calcite and then in-filled with brown phosphatic material that is isotropic in polarized light. Several other invertebrate shell fragments are also visible in this image. The detrital sand grains are very similar to those in the limestone in which the nodule was found.

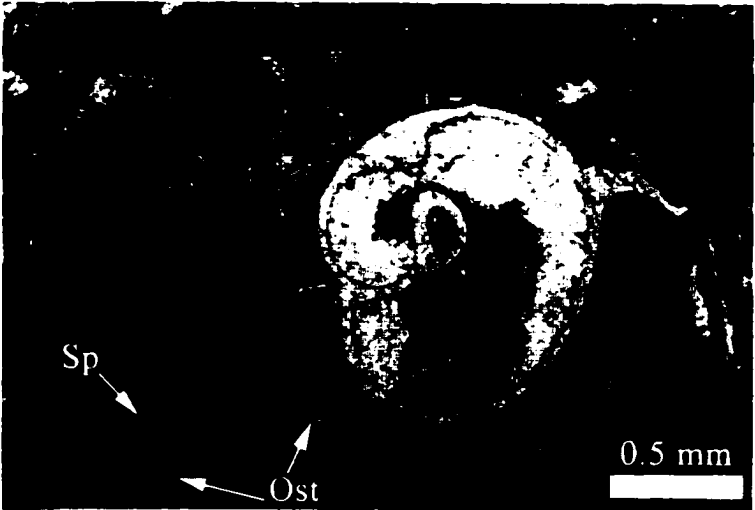
(A) Polarized light image of phosphatic nodule. The gastropod shell, center, has a sparry calcite infilling followed by phosphatic material (isotropic). Several moderately well-rounded quartz grains are visible along with a few grains that are much more angular.

(B) Same view as in **A** using cathodoluminescence. The carbonate materials are luminescing shades of yellow-orange and red (possible dolomite). Most of the limestone is calcitic because it dissolves easily in HCl. The phosphatic material does not display luminescence, but this may be due to the brightness of carbonate materials overwhelming the camera systems. Compared to the other type of phosphatic nodules found at this location, which contain practically no carbonate and no skeletal grains, this is carbonate rich. A possible sponge spicule with triaxon morphology is labeled **Sp**. The circular carbonate fragments are ostracod carpaces that have the typical radiating prismatic wall structure, **Ost**. Other carbonate debris includes: pelloids, fragments and valves of ostracods, and possibly sponge spicule fragments. Because of the very bright luminescence of the carbonate fragments, quartz grains’ luminescence is overwhelmed and underexposed in the photograph.

(A)



(B)



Besides detrital minerals, cubic, purple fluorite and sphalerite were found in the heavy mineral separate at this locality along with unusual composite pyrite grains that have small inclusions of a potassium aluminosilicate mineral suspected to be potassium feldspar. Pyrite also engulfed rhombic dolomite. Analysis of these minerals was done using only qualitative EDS, and no percentage oxides data were acquired. It was hoped that unusual trace elements might be found in the pyrite or fluorite, but only major elements were detected. The composite cubic fluorite crystals, some up to about 0.5 mm in size, probably were authigenic as they showed no evidence of abrasion. These crystals were occasionally found in thin sections, typically in sparry areas, where their distinctive purple color attracted the eye.

I-80 Sandstone near Nedrow

The location is described by Dossert and Chamberlain (1983), who call the rock Oriskany Sandstone. Ver Straeten and Brett (personal communication, 1997) also interpret this location as Oriskany Sandstone or Schoharie Formation grit; however, it is certainly an unusual facies. No authigenic tourmaline was found. The rock is composed of pitch black and red subunits (see Dossert and Chamberlain [1983] for a measured section). Both units are oolitic. The red units have abundant hematite ooids and are very similar to samples of the typical Clinton red oolite found in many introductory geology laboratory sets and described petrographically by Cotter and Link (1993). There are, however, fewer fossil fragments. Only a few rare brachiopod (disarticulated/isolated) valves were found in the hematic sandstone, and these were not hematitic but remained as carbonate with a gray color. The valves appear abraded and broken. They could not be

easily removed from the matrix and were not identifiable. No whole shells or large fragments were found in the black layers. None of the very large typical brachiopods of the Oriskany Sandstone were found.

Since the hematitic oolite is very similar to what most students see in their introductory geology sets and because not only is the dark rock similar texturally, but may be the source of the hematite in the red layers by alteration (Cotter and Link, 1993), the dark layers are described in some detail. The red layers have essentially the same texture and mineralogy as the black layers.

The dark bands contain round, fist-sized nodules of the same material as the containing beds (matrix) (no nodules were recognized in the hematitic rock). Both the nodules and matrix are considered here as being chamosite. This interpretation is based on thin-section petrography and whole-rock analysis. Chamosite ooids with and without nuclei were found throughout the entire black unit (Figure 3.16). Superficial ooids are also present and nucleate on the same materials. The ooids were of the following shapes: spherical, lopsided partial coating on quartz, bean shaped, oval shaped, and sphaoidal (deformed). Superficial ooids have coatings with the same size laminae found in larger grains' cortices and typically have only a few laminae. The cortices of the chamosite ooids are well-defined, thin laminae that can be traced around the circumference of the ooids. Laminae typically thicken over embayed areas of the nuclei (if present) and are also broader on the long ends of elliptical ooids and thinner on the short axes. On spherical ooids the thickness of laminae does not vary.

All ooids have a faint brown to brown-green color in plane light and display

Figure 3.16. Chamosite ooids in an oolitic ironstone deposit. This unusual deposit on Route 81, just south of Syracuse, has been correlated with the Oriskany Sandstone by Dossert and Chamberlain (1983) and to the Schoharie Formation by Brett and Ver Straeten (1997). (This is their stop D-2b.)

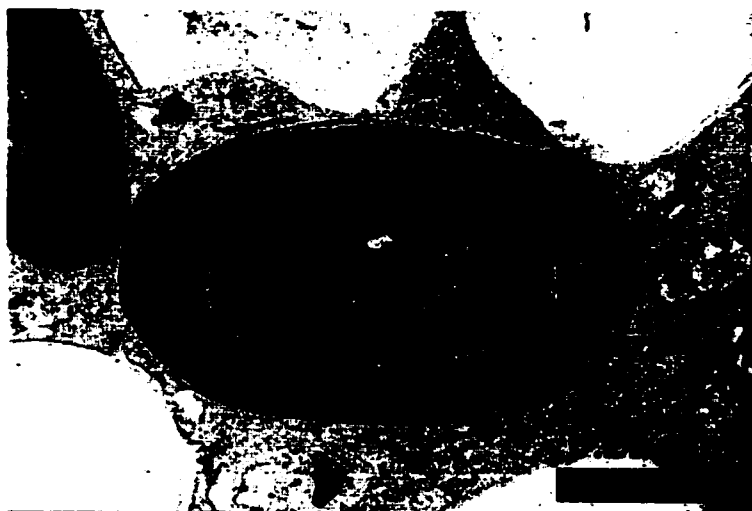
(A) Hematite and chamosite ooid. This example is from a hematite-rich layer, but there is a core (nucleus) of chamosite (green-brown), and several small layers in the grain are also chamosite. Ooids from this unit have well-defined concentric layers and vary from spherical to elongate ovoid and bean shaped. Notice that in this example the nucleus is bean shaped and that the first cortical layer is much thicker one side of the nucleus than on the other side. Typically, embayed areas on nuclei have thicker coatings on the embayment side. Some ooids are also eccentric and probably formed in a lower energy setting with only periodic agitation and turning. Some have quartz nuclei, while others appear to lack a foreign nucleus. The ooids and detrital grains float in a matrix, which is a green-brown color and is composed of chamosite with quartz and carbonate silt. Since grains do not touch each other, the intergranular material fits the criteria of a matrix that is depositional in origin rather than a post-depositional cement. Note that quartz grains in this view appear to have small dust lines that separate detrital cores from overgrowths. Examination of these and similar, irregular overgrowths indicates that they are abraded and the sand grains are reworked from an older sandstone. Sandstone intraclasts have also been found in this unit.

(B) Same field of view as in A (above), crossed polarizers. In polarized light the anomalous interference color of chamosite (a member of the chlorite group), blue-green color, to low birefringence, near black, is apparent in the ooid's core and several layers. Hematite layers show extreme birefringence that is masked by the red coloring of the mineral.

(C) A lopsided, chamosite-rich, superficial ooid. This is apparently a fragment of a larger broken ooid that was then coated with additional chamosite. One outer coat is obvious on the left side of the photograph. The green color, which is characteristic of chamosite, dominates. Other grains that are only partially visible in the field of view are a mixture of hematite-rich (red colored) and chamosite-rich ooids (green grain below the chamosite ooid being discussed). However, some layers of the rock are dominated by hematite or chamosite ooids, and black nodules in the sandstone have no hematite but do have chamosite ooids.

(D) Same field of view as in C (above), crossed polarizers. The central grain shows anomalous green interference colors. Note that the pure chamosite grain below has very low order birefringence. The hematite-rich ooids are red colored, and the matrix of chamosite (with some silt) is also dark because of low birefringence.

(A)

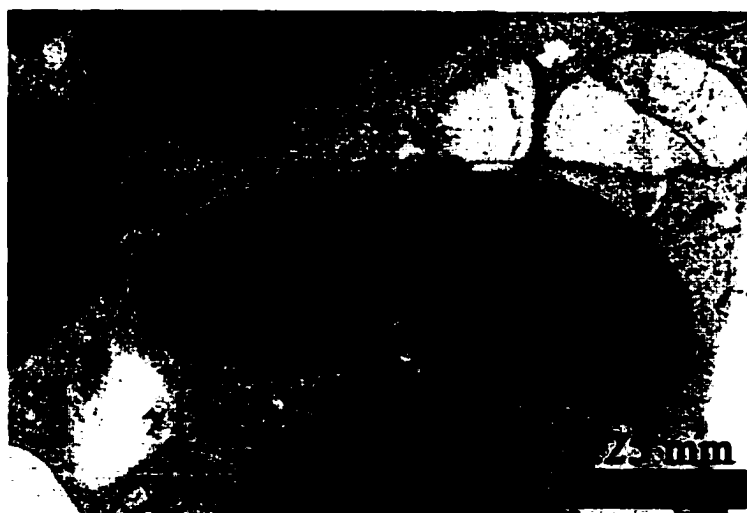


(B)



Figure 3.16—Continued

(C)



(D)



anomalous extinction colors of a blue-green typical of chamosite and other members of the chlorite group (Nesse, 1991). The ooids do not display cathodoluminescence.

The rock can be classified as a sandy chamosite ooid wackestone (the hematitic layers can be classified in the same way). Isolated quartz grains, partially coated quartz grains, detrital carbonate rock fragments, and chamosite ooids float in a matrix of chamosite with a small amount of admixed carbonate. No carbonate staining was attempted, but the rhombic nature of the carbonate suggests it is dolomite. Though some carbonate may be acting as cement, overall the rock is clayey in texture and much of the carbonate appears to be detrital (matrix). Dolomite rhombs, up to 100 μm in longest dimension, replace portions of the chamosite ooids, arguing for an authigenic origin rather than the detrital origin proposed for matrix carbonate. The matrix dolomite may have recrystallized or acted as nuclei for growth of the later coarser dolomite rhombs. Some of these rhombs are replaced by pyrite with a box-work appearance. Pyrite is altogether rare in this unit, and was only observed when it replaced dolomite.

The quartz grains are of interest in that they range from well rounded with no evidence of overgrowth quartz to angular fragments composed of multiple detrital grains attached to each other by quartz overgrowths. This interpretation is evinced by obvious dust lines on well-rounded detrital sand grain cores and by straight-line contacts of the overgrowths. These grains could be called polycrystalline quartz, but they are locally derived. True polycrystalline quartz with sutured subgrain boundaries is also present in small quantities.

Detrital feldspar is also present in trace amounts and is relatively unaltered. The

freshness may be due to deposition in a matrix that protected it from subsequent alteration. There are a few grains that appear to be embayed (replaced) by carbonate, though this causes only grain loss.

Since the same texture and detrital minerals are found in the hematite ooid-rich red layers, they are not described in detail here. The only difference is that these layers have hematite rather than chamosite, and it has been suggested that many marine sedimentary ironstones of Paleozoic age were originally deposited as chamosite and later oxidized to hematite (Cotter and Link, 1993).

Heavy minerals were separated from the black, chamosite-rich sandstone. The heavy mineral separate was composed of the typical heavy minerals found in the Oriskany Sandstone, well-rounded tourmaline, zircon, and rutile. The tourmaline did not have any overgrowths. A few very angular, broken pieces of what were probably euhedral zircon crystals were found (Figure 3.17). These suggest that the angular zircon may have been derived from a tephra deposit and have a different origin from the rest of the heavy mineral suite. These angular grains make up less than a percent of the heavy mineral suite.

Oriskany Falls

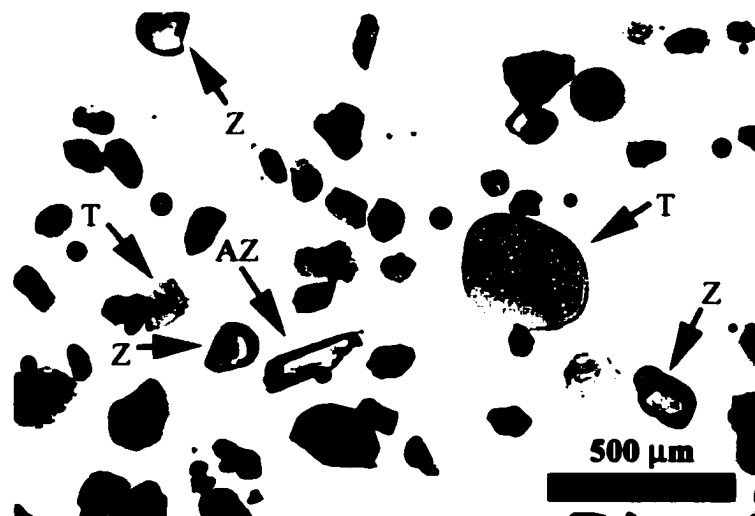
The samples were taken from the wall of the Eastern Rock Products Quarry, Oriskany Falls, Oneida County, New York. The sandstone is light gray to almost white and is composed almost entirely of monocrystalline quartz with a trace amount of feldspar. There is an abundance of large calcitic brachiopod fossils, and many have original parallel fibrous wall structure. Brachiopod shells investigated were

Figure 3.17. Heavy minerals and angular zircon from near Syracuse. This sample was taken from a chamosite-cemented sandstone along Route 81, just south of Syracuse, New York, location of Dossert and Chamberlain (1983). The heavy mineral suite contains minerals typical of the Oriskany Sandstone, well-rounded tourmaline, zircon, and rutile, but also contains some angular zircon. Angular zircon is unusual in the Oriskany Sandstone and has been found at only a few localities. It is suspected that the slender broken grains illustrated here are derived from a tephra deposit that occurs locally.

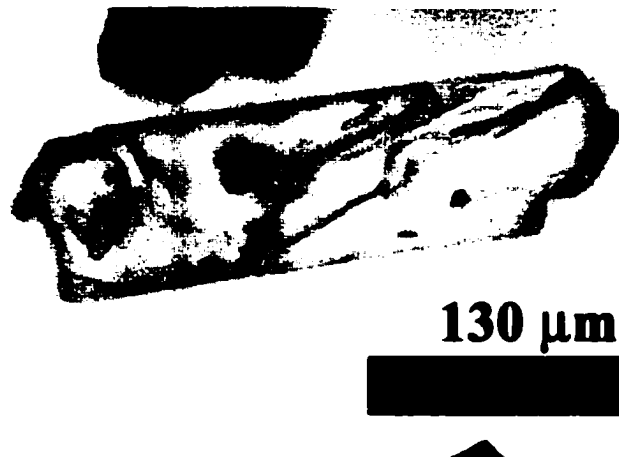
(A) Plane-polarized light micrograph of the heavy mineral suite, well-rounded to rounded zircon (Z) and tourmaline (T) are present, along with some elongate slender broken crystals of zircon (AZ).

(B) Plane-polarized light micrograph of a broken zircon crystal. The crystal still retains unabraded crystal faces and is not rounded. Compared to rounded zircon crystals shown above, this crystal clearly has not suffered the same abrasion history and may be derived from a local ash layer.

(A)



(B)



nonluminescent, but sometimes had luminescent cement filling fractures in them.

The sandstone is moderately well indurated and has a mostly siliceous cement; some carbonate cement is present, and in patches it can be the only cementing agent. Staining with alizarin red and potassium ferrocyanide detected calcite, dolomite, and ferroan dolomite. Douglas (1984) reported ankerite (as well as reporting all the other minerals found in this study). Ankerite must contain at least 20% iron (this was not tested for in this study). Small dolomite rhombs and anhedral patches of dolomite cement are scattered throughout the sandstone. However, pore-filling carbonate minerals are much more abundant near carbonate shell material than in areas where there are no fossil shell fragments. In fact, near shell fragments the only cement may be carbonate, while farther away in the same thin section silica cement may dominate with only small patches of anhedral carbonate cement. As reported by both Baker (1983) and Voorhees (1982), most of the carbonate cement is anhedral dolomite and rhombic ferroan dolomite or ankerite (Figure 3.18). Both authors also report dedolomite (areas of dolomite replaced by calcite).

Many of the quartz grains from the Oriskany Falls samples have clearly visible quartz overgrowths on the grains. This is one of the best localities for overgrowths with dust lines (Figure 3.1). The dust lines on detrital quartz grains indicate that most sand grains were well rounded when deposited. They also indicate how much the original pore space was reduced by cementation. Cementation by quartz authigenesis is important throughout the sandstone, and in fact even when all carbonate cement was removed with acid, the sandstone remained, consolidated and mostly well cemented. In samples where

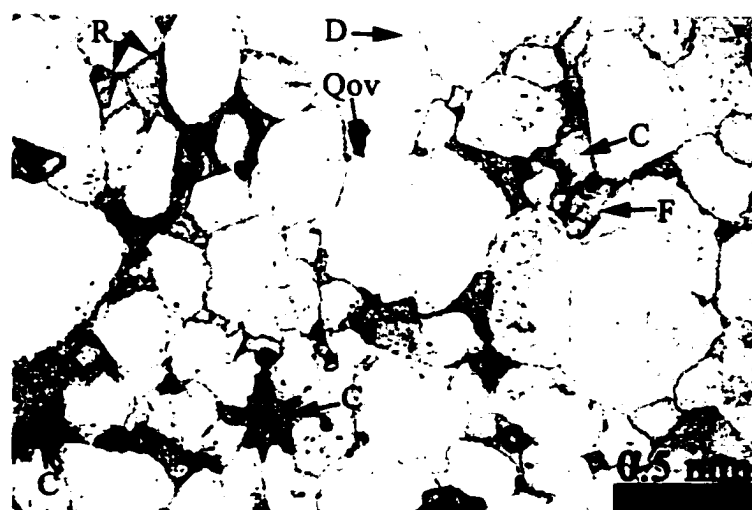
Figure 3.18. Oriskany Sandstone from Oriskany Falls, New York. The Oriskany Sandstone near its type locality is composed mainly of monocrystalline quartz, but is variable in amount of carbonate and silica cement. It always contains some silica cement, but some layers and even portions of thin sections can have from zero to almost all carbonate intergranular cement. Dolomite is the most common carbonate cement and usually anhedral in habit; calcite, ferroan calcite, and ferroan dolomite also occur. Interestingly, though there is a diverse mineralogy in the cement, fossils are all still calcite. In this example, there are approximately even amounts of carbonate and silica cement. Anhedral dolomite embays quartz grains in this field of view. A small amount of intergranular porosity is present in most thin sections, but very little is present in this example.

(A) Plane-polarized light micrograph of the sandstone. Monocrystalline quartz with small overgrowths (Qov) composes the sandstones' framework, but dust lines (D) are uncommon in this view. One feldspar grain (F) is present and exhibits a small amount of alteration to clay minerals that gives it a turbid look. Carbonate (C) fills a considerable amount of the intergranular porosity; in this example it is a combination of dolomite and ferroan dolomite, but only a few rhombic crystals are present (R); most of the dolomite is anhedral.

(B) Same field of view as in **A** viewed with cross-polarized light. Carbonate cement (C) with its high order interference colors (reds and greens) contrasts strongly with quartz grains and silica cement. Because of cement and quartz overgrowths, the outline of detrital grains is obscured.

(C) Same field of view as in **A** and **B** viewed using cathodoluminescence. Quartz grains' detrital cores luminesce shades of blue. The rounded nature of the detrital grains is clear. One grain of feldspar (F) is present and luminesces a bright blue. Quartz cement is nonluminescent, but carbonate cement (C) luminesces shades of orange. Notice that the interior of carbonate-cemented pores is darker than the exterior of pores. There is a medium orange strip of brightly luminescing dolomite that rims almost all carbonate-cement-filled pores. It is believed that the dolomite becomes more iron rich towards the interior of the pores and that as the iron content increases it causes a decrease in the luminescence of dolomite towards the interior of the pores. Some pores only have the early brightly luminescent dolomite and probably were filled before conditions changed to allow precipitation of ferroan dolomite. Similar situations have been observed in stained sections of the same rock, and dolomite followed by ferroan dolomite is the most common pore-filling sequence.

(A)



(B)

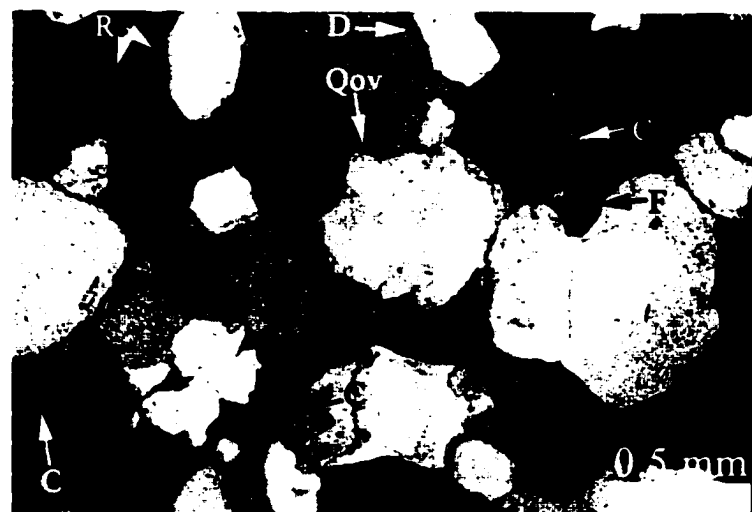
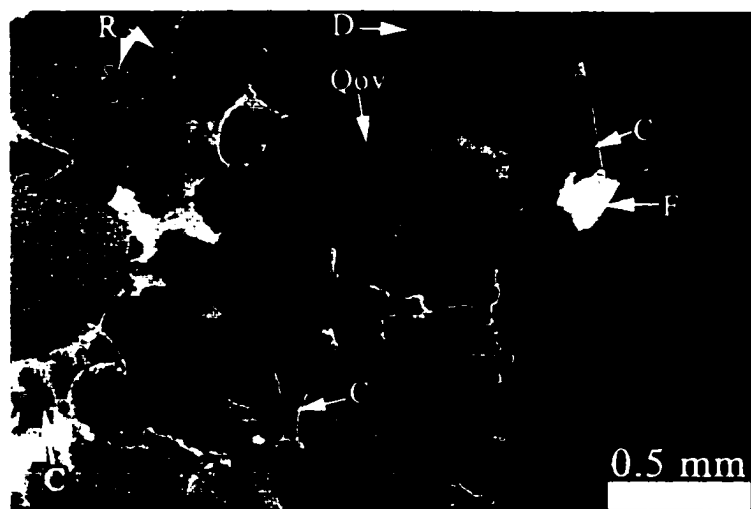


Figure 3.18–Continued

(C)



there is a combination of carbonate and silica cement, carbonate cement embays small portions of some silicate grains and cement.

There is some porosity in the sandstone (Figure 3.1C). Point counting gave 2% porosity. It is mostly intergranular porosity and appears to be primary in origin. The porosity is due to incomplete cementation by silica and carbonate. Overgrowth boundaries on quartz often have straight sides facing into pore space, and impregnation with blue-dyed epoxy revealed pores that have straight-sided boundaries between quartz overgrowths. Minor amounts of pyrite are found in the intergranular porosity. Mostly the pyrite is anhedral and appears to have formed late, filling pore spaces that remained open after quartz authigenesis had been completed.

At this locality there is no limonite staining or obvious dissolution porosity, and the sandstone appears to have remained unaffected by surface weathering process. The same seems true of the Oriskany Sandstone from the Seneca Stone Corporation Quarry, Seneca County, New York, and for core samples, and this suggests that much of the vug porosity, dissolution of fossil fragments, and limonite staining found at other localities is due to recent weathering in surface exposures.

Seneca Stone

Samples of sandstone from the Seneca Stone Corporation Quarry, Seneca County, New York, are very similar to those from the Oriskany Falls location. The unit has been well described by Brett et al. (2000) and Oliver and Hecht (1994); it is very clean quartz sandstone with abundant brachiopod and other invertebrate fossils. Some differences do exist between this locality and Oriskany Falls; for instance, at this locality lithoclasts of

underlying units of Helderberg Group have been incorporated into the sandstone. The lithoclasts are angular, light brownish gray and exhibit a micritic texture. No fossils were evident in the lithoclasts. The Oriskany at this location has a more diverse fauna including: tabulate corals (favositid) (Oliver and Hecht, 1994), platyceratid gastropods, and the ubiquitous large-shelled brachiopod fauna.

Petrographically, the sandstone is a very well consolidated quartzarenite with both silica and carbonate cement. Monocrystalline quartz dominates the detrital constituents, and there is a trace amount of potassium feldspar and polycrystalline quartz. Feldspar overgrowths occur on a few feldspar grains. They are small, only a few microns in thickness, and rare, occurring on about 25% of the feldspar grains examined. Small inclusions give them a cloudy appearance, and they are similar to overgrowths found at other localities (see the description from Oriskany Falls, above).

Quartz, present as syntaxial overgrowths on quartz grains, is present on most grains. Dust lines are occasionally present, but mainly grains have overgrowths without dust lines, and this can give the impression that the grains are subangular (Figure 3.19). However, cathodoluminescence reveals that most grains are moderately well rounded to well rounded. Carbonate cement is mainly anhedral, void-filling ferroan dolomite that is more abundant near fossil fragments. It makes up about 16% of the sandstone. Some saddle dolomite and rhombic dolomite is also present. Embayment by carbonate cement modifies quartz grain outlines, so that they appear more angular (Figure 3.19).

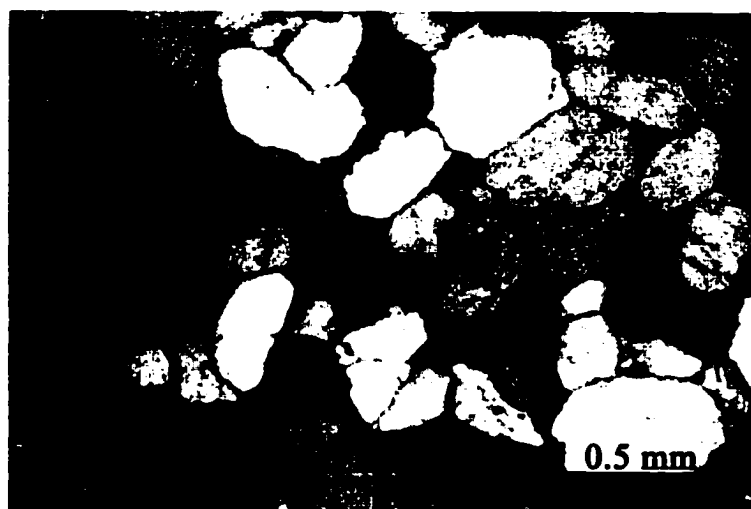
As well as the usual authigenic quartz, carbonate, and pyrite present at many localities, there is some purple fluorite (very similar to that found at the Nedrow Exit

Figure 3.19. Oriskany Sandstone from the Seneca Stone Corporation Quarry, Seneca County, New York. The sandstone is cemented by a combination of quartz and carbonate material. The carbonate is anhedral, void-filling calcite that is more abundant near fossil fragments. Quartz cement is present as syntaxial overgrowths on quartz. Original detrital grain outlines become much clearer using cathodoluminescence. In this sandstone several of the grains that appear subrounded in polarized light microscopy turn out to be well rounded when their luminescent image is observed.

(A) Cross-polarized light image of sandstone. Syntaxial overgrowths and calcite cement have filled most of the available pore space. Several small dust lines are visible in this view on quartz overgrowths.

(B) Same field of view as **A** (above) imaged with cathodoluminescence. The original detrital grains of quartz luminesce shades of blue and purple. Carbonate cement is orange, while quartz cement is nonluminescent. Except for the very large area of carbonate on the left side of the image, carbonate and silica cement are present in subequal amounts. Anhedral calcite cement embays quartz grains, and this is well displayed on the left side of the image. Even when the sandstone's carbonate cement is completely removed by hot hydrochloric acid digestion, the rock remains consolidated because of the silica cement. The red arrows point to quartz cement that has partially filled intergranular pore spaces. A feldspar grain luminesces a bright blue near the center of the field of view. The feldspar grain appears to have a small, nonluminescent overgrowth on it that is better developed on the top and right side of the grain.

(A)



(B)



locality described above). The fluorite is much less abundant than pyrite at this location and occurs as small cubes and series of connected cubic crystals no more than about 1.0 mm in diameter. It is associated with pyrite, and sometimes the minerals make up composite grains, in which pyrite seems to coat the fluorite. A small amount of sphalerite was also found at this location in the heavy mineral separate.

Chemical analysis of the fluorite using energy dispersive spectroscopy revealed only calcium; fluorine is not detectable. The spectrum was searched to see if any rare earth element peaks were present. None were found.

Skaneateles Falls

A sample was taken from Skaneateles Falls at the Carrigan Quarry location described by Baker (1983). No major difference in the sandstones' texture or overall composition could be found compared to other Oriskany Sandstone locations for the Carrigan Quarry location, though the amount of fossil material seemed reduced compared to other localities in the Finger Lakes area. A few *Costispirifera* internal molds were found as well as a little carbonate shell material. The sandstone is mainly tan to white, colored with a little limonite staining. Baker (1983), who studied the sequence in more detail, believes that all but the basal foot of the sandstone should be placed in the Springvale Sandstone. She based her placement mainly on the lack of fossils and what she interprets to be phosphate nodules. In the collection made for the present study, no phosphatic nodules were encountered, but lithoclasts of micritic limestone and chert were found, and it is not clear how to interpret the unit's stratigraphic position, but one line of evidence that supports Baker's (1983) assertion is that only reworked, strongly abraded

overgrowth tourmaline was found at this location.

Petrographically, the sandstone from Carrigan Quarry appears to have the typical appearance of the Oriskany Sandstone from western New York (Figure 3.20), moderately well-rounded, medium-grained monocrystalline quartz with a trace of potassium feldspar. The feldspar is moderately fresh, and feldspar overgrowths similar to those described above were found. They are cloudy and brown close to the detrital core and become clear as one moves away from the core. The overgrowths occur mainly on microcline grains, but do not have twinning and do not go extinct precisely with the detrital cores. The overgrowths of feldspar fill available pore space, but are only around 10 μm in maximum thickness. They are not very abundant, because there is only a trace of feldspar in the sample. However, they occur on 75% of the feldspar grains present in the sandstone.

The sandstone is cemented by a combination of authigenic quartz occurring as syntaxial overgrowths with dust lines present, and anhedral to rhombic pore-filling carbonate cement. The cement is about 50% silica and 50% carbonate (1.6%), mainly ferroan dolomite, but brachiopod shells remain calcitic. At this location both brachiopod molds and carbonate shell fragments are present. One calcitic brachiopod fragment encountered in thin section was just over 2.5 cm long. The shell fragment was nonluminescent.

Skaneateles Township, General Crushed Stone Quarry Well # 3-9R

Samples from a core from Skaneateles Township, Onondaga County, were supplied by the New York State Geological Survey. The core is identified as Hole #2 (2-69) Well no. (3-9R), location latitude 42'-59'-55", longitude 76'-24'-27". The well was

Figure 3.20. Sandstone from the Carrigan Quarry, Skaneateles Falls, New York. This sandstone has been attributed to the basal Onondaga Formation by Douglas (1984), but is petrographically indistinguishable from the Oriskany Sandstone. It is cemented by a combination of quartz and carbonate cements.

(A) Petrographic thin section viewed using plane-polarized light. Quartz (Q) and carbonate (C) cement are indicated. These cements occlude all porosity, creating a hard and well-indurated sandstone.

(B) Same view as in **A** (above) using cross-polarized light. Well-developed quartz overgrowths are recognizable by their straight-line contacts with each other (Q), but no dust lines are visible on detrital cores of quartz grains. Carbonate cement is evident by its high birefringence.

(C) Same view as in **A** and **B** (above) using cathodoluminescence. Notice that detrital outlines of quartz grains are now clearly visible because authigenic overgrowths (Q) do not luminesce. Carbonate cement luminesces shades of orange. An untwinned detrital feldspar grain in the center of the field of view luminesces a bright blue (F) and is now recognizable.

(A)



(B)



Figure 3.20—Continued



drilled on the property of the General Crushed Stone Quarry, and a sample was taken at a depth of 37 ft (11.2 m) for thin sectioning. The rock is enriched in dark, phosphatic and carbonaceous material (hereafter referred to as dark material) compared to typical Oriskany Sandstone. This dark material occurred both as dispersed material disseminated throughout the sandstone, giving the rock a salt-and-pepper appearance, and as discrete nodules. In the salt-and-pepper sandstone, quartz and dark material appear about equigranular. As well, in some parts of the core, the dark material seemed to be swirled and suggested bioturbation of sandstone.

In hand sample, the sandstone is very similar to that taken from the Carrigan Quarry, but there are some dark nodules and perhaps the sandstone is a little fresher. This is evident because the core material is not limonite stained. A small amount of shell material is visible. Dolomite is abundant at this locality, giving the sandstone a saccharoidal texture. In thin section, the sample is texturally and mineralogically similar to the Carrigan Quarry sample. A few feldspar grains with overgrowths were observed. The overgrowths appear to have formed in place as they fill all available pore space (Figure 3.21). Brachiopod fossils are rare in the core, and only fragmental material has been found.

There is also a little more carbonate cement (5%) than at the Carrigan Quarry. The cement displays more dolomite crystals with rhombic habit and saddle-shaped habit; interestingly, most of these dolomite crystals are rimmed by pyrite. This was not true of the Carrigan Quarry sample, but perhaps surficial weathering oxidized the pyrite. The rimming pyrite is probably later than the dolomite, because it is found on the outside of

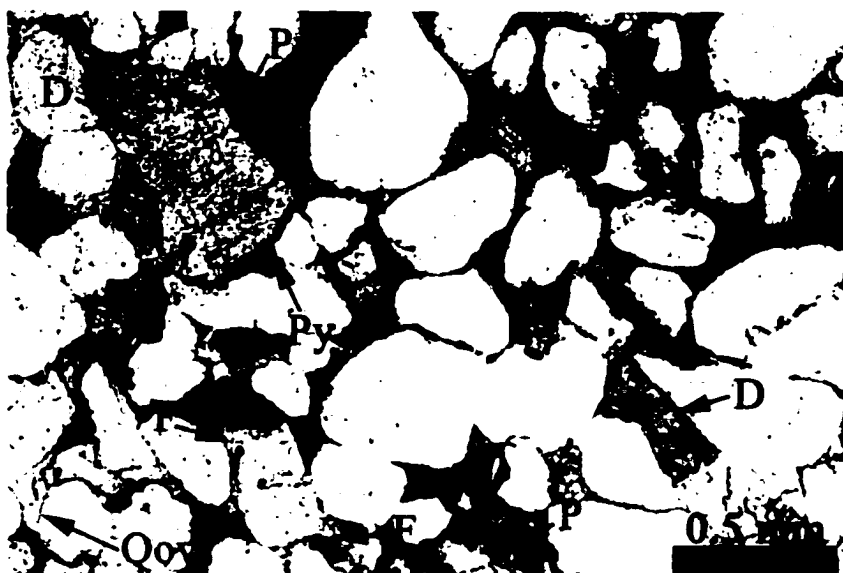
Figure 3.21. Petrographic thin section from a core from Skaneateles Township, New York. The core was provided by the New York State Geological Survey. The sample was taken at a depth of 37 feet (11.3 meters). The sandstone contains phosphatic nodules and disseminated dark material that includes phosphate and perhaps some carbonaceous debris. This thin section intersected a phosphatic nodule embedded in a quartz arenite cemented with both silica and carbonate cement.

(A) Plane-polarized light micrograph of the sandstone. A portion of a phosphatic nodule (Ph) is visible in the upper right hand corner of the micrograph. The cryptocrystalline phosphate has a mahogany color and cements together subrounded to subangular quartz grains (colorless). Notice that quartz grains in the phosphatic nodule do not touch, but in the sandstone most quartz grains are in contact with their neighbors. A saddle dolomite rhomb (D) is visible to the upper left; it is partially rimmed with pyrite (Py), which fills the remainder of the pore; notice that the opaque pyrite follows the dolomite rhomb conforming to its contour. Rimming pyrite is very common in this sandstone, and observation of many grains reveals the paragenetic sequence is dolomite followed by pyrite. A small quartz overgrowth (Qov) is visible to the lower left; near it is a feldspar grain that has been overgrown by authigenic feldspar (F) on both ends. The authigenic feldspar fills the remaining pore space around the detrital feldspar grain. There is a little porosity (P) visible in the thin section; this pore was originally filled with blue-dyed epoxy, but cathodoluminescence-beam damage has scorched the epoxy, turning it an amber-brown color.

(B) Same field of view as in **A** viewed with cross-polarized light. The phosphatic nodule can be seen to be nonbirefringent.

(C) Same field of view as in **A** and **B** viewed using cathodoluminescence. The phosphatic nodule (Ph) luminesces a lilac-blue color. Most phosphatic nodules in the Oriskany Sandstone luminesce this color, though skeletal debris sometimes luminesces in muted yellow-orange and red colors as well. In this view, there is some evidence of embayment of enclosed quartz grains by the phosphate. The sharp contact with enclosing sandstone and lack of embayment of quartz grains in the sandstone that the nodule is in contact with suggests that the phosphatic nodule is an intraclast. Dolomite (D) luminesces a red color towards the exterior, but has a virtually nonluminescent interior. This is probably a result of iron content. The interior of the dolomite is more ferroan than the exterior. Interestingly, this sequence of ferroan core and less iron-rich rim is common to most Oriskany localities in central New York. Note that there is a little orange luminescing dolomite as well; this dolomite probably has a lower iron content. The feldspar grain luminesces a bright blue, but its overgrowth (F) shows a much darker blue luminescence (arrows point to the two ends of the grain that have overgrowths). It is actually probably nonluminescent (a common feature of feldspar overgrowths), but extraneous light from the detrital core illuminates it.

(A)



(B)

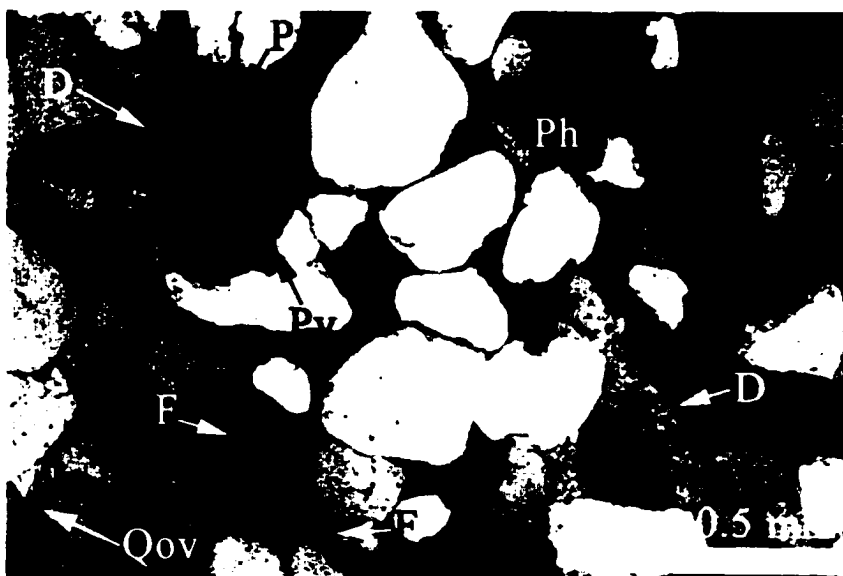
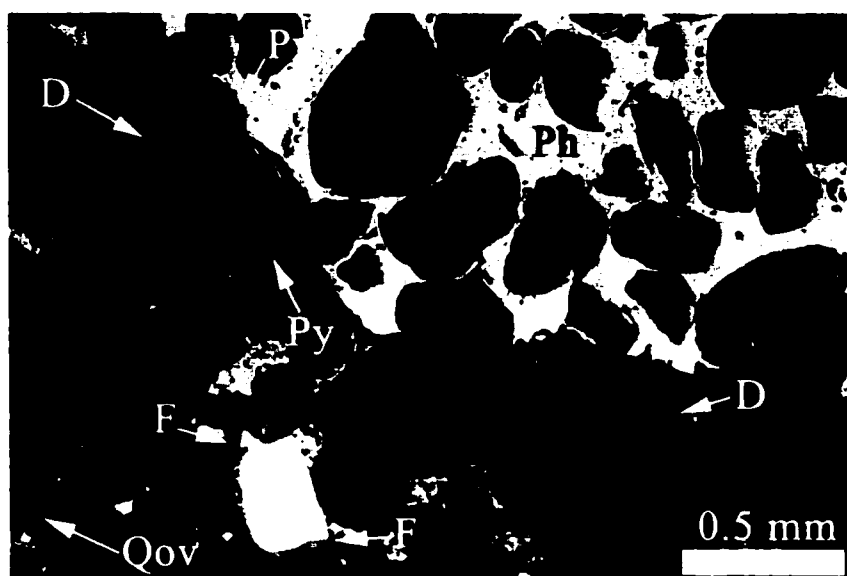


Figure 3.21–Continued

(C)



the rhombs with a straight-sided termination (in all cases) against the dolomite and an irregular surface against the side of the pore space. As evidence of its later growth, pyrite does not usually fill pores and leave a straight surface on the side facing into the pore, and thus it appears that after the dolomite rhomb formed, pyrite filled any remaining space. Another line supporting this paragenetic sequence is that pyrite goes around rhomb corners and follows the curved surface of saddle dolomite (Figure 3.22). Pyrite sometimes fills remaining pore space between adjacent dolomite crystals, and fractures (probably due to compaction) in the dolomite rhombs are also filled with pyrite.

The discrete phosphate nodules in the core are rounded to subangular, and their maximum dimension is around 2.5 cm. Since the example studied from this core appears to be different than the surrounding sandstone in which it was found, it is described separately. One nodule from the core was thin-sectioned. It was subrounded with dimensions of about 1 cm by 0.5 cm and was composed of cryptocrystalline phosphatic matter surrounding medium-sized quartz sand grains. No fossils were found in the nodule. Cathodoluminescence analysis of the phosphate resulted in a homogeneous violet-blue color (Figure 3.21). The enclosed quartz grains are not well sorted, and some are the same size as found in the sandstone; others are slightly smaller than in the surrounding sandstone, and all float in the phosphatic material and show no sign of compaction. In fact, there is a little porosity in the nodule that was filled by blue-dyed epoxy. That grains do not actually touch each other suggests that this phosphate did not precipitate around grains but that grains perhaps fell into it as it formed. A few quartz grains protrude from the nodule and have minor overgrowths on the side that is exposed

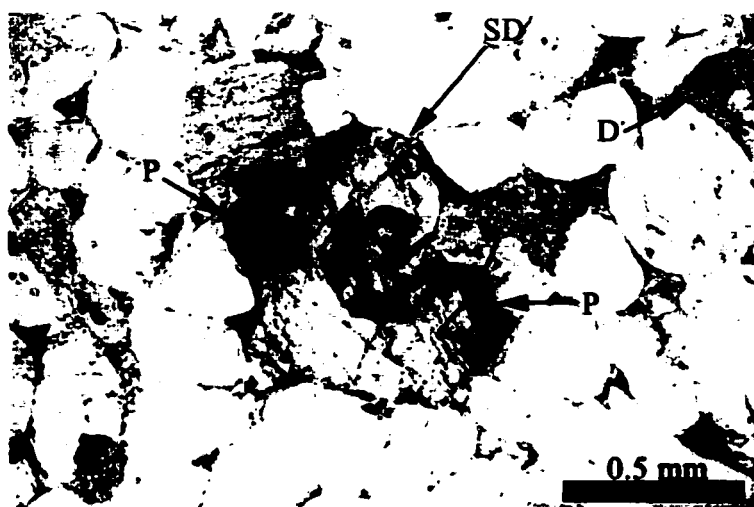
Figure 3.22. Saddle dolomite with a pyrite rind in sandstone. The sample is from a core situated in Skaneateles Township, Onondaga County, identified as Hole #2 (2-69) Well no. (3-9R), location latitude 42°-59'-55", longitude 76°-24'-27", supplied by the New York State Geological Survey. The samples was taken at a depth of 37 feet (11.3 meters). Dolomite is quite abundant in this sample, giving hand samples of the core a sucrosic look.

(A) Plane-polarized light micrograph of a large saddle dolomite crystal (SD) that appears to have grown displacively in the sandstone. The dolomite is rimmed by pyrite (P), and pyrite also fills in cracks in the dolomite, indicating that pyrite formed first. A limonite stain in the center of the crystal is a clue to the ferroan nature of the dolomite. Much of the dolomite in this sample, including anhedral pore-filling dolomite, is ferroan and is either nonluminescent or luminesces only a dull red (see Figure 3.21).

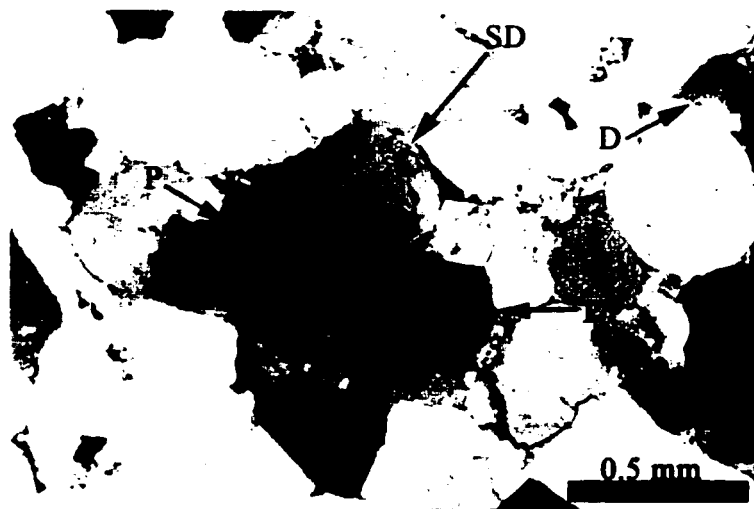
(B) Cross-polarized light micrograph of the same area seen in **A** (above). Notice that the saddle dolomite (SD) crystal is extinct in its center. The crystal has strong undulose extinction, indicating that it has been stressed. Cracks in the dolomite also suggest either displacive stress or compaction stress. Since the dolomite crystal is much larger than surrounding pore spaces, it probably displaced quartz grains as it grew.

The sand grains in this view do not display quartz overgrowths and appear to be mainly cemented with anhedral dolomite. Strong suturing at quartz grain boundaries suggests that the sandstone had been moderately to strongly compacted before dolomite formed.

(A)



(B)



and in contact with the sandstone. It thus appears the nodule is detrital in origin and can be considered an intraclast. A couple of other much smaller sand-sized grains of phosphate were observed; they did not contain quartz grains, and appear to be detrital in origin.

This sample's detrital component resembles what has been called the Springvale Sandstone, but there are not as many nodules, black layers, or glauconite as appear in typical exposures of the Springvale or basal Onondaga sandstones. Because highly abraded tourmaline overgrowths were found on detrital tourmaline, it appears that this sandstone was derived by reworking of Oriskany Sandstone and can tentatively be considered as a sandstone unit developed at the base of the overlying Onondaga Limestone.

Yawgers Woods

Yawgers Woods is located close to the shore of Lake Cayuga, approximately 0.5 miles (0.8 km) west of the intersection of Route 326 and Weed Road, Cayuga County, New York (Oliver and Hecht 1994). The exposure is a small ledge with loose blocks in the woods.

The sandstone is white to limonite stained, friable, highly fossiliferous, and has received considerable paleontological study since its early description by Dewitt Clinton in 1810 (Wells, 1963).

The sandstone is a medium-grained quartzarenite with about 1% feldspar. The feldspar is subangular to rounded, and most grains have small authigenic overgrowths on them (Figure 3.23). Some of the feldspar overgrowths give evidence of early formation

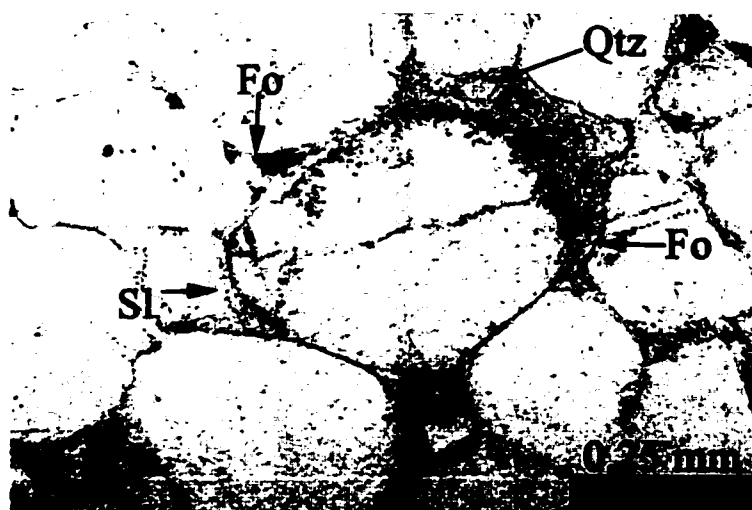
Figure 3.23. Detrital feldspar with an authigenic overgrowth from the Oriskany Sandstone at Yawgers Woods. Authigenic overgrowths on feldspar are not uncommon in the Oriskany Sandstone; however, because there is only a trace of feldspar in the sandstone they are not volumetrically significant. In this example, cathodoluminescent microscopy proves that a rounded detrital core was overgrown by an authigenic, pore-filling overgrowth.

(A) Plane-polarized micrograph of sandstone with a detrital feldspar in the center of the field. The feldspar overgrowth (Fo) is cloudy from inclusions and fills in pore space around the detrital grain. At one point a detrital quartz grain is surrounded by the overgrowth (Qtz); while at another point, the overgrowth makes a straight-line contact (Sl) with a quartz overgrowth that grew into the same pore space.

(B) Cross-polarized light micrograph of the same area shown in **A** (above). The detrital grain displays microcline twinning. The overgrowth is untwinned (Fo). To the upper right, the detrital overgrowth fills in pore space and grows around a detrital quartz grain (Qtz). The overgrowth to the left side has filled all pore space and makes contact with detrital and authigenic quartz. This suggests that quartz and feldspar form at about the same time in the sandstone. A dust line (Dl) on a detrital quartz grain indicates that significant quartz authigenesis has occurred and that the original detrital grains were moderately well rounded.

(C) Cathodoluminescent image of approximately the same area shown in **A** and **B** (above). In this image detrital quartz grains luminesce (Qtzdc), while quartz overgrowths are nonluminescent. The detrital feldspar core (Fdc) luminesces a bright blue; authigenic feldspar luminesces a darker blue (Fo). Note that the lighter blue detrital core is well-rounded and that the darker overgrowth feldspar grows into interstitial pore space and makes relatively sharp contact with authigenic quartz overgrowth. On the left side of the illustration, the authigenic overgrowth from the quartz grain labeled Qtzdc makes contact with the feldspar overgrowth. There is a straight-line contact at that point; it is thus clear that feldspar and quartz made contact by growth rather than compaction. To the upper right, a rounded detrital quartz grain (Qtz) is in contact with the feldspar overgrowth. In this example, it appears the feldspar grew around the detrital quartz grain. On the right side of the feldspar grain, the overgrowth appears to have a second zone of brighter feldspar, but it is more likely that the overgrowth thins on this side and that the underlying epoxy or glass from the microscope slide is luminescing and affects the appearance of the overgrowth.

(A)



(B)



Figure 3.23–Continued

(C)

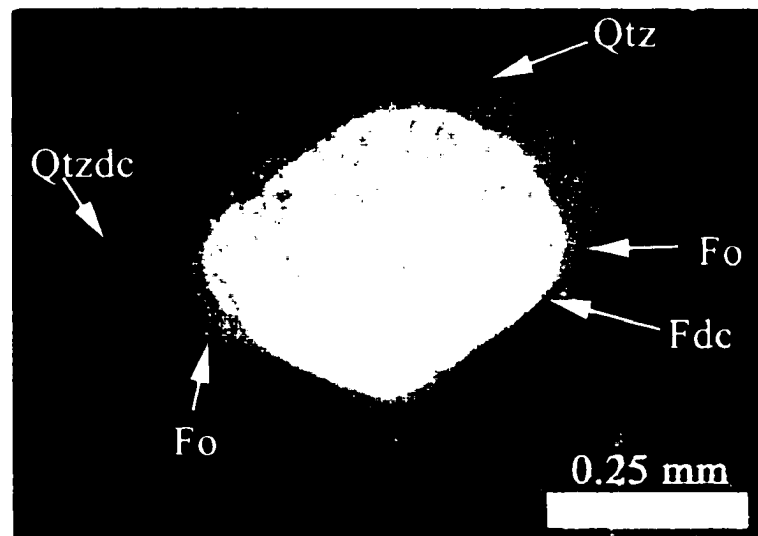


Figure 3.24. Feldspar overgrowth partially engulfed by quartz overgrowths. In this sample from Yawgers Woods, Cayuga County, New York, detrital microcline feldspar is overgrown by syntaxial authigenic feldspar.

(A) Plane-polarized light micrograph of the sandstone. Several quartz grains can be seen in this view. When the feldspar overgrowth (F) makes direct contact with detrital quartz grains, there are no overgrowths on the quartz grains (see the left hand side and bottom of the feldspar grain). Quartz overgrowths, identifiable because of dust lines (DI), appear to run into the feldspar overgrowth and stop growing. The quartz overgrowths have euhedral outlines when they are not interfered with and grow into pore space (P). Pore spaces are not all labeled, but can easily be seen because of the blue-dyed epoxy that fills them.

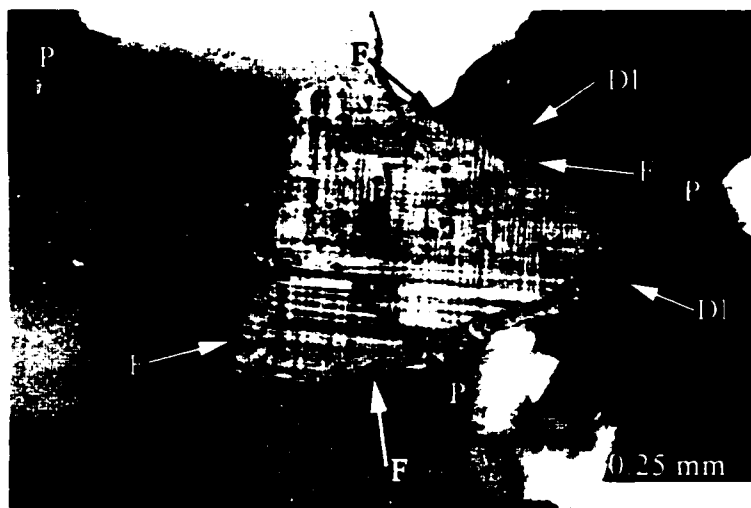
(B) Cross-polarized light micrograph of the same area seen in **A** (above). In this position, the overgrowth can be seen to go extinct in a position just slightly different from the detrital core. The detrital core displays good scotch-plaid twinning typical of microcline, and perhaps some twinning is present in the overgrowth, though this is hard to discern because the overgrowth is full of inclusions. Inclusions are common in most overgrowths, but sometimes larger overgrowths have fewer inclusions and become clear as they grow farther from the detrital feldspar grains.

The feldspar overgrowth can be seen to abut against the surrounding quartz grains, and particularly at the bottom of the feldspar grain, the overgrowth can be seen to grow around protrusions on the detrital quartz grains. Open porosity (P) appears to be primary, and both feldspar and quartz seem to have stopped growing before filling all available space in this example.

(A)



(B)



before quartz overgrowths (Figures 3.23 and 3.24). Heavy minerals include abundant pyrite, tourmaline, and zircon, including tourmaline with overgrowths.

Abundant quartz overgrowths can be recognized by well-developed dust lines on well-rounded detrital quartz grains. Authigenic quartz acts as the major cement in the sandstone. A small amount of anhedral ferroan dolomite cement (3.5%) is present and slightly embays quartz grains. Porosity is present as both intergranular porosity and moldic porosity. About 50% appears to be primary and 50% appears to be fossil moldic. It is likely that some of the moldic porosity is from recent weathering in the exposure.

Both calcitic fossils and molds of fossils are present. The fossils and molds are typically stained with limonite and contrast against the white quartz sandstone. *Costispirifer arenosus* appears to be the most abundant brachiopod. In the present study, only brachiopod fossils were found, but a report by Cahall (1956) indicates that this exposure has a more diverse fauna, including gastropods and cephalopods. Oliver and Hecht (1994) reported on well-preserved favositid corals from the locality.

Green Pond Outlier Samples

Because the Green Pond Outlier is separated from the main belt of Lower Devonian sediments, it has somewhat different history and stratigraphy that are discussed below.

Paleozoic, Silurian through Middle Devonian, strata are preserved in an outlier approximately 35 km (19 mi) southeast of the main exposure belt in Orange County, New York, and Passaic County, New Jersey, that runs from Cornwall, New York, to Flanders,

New Jersey (~80 km) (Finks, 1968; Barnett, 1976b; Mitchell and Forsythe, 1988).

Sedimentary units with a thickness of ~2,400 m were preserved in this northeast-southwest trending synclinorially down-folded and faulted belt, which is surrounded by Proterozoic metamorphic and igneous rocks of the Reading Prong (Hudson Highlands and New Jersey Highlands, along with minor amounts of Cambrian and Ordovician sedimentary rock) (Drake, 1970; Mitchell and Forsythe, 1988). The time of formation of this down-dropped block is unclear, and it may have become a tectonic feature during either Paleozoic or Mesozoic time, but units could have been deformed at an earlier time, perhaps even during the Acadian or Alleghenian (Offield, 1967; Mitchell and Forsythe, 1988). Mitchell and Forsythe (1988) suggest a post Middle Devonian age for deformation.

The Lower Devonian Connelly Conglomerate and associated sediments (mostly quartz pebble conglomerate and coarse sandstone) in the Green Pond Outlier were deposited in a marine environment of moderate wave energy and contain the large-shelled brachiopod fauna typical of the Oriskany Sandstone and Glenierie Limestone (Waines and Hoar, 1967). The units have been moderately deformed in a style similar to the Valley and Ridge Paleozoic sediment (Finks, 1968; Barnett, 1976b). They appear to have had a similar depositional history to the main belt of Deeparkian sediments in southeastern New York. The Connelly Conglomerate is reported to unconformably overlie the Central Valley Sandstone and is overlain by the Mountainville member of the Esopus Formation (Boucot et al., 1970; Rickard, 1975). There seems to have been no great erosional break between the Connelly Conglomerate and Esopus Shale (typically a sandstone in the

outlier); the lack of intervening Glenerie Limestone appears to be due to a facies change (Rickard, 1975). However, Boucot et al. (1970) report an abrupt contact, Jaffe and Jaffe (1967 & 1989) report the surface as unconformable, while Rickard (1975) shows no unconformity on his correlation chart. Deposition appears to have continued without a break from the Esopus into the overlying Pine Hill Formation (shale and sandstone), which in part (Kanouse Sandstone Member) has been correlated with the Onondaga Formation (Finks, 1968; Boucot et al., 1970). Thus the outlier appears to have been in a subsiding portion of the basin with nearly continuous sedimentation during Connelly through Pine Hills time (Siegenian through upper Emsian time) (Rickard, 1975), though not all workers agree with this interpretation (Barnett, 1976a). Because the Connelly Conglomerate is coarse grained, it appears to have been close to an Appalachian source of sediments to the east, but the unconformity at the base of the Connelly Conglomerate and the mature mineralogy compared to older Silurian units suggest that the Connelly Conglomerate is reworked from older sediments, just as the Oriskany Sandstone is in the main portion of the basin (Finks, 1968). Coarse sandstones and conglomerates similar to the Connelly Conglomerate occur in the Oriskany Group in Pennsylvania and Maryland.

Highland Mills

The Connelly Conglomerate is exposed on Interstate 87 thruway at Highland Mills, Orange County, New York (Boucot et al., 1970). The Connelly is tectonically deformed in the Green Pond Outlier (Barnett, 1976) and dips into the hill on the west side of the thruway. The Connelly Conglomerate is a medium-grained sandstone to fine-grained conglomerate. The conglomerate is composed mainly of rounded to subrounded

white quartz pebbles. The rock displays light limonite staining on weathered surfaces, but is white on fresh surfaces. It is strongly consolidated with silica cement; an occasional brachiopod valve can be found. Though the rock retains the identity of individual detrital quartz grains, it borders on what might be considered a metaconglomerate.

The rock is composed of over 99% detrital silica including: polycrystalline quartz (53%), monocrystalline quartz (33%), chert (7%), detrital sands, and silt-sized matrix (7%). There are trace amounts of detrital tourmaline and zircon. No feldspar or clay was found. Grain boundaries are sutured contacts, and no quartz overgrowths are evident (Figure 3.25). Many grains retain their original rounded- to subrounded outlines, but some chert grains appear to be plastically deformed around adjacent quartz grains, and the suturing of neighboring grains does cause some modification of original detrital grain shapes. Because of the strong suturing of some grains, it is difficult to recognize original detrital grain boundaries between some grains (which could lead to a small overestimation of polycrystalline quartz). Quartz grains have strongly undulose extinction and display abundant trails of microscopic fluid inclusions called Boehm structures that indicate high stress on the grains (Scholle, 1979). Grains also have pressure shadows associated with grain-to-grain point contacts. All of these features point to considerable stress that is probably the result of tectonic deformation.

Heavy minerals are very rare, perhaps because of the coarse grain size, and only a little tourmaline and zircon were found. Tourmaline and zircon were more noticeably angular than in the main outcrop belt. No euhedral grains were observed, and no

Figure 3.25. Connelly Conglomerate from Highland Mills, New York. The rock varies from a sandstone to granule-sized conglomerate. In most part, the rock is composed of quartz, but an occasional brachiopod valve can be found. No feldspar or other unstable minerals have been found in the unit.

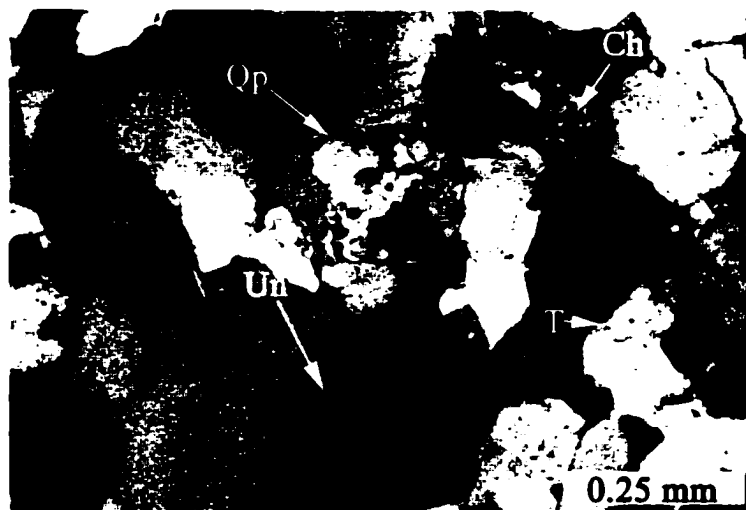
(A) Plane-polarized micrograph of the sandstone. Grain contacts are tightly sutured, and a small amount of limonite stains the sample. Polycrystalline quartz (Qp) and chert (Ch) are common at this location, and most monocrystalline quartz shows some undulose extinction. A small green tourmaline grain (T) is present in this view.

(B) Same view as above using crossed polarizers. This view reveals grain boundaries that at times are poorly visible in plane-polarized light. Several polycrystalline (Qp) quartz grains and chert (Ch) are visible in this view. Monocrystalline quartz often displays strong undulose extinction (Un) and is evidence of the strong level of compaction and stresses that affected the sandstone's texture.

(A)



(B)



overgrowth tourmaline was found. There is considerable amount hyacinth-colored zircon in the sample. The hyacinth grains are mostly well-rounded and spherical.

Monroe Bowl O Fun

The Connelly Conglomerate is exposed behind the Bowl O Fun bowling alley, 550 Route 17M, Monroe Township, Orange County, New York (which burned down on May 16, 1997) and in the cut wall of the parking lot (Jaffe and Jaffe, 1967 and 1989). The rock is a coarse-grained sandstone to conglomerate consisting of over 99% detrital quartz, heavily stained with limonite, and exhibits slickensides on the exposure. The rock is very well indurated and unlike other localities where the Connelly Conglomerate is exposed at this location it is difficult to see original pebble outlines (pebbles are typically 2-3 mm in maximum dimension). This makes it appear massive in overall texture, and hand specimens can be called metaquartzite.

Petrographic examination reveals that quartz grains are tightly sutured to each other. The sutured contacts penetrate what must have been original grain boundaries and are highlighted by limonite staining (Figure 3.26). The degree of grain penetration between individual adjacent detrital grains, whether they are monocrystalline or polycrystalline quartz or chert, is roughly the same. The contacts of grains are reminiscent of stylolites in their appearance (wavy and irregular) and strongly suggest that interpenetration is a result of pressure solution. The modification of grains by this process has destroyed original grain outlines, and this unit probably should be considered a metaconglomerate to quartzite.

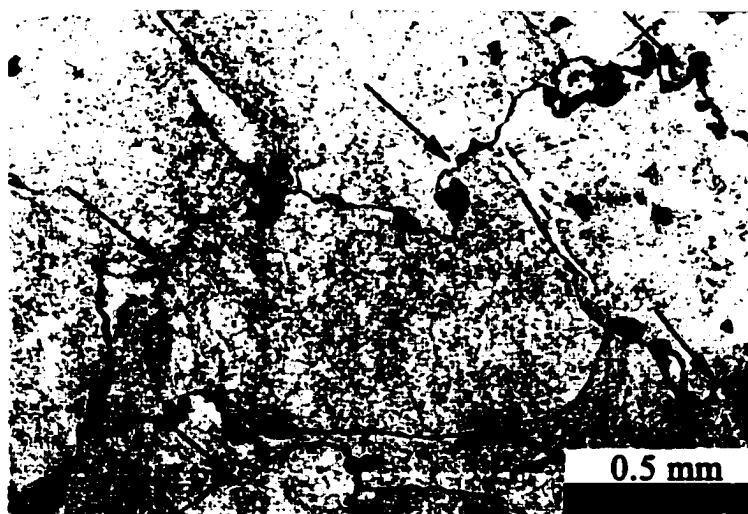
Even though there is strong solution at grain boundaries, individual grains are still

Figure 3.26. Petrographic thin section of Connelly Sandstone from the parking lot of the Bowl O Fun Bowling Alley, Monroe, New York. This coarse-grained sandstone is stained by limonite in the exposure, and limonite also highlights grain contacts in the sandstone. The Connelly Sandstone appears to have been subjected to compressional stresses that have caused strong suturing of grain contacts. Interpenetrative suturing accompanied by pervasive dissolution of grain boundaries has removed all porosity from the rock, creating a quartzite texture with little evidence of original detrital grain outlines at this location.

(A) Plane-light micrograph of coarse-grained quartzite. The sutured grain contacts are mostly visible and are highlighted by limonite. Arrows point to several grain boundaries that display strong suturing.

(B) Same field of view as **A** (above), cross-polarized light micrograph. Though individual grains are clearly visible, the grains display undulatory extinction and strain shadows that are the result of strain on the original detrital grains. The undulatory extinction can be very strong, but is distinguishable from polycrystalline quartz. A large polycrystalline quartz grain can be seen to the right of center. The polycrystalline quartz is composed of a coarse interlocking mosaic of crystals. The grain boundary of the quartz indicates that it acted as a single unit during deformation.

(A)



(B)



distinguishable, and they are mostly strained. Pressure shadows, undulatory extinction, and Boehm structures are clearly visible, and because the undulatory extinction can be so strong, it is difficult to distinguish between monocrystalline and polycrystalline grains. However, by careful examination there is more polycrystalline quartz, 61%, than monocrystalline quartz, 39%, and the remaining 1% is a fine, sand-sized matrix of quartz, a small amount of limonite at grain boundaries, and a trace of sericitic clay.

Heavy mineral separation resulted in a very low yield of tourmaline and zircon.

Pea Hill

The locality is described by Boucot et al. (1970). The Connelly Conglomerate was collected from a small road cut on an abandoned town road running southwest off of Otterkill Road, approximately 2.5 miles (4 km) west of West Cornwall, Orange County, New York. The unit is exposed on the flank of a syncline and has been strongly deformed, though this is not obvious in the exposure (Boucot et al., 1970). The rock is a white to faintly limonite-stained cream color, coarse-grained sandstone to fine conglomerate. Rounded to subangular well-sorted milky quartz grains of 5-8 mm compose the majority of the rock and may have given rise to the name Pea Hill. An occasional larger, 1 to 1.5 cm, well-rounded milky quartz pebble is present. No stratification or fossils were observed.

The sandstone is greater than 99% quartz. The heavy mineral yield was negligible, and only a small amount of tourmaline and zircon was detected. Detrital grains are dominated by polycrystalline quartz, 56%, followed by monocrystalline quartz, 25%, quartzite fragments, 7%, and chert, 2% (Figure 3.27). Quartzite grains appear to

Figure 3.27. Petrographic thin section of Connelly Sandstone from Pea Hill, West Cornwall, New York. The coarse-grained sandstone to granule-sized conglomerate is composed largely of polycrystalline quartz grains but has a finer grained matrix filling intergranular porosity, composed mainly of silt to fine sand-sized monocrystalline quartz and sericitic clays stained by limonite. The matrix is so strongly compacted that all grain boundaries are sutured, creating a texture similar to a fine-grained quartzite. Because the matrix has some sericite, it is less competent than the detrital grains, and stripping occurred during thin section grinding, creating damage spots in the thin section (D). Detrital quartz displays very strong strain shadowing, and most grains have been compacted and sutured so strongly that original detrital grain outlines are lost. There are a few grains that still suggest an original well-rounded grain outline.

Though it is not possible to see because of the coarseness of the grains, only one grain in the field of view is monocrystalline (m); all the other grains are polycrystalline quartz. The extremely high proportion of polycrystalline quartz in this sandstone is very unusual and suggests a crystalline rock source. In the detrital grains, particularly the monocrystalline grain, bubble trails cloud the grain; these are interpreted as Boehm lamellae (b) structures caused by compaction and intense strain in the quartz.

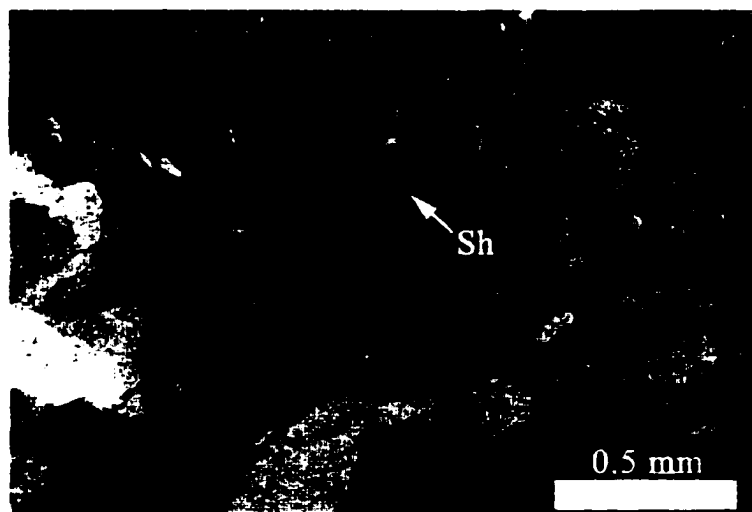
(A) Plane-polarized light image of the sandstone. Most of the dark sub-circular areas are damage spots caused by stripping of the thin section, D. Area labeled S is intragranular matrix that includes a substantial amount of highly birefringent sericitic clay material and some silt to fine sand-sized quartz. Strongly sutured grains display Boehm lamellae (b), bubble trails. Some matrix areas do not have as much sericite and are quartz-rich, QR.

(B) Same view as in A, above, cross-polarized light micrograph. The sericite clay shows high birefringence, but interference colors are partially masked by limonite staining the intergranular matrix. Perhaps limonite is derived from ferromagnesian minerals that were concentrated in the matrix material. Note the strain shadow visible on the monocrystalline quartz grain, Sh.

(A)



(B)



have been well indurated before deposition; they maintain their distinctive rounded grain boundaries and have high-birefringent clays or sericite mica in them, which is also present in the rock's matrix. However, sericite is smaller in the matrix. Matrix between the pea-sized quartz pebbles is fine sand to silt sized and includes particles of monocrystalline quartz and trace amounts of feldspar with an iron-stained moderate to high birefringent clay. Detrital grains in the matrix are moderately well rounded. Matrix makes up approximately 10% of the rock and is distinctive, because individual silt and sand grains retain their identity, most probably as a result of a small amount of clay that is present between grains. There is no porosity.

The texture of the rock has been greatly influenced by compaction and stresses that have caused grains to fracture and become strongly strained. Fracture, brittle deformation, has shattered grains that have been subsequently healed by quartz infilling of fractures. The fractures generally radiate out from point of contact between adjacent grains and are visible with a light microscope, but show up most clearly when cathodoluminescence microscopy is used (Figure 3.28). The quartz that heals the fractures is nonluminescent and contrasts with the detrital grains (Dickinson and Milliken, 1995). As well, point contacts of grains, where stress is concentrated, cause stress shadows that are visible in cross-polarized light. All grains in the sandstone display some degree of undulatory extinction, and usually grains have a very high degree of undulose extinction. Monocrystalline quartz grains are difficult to recognize because of undulose extinction and can be confused with polycrystalline quartz. It is only by a lack of distinctive extinguishing domains and lack of clearly visible crystal boundaries

Figure 3.28. Petrographic thin section of Connelly Sandstone from Pea Hill, West Cornwall, New York. Though in many instances pressure solution causes grains to suture to adjacent grains at their contact, in this example a quartz grain has shattered under conditions of brittle deformation. The fracture was rehealed by silica. Offset of the grain along the fracture is best recognized using cathodoluminescence.

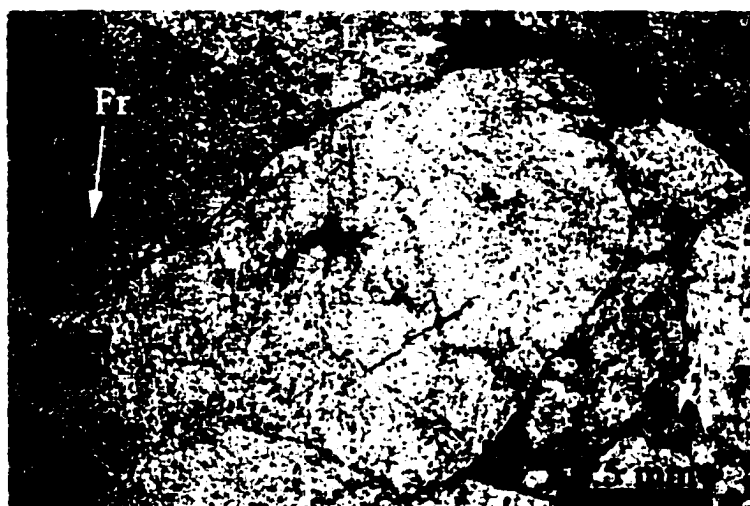
A) Plane-polarized light micrograph of the conglomerate. Large quartz grains are very closely packed in this sample. A small amount of detrital matrix (Ma) occurs between the grains. The matrix contains silt-sized quartz and a small amount of feldspar that are combined with a small amount of medium to high birefringent clay. Some limonite (Li) and limonite-stained clay are also present in the sandstone. Some healed fractures in the quartz grains are visible (Fr), but not particularly obvious. The quartz grains have many fluid inclusions and may be of vein/hydrothermal origin.

(B) Same field of view as in **A** viewed with cross-polarized light. Fractures are more obvious on the large polycrystalline quartz grain in the center of the field of view. Clay minerals (Li and in the matrix [Ma]) have a moderate birefringence and a hint of green color. Some of the clay may be chlorite.

(C) Same field of view as in **A** and **B** viewed using cathodoluminescence. The majority of grains in this field are only weakly luminescent with an orange-brown color. The polycrystalline quartz grain with blue luminescence can now be seen to have been intensely fractured. It has an offset fracture in the lower part of the grain that could be pieced back together. It is clear that this fracture is due to in situ brittle deformation of grains during compaction or tectonic deformation. The fractures were then healed by precipitation of nonluminescent quartz cement. Because the cement and the quartz grain have the same refractive index, the fractures do not stand out and are very hard to see in regular light. But they are easily recognized in cathodoluminescence. Notice that even on quartz grains with much lower luminescence fractures (Fr) are easily recognized.

The very high luminescence of this quartz grain is surprising and might be due to strain on the crystal lattice. Two small feldspar grains in the matrix luminesce a bright blue (Ma).

(A)



(B)

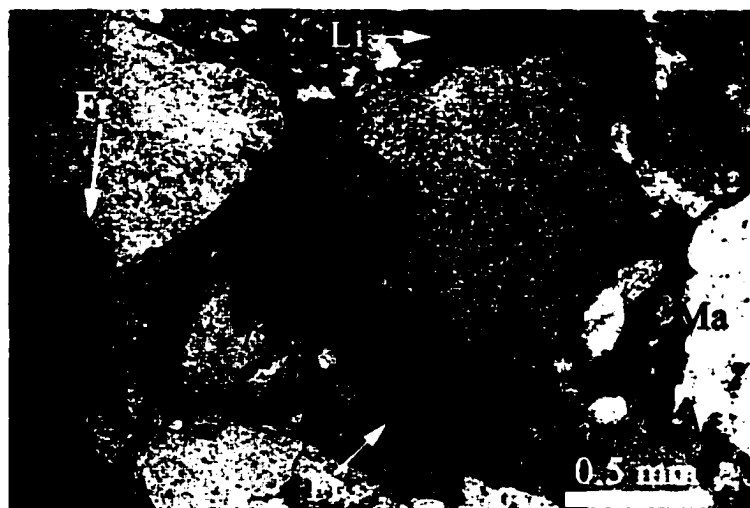
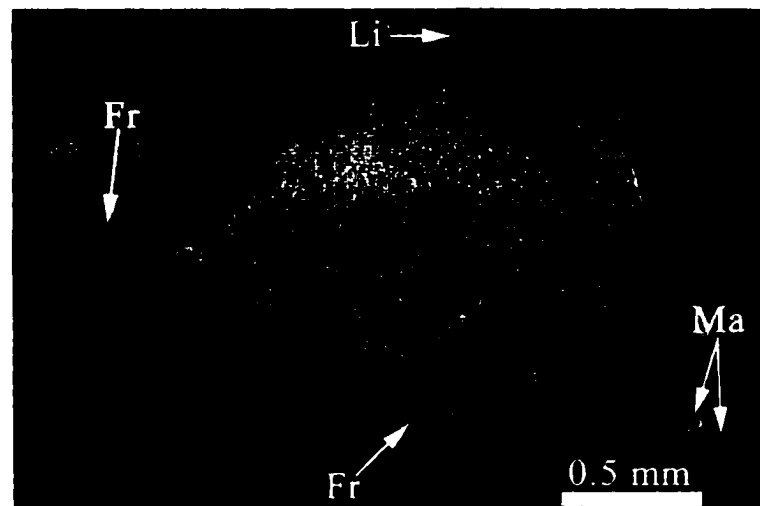


Figure 3.28—Continued

(C)



that some grains are recognized as monocrystalline. Most quartz grains display Boehm structures. Chert grains are typically rounded, but some appear to have deformed plastically around grains of polycrystalline and monocrystalline quartz.

Even though this rock has been deformed and modified by tectonic stresses, individual detrital grains are recognizable, and it should be classified as a conglomerate or pebbly sandstone rather than a metaconglomerate or quartzite.

Pennsylvania Sample

Stroudsburg

The sample was collected at section 15-d of Epstein et al. (1967) in unit 281 from a road cut on the southwest side of U.S. Interstate Highway 80, approximately 0.4 miles (0.64 km) southwest of Minisink Hill, near Stroudsburg, Pennsylvania. The white to light gray medium-grained sandstone is very well indurated with siliceous cement. It weathers a rusty orange color in places. Individual quartz grains and pebbles, seen on weathered surfaces, are well rounded and spherical. However, when the sandstone is broken, it tends to break through, rather than around grains, and a sledgehammer is needed for sampling. Some brachiopod fragments and molds are present, but not identifiable.

The sandstone has a noticeably higher amount of polycrystalline quartz than is typical in New York or farther south in Maryland and the Virginias. As well, much of the quartz shows strain shadows or undulatory extinction (Figure 3.29). No detrital feldspar was found. The cement can be seen occasionally as overgrowths on quartz grains (Figure

Figure 3.29. Photomicrographs of Oriskany Sandstone from Stroudsburg, Pennsylvania.

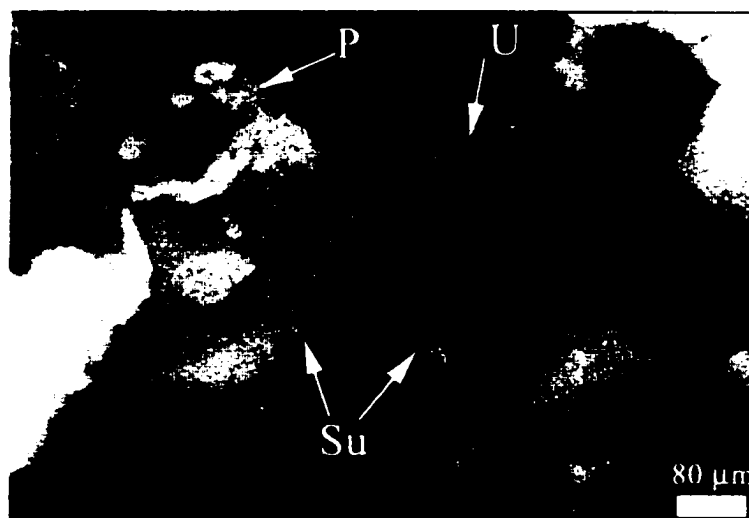
(A) Polarized-light photomicrograph of dust lines of overgrown detrital quartz (D) show the original well-rounded nature of the sand grains. Polycrystalline quartz is abundant at this location.

(B) Polarized-light photomicrographs of polycrystalline quartz (P) and also a monocrystalline grain displaying undulose extinction (U) are illustrated. Several other grains in this view exhibit less pronounced undulose extinction. Notice that in this view most grains have sutured contacts (Su) with neighboring grains. This type of grain contact is much more common than grains with overgrowth cement at this location.

(A)



(B)



3.29), but mostly grains do not show dust lines. Grain contacts are generally heavily sutured, and there is virtually no porosity.

Heavy minerals separated include very well rounded tourmaline and zircon. No other minerals were found. No overgrowth tourmaline was found.

Maryland Samples

Samples from Maryland were collected in the Valley and Ridge Province. The sandstone facies of the Oriskany Group is referred to as Ridgeley Sandstone.

Cumberland (Spring Gap)

The Oriskany Sandstone was collected at a railroad cut of the Western Maryland Railroad near Cumberland, Maryland, described by Yochelson and Kriz (1974).

According to Yochelson and Kriz (1974), approximately 20 ft (6.1 m) of the upper part of the Ridgeley member of the Oriskany Sandstone is exposed at this location. The rock varies from a well-indurated, calcite-cemented quartzarenite to a well-indurated, calcite-cemented quartz-pebble conglomerate.

The calcite-cemented quartzarenite and pebble conglomerate have similar properties. Both are cemented by a pervasive nonferroan calcite (based on staining). There is a small amount of embayment of silicate grain boundaries. The conglomerate has a matrix of small sand grains, which most likely infiltrated the coarser pebbles.

The conglomerate is composed of well-rounded quartz pebbles with a maximum size of about 1.5 cm. Most of the grains are monocrystalline quartz (approximately 82% of the detrital grains). Some of the monocrystalline quartz shows evidence of stretching,

with parallel fractures in it. More than half of the monocrystalline quartz displays strong undulatory extinction. These two characteristics suggest a possible derivation from metamorphic rocks. There are some polycrystalline quartz pebbles (approximately 18% of detrital grains), and they have two distinct crystal types. One is a polygonally sutured quartz made of semi-equant subcrystallites, each of which is sand sized; the other is composed of stretched quartz that suggests foliation and may be from a metamorphic rock.

Though there is no feldspar in the pebbles, the matrix sand contains several small feldspar grains; both plagioclase with albite twinning and microcline were recognized. A small amount of phosphate, probably fish fragments, is present. There are a few brachiopod shell fragments that display prismatic wall structure (columnar calcite crystals in the wall growing at right angles to the shells' surfaces). Other brachiopod shell fragments have parallel fibrous wall structures. The calcite cement is anhedral and displays considerable twin plane shear structures. The calcite cement embays all silicates, but is particularly aggressive in embayment of the plagioclase feldspar, which appears to have been considerably reduced in size. Some calcite, especially in brachiopod shells, has been replaced by anhedral, irregular patches of chert.

The calcite-cemented sandstone is composed mainly of medium-sized, subangular to rounded grains of monocrystalline quartz (95 %); a small amount of subrounded to rounded polycrystalline quartz (2.7 %), and a little bit of subrounded feldspar; microcline feldspar is most abundant, but there is some albite-twinned plagioclase. A couple of composite quartz-feldspar grains were observed, and it is most likely that they are

crystalline rock fragments. Carbonate fragments of sand size include fragments of brachiopods and unrecognizable subrounded grains that may be skeletal in origin.

Small quartz overgrowths are present on some grains, but there are few dust lines. This makes it difficult to assess the degree of rounding of quartz grains. However, feldspar grains are subrounded to rounded (Figure 3.30), and this suggests that the originally deposited quartz grains are more rounded than they now appear and were modified by quartz overgrowths. Both calcite and silica cements are patchy. Anhydral calcite is the more abundant cement. It embays silicate minerals and may have altered the textural appearance of grains, particularly plagioclase. There is also a small amount of pyrite in this sample (there was none in the conglomerate.). Pyrite occurs as irregular patches and blebs filling some intergranular pore space.

No tourmaline overgrowths were found at this site, and this may be due to early cementation or a facies change from a less calcareous to a more calcareous facies (Yochelson and Kriz, 1974).

Tonoloway Ridge

The locality described by Glaser (1979) is 2.2 miles (3.2 km) west of the I-70 interchange on U.S. 40 near Hancock, Maryland. The sandstone is exposed in an abandoned quarry and road cut just off of Sandy Mile Road, along Tonoloway Ridge. The sandstone layers are steeply dipping. The entire exposure is a pure white, medium-grained sandstone referred to as Ridgeley Sandstone. Some layers are extremely friable and crumble to individual grains on handling; other layers are extremely well indurated. Brachiopod valve casts can be seen in the more indurated layers, but are difficult to

Figure 3.30. Oriskany Sandstone from Spring Gap railroad cut near Cumberland, Maryland. The Oriskany at this location varies from medium-grained sandstone to a well-rounded conglomerate of quartz pebbles cemented by calcite. Feldspar is more abundant in the sandstone layers, but is also present in the matrix of the conglomerate. Both plagioclase and microcline feldspar are present, but microcline is much more abundant. In this view two feldspar (F) grains display moderate rounding and only minor alteration to clay minerals. One of the grains is partially replaced by calcite. Tight suturing in the sandstone might indicate late cementation, but it is believed that it, in part, represents quartz overgrowths without dust lines. A few small, poorly developed dustlines (D) support this idea. Small amounts of anhedral carbonate (C) and lesser amounts of pyrite (P) fill some of the pore space.

(A) Petrographic thin section viewed using plane-polarized light. Notice that the feldspars (F) are moderately well rounded and that because there are no syntaxial overgrowths on them, as there most likely are on the quartz grains in this view, their detrital outlines are visible. Small dust lines (D) are present on some quartz grains in this sandstone and indicate that those grains were moderately well rounded when deposited. Carbonate cement (C) occludes any porosity that is not filled with silica. It is believed that relatively early cementation prevented intrastratal dissolution of feldspar at this locality.

(B) Same view as in A (above) using cross-polarized light. Microcline twinning is displayed by the feldspar grain to the left, and can vaguely be seen on the grain on the right, which is not properly oriented to show it in this view. The grain to the left has been partially replaced by carbonate (C). Carbonate displays high birefringence. Quartz is also slightly embayed by carbonate, particularly on the grain in the upper right hand corner of the photograph.

(A)



(B)



identify. No carbonate remains in the rock. Glaser (1979) reported *Costispirifera* and *Acrospirifera*, as well as *Platyceras* gastropods.

The sandstone is composed almost entirely of monocrystalline quartz with a trace of rounded potassium feldspar. The quartz grains appear strongly sutured to each other, and it at first appeared that there was little cement (there are no dust lines indicating quartz overgrowths); however, investigation with cathodoluminescence revealed that there are considerable quartz overgrowths and that the original detrital outline of quartz grains is moderately well rounded (Figure 3.31). Based on cathodoluminescence, the sandstone is moderately well sorted. An estimate of quartz cement would be around 15%, and the cement is almost entirely responsible for porosity reduction in less friable layers at this locality. However, less indurated layers, so friable that they crumbled to individual grains, may have had a carbonate cement that was removed by percolating ground water in near-surface conditions (Seilacher, 1968). The fossil molds of brachiopods support this line of speculation, and it is suggested that oversized pores in the more indurated sandstone are the result of leaching of carbonate fragments (Figure 3.31). Since no carbonate is present and there is no evidence of embayment by carbonate cement in the well-indurated sandstone investigated with cathodoluminescence, it is likely that these layers were originally cemented by diagenetic silica.

West Virginia Samples

Dolly Sods Scenic Area

This location is 1 mile (0.6 km) southwest of Smoke Hole Caverns, West

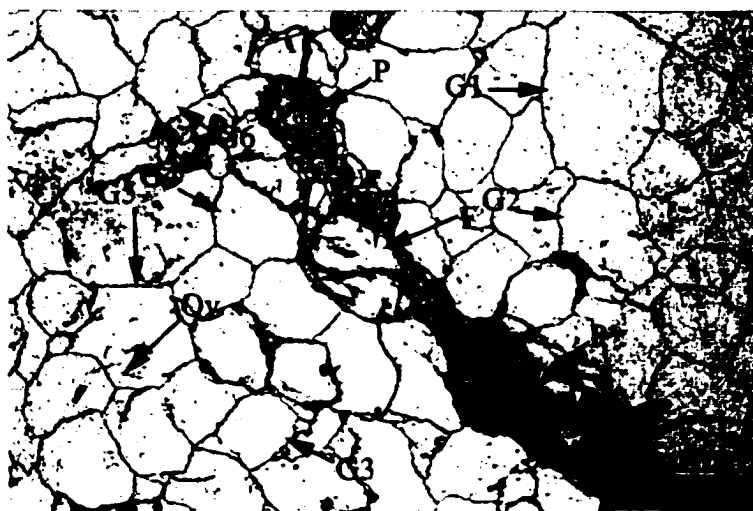
Figure 3.31. Oriskany Sandstone from Tonoloway Ridge, Hancock, Maryland. Most grains in this sample have significant quartz overgrowths, and this acts as the major cementing agent in some layers of sandstone from this locality. Other layers are more friable, and this is probably because of leaching of carbonate cement.

(A) Plane-polarized light micrograph of the sandstone. Because there are no dust lines visible in this sandstone, it was believed at first that cementation was the result of pressure solution, but cathodoluminescent microscopy revealed that the sand grains are overgrown by authigenic quartz. Grains G1 through G6 all have significantly modified grain outlines because of significant quartz overgrowth. At point Ov 3 large overgrowths have made straight-line contact. Feldspar (F) is not overgrown and shows significant detrital rounding. A large pore (P) in the center of the field of view (filled by blue-dyed epoxy) may have resulted from the leaching of a carbonate fossil or rock fragment. Two dark patches in the pore to the lower right are air bubbles. Note that detrital grain boundaries terminating at the edge of the pore must have been in contact with a grain or grains that are no longer present.

(B) Same field of view as in **A** viewed with cross-polarized light. Again no detrital grain contacts are evident and grains appear to be strongly sutured to each other. The same mineral grains and pore spaces are labeled as in **A** (above).

(C) Same field of view as in **A** and **B** viewed using cathodoluminescence. The detrital cores of quartz grains G1 through G6 are now evident and can be seen to be well-rounded. Authigenic quartz is nonluminescent. The blue-dyed epoxy in the pore space (P) does luminesce a blue-green color. The feldspar grain (F) has a strong blue luminescence, and quartz grains vary in their luminescence color and brightness from a violet to a dark blue color. It is now evident that significant amounts of intergranular space have been filled with nonluminescent silica cement. At point Ov and several other places in the field of view significant intergranular pore spaces have been filled. Note also that there is not much quartz authigenesis on quartz grains bordering the pore space. This suggests that the pore was filled at the time of quartz authigenesis and was leached at a later time, perhaps during recent near-surface weathering.

(A)



(B)

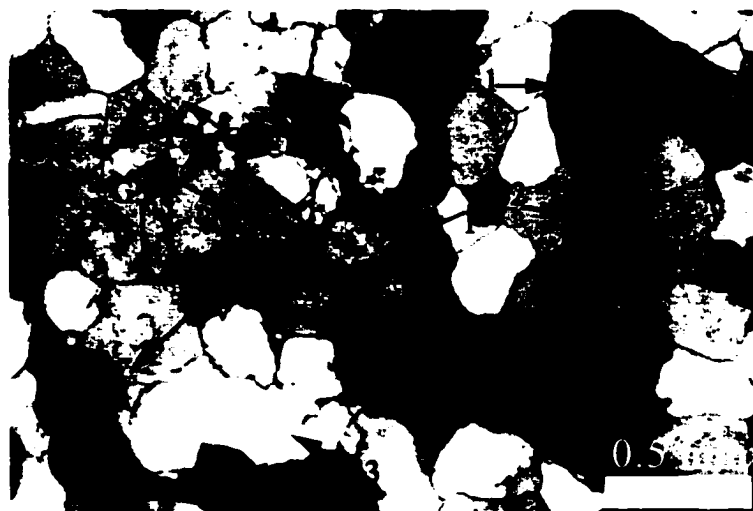
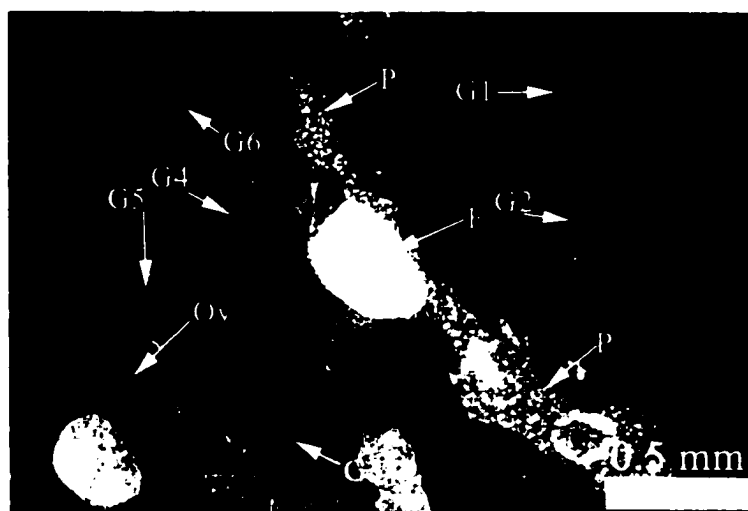


Figure 3.31—Continued

(C)



Virginia, at the intersection of West Virginia Routes 55 and 28, Hopeville and Jordon Run Roads. Samples were collected in the road cut just opposite the information sign. No stratigraphic section was measured.

The sandstone is a medium- to coarse-grained, limonite-stained quartzarenite. Abundant brachiopod molds of *Hipparionyx proximus* and *Costispirifer arenosus* were used to recognize the Oriskany Sandstone at this previously undescribed locality.

Monocrystalline quartz makes up almost 99% of the detrital component. Trace amounts of polycrystalline quartz, feldspar, and iron-stained clay are present. Feldspar was recognized by feldspar staining and by microcline twinning on much of the potassium feldspar. The feldspar grains have some alteration to low-birefringence clay minerals. Alteration varies from minor to significant clouding of the grains (Figure 3.32A and B).

The sandstone is devoid of carbonate material, but it clearly had abundant material at the time of cementation as evinced by the moldic porosity (Figure 3.32C and D). A few silicified brachiopod shell fragments have been found in thin section. The silicified shell fragments are elongate and of the same general size as the pore; thus both whole valves of brachiopods and fragments were deposited. Total porosity in the sandstone is 9.4%. Most of the porosity results from dissolution of shell fragments and other carbonate debris. The porosity may be due to near-surface recent weathering.

There is also considerable clay at this locality. The clay displays medium to low birefringence and is always iron stained. Clay coats almost all of the pores in the sandstone and is particularly abundant in vugs where fossils have been dissolved. This

Figure 3.32. Sandstone from Dolly Sods Scenic Area, West Virginia. The sandstone has a considerable amount of feldspar and also has significant porosity that is believed to be secondary in nature. In the exposure numerous molds of brachiopods are visible. Since there is no carbonate left in the rock, it is presumed that much of the porosity is formed by dissolution of carbonate material.

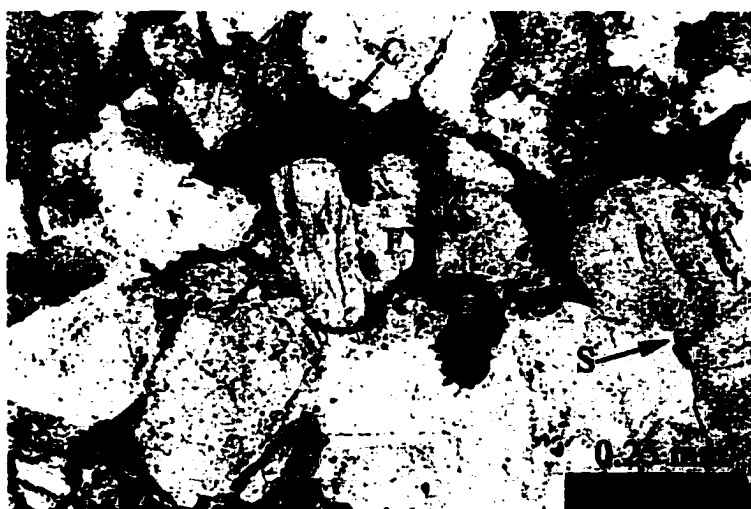
(A) Plane-polarized micrograph of porous sandstone. The pore walls are mostly coated with iron-stained clay minerals and are filled with blue-dyed epoxy. Only potassium feldspar has been found in thin section; the condition of feldspar in the sandstone ranges from slightly altered to moderately altered. A microcline grain (F) shows only minor alteration, yet it borders a rather large pore (P). Some quartz grains show moderately strong suturing.

(B) Cross-polarized light micrograph of the same view as seen in **A**, above. Microcline twinning is visible on the feldspar, and a large polycrystalline grain can be seen below the feldspar.

(C) Plane-polarized micrograph of very large, nearly rectangular pore. Elongate pores are very common in the sandstone and may be formed as a result of dissolution of brachiopod shell fragments. Several silicified shell fragments have an outline similar to the shape of this pore. Note that several of the sand grains that border the central pore have rounded outlines extending into the pore. Perhaps these grains were in contact with a carbonate fragment and thus avoided alteration of their original grain outline by such processes as quartz overgrowth or compactional suturing. At point B, a space between two pores has a bridging grain contact. This contact, possibly due to overgrowth, suggests that nonsilicate grains were probably present in the places that are now pores and prevented overgrowth into those areas. Perhaps the carbonate fragments were then removed by alteration. A clay coating fills the pores (C); the origin of this clay is unclear, but its rusty color is probably due to near-surface weathering.

(D) Cross-polarized light micrograph of the same view as seen in **C**, above. Clay in the pore spaces displays low to moderate birefringence.

(A)

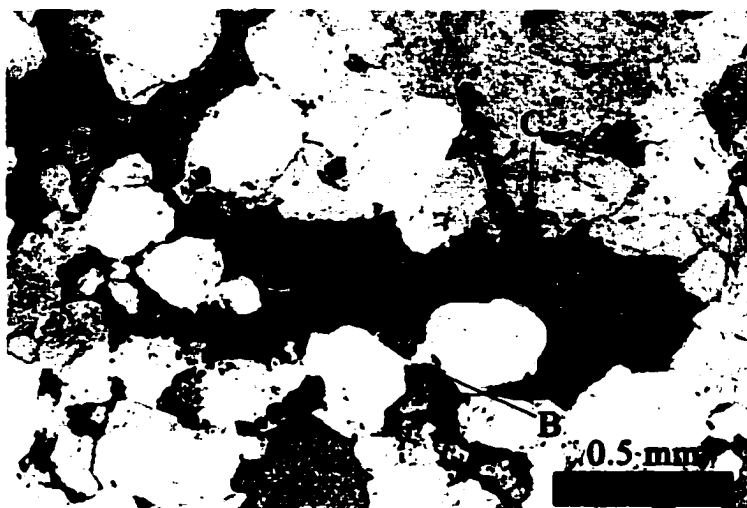


(B)

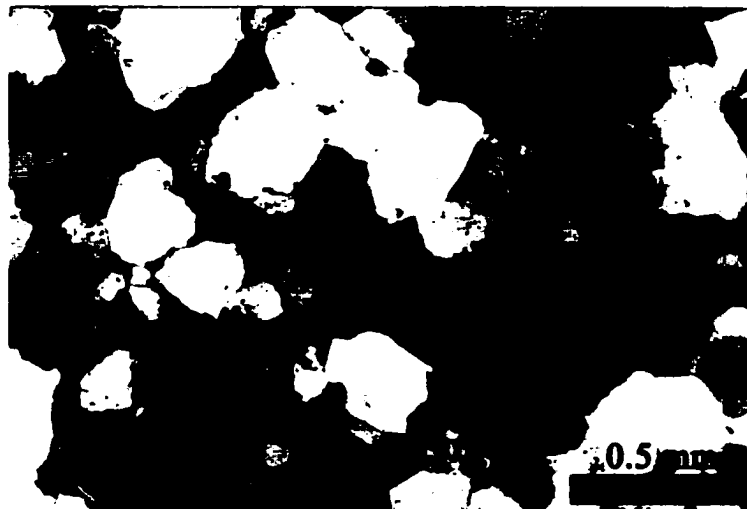


Figure 3.32–Continued

(C)



(D)



suggests that it is secondary in nature. When the clay was formed is unclear, but it seems reasonable that it formed after carbonate dissolution. Therefore the clay may be due to recent weathering under near-surface conditions and be a late stage component of the sandstone, unrelated to the sandstone's depositional history or original mineralogy.

Franklin, Pendleton County.

The location is Stop 1 of Fichter (1986), Oak Flats Section, 1.1 miles (1.76 km) west of Oak Flat on the south side of US 33. The Oriskany Sandstone is 130 feet (39 m) thick and is steeply dipping at this location.

The moderately coarse-grained to medium-grained sandstone has abundant brachiopod molds and is stained brown by limonite.

Petrographic analysis reveals that the sandstone is a well-cemented quartzarenite with 96% detrital quartz, and a small amount, 3.7%, of detrital feldspar. Most of the quartz is monocrystalline, but about 1% is polycrystalline. The polycrystalline quartz usually has elongated crystallites suggesting a metamorphic source. Small amounts of clay and limonite are present in pore spaces, but these may be due to modern-day weathering and infiltration. There is no carbonate in thin section. Quartz grain contacts are mostly sutured, but pore-bounding grains sometimes retain rounded outlines. This suggests that a non-quartzose material filled the pores, so that no overgrowth or suturing could occur. Since many of the pores are elongate rectangular to gently curved and are of the correct size, it is presumed that they are fragments of carbonate shells that were dissolved, leaving vugs. The carbonate was removed by leaching. Some pores that appear to be dissolution vugs are completely lined with iron-stained clay, while other

pores, particularly large pores, have either thicker pore linings on one side or no pore lining on one side, suggesting that clay infiltrated while carbonate grains were undergoing dissolution. Grains with thicker-on-one-side linings might be geopetal fillings of clay that infiltrated with the dissolving fluids.

Whether carbonate leaching is a result of surface weathering in recent exposure or is a diagenetic alteration is uncertain. However, one line of evidence supporting late stage carbonate dissolution is that pores are still open even though the sandstone is tilted at a high angle and has been deformed by considerable tectonic forces (Fichter, 1987). It is likely that these pores would have collapsed had carbonate leaching been prior to tectonic deformation. Since most of the clay is filling pores, it probably is a late stage infiltration after carbonate leaching.

Greenland Gap, Grant County

The Oriskany Sandstone was collected at Stop 11 of Avary (1986) at Scherr, West Virginia. Greenland Gap is a water gap through the Wills Mountain Anticline. The west-dipping beds of the Oriskany Sandstone are on the west limb of a small anticline, the Hopewell Anticline, a minor flexure on the western limb of the larger Wills Mountain Anticline. The Oriskany Sandstone at this location is medium grained overall with some fine and coarser grained portions. The silica-cemented sandstone is stained light brown by limonite and has a few scattered brachiopod molds.

The sandstone is composed of well-rounded monocrystalline quartz and a little feldspar. The feldspar grains are moderately rounded and relatively fresh. Staining revealed that most of the feldspar is alkali feldspar, and there is just a trace of plagioclase.

The alkali feldspar is mainly microcline that displays scotch-plaid type twinning, but there is some untwinned feldspar as well.

The sandstone is well indurated with silica cement (Figure 3.33A and B). The detrital quartz has well-developed overgrowths, many of which have dust lines that form a polygonal mosaic of quartz. Aside from authigenic silica, the only other authigenic component found is a small amount of pyrite. Pyrite is present in small anhedral masses.

Porosity appears to be mainly from the leaching of carbonate grains (Figure 3.33C and D). Though no carbonate was found in thin section, carbonate grains have been leached, leaving vug-type pores. The evidence to support this is that the pores are gently curving, subrectangular shapes similar in dimensions to brachiopod fragments. Since whole-shell brachiopod vugs are present, it is logical to assume these are fragments of shells. As well, portions of quartz grains that line these pore spaces do not have overgrowths. However, the portions of the same grains that are not facing into the pore spaces have overgrowths, and this suggests that carbonate grains and cement filled the vugs when quartz authigenesis took place. The carbonate prevented the sand grains in contact with the carbonate from forming overgrowths (Figure 3.33C and D).

Minnehaha Springs

This locality is a half mile (0.8 km) south of Minnehaha Springs on West Virginia Route 39 and is described by Kulander et al. (1986). As implied by its name, the area is known for its springs of hot water that are developed in the sandstone. The sandstone occurs as small ledges on the side of the road, is rusty brown in color, and contains many casts of brachiopods. It is moderately coarse grained and contains some pebble-sized

Figure 3.33. Four micrographs of the Oriskany Sandstone from Greenland Gap, Grant County, West Virginia. Sandstone at this locality is well indurated with silica cement. The detrital quartz has well-developed overgrowths that form a polygonal mosaic of quartz. Some porosity is developed, but it appears to be mainly from the leaching of carbonate grains.

(A) Plane-polarized light micrograph of interlocking quartz overgrowths. Several detrital grains can be recognized by dust lines (DL) developed between well-rounded detrital grains and authigenic overgrowths. All porosity has been occluded by quartz growth and minor amounts of pyrite (P).

(B) Same view as **A** (above) using cross-polarized light. In this view, though dust lines can still be observed on some grains, more striking is the polygonal nature of overgrowth contacts. Since they are due to the contact of crystal faces of the overgrowths, relatively straight-sided contacts have resulted.

(C) View of a portion of a large pore filled with blue-dyed epoxy. The pore is rectangular in outline and probably contained a carbonate shell fragment that was leached after lithification of the sandstone. Evidence supporting the idea of a carbonate grain is that quartz grains' boundaries within the pore space do not have overgrowths and were probably in contact with a softer carbonate grain; during compaction the sand grains were pressed into the shell fragment(s) before overgrowths could form. The shell fragment(s) must have been removed late in the sandstone's history (perhaps during recent weathering in the near surface), because during burial the very large, unsupported pore space would have collapsed. Supporting this suggestion is a delicate bridge of quartz grains at point A that must have been pinched between two carbonate fragments; quartz overgrowths formed between the grains, but the grains' outlines on either side of the pore are not overgrown. These grains certainly would not have stayed in this unsupported position for long during burial and compaction unless something (carbonate) was holding them in position.

(D) Same view as **C** (above) using cross-polarized light. Again the strongly polygonalized outline of grains away from the pore space is evident. The grains within the pore's walls have rounded, perhaps slightly embayed outlines that probably are close to the original detrital outline of the grains.

(A)



(B)

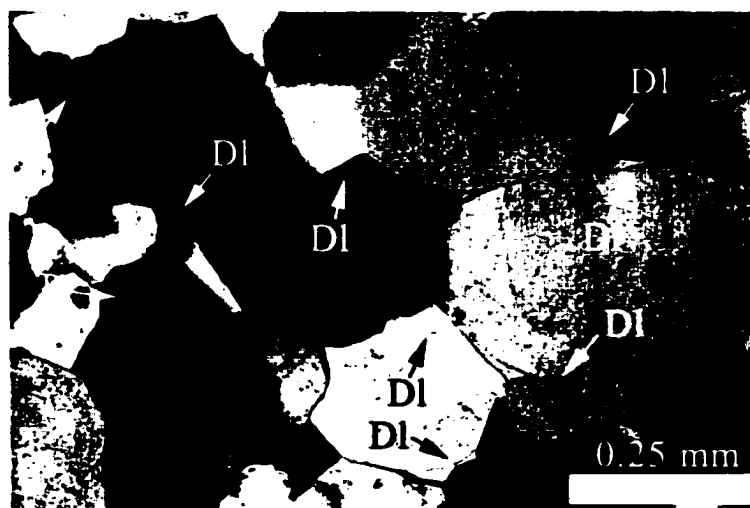
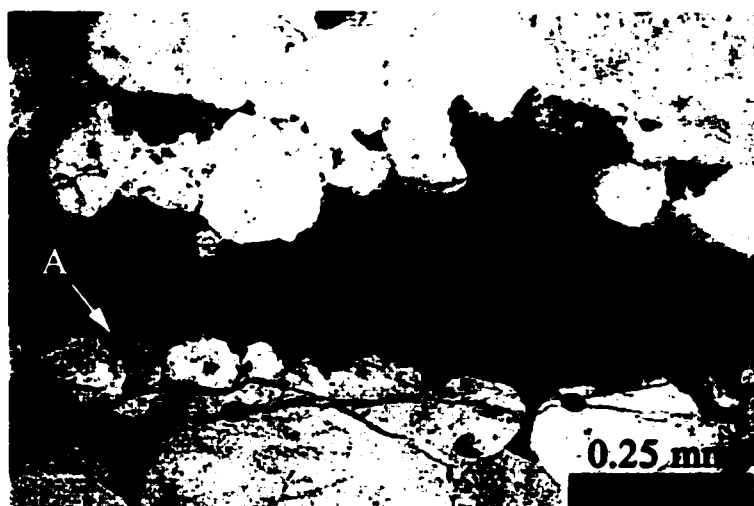


Figure 3.33—Continued

(C)



(D)



quartz. The sandstone is very friable and can be easily broken. Sorting is moderate, with a few larger pebbles. The pebbles are mainly monocrystalline milky quartz.

Mineralogically, the sandstone is a quartzarenite composed of over 99% detrital quartz with a trace of potassium feldspar (Figure 3.34); no shell fragments or other calcitic material remains. Monocrystalline quartz grains are subrounded to rounded and slightly modified by quartz overgrowths. There is a trace of polycrystalline quartz with sand-sized polygonal subcrystals. This sample shows stronger than usual compaction with detrital grains in close contact to each other. Because dust lines are absent, quartz overgrowths give the impression of pressure-sutured grains. Though there does seem to be some suturing due to grain dissolution, cathodoluminescence reveals that many grains have overgrowths and original grain outlines are intact without major modification. Potassium feldspar, recognized by cathodoluminescence (robin's-egg blue) and staining, is finer grained than quartz and is moderately rounded (Figure 3.34C). Some feldspar appears to have fractured in place; this may be a result of compaction or an artifact of thin sectioning.

The vugs, caused by the leaching of shell debris, and whole brachiopod valves attest to a dissolution event that probably removed almost all carbonate from the rock. There is about 7% porosity in the rock, most of which is probably the result of leaching of carbonate debris. Limonite staining has infiltrated between grain boundaries and into pore spaces, leaving a thin mahogany brown stain coating the grains around the pores.

Though limonite may act as a secondary cement, it is not very important mineralogically. Its origin is probably related to alteration and weathering in the near-

Figure 3.34. Petrographic thin section of Oriskany Sandstone, Minnehaha Springs, West Virginia. Though this is a mineralogically mature quartz arenite and grains in this image are tightly packed, the true nature of the grain contacts cannot be ascertained from this observation alone. The following micrographs show that though the grains do make contact with each other due to moderately strong compaction, some grains' polygonalized appearance are due to quartz overgrowths.

(A) Plane-light image showing mainly quartz grains making up the framework of the sandstone. The grains' contacts with each other appear to be moderately strongly sutured. Pore spaces are labeled P and appear as a dark yellow-brown due to beam damage to the epoxy that was heated by the electron beam during cathodoluminescence observation. To the upper right is a pore that is filled with iron-stained clay minerals, C. The iron staining may be due to oxidation of pyrite that is fairly abundant in this location. To the lower right is an area where 3 quartz grains appear strongly sutured, labeled S1; this is confirmed by cathodoluminescence. The grain labeled O has been enlarged by overgrowths; while the arrow pointing to S2 shows a contact between two strongly sutured grains that appear to be only one grain in this image.

(B) Polarized-light micrograph of the same area shown in A. The quartz grains to lower right, labeled S in A, are visible and show suturing. The overgrowth in the grain O can be seen to have grown in optical continuity with the detrital core. Pore spaces appear dark, because the epoxy is not birefringent.

(C) Cathodoluminescent image of the same area shown in A and B. From this image it can be seen that a little authigenic quartz has enhanced most grain contacts, but that in most instances detrital grains are tightly packed next to one another. This indicates moderately strong modification of sandstone and suggests that most primary porosity would have been lost. Therefore porosity is probably mainly due to postcompactional dissolution. The original outlines of quartz grains are now clearly visible, and the sandstone's original grains were subrounded. Feldspar, luminescing a brightly, is mainly in small grains and appears to be somewhat fractured. Commutation of feldspar is probably a result of both cleavage and alteration.

(A)

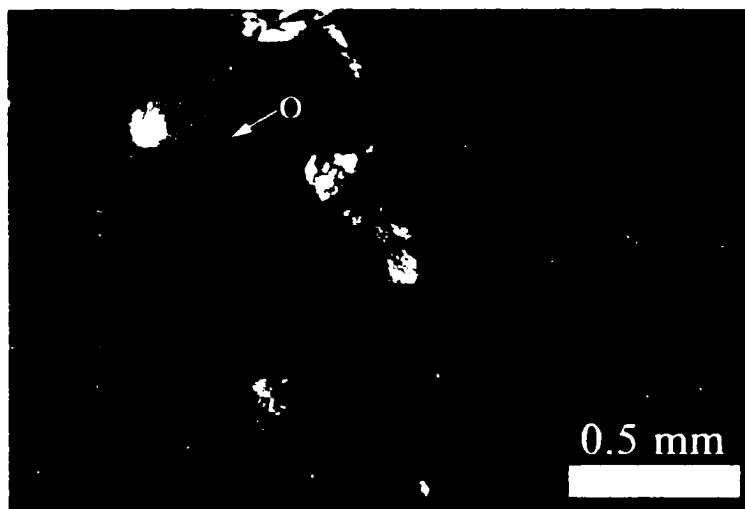


(B)



Figure 3.34—Continued

(C)



surface environment and has a recent origin.

Only well-rounded tourmaline and zircon were found in the heavy mineral suite.

Tourmaline overgrowths were abundant.

Virginia Sample

Warm Springs

A sample was collected at Warm Springs, Bath County, Virginia; here 10 feet (3 m) of Oriskany Sandstone are exposed in a road cut described by Stow (1931). The location is on Route 39 approximately 5 miles (8 km) west of Warm Springs, Virginia.

The sandstone is limonite stained, medium grained, and has abundant fossil molds of brachiopods. The rock is well consolidated and appears a little more resistant to erosion than at Minnehaha Springs, West Virginia, just a few miles away.

Petrographically, the rock is a quartzarenite with over 99% detrital quartz and a trace amount of potassium feldspar. Sand grains range from moderately well rounded to subangular. There are no dust lines on quartz overgrowths; however, cathodoluminescence reveals that quartz overgrowths are the main cause of cementation in the sandstone (Figure 3.35). Without cathodoluminescence, this rock would appear to have many sutured contacts that caused consolidation.

There is a trace amount of opaque mineral in the sandstone, and during heavy mineral separation a lot of pyrite was found in the heavy mineral separate. The pyrite is mostly in anhedral, bleb-shaped masses.

The rock has 7.5% porosity grains (Figure 3.36), and most of it appears to be vugs

Figure 3.35. Petrographic thin section from Warm Springs, Virginia.

(A) Plane-light image of quartz arenite with several feldspar (F1-F3) grains in view. Pore spaces (P) show a faint blue color from blue-dyed epoxy, and iron-stained clay minerals coat and partially fill pores (C). Most of the pores were probably created by dissolution of feldspar or carbonate minerals. The rounded feldspar grains show minor alteration, particularly along fractures, but maintain their optical properties.

(B) The same field of view as in **A** is shown using crossed polars. Grain F1 shows microcline twinning. Staining techniques used on another thin section reveal that potassium feldspar dominates the feldspar in this locality. Note that many of the quartz grains, such as the large quartz grain below F2, appear to have sutured or interpenetrating contacts with adjacent grains.

(C) Cathodoluminescent image of the same field of view seen in **A** and **B**. The detrital feldspars are luminescing a robin's-egg blue color (this includes several grains not labeled in **A**). At this high accelerating voltage, 20 KV, quartz grains also luminesce faintly in blue to brown-blue shades. Note that grain boundaries of the quartz do not show the suturing implied above in the cross-polarized light image, **B**. Grain boundaries in general are now seen to be subrounded to rounded, because silica cement does not luminesce. Places where silica cement could easily be mistaken for sutured grain contacts are pointed to by arrows. The arrows thus point to overgrowths that are nonluminescent and could only be recognized by their contrast to the luminescent detrital quartz. Though no dust lines are present, it is clear that the cement in this field of view is mainly due to overgrowth rather than pressure solution.

(A)



(B)



Figure 3.35–Continued

(C)

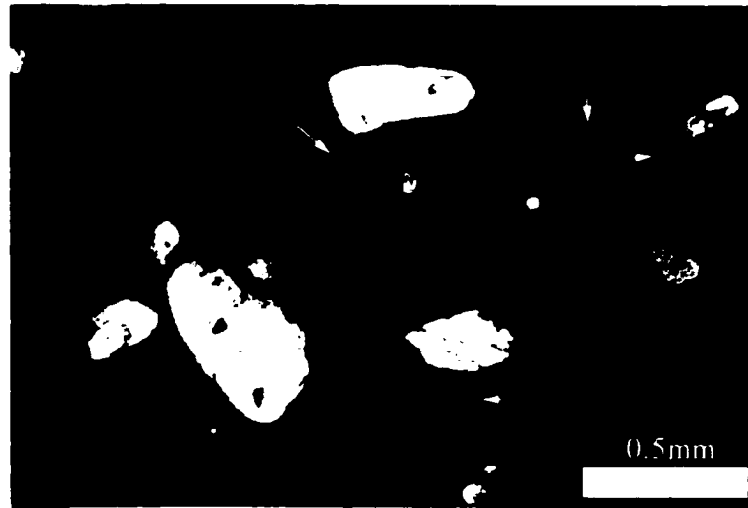


Figure 3.36. Petrographic thin section from Warm Springs, Virginia. In this view several pore spaces are developed in the sandstone. Two of the pore spaces are developed by intrastratal dissolution of feldspars that are only partially dissolved. The other two large pores are most likely due to the complete dissolution of framework grains. Thus mineralogical alteration of the sandstone has resulted from diagenetic as well as depositional processing.

(A) Plane-light micrograph of sandstone. Pore spaces are highlighted by blue-dyed epoxy. The interior of one pore is lined by pyrite (P), while another has a significant amount of moderately high-birefringent clay (C) in its interior. Several grains have rinds of intragranular clay (IC) that may have resulted from collapse of pore spaces during compaction. Two feldspar grains (F) in this view have been partially dissolved. Blue-dyed epoxy highlights the grains' intragranular porosity. That these grains have undergone intrastratal dissolution is clear, because in their present condition they would have fragmented during transportation and certainly would not have survived compaction. Their original detrital outlines would presumably be the pore spaces' shapes.

(B) Cross-polarized image of the same area as in A (above). Clay minerals, both in pore spaces and at grain boundaries, display moderately high birefringence. The relatively tightly sutured nature of the grain boundaries seen here is due, at least in part, to overgrowth of quartz on detrital grains. This cannot be seen here, but was revealed by cathodoluminescence imaging. Interestingly, dust lines on quartz overgrowths are rarely seen in samples of the Oriskany Sandstone in the southern Appalachians.

(A)



(B)



due to dissolution of carbonate shell material and grains. A few pores are formed by dissolution of unstable minerals such as feldspar and are the same size as that of detrital. These small pores have somewhat irregular outlines. Most pores are lined by some clay minerals. The clay has moderate birefringence and is iron stained. It is likely that at least some of the dissolution porosity is the result of recent weathering.

Heavy minerals encountered in thin section included trace amounts of rounded tourmaline (some with overgrowths) and rounded zircon crystals.

DISCUSSION OF CONSTITUENT MINERALOGY AND PETROGRAPHY

The Oriskany Sandstone's petrography indicates the conditions under which it evolved to its present state. Listed below are constituent minerals; their significance and paragenesis are discussed briefly.

It is clear that there are some aspects of the petrography that require further clarification. In this report, aspects of the sandstone's detrital framework mineralogy and diagenesis are discussed because they may have some bearing on the problem of authigenic tourmaline. An attempt has been made to include all relevant mineralogical information from previous studies when their details have bearing on the tourmaline problem, especially regarding silicate mineral authigenesis. Direct observations of tourmaline overgrowths by other investigators are discussed in the next chapter.

Based on the available evidence, several aspects of the sandstone's petrography are important to understanding its present condition and have bearing on the origin of the

unusual authigenic tourmaline overgrowths found in the sandstone. These include: 1) the source of sediments, 2) the timing of formation of authigenic components, and 3) tectonic history and its effect on the sandstone.

Discussion of Detrital Components

The detrital components, rock fragments, and minerals are discussed in this report in the order of abundance in which they are mostly commonly encountered: quartz (both monocrystalline and polycrystalline), feldspar, rock fragments (mostly of local derivation from sedimentary sources), trace amounts of mica, and a mature suite of heavy minerals. As pointed out in Chapter 1, the Oriskany Sandstone is extremely mature and clean, and for this reason is a good glass sand. This is probably a result of its derivation from older sedimentary units, and it is clear that the older Paleozoic sandstones around the margins of the Appalachian Basin were the primary sources for the sands (Voorhees, 1982; Regan, 1982; Dott and Batten, 1981).

Classification of the Sandstone

At almost every location where the Oriskany Sandstone is found and reworked sands from the Oriskany are formed into new units, it is clear that the detrital component is always greater than 95% quartz. Most samples would then be classified as quartzarenites according to Folk's (1968) classification, and none of the subordinate ternary diagrams are needed for classification. Two quartz-rich conglomerate samples have enough chert to be classified as subchertarenites according to Folk (1968), but the maximum chert value is only ~7.5% (Connelly Conglomerate, Highland Mills, Orange

County, New York). One conglomerate sample (Connelly Conglomerate, Pea Hill, Orange County, New York) has ~9% quartzite or quartz sandstone clasts and ~3% chert in its detrital fraction; this would classify as a subsedarenite according to Folk (1968). These deviations may be the result of local sources, perhaps created by local faulting and uplifts (Drake, 1970; Mitchell and Forsythe, 1988).

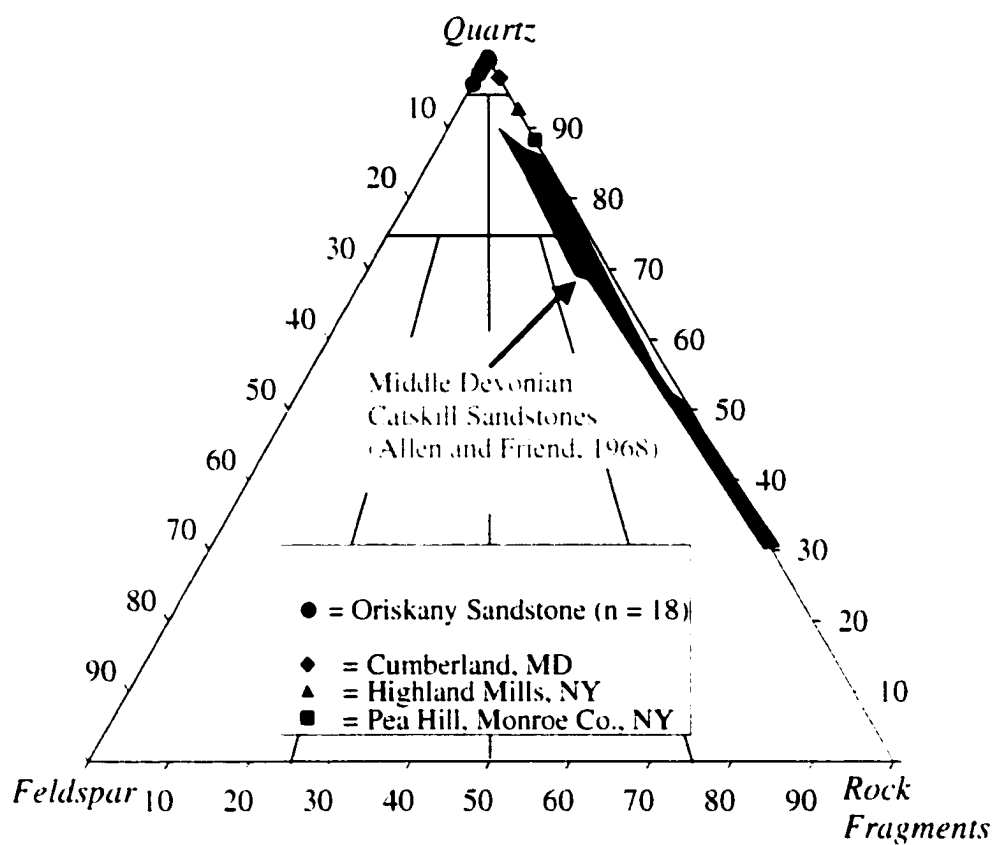
Because of the almost extremely mature and invariable mineralogy of the detrital components, no publication or thesis has ever graphed the data on ternary diagrams (Figure 3.37). In order to contrast the composition of the Oriskany Sandstone, sandstone compositions from the Middle Devonian Catskill Fan-Delta Complex are also plotted (Allen and Friend, 1968). A comparison of these data sets shows that the Oriskany Sandstone's composition is a base line for nontectonically influenced sandstones in the Appalachian Basin. The changeover from a pure-quartz sandstone to a litharenite happens very suddenly as metamorphic rock fragments and mica become abundant detrital component during the Middle Devonian.

Monocrystalline Quartz

Most quartz grains in the Oriskany Sandstone are monocrystalline; exceptions to this are found when quartz-pebble conglomerate is abundant. Though some work has been done using quartz as an indicator of provenance, this study did not discover any significant variations in monocrystalline quartz from New York to West Virginia (Seyedolali et al., 1997). The quartz grains are predominantly well rounded and moderately spherical (Powers, 1953). Stow (1931) remarked on the uniformity of sand size and condition from all along the exposure and reported that typically the Oriskany

Figure 3.37. QFR ternary diagram based on Folk (1968). Black dots represent typical Oriskany Sandstone; these plot in the quartzarenite field and are composed of more than 95% quartz. Eight samples contain only monocrystalline quartz in the detrital fraction and plot at the quartz apices. There is a great deal of overlap on these samples regardless of geographic location. Three samples, all conglomerates, one from Cumberland, Maryland, and two samples of the Connelly Conglomerate, from southern New York, Highland Mills and Pea Hill, both in the Green Pond Outlier, contain enough chert pebbles to plot as sublitharenites, and according to the Folk's (1968) classification would be called chert-sublitharenites. Two samples, both sandy limestones, were not plotted.

In order to facilitate a comparison to less mature Middle Devonian rocks, data from Allen and Friend (1968) on sandstone compositions from the Catskill Fan-Delta Complex (blue polygon) that derived its detritus from an eastern up-lifted area during the Acadian Orogeny are plotted for comparison. The sandstones of the Catskill complex range from phyllarenites to sedarenites and were derived from an actively uplifting source area and were deposited under a variety of depositional settings (Friedman, 1988). They are much more lithologically diverse than the Oriskany Sandstone that appears to have formed during a time of tectonic quiescence and to have been derived from older mature sandstones on the margins of the Appalachian Basin.



Sandstone is medium-grained monocrystalline quartz.

The modification of these grains by quartz authigenesis is described below (see Authigenic Quartz).

Polycrystalline Quartz

Polycrystalline quartz is rare in typical Oriskany Sandstone. This deficiency in polycrystalline quartz may indicate greater maturity, because polycrystalline grains are eliminated by recycling and weathering processes (Pettijohn et al., 1987). Polycrystalline quartz is much more common in the conglomeratic units in eastern New York, New Jersey, Pennsylvania, and Maryland; however, no quartz conglomerate is known from central and western New York. In West Virginia and Virginia, no conglomerate was collected in this study, and the sandstone rarely has much polycrystalline quartz in these states.

When encountered, two types of polycrystalline quartz are found: polygonized polycrystalline quartz with relatively uniform-sized crystals and relatively straight contacts and polycrystalline quartz with well-oriented, sutured crystals that can be considered tectonized. These two types both occur in metamorphic rocks, and polygonized quartz could be from igneous sources as well (Pettijohn et al., 1987).

The greatest amount of polycrystalline quartz was found in the Green Pond Outlier where polycrystalline quartz composes 46-60% of conglomeratic units. The next highest number was in the conglomerate unit at Cumberland, Maryland, at 11%.

Feldspar

Potassium feldspar (K-feldspar) is far more abundant than plagioclase feldspar.

K-feldspar varies from 0 to 3.4%, but is rarely present in more than trace amounts. K-feldspar grains often are subrounded to rounded, and some are slightly altered to low-birefringence clays. Plagioclase is only present in trace amounts and is absent from most samples. This probably reflects its lower stability in the sedimentary environment compared to K-feldspar (Pettijohn et al., 1987). The K-feldspar in samples from New York has feldspar overgrowths; interestingly no feldspar overgrowths were found in the southern samples, yet the total amount of detrital feldspar in these samples does not seem to be any lower than in New York.

Rock Fragments

Rock fragments are generally uncommon in the Oriskany Sandstone; however, a basal conglomerate composed of underlying rock units is locally developed in many places and a basal conglomeratic lag deposit also occurs (Brett et al., 1997). These units typically have nonsilicate rock fragments such as carbonates, phosphatic nodules, or chert derived from older units in the area. Besides the basal units, occasionally a sedimentary rock fragment of siltstone, sandstone, or carbonate can be found in almost any location. The Green Pond Outlier samples contained some quartzite pebbles. A few quartzite and a few quartz and feldspar (possibly plutonic) rock fragments were observed, but they occur only in trace amounts. As well, at the Cherry Valley location quartz-and-mica rock fragments (tectonite or schist fragments) are found in trace amounts.

Mica

Mica was only found in the sample from Cherry Valley, New York, and in the matrix material from the Pea Hill location in the Green Pond Outlier (described here as

sericite, a high birefringent white mica).

The mica flakes at the Cherry Valley location appear to be detrital, both biotite with characteristic pleochroism in sections cut parallel to the cleavage and white mica (probably muscovite) were observed. These flakes were found in the silt-sized fraction and may be derived from an eastern source or possibly from an ashfall.

The sericitic mica in the Pea Hill location occurs in trace amounts in the conglomerate's matrix and could be authigenic or detrital. Since it is also found in quartzite fragments at this location, perhaps it is a metamorphic mineral derived from the quartzite.

Discussion of Nonopaque Detrital Heavy Minerals

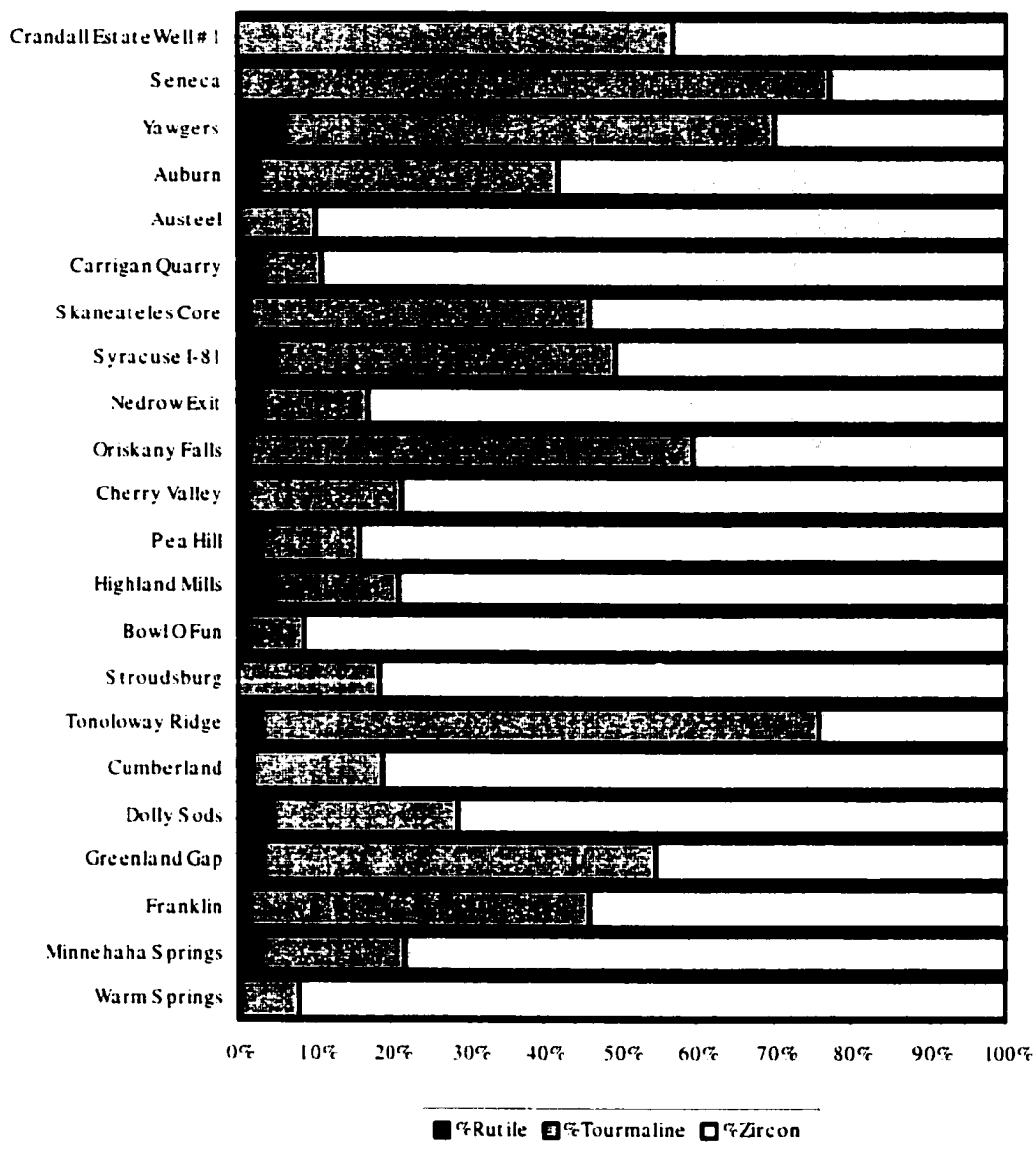
Heavy mineral data were acquired for each locality where quartz sandstone was well developed (Figure 3.38). Several exceptions were either limestone-rich facies where sand was too rare to sample easily and the ironstone where high content of insoluble minerals flooded the attempted heavy mineral separates to such a great extent that residues were unusable. Heavy minerals were point-counted using the ribbon method (Van der Plas, 1962), allowing the reporting of the number percentage of heavy minerals. Careful processing was done to avoid excessive breakage or alteration of the heavy mineral suite. Further details of the methods used are discussed in Chapter 2.

The heavy mineral suite investigated is very mature, both mineralogically and texturally. Typically, the heavy minerals are all very well rounded; sphericity, however, is greatly affected by the original habit of the minerals, and rutile, tourmaline, and zircon

Figure 3.38. Abundances of nonopaque detrital heavy minerals. Rutile, tourmaline, and zircon are the only detrital heavy minerals in samples of the Oriskany Sandstone and also in several sandstones and a sandy limestone deposited at the base of the overlying Onondaga Limestone (sometimes referred to as the Springvale Sandstone [Oliver, 1967]) from western New York.

The samples are ordered geographically, running from western New York eastward to the Green Pond Outlier and then southward to Virginia (see Figure 1.1 for locations).

The following abbreviations of locality names are used: 1. Crandall = Crandall Estate Well #1, East Independence Field, NY, 2. Seneca = Seneca Stone Quarry, NY, 3. Yawgers = Yawgers Woods, NY, 4. Auburn = Auburn, NY, 5. Austeel = the Austeel Plant location, Auburn, NY, 6. Carrigan = Carrigan Quarry, Skaneateles, NY, 7. Skan. Core = the Skaneateles Township, General Crushed Stone Quarry Well # 3-9R, NY, 8. Syracuse = I-81 near Syracuse, NY, 9. Nedrow = the Nedrow Exit on I-81 south, NY, 10. Oriskany Falls = Oriskany Falls, NY (the type locality), 11. Cherry Valley = the Cherry Valley location, Otsego Co., NY, 12. Pea Hill = the Green Pond Outlier locality near West Cornwall, NY, 13. Highland Mills = the Green Pond Outlier sample near Highland Mills, NY, 14. Monroe Bowl O Fun = the Green Pond Outlier, near Highland Mills, NY, 15. Stroudsburg = Stroudsburg, PA, 16. Tonoloway = the Tonoloway Ridge location near Hancock, MD, 17. Cumberland = Cumberland MD, 18. Dolly Sods = Dolly Sods, WV, 19. Greenland = Greenland Gap, WV, 20. Franklin = Franklin, WV, 21. Minnehaha = Minnehaha Springs, WV, 22. Warm Spring = Warm Spring, VA



all tend to be elongate parallel to the c-axis (Milner, 1962). This results in egg-shaped rather than spherical grains. A few exceptions to this may be the result of influx of fresh material in ashfalls (as discussed below). Only rutile, zircon, and tourmaline occur in the detrital suite. However, the suite often has phosphatic skeletal debris, iron-rich carbonate, pyrite, and fluorite, which are locally derived.

The presence or absence and the percentage of authigenic tourmaline grains was recorded. Another characteristic of the heavy mineral suites that seemed to have some significance was the condition of zircon. Two noteworthy properties were the presence or absence of hyacinth zircon and the presence of euhedral zircon (both discussed below); no other great variations in the character of the other minerals were found (Figure 3.39).

Because so little variation was found in heavy minerals and no clear geographical trends have been discovered, the heavy minerals are described below by individual mineral species. Significant variations are described in a general discussion with reference to individual locations or regions when necessary.

Rutile

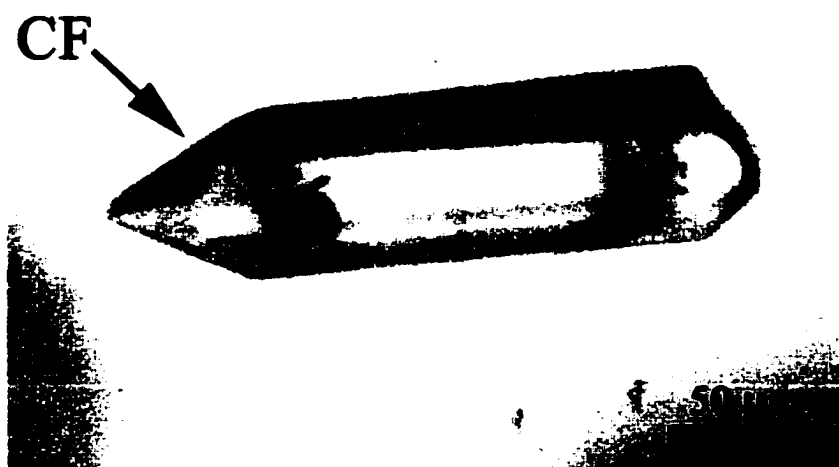
Rutile is the least abundant of the heavy minerals. It never occurs in quantities greater than 3.5%. Most rutile is well rounded and only slightly transparent. A few angular grains may be due to breakage. A foxy brown color is most common, but a few yellowish-brown grains occur as well. Grains sometimes have striations and geniculate twinning. No obvious variations were discovered in the geographical distribution of rutile and small amounts are present in almost every sample. Rutile is typically derived from metamorphic and igneous rocks, but in this case because of its high roundness, it is

Figure 3.39. Zircon grains. Some zircon grains have distinctive properties that suggest something about their provenance. Zircon grains with these distinctive properties are rare in the Oriskany Sandstone and when found are worthy of notice.

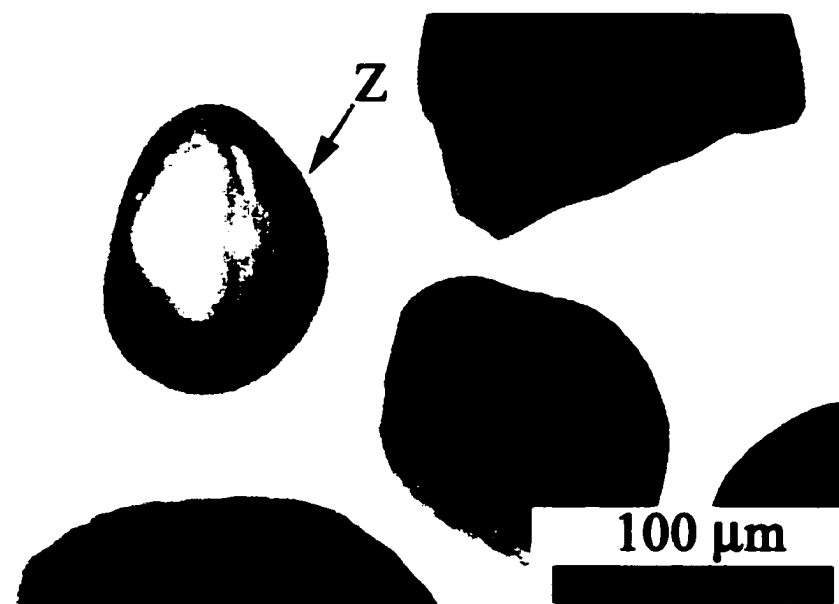
(A) Plane-polarized light micrograph of euhedral zircon crystal separated from sandstone collected at the Austeel Plant, Auburn, New York. Well-developed and completely unabraded crystal faces (CF) are visible on the pyramidal termination of this grain. This grain was most likely derived from local reworking of a volcanic ash deposit.

(B) Plane-polarized light micrograph of a well-rounded, hyacinth zircon grain separated from the Connelly Conglomerate near Highland Mills, New York. Though light pink zircon crystals are found in many locations in small quantities, these darker purplish-pink grains are usually uncommon. However, samples from the Green Pond Outlier contain considerably more of these hyacinth grains than are present in most locations. The conglomerates and sandstones in the Green Pond Outlier may derive their zircons from Precambrian crystalline rocks of the Reading Prong that are rich in these zircons. The hyacinth color is caused by long exposure to radiation.

(A)



(B)



probably sourced from older sedimentary rocks.

Tourmaline

Tourmaline occurs in every sample and varies in abundance from 7.5 to 77%. It displays a great variety of colors, and these color variations are related to differences in the chemistry of individual species in the tourmaline group (Krynine, 1946). Tourmaline in the Oriskany Group has received a great deal of attention. In this study, Chapter 4 is devoted entirely to description of the chemical varieties of tourmaline found by microprobe analysis (Henry and Guidotti, 1985). Several authors have described the overgrowths from the Oriskany Sandstone and reference should be made to Table 4.1 for details.

In almost every locality investigated, the tourmaline was well rounded. Overgrowths are present on these grains in almost every region, but local variations probably result in the absence of overgrowths in some samples.

Notably, overgrowth tourmaline was not found in the conglomeratic units of the Ridgeley Sandstone or Connelly Conglomerate investigated in this study. Overgrowths have not been reported and are apparently absent in eastern New York and northeastern Pennsylvania (Stow, 1931; Hodgson, 1970; Voorhees, 1982; Regan, 1982). In the Green Pond Outlier, not only are overgrown tourmaline grains absent, but most of the tourmaline grains are angular (most but not all zircon is angular as well). However, because the Green Pond Outlier samples are so well indurated, it is not entirely clear whether the angularity is a result of breakage during processing. There is evidence from zircon discussed below that suggests that the angular tourmaline in the Green Pond

samples may be derived from a different source than tourmaline from other localities within the Appalachian Basin.

Aside from these anomalies, typical tourmaline from the Oriskany Sandstone is mostly brown, well-rounded, and moderately spherical to egg shaped. Interestingly, younger units from New York State, starting with the Carlisle Center Formation in the Cherry Valley and continuing into Middle and Upper Devonian rocks, including rocks as far west as Allegany County, contain significant amounts of prismatic euhedral tourmaline that appears to be derived from a new crystalline source. Thus there is strong evidence that a new source of tourmaline, most likely from Acadian uplift along the eastern margin of the Appalachian Basin, takes over in younger Devonian rocks of New York.

Zircon

Most zircon found in the Oriskany Sandstone is colorless, well rounded and egg shaped, suggesting that it comes from older sedimentary units and has been through several cycles of sedimentation. Zircon has been found to vary, making up 22 to 92% of the heavy mineral fraction of the sandstone. The reason for this great variation might be related to supply of zircon, but since no differences between the characteristics and size of the zircons are apparent, the most likely explanation is size sorting prior to deposition. Typically, the tourmaline grains are larger than the zircons, and this plus the difference in specific gravity of zircon (4.67) versus tourmaline (3.25) could result in a fractionation without there being a different source (Rittenhouse, 1943). Though it is clear hydraulic factors may complicate the problem of interpreting provenance of the heavy minerals by

using quantitative measurements alone, and this makes careful evaluation of varietal differences more important. Varietal differences are discussed below.

Zircon being one of the most persistent heavy minerals often occurs in quartzarenites and is found with the same appearance in many Paleozoic sandstones on the North American craton (Potter and Pryor, 1961). However, there are a few varieties of zircon that can have real significance as indicators of provenance. One such type is hyacinth zircon discussed by Friedman et al. (1992), and another is euhedral zircon that is often derived from tephra. Both of these less frequently observed types have been found in this study.

Hyacinth zircons have been found to be relatively common in the heavy minerals separated from the Connelly Conglomerate of the Green Pond Outlier. According to Friedman et al. (1992), these purplish-lavender zircons are indigenous only to very old crystalline rocks (>2,600 Ma). Hyacinth zircons have been found in gneisses of the New Jersey Highlands, and this strongly supports the idea that the Green Pond samples of the Connelly Conglomerate are locally derived, though perhaps through several sedimentary cycles, from the Highland Complex.

Some of the younger sandstones that almost certainly derive the bulk of their detrital components from reworking of the Oriskany Sandstone in western New York have been found to contain small, but significant amounts of euhedral to very angular zircons. These idiomorphic zircon grains are significant because they are the only euhedral detrital mineral derived from a crystalline rock source found in the sandstones (Callender and Folk, 1958; Friedman, 1965; Tucker et al., 1998) (Figure 3.39).

Typically, these crystals are smaller than the majority of rounded detrital zircons (yet not small enough to have been encased in the quartz grains of the sandstone). Their different shape, elongate, and overall size not only make them stand out, but suggest that they might have behaved differently during transport than the larger more rounded grains. One possible reason that the two types occur together is that the euhedral grains are derived locally from ash beds and were not subjected to much abrasion, transport, or hydraulic sorting before being incorporated into the sandstones.

A zircon sample from the base of the Onondaga Limestone near Nedrow, New York (which is between 388 and 390 million years in age [Friedman, pers. Comm., 2001]), was analyzed by single crystal mass spectrometry, and an age of 408 million years (probably just a little younger than the Oriskany Sandstone) supports the interpretation of a local origin. A second set of angular to euhedral zircon crystals is present in the sample collected at the Austeel plant in Auburn, New York. Though these crystals are euhedral, they are smaller, stubbier, and have needle-like, slightly rounded terminations that give them a different appearance from those found at the Nedrow locality. They most likely are derived from a different ash bed (Figure 3.39).

Variations in Heavy Minerals

Though the abundance of individual mineral species does vary, it does not appear that a direct conclusion can be drawn from the variations of rutile, tourmaline, and zircon. The reasons for the variations in these minerals could be related to the complex interaction of a series of variables related to: 1) source rocks, 2) ultimate provenance, 3) hydraulic sorting, 4) possible diagenetic alteration, 5) a bias created during sampling

and processing. Any comments on this can only have qualitative significance because no detailed investigation was carried out to discover which of these variables were active or most effective.

A review of heavy mineral sampling techniques and processing is given in Mange and Maurer (1992), and a detailed description of preparation methods is given in Chapter 2.

The suite of heavy minerals found in the Oriskany Sandstone is typical of Paleozoic Rocks of the Appalachian Basin and Midcontinent Region of North America (Stow, 1931; Martens, 1937, 1939; Tuttle, 1940; Krynine 1940a and b, 1946; Potter and Pryor, 1961). The kinds of minerals, textures, and grain-size range are consistent with reworking from older Paleozoic sandstones; for instance, Tuttle (1940) described evidence for reworking of Cambrian Gatesburg Formation heavy minerals into the Tuscarora Sandstone in West Virginia; of particular importance, tourmaline with overgrowths was one of the reworked constituents. Krynine (1946) recounts several similar incidents.

From the above information on reworking of mineral species, it is clear that the ultimate crystalline source is not necessarily the proximal source of the heavy minerals, and if the heavy minerals are not transported great distances, the effects of hydraulic sorting from a past depositional environment may be inherited by the heavy minerals in the new sandstone.

In the Oriskany Sandstone, there is some evidence from abrasion of overgrowths on both tourmaline and quartz grains and from locally derived lithic fragments that

supports the idea of local reworking without prolonged sedimentary processing. Thus in the Oriskany Sandstone, because of the complex history of reworking of deposits within the Appalachian Basin, it seems that finding the reason for the variations in the number percentages of rutile, tourmaline, and zircon might not have any value in learning their ultimate provenance and might not necessarily reflect a change of provenance between samples.

Destruction of less stable minerals during weathering could cause losses that might be a problem in interpretation of the provenance of the sandstone. As well, intrastratal dissolution of heavy minerals has been a nagging problem for sedimentary petrologists since its significance was recognized in the middle of the last century by several prominent sedimentary petrologists (Pettijohn, 1941; Van Andel, 1959).

For these reasons, as early as the late 1930s Krynine and his students were using a method of provenance analysis now called varietal study. Varietal studies can be based on optical or physical properties of minerals or on variations in mineral geochemistry.

In this study, physical properties of crystal shape and color have already been mentioned. Because only ultrastable minerals, rutile, tourmaline, and zircon, are found in the Oriskany Sandstone and they are most clearly derived from older Paleozoic sandstones, it is unlikely that misinterpretations due to surficial weathering patterns or intrastratal dissolution would be a problem, and neither is suspected of causing any geographical variations in heavy minerals.

Geochemical analysis of provenance has also been attempted in this study, using detrital tourmaline that was analyzed during investigation of authigenic tourmaline, and

the results of that study are presented in Chapter 4.

Discussion of Authigenic Components

Authigenic Quartz

The formation of authigenic quartz is fairly easily explained in a quartz-rich sandstone whose formation fluids at some point can be presumed to have become saturated with respect to silicic acid. Silicic acid may be derived from either organic silica or from solution of detrital quartz, particularly during burial (Pettijohn et al., 1987).

Authigenic quartz is present in almost every Oriskany Sandstone sample and does not seem to follow a geographical trend. It occurs mainly as syntaxial overgrowths. Often a dust line indicates the boundary between the detrital grain and the overgrowth. However, some localities have well-developed overgrowths with no dust lines, particularly in the southern states. Overgrowths without dust lines could only be positively identified by using cathodoluminescence.

Authigenic quartz also can replace fossils and carbonate fragments (Maliva, 1992) and has been found filling tectonically fractured quartz grains in the Green Pond Outlier.

In western New York, samples contain between 2.5 and 19% quartz overgrowths by weight (Douglas, 1984); it is reasonable to assume similar numbers for the Oriskany Sandstone in general. The overgrowths can be so pervasive that they are the only constituent of the cement and occlude all porosity. Heald et al. (1962) found euhedral faces growing on 85 to 90% of quartz grains from subsurface samples in West Virginia, and Voorhees (1982) reported up to 90% of the grains have overgrowths in central and

eastern New York. These figures are probably typical where quartz is the major cement; however, quartz is often not the only cementing agent and under certain conditions quartz cement is absent or replaced by carbonate cement. As well, if early cement such as carbonate or matrix material occludes all porosity, no quartz overgrowths may form.

Typically, the sand grains reworked from the Oriskany Sandstone into matrix-rich sandstones with phosphatic cement, phosphate nodules, or chloritic cement do not have overgrowths (the only exception is the I-81 location described above, but this sandstone may not have the same origin as the ones discussed here). These sandstones, typically developed in the base of the Onondaga Limestone, have suggested to several authors that the Oriskany Sandstone was unconsolidated when reworking occurred (Apsouri, 1934; Dennison, 1961; Baker, 1983). When sands are reworked from the Oriskany Sandstone into matrix-free units, overgrowths are found in those samples of basal Onondaga Limestone. This supports the idea that quartz overgrowths do not form in the Oriskany Sandstone until at minimum after the deposition of the basal Onondaga Limestone begins.

Authigenic Carbonate Minerals

Authigenic carbonate minerals in the Oriskany Sandstone include: calcite, ferroan calcite, dolomite, ferroan dolomite, ankerite, and dedolomite (Heald et al., 1962; Voorhees, 1982; Douglas, 1984; Foreman and Anderhalt, 1986). These cements are present alone or in complex mixtures that are difficult to interpret (Douglas, 1984). Carbonate material except for fossil material almost never fills voids larger than those created by intergranular porosity. The lack of large void-filling cement areas hinders

interpretation of cement stratigraphy and complicates investigation by methods such as cathodoluminescence that are most effective when applied to larger (lower magnification) areas of samples.

Most calcite cement is anhedral, and no poikilotopic cements were found. It is believed to be the earliest formed cement and is often found partially filling voids that are later filled with ferroan cements. It also forms syntaxial overgrowths on echinoderm debris according to Malvina (1992). Calcite cement in the Oriskany Sandstone generally luminesces shades of yellow and light, bright orange (Baker, 1983). Some calcite may form in a later diagenetic event, replacing dolomite and creating a pseudomorphic texture after dolomite called dedolomite (Baker, 1983). Occasionally glide plains or tectonic fractures can be seen in calcite, particularly in shell fragments. When preserved, most shell material remains calcitic. Shells are almost entirely nonluminescent using the cathodoluminescent technique.

Well-preserved carbonate skeletal debris, including brachiopods, corals, echinoderms, and gastropods, not only suggests that deposition at many localities took place in marine waters of normal salinity (Heckel, 1972), but shows that early loss of carbonate by meteoric diagenesis is unlikely. The loss of most carbonate shell material is inferred to occur late, because sandstone that has certainly been deformed and deeply buried in the Valley and Ridge province of the Appalachians retains identifiable molds of large brachiopods (some more than 5 cm in diameter) that could not have survived intact during these burial conditions.

Ferroan calcite is not a particularly common component of the sandstones, but

some void-filling anhedral ferroan calcite (recognized by staining) was found at several of the New York localities and was reported by Foreman and Anderhalt (1986) in southwestern Pennsylvania. Because it is rather uncommon, no luminescent color was ascribed solely to ferroan calcite. It is typically found as anhedral cement filling intergranular pore spaces.

Dolomite occurs frequently as both a cement and as individual grains in matrix-rich rocks, such as those occurring in the Springvale Sandstone and basal Onondaga Limestone when sandstone is developed in it. The dolomite most frequently is anhedral, but rhombic dolomite is also common, and some saddle dolomite has been observed. The saddle dolomite has large curved faces, and some of it appears to have been strained by compaction or by the force of its crystallization and has an undulose extinction. Dolomite sometimes has fractures running through the crystals that appear to be related to compaction. It luminesces an orange to orange-red color. Since not all slides were stained, some of the dolomite may be ferroan.

Ferroan dolomite was recognized by staining with potassium ferrocyanide. In thin section, ferroan dolomite forms anhedral masses and rhombs. Ferroan dolomite is more common than ordinary dolomite in the Oriskany Sandstone. Some ferroan dolomite luminesces dull red, but much is nonluminescent. In the same pore space, gradational luminescence has been observed, and the trend is from a luminescent exterior in the pores to a duller and eventually nonluminescent pore interior, suggesting that iron content increases in the pore fluids over time.

There is generally not a very great quantity of authigenic carbonate in the

Oriskany Sandstone. It appears that ample detrital and biogenic carbonate was available as the sources of calcium and magnesium to explain the small amount of carbonate found in many samples (Baker, 1983). Carbonate units that typically occur both above and below the sandstone also could contribute ions during sedimentation and compaction. As well, some early calcite cement may be ascribed to direct precipitation from seawater, but no early bladed or rim cements are retained in the Oriskany Sandstone. The evidence supporting early carbonate precipitation is the high volume of porosity filled by the cement. Generally, uniform-sized and spherical sand grains have between 28 to 48% pore volume before compaction depending on sorting (Pettijohn et al., 1987), and the samples suspected of having early carbonate cement or matrix have approximately 28% calcite cement and almost no quartz overgrowths. Early cement or matrix would inhibit quartz overgrowths. Foreman and Anderhalt (1986) believe that most of the carbonate cements do not form until the Oriskany Sandstone is nearing its maximum burial depths, which suggests that some of the carbonates are derived from adjacent units undergoing dissolution. They ascribe ferroan cements to the later stages of diagenesis.

It appears that most of the carbonate cements formed later than quartz overgrowths, a situation that is not uncommon in sandstone (Boggs, 1987). Often quartz overgrowths are embayed by the carbonate cements. Calcite cement seems to generally form before dolomite cement, and ferroan cements typically are found in the interior of pores indicating that they formed last.

The distribution of carbonate cements may be related to facies changes, available sources of carbonate from adjacent units, and tectonic events that have influenced the

sandstone's permeability and porosity. So far only limited study has been done on the geographic variations in cement (Foreman and Anderhalt, 1986). Though in this study very little carbonate cement was found in the southern samples, it appears that this was a chance result and that carbonate cements are about as common throughout the entire outcrop Appalachian Basin (MacQuown, 1940; Martens, 1939). Carbonate cements are probably best studied from core material and fresh quarry samples, since there appears to be considerable recent weathering of carbonate cements in natural exposures.

Because of lack of carbonate in the southern samples collected in this study, it is difficult to fully contrast geographical trends, but information from other authors supports the idea that the similar diagenetic processes were probably active and affected the unit in the same manner from New York to West Virginia (MacQuown, 1940; Martens, 1939; Heald et al., 1962; Foreman and Anderhalt, 1986).

Authigenic Feldspar Overgrowths

The authigenic feldspar found in the Oriskany Sandstone has features in common with feldspar from other sandstones described in cratonic North America and in the Appalachian trend, though its abundance seems to be considerably less (Buyce and Friedman, 1975).

All authigenic feldspar found in the Oriskany Sandstone is present as nonluminescent overgrowths, and they typically are thin rinds of around 10 μm , with greatest thicknesses no more than 30 μm , that surround detrital cores and fill in available intergranular pore space. Though the overgrowths grow from both twinned detrital microcline and untwinned detrital cores, they are usually untwinned and have a slight

difference in their extinction angle from that of the detrital core. They often start with a somewhat turbid, brown-red-stained or inclusion-rich inner zone and then become clear and inclusion free as they extend into surrounding pore space (see Figure 3.5). These overgrowths are very similar to those described by Carozzi (1960), who explains that the difference in extinction angle between the core and overgrowth is due to monoclinic (orthoclase) overgrowths growing on triclinic detrital cores (microcline). Both Carozzi (1960) and Duffin et al. (1989) describe overgrowths that start with a turbid inner zone that contains microinclusions of hematite. Since these descriptions of inclusions seem to fit in detail the overgrowths from the Oriskany Sandstone, it is possible that the inclusions are also hematite, but no chemical analysis has been done to confirm this.

Though the timing of feldspar authigenesis is not entirely clear, evidence supports formation early in the sandstone's diagenetic history. Evidence for this includes engulfing of quartz grains that do not have overgrowths, suggesting preauthigenic quartz formation, and complete filling of pore spaces. As well, in some instances feldspar overgrowths meet quartz overgrowths along straight-line contacts that suggest that both minerals were growing contemporaneously. The reason for assuming contemporaneous growth is that had feldspar not filled part of the pore's space before or at the same time as quartz, authigenic quartz would have filled in all available pore space as it did in surrounding regions during the pervasive cementation of the sandstone. Many authors have found evidence of early feldspar overgrowths, and it is assumed that similar circumstances could be involved here (Buyce and Friedman, 1975; Kastner and Siever, 1979).

As has been pointed out by Buyce and Friedman (1975), small amounts of authigenic feldspar making up less than 2% of a limestone are extremely common. An estimate of the amount of feldspar overgrowths in the Oriskany Sandstone would be difficult since in most instances detrital feldspar is present in trace amounts. Certainly there is much less than even a percent authigenic feldspar.

Perhaps since the Oriskany Sandstone is often associated with limestone units both above and below, is marine in origin, and had laterally equivalent limestone facies forming close by in the basin, for example, the Glenerie Limestone of southeastern New York and the Licking Creek Limestone of the southern exposure belt (Head, 1974), it could acquire the necessary ions for authigenic feldspar formation under conditions similar to the way it occurs in limestone.

How the constituents necessary for authigenic feldspar enter the sandstone is conjectural. Following the idea of Chamberlin (1897), there are at least 3 hypotheses for authigenic feldspar overgrowth formation: 1) syndepositional feldspar overgrowths form at the time of sand deposition, directly precipitated from seawater, here considered a form of authigenesis called isochemical precipitation (Kastner and Siever, 1979); 2) feldspar overgrowths form after deposition from constituents present in the pore water and detrital components, isochemical precipitation (*sensu stricto* of Kastner and Siever, 1979); and 3) feldspar overgrowths form after deposition from constituents carried to the sandstone by migrating fluids (brine/hydrocarbons or meteoric water); this type of precipitation is an exchange reservoir model (Kastner and Siever, 1979).

Sparse amounts of authigenic feldspar in a sandstone can be attributed to an

isochemical model of formation where constituents necessary for feldspar formation, Si, K, Na, Al, are derived from local conditions (Kastner and Siever, 1979); several researchers have pointed out that potassium feldspar can theoretically precipitate from normal seawater if the K^+/H^+ ($=10^6$) concentration of seawater is combined with conditions of silica saturation (Buyce and Friedman, 1979) and have suggested this as a mode of formation. As mentioned above, quartz overgrowths form rather early in the diagenetic history of the sandstone, and this would mean that silica saturation was achieved. The Oriskany Sandstone's pore spaces could have been in direct contact with seawater, and certainly were flushed with marine water during the marine transgression that preceded Onondaga Limestone deposition.

Pettijohn et al. (1987) suggest a "distillation" process in which less pure detrital feldspar becomes unstable and dissolves and then is reprecipitated on the remaining detrital core. The pure end member, authigenic feldspar, is stable under the conditions of diagenesis. Though this type of reaction would limit the size of overgrowths, because during the isochemical reactions there would be a point at which the detrital core would be isolated by precipitation of an overgrowth rind, it could produce the type of overgrowths seen in the Oriskany Sandstone and would explain the dependence on the presence of detrital feldspar for authigenic precipitation. None of these possibilities require an outside source for constituents and are therefore forms of the isochemical model.

Other authors have argued that conditions in the Paleozoic seas allowed for direct precipitation of potassium feldspar on the sea floor (Weaver, 1967; Woodward, 1972).

Direct precipitation from seawater during deposition, though possible, would most likely result in larger accumulations of potassium feldspar. For instance, in an example from the Ordovician St. Peter Sandstone, Woodward (1972) describes both overgrowths and whole beds of massive potassium feldspar (sanidine).

Since direct deposition from seawater seems unlikely, the only isochemical alternative is that constituents present in the pore water and detrital components provide the necessary materials for authigenesis.

If an exchange model is invoked to explain the feldspar overgrowths, it would have to be reconciled with observations made about the sandstone's petrogenesis and burial history. The timing of feldspar overgrowths then becomes very important. A brine solution would have to be pushed through the Oriskany Sandstone at the time feldspar overgrowths form. The overgrowths appear to form relatively early in the diagenetic history of the sandstone, probably before much burial. Stratigraphic analysis and paleogeography suggest little tectonic activity that would have been necessary to push fluids from the basin margin through the sandstone until perhaps the Middle Devonian. At the time of deposition of the Catskill Fan Delta complex, peripheral loading due to Acadian tectonic activity could have initiated a fluid migration event that would likely have used the Oriskany Sandstone as a permeable conduit (Evans and Battles, 1999).

Though certainly an external source for brine caused by loading in a peripheral area such as the Appalachian geosyncline is a possibility for the source of constituents for feldspar overgrowths, further work would be needed to document this source. Dorobek (1989) and Evans and Battles (1999) have found evidence of fluid migration events in

Lower to Middle Devonian rocks of the Appalachian fold belt that may have involved brines with temperatures between 220° and 300°C, but they date them as Alleghenian. Dorobek (1989) suggested that some of the fluids could be derived from Cambrian shales in the geosyncline that had access to thrust faults that ramped upwards through Silurian evaporites and terminated in the Helderberg Group. He points out that liquid petroleum was being generated from Lower and Middle Devonian units that had entered the oil-generative window. Friedman et al. (1992) have mentioned how high K₂O in Cambrian shales can be, up to 3 times the level found in average shales, and evaporites might also have contributed potassium. If their hypothesis of Alleghenian fluid migration is correct, this would probably mean that very little diagenetic alteration takes place until very late in the sandstone's history, during the Pennsylvanian.

So far none of the authors who suggested a fluid migration event have described the presence of authigenic feldspar overgrowths, and it is interesting that authigenic feldspar overgrowths have only been recognized in the Oriskany Sandstone in New York on the Appalachian Plateau, while one would expect fluids to have been more concentrated and hotter in the folded Appalachians.

Perhaps in New York State an earlier, Acadian brine migration event has so far gone unrecognized, or the overgrowths are not due to fluid migration from the foreland basin but came from a cratonic source. For instance, K/Ar dates averaging between 414 and 377 Ma for authigenic K-feldspar have led Duffin et al. (1989) to propose a K-feldspar forming brine migration in the Midcontinent region in the Early Devonian between 386 and 408 Ma from a source in the Michigan Basin, and it is possible that

distal fluids from this event could have traveled as far as Central New York (a distance not that much greater than proposed by Duffin et al. [1989]). As mentioned under the section on paleogeography, the Findlay Arch was probably not an effective barrier at the time of deposition of the Oriskany Sandstone, and the Michigan and Appalachian Basins could have been connected. Perhaps fluid with a high K/Na ration derived from Silurian evaporites was able to migrate from the Michigan Basin through the Chatham Sag of Ontario into New York. Duffin et al. (1989) propose that as the Findlay Arch rose (probably after Oriskany Sandstone deposition [Duffin et al., 1989; Craig and Vernes, 1979]), it set up a gravity-driven hydrogeological flow pattern that would have carried fluids from the Michigan Basin to the Upper Mississippi Valley. They show a similar gravity-driven flow entering the Appalachian Basin, and evaporite brines in Silurian rocks of New York along with Michigan Basin brines could have entered the Oriskany Sandstone. Since evaporites of the correct age are located in this northern part of the Appalachian Basin, perhaps a separate flow event influenced the diagenesis of the Oriskany Sandstone in New York. More detailed study to resolve problems of geographic distribution and origin of authigenic feldspar, and further geochemical evidence will be needed.

Pyrite

Pyrite, when present, is always in amounts of less than 1%. It occasionally occurs as round balls (framboidal pyrite) and as cubic crystals, but mostly occurs as anhedral masses that fill intergranular pore spaces. It acts as a rind growing on ferroan dolomite crystals in the Skaneateles Township core, but is also sometimes found as inclusions in

carbonate cement. Sometimes pyrite partially replaces shell material. Pyrite has never been found as an inclusion in either quartz or feldspar overgrowths or in tourmaline overgrowths from the Oriskany Sandstone.

Most pyrite appears to form late; for instance, it is found between well-formed quartz overgrowths and encrusting late-stage cement. When it is found as inclusions in carbonate, it is usually in a ferroan carbonate phase. It also is found replacing dolomite in a few examples. Partial replacement of shell material was observed only rarely; coral fragments and phosphatic skeletal debris were replaced, perhaps as a result of microreducing environments associated with decay of organic material.

Phosphate, Chamosite, and Hematite

Phosphate, chamosite, and hematite are not generally common cements in the Oriskany Sandstone, but occur with frequency in the Springvale Sandstone and/or Onondaga sandstone. Apsouri (1934), Cowan (1977), Baker (1983), and Oliver and Hecht (1994) all reported on aspects of the phosphatic deposits. Dossert and Chamberlain (1983) report on the general geology of the chamosite and hematite.

For a theory of the origin of the phosphate, Baker (1983) gives a thorough description. It is clear from Baker's (1983) research and from the little investigation done here that phosphatic facies are the result of a depositional or near-surface pore water precipitation prior to complete lithification. Baker (1983) cites a model similar to Heckel's (1977) model for formation of phosphatic black shales to explain the origin of the phosphate nodules under dysaerobic to anaerobic conditions in a marine environment during transgression. She also documents the textures of phosphate and describes:

phosphatic cements, ooids, and nodules that form early and have later beds draped over them. Her results clearly indicate that phosphate occurs both as syndepositional accumulations and as detrital clasts.

Cotter and Link (1993) describe chamosite and hematite oolite units in the Silurian Clinton ironstones of Pennsylvania that are similar in detail to the unit investigated here and that clearly formed under unusual depositional conditions, rather than forming diagenetically. They suggest that the ooids formed as chamosite or berthierine ooids in a dysaerobic depositional zone between aerobic shoal crests and an anaerobic bottom-water environment. They suggest that oxidizing conditions during diagenesis altered some of the original ooids to hematite and explain the mixture of these two types of ooids in the same rock unit as being a result of only partial oxidation of chamosite to hematite.

The depositional conditions under which phosphatic and chamosite form are nearly identical, and they are often associated, as is apparently the case in the formation of these sandstones (Cotter and Link, 1993).

Minor Authigenic Constituents

Minute amounts of minerals such as fluorite, sphalerite, and celestite have been found in this study or observed by other researchers (Stow, 1928). These have contributed to a better understanding of the burial in younger Devonian units and further research is needed on these constituents in the Oriskany Sandstone (Friedman and Sanders, 1982).

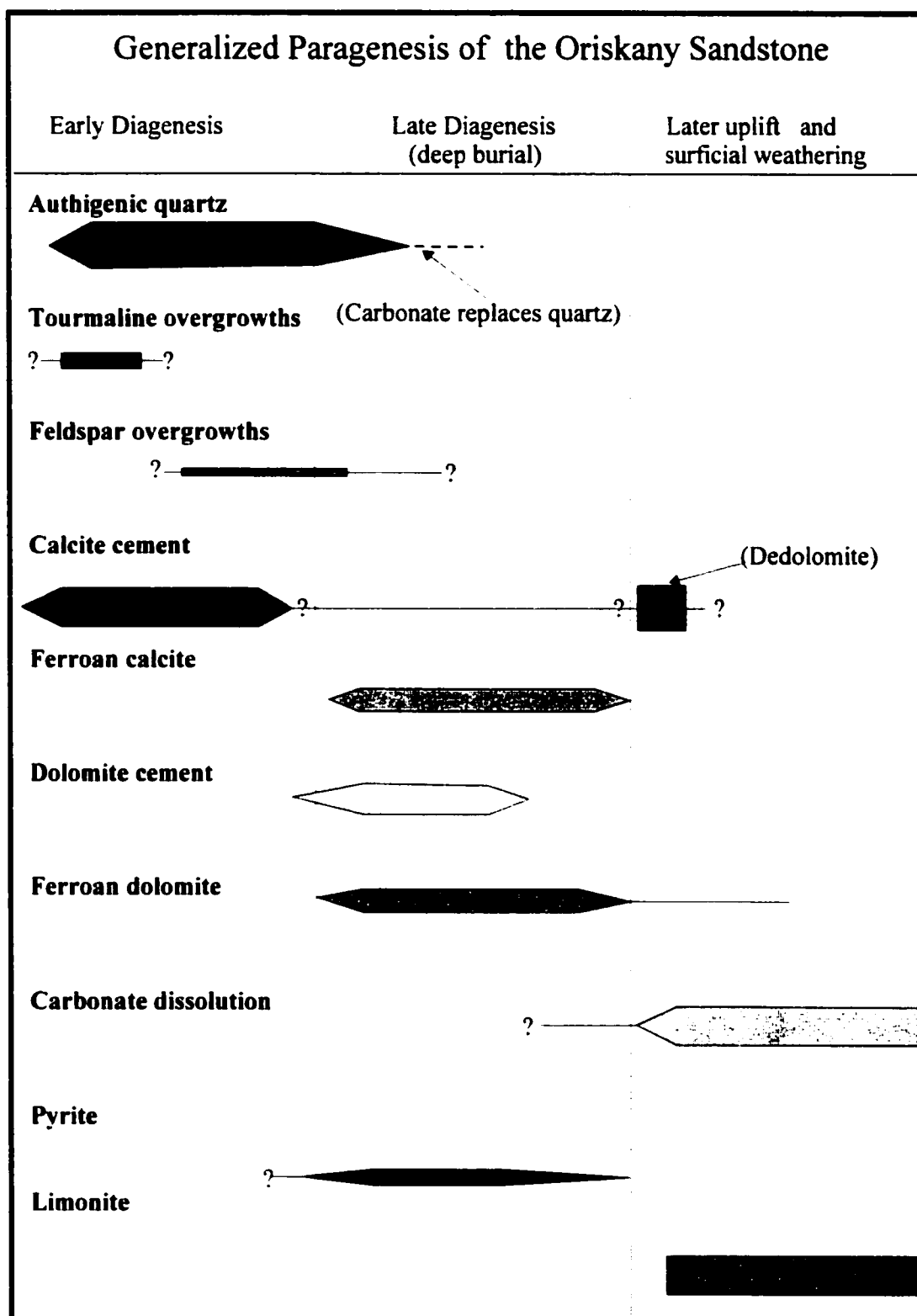
Paragenetic Sequence

Based on the observations made in this study and available information in the literature, a generalized paragenetic sequence is proposed for the Oriskany Sandstone. Though it is clear that local conditions affecting the supply of constituents for authigenic mineral formation, subsidence rates, tectonic influences, and the lithologies above and below the Oriskany Sandstone modified the diagenetic environment of the sandstone, it appears that the same general sequence of diagenetic changes and the same authigenic minerals occur in the Oriskany Sandstone from New York to West Virginia. Thus even though it is highly speculative, the paragenetic sequence is based on information from a fairly uniform body of rock that is generally bounded by similar rocks above and below in the stratigraphic sequence and gives a starting point for future investigations (Figure 3.40).

Figure 3.40. Generalized paragenesis of the Oriskany Sandstone. The schematic diagram shows the generalized order of formation of diagenetic minerals in the Oriskany Sandstone. It is intended to show the sequence of formation of minerals, but there are exceptions to the sequence and many of the southern samples in this study do not have carbonate. As well, several samples studied lack at least some of the other diagenetic components. Information from this study is combined with information from the literature (Maliva, 1992; Foreman and Anderhalt, 1986; Douglas, 1984; Voorhees, 1982). Friedman (1987) and Sarwar and Friedman (1995) have demonstrated that a burial depth of at least 6 km was obtained by some of the northern Appalachian Middle Devonian rocks.

The diagram is broken into three sections: early diagenesis includes authigenic mineralization up to the time when the sandstone is moderately compacted and at least partially cemented; deep burial begins when the sandstone is dominantly influenced by nonmeteoric fluids, is moderately lithified, and continues until the unit begins to be uplifted; uplift subjects the unit to meteoric fluids and brings it back to the surface where it is affected by weathering conditions.

The relative importance of authigenic components and processes such as dissolution are indicated by the thickness of the bars. When the full extent of the burial environment is unclear question marks are used. Further details on the paragenetic sequence of individual samples can be found in this chapter, and details of the timing of tourmaline authigenesis and its relationship to other minerals are discussed in Chapter 4.



CHAPTER 4

TOURMALINE OVERGROWTHS

HISTORY OF INVESTIGATION OF AUTHIGENIC TOURMALINE

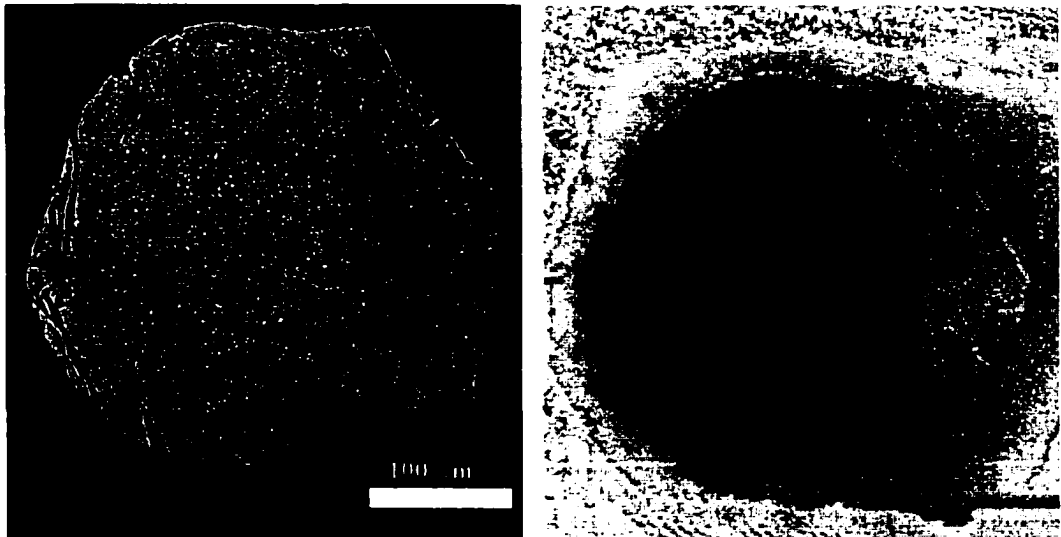
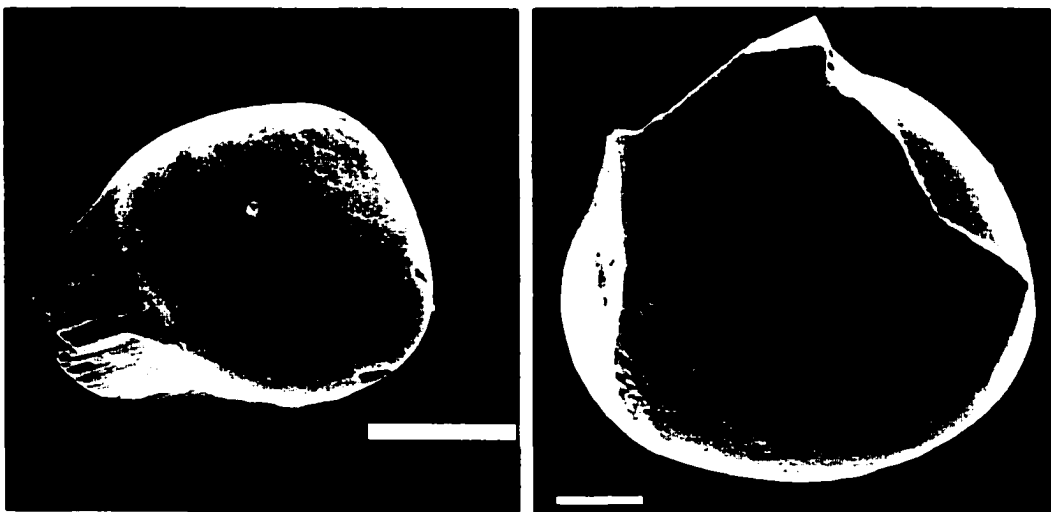
An unusual aspect of the Oriskany Sandstone is its abundance of tourmaline with overgrowths that are in the schorl-dravite series, herein referred to as authigenic tourmaline. Authigenic tourmaline is distinct from other varieties in that it is present as outgrowths on preexisting detrital tourmaline grains and grows in or has the characteristics of tourmaline that grows in the host rock without evidence of metamorphism of that rock (Figure 4.1). Stow (1931) discovered authigenic tourmaline in the Oriskany Sandstone. He found authigenic tourmaline in 30 out of 70 localities from west-central New York to southern West Virginia. The sheer abundance of authigenic tourmaline over such a large areal extent, estimated minimum of Krynine (1946) of 55,000 mi² (143,000 km²), makes this unit the most noteworthy example of the phenomenon of authigenic tourmaline yet reported.

Alty (1933) discovered grains of tourmaline similar to those in the Oriskany Sandstone in a Lower Devonian sandstone in Monroe County, Michigan. Her description of the tourmaline indicates it is identical to tourmaline in the Oriskany Sandstone. It is very likely that the sandstone is a correlative of the Oriskany Sandstone or is derived from reworking of the Oriskany Sandstone. Thus her finding extends the area over which authigenic tourmaline formed during the Lower Devonian or is perhaps redistributed by

Figure 4.1. Tourmaline grains exhibiting euhedral overgrowths. This sample is from Oriskany Falls, Oneida County, New York.

(A) Two photographs of the same grain. The left photograph shows the grain in BSE. Zonation is clearly seen, and the sharp zones have a point of termination in about the middle of the grain. The outermost zone is very dark. The same grain is shown on the right in plane-polarized transmitted light. The termination of the overgrowth, its sharp crystal faces, and the differences in color between the overgrowth and dark detrital core are well exhibited.

(B) Two SEM images showing overgrowth morphology. The left-hand picture shows multiple prismatic faces and a rough termination. Note a small discontinuity in the overgrowth close to the core that may be a growth zone. The grain on the right is tipped at an angle, and three surfaces of the overgrowth can be seen. The meeting of the front and top surfaces is clearly a sharp contact of two crystal faces. The c-axis is parallel to the front crystal faces and emerges from the top surface. On the front surface a series of small concentric zones, probably due to growth, can be seen.

(A)**(B)**

reworking. Study by Alty (1933) indicates that growth occurred only on one end of the tourmaline seed crystal (detrital grain hereafter referred to as detrital core), the antilogous end, and is elongate parallel to the c-axis, and this is a characteristic that appears to be a trait inherent in authigenic tourmaline but not in metamorphic overgrowths (Henry and Guidotti, 1985).

This type of growth with elongation parallel to the c-axis from the antilogous end has also been observed on synthetic tourmaline crystals that grow in sprays from a common point (Barnes, 1950). (No seed nucleus was used in the crystals' synthesis.) Voskresenskaya and Barsukova (1971) also reported c-axis elongated growth on one end of the seed crystal that they grew hydrothermally. An illustration of their tourmaline crystals that were grown on spherical cores looks like tourmaline crystals described here. Interestingly, there do not appear to be terminations on their overgrowth crystals.

Krynine (1946) reported on detrital tourmaline with overgrowths from the Oriskany Sandstone and from older Silurian, Ordovician, and Cambrian sandstones of the Appalachian Basin. His illustrations are strikingly similar to those shown by Stow (1932) and Alty (1933), and he considered that each stratigraphic occurrence was a separate event (in time) of authigenesis and suggested that the tourmaline actually formed on the sea floor, though he gave no supporting evidence. Krynine (1946) also appears to believe that authigenic tourmaline in the Oriskany Sandstone is all formed within the sandstone penecontemporaneously with its deposition, but he does not describe the evidence on which he based his claim.

Authigenic tourmaline overgrowths have been reported from many other locations

and stratigraphic horizons outside the Appalachian Basin. As with Appalachian Basin samples, they are diverse in color and other optical characteristics but appear to share the characteristics of being elongate along only one end parallel to the c-axis, of being lighter in color than the grains they grow on, and of being chemically distinct from the core they grow on. Table 4.1 lists some of the characteristics of reported tourmaline overgrowths and tourmaline interpreted as authigenic by the authors from worldwide reports.

Not all sedimentary authigenic tourmaline occurs as overgrowths; some are neoformed crystals (Gautier, 1979; Ricketts, 1978). For instance, in limestones and chemical precipitates such as gypsum, such crystals have a euhedral outline (Henry, 1996; Spencer, 1925) and have been interpreted as authigenic because of their unabraded and euhedral outline. They also occur in clastic rocks (Gautier, 1979; Ricketts, 1978). Isolated euhedral crystals have never been reported from the Oriskany Sandstone and are unknown from the Appalachian Basin sandstones.

Tourmaline that forms overgrowths at elevated temperatures under metamorphic conditions, either regional (Henry and Dutrow, 1996; Henry and Guidotti, 1985) or contact (Smithson, 1942), can create grains with similar attributes to authigenic tourmaline found in the Oriskany Sandstone; however, metamorphic tourmaline tends to display growth on both ends of the detrital core (Figure 4.2).

GENERAL FEATURES OF ORISKANY SANDSTONE TOURMALINE

A brief description of the properties of overgrowth tourmaline is given here,

Table 4.1
Descriptions of Authigenic Tourmaline from the Literature

Author	Location & Age	Crystal Form	Color	R.I. ω & ϵ	Maximum Size	Unusual Character	Sediment Type
Alty, 1933	Monroe, Michigan, Devonian	ang., abr.	cls. to lt. bl.	1.628 1.610	<0.1mm	-	ss & CO ₃
Awasthi, 1961	Mirazapur district, India, PreC	-	cls.	1.63 1.61	0.02 -0.12 mm	authi. zircon is present	qtz. ss. rich in glauc.
Chatterjee et al., 1975	Bangakpur District, India, PreC	-	lt. bl. to cls.	1.63 1.61	<0.2 mm	-	meta qtz. pebbles
Gautier, 1979	Eagle Ss. Montana, Up. Cret.	euh., pris.	cls. to bn. & y.	-	0.12 mm	both ovgr. & prisms	feldspathic to lithic arenite
Gokale & Bagchi, 1959	Kalava, India	-	lt. bl. to cls.	1.63 1.61	-	-	ortho-qtzt.
Govinda & Nagaraja, 1969	Mysoure, India, PreC	ang.	lt. bl., cls., lt. gn.	biref. 0.019	<0.11 mm	zoned, authi. zircon, feldspar	arkose
Heinrich, 1965	Michigan Basin, Devonian	euh. & ang.	cls.	-	-	-	unknown
Henry, 1996	G. of Mexico, Tertiary	euh.	br.	-	<0.06 mm	sector zoned	cap rock of salt dome in calcite
Henry, et al., 1994	Rose Hill Fm., Sil. Virginia	euh.	-	-	-	iron-rich overgr.	sed. iron-stone
Jensen, 1932	Oriskany, Wayne, NY	ang. abr.	cls.	-	-	-	qtz. ss.
Krynine, 1946	Appalachian Basin Gatesburg Fm., Camb.	euh.	cls.	1.63, 1.612	-	feathery, prisms, delicate	qtz. ss.
Author	Location & Age	Crystal Form	Color	R.I. ω & ϵ	Size	Unusual Character	Sediment Type

Table 4.1—continued

Author	Location & Age	Crystal Form	Color	R.I. ω & ϵ	Maximum Size	Unusual Character	Sediment Type
Martens, 1937	Oriskany Ss., W. Va.	-	cls.	-	-	similar to Stow, 1931	qtz. ss., well samples
Martens, 1939	Appalachian Basin, Keefer Ss., Low. Silurian	euh. & ang. abr.	-	1.63, 1.612	-	similar to Stow, 1931	qtz. ss.
Mange & Maurer, 1992	N. Tunisia, L. Cret.	pris.	bl.-gn.	-	0.01 to 0.1 mm	inter- grown with qtz.	unknown
O'Connor, 1990	Virginia, Tuscarora Fm., Ord.	-	cls.	-	-	boron & alkali deficient	qtz. ss.
Potter & Pryor, 1961	Upper Mississippi Valley, Penn.	rnd. abr.	-	-	-	-	ss.
Ricketts, 1978	Fairweather Fm., Alaska, PreC.	euh.	gn.	-	<1 mm	isolated crystals	qtz. ss.
Smithson, 1942	Yorkshire, England, Sil.	pris.	-	-	-	both growth & corrosion	contact meta qtzt.
Stow, 1931	Oriskany Ss., 30 locations in all	pris.	cls. to lt. bl.	-	-	-	qtz. ss.
Tuttle, 1940	Appalachian Basin Tuscarora, Ord., & Gatesburg, Camb.	euh. & abr.	cls.	1.63 1.612	-	reworked Gatesburg. Fm. in Tuscarora	qtz. ss.

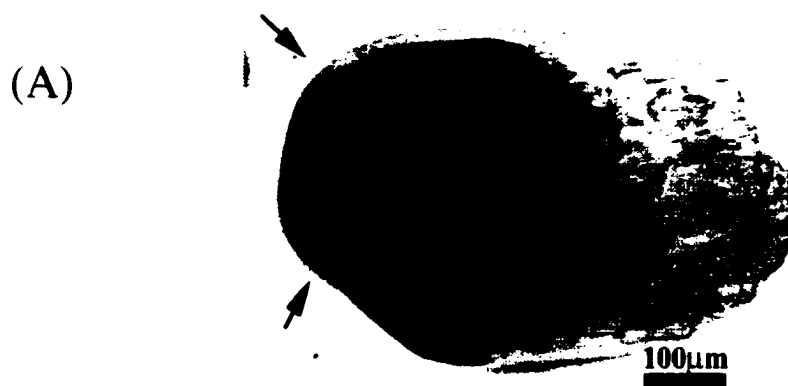
The following abbreviations are used (Mitchell and Maher, 1957): abraded = abr., angular = ang, authigenic = authi., birefringence = biref., blue = bl., brown = bn., carbonate rock = CO₃, colorless = cls., green = gn., light = lt., metamorphic = meta., overgrowth = ovgr. PreC = Precambrian, prismatic = pris., quartz = qtz., quartzite = qztz., refractive = R.I., ss = sandstone, sed. = sedimentary, yellow = y.

Figure 4.2. Detrital tourmaline grains that have the morphology typical of metamorphically enlarged tourmaline (Henry and Dutrow, 1996). These grains both show enlargement of rounded detrital grains (cores) by an overgrowth of chemically dissimilar tourmaline that produces great contrast between the core and overgrowth. The grains were most likely eroded from a metamorphic rock in which the cores were overgrown by the new tourmaline. The grains have undergone a complete sedimentary cycle, including presumed metamorphism and re-rounding, before deposition in a sandstone.

Both specimens have their c-axis lying in the plane of the paper, and arrows point to the overgrowth's short projections on one side.

(A) Plane-polarized light image of tourmaline from Des Moinesian sandstone from Iowa. Mounted in oil, $N_d = 1.6$.

(B) BSE image of tourmaline from Atokan Sandstone from Iowa (this grain looked very similar to A in plane light). The two parallel dark streaks beneath the word "core" are damage created by polishing during sample preparation. The bright dots in the overgrowth are sulphide minerals (not found in Oriskany overgrowths).



followed by descriptions of tourmaline overgrowths from each sample location.

General Morphology of Tourmaline Overgrowths

Some tourmaline overgrowths in the Oriskany Sandstone are acicular and bounded by nearly perfect crystal faces, creating euhedral overgrowths on detrital cores. However, many of the tourmaline overgrowths are more ragged and appear to have been abraded or broken. This is most likely the result of the tourmaline grains being reworked after formation.

To characterize the degree of abrasion displayed by the tourmaline in the various samples, the following terms are used: euhedral, slightly abraded, moderately abraded, strongly abraded. Though euhedral would generally imply no transportation, euhedral detrital tourmaline has been reported in close proximity to its source rocks (Dietrich, 1985). Slightly abraded grains would have a relatively fresh appearance, but have some scratches, damage to crystal faces, and slight rounding of corners on the overgrowths. Moderately abraded grains have outlines that display removal of material, broken edges on some crystal faces, partial removal of the overgrowths by conchoidal fracture, and slightly hackly fracture of the overgrowths. Strongly abraded grains may have considerable breakage evident on the overgrowths; large portions of the overgrowths' original outline are modified by loss of material; sometimes whole areas of the overgrowth have been removed down to the detrital core, creating bald spots on the overgrowths. Strongly abraded grains often have a hackly appearance (Figure 4.3).

Because of the acicular and polar nature of the tourmaline overgrowths, they do

Figure 4.3. Tourmaline overgrowths that display abrasion.

(A) SEM image, Warm Springs, Virginia, this grain had a relatively large overgrowth. Approximately half of it has been broken off and on the upper portion a “seam line” remains (pointed to by arrows) that connects the overgrowth to the rounded detrital core. At point A, the abraded overgrowth is splintery or hackly (described by Stow [1932]), while at B the overgrowth shows a conchoidal fracture.

(B) SEM image, Tonoloway Ridge, Maryland, this grain shows splintery abrasion with the apex of the overgrowth still intact. In all likelihood the overgrowth covered a greater area of the grain and was much better formed. This can be guessed at by a look at the seam line that goes quite far back away from the apex and displays the scars and remnants of the overgrowth.

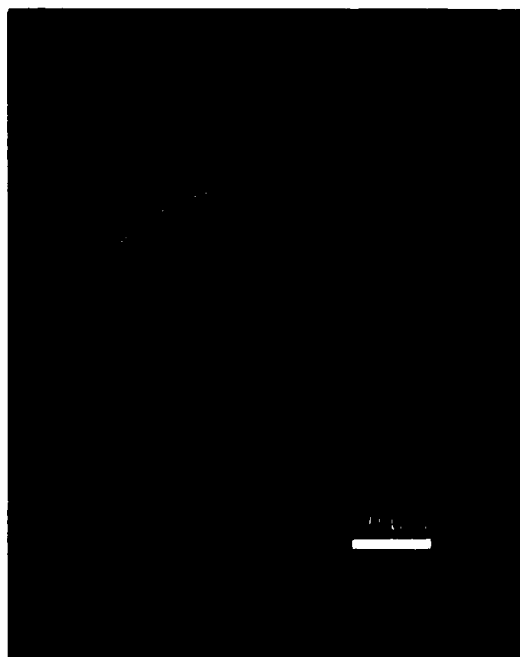
(C) BSE image, Minnehaha Springs, West Virginia, this grain shows that abrasion has interrupted the zonation pattern of the grain and removed a significant amount of the overgrowth, as can be seen by imagining the extension of the zoning pattern.

(D) BSE image, Nedrow, New York, the grain displays splintery remnants of a once-larger grain. All examples from this location show significant abrasion, which is probably evidence of reworking.

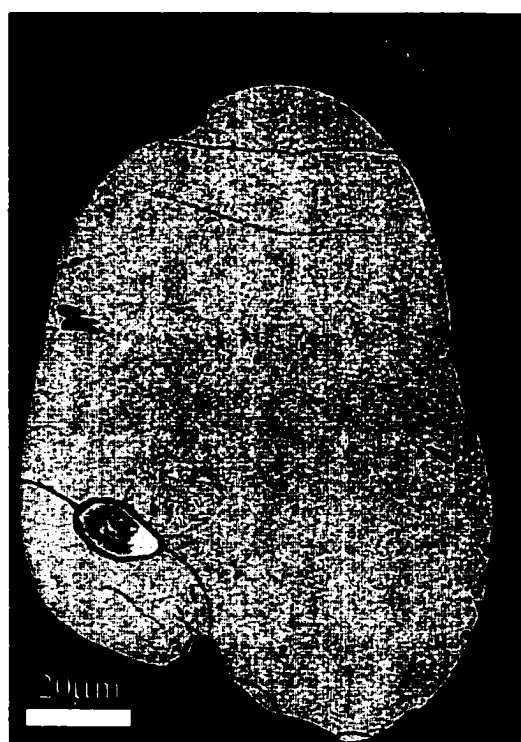
(A)



(B)



(C)



(D)



not show rounding in the manner seen on individual quartz grains, so the more commonly used terminology for rounding of detrital grains is not applied here (Powers, 1953).

However, the grains can become rounded.

Strongly abraded grains with relatively small overgrowths are encountered that have subrounded to rounded outlines. As these grains begin to be dominant, there is a clear trend of reduced population of overgrowth grains. The overgrowths tend to be removed preferentially to the rest of the grain. Krynine (1946) described grains that had almost no overgrowth remaining, but which had a scar-like mass on one end of the crystal.

Another factor in understanding the morphology of the overgrowths is that they tend to be composed of parallel subcrystals here referred to as “crystallites” that become obvious on broken overgrowths. These crystallites can create the hackly appearance observed by several workers in past studies (Stow, 1932; Krynine, 1946).

General Chemistry of Oriskany Tourmaline

Recent work on the chemistry of tourmaline by microprobe analysis has facilitated a better understanding of the petrogenesis and chemistry, and the techniques of microprobe analysis and electron imaging have made it possible to better understand the origin of the tourmaline overgrowths in the Oriskany Sandstone (Henry and Guidotti, 1985; Taylor and Slack, 1984; Henry and Dutrow, 1992, 1996).

No previously published data on the chemistry of the Oriskany Sandstone overgrowths is available. In the course of this investigation, chemical zonation of the

overgrowths was discovered using techniques of electron microscopy; until now no one has published electron images of authigenic tourmaline overgrowths or tourmaline overgrowths with zonation patterns.

Tourmaline group minerals can be classified into several species. These species can be characterized by their major cations (Dietrich, 1985). As well, because there is a solid solution and substitution between certain cations, it is possible to refer to mixed non-end member compositions. In this study, tourmaline overgrowths were analyzed by wavelength dispersive spectroscopy using electron microprobe techniques (See Chapter 2), and were found to all be in the schorl-dravite solid solution series, $\text{NaFe}_3\text{Al}_6(\text{BO})_3\text{Si}_6\text{O}_{27}(\text{OH},\text{F})$ to $\text{NaMg}_3\text{Al}_6(\text{BO})_3\text{Si}_6\text{O}_{27}(\text{OH},\text{F})$. The ideal formula for tourmaline is $\text{XY}_3\text{Z}_6(\text{BO})_3\text{Si}_6\text{O}_{27}(\text{OH},\text{F})$. In the tourmaline investigated here X is typically Na (Ca is only found in the detrital cores). Y is predominantly Fe^{2+} and Mg^{2+} (which can completely substitute for each other), but some V^{3+} may occur with coupled substitution or crystal lattice defects to prevent charge imbalance. Z is Al^{3+} , Fe^{3+} , V^{3+} , Cr^{3+} or Ti^{3+} . Though Ca and Ti occur in detrital tourmaline cores, they are found only in small quantities in the overgrowths.

Data on tourmaline composition are plotted on Al-Fe-Mg ternary diagrams with the compositional petrogenetic fields defined by Henry and Guidotti (1985). These fields and this method of presentation of data have been widely accepted (Taylor and Slack, 1984; Chaussidon and Albarede, 1997; Henry and Dutrow, 1992 & 1996; Roda et al., 1995; Slack, 1996; Novak et al., 1999), and are useful not only for petrogenetic information but for graphical comparison of samples. The diagrams also can be used to

plot the chemical evolution of overgrowths with respect to the elements Al, Fe, and Mg.

Tourmaline zonation in these samples is mainly the result of fluctuations in Fe and Mg (as will be shown below). Vanadium sometimes appears to influence zoning. Some zoning can be seen optically in a few samples, but is best seen using backscattered electron imaging (BSE). Zoning, visualized with BSE, is visible on some grains in every sample investigated.

SAMPLE DESCRIPTIONS

The samples are described by state, and descriptions are limited to samples that contain tourmaline with overgrowths. Details of the locations are described in the petrography chapter.

New York Samples

Auburn

Tourmalines separated from this location have well-developed, euhedral overgrowths to slightly abraded overgrowths, which are present on ~76% of the grains (Figure 4.4 and 4.5). The overgrowths are all zoned, and the zonation pattern appears to reflect the crystals' boundary during growth. Some grains have a point of inflection in the zones that may represent prior crystal terminations as the overgrowths grew into pore spaces. The boundaries between zones are sharp and well defined.

The overgrowths typically have 3 zones, though a 4th zone is apparent on a few

Figure 4.4. BSE images of overgrowth tourmaline from Auburn, New York. The overgrowths vary from euhedral to moderately abraded. The zoning typical here is at least 3 zones, with a darker interior followed by a lighter zone, followed by a dark outer zone.

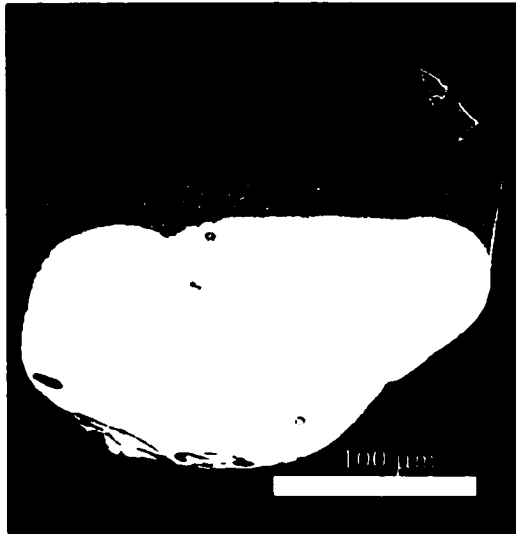
(A) Tourmaline with a euhedral overgrowth. The size of this overgrowth is quite significant, almost doubling the grain size. The trace of a microprobe transect, with probe damage spots, visible in the overgrowth, can be seen running from near the middle of the overgrowth (close to the start of the fracture in the grain) to the outermost zone of the grain.

(B) Tourmaline overgrown with a somewhat irregular overgrowth outline. Several quartz grains (lighter gray and irregular in shape) interrupt the outer zones, and it seems fairly clear that the quartz was incorporated during overgrowth formation.

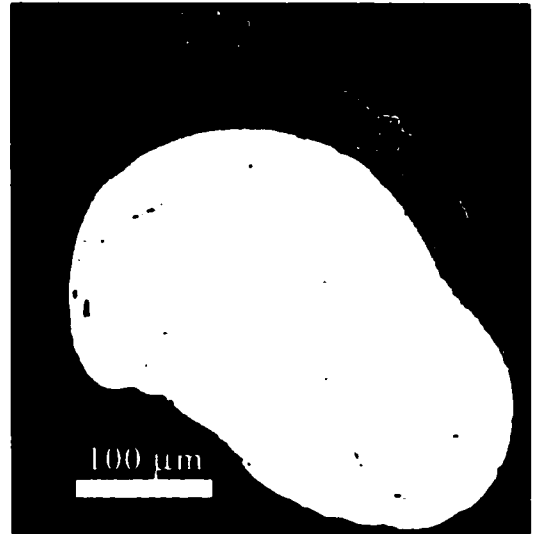
(C) Again 3 zones can be seen in the overgrowth; the innermost zone is irregular on the right side and has a zigzag pattern. This grain exhibits moderate abrasion.

(D) Tourmaline grain with moderate evidence of abrasion. Note that to the sides of the overgrowth a little bit of remnant overgrowth seems to indicate that the overgrowth was once considerably larger.

A.



B.



C.



D.

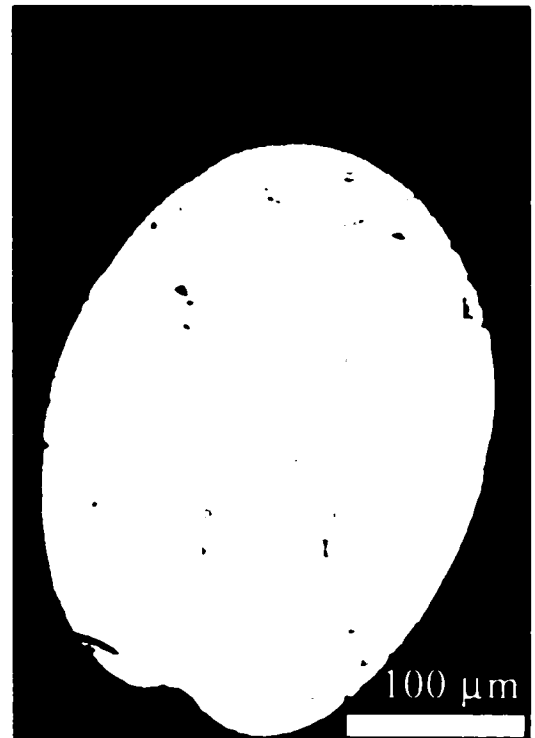
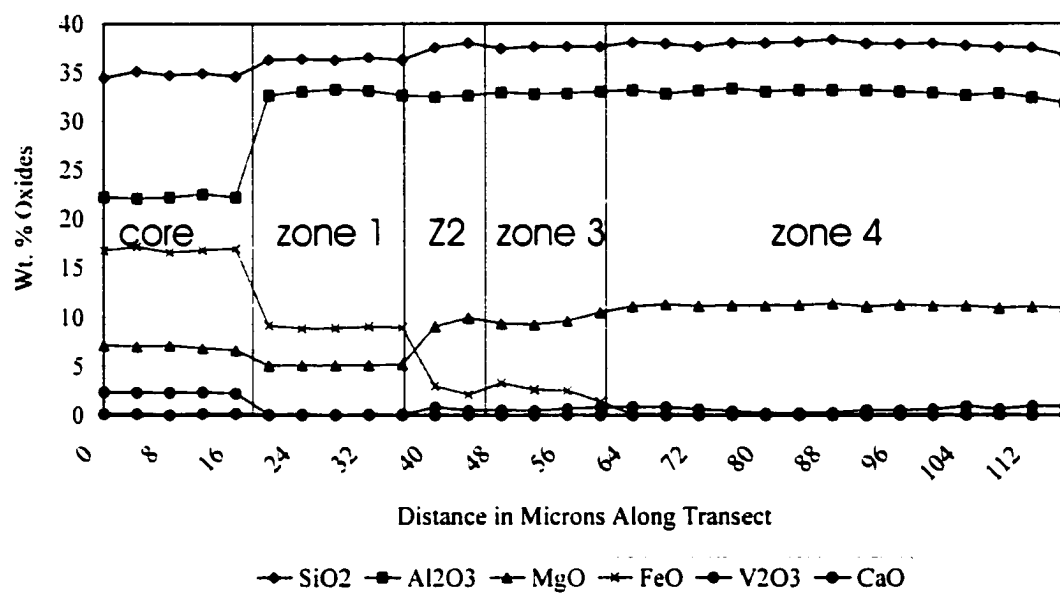


Figure 4.5. Transect of zoned tourmaline from Auburn, New York. Tourmaline overgrowths from Auburn have 3 to 4 well-defined zones visible in BSE (this is grain aub2b). The line of the transect is shown on the BSE micrograph in red. There are 4 obvious zones in the BSE image and microprobe transect of 116 microns; zones 2 and 3 do not have great contrast and were highlighted with ticks. Note the overall depletion of Fe from the core to the end of the overgrowth and the corresponding decrease in brightness in the BSE image. Brightness is related to atomic number contrast in the micrograph, and a small reversal in the overall trend is found in zone 3 that brightens slightly over zone 2; this is also seen as a small increase of Fe on the graph. Fe drops to near zero in the outermost zone.

Vanadium is low in zone 1, increase to 0.82 weight % in zone 2, decreases slightly to maximum of 0.79 in zone 3, and increases to a maximum of 0.94 in zone 4. The fluctuations in V in the samples from Auburn, New York, do correspond to BSE zoning in these samples.



grains. The outermost zone is always a dark zone in BSE, and several of the examples have inclusions of quartz in the outer zone (Figures 4.4 and 4.5).

The overgrowths do not show evidence of fracturing, while the detrital well-rounded tourmaline cores, though remaining intact, have multiple fractures developed in them. Small fragments of quartz on some of the overgrowths are probably remnants of bigger grains that were attached but broke loose when the sandstone was crushed and processed for heavy mineral separation.

Tourmaline overgrowths with quartz attached to them seem to have grown around the irregularly shaped quartz grains. Zones continue on either side of such interruptions, and where the quartz is in part directly touching the detrital tourmaline core there is no overgrowth.

Chemically the tourmaline overgrowths are schorl-dravite. While plots based on Henry and Guidotti (1985) place the detrital cores mainly in field 6 on Al-Fe-Mg diagrams, with 2 samples plotting in field 2 (Figure 4.6), the field 2 samples may be in the schorl-elbaite solid solution series and could be derived from granitic rocks (Roda et al., 1995).

Overgrowths plot consistently in field 7 and on the border of fields 5 and 7 or 4 and 7. A few grains have initial zones that plot in field 4 or on the borderline with fields 4 and 5. With progressive growth, the tourmaline becomes more and more magnesium rich. In most cases the amount of iron drops significantly from the inner part of the overgrowth, near the detrital core, to the point where there is almost no iron at the outermost edge of the overgrowths. Iron, measured as FeO, drops from highs of around

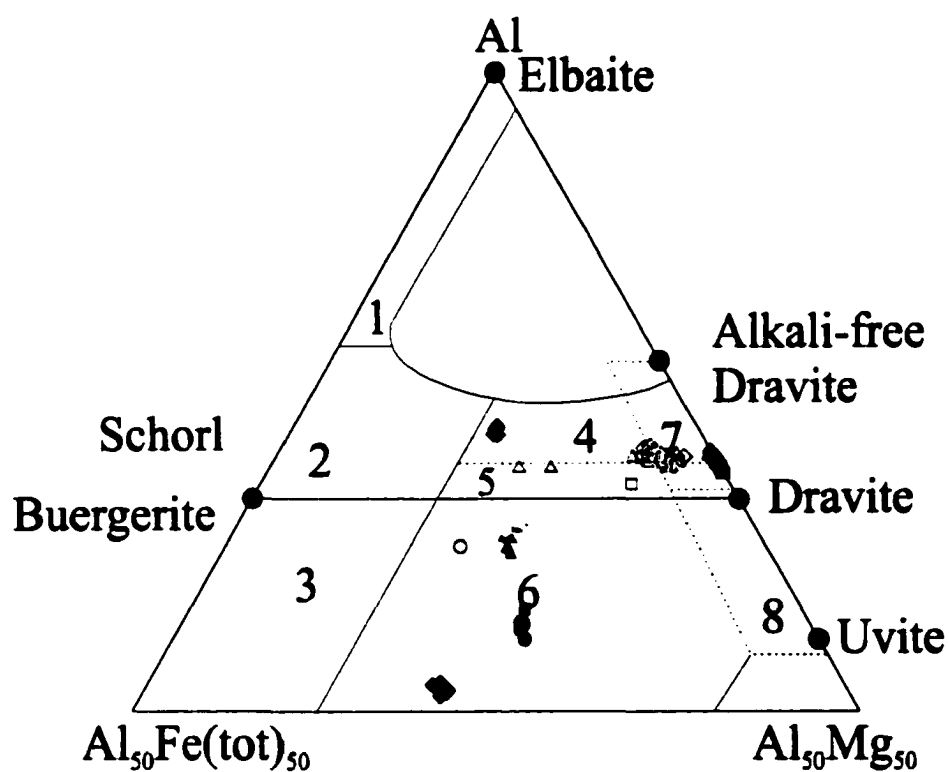
Figure 4.6. Tourmaline Al-Fe-Mg ternary diagram for samples from Auburn, New York.

In this example, 9 tourmaline grains were analyzed by electron microprobe transects. For clarity, two triangular diagrams were used, (A) and (B). Each colored symbol represents a single point analysis. Solid symbols represent the detrital core, and hollow symbols represent the overgrowth.

Because the overgrowths are compositionally zoned, data from any one overgrowth will tend to vary. Observations of well-zoned tourmaline overgrowths show a strong tendency for migration of the composition away from the detrital core as the overgrowths become progressively enriched in Mg (this is particularly true of samples from central New York); thus points migrate from initial fields 4 and 5 toward field 7, and often the outer pure dravitic zones plot along the diagram's margin somewhere along the tie-line between alkali-free dravite and dravite, as they do in this sample.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe³⁺-rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammities coexisting with an Al-saturating phase, (5) metapelites and metapsammities not coexisting with an Al-saturating phase, (6) Fe³⁺-rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)



Core Overgrowth



= Aub3btrans2

= Aub3btran1

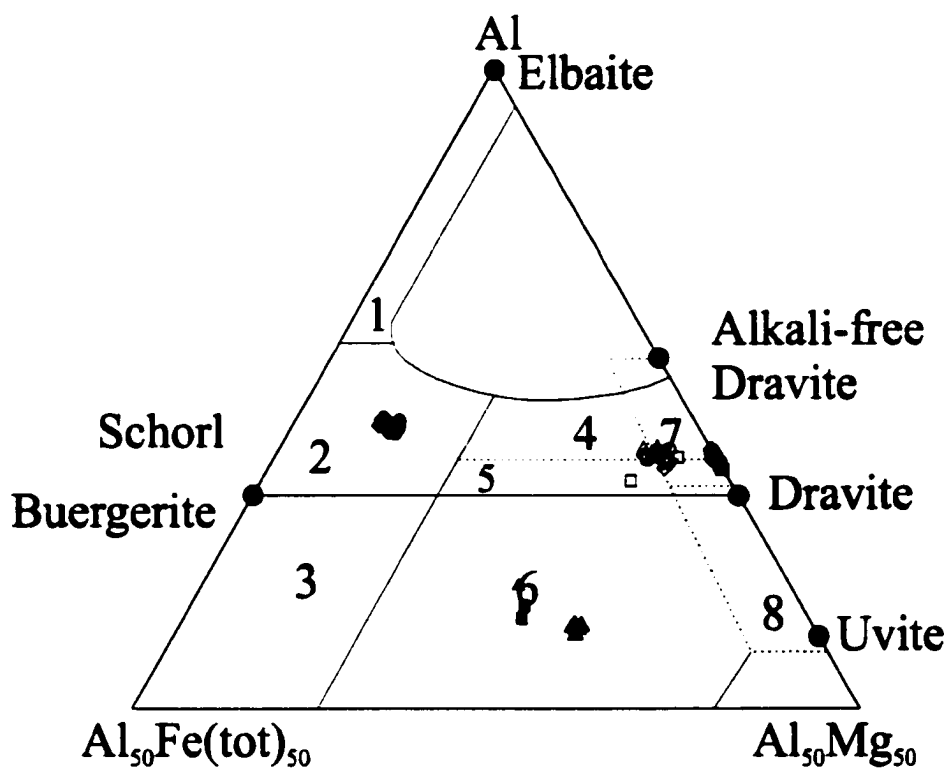
= Aub2b

= Aub1b2

= Aub1b

Figure 4.6—Continued

(B)



Core Overgrowth

▲	△	= Auburng4
◆	◇	= Auburng3
●	○	= Auburng2
■	□	= Auburng1

8%, but more typically 3 to 4 weight % to less than 0.1 weight % as the transect is followed from the core to the overgrowth (Figure 4.5). When iron is lacking, the overgrowths plot along the side of the diagram in field 7. Field 7 is the zone of low-Ca-metaultramafics and Cr- and V-rich metasediments. Vanadium in the overgrowths varies from a minimum of about 0.2 weight % to a high of around 1.5 weight %. Chromium is below reliable detection limits, with a maximum of about 0.1 weight %. Calcium drops below detection at the core overgrowth interface; as well, aluminum and silicon tend to increase. Aluminum goes up, in general, to about 33 weight % Al_2O_3 (detrital cores have Al values from a minimum of 25 to about 33 weight % Al_2O_3). Si in the overgrowths has values of about 37 to 38 weight % SiO_2 (Si in the detrital cores varies from about 33.5 to 38 weight %).

Austeel Plant

Tourmaline separated from this locality had rare but large overgrowths. Overgrowths occur on ~32% of tourmaline grains, but tourmaline makes up only ~10% of the detrital heavy mineral suite. The overgrowths are large, up to about 300 μm long, and are light green to almost aquamarine in color. They are slightly to moderately abraded in all examples studied (Figure 4.7). The maximum number of zones shown by a grain was 3, but most exhibit 2 zones; an inner lighter and outer darker zone are displayed by 7 of the 8 grains examined.

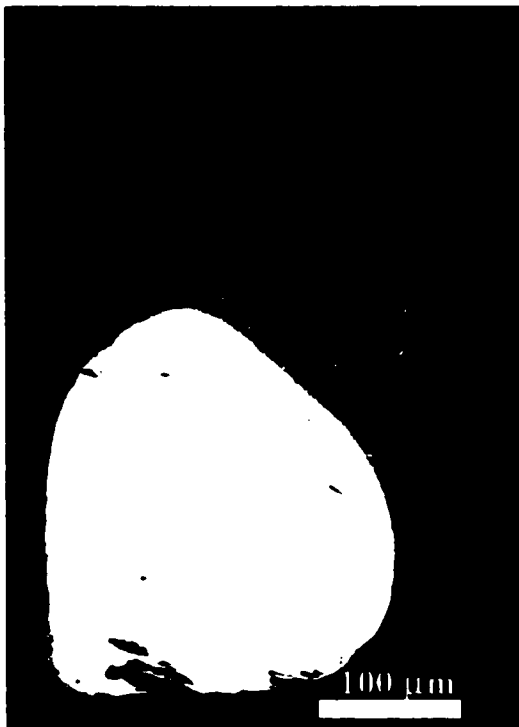
Chemically, these overgrowths are in the schorl-dravite series (Figure 4.8). The inner zone has more iron than the outer dark zone. Iron steadily drops off to trace amounts from the core to the tip of the overgrowths. In 4 of the 6 grains analyzed, the

Figure 4.7. Two large overgrowths with very large zones. These are typical of tourmaline from the Austeel Plant locality, Auburn, Cayuga County, New York.

(A) Note that at its widest point the dark outer zone is about 150 microns in length. The inner zone is not uniform in size and has a curved shape. This may be an inflection due to formation of a crude termination formed as the crystal grew.

(B) Though the outer zone is a little larger (~165 microns), this sample has more uniform zones. Both examples have a very small inner dark zone (around a micron in width) that is too small to analyze. As well, both grains display evidence of moderate abrasion.

A.



B.

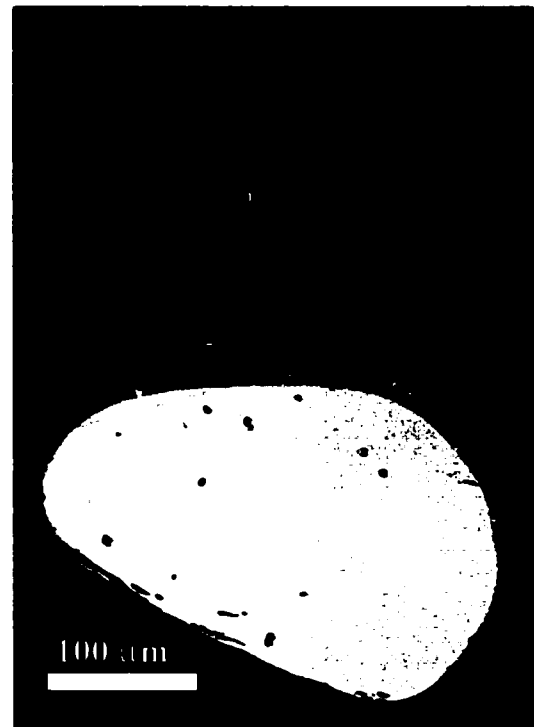


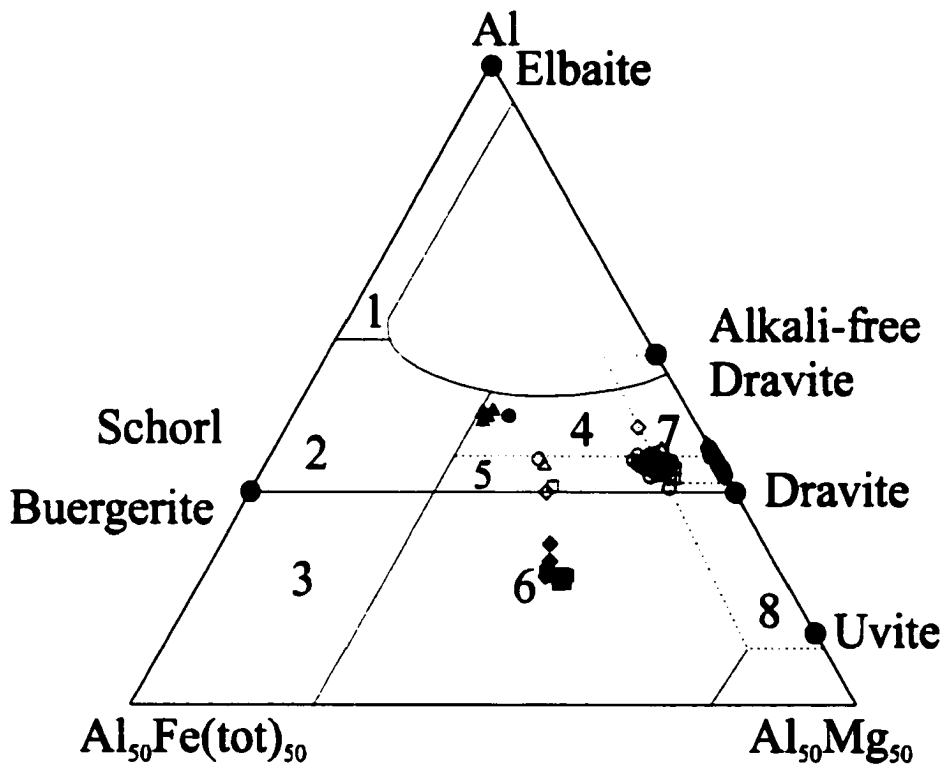
Figure 4.8. Tourmaline Al-Fe-Mg ternary diagram for samples from the Austeel Plant, Auburn, New York.

These grains when plotted on triangular diagrams are in three distinct groupings without a drawn-out transitional zone. A dark inner zone that ranges from very small to moderate that plots in field 4 is rarely present or is underdeveloped in most overgrowths (as in grain Spring4b and spring5b). A middle brighter zone that plots on the border of fields 4, 5, and 7 is usually well developed. A dark outer zone that is dravitic in composition plots on the tie-line in field 7. It is difficult to explain exactly why a few data points plot in isolated areas of the fields discussed, away from the main groupings. This may result from overlaps with the detrital core, inclusions, or damage to the grain.

The detrital cores plot in fields 2, 4, and 6 on Al-Fe-Mg diagrams. Plotting in these zones indicates a mixed provenance of Li-poor granitoids, metapelites, and metapsammites coexisting with an Al-saturating phase and Fe^{3+} -rich quartz-tourmaline, calc-silicate rocks, and metapelites according to Henry and Guidotti's (1985) petrogenetic diagrams

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. $\text{Fe}(\text{tot})$ is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

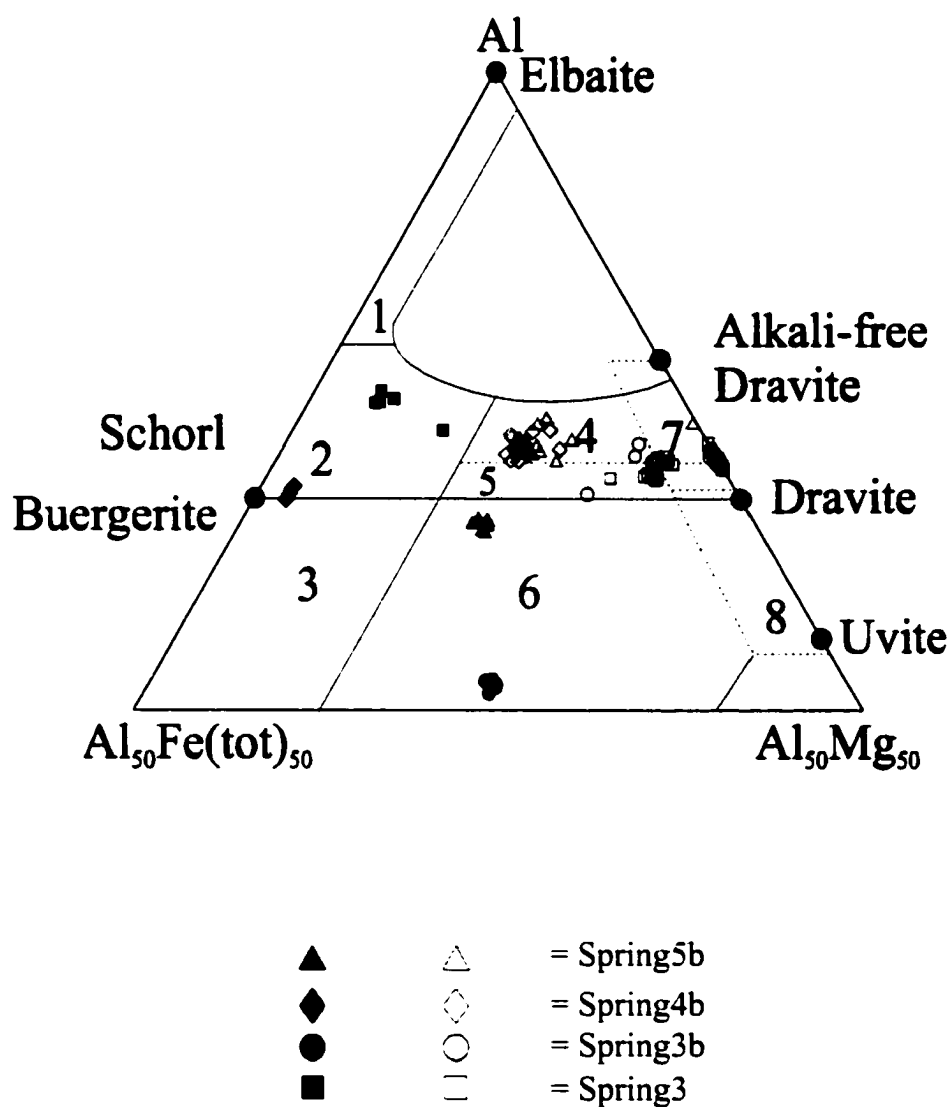


Core Overgrowth

▲	△	= Spring2b
◆	◇	= Spring2
●	○	= Spring1b
■	□	= Spring1

Figure 4.8—Continued

(B)



amount of iron in the darker outer zone is below detection of the electron microprobe, and the darker zone is essentially a pure dravite. These grains with a pure dravitic outer portion of the tourmaline when plotted on triangular diagrams show three groupings of the data points, without any drawn-out transitional zone. The distinct groups appear to be related to zoning (Figure 4.8). Thus the overgrowths in field 7 fall in two distinct groups: the outer zone plots very close to pure dravite and the other zone near the border with field 5; a few points plot on the border between 4 and 5 and on the border between fields 4 and 7. It is difficult to explain exactly why a few data points plot in isolated areas of the fields discussed, away from the main groupings. There are several possible reasons: 1) analysis at boundary zones at points that cross both zones, 2) extraneous inclusions, 3) problems with sample preparations. In all examples investigated, the boundary of the inner dark and outer bright zones is sharp and can vary from a wavy to a straight surface that appears to be a result of crystal faces developing on the overgrowths.

The vanadium and chromium content of these samples is the highest of any found in the study. Vanadium averages 1.4 weight % V_2O_3 in the overgrowths. A maximum of 2.8 weight % was found. Chromium is present at levels reaching 1.9 weight % Cr_2O_3 , with levels averaging around 0.67.

No examples of composite grains with quartz and tourmaline were found. The detrital cores plot in fields 2, 4, and 6 on Al-Fe-Mg diagrams. Plotting in these zones indicates a mixed provenance of Li-poor granatoids, metapelites, metapsammites coexisting with an Al-saturated phase and Fe^{3+} -rich quartz-tourmaline, calc-silicate rocks, and metapelites according to Henry and Guidotti's (1985) petrogenetic diagrams.

Crandall Estate Well #1

Tourmaline overgrowths occur on ~95% of tourmaline grains, and tourmaline makes up ~57% of the detrital heavy mineral suite. The tourmaline grains have well-rounded detrital cores, and many of the grains of tourmaline have medium to large, euhedral to moderately abraded tourmaline overgrowths. The colorless tourmaline overgrowths have typically between 5 and 7 zones that are well defined in BSE images, and more finer zonation may be present (Figure 4.9).

Many of the overgrowths are fractured, and this seems to have happened in the sandstone. Because the sandstone is very well indurated, it is possible that during crushing many grains suffered fractures (Figure 4.10). However, there are composite tourmaline and quartz grains, and where quartz meets tourmaline there are fractures that suggest that compaction after overgrowth formation has pushed the quartz grains into the tourmaline.

A few grains with tourmaline overgrowths appear to have in effect been microstylolitized (Figure 4.11). The zonation of the overgrowths seems to indicate that compactive forces caused a disruption of the overgrowth. Sometimes zones seem to be displaced along fracture lines, and in other cases there is distortion of the straight zoning pattern. Stylolites are present in hand samples of the sandstone and are illustrated in Chapter 3 (Figure 3.12).

SEM images of the overgrowths indicate that the prismatic faces of tourmaline have not suffered much abrasion (Figure 4.12). Even though most tourmaline overgrowths are fractured, a few have been observed that have terminations. These lines

Figure 4.9. Microprobe transect and analysis of individual zones of an overgrowth from the Crandall Estate Well #1. Data are plotted on the Al-Fe-Mg ternary diagram. This sample was taken at a depth of 4,999 ft (1524 m) from the East Independence Field, Allegany County, New York.

(A) The tourmaline overgrowth has 5 zones. Three well-defined zones were analyzed by individual transects that indicate that each zone is relatively uniform in composition. These transects are plotted on an Al-Fe-Mg ternary diagram (See **B** below). There is fluctuation of iron from 8.48 weight % FeO at the beginning of the inner bright zone to 6.47 weight % in the outer dark zone and of magnesium from 5.49 weight % MgO at the beginning of the inner bright zone to 7.11 weight % in the outer dark zone. The outermost dark zone points are almost the same as the innermost dark zone points plotted on the ternary diagram and though not analyzed by an individual transect would plot in the same place as the inner dark zone (some of the transect points are hidden behind the individual transect of the innermost dark zone).

(B) Al-Fe-Mg ternary diagram. Symbols in red are from a single transect from the detrital core (solid red) to the outer edge of the grain perpendicular to the overgrowth as shown above in **A**. There is a general trend of increasing aluminum from the detrital core to the overgrowth, which is accompanied by increasing magnesium content and a decrease in iron compared to the detrital core.

The innermost bright zone of the overgrowth (two open red squares in the upper left corner of field 4) is a poorly defined transitional zone. This innermost zone has the highest aluminum content. Aluminum content becomes more uniform and slightly lower in the 4 well-defined zones that follow. Both iron and magnesium fluctuate in the following zones. However, conditions during the formation of the outer and inner dark zones are very similar and plot on top of each other.

The tendency for all overgrowth analyses from this sample to plot within field 4 suggests that the rock coexisted with an Al-saturating phase (Henry and Guidotti, 1985).

The petrogenetic fields for the Al-Fe-Mg ternary diagram shown are as follows (after Henry and Guidotti, 1985): (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe³⁺-rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe³⁺-rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr- and V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

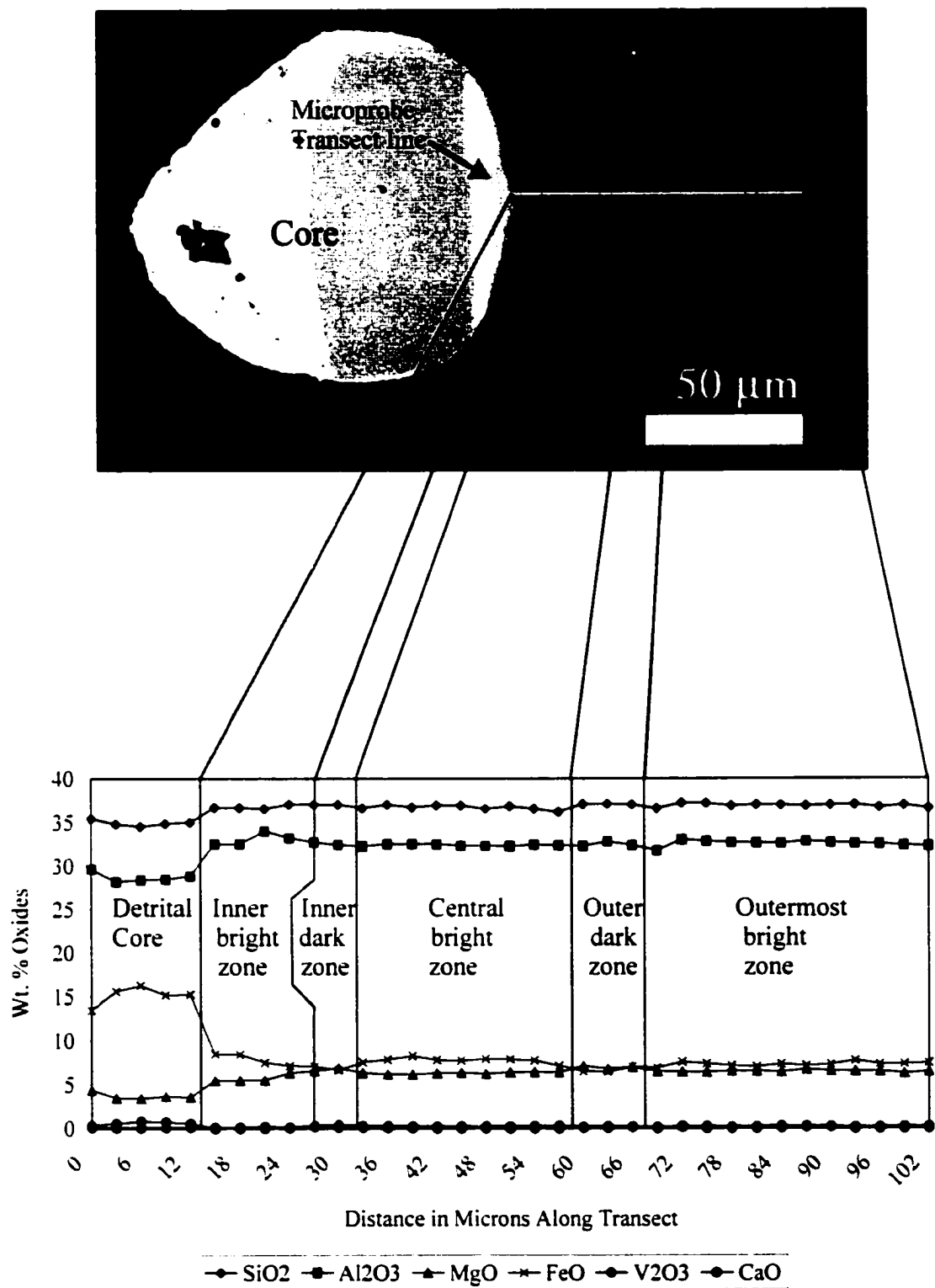
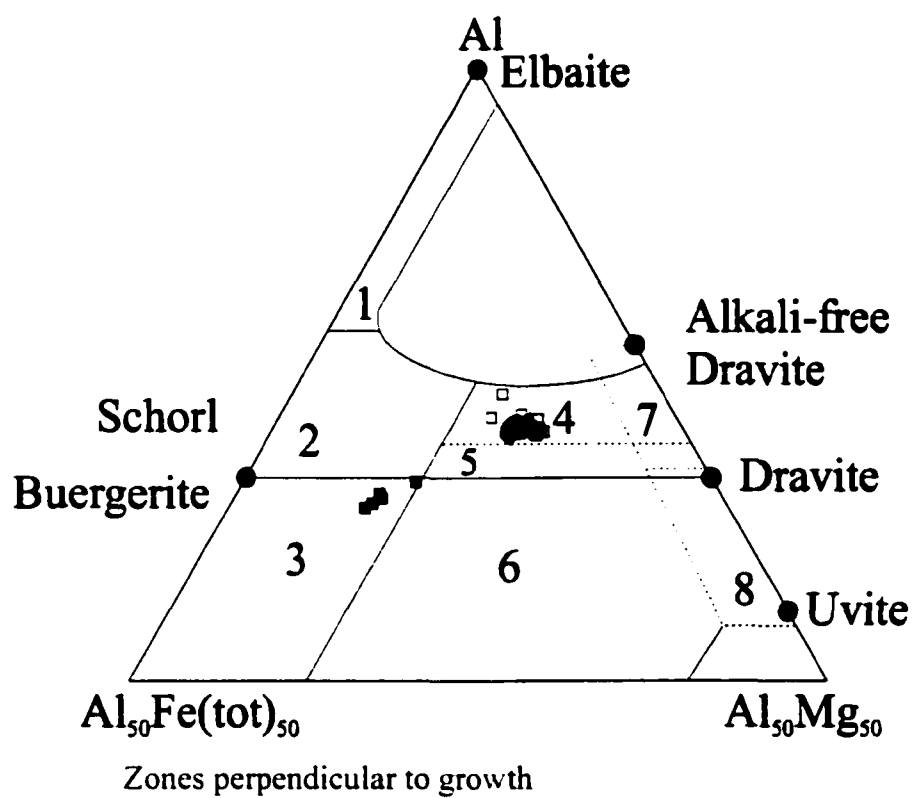


Figure 4.9—Continued

(B)



- ▲ = Outermost bright zone, N = 11
- ◆ = Central bright zone, N=12
- = Innermost dark zone, N = 11

Transect parallel to the C-axis

Core Overgrowth

■ □ = Crandall Estate #1 Well Grain 5

Figure 4.10. Tourmaline grains from the Crandall Estate Well #1. These grains were taken from a core extracted at 4,999 feet (1524 m) in the East Independence Field, Allegany County, New York.

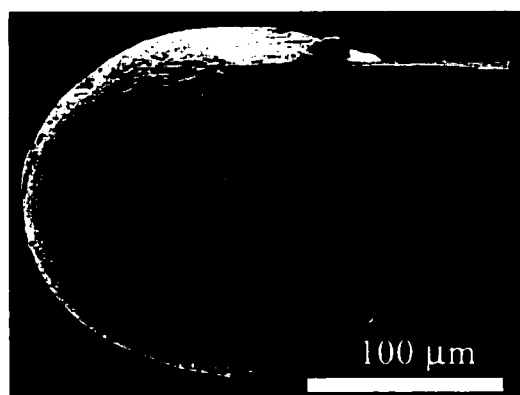
(A) Tourmaline grain displaying a well-rounded core enlarged by a well-developed and unabraded overgrowth. Though not abraded, the overgrowth is broken. This may be due to the very indurated nature of the rock and fracturing during processing or may be due to in situ breakage of the overgrowth during compaction. Since most grains still have flat unabraded overgrowths, it is possible that these grains grew in the sandstone and are not reworked. The c-axis is oriented parallel to the long dimension of the photograph.

(B) Another tourmaline with similar shape to A (above). Note the overgrowth is more fractured than in A. Blade-like crystallites can be seen both in the overgrowth and extending back onto the core where the overgrowth is attached.

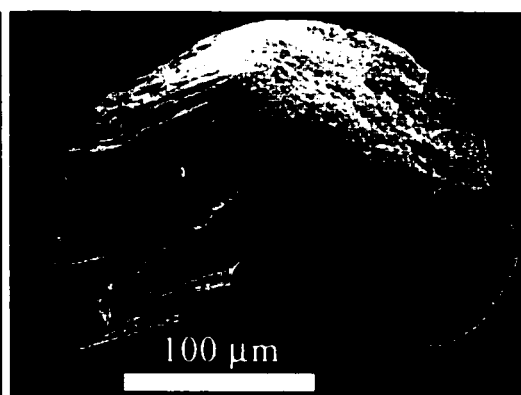
(C) Tourmaline with fractured overgrowth. Note that much of the grain has been removed. One observation, made on many grains from this locality, is that only half of the overgrowth remains. The half is usually to one side that still appears unabraded. In this photo the half of the grain that is less broken is oriented downward (the broken half is visible). The grain's morphology can be likened to a finger with a long fingernail. The core of the grain is like the fingertip, while the overgrowth extends like the nail on only one side. Though it is unclear why this happens, perhaps there is some kind of pressure on the grains that splits them.

(D) Grain with a "bald spot" due to breakage of the overgrowth. Note that there is a hollow spot in which the overgrowth is missing, creating an amphitheater-like depression in the overgrowth. The surface exposed, by the presumed breakage and loss of part of the overgrowth, may be the detrital core. The surfaces remaining do not appear abraded and appear to display several crystal faces. These flat-sided surfaces are probably growth faces since typically tourmaline breaks with a conchoidal fracture. The face labeled **P** appears to be a prism face developed parallel to the c-axis, while the crystal face labeled **T** may be a terminal face. A few tourmaline grains from this locality have fully developed euhedral overgrowths with both terminal and prism faces, but they are rare and none could be obtained for illustration.

(A)



(B)



(C)



(D)

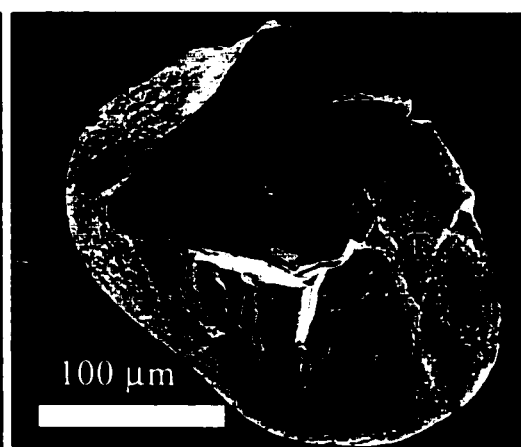


Figure 4.11. Tourmaline grains that may have suffered pressure solution. These grains are from the Crandall Estate Well #1, Allegany County, New York. The sample is from a depth of 4,999 ft (1,524 m), and tourmaline grains' overgrowths appear to have been altered by disrupting forces.

(A) A quartz grain appears to have caused the disruption of this tourmaline overgrowth. To the lower left, zones appear to have been disrupted and offset by compaction. In grains where tourmaline either grows into contact, or a quartz overgrowth makes contact with tourmaline, zones are not typically disrupted.

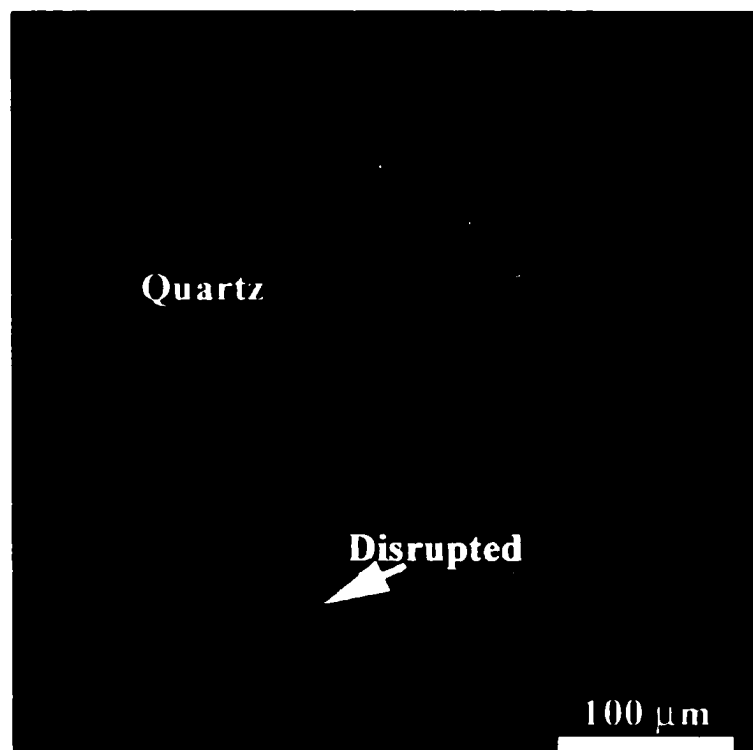
(B) Tourmaline grain with a well-developed overgrowth with at least 6 zones visible in it. The upper area close to the detrital core seems to have been disrupted. Note that there are also many healed fractures in this grain's core.

(C) Another grain that appears to have displaced zones. Arrows point at a prominent dark zone that seems to be offset. Note that small linear fractures or cavities (dark in color) run parallel both to each other and to the direction of displacement. Similar fractures or cavities are present in **A** (above) and have not been seen at other locations.

(D) Tourmaline grain with a well-developed overgrowth; note that the zonation pattern is distorted on the left side (arrow) and to a lesser extent on the right side. Microprobe analysis points can be seen as spots running in a line parallel to elongation of the overgrowth. The fracture running through the detrital core is most likely due to polishing of the sample.

Note also that the strong linear effect shown in **A**, **B**, and **C** above is not typical of damage caused by processing or polishing techniques. That type of fracture is conchoidal damage that breaks along the weak basal parting present in tourmaline at a right angle to the c-axis.

(A)



(B)

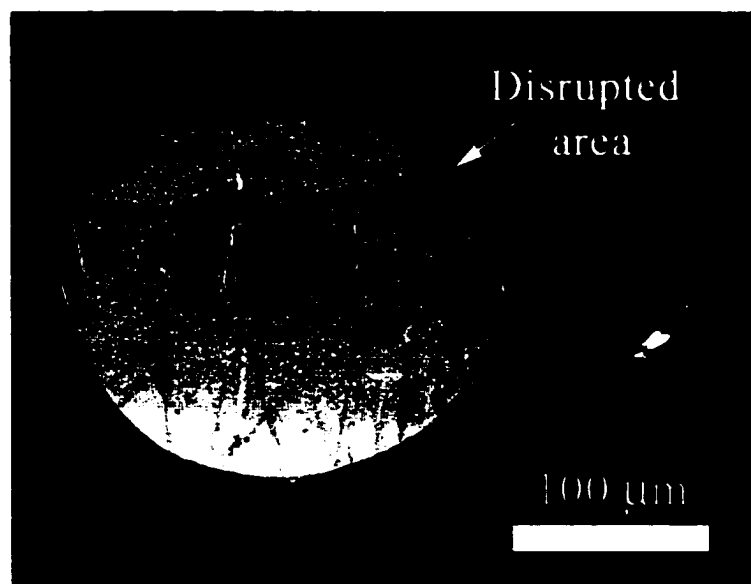
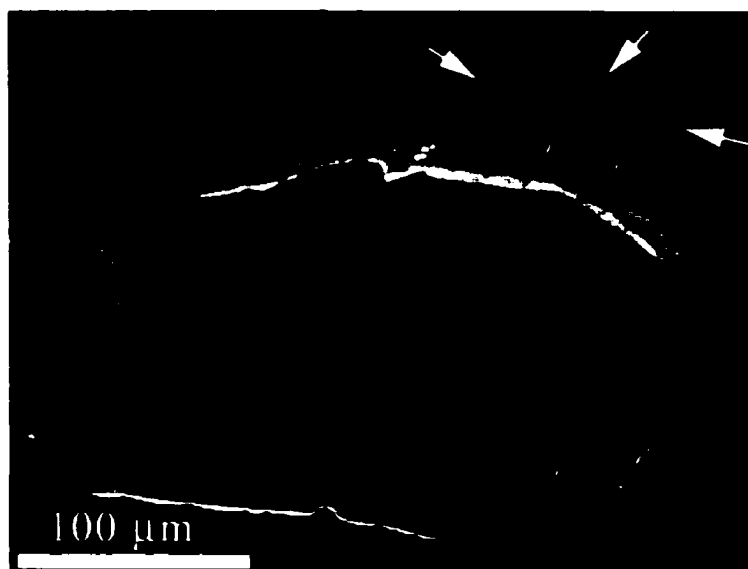


Figure 4.11–Continued

(C)



(D)

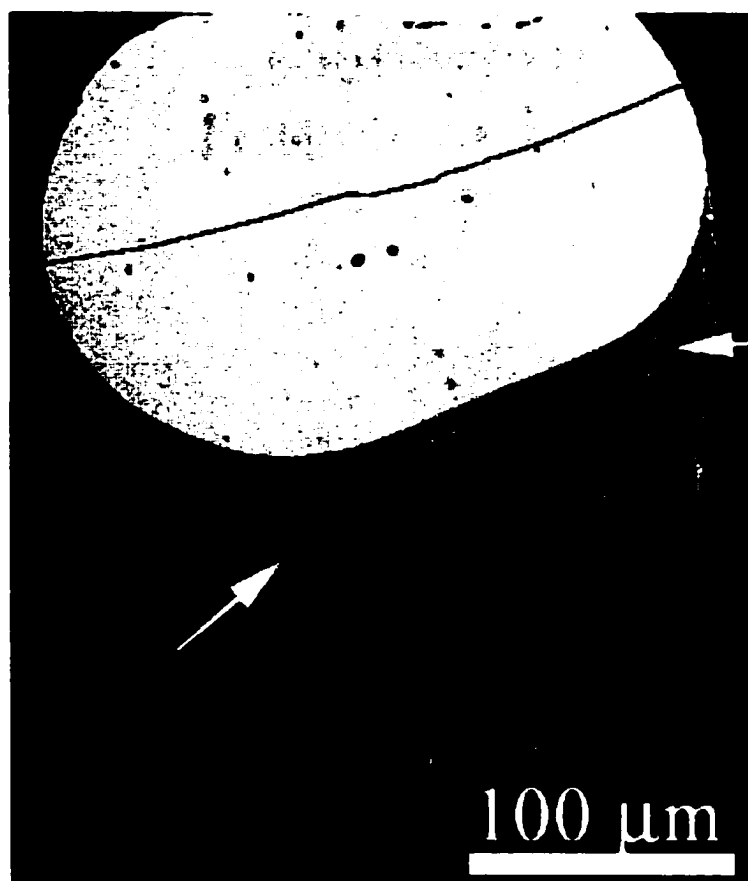


Figure 4.12. Tourmaline overgrowth with quartz grains attached. This sample, taken at a depth of 4,999 ft (1,524 m), is from the Crandall Estate Well #1, Allegany County, New York.

(A) This grain has two small quartz grains attached at the far end of the overgrowth. Quartz grain **B** displays authigenic quartz overgrowth, while grain **A** is fractured and does not display overgrowth. Both quartz grains were most likely pieces of larger grains but have been broken loose during processing. Note that grain **A** is engulfed inside the tourmaline overgrowth; it is unclear whether the grain was forced in by pressure solution or was engulfed by tourmaline growth. But stylolites and other evidence of compaction strongly support the pressure-solution possibility. On the fractured surface of the tourmaline below **A**, small pores in the tourmaline overgrowth can be observed. Striations on the tourmaline are labeled **S**. They may be formed as crystallites fuse to form the overgrowth.

(B) The contact with grain **B** seems to be a growth contact, though it is not entirely clear which mineral, the quartz or the tourmaline, has grown onto the other. The relatively straight-line contact suggests that the contact was due to growth in the pore and that both grains had grown into the same pore.

(C) An inspection of the tourmaline overgrowth and quartz overgrowth grain **B** suggests that there is little abrasion to the overgrowths and that small-bladed crystallites remain straight-sided. It is suggested that this overgrowth formed in place or was only moved by resedimentation a short distance. Notice that not all of the overgrowth's crystallites meet perfectly and that a space between adjacent crystallites (**Ch**) could create a channel or pore in the overgrowth.

(D) Closer inspection of grain **A** reveals the uneven nature of the contact between the quartz and tourmaline. The grain as a whole is inside the overgrowth that surrounds it on 3 sides. The letter **S** and arrow point to the uneven surface of contact along the base of the quartz grain.

(E) Close-up of grain boundary seen in **D** (above). Notice that there is a gap between the quartz grain above and the tourmaline grain below (arrows point to the ends of the gap labeled **Sty** that runs from the dark spot pointed to in **D** [above] labeled **S** to the far left side of the gap where it terminates against the tourmaline overgrowth). The contact between the two grains leaves a jigsaw-puzzle-like surface of salients and recesses that can be fitted together. The unevenness of the contact is strikingly similar to the surface of macroscopic stylolites, and the fact that the surfaces are clean at the contact and pulled apart suggests that they might have been formed by dissolution. The foreground of the image shows a fractured and uneven surface that looks different from that at the contact surface. Probably this foreground surface was broken away during sample preparation. Other evidence of a pressure-solution origin for this feature is discussed in the text.

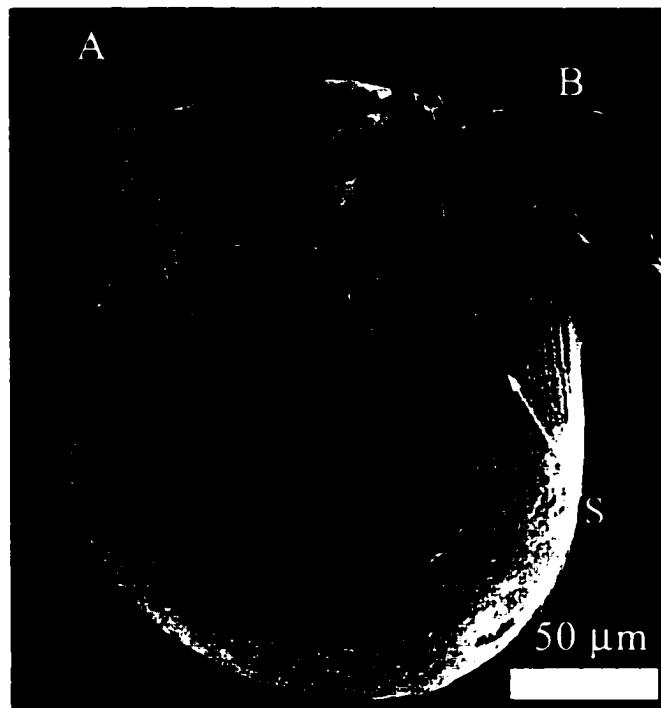
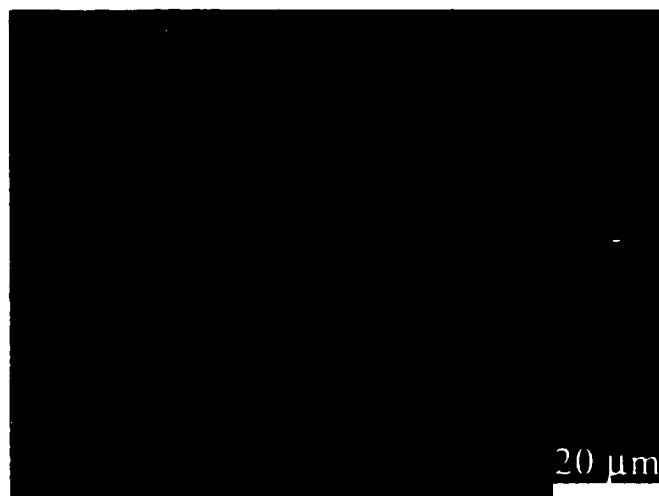
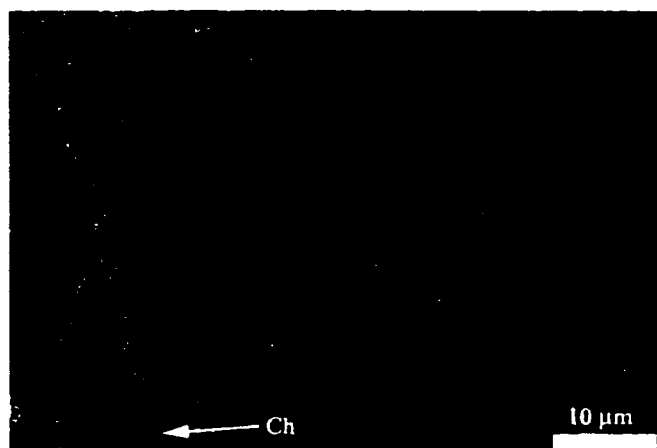
(A)**(B)**

Figure 4.12—Continued

(C)



(D)

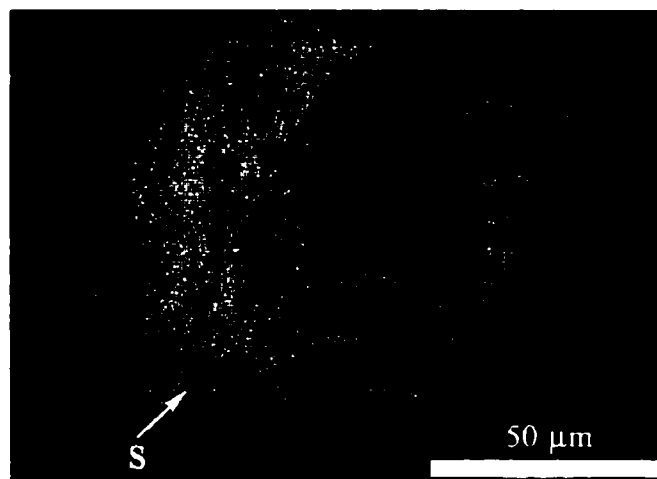
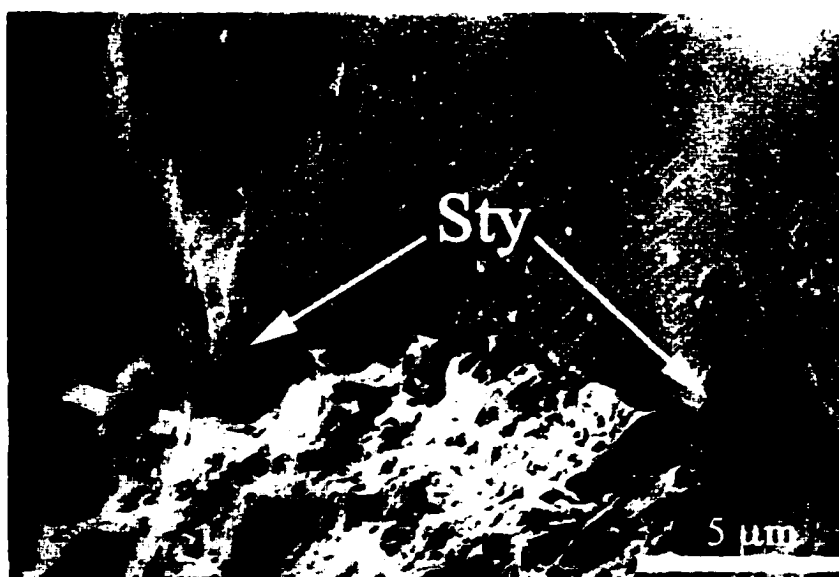


Figure 4.12–Continued

(E)

of evidence support the idea that the tourmaline is in situ or only slightly resedimented.

SEM micrographs of this sample reveal part of the reason why broken grains may appear hackly or splintery. Close-up images reveal that the overgrowths are made of bladed parallel sheaths of crystallites (Figure 4.12). The crystallites' relationship to the detrital cores can be likened to the way feathers grow on a bird, small blade-like crystallites growing parallel to each other. Occasionally, some portion of either the detrital core or a growing end of a crystallite may be interfered with by an obstruction and fail to grow. This leads to channels or voids forming between the parallel crystallites (Figure 4.13)

Vanadium is low in these samples; vanadium in the overgrowths averages 0.14 weight %, and the maximum found in an overgrowth was 0.42 weight % V_2O_3 .

On the diagrams of Henry and Guidotti (1985), the overgrowths plot in a tight cluster in field 4 on Al-Fe-Mg diagrams (Figure 4.14). Analysis of individual zones shows that the zones are homogeneous and chemically distinct from each other; fluctuations of Fe and Mg are responsible for the zones (Figure 4.9). Detrital cores plot in fields 3 and 6 on Al-Fe-Mg diagrams.

Nedrow

Sand was extracted from the basal Onondaga limestone by dissolving it with warm hydrochloric acid. It contained tourmaline with small, strongly abraded overgrowths. Overgrowths occur on ~32% of tourmaline grains, but tourmaline only makes up ~14% of the detrital heavy mineral suite. Several of the grains examined are quartz and tourmaline composite grains.

Figure 4.13. Tourmaline overgrowth displaying pores. This sample is from the Crandall Estate Well #1, taken from a core at 4,999 ft (1524 m).

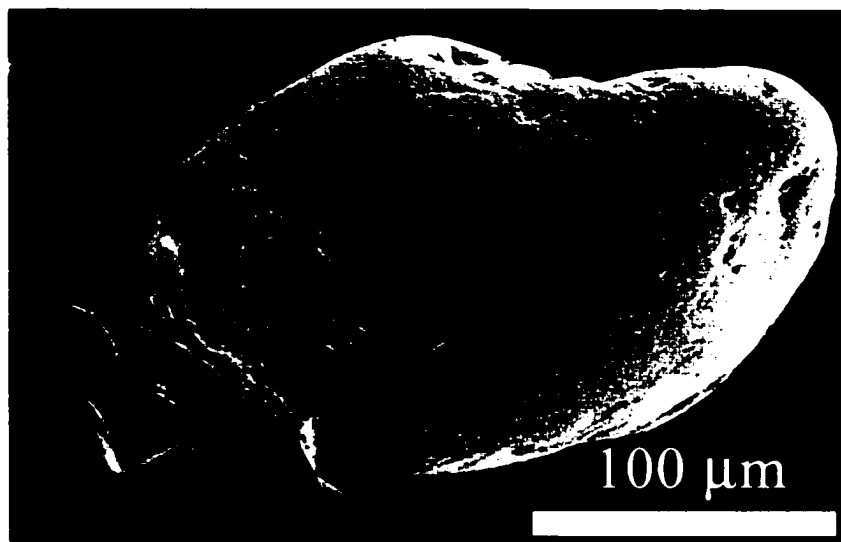
(A) Tourmaline grain with overgrowth. The c-axis is oriented toward the lower left corner. The grain is broken, so that the internal structure is visible in a section that is oriented at a slight angle to the c-axis. The inner outline of the detrital core with a rounded outline is visible in the overgrowth; however, this core is still overgrown by authigenic tourmaline that has a splintery appearance. The outer part of the overgrowth does not have this splintery texture, but a parallelism of subcrystallites gives a striated appearance to the overgrowth

(B) Close-up of **A**. Several features visible on this overgrowth have been observed on other grains from other locations. Cavities or pores in the grain are well illustrated in this example. The external pores visible on the right side of the photograph can be seen to have an elongate and tubular appearance. These are suspected to be exactly like internal pores. Internal pores are more common and occur throughout the zone of roots, near the detrital core, and to a lesser extent farther from the core as in region A indicated in this photo.

(C) Close-up of region A in photograph **B** above. The cavities intercepted by the break in the overgrowth are sliced obliquely in this section. They intercept at an angle that is close to parallel to the c-axis. The letters A, B, and C indicate small, separate crystallites that have grown in the plane just above the plane that contains the pores. The pores are rectangular cavities that are conjectured to resemble the external pores labeled in photograph **B** above.

(D) Close-up of a portion of the internal area of the overgrowth. This photograph shows a region of the overgrowth that is very close to the detrital core in the zone of roots. Note that the acicular to bladed subcrystals in this region are much more numerous than in portions of the overgrowth that are farther from the detrital core. It is believed that the failure of some portions of the core to allow nucleation leaves regions of open space between the crystallites that become pores as surrounding crystallites elongate.

(A)



(B)

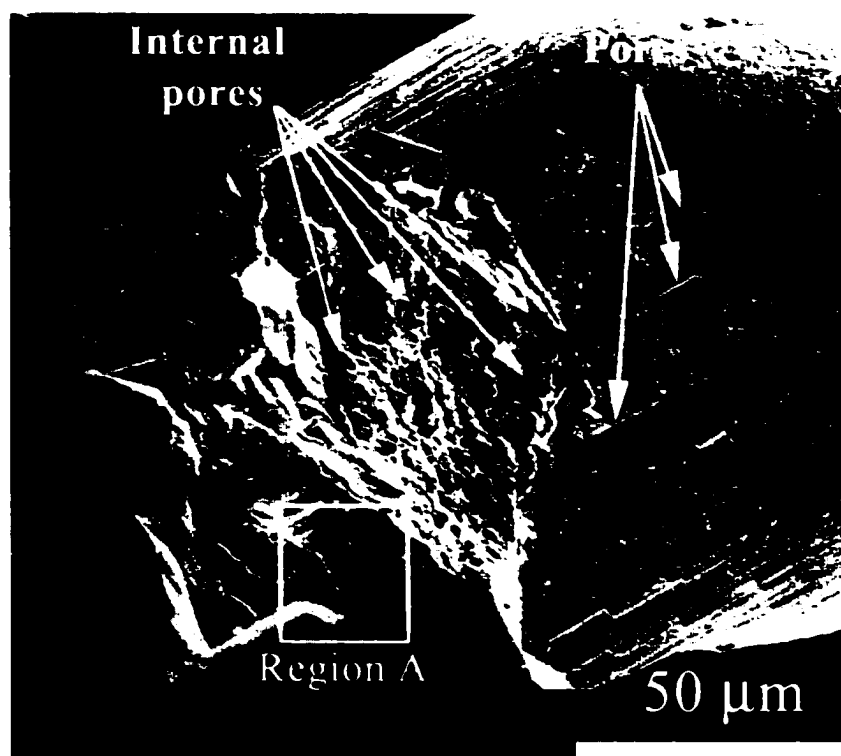
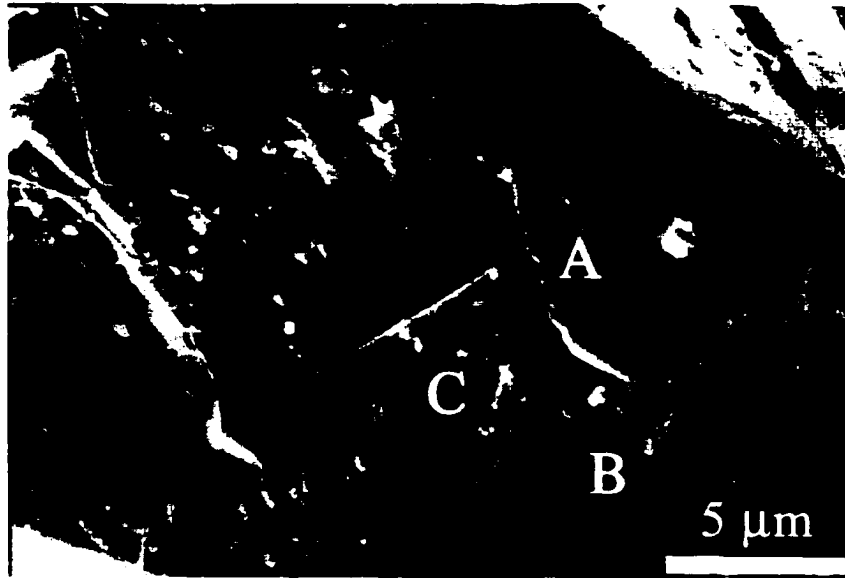


Figure 4.13–Continued

(C)



(D)

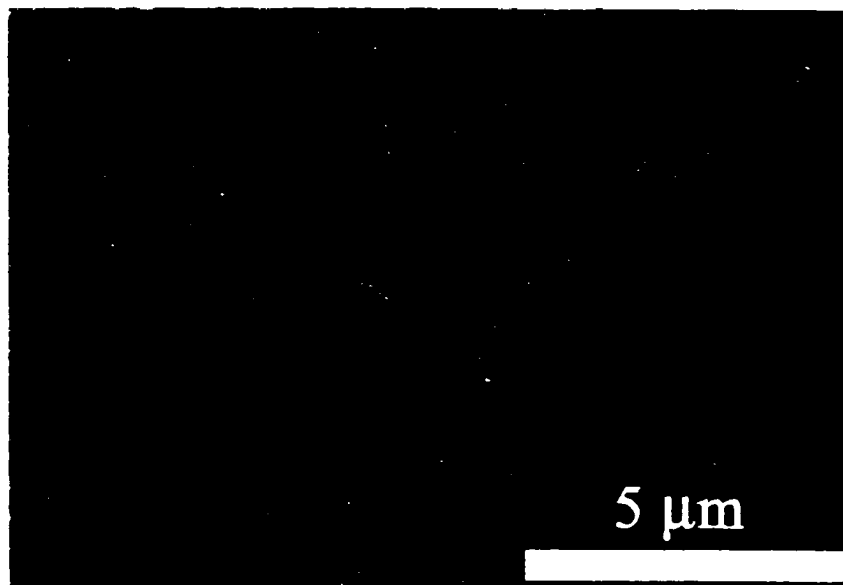


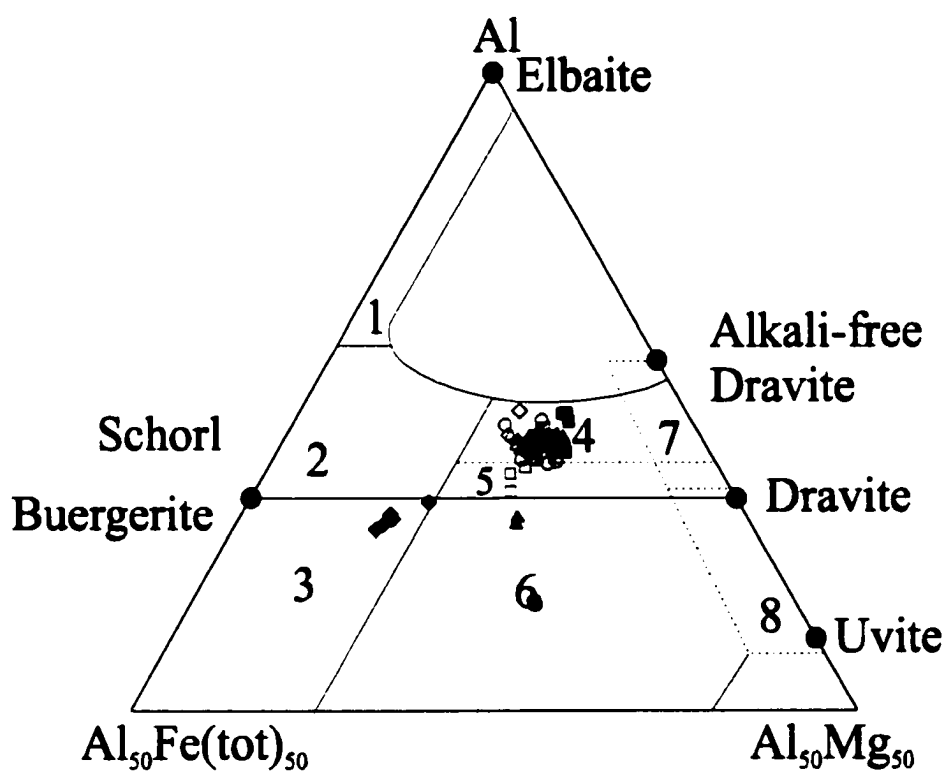
Figure 4.14. Tourmaline Al-Fe-Mg ternary diagram for samples from the Crandall Estate Well #1. This sample was taken at a depth of 4,999 ft (1524 m) from the East Independence Field, Allegany County, New York.

(A) Tourmaline overgrowths on both diagrams **A** and **B** plot predominantly in field 4. The tendency for all overgrowth analyses from this sample to plot within field 4 suggests that the rock coexisted with an Al-saturating phase (Henry and Guidotti, 1985). In some samples from New York much greater variation occurs in the overgrowths due to zoning, but they typically start by plotting in field 4. Samples from Maryland and West Virginia also plot in this same field, suggesting that a very similar environment of formation was involved in all of the overgrowths' genesis.

(B) Several of the grains were analyzed for boron as well as the usual heavier elements in most analyses. The coincidence of points on both normal and boron analyses corroborates that there is no problem with plotting data in the normal low total analysis.

The petrogenetic fields for the Al-Fe-Mg ternary diagram shown are as follows (after Henry and Guidotti, 1985): (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe³⁺-rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe³⁺-rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr- and V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

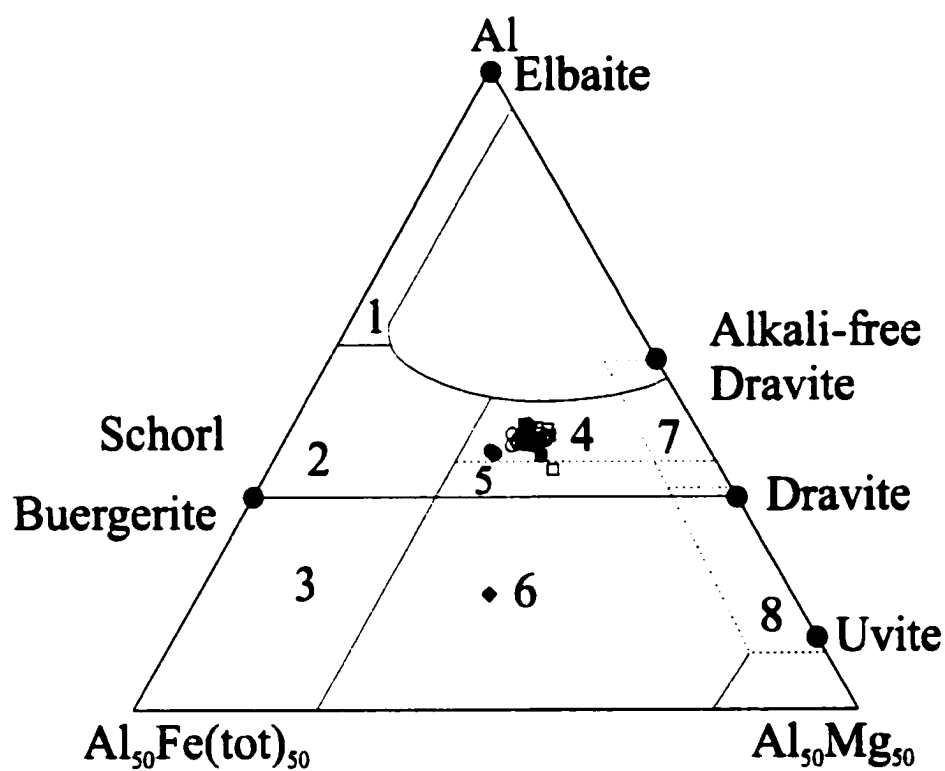


Core Overgrowth

▲	△	= Crang6
◆	◇	= Crang5
●	○	= Crang4
■	□	= Crang3

Figure 4.14—Continued

(B)



Core Overgrowth

◆	◇	= Cranboron3
●	○	= Cranboron2
■	□	= Cranboron1

The overgrowths have a hackly to patchy appearance, with a maximum length of around 60 μm , and the smallest is about 10 μm (Figures 4.3D and 4.15). SEM images reveal that several isolated prismatic elongations are present, giving the hackly appearance described from locations with abraded overgrowths. The prisms of authigenic tourmaline appear quite delicate. They show a maximum of 2 diffuse zones, and many have no zoning. Many of the detrital cores have small fractures, but some of these could have been caused by polishing.

The inner zone is lighter in BSE, and the outer zone, which is usually smaller, does not have a sharp or clearly distinct boundary (Figure 4.15). The zones are the result of decreasing Fe and increasing Mg from the detrital core to the overgrowth. The outer zone can have practically no Fe and plots as a dravite. The Fe in the overgrowths drops from about a maximum of 5 weight % to below detection limits, while Mg varies from around 8.5 weight % to about 12 weight %.

Vanadium is quite high in these samples; vanadium in the overgrowths is on average greater than 1 weight % and is as high as 2.5 weight % V_2O_3 .

On Al-Fe-Mg diagrams, most of the overgrowths plot in fields 5 and 7, with several plotting in field 4 or on the border between 4 and 5 (Figure 4.16).

Detrital cores plot predominantly in field 6, with one plotting in field 3 on Al-Fe-Mg diagrams.

Oriskany Falls

This sample contains the finest examples of euhedral tourmaline overgrowths found in the Oriskany Sandstone (Figure 4.1). Some slightly abraded grains are also

Figure 4.15. Tourmaline grains from Nedrow, New York. The tourmaline has small overgrowths that appear hackly and abraded.

(A) SEM image. The protrusions are all tourmaline growth that shows some possible crystal faces. The sample with many small stubbly protrusions shows an unusual elongation of the grain; if tourmaline is aligned parallel to the c-axis then the elongation of this grain is at right angles to C.

(B) Tourmaline with very small acicular needles that give the grain a hackly to splintery appearance.

(C) BSE Image. The arrow points to the dark outer zone of the grain. Note that judging by the amount of the circumference of the grain that is overgrown, the original overgrowth must have been much larger than what remains.

(D) This grain appears to show the splintery type of overgrowth protrusion shown in **B** (above). Arrows point to the dark outer zone of the overgrowth. This outer zone is somewhat irregular and indistinct.

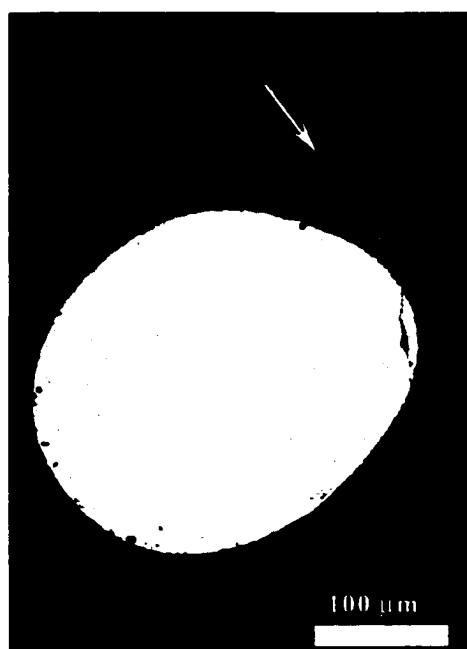
A.



B.



C.



D.



Figure 4.16. Tourmaline Al-Fe-Mg ternary diagram for samples from near Nedrow, New York.

These tourmaline grains were separated from a sandy limestone at the base of the Onondaga Limestone and were highly abraded. The grains typically only have two diffuse zones that appear to be reflected in the drawn-out pattern, rather than clustering, of the analyses.

On Al-Fe-Mg diagrams, most of the overgrowths plot in fields 5 and 7, with several plotting in field 4 or on the border between 4 and 5. The regions in which the overgrowths plot are fairly typical of samples from New York, where the pattern of depletion of the overgrowth with respect to Fe from the inner part of the overgrowths to the outer zone is commonly seen.

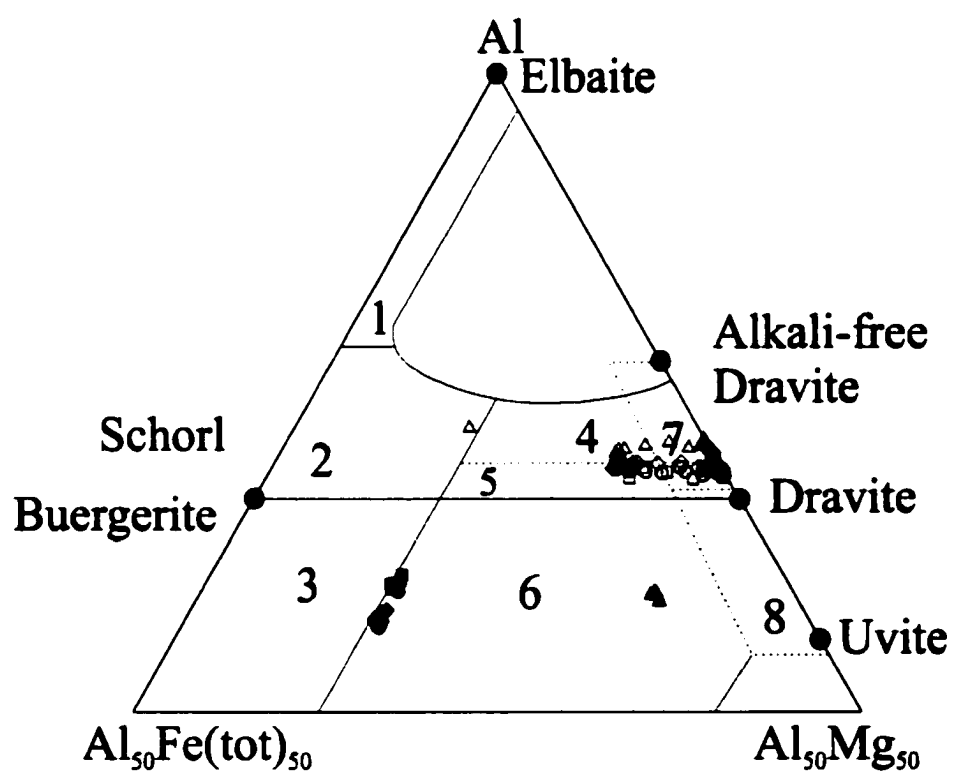
The outer zone points plot in field 7, the field for rocks formed in Cr, V-rich metasediments, and in fact these samples have one of the highest concentrations of V found; V_2O_5 reaches 2.5 weight % in overgrowths and Cr_2O_3 levels of up to 0.4 weight % in several overgrowths.

There are replicate analyses on the diagrams **(A)** and **(B)**. Nedg2 (diagram **A**) was done at Rensselaer Polytechnic Institute and is replicated by Nedamnh 3 done at the American Museum of Natural History (diagram **B**). The same is true of Ned1 and Nedlamnh. Ned1transect 2 is a second analysis of Ned 1. These replicate and duplicate analyses give some assurance that the data are reproducible within the precision of analysis in separate laboratories.

Detrital cores plot predominantly in field 6, with one plotting in field 3 and one in field 2. This suggests a mixed provenance of granitic and metamorphic source rocks.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

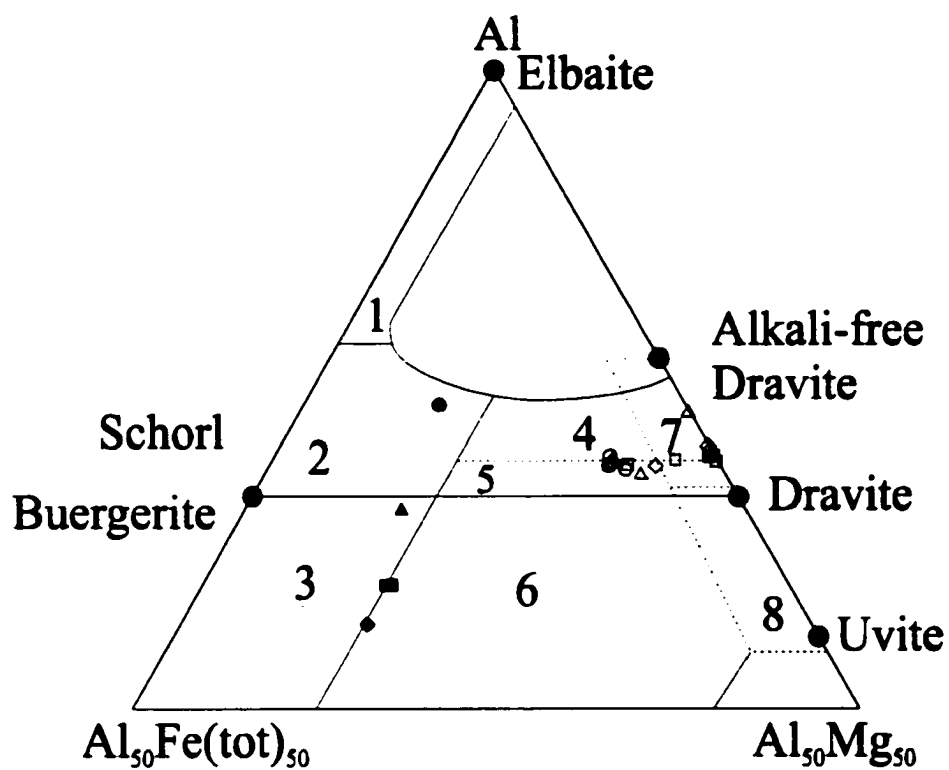


Core Overgrowth

▲	△	= Nedg3
◆	◇	= Nedg2
●	○	= Nedltrans2
■	□	= Nedl

Figure 4.16–Continued

(B)



Core Overgrowth

▲	△	= Nedamnh4
◆	◇	= Nedamnh3
●	○	= Nedamnh2
■	□	= Nedamnh1

present. The detrital core grains are typically very well rounded and spherical, but overgrowths also are present on some broken grains found in this location. Overgrowths often terminate with a sharp, straight boundary, and many have what appears to be pointy crystal terminations. A few overgrowths may be slightly abraded. Tourmaline overgrowths occur on ~90% of the grains, and tourmaline makes up ~59% of the detrital heavy mineral suite.

The overgrowths show up to 8 zones in BSE, though typically there are around 6 resolvable zones (Figure 4.17). Some of the innermost zones show a zigzag pattern that is very different from the more ordered external zones, and it is difficult to analyze these without overlapping on several small zones (Figure 4.18).

Microprobe analysis reveals that the outermost zone present on some grains is almost pure dravite and deficient in Fe (Figure 4.19). All inner zones seem to have around 8 weight % FeO, fluctuating between 6.5 to 9 weight %. Several samples from other locations exhibit similar fluctuations, but Oriskany Falls samples' pattern of rapid Fe depletion in the outer zone is more abrupt than in other samples.

Several of the tourmaline grains have overgrowths attached to quartz grains. In this instance, a relationship seems to be apparent; in one example a quartz grain has a clearly defined overgrowth, and it appears that the tourmaline is engulfing the quartz overgrowth; in another incidence a tourmaline overgrowth grows into an open space in a quartz grain that does not have a quartz overgrowth on it, suggesting the tourmaline formed before quartz authigenesis. This seems to argue for the paragenetic sequence of quartz authigenesis being either pre-overgrowth or contemporaneous with tourmaline

Figure 4.17. Transect of zoned tourmaline from Oriskany Falls, New York. Tourmaline overgrowths from Oriskany Falls have up to 8 well-defined zones visible in BSE (this is grain of lg2).

The line of the transect is shown on the BSE micrograph in red (position indicated by arrow with open circle at starting point). There are 8 zones in the BSE image and microprobe transect of 104 microns; zones 1 and 2 are zigzag zones (described in the text) and were difficult to analyze. Note the fluctuations of Fe and Mg cause changes in brightness in the BSE image. Brightness is related to atomic number contrast in the micrograph. Zone 2 is one of the darkest zones; a small increase of Mg above Fe occurs on the graph. Zone 3 is the brightest zone, and it contains 9.7 weight % FeO. Fe drops to near zero in the outermost zone. Zones 5, 6, and 7 are difficult to see because there is only a little contrast, but close-up inspection shows they are bright. These 3 zones have relatively stable Fe and Mg contents, and fluctuations in V and Al may cause the BSE zoning. The highest value of V is reached in zone 5 and is 1.5 weight % V_2O_3 . Note how in zone 6 V drops off, reaching 0.56 weight % V_2O_3 . Zone 7 is typical of overgrowth tourmaline from this locality. Mg rises while Fe drops to near zero; V is 0.4 weight % V_2O_3 . This nearly pure outer zone typically plots on Al-Fe-Mg diagrams along the tie-line between alkali-free dravite and dravite.

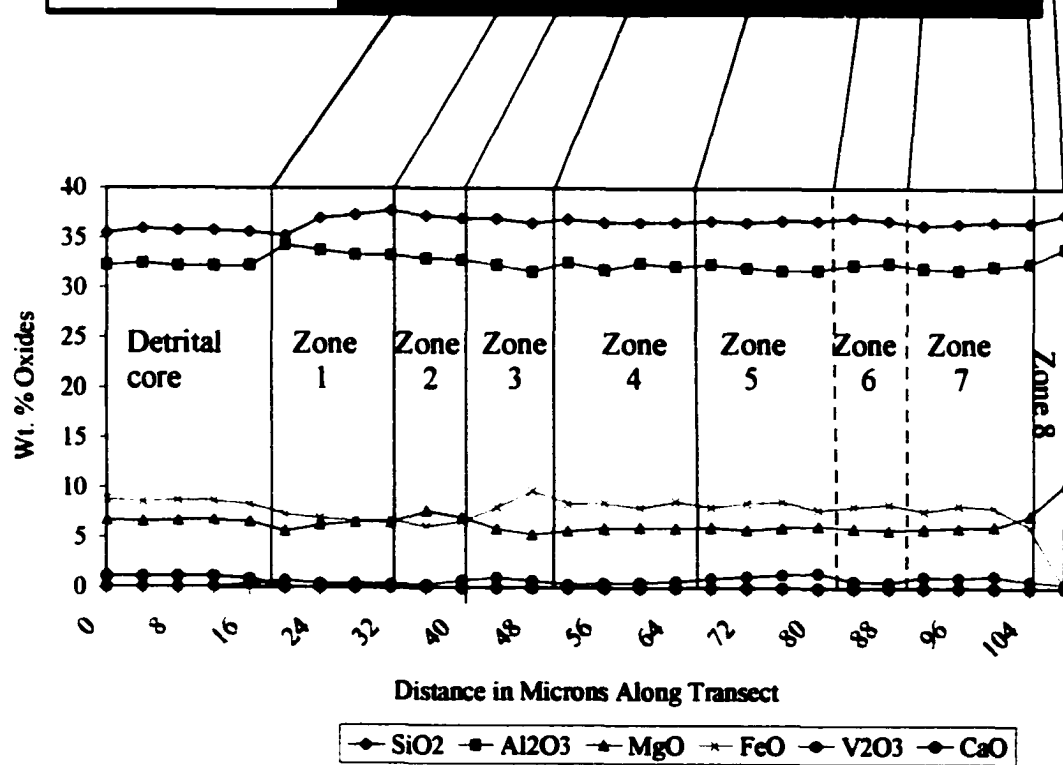
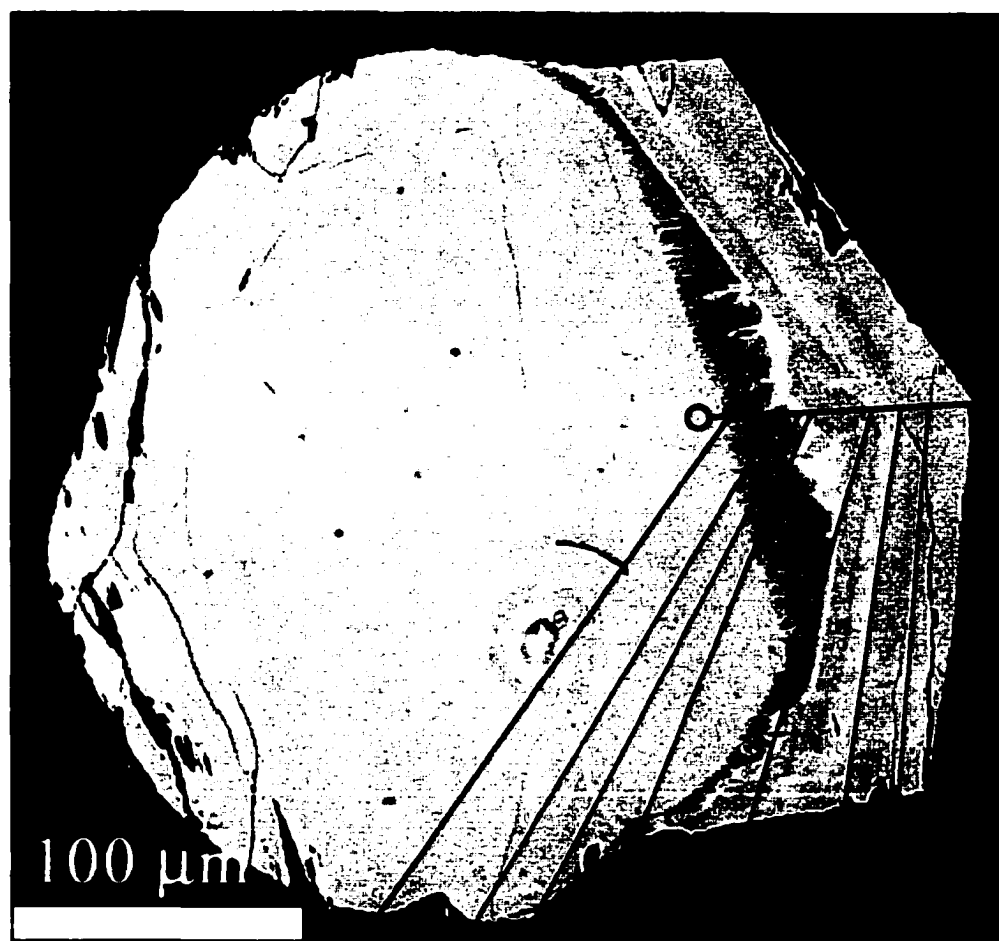


Figure 418. Interior zigzag type of zoning in tourmaline overgrowths. These two grains are from Oriskany Falls, New York, the only locality with overgrowths that displays this type of zoning.

(A) The zigzag pattern is very well developed in this grain with a minimum of 4 zones involved (arrow).

(B) This grain shows the pattern, but it is less prominent with at least 3 zones involved. This type of zoning is fairly common at Oriskany Falls, but is unknown at other locations. Following the initial zigzag interior zones (arrow), exterior zones become much more regular with usually only a single deflection point in the zones that is formed by termination of the crystal during growth.

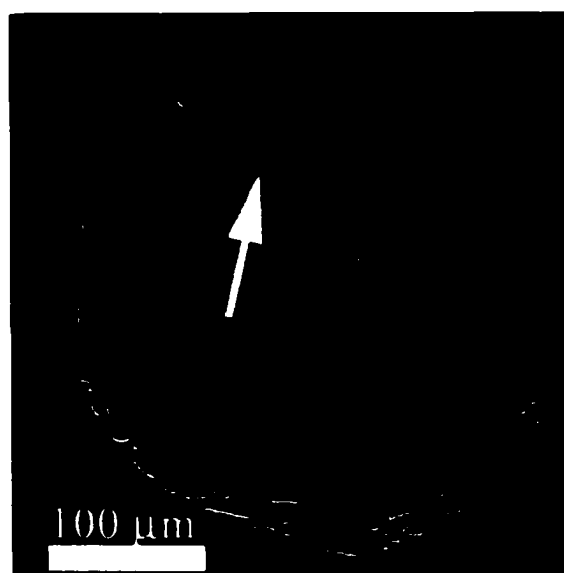
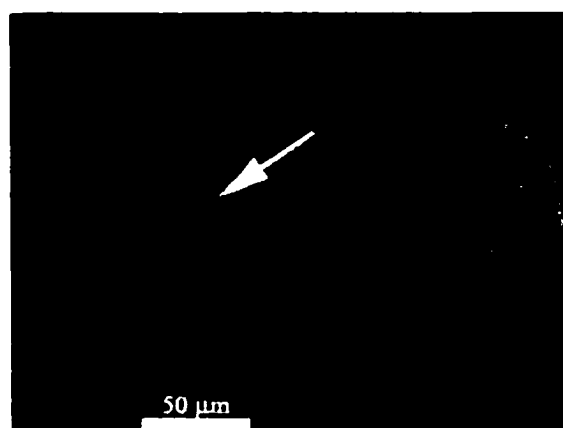
(A)**(B)**

Figure 4.19. Transects parallel to zones of overgrowth from Oriskany Falls, New York.

(A) This overgrowth has 8 well-defined zones visible in BSE (this is grain of gl). A microprobe transect subparallel to the c-axis and 3 small transects parallel to the zones were made as indicated by red lines with labels.

(B) It is interesting to note that the clusters of points for the 3 zones apparently reflect the extremes of the compositional variations and that most of the transect points from the c-axis parallel transect plot in the same positions (so main points are hidden) as the 3 individual zone transects. Points from the inner zone 1 (blue dots) have an intermediate FeO content and lower V_2O_3 (average 6.8 weight % FeO; average 0.23 weight % V_2O_3 [n = 10]) compared to zone 2 (purple dots) that is iron rich and has higher V_2O_3 (average 8.5 weight % FeO; average 0.77 weight % V_2O_3 [n = 28]) and zone 3 that is iron poor and has intermediate V_2O_3 content (average 2.1 weight % FeO; average 0.35 weight % V_2O_3 [n = 23]).

That the sample's V_2O_3 fluctuates up and down indicates that there is probably a discontinuous source of V, as there appears to be for Fe and Mg, but because zone 2 has the lowest V and an intermediate Fe concentration, a clear relationship between V and other constituents supplied cannot be made.

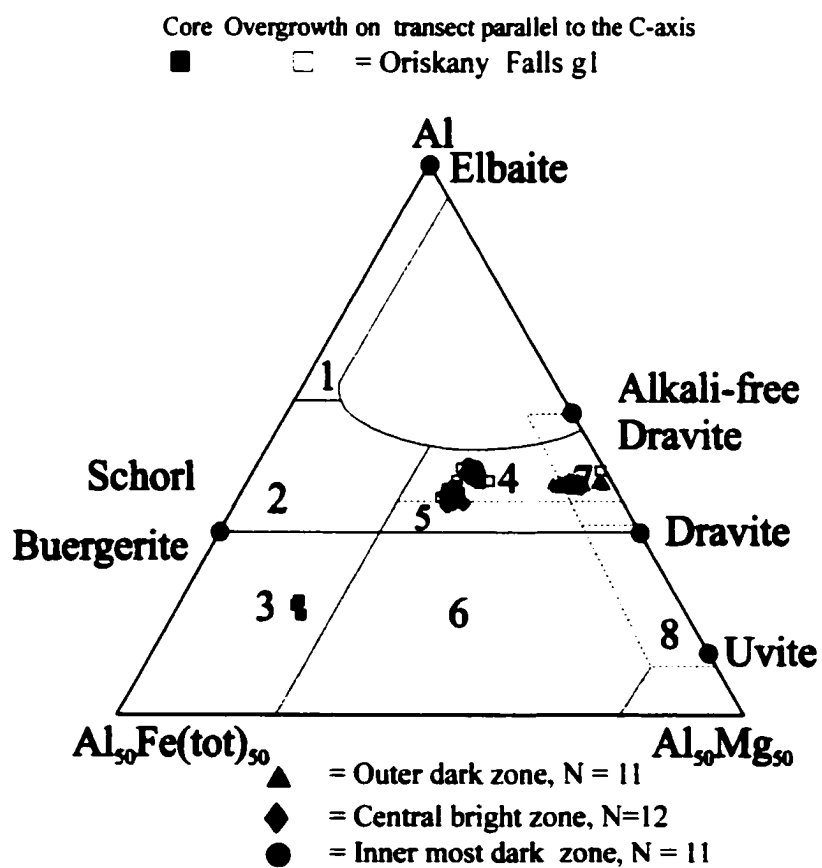
The final zone seems to have an exterior portion that is probably iron-poor that was only intersected by one analysis on the parallel to c-axis transect (outermost red square on the dravite to alkali-free dravite tie-line). It is also clear from this example that even tourmaline that plots in fields 4 and 5 can have some V. This suggests that V should be analyzed for on all authigenic tourmaline no matter what field it plots in.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammities coexisting with an Al-saturating phase, (5) metapelites and metapsammities not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)



(B)



overgrowth formation (Figure 4.20) However, it should be cautioned that since these composite grains survived crushing, it is possible they could survive brief reworking.

Vanadium is moderately high in these samples; vanadium in the overgrowths is on average greater than 0.7 weight % and as high as 1.6 weight % V_2O_3 .

On Al-Fe-Mg diagrams most of the overgrowths plot in fields 4 and 7, with one plotting in field 5 near the border between 4 and 5. The majority of points on transects plot in field 4 and only a few analyses plot in field 7. The field 7 points are all from the outermost zone of growth (Figure 4.21). Transects parallel to zonation indicate that the zones are homogeneous (Figure 4.19).

Detrital cores plot predominantly in field 6, with one core plotting in field 3, one in 5, and one in 8 on Al-Fe-Mg diagrams.

Seneca Stone

Tourmaline overgrowths are abundant, ranging from euhedral to moderately abraded, and show typical characteristic zoning as well as an unusual wavy or sinuous zoning patterns not seen at other localities. Composite overgrowths showing both types of zoning are also present. Tourmaline overgrowths occur on 96% of tourmaline grains, and tourmaline makes up ~77% of the detrital heavy mineral suite.

The wavy zoning appears as curvy or rippled-looking areas of light and darker contrast with more diffuse boundaries than in the more angular and more sharply defined typical zoning seen in other localities. These wavy zones may be totally independent of the linear zones (Figure 4.22); they appear to run in on each other on the same grain. Chemical analysis shows that the zones are moderately homogeneous, but less so than

Figure 4.20. Euhedral tourmaline overgrowths attached to quartz. This sample is from Oriskany Falls, Oneida County., New York.

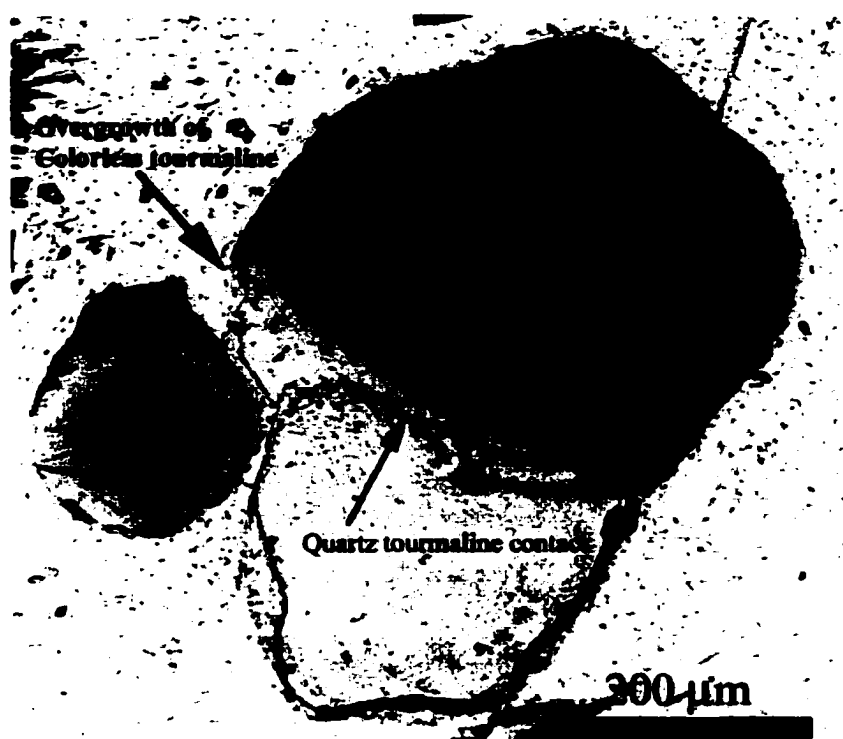
(A) Plane-polarized light micrograph of tourmaline attached to a quartz grain.

(B) BSE image of the same quartz grain attached to a euhedral tourmaline overgrowth. The tourmaline and quartz are strongly fused, and the overgrowths interlock.

(C) A close-up image shows that the detrital quartz grain has a dust line at its contact with the quartz overgrowth (white arrows). The overgrowth exhibits pyramidal terminations that are intersected by the tourmaline. This strongly suggests that tourmaline enveloped an already growing quartz overgrowth, and the paragenetic sequence of quartz authigenesis followed by tourmaline authigenesis is implied.

(D) Another composite grain from Oriskany Falls. Note that this grain has a euhedral overgrowth that is disrupted by a quartz grain and grows into a hollow of that grain (arrow). This suggests that even though there was clearly a pore that was accessible to fluids, no quartz authigenesis occurred. Thus it appears that quartz and tourmaline growth overlapped and that similar conditions were present during the growth of both minerals.

A.



B.

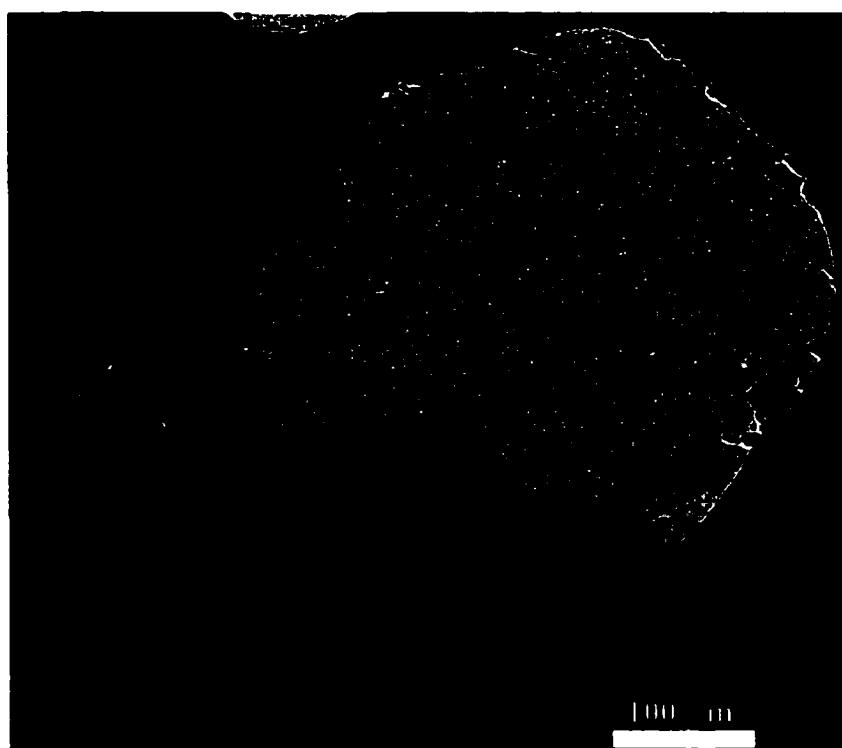


Figure 4.20—Continued

C.



D.

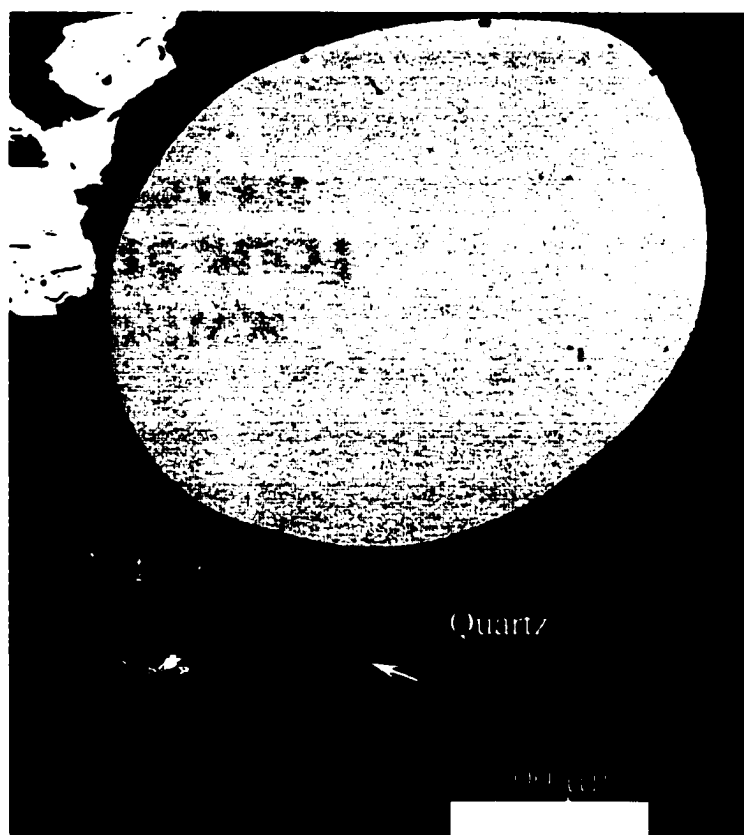


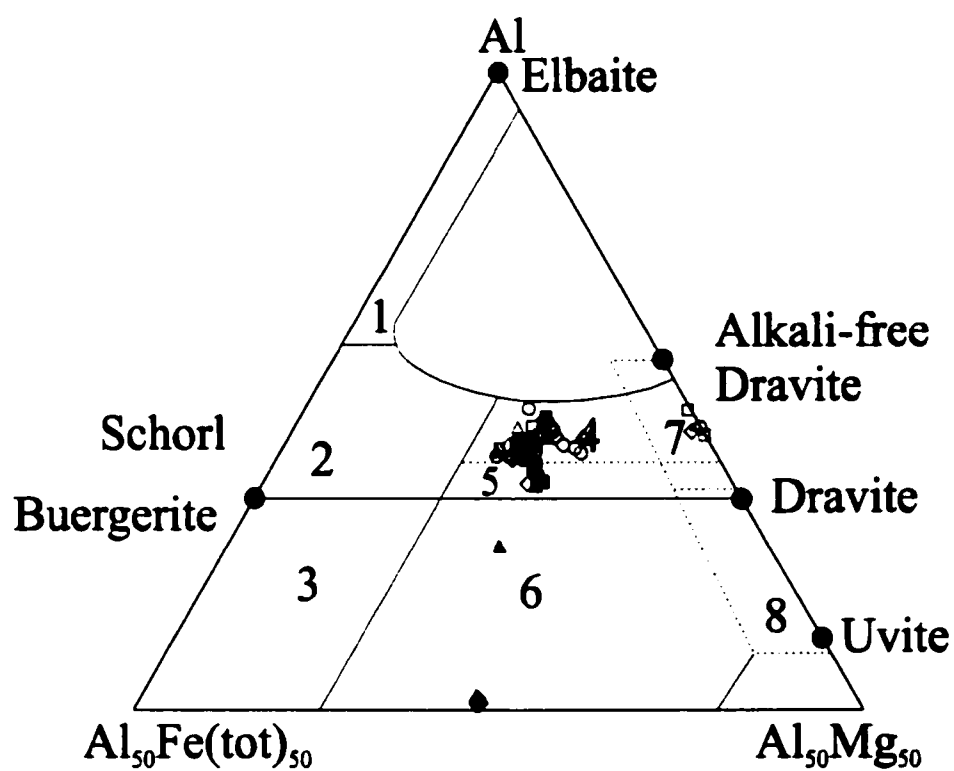
Figure 4.21. Tourmaline Al-Fe-Mg diagram ternary diagram for samples from the Oriskany Falls, New York.

The overgrowths are relatively large, many are over 100 microns in size, and they have up to 8 distinctive zones. This leads to a grains plotting in several fields on Al-Fe-Mg diagrams. Most of the overgrowths plot in fields 4 and 7, with one plotting in field 5 near the border between 4 and 5. Analysis shows that the majority of points on transects plot in field 4 and only a few analyses plot in field 7. The field 7 points are all from the outermost zone of growth, which is a nearly pure dravitic composition that is common at this locality and in several of the other locations in the New York region. Field 7 is the zone of low-Ca metaultramafics and Cr, V-rich metasediments on the petrogenetic diagram, and V in the overgrowths reaches levels of up to ~1.7 weight % V_2O_3 .

Detrital cores plot predominantly in field 6, with one core plotting in field 3, one in 5, and one in 8 on Al-Fe-Mg diagrams. This diversity of compositions of the detrital cores is not surprising because it is believed that the tourmaline detrital cores have been through several cycles of sedimentation due to reworking.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammities coexisting with an Al-saturating phase, (5) metapelites and metapsammities not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

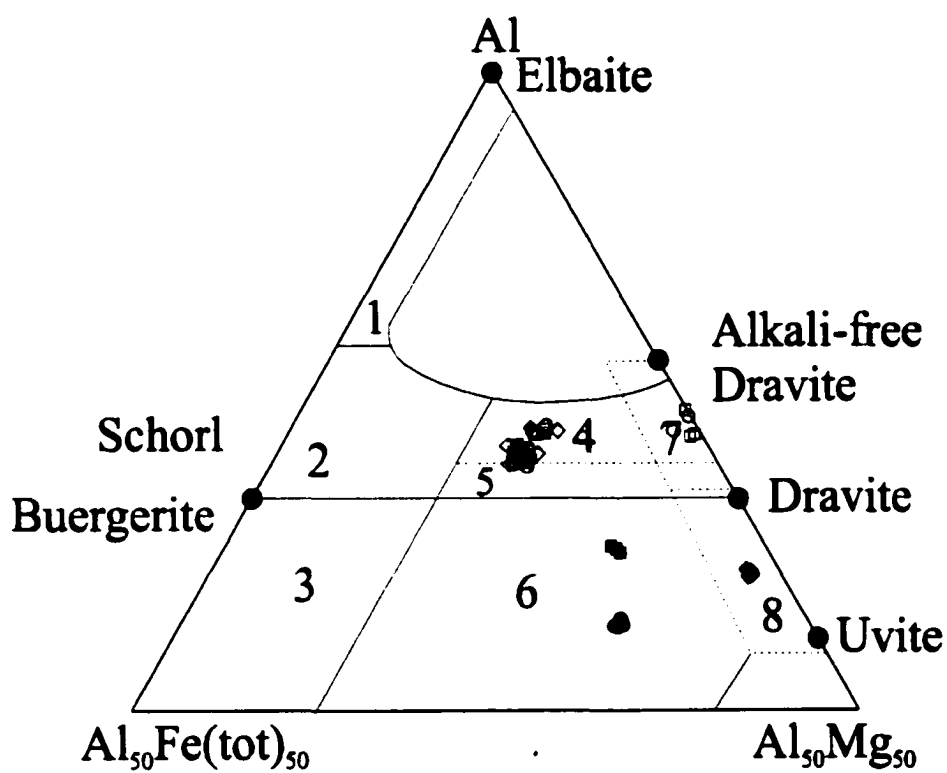


Core Overgrowth

▲	△	= Orf3boron
◆	◇	= Oriskfg3
●	○	= Oriskfg2
■	□	= Oriskfg1

Figure 4.21–Continued

(B)



Core Overgrowth

◆	◇	= Of3c
●	○	= Of2c
■	□	= Of1c

Figure 4.22. Overgrowths from Seneca Stone Quarry, New York.

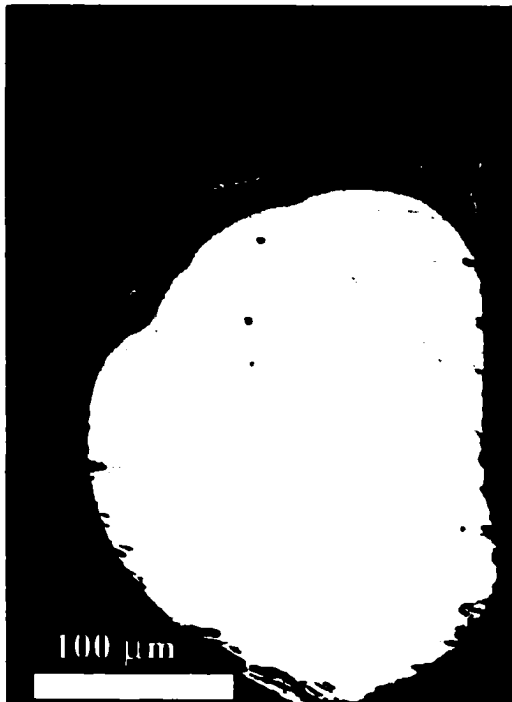
(A) To the right the projecting portion of the overgrowth displays linear concentric zoning, while to the left side the overgrowth displays a sinuous and somewhat blurred type of zoning.

(B) This grain's overgrowth is completely of the sinuous zoned type. The gray area on the left side, Q, is a quartz grain that was engulfed during growth.

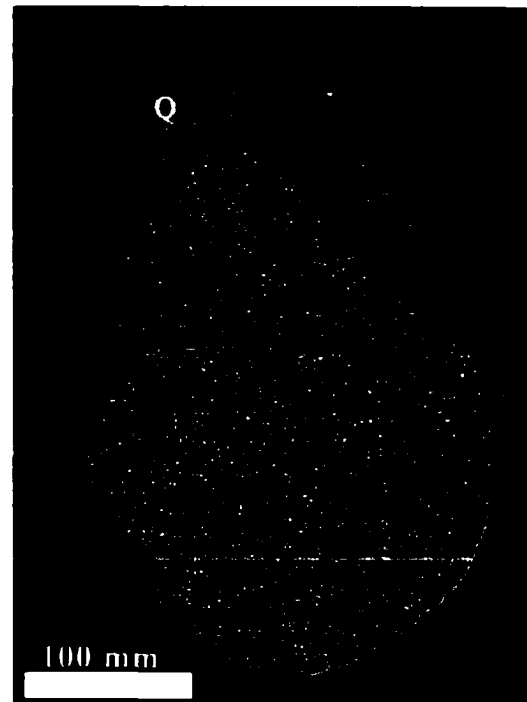
(C) Displays a wavy interior zone followed by concentric straight zones. Sinuous zones to the lower right seem to have traces of the light-dark zoning seen to the left but are very irregular in both shape and width.

(D) A grain that displays straight well-developed uniform zones.

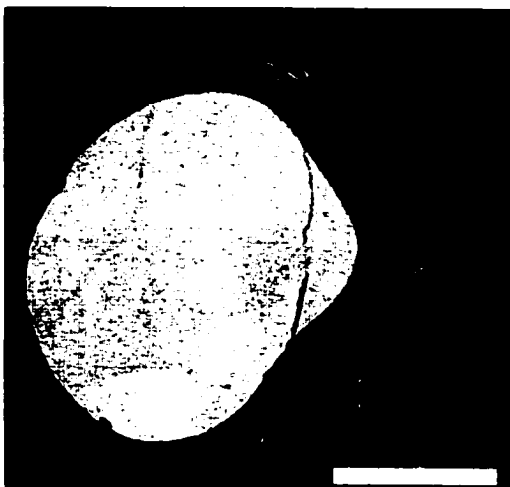
A.



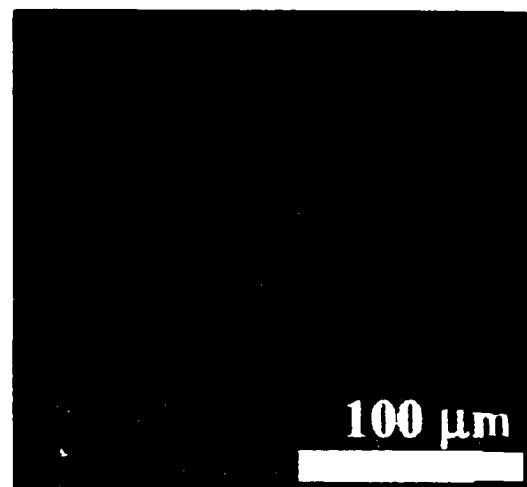
B.



C.



D.



straight-bounded zones found in the same sample.

In many cases the wavy zones appear to occur toward the extremity of the grain, either after a period of normal growth or to one side. However, some overgrowths that appear to grow off of the end of the core grain have only a wavy overgrowth.

In general, overgrowths from this locality display a wide range of numbers of zones, from 2 to 10, with 6 zones of alternating dark and light bands being typical. The number of zones is the greatest observed from any of the localities studied.

Vanadium is present in these samples, but is not particularly high; vanadium in the overgrowths is on average 0.2 weight %, though it can reach 0.67 weight % V_2O_5 .

The overgrowths mostly plot in fields 4 and 7 on Al-Fe-Mg diagrams with a couple of overgrowth analyses on the border with field 5 (Figure 4.23).

Detrital cores plot predominantly in field 6, with a few plotting in field 4.

Skaneateles Falls

Tourmaline from the Skaneateles Falls Carrigan Quarry location contained only small, ragged overgrowths on well-rounded detrital tourmaline. Tourmaline overgrowths occur on ~50% of tourmaline grains, but tourmaline only makes up ~8% of the detrital heavy mineral suite. Detrital tourmalines in the samples were strongly abraded and similar in their physical properties to other locations. Because the overgrowths were very small, and not too abundant, only a limited number of grains were found for analysis.

The overgrowths display 1 to 3 zones in BSE. Zoning in these samples is controlled by fluctuations in Fe and Mg. Generally, a decrease in Fe from interior to the outer zone of the overgrowths takes place, and FeO can drop to near zero in the outermost

Figure 4.23. Tourmaline Al-Fe-Mg ternary diagram for samples from the Seneca Stone Quarry, Seneca County, New York.

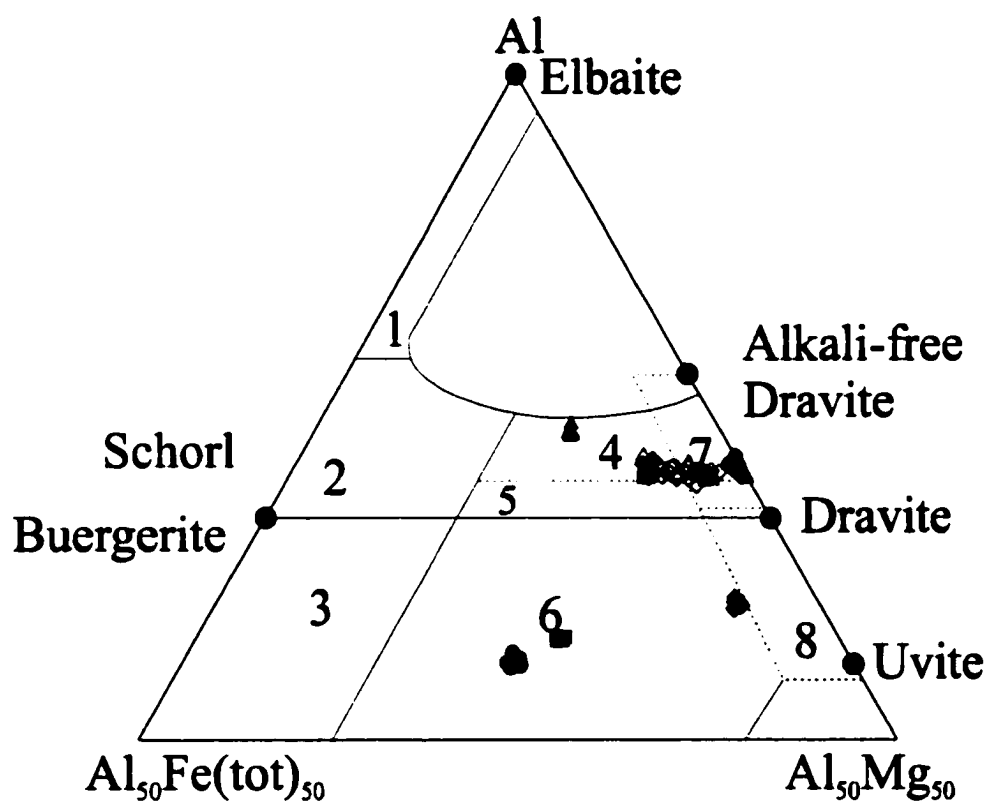
The data are plotted on 3 ternary diagrams for clarity, **A**, **B**, and **C**. The relatively large overgrowth with up to 10 zones plots in a drawn-out area from fields 4 and 7 on Al-Fe-Mg diagrams, with a couple of overgrowth analyses on the border with field 5.

(D) An analysis of the outermost dark zone shows that it is depleted in FeO and plots in field 7 ($n = 19$ points) along the tie-line between alkali-free dravite and dravite. An inner brighter zone is more enriched in FeO, plots in a more drawn-out region along the border with fields 4 and 5, and crosses into field 7. However, this is probably because the zone was a sinuous zone and not a normal sharp zone (see text for details).

Detrital cores plot predominantly in field 6, with a few plotting in field 4, suggesting derivation from metamorphic rocks.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe³⁺-rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe³⁺-rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

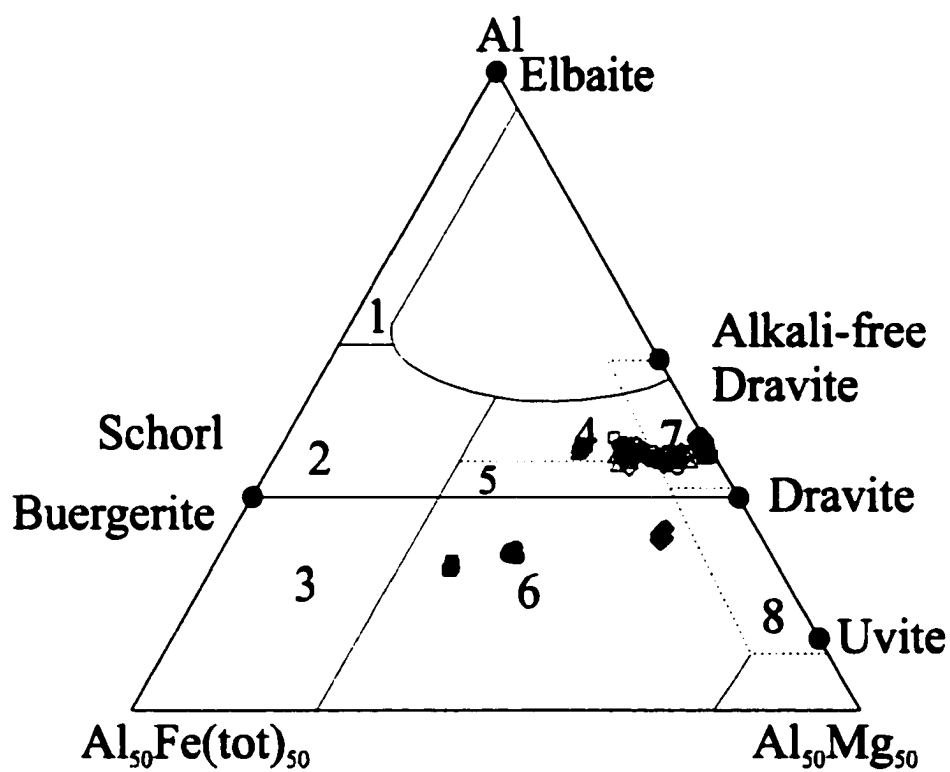


Core Overgrowth

▲	△	= Senlg5
◆	◇	= Senlg4
●	○	= Senlg3
■	□	= Senlg2

Figure 4.23–Continued

(B)

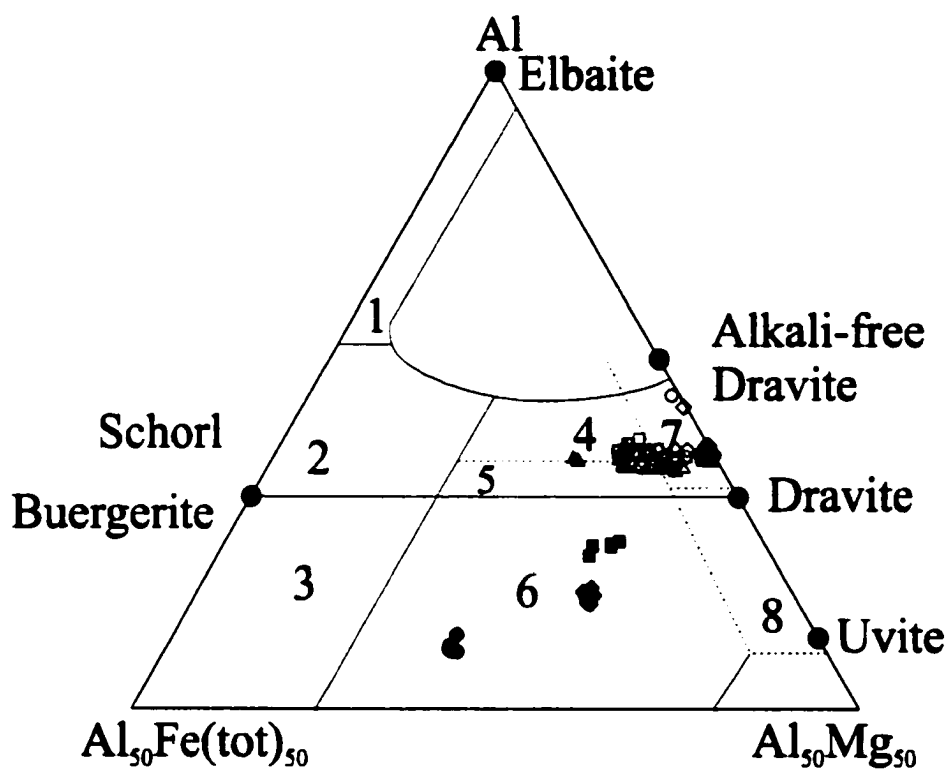


Core Overgrowth

▲	△	= Senlc
◆	◇	= Senlg8
●	○	= Senlg7
■	□	= Senlg6

Figure 4.23–Continued

(C)

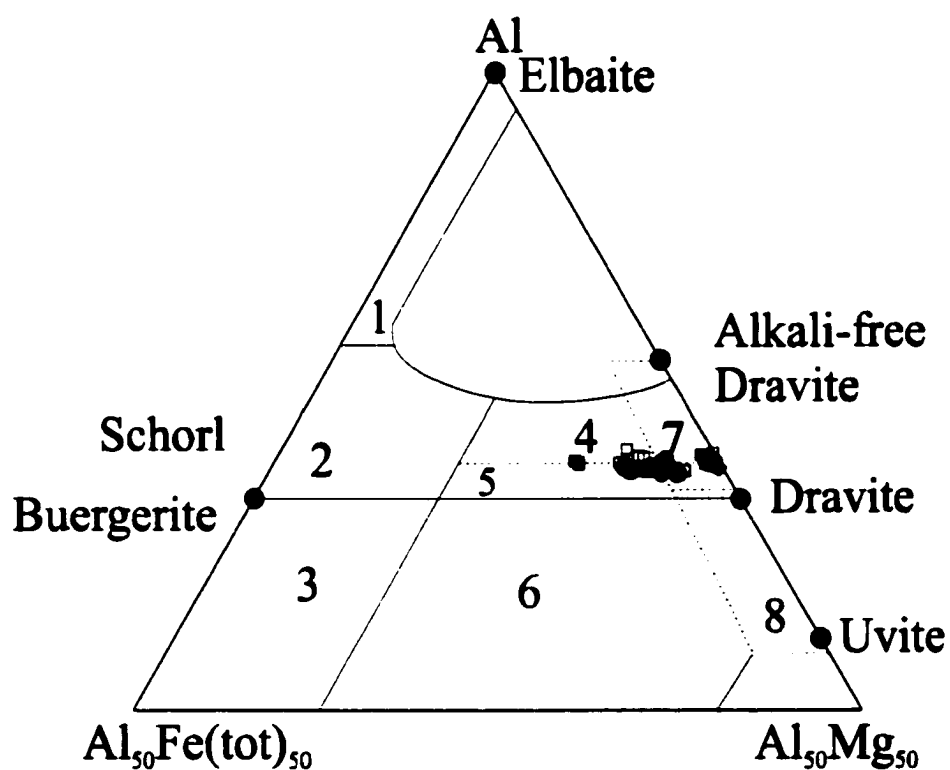


Core Overgrowth

▲	△	= Sen6c
◆	◇	= Sen5c
●	○	= Sen3c
■	□	= Sen2c

Figure 4.23–Continued

(D)



Zones perpendicular to growth

- ◆ = Outermost dark zone, N = 19
- = Innermost bright zone, N = 35

Transect parallel to the C-axis

Core Overgrowth

■ □ = Seneca Stone g6_7-6

zone. This would create a very dark BSE zone on the exterior of the grain.

Vanadium was very low in this sample, averaging less than 0.1 weight %, which is surprising because just about a mile away at the Skaneateles Township General Crushed Stone Quarry Well # 3-9R the level of V_2O_5 is typically over 1 weight % in the overgrowths.

On Al-Fe-Mg diagrams, most of the overgrowths plot in fields 5 and 7 (Figure 4.24). There is a tight cluster of points plotting at the corner between 4, 5, and 7. The field 7 points are all from the outermost zone of the overgrowths.

Detrital cores plot in fields 4, 5, and 6 on Al-Fe-Mg diagrams. Most detrital cores plot in field 6 ($n = 3$ grains), with two cores plotting near the boundary between fields 4 and 5; both grains have some points that plot on or near the boundary on either side and one plotting in field 4.

Skaneateles Township, General Crushed Stone Quarry Well # 3-9R

The sample from the core contained overgrowth tourmaline on ~80% of the grains, and tourmaline makes up 45.5% of the detrital heavy mineral suite.. All of the tourmaline overgrowths observed in this sample are moderately to strongly abraded (Figure 4.25 and 4.26). The overgrowths display 1 to 3 zones in BSE. Quite a few composite tourmaline grains were found, with the overgrowths attached to quartz grains. The composite grains may have equal amounts of quartz and tourmaline. Their combined specific gravities, however, had to be greater than that of the heavy liquid used for the separation (2.89). The contacts between quartz and tourmaline seem to be either formed by compaction or to result from quartz authigenesis, because no obvious growth faces or

Figure 4.24. Tourmaline Al-Fe-Mg ternary diagram for samples from the Carrigan Quarry, Skaneateles Falls, New York.

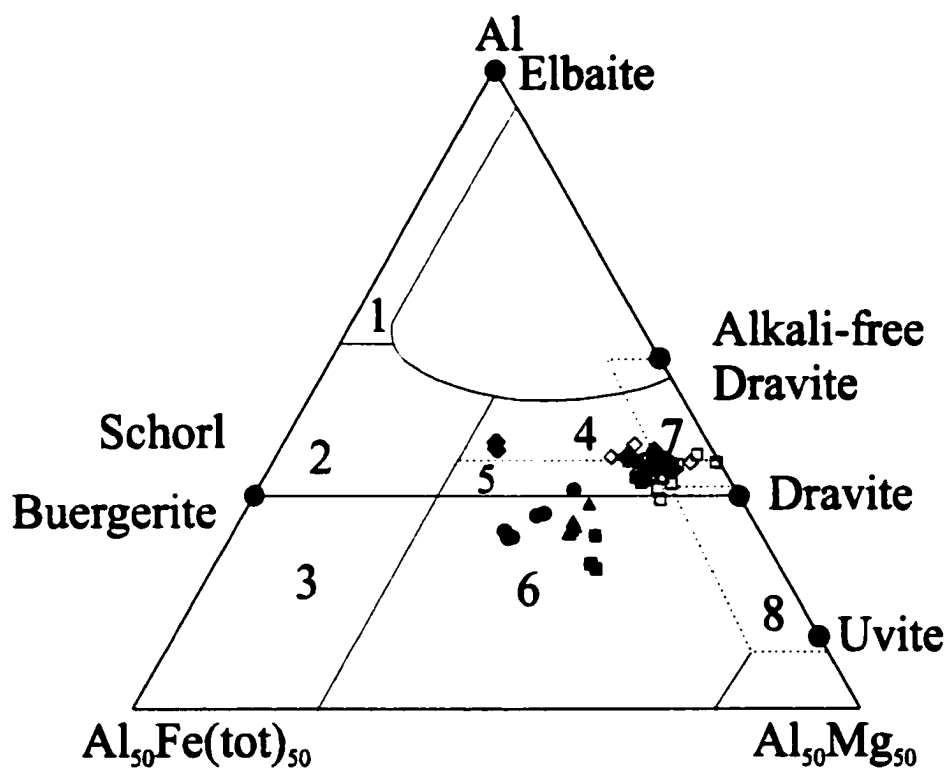
These overgrowths are generally strongly abraded and display 1 to 3 zones. Samples with 2 or 3 zones have points plotting in fields 5 and 7 of the Al-Fe-Mg diagram.

On triangles **A** and **B**, most of the overgrowths plot in fields 5 and 7. There is a tight cluster of points plotting at the corner between 4, 5, and 7. The field 7 points are all from the outermost zone of the overgrowths. This indicates that a general depletion in Fe occurs from the interior of overgrowth to the exterior zone that plots between the alkali-free dravite and dravite tie-line. Interestingly, this sample had very low vanadium values and V_2O_5 only reaches levels of about 0.1 weight %.

Detrital cores plot in fields 4, 5, and 6 on Al-Fe-Mg diagrams. Most detrital cores plot in field 6 ($n = 3$ grains), with two cores plotting near the boundary between fields 4 and 5 (grains Carrigan 2 and 5a); both grains have some points that plot on near the boundary on either side and one plotting in field 4. While grain Carrigan 5a appears to have an intermediate composition that plots on the fields' borders, compositional zoning is suspected in grain Carrigan 2.

The petrogenetic fields for the Al-Fe-Mg ternary diagram shown are as follows (after Henry and Guidotti, 1985): (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr- and V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

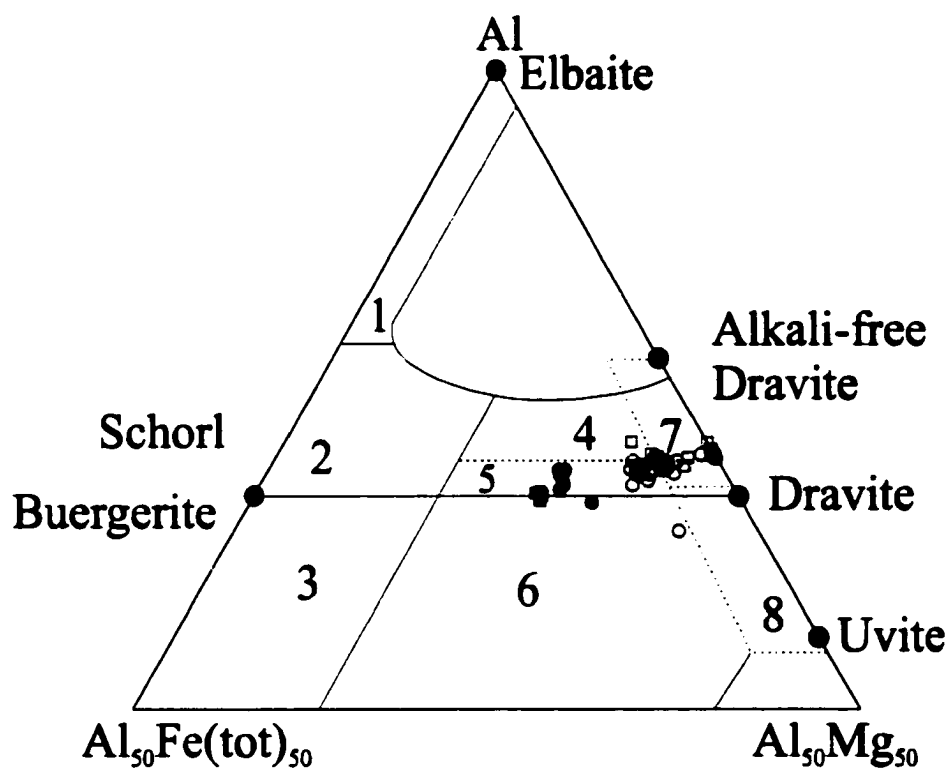


Core Overgrowth

▲	△	= Carrigan4
◆	◇	= Carrigan3
●	○	= Carrigan2
■	□	= Carrigan1

Figure 4.24—Continued

(B)



Core Overgrowth

● ○ = Carrigan5b
 ■ □ = Carrigan5a

Figure 4.25. Tourmaline from a core near Skaneateles Township, Onondaga County. The samples were supplied by the New York State Geological Survey. The core is identified as Hole #2 (2-69) Well no. 3-9R, location latitude 42°-59'-55", longitude 76°-24'-27". The well was drilled on the property of the General Crushed Stone Quarry, and a sample was taken at a depth of 37 feet (11.3 m).

(A) Abraded tourmaline grain. This grain displays splintery texture, and a few pieces of the overgrowth appear to have broken during preparation. Similar splintery grains have been found at other locations, and they appear to displaying an original texture rather than a texture created as an artifact of crushing the sample. The grain displays 3 zones; the inner 2 are well displayed. The bright inner zones can be seen to have covered a greater area on the sides of the grain, but the overgrowth has since been abraded away.

(B) This is a composite quartz tourmaline grain separated from the core. The contact between the overgrowth and the quartz grain is irregular and may be the result of pressure solution, rather than due to growth of either mineral.

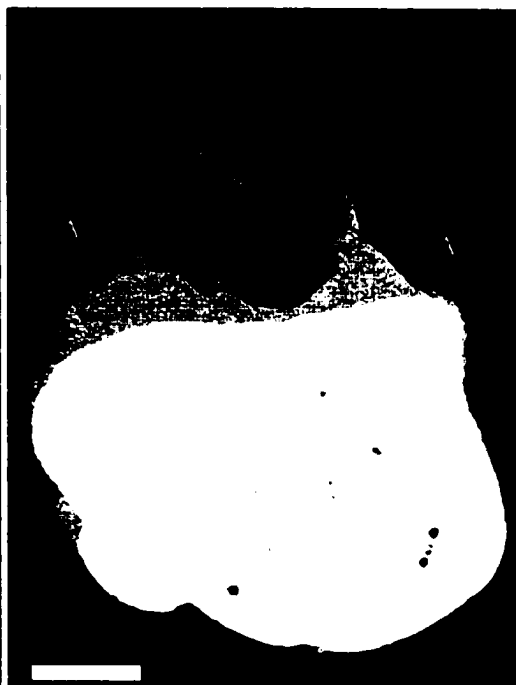
(C) This grain displays a rounded overgrowth. Abrasion is beginning to round the overgrowth, and this grain is beginning to look as if it had been abraded by multicycle reworking similar to that illustrated by Potter and Pryor (1961). Parts of the overgrowth are missing, due to fractures on both the left and right sides of the grain, leaving small isolated portions of the overgrowth to the sides of the main growth.

(D) Another moderately abraded grain displaying a splintery overgrowth. This grain shows only one well-developed zone and two zones that are less clear. There appears to have been a dark outer zone that has mostly been removed by abrasion. Besides the major zone that makes up most of the overgrowth, there may be a small inner zone that is just slightly different in contrast to the major zone and contains small inclusion spaces/cavities that are common in some localities and have been referred to as a zone of roots by Krynine (1946).

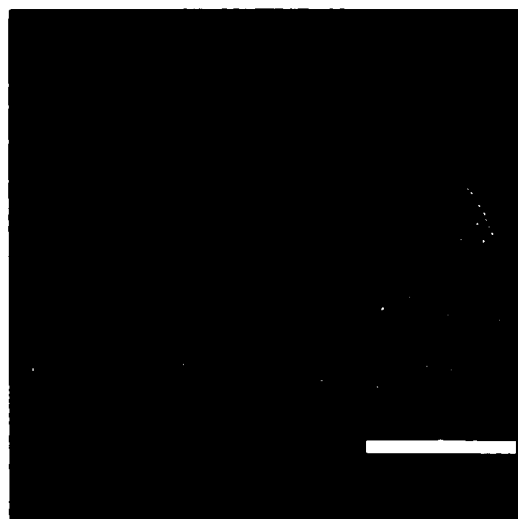
(A)



(B)



(C)



(D)

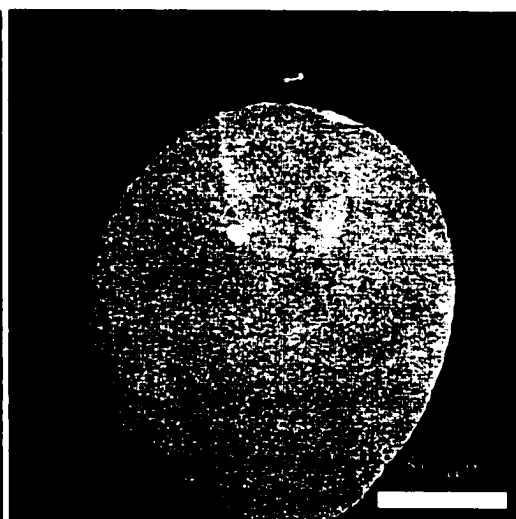


Figure 4.26. Tourmaline from a core provided by the New York State Geological Survey from Skaneateles Township, Onondaga County. The core is identified as Hole #2 (2-69) Well no. 3-9R. The sample is from 37 ft (11.3 m). The condition of tourmaline varies from moderately to strongly abraded.

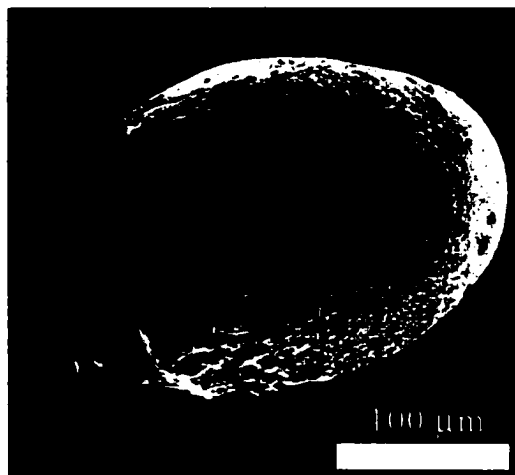
(A) One of the least abraded tourmaline shows a “splintery” fracture. Notice that the individual splinters are flat-sided, and are all oriented parallel to each other. This example has suffered moderate abrasion and loss of overgrowth material.

(B) Abrasion has removed a considerable amount of the overgrowth, and individual elongate splinters have been sheared off to a high degree. Though the grain still shows some indication of the original overgrowth’s extent, it has been highly modified by abrasion.

(C) Strongly abraded grain with only hints that the overgrowth had extended beyond the detrital core. Note that subcrystals or splinters still retain hints of the stage of splintering, but this grain overall does not have a splintery appearance and is beginning to round.

(D) The extent of rounding in this grain’s overgrowth is clear evidence that it suffered strong abrasion after formation. Small amounts of prismatic growth can be seen extending away from upper end of the grain, and a large area bears scarring left after removal of the overgrowth by erosion. Such rounded overgrowths must have been reworked and traveled some distance before redeposition. That grains such as this are found mixed with only moderately abraded grains suggests that a relatively large geographic area provided overgrown tourmaline to the sediment deposited here.

(A)



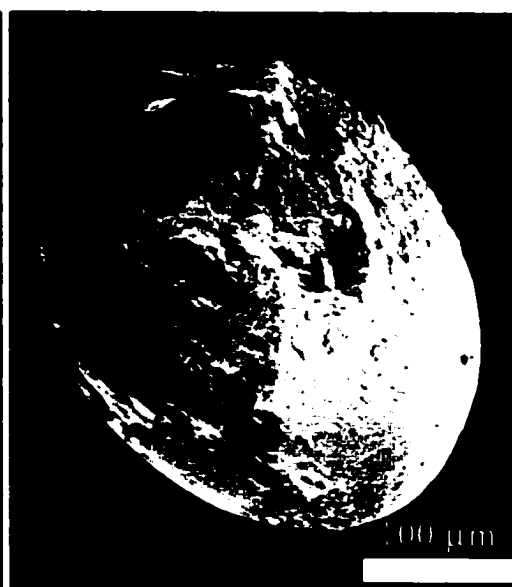
(B)



(C)



(D)



growth zoning patterns can be related to the tourmalines' contact with the quartz grains. It does not appear that the quartz has enlarged by overgrowth to link the quartz to the tourmaline, and no dust lines can be recognized on quartz overgrowths. As well, there are no straight-sided crystal faces on quartz grains. The irregular boundary at the interface of the quartz and tourmaline suggests that the welding of the grains may be due to pressure solution (Figure 4.25B).

Vanadium is moderately high in these samples; vanadium in the overgrowths averages 1.1 weight %, and the maximum found in an overgrowth was 1.9 weight % V_2O_3 .

On Al-Fe-Mg diagrams, most of the overgrowths plot in fields 5 and 7. There is a tight cluster of points plotting at the corner between 4, 5, and 7. Most points on every transect plot in this corner of field 5, and only 1 or 2 plot in fields 4, 5, and 7 (Figure 4.27). The field 7 points are all from the outermost zone of the overgrowths.

Detrital cores plot in fields 2, 4, 5, and 6 on Al-Fe-Mg diagrams. Most detrital cores plot in field 6 ($n = 7$ grains), with some cores plotting in fields 4 ($n = 3$), 2 ($n = 1$), 5 ($n = 1$), and 2 grains had points that plotted in both fields 2 and 5 on the same detrital core.

Yawgers Woods

Tourmaline overgrowths occur on ~70% of tourmaline grains, and tourmaline makes up 64% of the detrital heavy mineral suite. A few of the overgrowth appear euhedral, while the majority seem to be moderately to strongly abraded (Figure 4.28). The grains show between 1 and 4 zones. One of the euhedral grains shows only 2 zones,

Figure 4.27. Tourmaline Al-Fe-Mg ternary diagram for samples from the Skaneateles Township, Onondaga County, New York, provided by the New York State Geological Survey. The sample was taken at a depth of 37 feet (11.3 meters). This sample was taken within a mile of the Carrigan Quarry sample.

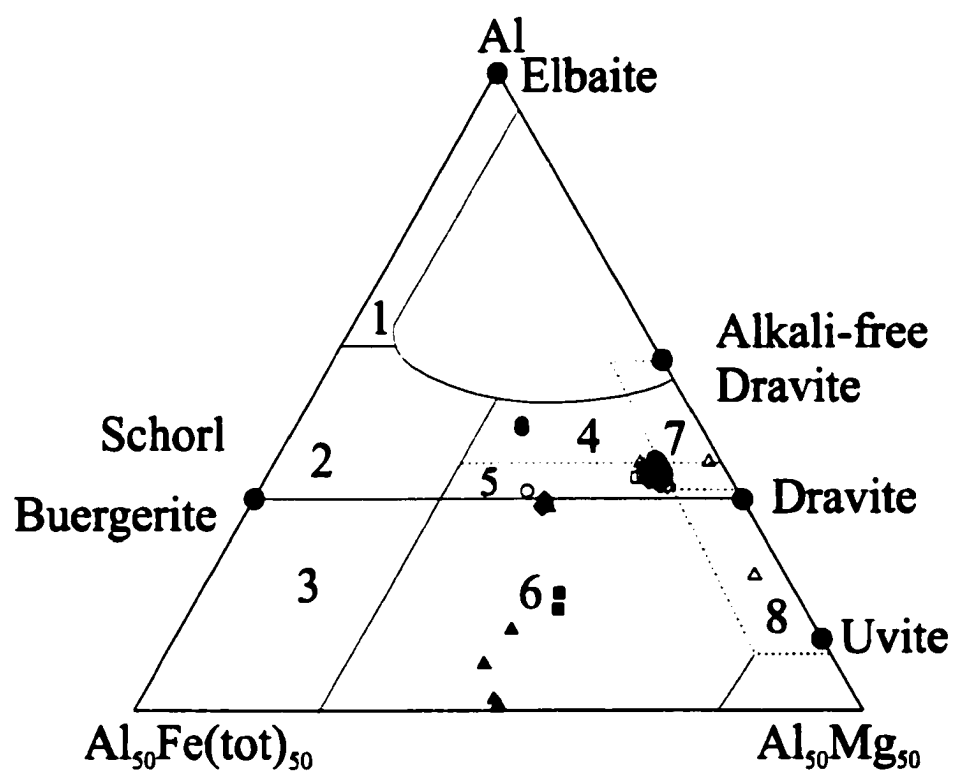
Because of the large number of samples, the data are plotted on several ternary diagrams. The overgrowths are strongly abraded and have between 1 and 3 zones. Vanadium in the overgrowths averages 1.1 weight %, and the maximum found in an overgrowth was 1.9 weight % V_2O_3 .

Most of the overgrowths plot in fields 5 and 7. There is a tight cluster of points plotting at the corner between 4, 5, and 7. The field 7 points that plot along the alkali-free dravite and dravite tie-line are all from the outermost zone of the overgrowths, which reaches a nearly pure dravitic composition. The composition and pattern in which the points plot is typical of tourmaline from the Finger Lakes region of New York.

Detrital cores plot in fields 2, 4, 5, and 6 on Al-Fe-Mg diagrams. This suggests a mixed granitic and metamorphic source for the tourmaline, but is not unexpected as this is typical of most samples.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammites coexisting with an Al-saturating phase, (5) metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

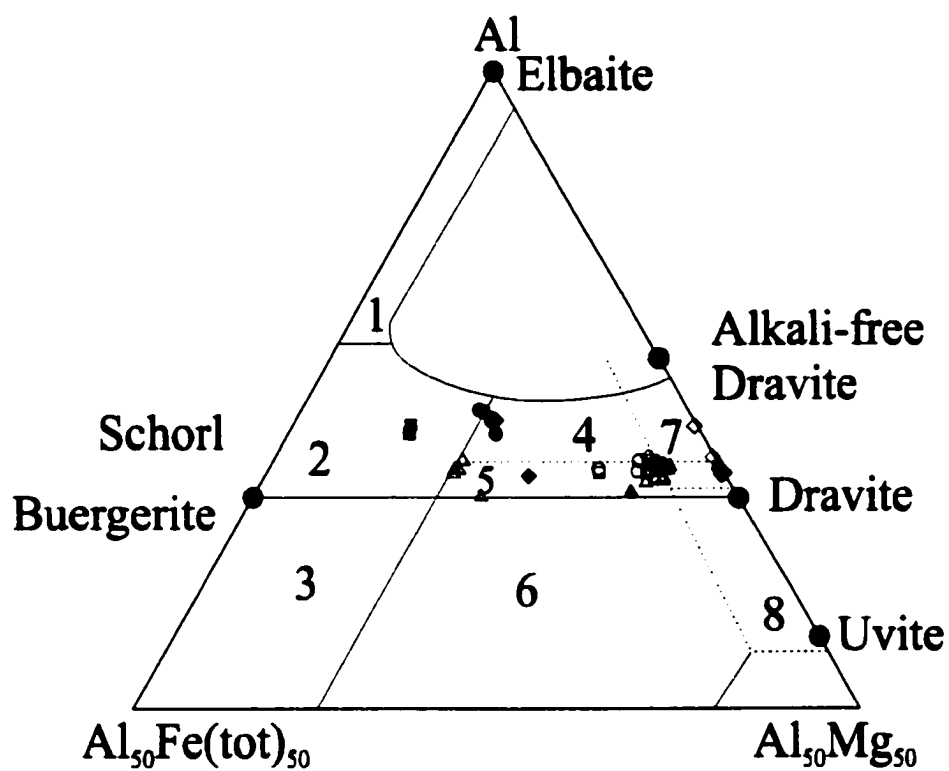


Core Overgrowth

▲	△	= Skan4
◆	◇	= Skan3
●	○	= Skan2
■	□	= Skan1

Figure 4.27–Continued

(B)

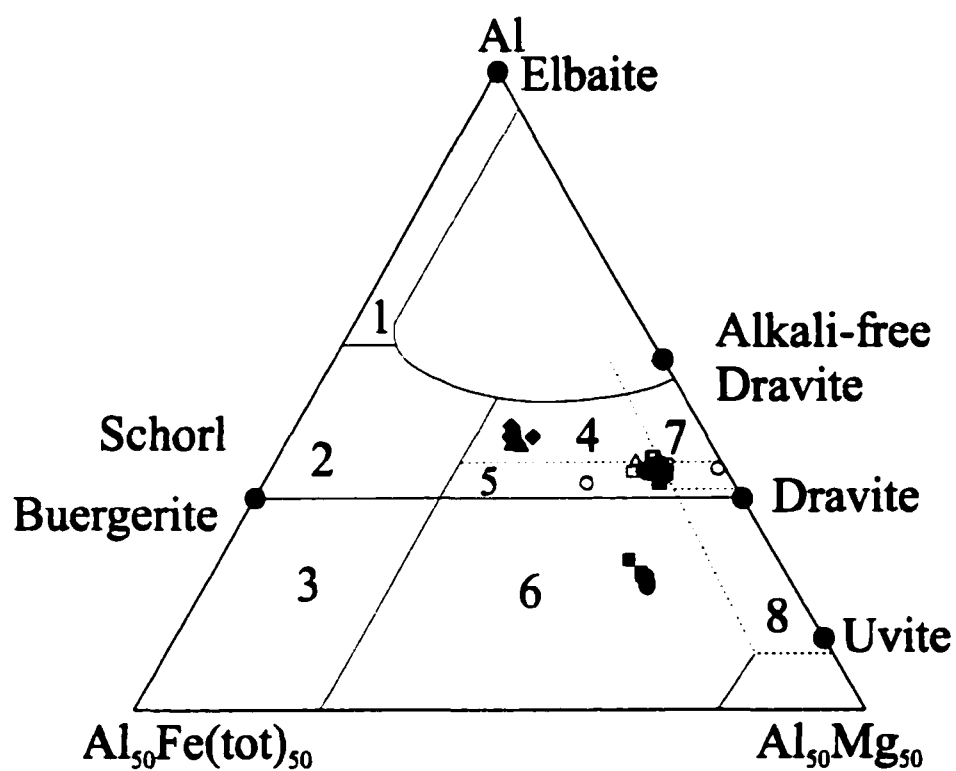


Core Overgrowth

▲	△	= Skan9
◆	◇	= Skan8
●	○	= Skan7C
■	□	= Skan5

Figure 4.27–Continued

(C)

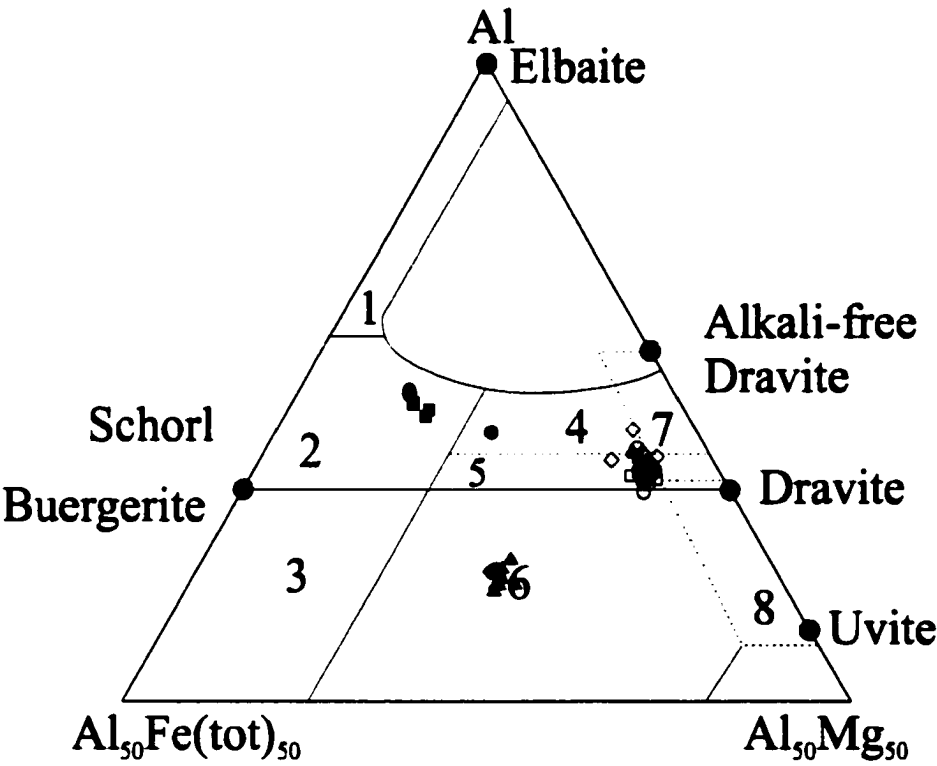


Core Overgrowth

▲	△	= Skan11transect2
◆	◇	= Skan11
●	○	= Skan10transect2
■	□	= Skan10

Figure 4.27–Continued

(D)



Core Overgrowth

▲	△	= Skan13transect2
◆	◇	= Skan13
●	○	= Skan12transect2
■	□	= Skan12

Figure 4.28. Samples from Yawgers Woods, New York. Tourmaline grains from this locality show a mixture of textures from euhedral crystal outgrowths to highly abraded grains.

(A) SEM image of grain with what appears to be a euhedral overgrowth. Note that the shape of the termination of the overgrowth is the same shape as the zoning pattern seen in grain C below.

(B) BSE image of a grain showing a relatively unabraded overgrowth. The zoning of this grain is somewhat irregular. There are two zones and the inner zone is ragged. Though there is little supporting evidence, perhaps this grain's two zones were separated by a brief period of erosion causing the inner zone some abrasion followed by regrowth after a second deposition.

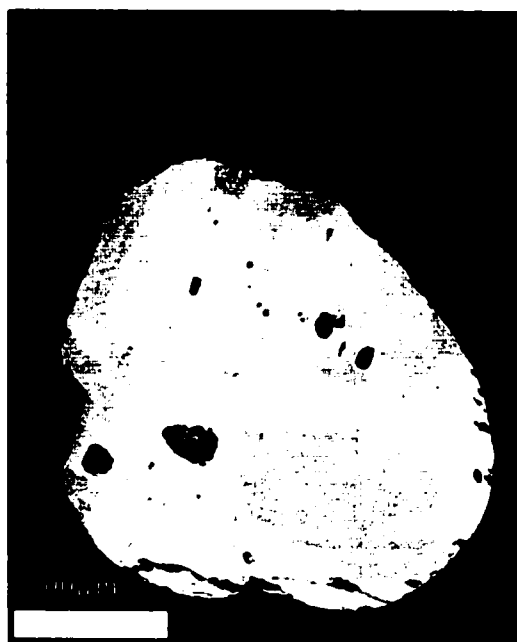
(C) BSE image of a grain that shows some abrasion. Well-developed zones end in a pyramid-like termination. There are several small zones followed by a large dark outer zone similar to the outer zone seen in B. Faint microprobe damage from analysis points can be seen following the medial line of the overgrowth and transecting the pyramidal termination of the zones.

(D) BSE image of highly abraded tourmaline overgrowth. The overgrowth displays 3 to 4 somewhat irregular zones, including a very bright inner zone and a moderately dark outer zone. The overgrowth must have covered significantly more of the grain, as can be inferred from remnant visible from near the upper left corner of the image to the lower right corner.

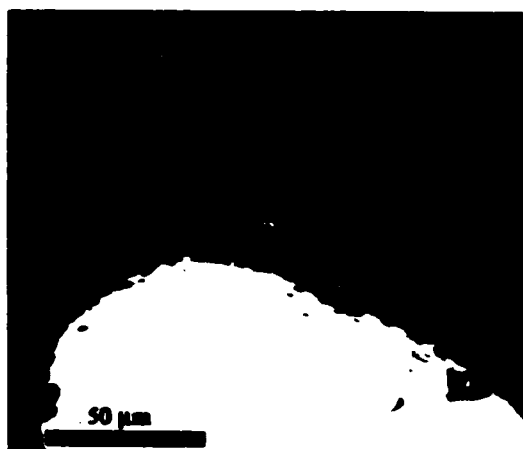
(A)



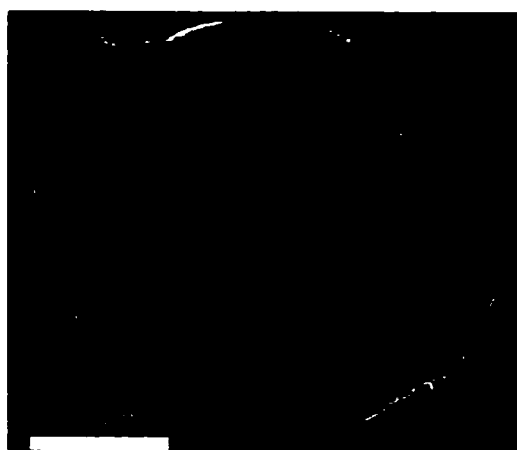
(B)



(C)



(D)



while one of the moderately abraded grains shows 4 zones. Generally the grains start with inner lighter zones and end in a dark zone. Some of the grains have very sharply defined light and dark banded zones, while others have only irregular diffuse zones (Figure 4.29).

It is interesting to note that one of the grains with a euhedral overgrowth has a sharp and pointy termination that looks similar to the deflections seen in zoned crystals using BSE. It is possible that at Yawgers Woods both resedimented tourmaline with overgrowths and new overgrowths formed in situ are present, but further analysis would be needed to confirm this proposal.

Vanadium in the overgrowths averages 0.39 weight %, and the maximum found in an overgrowth was 0.72 weight % V_2O_3 .

On Al-Fe-Mg diagrams, all of the overgrowths plot in fields 4 and 7, with 4 of the 6 investigated grains plotting in field 5 near the borders with 4 and 7 (Figure 4.29). Most of points on individual transects plot in two clusters in fields 4 and 7. The field 7 points are all from the outermost zone of growth.

On Al-Fe-Mg diagrams, 3 of the detrital cores plot in field 6, with one core plotting in field 4, one core plotting with points in both 3 and 2, and one with points plotting in fields 6, 4, and 2.

Green Pond Outlier

Though tourmaline overgrowths were searched for in heavy mineral suites, none were found. Kilogram-sized samples of the Connelly Conglomerate from 3 localities

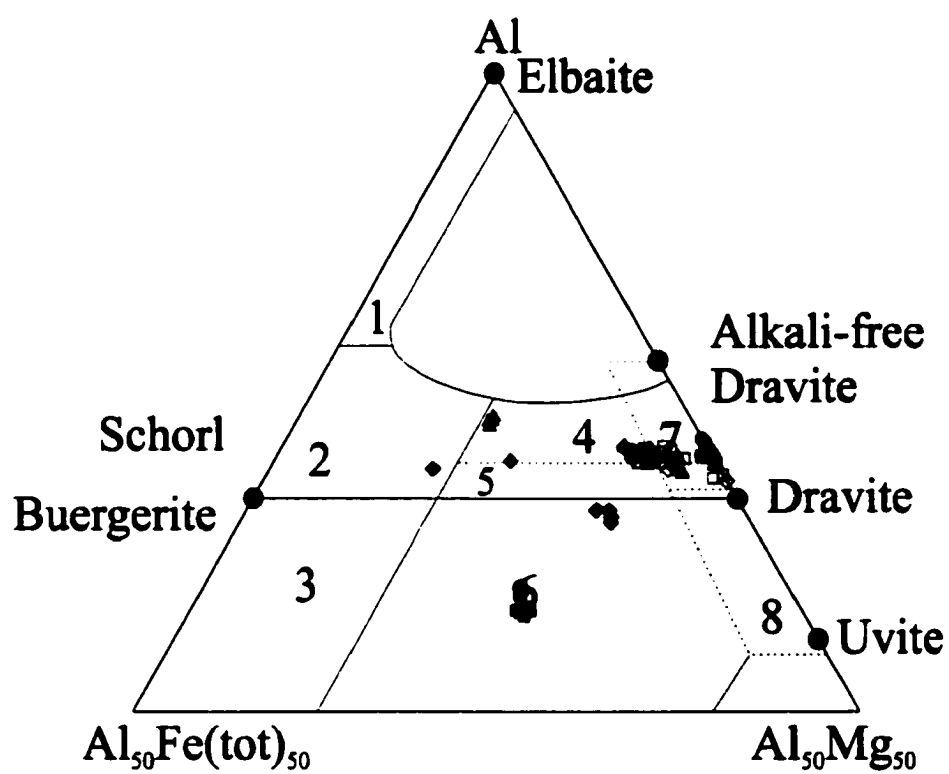
Figure 4.29. Tourmaline Al-Fe-Mg ternary diagram for samples from Yawgers Woods, Cayuga County, New York.

All of the overgrowths plot in fields 4 and 7, with 4 of the 6 investigated grains plotting in field 5 near the borders with 4 and 7. Most of points on individual transects plot in two clusters in fields 4 and 7. The field 7 points along the alkali-free dravite to dravite tie-line are all from the outermost zone of growth, which is depleted in FeO. As is typical for samples from New York, there is a moderate amount of vanadium in the sample. Vanadium averages 0.39 weight %, and the maximum found in an overgrowth was 0.72 weight % V_2O_3 . This is in line with the grains' overgrowths plotting in field 7 of the diagram.

Three of the detrital cores plot in field 6, with one core plotting in field 4, one core plotting with points in both 3 and 2, and one, sample Yaw g3, has points plotting in fields 6, 4, and 2, suggesting it is compositionally zoned. The diverse fields in which the cores plot in suggest that the sample is derived from multiple sources, and most likely reworking of older sedimentary units is involved. The original sources were a mixture of granitic and metasedimentary rocks.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammities coexisting with an Al-saturating phase, (5) metapelites and metapsammities not coexisting with an Al-saturating phase, (6) Fe^{3+} -rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)



Core Overgrowth

▲	△	= Yawg1c
◆	◇	= Yawg3
●	○	= Yawg2
■	□	= Yawg1

were separated for heavy minerals (see petrography section for locations). The heavy mineral separates were extremely small residues that contained only a few detrital tourmaline and zircon grains, all of which were well-rounded and moderately spherical. Petrographic analysis of several thin sections from each location also revealed no tourmaline overgrowths, and thus they appear to be absent from the outlier.

Pennsylvania Sample

Stroudsburg

Only one sample was collected from northeastern Pennsylvania near Stroudsburg on Kittatiny Ridge. No tourmaline overgrowths were found in a heavy mineral sample separated from a kilogram-sized sample, and none were found in several petrographic thin sections.

Maryland Sample

Tonoloway Ridge

Tourmaline overgrowths occur on ~82% of grains separated from this unit. They are very small, highly abraded overgrowths of colorless tourmaline (Figure 4.30).

Petrographic analysis gives evidence of abrasion due to reworking. Several grains with highly abraded overgrowths were encountered in thin section. The overgrowths abut against adjacent grains and do not appear to have formed by enlargement into pore spaces.

SEM analysis reveals that some of the overgrowths are hackly (Figure 4.30),

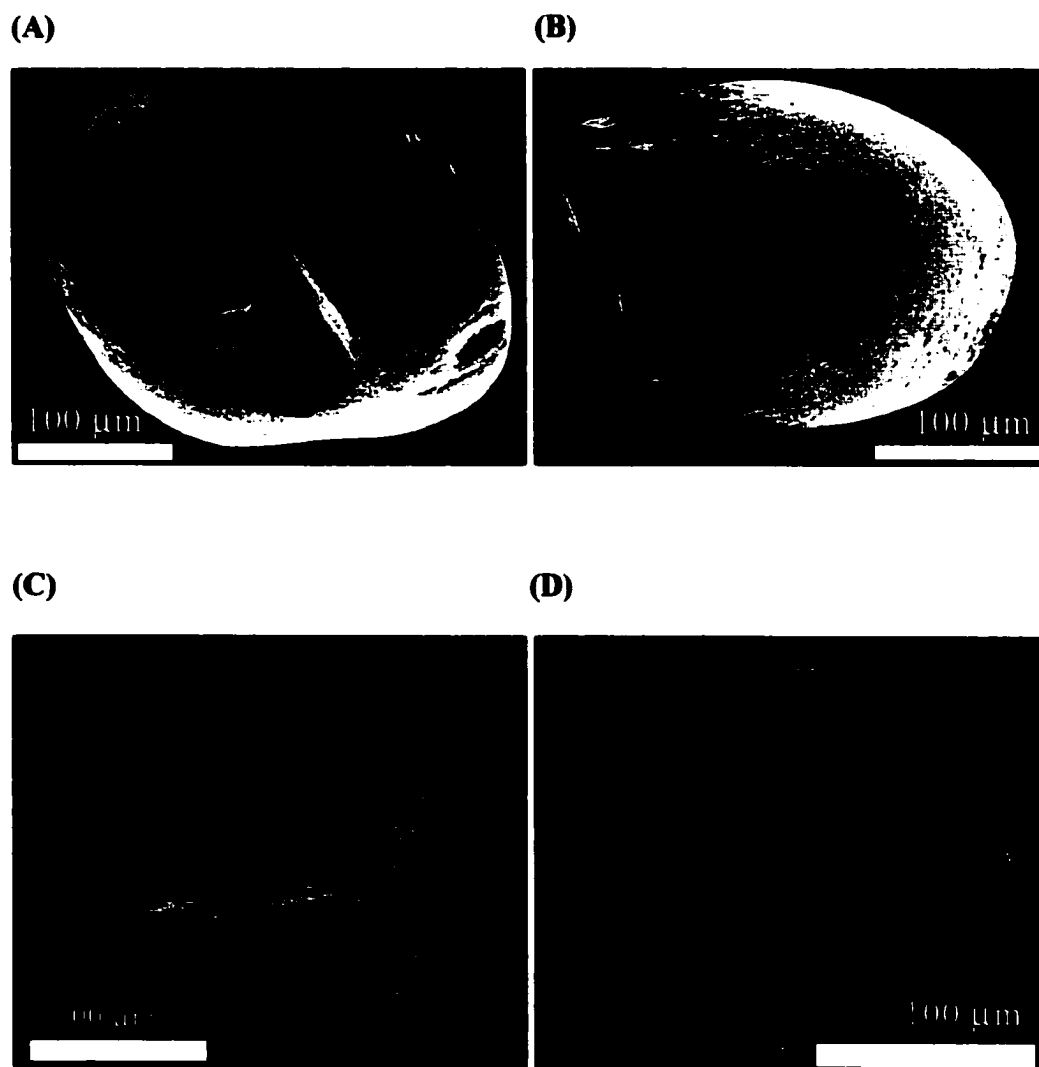
Figure 4.30. Tourmaline from Tonoloway Ridge, Hancock, Maryland. Most grains with overgrowths from this location show evidence of strong abrasion.

(A) Tourmaline grain showing moderately strong abrasion and loss of overgrowth material. The prismatic crystallite structure can be seen extending toward the detrital core.

(B) Tourmaline grain showing a small amount of overgrowth remaining on the end of a well-rounded oval grain. The c-axis of the grain is oriented parallel to the long axis of the grain. One area of the grain still has some remnant of the overgrowth crystal face(s), but much of the overgrowth is abraded.

(C) The tourmaline overgrowth on this grain shows remnants of a splintery-textured overgrowth with parallel subcrystals. Though the original outline of the detrital grain appears to have been irregular, there is evidence that the overgrowth has been stripped from a significant area of the grain's surface. Note the small crystallites sticking out on the broken portion of the overgrowth some distance to the right of the protruding portion of the overgrowth.

(D) Another grain with only minor remnants of the prismatic tourmaline overgrowth. This grain has undergone significant rounding after the formation of the overgrowth. Note that a small inclusion juts out from the surface of the detrital core near the base of the grain.



while others have only small remnants of the overgrowth remaining.. The hackly grains are very similar to grains from other localities, but are the smallest noted in the investigation. Splinters appear to be crystallites that all nucleated from the surface and grew parallel to each other. Away from the broken apex, these same crystallites impart a striated (parallel to c-axis) appearance to the overgrown grains (Tuttle, 1940).

One notable point is that the amount of breakage of the grains is quite variable. This may be a result of the tourmaline overgrowth grains being derived from several sources, some closer than others, but might also be related to the shape of the detrital core, the size of crystallites, or some other unknown variable. Figure 4.31A and B shows the extremes of hackly texture of the overgrowths, while Figure 4.31C and D shows grains intermediate in nature that have some breakage and yet retain some regions of prismatic or terminal crystal faces. Since there seems to be a continuum of grain abrasion, perhaps the best explanation would be that some grains are sheltered from abrasion, though certainly a mixed provenance cannot be entirely ruled out.

Only a few grains had overgrowths large enough to analyze. The overgrowths plotted in a tight cluster in field 4 on the Al-Fe-Mg diagram (Figure 4.32). The detrital cores plotted in fields 5 and 6.

West Virginia Samples

Franklin

Small strongly abraded tourmaline overgrowths were found on ~29% of the overgrowths. Tourmaline makes up 45% of the detrital heavy mineral suite. Tourmaline

Figure 4.31. Examples of prismatic and hackly tourmaline overgrowths from Tonoloway Ridge, Hancock, Maryland. The tourmaline from this location varies in a continuous spectrum from extremely splintery to a denser less splintery or prismatic appearance.

(A) This tourmaline grain, also illustrated in Figure 4.3, displays the splintery texture first described by Stow (1931). Hackly texture is commonly seen on abraded overgrowths.

(B) Close-up of A. The individual prismatic subgrains or crystallites can be seen. Notice that they are parallel to each other and are all aligned parallel to the c-axis of the detrital grain.

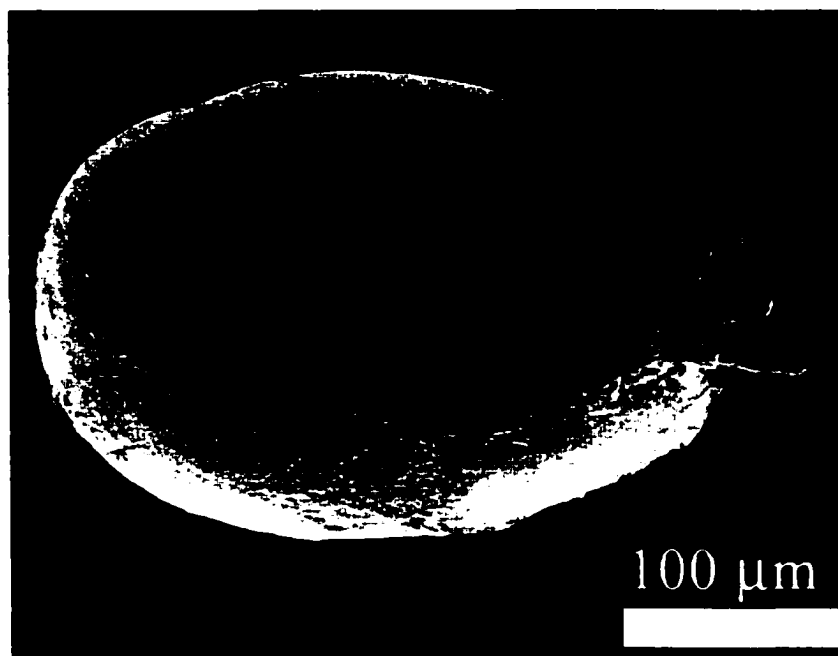
(C) Grain showing a more prismatic overgrowth. The detrital core boundary with the overgrowth appears to be splitting loose with a fracture developing in the direction perpendicular to c (in this direction tourmaline has a well-developed basal fracture). The overgrowth itself is oriented so that the c-crystallographic axis is nearly vertical. There is a well-developed fracture on the large crystallite that has sheared it off, exposing a nearly basal cross section. Small pores can be seen in the overgrowth.

(D) Close-up of C. Surprisingly little abrasion is evident on this grain's overgrowth. Crystal faces are clearly visible. The overgrowth appears to be composite in nature. It is unclear whether this grain was protected from abrasion (perhaps because it was transported in an enclosing rock fragment) or whether it has grown directly in the sandstone. Since the heavy mineral sample contained a spectrum of grain textures, dominated by moderately to highly abraded tourmaline overgrowths, perhaps it was just a grain derived more locally than many of the other grains. Note that the large broken prism (Br) has several small pores or channels developed in the overgrowth. This same prism shows striations parallel to the c-axis that are typical of tourmaline.

Small amounts of clay material encrusting the overgrowth may be either authigenic or a result of inefficient cleaning of the grain after separation.

That a few of the subcrystals appear to end in terminations suggests that the grain is polycrystalline. This texture is unusual and has not been noted in other examples.

(A)



(B)

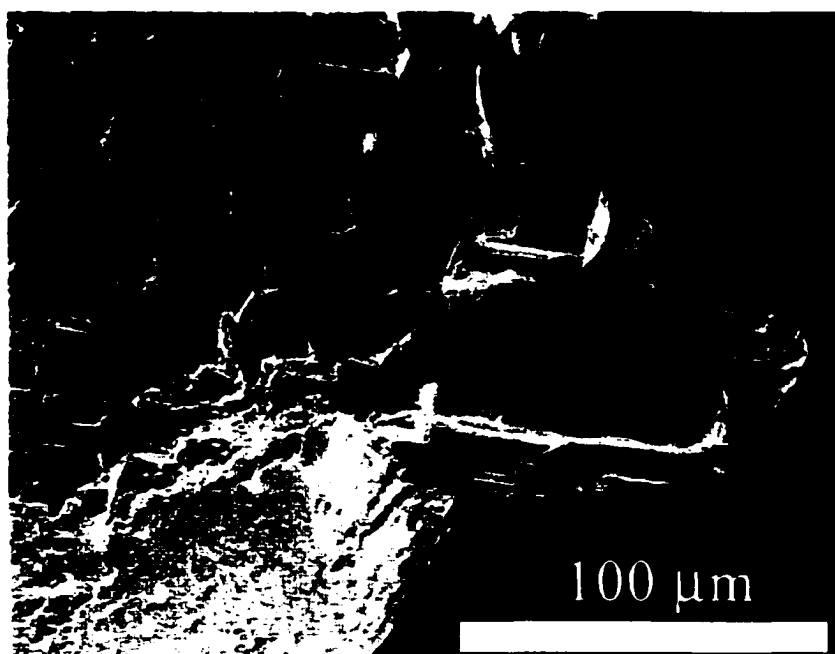


Figure 4.31–Continued



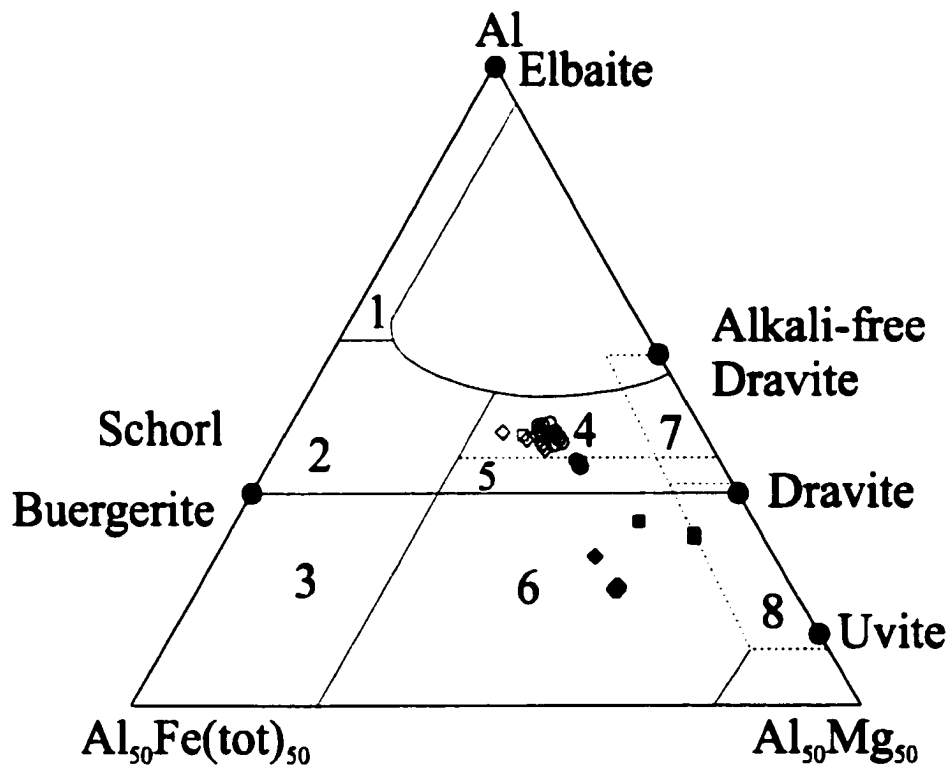
Figure 4.32. Tourmaline Al-Fe-Mg ternary diagram for samples from Tonoloway Ridge, Hancock, Maryland.

Tourmaline overgrowths are very strongly abraded at this locality, and only a few grains had overgrowths large enough to analyze. The overgrowths plotted in a tight cluster in field 4 on the Al-Fe-Mg diagram. These grains plot in almost the same position on the diagram as grains from the Crandall Estate #1 Well and Minnehaha Springs, and this suggests that these samples formed in similar environments. On the petrogenetic diagram, tourmalines that grow in this field form in a metamorphic environment with an Al-saturating phase. No feldspar overgrowths or other evidence of Al-rich phase is evident, and this might suggest a reassessment of this petrogenetic field; however, because the overgrowths are clearly reworked, their position may have bearing on the host rock in which they formed.

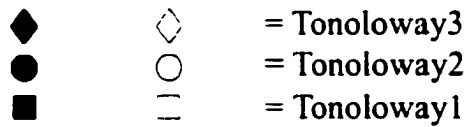
The detrital cores plotted in fields 5 and 6; plotting in these fields suggests that the grains originally were derived from a metamorphic source.

The compositions and labeled petrogenetic interpretative fields are those of Henry and Guidotti (1985) and are derived from reported tourmaline compositions and their association with different crystalline rock types. Fe(tot) is the total iron detected in tourmaline analysis. (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe³⁺-rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammities coexisting with an Al-saturating phase, (5) metapelites and metapsammities not coexisting with an Al-saturating phase, (6) Fe³⁺-rich quartz tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr, V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)



Core Overgrowth



overgrowths were probably present on many of the grains that no longer have overgrowths. This conjecture is made because bald and roughed-up ends are present on many of the tourmaline grains corresponding to the position where polar overgrowths would have formed. The tourmaline overgrowths in this sample were deemed too small to attempt to analyze using the electron microprobe.

Greenland Gap

Small tourmaline overgrowths occur on 77.5% of tourmaline grains, and tourmaline makes up ~53% of the detrital heavy mineral suite. The overgrowths are strongly abraded. These are some of the smallest overgrowths observed, and overgrowths appear to have been sheared off of the tourmaline cores (Figure 4.33). So small were the clear and colorless tourmaline overgrowths that the sample was at first thought to be devoid of overgrowths. However, even though the tourmaline overgrowths show overall abrasion, crystal faces have been preserved on some grains. Composite quartz and tourmaline grains with quartz overgrowths evident have been found (Figure 4.34). In one example, the tourmaline and quartz seem to have grown together with mutual growth from both minerals, creating a smooth boundary between the minerals (Figure 4.34). Thus paragenetic evidence suggests that both quartz and tourmaline diagenesis overlapped in time.

Even though the sandstone was moderately well indurated with silica cement, there is no evidence of excessive breakage of the overgrowths. Certainly much larger overgrowths were separated from pervasively cemented sandstone samples at other locations. The grains do not look as if they were recently broken. Several grains have

Figure 4.33. Tourmaline overgrowths from Greenland Gap, West Virginia. The tourmaline overgrowths all show abrasion and rounding.

- (A) Well-rounded tourmaline grain with a small amount of authigenic overgrowth remaining. It appears that a small “bald spot” created by abrasion may have formed in one area that is completely surrounded by remaining overgrowth material.
- (B) Another grain with only remnant tourmaline overgrowth remaining. Note that there is some hint of crystal faces formed during authigenic growth that have not been badly abraded.
- (C) This tourmaline grain has an abraded overgrowth that is quite roughed up. Little hint of its original prismatic nature of growth is preserved.
- (D) Though there is still some overgrowth extending from the grain (bottom center of photograph), the grain is beginning to lose material from the overgrowth area and rounding is clearly taking place.

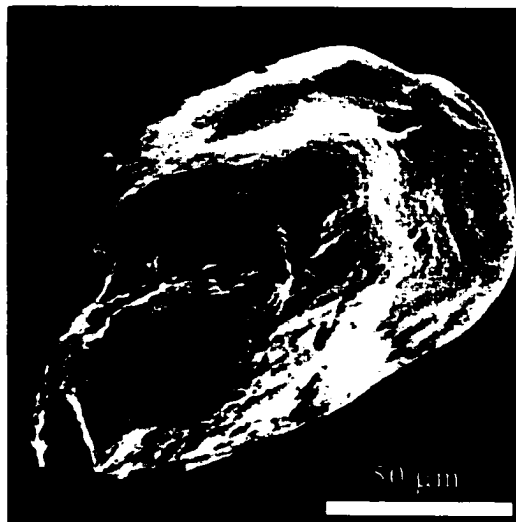
(A)



(B)



(C)



(D)

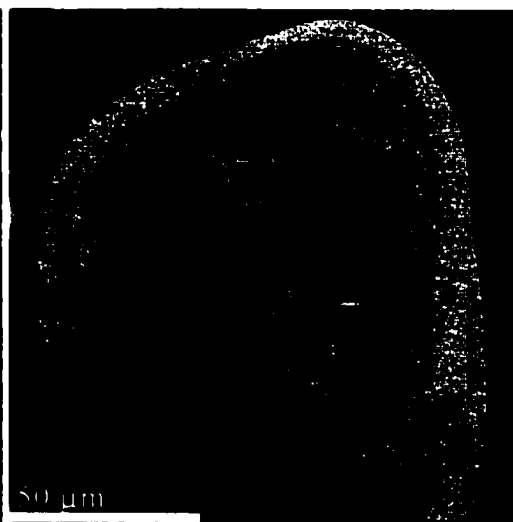


Figure 4.34. Composite grain of quartz and overgrowth tourmaline. This sample is from Greenland Gap, West Virginia.

(A) Tourmaline grain with a tourmaline overgrowth interlocked with quartz. Though this grain may have been transported after formation, the relationship formed between overgrowth tourmaline and quartz is preserved. The quartz grain to the upper right (mostly inside of the drawn rectangle) has been overgrown by authigenic quartz that has a pocked texture. The overgrowth quartz and tourmaline seem to have grown together to form a smooth-faced contact. A red arrow shows the orientation of the c-crystallographic axis.

(B) Close-up of the boxed area in **A**. Note that a hexagonal crystal outline is partially formed on the quartz grain (4 of 6 prismatic faces are visible). The long dimension of the picture parallels the c-crystallographic axis.

(C) Close-up of **B**. The pockmarked quartz is above. A partial hexagonal outline is visible, and the contact with the tourmaline overgrowth below (no pockmarks) is shown. The contact of the two grains is clearly seen to be a straight line. This strongly suggests that both the tourmaline and the quartz had well-formed crystal boundaries when contact between the grains was made. They most likely grew in the same pore space, before the grain was resedimented.

(D) A closer view of the contact of the two minerals. Note that there is a texture of small, roughly triangular pits on the tourmaline's surface and that they contrast strongly with the circular and possible bubbly origin of the pits in the quartz.

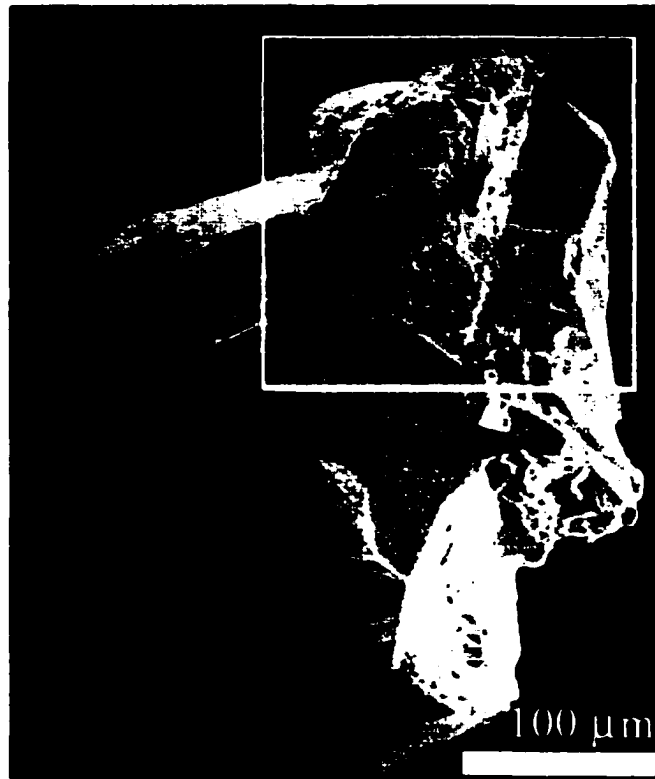
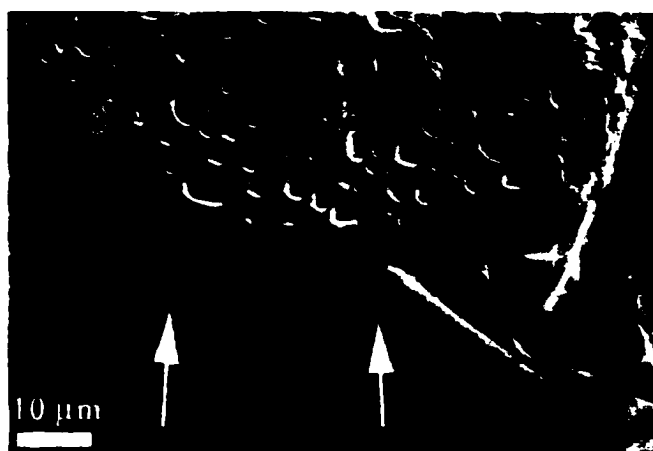
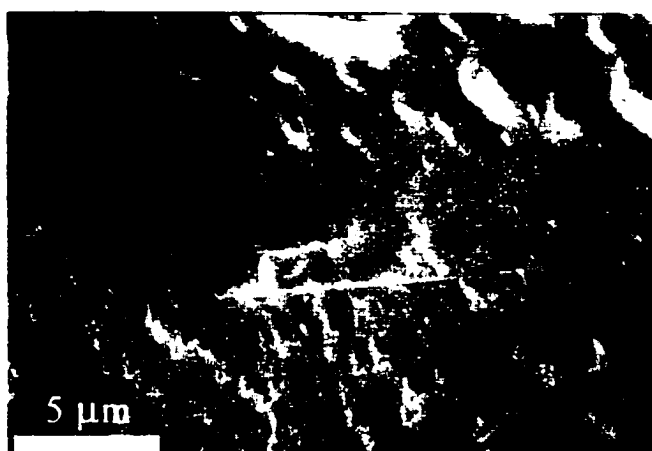
(A)**(B)**

Figure 4.34—Continued.

(C)**(D)**

been found that show an interesting breakage pattern of the overgrowth. This pattern is reminiscent of exfoliation of rocks. The grains' overgrowths seem to have, during their abrasion and breakage, separated in such a way that a layered appearance was produced in the overgrowths (Figure 4.35), and a similar separation occurs between the overgrowths and the detrital cores. The breaking away of the overgrowths from the detrital cores, along curved surfaces, which are certainly related to the original outline of the detrital grain, creates "bald spots." The bald spots can be right on the end of elongate grains or to the sides of the remaining abraded overgrowth (Figure 4.35).

The amount of rounding on some of the overgrowths suggests moderate transport and abrasion. The fact that there are tourmaline overgrowths attached to quartz grains indicates that composite grains can survive moderate transport. These observations strongly suggest that the grains are naturally reworked and that composite grains may have a shielding effect that helps preserve overgrowth during transport (Figure 4.34).

Minnehaha Springs

Tourmaline overgrowths occur on ~97% of tourmaline grains, but tourmaline makes up only ~19% of the detrital heavy mineral suite. Samples of tourmaline extracted from this sandstone seem to have slightly to moderately abraded overgrowths (Figure 4.3C). Some of the examples show excellent zonation with up to 5 zones, while others have very small overgrowths with no zones. The cores are well rounded and often fractured. In one example it appears that a fractured detrital grain was "healed" by growth of new tourmaline that occurs both as an overgrowth on the outside of the grain and as a fracture fill inside the grain. That is the authigenic tourmaline grows to suture

Figure 4.35. Tourmaline showing breakage, Greenland Gap, West Virginia. The overgrowths are abraded and probably were broken during erosion and transportation before being redeposited.

(A) Well-rounded tourmaline with abraded overgrowth on one end. This stubby overgrowth has been fractured (**Br**), and apparently there is separation between what appear to be discrete layers (or sheets) in the tourmaline overgrowth. At point **Zo**, the layers look like zoning. It is unclear whether these zones correspond to the type of zones seen in polished grains investigated by BSE. The zones may be a type of exfoliation, but why the overgrowth should break along these layers is unclear. Whether there are compositional differences was not investigated; however, internal zones investigated with BSE do not always reach as far around the grain as the overgrowth and are overstepped by later zones, outer zones, and it is possible that a similar situation occurs here.

(B) Close-up of region labeled **Br** in A (above). The breakage of fracture has opened up fairly parallel to the elongate striations seen on this part of the overgrowth. Though the striations do not appear to be parallel to the c-axis, their orientation is somewhat ambiguous, because the cause of the fracturing is unclear. It is possible that with the breaking-off of a central portion of the overgrowth the remainder was splayed and bent inward toward the missing central part of the overgrowth. The open fracture at **Br** seems to have opened more toward the right of the photograph than to the left, and it appears that the whole front section has been slightly bent and offset against the vertical fracture (**Vf**). The boundary with the overgrowth and a fractured area is shown at **O**. Note the many lamellar fractures that look like exfoliation sheets at **Fr**. Though tourmaline is not supposed to have a good cleavage in any direction (Dietrich, 1985), this type of breakage certainly is reminiscent of cleavage in sheet silicates.

(C) Another type of abrasion phenomenon, noted on several grains from this location, also looks very much like exfoliation sheeting with curved surfaces. This grain has clearly lost a significant amount of its overgrowth from the elongate end of the ovoid grain. There is what could be called a "bald spot" in the central portion, and all around is an area of overgrowth, making a sort of circular area at the end of the grain. The overgrowth has clearly broken off, exposing a surface that is almost certainly related to the original grain outline before overgrowth. With this in mind, the pockmarked area is most likely the zone of roots. Then there is another sheet that has also had significant loss and extends back some 40 μm in a V-shaped region. This then shows that there is a second sheet surface above, which was most likely the growing outer surface of the overgrowth and which shows striations, (**S**) similar to those seen at many other locations, paralleling the c-axis direction.

(D) Close-up of the end of the grain shown in C. The roughness of the bald spot at the end of the grain is clearly visible. Fracture is shown on the edges of the broken sheets.

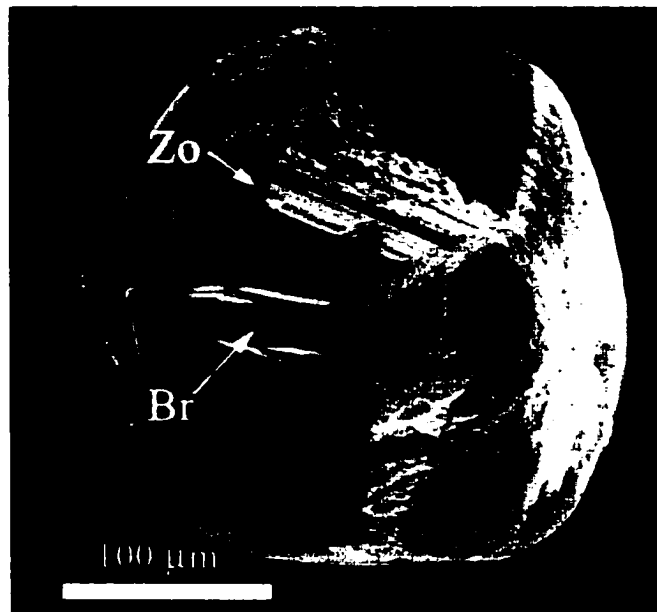
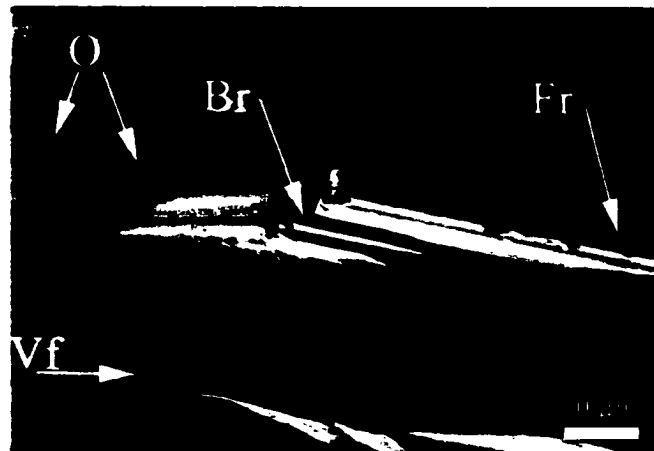
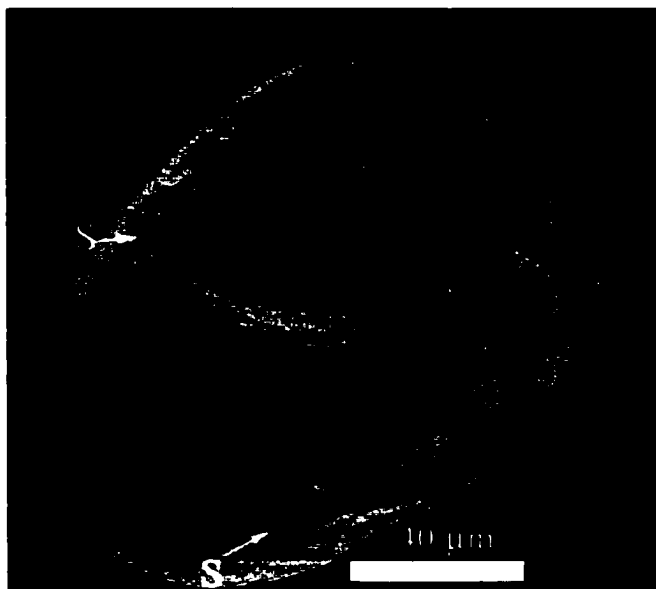
(A)**(B)**

Figure 4.35—Continued

(C)



(D)



together a fractured grain (Figure 4.36). There are also composite quartz and tourmaline grains in this sample. The uneven nature of the meeting of the two minerals seems to be due to compaction. No evidence of quartz authigenesis connecting the grains has been found (Figure 4.37).

Vanadium is moderately low in these samples; vanadium in the overgrowths averages 0.04 weight %, and the maximum found in an overgrowth was 0.24 weight % V_2O_5 .

On Al-Fe-Mg diagrams, most of the overgrowths plot in field 4 with one plotting in field 5, and 4 grains near the border between 4 and 5 with points in both fields (Figure 4.38). Whenever the overgrowths have any points that plot in field 5, it is only a few points and the majority of points plot in field 4. A couple of overgrowths had a point that plotted in field 6, but these may be bad analyses (the detrital cores plot in field 6 also, so there may be an overlap of analyses).

On Al-Fe-Mg diagrams, the detrital cores plot in a wide range of fields: 3 grains plot in field 2, 2 grains have points that plot in both fields 2 and 3, 6 grains plot in field 4, 5 grains plot in field 2, 3 grains plot in fields 5 and 6, 6 grains plot in field 6, and 1 grain plots in field 8 (Figure 4.38). The majority of detrital grains seem to be derived from metamorphic rocks. A granitic source is also indicated since some grains plot in field 2.

Virginia Sample

Warm Springs

The Warm Springs sample was collected only a few miles east of the Minnehaha

Figure 4.36. Fractured tourmaline grain “healed” by authigenic tourmaline. This grain is from Minnehaha Springs, Pocahontas County, West Virginia.

(A) This tourmaline grain was apparently fractured prior to tourmaline authigenesis and then healed by authigenic tourmaline precipitation. The tourmaline was analyzed and had a composition similar to the overgrowth on the upper part on the micrographs. A microprobe transect revealed a depletion of Fe across the overgrowth from the lower part of the fracture to the upper part. This is in the same direction and displays the same overall trend of depletion of Fe as seen in the true overgrowth above.

(B) Close-up of the grain reveals that the amount of offset along the fracture is about 20 microns. Points of past coincidence can be matched up between the two sides. It is unclear whether the overgrowth increased the separation of the fracture.

(A)



(B)

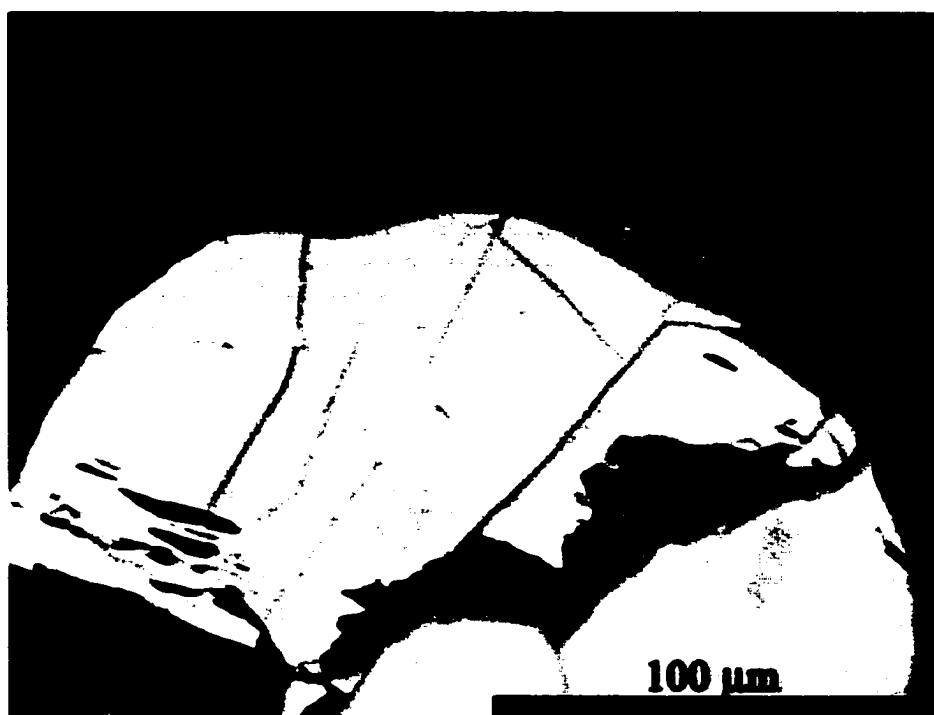


Figure 4.37. Tourmaline grains with overgrowths attached to quartz grains.

(A) BSE image, Minnehaha Springs, West Virginia, a quartz grain appears to have been forced into the tourmaline overgrowth. Tourmaline growth zones terminate against the irregular surface of the quartz grain, but the contact between the quartz and tourmaline is irregular. Note that the tourmaline overgrowth seems to be somewhat abraded, and this suggests that either the composite grain was reworked and then reincorporated in a new deposit or that the tourmaline overgrowth was abraded prior to the quartz grain being forced into the overgrowth during compaction or later during deformation that affected the Valley and Ridge province. Note the vertical fractures that run the length of the tourmaline grain; these fractures have been noted in several grains from this location and appear to be related to the forcing of the quartz grain into the overgrowth. This suggests that most likely the composite grain was formed in the Oriskany Sandstone during later deformation of the unit.

(B) SEM image of tourmaline grain from Nedrow, New York, this grain exhibits only small contact points of tourmaline and quartz.

(C) Close-up of B, the contact between the quartz and tourmaline (below) is shown on the right with arrows. Small overgrowths of quartz producing pyramidal faces are labeled Q. All tourmaline overgrowths at Nedrow appear to be abraded, and it is not clear whether this grain is a reworked composite grain from an older sandstone or whether a small amount of either quartz or tourmaline growth has cemented the grains together. The small contact points pointed to appear to be tourmaline, suggesting that either some tourmaline regrowth has taken place on the tourmaline or the grain was reworked as a composite.

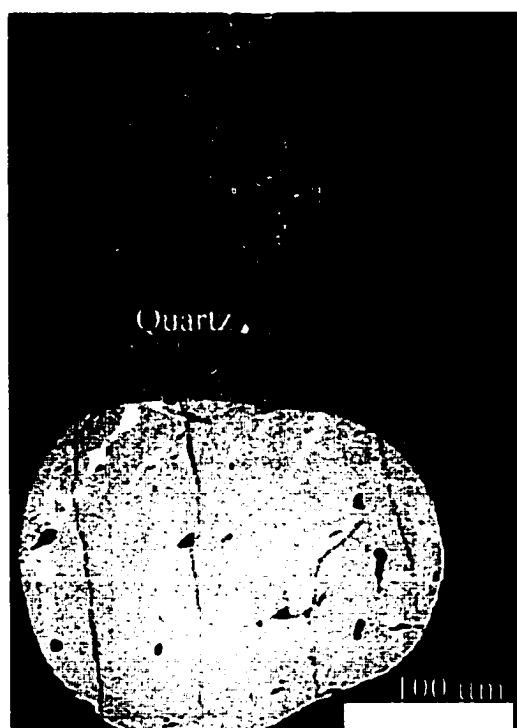
(A)**(B)****(C)**

Figure 4.38. Tourmaline Al-Fe-Mg ternary diagram for samples from the Minnehaha Springs, West Virginia.

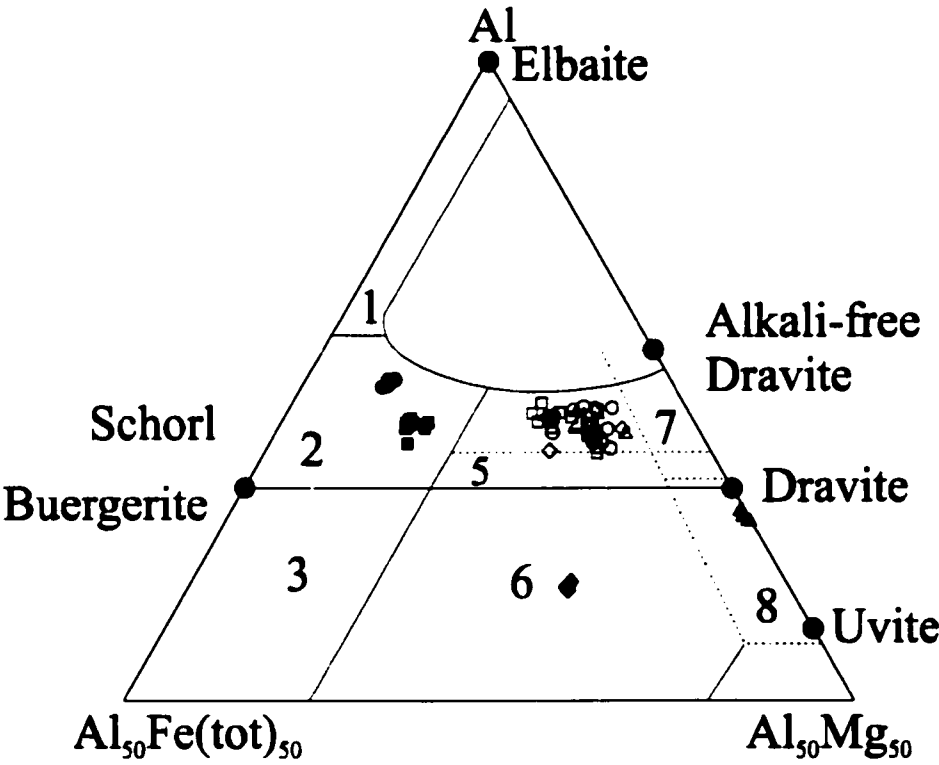
For convenience of reading, the overgrowths are plotted on 5 separate diagrams. On Al-Fe-Mg diagrams, most of the overgrowths plot in field 4 with one plotting in field 5, and 4 grains near the border between 4 and 5 with points in both fields. Whenever the overgrowths have any points that plot in field 5, it is only a few points and the majority of points plot in field 4. One overgrowth has a point that plotted in field 6 (ms-1 g200 and ms-2 g1400), but these may be bad analyses (the detrital cores plots in field 6, so there may be overlap of analysis of the detrital core and overgrowth).

The occurrence of most points in field 4 is typical of the inner zones of the New York samples, and it appears that tourmaline in all localities starts to grow in this field.

The detrital cores plot in a wide range of fields. The majority of detrital grains seem to be derived from metamorphic rocks, but a granitic source is also indicated because some grains plot in field 2. This suggests a mixed source for detrital cores, and most likely is the result of multiple cycles of sedimentary reworking.

The petrogenetic fields for the Al-Fe-Mg ternary diagram shown are as follows (after Henry and Guidotti, 1985): (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and their associated pegmatites and aplites, (3) Fe³⁺-rich quartz-tourmaline rocks (hydrothermally altered granites), (4) metapelites and metapsammities coexisting with an Al-saturating phase, (5) metapelites and metapsammities not coexisting with an Al-saturating phase, (6) Fe³⁺-rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites, (7) low-Ca metaultramafics and Cr- and V-rich metasediments, and (8) metacarbonates and meta-pyroxenites.

(A)

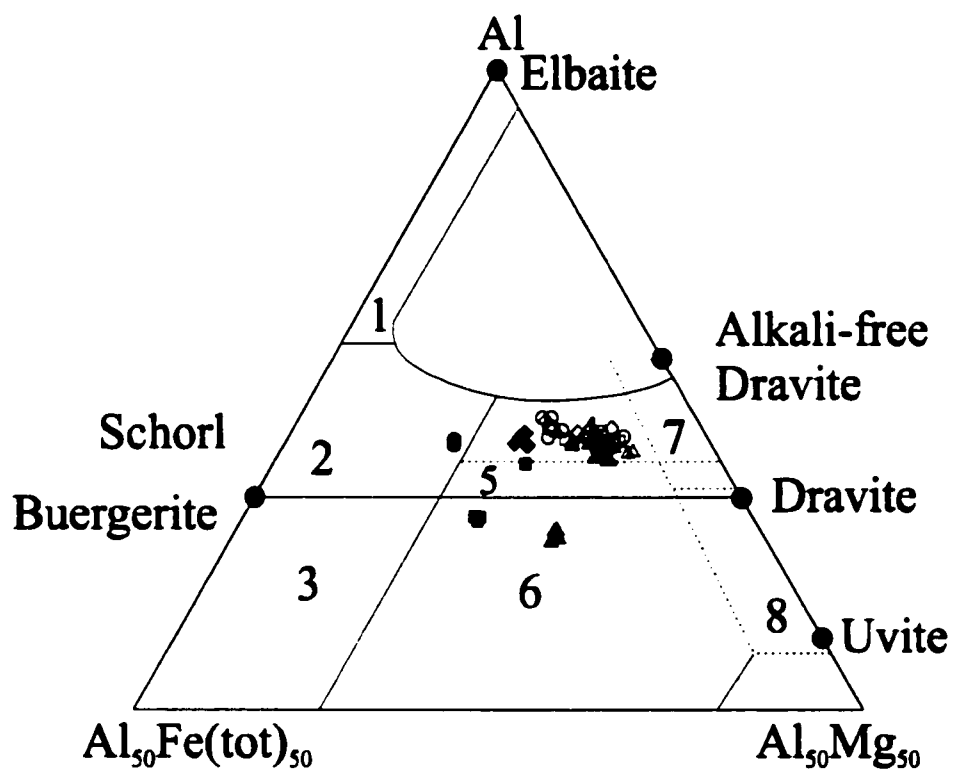


Core Overgrowth

▲	△	= Ms499
◆	◇	= Ms399
●	○	= Ms299
■	□	= Ms199

Figure 4.38–Continued

(B)

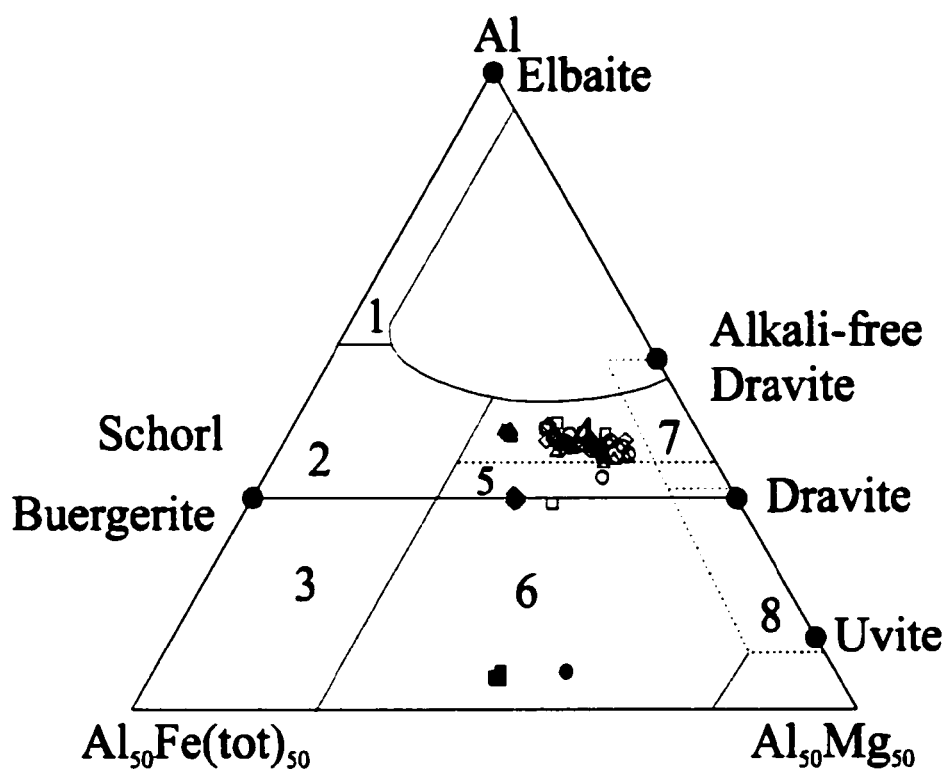


Core Overgrowth

▲	△	= Ms-1g100
◆	◇	= Ms799
●	○	= Ms699
■	□	= Ms599

Figure 4.38–Continued

(C)

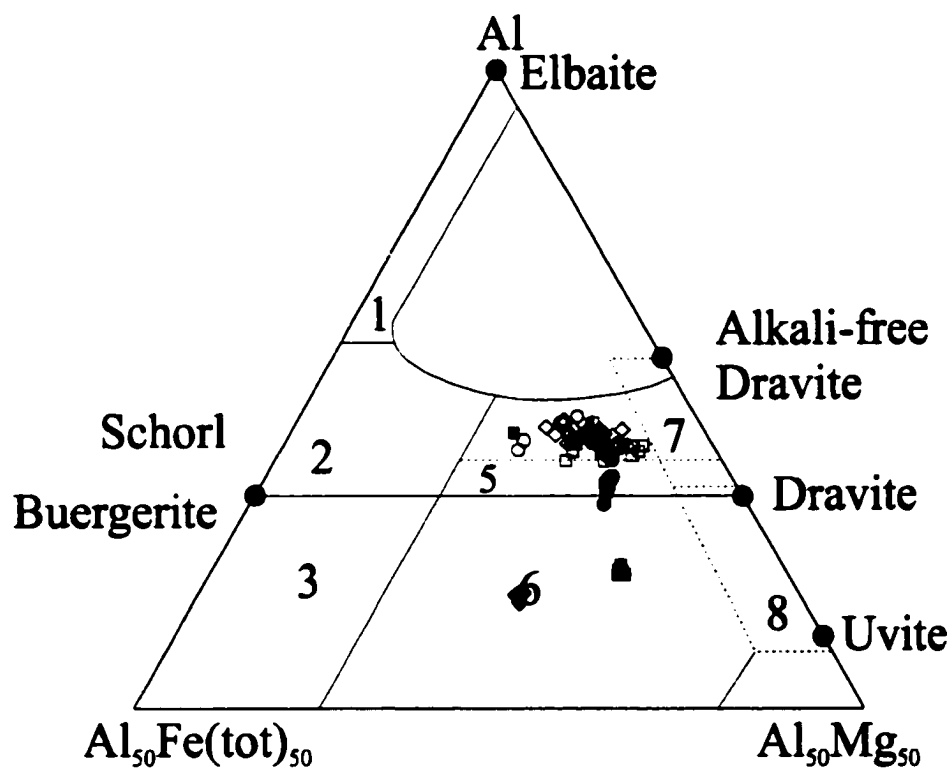


Core Overgrowth

▲	△	= Ms-1g500
◆	◇	= Ms-1g400
●	○	= Ms-1g300
■	□	= Ms-1g200

Figure 4.38–Continued

(D)

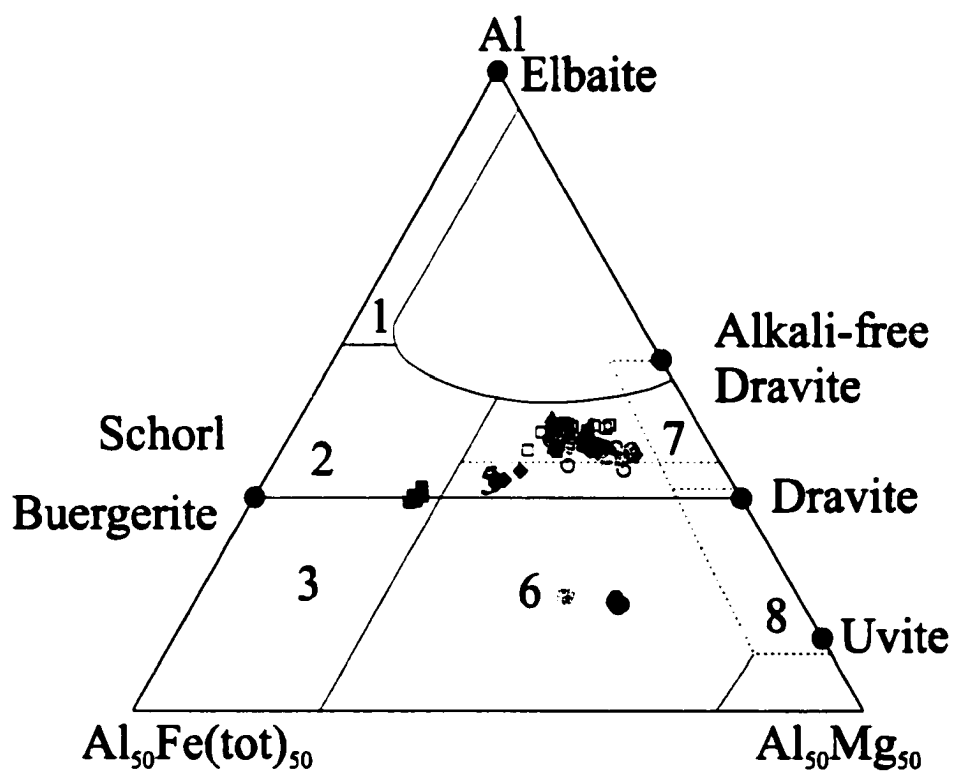


Core Overgrowth

▲	△	= Ms-2g900
◆	◇	= Ms-2g800
●	○	= Ms-2g700
■	□	= Ms-2g600

Figure 4.38–Continued

(E)



Core Overgrowth

▲	△	= Ms-2g1400
◆	◇	= Ms-2g1300
●	○	= Ms-2g1200
■	□	= Ms-2g1100
	—	= Ms-2g1000

Springs locality discussed above, and tourmaline grains with overgrowths have identical appearance to those from Minnehaha Springs. Thin-section petrography confirms the abraded nature of the overgrowths (Figures 4.39 and 4.3A).

Tourmaline overgrowths occur on ~87% of the grains, but tourmaline only makes up ~7.5% of the detrital heavy mineral suite. No chemical analyses were done on this sample.

DISCUSSION

Two areas of investigation, the morphology and chemistry of the tourmaline overgrowths, are discussed. Though some areas of investigation still require further study, several new discoveries have been made. These new discoveries along with information from past studies lead to a general theory of the origin and history of authigenic tourmaline in the Oriskany Sandstone.

Overgrowth Morphology

Most of the overgrowths occur on rounded detrital grains (cores). Observation of the detrital cores in sectioned plan views and on tourmaline grains where part of the overgrowths is missing reveals a smooth, unpitted sharp contact with the overgrowth. There is no evidence of dissolution of the detrital cores from observations of more than 200 grains. Often near the detrital core there are small elongated pits or vacuoles that typically extend less than 25 μm from the detrital core. These are referred to as a zone of

Figure 4.39. Petrographic thin section of the Oriskany Sandstone from Warm Springs, Virginia. A green tourmaline with a colorless overgrowth (Ov) is visible in the center of the field of view. The sandstone contains abundant tourmaline with overgrowths, but they are rarely encountered in thin section because heavy minerals make up only around 0.01% by weight of the sandstone. Encountering such grains is important because it indicates the nature of the overgrowths in the sandstone without the problem of breakage caused by sample crushing. In this example, the tourmaline overgrowth appears abraded. All of the overgrowths in this sample, examined in both thin section and heavy mineral separates, appear at least slightly abraded.

(A) Plane-polarized light micrograph of thin section containing a tourmaline with an authigenic overgrowth (Ov). In plane light, the mineral grain is displaying moderate absorption in this view, with the c-axis of the grain at approximately 40 degrees to the polarizer. The overgrowth is poorly resolved, but some striations are visible on it. The area to lower right is a pore filled with blue-dyed epoxy. A small amount of high birefringent clay is visible in this pore (C). Monocrystalline quartz grains encase the tourmaline grain on three sides.

(B) Cross-polarized light micrograph of the same area seen in **A** (above). In this position the tourmaline and its overgrowth display close to their maximum interference color. However, the birefringence of the detrital core is masked by strong absorption. The overgrowth appears subangular. Clay (C) can be seen to display high birefringence.

(C) Close-up of tourmaline seen in **A** and **B** (above). The overgrowth is clearly visible, and small striations can be seen on the overgrowth. The overgrowth is obviously somewhat abraded and a portion of the central region of the overgrowth has been removed. Iron-stained clay associated with the grain is not considered to be a weathering product of the tourmaline that remains unaltered. Since the overgrowth is clearly encased in the sandstone and it appears abraded, it is assumed that this indicates that the overgrowth has been slightly reworked (resedimented) and did not form in this sandstone unit. However, since abrasion is only slight to moderate for grains from this location, it is believed that a very near-by source supplied the tourmaline.

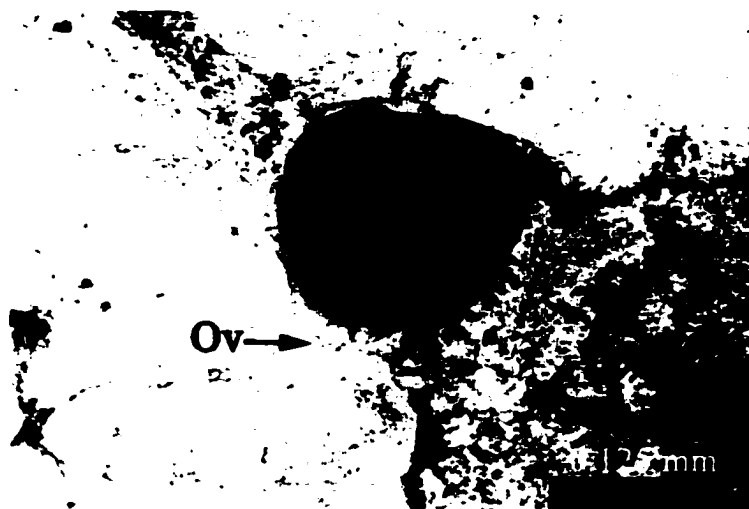
(A)**(B)**

Figure 4.39—Continued

(C)



roots by Krynine (1946), though he thought they extend into the detrital core.

The tourmaline overgrowths have prism faces obvious on almost all but highly abraded grains. The overgrowths do not typically have well-formed or obvious terminations. Tourmaline overgrowths from Oriskany Falls have been found to have terminations, and it is suspected that some of the grains from Yawgers Woods also have terminations (Figures 4.1 and 4.28). Further work is needed to describe the crystallographic aspects of the overgrowths. This is a complex field of investigation as over 59 forms of crystals are known, and more than 170 crystal faces have been reported (Dietrich, 1985).

Most abraded overgrowths when investigated in transmitted plane light appear to show prismatic crystallites that run parallel to each other and the c-axis of the detrital core. These parallel crystallites are best seen on broken grains using the SEM, and some unbroken grains do not show this morphology (Figure 4.1). This morphology of parallel smaller prisms gives a hackly fracture to broken overgrowths and has been illustrated and described by many authors from various parts of the world (Stow, 1931; Tuttle, 1940; Smithson, 1942). The term “splintery” is often used to describe the morphology, but is less accurate than “hackly,” because splinters are often more haphazardly arranged.

The idea of crystallites suggests that there is a polycrystalline nature to the overgrowths and that each isolated crystallite is a separate growth. However, this may not be entirely true as some grains do not show any obvious evidence of separate crystallites, although they may not always be visible on abraded grains.

In BSE, no evidence of such crystallites is found in any grains. Perhaps the

crystallites' rates of growth are so similar that between crystallites no chemical inhomogeneity exists and boundaries between adjacent crystallites do not vary chemically. If this is true, then atomic number contrast seen in BSE would not detect crystallite grain boundaries (Reed, 1995). Optically, the crystallites are visible in plane light, but they are all in optical continuity with the detrital core and have the same extinction position as the core.

Crystallites have not been observed to have their own terminations, but this may be a result of the crystallites only being obvious on broken, abraded grains. Crystallites have been seen to coalesce at their apices into a crystal face.

Even though crystallites are only visible on broken grains, they are believed to be present in all overgrowths. One line of evidence that supports this belief is that minute pores developed in overgrowths (Figure 4.13). The pores appear to be due to the failure to nucleate and/or the insertion of an obstacle that stopped some crystallites from growing, while adjacent areas of the overgrowth continued to grow. Thus the shape of the pores is that of the missing crystallites. The pores are rectangular and oriented parallel to the c-axis. They tend to be present near the detrital core and become less abundant farther away (Figure 4.13).

Careful examination of overgrowths shows that the zone of roots described by Krynine (1946) is composed of these pores (Krynine believed that the zone of roots was from pits in the detrital core). That pores are less abundant farther from the detrital core indicates that there must be some lateral growth of adjacent overgrowth crystallites to fill the open areas. This may happen in a way similar to how drusy quartz fills geodes

described by Sinkankas (1966). In that example individual quartz crystals widen noticeably as they grow toward the center of the geode, producing carrot-shaped crystals. This has not yet been observed in tourmaline crystallites. One type of crystallite interaction that has been observed is that adjacent crystallites may weld to their neighbors to give a sheet-like appearance (Figure 4.35).

Since crystallites appear to grow together to form the overgrowths, it is reasonable to assume that during abrasion, collisions with other grains tend to break up the crystallites in the overgrowth. The prismatic crystallites then would break along tourmaline's good basal parting (at right angles to the c-axis) and fall free (Dietrich, 1985). This creates the hackly texture. Observations of this texture suggest that rather than resembling wood splinters that tend to bend, the crystallites remain straight.

If the hackly texture is a result of breakage during transportation, then it is possible to argue that samples with this texture are reworked. However, a few grains might be sheltered from breakage by remaining as subgrains in detrital rock fragments. This would in part explain why some unabraded grains are often found mixed in with hackly grains. As well, hackly texture probably would not happen to grains that suffered only one blow that broke the overgrowth, so they are not likely to be generated in crushing.

Zonation of Overgrowths

Zonation of authigenic tourmaline has never been reported from the Appalachian Basin samples. The only reported zoning in authigenic tourmaline is sector-zoning from

isolated euhedral crystals (Henry, 1996); thus the information presented here is new and preliminary in nature.

When well developed, the pattern of zonation is similar to that seen in many igneous minerals and in calcite cements with multiple growth zones. For instance, the type of zoning is similar to zoning in rhythmic amphibole overgrowths illustrated by Bowes and Kinloch (1964). In some samples zoning is not well developed, while in other samples abrasion has removed parts of the overgrowths, and their zonation patterns are not complete.

The idea that the zones are growth zones is supported by observations made on a euhedral crystal from Oriskany Falls. SEM analysis of the overgrowth revealed zoning on the overgrowth's surface (Figure 4.1B). Since secondary electrons from the specimens' surfaces typically only indicate differences in surface topography, this unusual finding is probably related to surface differences due to growth zoning. Though the zones on this euhedral crystal do not show up as clearly, they do seem to be the same size and shape as zones seen in the light microscope and using BSE described below.

Optical transmitted light and electron microscopy both reveal zonation within overgrowths (Figure 4.40). However, many overgrowths that have zones visible in BSE do not show zones optically.

In optical microscopy, zones are shown by changes of color and by contrast differences, most likely due to variations in refractive indices. According to Nesse (1991), tourmaline exhibits pleochroism with the darkest color when the long dimension (c-axis) is perpendicular to the vibration direction of the polarizer, and pleochroism is

Figure 4.40. Optical and electron images of zones in overgrowths. The zones are only faintly discernable because of lack of contrast in the specimens.

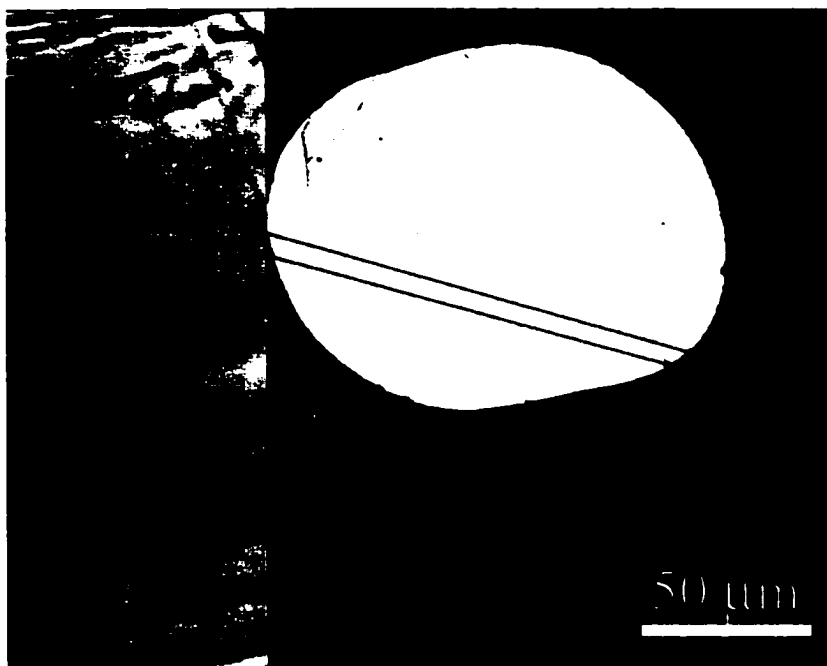
(A) Tourmaline grain from Crandall Estate Well #1 , 4999 ft (1524 m), Allegany County, New York. Both plane light and BSE images are shown. The BSE micrograph (right) displays a minimum of 6 zones. The intensity of these zones appears to be mainly related to iron content. The amount of FeO as a weight percentage is shown for 3 conspicuous zones that were analyzed. The actual analysis points are visible as small damage spots on the overgrowth, and the line of the microprobe transect can be discerned. The innermost zone was not analyzed properly, because the microprobe spot can be seen to intersect both that and the next outer zone. A difference of about 0.74 weight percent FeO caused a slight difference in color just detectable with the camera (the zones are easier to discern by eye). Arrows point to points of correspondence on the plane-polarized light color micrograph (left).

(B) Tourmaline grain from Oriskany Falls, New York. Plane-polarized light image from a thin section of sandstones. Several weakly visible zones are displayed by this grain when it is rotated so that the c-axis is perpendicular to the polarizer. This absorption/pleochroism phenomenon is very strong in the detrital core (going from light brown to very dark brown), but is weak in the overgrowth. Two zones appear to be lighter colored (almost colorless): an exterior zone and an interior zone (both labeled light). These two zones are relatively uniform in thickness and are similar to those seen on other grains in BSE image. Note that in the innermost dark zone a series of small striae or inclusions that run exactly parallel to the c-axis terminate within that zone and do not continue into the first light zone. The nature of these striae is still poorly understood; however, they almost always occur close to the detrital core and have been termed a zone of roots (Krynine, 1946).

(C) Another tourmaline grain from Oriskany Falls displaying optical zoning. This grain is mounted in epoxy resin with a refractive index of 1.54. The arrow shows the direction of vibration of the polarizer.

(D) Close-up of C. The grain has been rotated to provide a better view. Again the grain and detrital core are displaying maximum absorption. The overgrowth and surrounding mounting media have a yellow cast that is a result of the epoxy's color. The 5 zones labeled are clearest on the right hand side of the overgrowth. To the left side, fracturing of the grain prevents viewing of the zones. There is also fracturing to the lower right side of the overgrowth. However, the innermost zones shows the deflection and termination of the zone in the same style as seen in BSE images, and the visible zones are sharply bounded and straight sided. Because the zones appear to be a result of variations in absorption/pleochroism, the composition of the darker zones can be assumed to be more iron-rich as iron is the most likely cause of pleochroism in the schorl-dravite series.

(A)



(B)

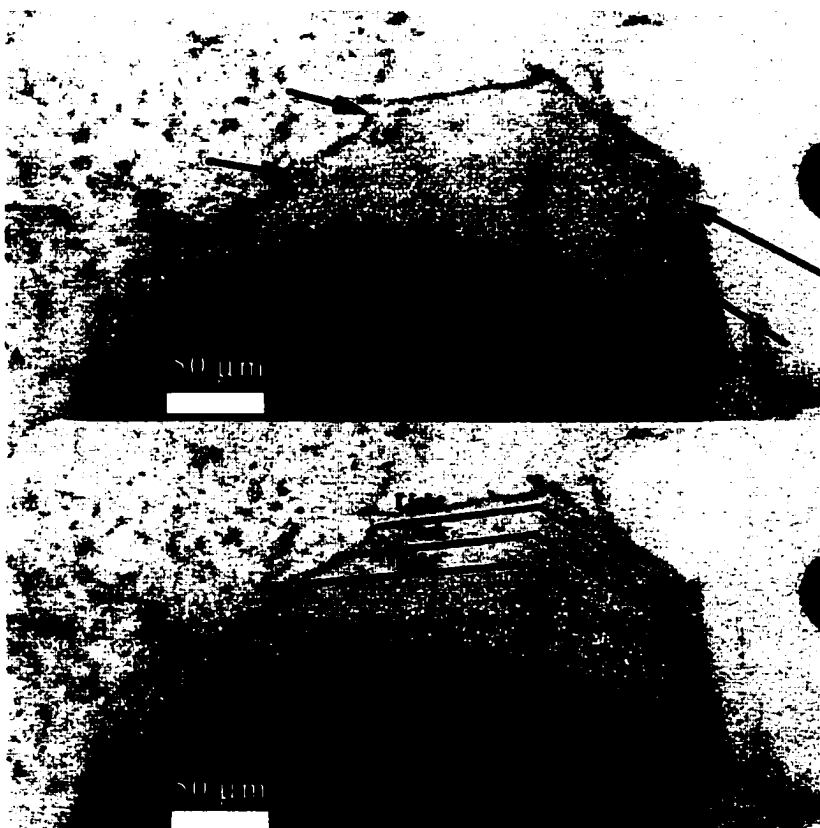
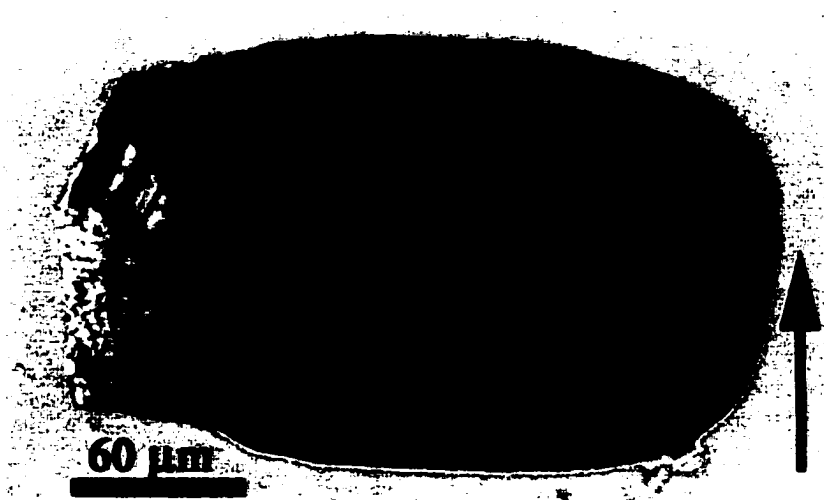
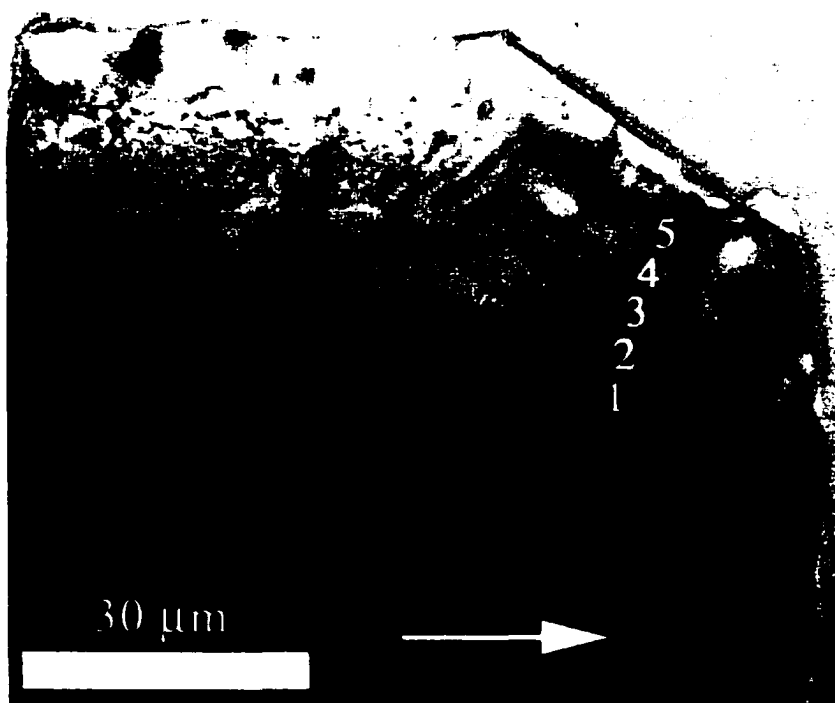


Figure 4.40—Continued

(C)



(D)



greater in Fe-bearing varieties of tourmaline. Pleochroism has been observed on some overgrowths and appears to actually vary with the composition of the zones of individual overgrowths. This zonation phenomenon has not been previously reported, though Stow (1931) reported that absorption in the overgrowths is sometimes the same color as in the detrital cores.

That some overgrowths in samples that exhibits BSE zonation do not seem to exhibit optical zonation is probably a result of the methodology and conditions of observation. The samples in grain mounts are not all oriented the same way, the grains' thicknesses and shapes are not all the same, the grains may have more mounting media above or below, all of which could affect lighting and visibility of zones in the overgrowths. Thus future study with more uniform conditions will probably lead to a better understanding of optical zoning. However, the preliminary results suggest that pleochroism and refractive indices in these samples can be directly related to compositional zonation. Pleochroism is known to be a function of iron content in tourmaline (Nesse, 1991), and fluctuations in iron content can be directly related to optical zones (Figure 4.40). Careful observation, though only on a limited number of samples, has revealed that optical zones correspond precisely (are the same shape and size) to chemical zoning visible in BSE.

BSE is the best method to visualize zonation patterns. Zones as small as one micron across have been recognized on specimens prepared for microprobe analysis (only zones greater than about 5 μ m could be analyzed chemically [Reed, 1995]). On several grains, microprobe analytical transects were taken along these zones in directions both

perpendicular and parallel to the zonation. Thus both multiple zones in transects and zones of constant BSE contrast, at right angles to the transects, were analyzed on the same grains (Figures 4.9, 4.17, and 4.19).

In any sample location, most overgrowths show the same size and type of zoning; however, differences between sample locations exist. These differences include: differences in chemistry (discussed below) and differences in the morphology of zones. For instance, the overgrowths from the Seneca Stone Quarry show both sharp straight zones (common to most localities) and an unusual sinuous type of zoning that is unknown in other localities (Figure 4.22). As another example, several localities such as Auburn, the Crandall Estate Well #1 Core, Oriskany Falls, the Seneca Stone Quarry, and Yawgers Woods in New York, and the Minnehaha Springs location in West Virginia have overgrowths with zones that appear to reflect the shape of the crystal faces of the overgrowth and have a point of inflection within the overgrowth that creates a sharp and pointy kink in the zones (Figure 4.28). This is apparently due to two faces joining as a crystal termination. In contrast, samples from the Auburn Austeel plant location have zones that are well developed and large, but either don't have any inflection in the zones or have a much subdued and rounded inflection in the zones (Figure 4.7).

The number of zones present on individual grains seems to be about the same for localities where the overgrowths are well formed and not too abraded. For instance, samples from the Austeel plant location show two or three zones, the last zone being the widest (Figure 4.7). The samples from the Auburn locality typically have 3 or 4 zones.

The zonation patterns in each sample from which tourmaline grains were

separated show a similarity of zoning that suggests growth under a similar set of circumstances. Pertinent characteristics of zoning are summarized in Table 4.2. For instance, samples from Oriskany Falls taken at a distance of about 200 ft (61 m) from each other produced similar grains with similar zonation patterns.

Krynine (1946) who investigated tourmaline overgrowths from many different formations by optical methods believed that in any given formation “overgrowths are identical in their properties” (p. 71). Krynine had clearly not recognized zonation in the overgrowths, nor had any of his students mentioned this phenomenon (Martens, 1937, 1939; Tuttle, 1940). Krynine’s statement is clearly somewhat inaccurate in light of discoveries made here, yet there is still a possibility that the tourmaline overgrowths from other Paleozoic sandstones such as the Ordovician Tuscarora and Cambrian Gatesburg Formations will vary in their zonation patterns and have distinctly different patterns than those found in the Oriskany Sandstone. Because the recognition of zonation and the termination of zonations against adjacent detrital components is one of the best criteria for recognizing whether the tourmaline has formed in place or is transported to the sandstone from another location, it is a characteristic that should be carefully investigated in any future studies.

Tourmaline Chemistry

Chemical analysis of tourmaline overgrowths has been done on most of the samples from New York, on one sample from Maryland, and one sample from West Virginia. No published chemical analyses of tourmaline overgrowths from the Oriskany

Table 4.2
Tourmaline Descriptions

Name of Location	Texture of overgrowths	Size of overgrowths in microns parallel to the c-axis, n = 50 grains	% Tourmaline with overgrowths	Chemistry Fields after Henry & Guidotti (1985) of the detrital Most abundant field first
Auburn	unabraded to euhedral	maximum 113 average 87	~76%	core 6, 2 overgrowth 7, 4, 5,
Austeel	slightly to moderately abraded	maximum 237 average 160	~32%	core 6, 2 & 4 overgrowth 7, 5, 4
Carrigan Quarry	highly abraded	maximum 95 average 55	~50%	core 6, 5, 4 overgrowth 4 & 5 & 7
Crandall Estate #1 Well	slightly abraded. to euhedral	maximum 175 average 94	~95%	core 6, 4, 3 overgrowth 4
Oriskany Falls	slightly abraded to euhedral	maximum 142 average 74	~90%	core 6, 4, 8 overgrowth 4, 7, 5
Nedrow Exit	highly abraded	maximum 71 average 44	~32%	core 6, 2 & 3 overgrowth 5, 7, 4
Seneca Stone Quarry	unabraded	maximum 109 average 93	~96%	core 6, 4 overgrowth 4 & 5 & 7
Skaneateles core	moderately abraded to highly abraded	maximum 92 average 55	~80%	core 6, 4, 2, 5 overgrowth 5, 7, 4
Yawgers Woods	abraded to euhedral	maximum 79 average 55	~70%	core 6, 4 & 2 overgrowth 4,5,7
Tonoloway Ridge	highly abraded	maximum 100 average 68	~82%	core 6, 5 overgrowth 4
Franklin	highly abraded	maximum 62 average 29	~29%	-
Greenland Gap	highly abraded	maximum 65 average 25	~77.5%	-
Minnehaha Springs	moderately abraded	maximum 89 average 41	~66%	core 6, 2 & 4, 8 overgrowth 4
Warm Springs	moderately abraded	maximum 86 average 44	~87%	-

Sandstone exist, no papers on tourmaline overgrowths formed under supposedly sedimentary conditions in a sandstone publish chemical analyses of overgrowths, and only a few papers on sedimentary rocks with diagenetic tourmaline (exclusive of sandstones) and on low-grade metamorphic overgrowths have published compositions (Krynine, 1946; Henry and Dutrow, 1992; Henry, 1996). Most previous work on the chemistry of overgrowths is based on inferences drawn from refractive index, color, and other optical properties and relies on data from metamorphosed rocks (Henry and Dutrow, 1992). One likely reason for the lack of data is that the overgrowths are small and only methods capable of chemical microanalysis can be used.

Because tourmaline is boron bearing with variable amounts of water, OH, F, Cl, and Li, it is difficult to analyze by microanalytic techniques, which cannot detect or are less sensitive to low-energy X-ray emissions from light elements (McGee et al., 1991). The complex chemistry and substitutions make the tourmaline group one of the most diverse silicate groups (Krynine, 1946; Henry and Dutrow, 1996). Tourmaline analyses in this study have been done with and without detection of boron, Cl, and F. Lithium is not believed to be present. It was not possible to detect H. The analyses with boron total between 95 and 98 weight %. It is believed that the remaining undetected weight percentage is water. Analyses without boron total between 84 and 89 weight %. One reason for the range in totals is probably variable water content (Dietrich, 1985).

The purpose of analysis of the tourmaline overgrowths was twofold: 1) to characterize the chemistry of overgrowth tourmaline using electron microprobe analysis and 2) to recognize differences between tourmaline localities that might be of value in

interpreting the origin of the tourmaline.

As well, an analysis for comparison has also been made between the detrital core of each grain and the overgrowth. Because the detrital core represents a mineral eroded from a preexisting rock in which the detrital core tourmaline formed, a petrogenetic understanding of tourmaline detrital cores should also be of use in interpretation of the provenance of the tourmaline and perhaps the ultimate provenance of the Oriskany Sandstone (Henry and Guidotti, 1985).

To facilitate comparisons, all data were plotted on Al-Fe-Mg ternary diagrams with the compositional petrogenetic fields defined by Henry and Guidotti (1985). Individual samples are plotted by locality in the descriptions given above. These are the first plots of such data known to the author and should have value for future investigations of authigenic tourmaline.

Tourmaline Overgrowth Al-Fe-Mg Ternary Diagrams

A comparison of the results of plotting tourmaline overgrowths on ternary diagrams indicates that there is considerable similarity between overgrowth tourmaline compositions from all locations compared to detrital-core compositions. As well, though not shown on the diagrams, Ca is always excluded from the overgrowths. This probably is a result of the overgrowths being low-temperature examples of the schorl-dravite series, and as is typical of low-temperature and authigenic minerals, there is little substitution of cations (Woodward, 1972).

Detrital tourmaline cores plot in a wide range of different fields on the ternary diagrams; in contrast, the overgrowths almost all have similar ratios of Al to cations and

plot in fields 4, 5, and 7. Though this suggests that the overgrowths all may form in a similar environment, it must be remembered that indications of abrasion are very common in most samples and the overgrowths may not have formed in the environment that formed the Oriskany Sandstone and there is a possibility that some of the composite quartz-tourmaline overgrowths are reworked.

Because the zonation pattern observed in the overgrowths is most likely a growth zoning pattern, tourmaline overgrowths recorded changes in conditions in the environment of formation as they grew. An overall trend of depletion of Fe and increase in Mg is suggested for most localities. Several locations, such as Minnehaha Springs (Figure 4.38), the Crandall Estate Well #1 (Figure 4.14), and Tonoloway Ridge (Figure 4.32), plot with their points clustered in field 4 of the Al-Fe-Mg ternary diagram. Field 4 is the field for metapsammities coexisting with an Al-saturating phase. It is believed that all overgrowths start to grow in such an environment. Zoning can occur due to minor fluctuations in Fe and Mg in this field; for example, zoning is seen in the Minnehaha Springs and Crandall Estate Well #1 samples (Figures 4.3c and 4.9) that plot in field 4.

In the Crandall Estate sample, plots of individual zones were done on a tourmaline overgrowth, and distinctive zones plotted in separate areas of the diagram (Figure 4.9). The zones start with a bright BSE contrast, Fe-enriched innermost zone. This is followed by 4 alternating Mg-enriched darker and Fe-enriched brighter contrast zones. The zones are produced by small fluctuations of Mg and Fe, which vary from almost equal amounts of oxides to a 3 weight % difference between FeO (8.47%) and MgO (5.5%).

In a similar situation, moderately large overgrowths from the Auburn location had

3 to 4 well-developed zones (Figure 4.5). Inner zones start by plotting in field 4 or close to the field 4 and 5 boundary with field 7. However, as is typical of the samples from around the Finger Lakes region, such as the Seneca Stone Quarry, Yawgers Woods, the Austeel Plant in Auburn, the Nedrow Exit locality, and Oriskany Falls, the fluctuations are more extreme and Fe drops to near 0 weight % FeO in the outermost zone of well-developed overgrowths, indicating depletion of Fe over time (Figure 4.5). The outer zones from these localities typically plot close to the dravite-alkali free dravite tie-line in field 7 on the Al-Fe-Mg ternary diagrams. This is the region of the diagram indicative of tourmalines forming in either a low Ca-metaultramafic rock or a Cr-, V-rich metasediment (Henry and Guidotti, 1985). In fact, the tourmaline grains do typically have V enrichment, and some have Cr enrichment. The enrichment of the overgrowths occurs as soon as they begin to grow from the detrital cores (Figure 4.41). The cores do not typically contain appreciable V or Cr (a strong argument against theories of formation by partial dissolution of detrital tourmaline and subsequent reprecipitation of authigenic tourmaline in the sandstone). Also as mentioned above, Ca is not incorporated in the overgrowths, but is common in the detrital cores, suggesting the environment of formation might be a Ca-poor environment (as suggested for tourmaline forming in this field [Henry and Guidotti, 1985]).

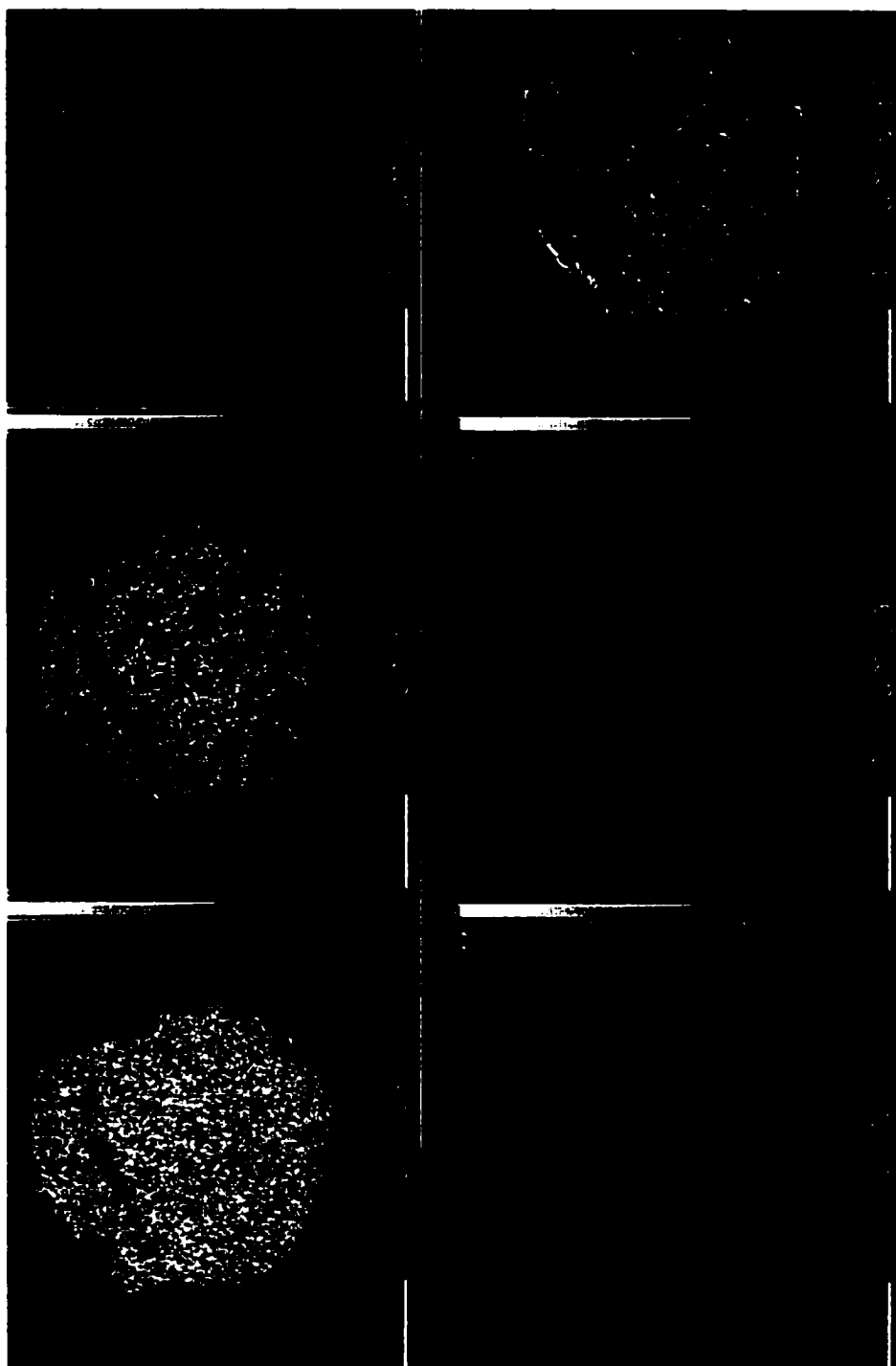
Detrital Tourmaline Cores

As can be seen above, detrital cores plot in a number of fields on Al-Fe-Mg ternary diagrams, indicating more diverse environments of formation than the overgrowths. The probable reasons the detrital cores plot in other fields are: 1) most importantly, many of

Figure 4.41. Elemental dot map of tourmaline with an overgrowth from Oriskany Falls, New York. This is the same tourmaline grain shown in Figure 4.17 (grain of 1g2). It has an unabraded to euhedral outline, and the outermost zone has a point of inflection that is believed to be a termination of the overgrowth.

Individual dots in the 5 of 6 boxes represent elemental presence or absence of the indicated element (see lower right of each box). Brightness of color corresponds to concentration of the element at that point on the map. The lower right box is a backscattered electron image (but a much better photograph is given in Figure 4.17). The elements analyzed for are, from upper right to lower center, V, Fe, Na, Mg, and Ca.

Notice that the overgrowth is defined by the vanadium map and that the absence of Ca in the overgrowth defines the rounded shape of the detrital core. V seems relatively constant in abundance, except in the innermost zone of the overgrowth, though small fluctuations are known to exist from microprobe transect (Figure 4.17). V is clearly present throughout the overgrowth, and the absence of V in the detrital core argues against the tourmaline forming from pressure solution and reprecipitation of detrital tourmaline. A magnesium-rich outer zone is clearly visible, and this would plot somewhere in field 7 on the Al-Fe-Mg ternary diagram. The interior zone also appears to have a slightly enriched Mg content. Fe seems slightly depleted in the innermost zone of the overgrowth, and careful observation will show that the outermost Mg-rich zone is actually absent on the Fe dot map.



the detrital cores are other species of tourmaline and are not in the schorl-dravite series; 2) the presence of elements other than Al^{3+} in Z site locations (Ti^{3+} is particularly common); 3) more marked changes in Fe and Mg occur in detrital cores than in the overgrowths; and 4) possible coupled substitutions involving the cations in any of the sites. The detrital cores mainly appear to be derived from metamorphic terranes, and apparently very little granitic or pegmatitic rock was available as a source for the detritus. Since the detrital cores are texturally mature, well rounded, and spherical in many instances, it is likely that they have been through multiple cycles of reworking and could potentially be very old. Similar mature sandstones with mature heavy mineral suites, comparable to the Oriskany Sandstone, have been deposited in the Appalachian Basin since the Cambrian (Tuttle, 1940; Krynine, 1946), so the diverse nature of the overgrowths may be a result tourmalines' great resistance to abrasion and chemical weathering, and of multiple episodes of reworking and mixing of detrital tourmaline suites (Hubert, 1962).

Vanadium and Chromium in Authigenic Tourmaline

Enrichment of V and Cr has not been reported for authigenic tourmaline, but vanadian tourmaline has been reported from metamorphic rocks. These metamorphic tourmalines typically have considerably more V or Cr than encountered in this study, but their occurrence may have some bearing on the origin of the tourmaline described here.

Most vanadian and chromian tourmalines reported in the literature are green colored; in this study only the highest vanadium-bearing tourmaline from the Austeel Plant in Auburn, New York, had a green color (Snetsinger, 1966; Webster, 1961). This

tourmaline had a maximum of 2.8 weight % V_2O_3 and almost 2.0 weight % Cr_2O_3 in the same grain (sample Spring 1). This particular grain appears to be reworked into an overlying sandstone termed the Springvale Sandstone by Baker (1983).

In the literature, Cr^{3+} typically substitutes for Al^{3+} in the Z structural site of tourmaline; while V^{3+} may substitute for Mg^{2+} or Fe^{2+} in a Y structural site, the charge increase being compensated for by a coupled substitution of Al for Si and vacancies in the X site (Kazachenko et al., 1993). Another possibility is that V^{3+} substitution in a Y site, for either Mg^{2+} or Fe^{2+} , creates a charge imbalance that is compensated for by loss of a Na^+ . This creates an alkali-defect tourmaline with the basic formula $\square(Y^{2+}_2, Y^{3+})Al_6(BO_3)_3Si_6O_{18}(OH)_4$, where $\square$ represents a vacancy in the X-site because Na^+ is dropped to nullify the charge imbalance (compare normal schorl or dravite with the formula $Na(Y^{2+})_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$) (Henry and Guidotti, 1985). X-site vacancies (particularly Na) due to V substitution for Mg and Fe would explain why the tourmaline in the New York samples would move toward the tie-line between alkali-free dravite and dravite.

The distribution of V in the overgrowths appears to influence zoning patterns in some overgrowths. Sometimes V fluctuations appear to act independently to create zones within regions where neither Mg or Fe fluctuations occur (Figure 4.17). (Either the replacement of Al^{3+} by V or alkali-defect tourmaline would create brighter zones because of vanadium's higher atomic weight creating contrast in BSE images.) But in other examples, even though V may increase in a particular zone, the contrast of the zone is more strongly influenced by Mg and Fe fluctuations, and the influence of V on the zoning

pattern is not apparent (Figure 4.5). When vanadium is present, it is usually present throughout the overgrowths and actually defines the extent of the overgrowths (Figure 4.41); but as mentioned above only some of the New York samples have significant V. Vanadium values in transects seem to fluctuate in a steady up-and-down pattern over 10s of microns. Small vanadium fluctuations seen in microprobe transects suggest that it is not being supplied at a steady state and that the up-and-down fluctuations represent changes in the supply of V over time. Since V increases and decreases do not always follow fluctuations of Mg and Fe, these elements appear to influence the uptake of vanadium.

Vanadium is not very concentrated in seawater, occurring at concentrations of about, 0.0003 ppm, but is concentrated by some marine organisms (holothurians and ascidians up to 57 ppm), organic compounds such as porphyrins in crude oil (0.1-1,600 ppm), and the average concentration in marine shales is about 130 ppm, although some black shales have up to 16,000 ppm (Goldschmidt, 1958; Krauskopf, 1977; Breit and Wanty, 1991).

Most V- and Cr-bearing tourmalines are found in graphitic host rocks and are suspected to get their V from organic-rich, marine shales, and this is often suggested as the source for other V-bearing minerals as well (Snetsinger, 1966; Dietrich, 1985; Kazachenko et al., 1993; Morand, 1990). In these scenarios, V and Cr are released during contact or regional metamorphism from an organic complex. V and Cr are often enriched in organic black shales, phosphorites, and kerogen, and during heating as rocks mature and release hydrocarbons the petroleum may carry the V to a new environment (Breit and

Wanty, 1991). However, under low-oxygen conditions in carbonaceous sediment vanadium can accumulate directly in sediments. Concentrations of up to 800 ppm in the solid fraction of recent sedimentary deposits have been documented (Breit and Wanty, 1990). Though this vanadium might become available for authigenic tourmaline, the conditions of accumulation are very different than in the Oriskany Sandstone.

The source of vanadium in the tourmaline is unclear, and V is not strongly concentrated in the samples of Oriskany Sandstone reaching only up to 10 ppm V. Often V is below the detection limits (5 ppm V detection limit) (the very low overall concentrations precludes concentration mechanisms such as flow rolls that concentrated both U and V in Colorado Plateau sandstones). However, V is much more concentrated in basal sandy Onondaga Limestone that contains phosphatic nodules (26 ppm) and isolated phosphatic nodules (104 ppm) at the Nedrow location, is also concentrated in the matrix-rich black sandstone at the Austeel plant in Auburn (165 ppm), and is found in highest concentration in the chamositic unit (575 ppm) and hematitic unit (618 ppm) on Interstate 81 south of Syracuse, New York. These higher concentrations are in line with findings from many authors for these types of deposits (Breit and Wanty, 1990) and are not surprising.

The relatively low concentrations in typical Oriskany Sandstone suggest that (as appears to be the case for boron discussed below) V may be almost entirely concentrated in the tourmaline overgrowths in the sandstone. Vanadium may have entered the sandstone in a fluid phase, or perhaps was released by organic material, leaving no traces; or V may have been present in the overgrowth tourmaline that was reworked into the

sandstone. Since V was available for tourmaline, it must have been in a reduced state as V^{+3} ion, indicating a low-oxygen reducing diagenetic environment at the time of formation of the tourmaline (Kazachenko et al., 1993). Though such conditions were clearly achieved during later diagenesis when ferroan cements form (Sternbach and Friedman, 1986; Foreman and Anderhalt, 1986), it is also possible that these conditions were achieved during deposition and that diffusion in the sediments could bring in vanadium. However, only relatively small amounts of vanadium have been documented to diffuse into sediments, and an estimated rate for carbonaceous anoxic bottom sediment is on the order of $1.0 \mu\text{gcm}^{-2}\text{yr}^{-1}$ that could, according to Breit and Wanty (1991) account for as much as 500 ppm concentration; however, diffusion was only active to 1 meter depth in their report from the Black Sea. Thus this seems an unlikely scenario in a sandstone that shows little evidence of accumulation under anoxic conditions. However, the unusual chamositic and phosphatic units' vanadium could be accounted for in this scenario since they most likely formed under low-oxygen conditions (Cotter and Link, 1993).

Thus if the V is not brought into the sandstone by reworking of the tourmaline overgrowths into the sandstone from some older unit, then either a very unusual concentration of V by marine organisms that releases the V upon decay of the organisms without leaving a trace or an external source for the V is most likely. If V is from an external source, perhaps a petroleum or related formational water seepage on the basin floor, then the fluid would most likely have to come from moderate depths of perhaps 2 km, assuming a geothermal gradient of $\sim 25^\circ\text{C}$ per km, given that vanadium is lost to

migrating fluids from porphyry systems at temperatures beginning at about 50°C (Breit and Wanta, 1991).

This possibility, that vanadium is released at depth, suggests that the tourmaline overgrowths more likely grew at a greater depth, but since the tourmaline could not have reached such depths after the time of deposition to allow for reworking of the tourmaline into the basal Onondaga Limestone and Springvale Sandstone, this line of evidence suggests that tourmaline overgrowths did not form in the Oriskany Sandstone at all.

Origin of the Overgrowths

To explain the formation of tourmaline in strata-bound deposits, most authors have either suggested a fluid phase carrying constituents to the unit where the tourmaline forms or an unusually boron-rich host rock (Ethier and Campbell, 1977; Slack, 1996). In either case some type of maturation, arrival of late-stage plutonic fluids or concentrated brines or heat driving off boron absorbed to clay particles during deep burial or metamorphism, caused tourmalinization. The problem with accepting maturation with the Oriskany Sandstone acting as its own source rock for constituents for tourmaline overgrowths is that: 1) evidence suggests early formation of overgrowths; 2) quartzarenites are not rich in constituents necessary for growth of tourmaline; and 3) early reworking of tourmaline suggests that not much time or depth of burial could be involved in tourmaline formation. Thus it is hard to envision a boron-rich phase formed during deposition maturing and causing tourmalinization in the Oriskany Sandstone.

The problem of accepting an external source for constituents necessary to form

tourmaline is that no tourmalinizing fluid from an external source has yet been documented.

There are at least 4 possibilities for the origin of the tourmaline in the Oriskany Sandstone: 1) Though the constituents necessary to form tourmaline are not enriched in typical quartzarenites, it might be possible that the tourmaline precipitates directly from seawater (Krynine, 1946) or at least from pore fluids in a near-surface environment where pore fluids could be recharged by marine waters. 2) The overgrowths might have formed in another sediment type alongside the Oriskany Sandstone and been transported to the quartzarenite environment. 3) Tourmaline never actually formed in the Oriskany Sandstone, but is derived from some other unit that was being eroded all along the basin margin, and local differences in abrasion and chemistry are related to local rates of erosion and abrasion and to local variations in the source of the tourmaline. Or 4) evidence of late-stage authigenic tourmaline formation has been missed and an external source for constituents is implicated.

If a direct or early precipitation from marine-derived pore fluids is considered, one important consideration is the amount of boron necessary to form tourmaline. As pointed out by Ethier and Campbell (1977), boron is the constituent most likely to be a limiting factor in tourmaline formation, and most hypotheses for strata-bound tourmalinites require high boron concentrations as well (Slack, 1996). If the amount of tourmaline can be related to boron concentration, it might be possible to evaluate the feasibility of direct precipitation without an external source. Though only approximate, Stow (1931) found no more than 0.2 weight % heavy minerals in any Oriskany Sandstone samples; in this

study the maximum amount of tourmaline in any sample was 77%, of which a maximum of 96% of the grains were overgrown; overgrowths by visual inspection never make up more than a third (and usually make up much less) of the volume of tourmaline. Based on these maximal estimates, less than 0.05 weight % authigenic tourmaline is present in the samples.

Based on calculations given by Ethier and Campbell (1977), if authigenic tourmaline is the only constituent that contains boron formed during authigenesis, the rock has gained only about 14 ppm boron during authigenesis. Given that whole rock data from quartzarenites from the Seneca Stone Quarry, Oriskany Falls, Auburn, and Yawgers Woods localities contained 20, 19, 16, and 22 ppm boron respectively and that at least 66% is from detrital cores, it is clear that estimate is within reasonable expectations. Since normal seawater contains about 4.6 ppm boron, it is possible to generate the concentration in the sandstone resulting from authigenic tourmaline by only exchanging pore fluid volumes a relatively few times (Krauskopf, 1979). These results support the possibility of a direct seawater precipitation or early diagenetic model without need for an external source for boron if a moderate water/rock ratio is assumed during formation. Other constituents such as Al, Mg, Fe, and Na might be derived either from the breakdown of unstable silicates such as feldspar, garnet, or hornblende, or might come from as yet undetected thin ash deposits (as discussed in Chapter 1, Acadian tectonism was active in Maine at the time and temporally ash could have been available).

Evidence that the tourmaline overgrowths formed in another sediment alongside the Oriskany Sandstone and were reworked into the Oriskany Sandstone is lacking.

There is also no known facies forming alongside the Oriskany Sandstone that appears more conducive to tourmaline overgrowth formation. In many instances tourmaline overgrowths do show evidence of reworking, and though some localities appear to have tourmaline growing in them, they might be reworked and only transported a small distance, escaping much evidence of abrasion. Though examples of quartz intergrown with tourmaline suggest that overgrowth formation may be early and penecontemporaneous with quartz formation, it does not necessarily mean that these composite grains formed in the Oriskany Sandstone. These compound grains that survived sample processing and heavy mineral separation might also indicate an ability to survive reworking.

Alternatively, though no petrographic evidence so far supports this possibility, either deep burial and compaction or alternatively overthrusting can generate fluids (brines and/or petroleum) from shales that could be enriched in constituents necessary for the formation of authigenic tourmaline (Dorobek, 1989). Magnesium- and iron-rich fluids generated from compaction of shales are capable of forming minerals such as ferroan dolomite (Mg and Fe) (Stemberch and Friedman, 1986). These fluids can be generated from the transformation of smectite or montmorillonite clay to illite in shales, and when this happens adsorbed boron could also be released to form tourmaline (Eithier and Campbell, 1977; Dietrich, 1985; Slack, 1996). Such fluids are often suggested in the mechanism of petroleum generation and migration as well (Selley, 1985; Friedman and Sanders, 1982) and have been suggested for tourmaline formation in older rocks in the Appalachian Basin.

The strongest evidence of this deep burial origin comes from vanadium found in relatively high concentrations in the New York overgrowths. As discussed above, vanadium is usually not concentrated in quartzarenites, and it is not particularly concentrated in the Oriskany Sandstone. The fact that V is concentrated in the unusual facies of the Springvale Sandstone and phosphatic facies of the basal Onondaga Limestone would then be coincidental and a result of the fact that these facies concentrate vanadium.

CHAPTER 5

CONCLUSIONS

The Oriskany Sandstone is easily identified and an excellent unit for correlation all along its exposure. Conditions of deposition and sources of detritus must have been very similar to create such a homogenous sandstone unit throughout the Appalachian Basin from New York to southern Virginia (Stow, 1931).

Geographically, the Appalachian Basin was located in southern latitudes at the time of deposition and was in a tropical to subtropical climatic zone within the carbonate depositional belt. Evidence from this study and provided by many workers (see Table 1.1) supports the idea that the Oriskany Sandstone was deposited under marine conditions during the initial transgression of the sea following the Wallbridge Unconformity. Large-shelled brachiopods thrived in this environment, and correlation of the unit based on these fossils is relatively easy. The sediments were derived by reworking of older Paleozoic sandstones, and a mature mineralogy and texture of detrital grains resulted (Figure 3.40). This led to the formation of quartzarenites that are very similar petrographically along the entire length of the deposit.

Except for a few incidences where chert becomes important in conglomeratic units such as the Connelly Conglomerate in the Green Pond Outlier, the unit remains a quartzarenite. Small amounts of detrital feldspar are present in most samples, but mica and ferromagnesian silicates are rare.

Samples from the Green Pond Outlier generally lack feldspar, have increased

quantities of polycrystalline quartz and chert, lack tourmaline with overgrowths, and have more abundant hyacinth zircon than other samples. Both the coarse grain size and mineralogy suggest that the Connelly Conglomerate and Central Valley Sandstone are derived from a different, and most likely local, source in the Reading Prong.

The Oriskany Sandstone is cemented by either quartz or carbonate or a combination of these two. Well-developed quartz overgrowths are frequently encountered in the sandstone; the overgrowths often have a dust line separating them from the detrital grain. However, some grains without dust lines are difficult to distinguish from quartz grains sutured together by compaction. Cathodoluminescence revealed that several samples without dust lines actually were cemented by pervasive quartz cement and had not been sutured. Strongly sutured contacts and brittle deformation that fractured quartz grains were common in the Green Pond Outlier samples, which were subjected to strong stresses during deformation.

Though only investigated in New York and Maryland, carbonate cement is an important constituent. It was lacking in most southern samples in exposures visited and in the Green Pond Outlier, most likely due to dissolution during uplift and recent weathering, but information from other authors is used to fill in the gap in the data. Pervasive carbonate cement in some samples and anhedral calcite in the vicinity of unaltered shell material appear to be early formed. Many shells are also still calcitic. Anhedral dolomite appears to form next and often lines the outer portions of pores that are later filled with anhedral ferroan calcite or dolomite. Anhedral and rhombic ferroan cements often seem to become more iron-rich in the interiors of pores, grading from

luminescent red to a nonluminescent dark color in the interior of pores. Saddle dolomite often is nonluminescent and is associated with late pyrite that in some instances rims the dolomite rhombs and in other instances replaces dolomite. There is some early pyrite as well, and this is often found in pore throats or encased in later carbonate cements.

Feldspar overgrowths have only been found in New York. There is unequivocal petrographic evidence that indicates that feldspar overgrowths form in the sandstone, and it appears that they form relatively early and intergrow with quartz overgrowths in some cases. The source of the constituents forming the feldspar overgrowths is still uncertain, and either a local isochemical source for chemical constituents from dissolving detrital grains or a direct deposition from modified seawater in early diagenesis could have formed the overgrowths (Woodward, 1972; Kastner and Siever, 1979). It is also possible that a fluid migration event influenced rocks in the northern Appalachian Basin during the Early Devonian between 408 and 386 Ma. This event, which is well documented in the Midcontinent region, is believed to have derived its K-feldspar-forming brine from a source in the Michigan Basin. Duffin et al. (1989) indicate that distal fluids from that event could have traveled as far as central New York.

Because there is quantitatively so little feldspar in the sandstone (less than 1% in most samples with overgrowths), not enough observations were made to rule out any of these possibilities. Further investigation will be needed to confirm the origin of the feldspar overgrowths.

A generalized paragenetic sequence for the Oriskany Sandstone is proposed, based on thin-section petrography, scanning electron microscopy (SEM), electron

microprobe, and cathodoluminescent petrography. The sequence is as follows: early? formation of tourmaline overgrowths (all tourmaline may be reworked) and contemporaneous quartz and calcite cements, followed by feldspar overgrowths, then dolomite, then during deep burial ferroan dolomite and ferroan calcite, and then pyrite (somewhat overlapping with ferroan carbonates). During uplift some carbonate cement is leached, dolomite is partially replaced by calcite, and shell material is lost, creating vug porosity. When exposed to near-surface conditions, pyrite and ferroan carbonates are oxidized to limonite, and some clay minerals infiltrate from above.

Authigenic tourmaline overgrowths are extremely abundant, but two distinctive types occur: abraded and euhedral. SEM was important in documenting the continuum from euhedral to slightly abraded, moderately abraded, and strongly abraded. No previous SEM micrographs have been published, and though Tuttle (1940) reported abraded overgrowths in Ordovician sandstones in the Appalachian Basin, he did not describe the extent of and variation in abrasion of the overgrowths. It was found that a range of textures occurred in a single sample, partially due to composite quartz-tourmaline grains that sheltered some overgrowths from abrasion, but sample localities could still be characterized as having a certain range of abrasion for the locality (Table 4.2).

SEM analysis has led to a better understanding of the morphology of overgrowths. They are not single masses of tourmaline, but are composed of blade-like crystallites that form sheaths and grow together to form terminations and crystal faces. The failure of crystallites to grow, perhaps due to obstructions on the surface of the detrital cores,

creates pores or cavities in the overgrowths that typically disappear as the crystals grow. These cavities are what Krynine (1946) described as a zone of roots, but his interpretation of them as being solution pits in the detrital cores was incorrect.

Quartz-tourmaline in composite grains was investigated by both backscattered electron microscopy (BSE) and SEM, and several relationships were discovered. Authigenic quartz can grow onto preexisting tourmaline overgrowths, either abraded or euhedral, creating composite grains. Tourmaline was also found to grow onto quartz grains and to penetrate into openings in quartz. Sometimes already-present quartz overgrowths were intercepted by growing tourmaline. This led to the conclusion that quartz overgrowths and tourmaline overgrowths form penecontemporaneously. As a last relationship, some quartz grains clearly were pressed into tourmaline overgrowths by compaction, creating composite sutured grains. Grains from at least one location, Minnehaha Springs, West Virginia, were abraded before this happened.

As well, BSE and SEM along with optical microscopy were used to discover never-before-reported growth zoning in the overgrowths. Up to 10 zones were found in some overgrowths. Well-developed zones with internal deflections of zones indicating prior terminations on the overgrowth crystals are common. Less common interior zigzag zones followed by normally banded zones were seen at Oriskany Falls, New York; undulose, more diffuse zones that occur throughout the overgrowths, side by side with normal zones and after normally banded zones stop, were found on some grains at the Seneca Stone Quarry, Seneca County, New York.

The truncation of zones by later abrasion was evident at many sample locations

(Table 4.2), and more surprisingly the offsetting of the zones in one deeply buried sample (Crandall Estate Well #1, at a depth of 4,999 ft [1523 m]) is evidence of microstylolites that affected individual tourmaline overgrowths in the heavily stylolitized sandstone. Interpenetrating of quartz and tourmaline in this sample resulted from pressure solution. Authigenic tourmaline was also found to “heal” cracks in detrital tourmaline grains.

The chemistry of the overgrowths' zones was investigated by wavelength dispersive x-ray analysis microprobe transects (WDS) that gave the chemical abundance of major and trace elements without analysis of light elements such as boron, fluorine, lithium, hydrogen, and oxygen. Several transects were also made using a special light-element-detecting multilayer synthetic spectrometer, and boron was analyzed. Boron remains relatively constant at about 10 weight % B_2O_3 throughout both the cores and overgrowths.

The analysis of the zones shows that fluctuations in Mg and Fe are responsible for the zoning pattern in most cases. These fluctuations, with as much as almost 10 weight % difference in FeO between adjacent zones, are responsible for the contrast differences seen in BSE. Differences of as little as ~0.5% cause detectable zoning. In some samples Mg and Fe fluctuated back and forth without any obvious depletion, creating up to 6 zones in the overgrowths. These tourmalines plotted in fields 4 and 5 on Al-Fe-Mg ternary diagrams. In many of the well-developed overgrowths from central New York, around the Finger Lakes region, a depletion of Fe is seen as the trend, and the final zone is often a nearly pure dravitic or alkali-free dravitic composition that gives an extremely dark outer zone in BSE. As well, many of the New York localities have significant

amounts of vanadium in the overgrowth. The vanadium appears to create zones in some sample localities, and the zones are similar to those created by Mg and Fe fluctuations.

Chemically, the tourmaline overgrowths are all in the schorl-dravite series.

Despite the zoning, overgrowths from all locations always have starting compositions in either field 4 or 5 on Al-Fe-Mg ternary diagrams. The depletion of Fe leading to nearly pure dravite to alkali-free dravite only occurs in New York samples from around the Finger Lakes and at Oriskany Falls that plot in field 7.

The detrital cores are more diverse, and tourmaline plots in a wide range of fields on Al-Fe-Mg ternary diagrams, but almost never in fields 1, 7, or 8. The detrital cores plot predominantly in fields 4, 5, and 6 that are consistent with initial derivation mainly from metamorphic terranes, though a proximal source in an older sandstone is indicated by the texture and heavy mineral maturity of the samples. Tourmalines from granites and pegmatites and their associated tourmalinized country rock typically plot in field 2 on these diagrams, and tourmalines of this composition are quite rare.

Because there is quantitatively very little authigenic tourmaline in the Oriskany Sandstone, perhaps a maximum of 0.05 weight % in typical samples, it is possible that boron for tourmaline formation is derived from seawater without much modification, and other constituents to form tourmaline may be derived from the degradation of unstable silicate minerals in the sandstone.

There are problems with this theory because petrographic evidence of direct formation in the sandstone is somewhat ambiguous, and stratigraphic reworking from an older formation that may have been more deeply buried when the tourmaline formed is

possible.

Vanadium and chromium in significant quantities were found in overgrowths from some of the New York samples, but were not found in the Maryland or West Virginia samples. It is proposed here that a local origin is responsible for these elements, and it is interesting to note that the same samples that plot in field 7 on Al-Fe-Mg ternary diagrams are the overgrowths that contain V and Cr. Field 7 is the field for Cr- and V-rich metasedimentary rocks, and it is shown here that authigenic tourmaline can also occur in this field (Henry and Guidotti, 1985). V^{3+} and Cr^{3+} probably were made available in a low-oxygen, reducing diagenetic environment and substitute in the Y and Z structural sites of the tourmaline. A coupled substitution to take care of charge imbalances when V^{3+} substitutes for Mg^{2+} or Fe^{2+} probably results in the X-site vacancies that are indicated by alkali-free dravite.

Though the source of V is still somewhat unclear, how V enters the overgrowths is significant to interpreting their origin. V is not concentrated in the Oriskany Sandstone, reaching only about 10 ppm. Vanadium in overgrowths has a maximum of 2.8 weight % V_2O_3 . Vanadium has not been previously reported in authigenic tourmaline, but does occur in metamorphic tourmaline.

Though V can be available in a sedimentary depositional environment, it is usually a low-oxygen reducing environment that is accumulating organic material that complexes the V. It has been suggested by several authors that V^{3+} only becomes available for silicate rocks during heating and maturation of carbonaceous source rocks at relatively high temperatures of at least 50° C (Kazachenko et al., 1993; Breit and Wanty,

1990). Sarwar and Friedman (1995) propose a geothermal gradient of between 25 and 30°C for the Appalachian Basin in New York; this would suggest that burial could have been as deep as 2 km when the tourmaline overgrowths formed. Alternatively, a fluid (probably petroleum) migrating into the Oriskany Sandstone could have formed the overgrowths, but it did not leave an elevated V level in the whole rock, just the tourmaline. This seems unlikely, and since both euhedral and slightly abraded tourmaline at Oriskany Falls have V in elevated levels, it is unlikely that only some tourmaline formed in the Oriskany Sandstone and some was reworked into it. More likely all the tourmaline is reworked.

Though the tourmaline overgrowths may not form in the Oriskany Sandstone, both the petrographic and geochemical data presented here clearly demonstrate that the tourmaline overgrowths are not a result of metamorphism and form under sedimentary conditions. If the tourmaline had come from a metamorphic source, the presence of relatively unabraded tourmaline overgrowths in a sandstone would be expected to be accompanied by less mature sediments, micas, feldspar, and other metamorphic minerals such as garnet or kyanite. That these metamorphic constituents are absent argues strongly for the authigenic origin.

Because only quartz has been found to intergrow and associate with the tourmaline, it is suspected that the overgrowths form in another quartz-rich sandstone.

In New York, the only place where vanadian tourmaline overgrowths were found, reworked tourmaline overgrowths with high vanadian compositions were also found in basal Onondaga Limestone (sandy limestone) at Nedrow, in the Springvale Sandstone

facies at the Austeel plant in Auburn, and in the Skaneateles Core. These tourmaline overgrowths are moderately to strongly abraded and may be polycyclic in origin, being first derived from a pre-Oriskany sandstone and then reworked from the Oriskany Sandstone. Though the vanadium content is consistent with a source from the Oriskany Sandstone (perhaps only proximal), their highly abraded nature makes it hard to compare them to Oriskany Sandstone samples, but when compared they are not identical in zonation pattern and some have even higher V levels than in the Oriskany Sandstone samples. However, perhaps more success could be made comparing New York Oriskany Sandstone samples to older samples, if they exist, because many of the New York overgrowths from the Oriskany Sandstone are only slightly abraded.

Tourmaline overgrowths have already been found in Cambrian and Ordovician sandstones in Pennsylvania and Virginia (Krynine, 1946, Tuttle, 1940), and they may occur in rocks of this age in New York. Armed with new information on the tourmaline overgrowths' geochemistry and zonation properties, perhaps other tourmaline overgrowths in older units could be searched out and a comparison to Oriskany Sandstone tourmaline could be made.

The answer to whether authigenic tourmaline forms in the Oriskany Sandstone may not be solved by further petrographic analysis of the Oriskany Sandstone, but might be resolved by further stratigraphic analysis of older units in the New York vicinity with petrographically identical tourmaline that can be proven as a source for the Oriskany Sandstone. What would be needed is to find tourmalines with similar zonation patterns and chemistries to the tourmalines described here.

It is believed that the information presented in this study will have value to future studies and that the techniques developed and discoveries made here will be of use to future investigators.

APPENDIX 1
PETROGRAPHIC POINT COUNTS

Explanation of Petrographic Point Counts

Qm = monocrystalline quartz

Qp = polycrystalline quartz

CO₃ cement = carbonate cement

PO₃ cement = phosphatic cement

K-feld = potassium feldspar

Chert = detrital microcrystalline and authigenic quartz

Sed. rock = sedimentary rock fragments

Pore = intergranular and intragranular porosity

Clay = all clay minerals in intergranular positions

Fossil CO₃ = carbonate fossils

Opaque = any opaque substance; most is pyrite

Heavy mineral = nonopaque detrital minerals such as zircon, tourmaline, and rutile

tr. = trace amounts not point-counted but observed

	Qm	Qp	CO ₃ Cement	PO ₄ Cement	K-feld	Chert	Sed. Rock	Pore	Clay	Fossil CO ₃	Opaque	Heavy Mineral	Total
Auburn	433	0	22	0	tr.	0	0	2	0	43	0	0	500
Austeel plant	426	0	15	0	3	0	0	0	0	53	3	0	500
Austin Glen, Glenerie Ls.	82	1	364	8	0	26	0	0	0	16	3		500
Carrigan Quarry	483	9	8	0	tr.	0	0	0	0	0	0	0	500
Cherry Valley	290	0	141	0	0	0	0	0	0	66	3	0	500
Crandell Estate Well #1 Nedrow	455	0	25	0	5	0	0	11	0		4	0	500
Onondaga Ls. Nedrow PO ₄ nodule	171	5	315	0	tr.	0	0	0	0	9	0	0	500
Oriskany Falls	430	0	60	0	tr.	0	0	10		0	0	0	500
Seneca	409	3	81	0	tr.	0	0	0	0	7	0	0	500
Skan. core	389	3	64	13	6	0	0	0	0	12	13	0	500
Yawgers Wood	455	0	17	0	6	0	0	7	0	12	3	0	500
I-81 samples contain hematite and chamosite ooids & matrix	Qm	Qp	CO ₃ Cement	Chamo- site ooids	Chamo- site matrix	K-feld	Sed. Chert	rock	Pore	Clay	Fossil CO ₃	Opaque	
black I-81	219	10	5	74	184	0	8	tr.	0	0	tr.	tr.	500
	Qm	Qp	CO ₃ Cement	hema- tite ooids	Chamo- site ooids	hema- tite matrix	K- feld	Che rt	Sed. rock	Pore	Clay	Fossil CO ₃	
red I-81	204	2	4	59	9	209	0	1	2			10	500

	Qm	Qp	CO ₃				Sed.			Fossil			
			Cement	Matrix	K-feld	Chert	rock	Pore	Clay	CO ₃	Opaque	Heavy	Total
Bowl O Fun	196	299	0	5	0	0	0	0	0	0	0	0	500
Highland Mills	165	265	0	35	0	35	0	0	0	0	0	0	500
Pea Hill	124	231	0	98	0	12	35	0	0	0	0	0	500
	Qm	Qp	CO ₃ PO ₄				Sed.			Fossil			
			Cement	cement	K-feld	Chert	rock	Pore	Clay	CO ₃	Opaque	Heavy	Total
Stroudsburg	456	44	0	0	0	0	0	0	0	0	0	0	500
Cumberland conglomerate sample	250	56	139	0	tr.	9	0	0	0	46	0	0	500
Cumberland ss	384	11	91	0	9	0	0	0	0	0	5	0	500
Tonoloway Ridge	473	22	0	0	tr.	2	0	3	0	0	0	0	500
Dolly Sods	417	3	0	0	3	0	0	47	30	0	0	0	500
Franklin	427	6	0	0	17	0	0	32	13	0	5	0	500
Greenland Gap	463	2	0	0	11	1	0	19	3	0	1	0	500
Minnehaha Spr.	453	3	0	0	2	0	0	36	4	2	0	0	500
Warm Springs	416	28	0	0	4	0	0	36	11	0	3	2	500

APPENDIX 2
HEAVY MINERAL POINT COUNTS

APPENDIX 2

HEAVY MINERAL POINT COUNTS

Heavy Minerals	Rutile	Tour- maline	Zircon	Total	% Tour- maline	% Zircon	% Rutile	% Tour Over- growths
Auburn	5	79	116	200	39.5	58.0	2.5	75.9
Austeel	1	19	180	200	9.5	90.0	0.5	31.6
Carrigan Quarry	6	16	176	198	8.1	88.9	3.0	50.0
Cherry Valley	2	41	157	200	20.5	78.5	1.0	0.0
Crandell Estate Well #1	0	114	86	200	57.0	43.0	0.0	94.7
Nedrow Exit	6	28	165	199	14.1	82.9	3.0	32.1
Oriskany Falls	2	115	79	196	58.7	40.3	1.0	89.6
Seneca	1	154	45	200	77.0	22.5	0.5	95.5
Skam. Core	3	89	108	200	44.5	54.0	1.5	79.8
Syracuse I-81	10	89	101	200	44.5	50.5	5.0	0.0
Yawgers	12	128	60	200	64.0	30.0	6.0	70.3
Bowl O Fun	2	15	183	200	7.5	91.5	1.0	0.0
Highland Mills	9	33	158	200	16.5	79.0	4.5	0.0
Pea Hill	6	26	168	200	13.0	84.0	3.0	0.0
Stroudsburg	0	37	163	200	18.5	81.5	0.0	0.0
Cumberland	4	34	162	200	17.0	81.0	2.0	20.6
Tonoloway Ridge	6	146	48	200	73.0	24.0	3.0	82.2
Dolly Sods	9	49	143	201	24.4	71.1	4.5	26.5
Franklin	2	90	108	200	45.0	54.0	1.0	28.9
Greenland Gap	7	102	90	199	53.1	46.9	3.6	77.5
Minnehaha	6	38	156	200	19.0	78.0	3.0	65.8
Warm Spring	1	15	184	200	7.5	92.5	0.5	86.7

APPENDIX 3
MICROPROBE STANDARDS

Sample name: Orthoclase OR-1					Formula: KAlSi_3O_8					
Source: Ingamells					Method of analysis: classical					
SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	K ₂ O	MnO	Total
64.39	18.57					1.14		14.92		99.80
Additional elements			BaO							
			0.78							

Sample name: Anorthite					Formula: $\text{CaAl}_2\text{Si}_2\text{O}_8$					
Source:					Method of analysis: --					
SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
44.09	35.46	0.08	0.46		19.45	0.4		0.01		100.01
Additional elements			P ₂ O ₅	BaO	SrO					
			0.02	0.01	0.03					

Sample name: Hornblende-Kakanui					Formula: --					
Source: E. Jarosewich					Method of analysis: <i>Geostandards News Letr. 4</i>					
SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
40.37	14.9	12.8	10.92		10.3	2.6		4.72	0.09	98.75
Additional elements			K ₂ O							
			2.05							

Sample name: Fayalite					Formula: --					
Source:					Method of analysis: --					
SiO ₂	Al ₂ O ₃	MgO	FeO	Fe ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
29.22			66.36	1.32				0.04	2.14	99.18
Additional elements			H ₂ O							
			0.1							

Sample name: Albite-Tiburon					Formula: $\text{NaAlSi}_3\text{O}_8$					
Source: U.C. Berkeley					Method of analysis: --					
SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
68.74	19.37		0.06			11.79				99.99
Additional elements			K ₂ O							
			0.03							

Sample name: Wakefield Diopside					Formula: --					
Source: George Harlow					Method of analysis: EPMA					
SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
55.5	0.04	18.6	0.11		26	0.03		0.03	0.02	100.33

Sample name: Synthetic MgF_2 Formula: MgF_2

Source: J. Webster Method of analysis: --

Mg	F	Total
39.02	60.98	100

Sample name: V-grossular Formula: --

Source: M. Engi Method of analysis: Webel, classical

SiO_2	Al_2O_3	MgO	FeO	V_2O_3	CaO	Na_2O	Cr_2O_3	TiO_2	MnO	Total
38.7	20.9	0.5	0.05	3.3	35.1	0.1	0.19	0.25	0.75	99.84

Sample name: Rhodonite, Minas Geras Formula: MnSiO_3

Source: C. Klein Method of analysis: Gonyer

SiO_2	Al_2O_3	MgO	FeO	V_2O_3	CaO	Na_2O	Cr_2O_3	TiO_2	MnO	Total
47.02		3.91	2.32		1.48				45.2	99.93

Sample name: Scapolite Formula: --

Source: U.C. Berkeley Method of analysis: --

SiO_2	Al_2O_3	MgO	FeO	V_2O_3	CaO	Na_2O	Cr_2O_3	TiO_2	MnO	Total
54.23	23.3				9.12	7.59				98.67

Additional elements K_2O Cl
1.69 2.74

Sample name: MgCr_2O_4 Formula: MgCr_2O_4

Source: P. Suddaby Via I. Ridley Method of analysis: Stoichiometry

SiO_2	Al_2O_3	MgO	FeO	V_2O_3	CaO	Na_2O	Cr_2O_3	TiO_2	MnO	Total
		20.96					79.04			100

Sample name: TiO_2 Formula: TiO_2

Source: Semi-elements Method of analysis: --

SiO_2	Al_2O_3	MgO	FeO	V_2O_3	CaO	Na_2O	Cr_2O_3	TiO_2	MnO	Total
								100		100

APPENDIX 4
CHEMICAL ANALYSES OF TOURMALINE

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Auburng1											
Core											
0	35.39	25.35	8.20	12.32	0.14	3.22	1.19	0.00	1.20	0.17	87.18
4	35.30	25.41	8.23	12.37	0.00	3.11	1.25	0.05	1.13	0.13	86.98
8	35.36	25.67	8.07	11.87	0.00	3.02	1.13	0.03	1.11	0.20	86.45
Overgrowth											
12	37.21	31.43	9.36	4.43	1.36	0.36	1.86	0.11	0.12	0.00	86.23
16	38.17	33.00	10.29	2.46	0.46	0.06	1.91	0.02	0.01	0.04	86.42
20	38.02	33.24	9.72	3.21	0.83	0.00	2.08	0.00	0.00	0.00	87.10
24	37.76	33.27	9.93	2.33	0.82	0.00	2.05	0.00	0.11	0.00	86.27
28	37.77	33.40	10.58	1.74	0.91	0.01	1.95	0.00	0.00	0.06	86.43
32	38.54	33.37	11.86	0.07	0.89	0.00	2.19	0.09	0.00	0.08	87.09
36	38.13	33.29	11.60	0.02	0.78	0.03	2.22	0.08	0.00	0.03	86.17
40	38.16	33.19	11.73	0.02	0.94	0.00	2.28	0.07	0.01	0.00	86.39
44	38.19	33.13	11.52	0.02	0.86	0.00	2.20	0.16	0.00	0.01	86.09
48	37.93	33.26	11.71	0.03	0.86	0.00	2.17	0.03	0.05	0.00	86.03
52	38.37	33.17	11.41	0.07	1.07	0.00	2.22	0.12	0.08	0.00	86.51
56	37.96	33.09	11.70	0.00	0.92	0.00	2.17	0.17	0.00	0.03	86.04
60	37.68	33.41	11.45	0.06	1.07	0.00	2.17	0.07	0.00	0.00	85.91
64	38.14	32.99	11.81	0.00	0.92	0.04	2.12	0.08	0.02	0.00	86.12
68	38.08	32.94	11.66	0.01	0.87	0.00	2.26	0.09	0.03	0.00	85.94
72	37.60	32.88	11.69	0.00	0.98	0.00	2.33	0.05	0.04	0.00	85.57
76	37.81	33.01	11.89	0.10	0.73	0.00	2.22	0.01	0.01	0.03	85.81
80	37.46	32.68	11.85	0.00	1.04	0.05	2.26	0.00	0.02	0.03	85.38
Auburng2											
Core											
0	34.83	32.36	2.64	13.47	0.15	0.48	2.07	0.00	0.71	0.04	86.76
4	34.62	32.57	2.56	13.49	0.09	0.50	2.03	0.06	0.67	0.07	86.66
8	34.58	32.58	2.61	13.36	0.07	0.42	1.92	0.00	0.66	0.04	86.24
12	34.46	32.56	2.50	13.80	0.07	0.50	2.03	0.01	0.62	0.21	86.76
16	34.90	33.20	2.61	13.17	0.07	0.46	1.94	0.06	0.71	0.00	87.12
20	34.79	32.93	2.66	13.60	0.00	0.51	2.15	0.00	0.67	0.24	87.55
24	34.73	33.06	2.53	13.59	0.00	0.41	1.98	0.04	0.65	0.10	87.10
28	34.67	33.02	2.53	13.65	0.00	0.51	1.96	0.04	0.66	0.01	87.05
32	34.62	32.88	2.67	13.34	0.03	0.42	2.07	0.01	0.63	0.06	86.73
Overgrowth											
36	37.94	33.27	9.86	2.84	0.64	0.00	1.88	0.01	0.00	0.08	86.51
40	38.41	32.94	10.31	2.27	0.49	0.03	2.17	0.00	0.00	0.00	86.62
44	38.38	33.24	9.81	2.80	0.47	0.03	2.06	0.00	0.00	0.07	86.86

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
48	37.82	33.22	9.77	3.23	0.41	0.02	2.25	0.00	0.03	0.00	86.75
52	38.42	33.62	10.21	1.94	0.68	0.00	2.18	0.01	0.03	0.00	87.09
56	38.81	34.00	11.63	0.15	0.96	0.03	2.13	0.00	0.00	0.00	87.72
60	38.51	33.33	11.58	0.06	0.73	0.02	2.19	0.01	0.02	0.02	86.48
64	38.74	34.04	11.49	0.00	0.67	0.02	2.12	0.04	0.02	0.00	87.15
68	38.49	33.70	11.55	0.14	0.45	0.00	2.11	0.02	0.03	0.08	86.56
72	38.80	34.02	11.84	0.07	0.25	0.02	2.13	0.07	0.00	0.00	87.20
76	38.75	33.79	11.60	0.00	0.44	0.00	2.11	0.03	0.00	0.00	86.71
80	38.46	34.05	11.54	0.06	0.27	0.01	2.14	0.03	0.01	0.04	86.61
84	39.05	33.86	11.71	0.01	0.47	0.05	2.03	0.05	0.01	0.00	87.24
88	39.13	34.26	11.99	0.03	0.74	0.00	2.10	0.00	0.03	0.02	88.30
92	38.87	33.98	11.75	0.04	1.05	0.00	2.00	0.08	0.03	0.01	87.82
96	38.74	33.87	11.68	0.08	1.11	0.00	2.14	0.06	0.00	0.00	87.67
100	39.30	34.25	11.80	0.07	0.92	0.02	2.04	0.00	0.01	0.01	88.41
104	39.34	34.14	11.73	0.06	1.14	0.00	2.21	0.00	0.00	0.00	88.63
108	39.22	34.19	11.79	0.04	0.86	0.02	2.19	0.07	0.06	0.00	88.45
112	39.07	33.85	11.70	0.00	1.05	0.00	2.28	0.05	0.03	0.00	88.04
116	39.48	34.73	12.26	0.06	1.11	0.02	2.33	0.05	0.08	0.04	90.17
Auburng3											
Core											
0	33.61	32.82	2.16	14.07	0.03	0.98	1.56	0.04	0.66	0.26	86.20
4	33.54	32.64	2.21	13.70	0.06	1.07	1.76	0.00	0.65	0.17	85.81
8	33.78	32.77	2.12	13.66	0.00	1.17	1.64	0.00	0.68	0.21	86.04
12	33.65	32.35	2.14	13.37	0.14	1.07	1.68	0.00	0.67	0.07	85.15
Overgrowth											
16	37.45	32.34	9.96	2.42	0.91	0.02	1.92	0.05	0.00	0.02	85.09
20	37.36	32.26	10.15	2.62	0.58	0.02	1.95	0.00	0.03	0.00	84.98
24	37.40	32.56	9.41	3.18	0.61	0.02	2.10	0.00	0.00	0.00	85.27
28	37.43	32.97	9.91	2.47	0.97	0.00	2.19	0.04	0.00	0.06	86.04
32	38.05	32.62	11.35	0.21	1.01	0.00	2.16	0.09	0.02	0.00	85.51
36	37.86	33.08	11.25	0.08	1.28	0.02	2.09	0.00	0.02	0.00	85.68
40	37.73	33.35	11.37	0.08	1.39	0.00	2.08	0.03	0.02	0.00	86.06
44	37.66	33.03	11.28	0.06	1.17	0.00	2.07	0.03	0.04	0.13	85.46
48	37.71	32.99	11.26	0.03	1.04	0.00	2.18	0.11	0.04	0.00	85.35
52	37.72	33.04	11.10	0.02	1.20	0.05	2.14	0.11	0.00	0.08	85.46
56	37.53	32.46	11.26	0.12	1.31	0.01	2.12	0.15	0.03	0.00	84.98
60	37.50	32.78	11.32	0.05	0.88	0.03	2.21	0.12	0.01	0.00	84.91
64	37.59	32.86	11.32	0.05	1.01	0.05	2.04	0.11	0.01	0.08	85.11
68	37.17	32.68	11.15	0.00	1.26	0.00	2.15	0.06	0.00	0.00	84.47

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
72	37.30	32.99	11.26	0.05	1.22	0.06	2.17	0.01	0.01	0.00	85.08
76	37.01	32.76	11.13	0.07	0.96	0.00	2.04	0.00	0.00	0.05	84.02
80	36.71	32.07	11.22	0.02	1.11	0.01	2.18	0.07	0.00	0.02	83.41
84	31.55	27.64	9.72	0.07	0.92	0.00	1.82	0.01	0.00	0.00	71.72
Auburng4											
Core											
0	36.23	25.72	9.97	10.11	0.03	2.96	1.22	0.16	0.48	0.10	86.99
4	36.10	25.62	10.02	10.16	0.07	2.77	1.39	0.13	0.54	0.10	86.90
8	36.03	25.54	9.78	10.33	0.18	3.09	1.21	0.16	0.64	0.04	86.99
12	36.32	25.42	10.00	10.72	0.03	3.12	1.19	0.17	0.62	0.20	87.80
16	35.91	25.42	9.66	10.28	0.10	3.10	1.22	0.19	0.50	0.06	86.45
20	36.15	25.65	10.09	10.71	0.02	2.98	1.19	0.16	0.52	0.14	87.62
24	36.17	25.63	9.93	10.55	0.13	3.04	1.27	0.19	0.62	0.08	87.60
28	36.35	25.12	9.84	10.17	0.06	3.05	1.20	0.10	0.56	0.19	86.63
32	36.18	25.34	9.66	10.58	0.10	3.01	1.20	0.15	0.65	0.19	87.07
36	36.18	26.93	7.84	11.88	0.12	1.83	1.76	0.14	0.63	0.10	87.40
Overgrowth											
40	38.91	33.50	10.17	2.33	0.44	0.04	1.91	0.07	0.02	0.05	87.44
44	38.32	33.46	9.48	3.10	0.45	0.06	2.14	0.03	0.00	0.00	87.04
48	37.11	32.70	9.67	2.88	0.62	0.00	2.16	0.05	0.00	0.05	85.24
52	38.24	32.97	9.67	2.75	0.27	0.00	2.07	0.06	0.01	0.03	86.08
56	38.31	33.61	9.85	2.42	0.62	0.00	2.00	0.04	0.06	0.01	86.92
60	38.40	33.51	11.40	0.19	1.05	0.00	2.15	0.00	0.06	0.00	86.75
64	38.60	33.38	11.46	0.07	1.13	0.00	2.13	0.03	0.00	0.16	86.96
68	38.76	33.47	11.62	0.11	1.41	0.00	2.15	0.00	0.00	0.02	87.54
72	38.46	33.65	11.48	0.01	1.14	0.00	2.12	0.09	0.00	0.02	86.97
76	38.62	33.44	11.37	0.08	0.95	0.00	2.08	0.18	0.00	0.04	86.76
80	38.47	33.51	11.57	0.03	0.91	0.00	2.08	0.13	0.06	0.00	86.76
84	38.32	33.15	11.35	0.00	0.87	0.06	2.03	0.13	0.01	0.01	85.93
88	38.46	33.74	11.56	0.05	0.59	0.02	2.07	0.12	0.04	0.04	86.69
Aublb											
Core											
0	34.26	24.93	7.98	12.70	0.06	2.52	1.53	0.00	0.97	0.19	85.13
4	34.63	25.26	8.15	12.72	0.14	2.80	1.45	0.05	0.74	0.07	86.00
8	34.99	24.95	8.16	12.55	0.13	2.75	1.36	0.01	0.85	0.18	85.93
12	34.78	24.73	8.16	12.21	0.00	2.76	1.32	0.11	0.78	0.23	85.09
Overgrowth											
16	36.30	31.36	8.54	4.29	1.48	0.19	1.86	0.16	0.08	0.07	84.33
20	37.65	32.66	10.46	2.09	0.46	0.00	2.16	0.00	0.02	0.03	85.54

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
24	37.24	33.29	10.03	2.89	0.55	0.04	2.06	0.04	0.00	0.00	86.14
28	36.67	32.50	9.61	2.98	0.55	0.00	2.06	0.00	0.00	0.00	84.37
32	36.99	32.60	9.86	2.41	0.81	0.03	2.09	0.00	0.02	0.00	84.81
36	37.13	32.55	11.08	0.13	0.95	0.00	2.18	0.02	0.00	0.00	84.03
40	37.29	32.87	11.38	0.09	1.16	0.03	2.16	0.09	0.00	0.08	85.15
44	37.58	32.48	11.57	0.00	1.07	0.00	2.24	0.06	0.00	0.00	85.00
48	37.51	32.51	11.37	0.08	1.14	0.03	2.12	0.15	0.01	0.00	84.91
52	36.83	32.52	11.27	0.02	1.22	0.00	2.16	0.13	0.02	0.16	84.34
56	36.78	32.64	11.29	0.05	1.04	0.00	2.10	0.12	0.01	0.04	84.08
60	37.09	32.80	11.51	0.04	1.06	0.00	2.10	0.11	0.01	0.00	84.71
64	37.56	32.52	11.01	0.04	0.80	0.01	2.12	0.17	0.00	0.00	84.22
68	36.90	32.63	11.33	0.05	1.21	0.00	2.11	0.09	0.04	0.00	84.35
72	37.13	32.01	11.18	0.00	0.90	0.00	1.98	0.17	0.03	0.00	83.40
76	36.72	32.25	11.39	0.03	1.24	0.01	2.21	0.07	0.04	0.00	83.98
80	36.65	32.23	11.51	0.00	0.71	0.02	2.30	0.07	0.02	0.01	83.52
84	37.13	31.99	11.25	0.00	0.92	0.04	2.30	0.00	0.01	0.01	83.64
88	36.39	31.87	11.09	0.00	1.15	0.01	2.40	0.05	0.00	0.11	83.07
Aub1trans2											
Core											
0	35.09	24.89	8.17	12.16	0.11	2.81	1.41	0.00	0.88	0.09	85.61
4	34.91	24.66	8.18	12.41	0.16	2.69	1.31	0.02	0.96	0.22	85.51
8	34.75	24.66	8.08	12.24	0.09	2.74	1.37	0.06	0.94	0.10	85.03
12	35.02	24.97	8.09	12.25	0.02	2.69	1.37	0.06	0.77	0.10	85.34
16	34.65	24.62	8.49	12.61	0.10	2.67	1.33	0.00	0.94	0.12	85.52
Overgrowth											
20	35.41	27.94	5.69	13.15	0.06	0.32	2.28	0.00	0.73	0.01	85.59
24	36.73	32.09	9.58	2.42	0.73	0.00	2.11	0.00	0.01	0.00	83.67
28	37.27	32.59	10.16	2.22	0.47	0.01	2.22	0.06	0.04	0.00	85.05
32	37.41	32.52	9.65	2.56	0.42	0.00	2.15	0.05	0.02	0.07	84.83
36	36.78	32.99	9.58	2.63	0.49	0.00	2.05	0.03	0.01	0.00	84.57
40	37.15	32.47	9.39	2.92	0.41	0.00	2.22	0.01	0.00	0.00	84.57
44	37.08	32.25	9.20	3.26	0.53	0.00	2.24	0.00	0.01	0.08	84.65
Aub2b											
Core											
0	34.42	22.14	7.13	16.73	0.12	2.36	1.64	0.03	0.98	0.12	85.69
4	35.10	22.04	7.03	17.10	0.13	2.33	1.49	0.00	0.94	0.12	86.28
8	34.73	22.15	7.12	16.56	0.03	2.32	1.46	0.01	0.93	0.12	85.42
12	34.91	22.48	6.87	16.78	0.18	2.35	1.51	0.00	0.96	0.17	86.20
16	34.58	22.16	6.63	16.95	0.18	2.24	1.65	0.00	0.78	0.20	85.36

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Overgrowth											
20	36.30	32.63	5.08	9.15	0.03	0.05	2.03	0.01	0.81	0.00	86.11
24	36.36	33.03	5.11	8.88	0.09	0.00	1.95	0.03	0.69	0.00	86.14
28	36.26	33.25	5.10	8.90	0.00	0.03	1.93	0.00	0.30	0.00	85.78
32	36.52	33.11	5.11	9.05	0.09	0.05	1.72	0.01	0.23	0.00	85.89
36	36.27	32.64	5.19	8.97	0.00	0.06	2.04	0.01	0.81	0.00	85.98
40	37.51	32.48	9.07	2.95	0.82	0.01	1.91	0.14	0.01	0.08	84.99
44	37.99	32.62	9.96	2.10	0.46	0.06	1.92	0.05	0.00	0.01	85.16
48	37.44	32.92	9.38	3.27	0.49	0.00	1.93	0.00	0.04	0.00	85.47
52	37.62	32.76	9.27	2.60	0.43	0.03	1.91	0.05	0.00	0.00	84.68
56	37.63	32.84	9.65	2.49	0.66	0.01	1.97	0.00	0.00	0.00	85.26
60	37.61	33.01	10.50	1.36	0.79	0.00	2.17	0.04	0.04	0.00	85.51
64	38.06	33.15	11.13	0.07	0.85	0.00	2.19	0.03	0.04	0.03	85.55
68	37.94	32.79	11.33	0.09	0.83	0.02	2.02	0.03	0.03	0.01	85.10
72	37.62	33.11	11.14	0.04	0.62	0.00	2.01	0.00	0.01	0.00	84.55
76	38.03	33.37	11.20	0.05	0.38	0.04	2.05	0.07	0.00	0.00	85.19
80	38.00	33.02	11.20	0.00	0.19	0.00	2.10	0.07	0.00	0.00	84.59
84	38.14	33.19	11.26	0.04	0.21	0.03	2.11	0.06	0.05	0.06	85.15
88	38.37	33.19	11.40	0.00	0.26	0.03	2.31	0.01	0.01	0.09	85.68
92	37.96	33.16	11.09	0.09	0.50	0.00	2.15	0.03	0.00	0.07	85.05
96	37.91	33.03	11.28	0.11	0.49	0.04	2.18	0.02	0.04	0.00	85.09
100	37.98	32.89	11.17	0.12	0.58	0.00	2.24	0.14	0.01	0.00	85.13
104	37.74	32.63	11.17	0.04	0.94	0.05	2.25	0.03	0.02	0.06	84.94
108	37.58	32.85	10.95	0.03	0.62	0.08	2.05	0.00	0.00	0.00	84.16
112	37.55	32.42	11.07	0.04	0.94	0.00	2.09	0.05	0.08	0.00	84.23
Aub3btransl											
Core											
0	35.53	27.52	6.95	11.15	0.06	1.04	2.33	0.00	1.06	0.05	85.69
4	35.64	27.89	6.83	11.15	0.17	0.91	2.29	0.00	1.00	0.03	85.91
8	35.75	29.48	6.86	10.44	0.03	0.52	2.53	0.00	0.55	0.01	86.16
12	35.64	29.02	6.54	10.11	0.09	0.61	2.48	0.00	0.62	0.03	85.13
16	36.10	28.71	6.63	10.22	0.01	0.58	2.56	0.03	0.82	0.00	85.66
20	35.75	28.80	6.80	9.94	0.09	0.81	2.41	0.00	0.69	0.05	85.34
24	36.01	27.91	6.55	10.88	0.05	0.87	2.45	0.02	1.13	0.03	85.90
28	35.85	28.20	6.76	10.80	0.02	0.83	2.41	0.03	0.90	0.02	85.83
32	35.32	28.06	6.63	10.14	0.06	0.82	2.41	0.07	1.03	0.13	84.65
Overgrowth											
36	36.68	31.48	6.19	8.90	0.12	0.11	2.26	0.05	0.30	0.10	86.18
40	36.04	31.32	6.95	7.46	0.36	0.18	2.23	0.03	0.37	0.00	84.94

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
44	36.77	31.78	8.84	3.61	0.93	0.04	1.88	0.09	0.01	0.08	84.02
48	37.31	32.53	9.72	2.31	0.75	0.07	2.01	0.05	0.09	0.03	84.88
52	37.14	32.71	9.63	2.48	0.61	0.00	1.84	0.10	0.02	0.04	84.57
56	36.94	31.83	9.99	2.21	0.80	0.00	2.06	0.03	0.09	0.09	84.04
60	37.06	32.36	10.30	1.75	0.57	0.01	1.82	0.01	0.09	0.00	83.97
64	37.43	32.34	10.24	2.23	0.49	0.00	2.03	0.00	0.00	0.00	84.76
68	37.57	32.54	9.98	2.28	0.47	0.02	1.85	0.00	0.03	0.00	84.73
72	37.16	32.61	10.08	2.18	0.39	0.00	1.84	0.00	0.00	0.01	84.26
76	37.40	32.68	10.00	2.22	0.61	0.00	1.85	0.05	0.02	0.01	84.84
80	36.87	32.84	9.57	2.54	0.53	0.05	1.92	0.00	0.00	0.00	84.32
84	37.40	32.95	9.61	2.71	0.47	0.00	1.85	0.00	0.03	0.01	85.03
88	37.34	32.83	9.49	2.72	0.60	0.00	2.06	0.07	0.02	0.07	85.21
92	37.48	33.11	9.95	2.49	0.65	0.00	2.04	0.03	0.01	0.00	85.75
96	37.79	33.02	10.25	1.63	1.02	0.02	2.01	0.00	0.00	0.09	85.84
100	38.15	33.12	11.12	0.28	0.54	0.01	2.11	0.03	0.06	0.00	85.42
104	37.52	33.18	11.54	0.08	0.93	0.00	2.11	0.01	0.05	0.00	85.43
108	37.28	33.11	11.49	0.00	0.93	0.03	2.21	0.00	0.03	0.00	85.08
112	37.56	33.10	11.65	0.04	0.71	0.03	2.34	0.03	0.03	0.03	85.51
116	37.82	32.60	11.39	0.03	0.84	0.01	2.40	0.17	0.01	0.03	85.30
120	37.75	32.79	11.54	0.00	0.85	0.00	2.40	0.04	0.01	0.00	85.38
124	37.57	32.81	11.42	0.04	1.08	0.00	2.18	0.03	0.00	0.00	85.12
128	37.51	32.75	11.71	0.05	1.18	0.03	2.25	0.00	0.00	0.01	85.49
Aub3btrans2											
Core											
0	35.83	29.18	6.54	9.79	0.05	0.86	2.39	0.03	0.39	0.00	85.06
4	36.07	29.64	7.01	10.25	0.07	0.91	2.44	0.00	0.27	0.00	86.66
8	35.91	29.25	6.70	10.25	0.02	0.83	2.33	0.07	0.23	0.11	85.70
12	36.23	28.45	6.55	10.80	0.05	0.98	2.29	0.00	0.70	0.06	86.10
16	35.76	27.43	6.78	11.72	0.05	1.01	2.25	0.00	1.01	0.00	86.01
20	35.43	29.40	6.49	10.19	0.17	1.14	2.23	0.00	0.51	0.12	85.68
24	35.61	29.19	6.63	10.41	0.11	1.07	2.12	0.00	0.67	0.01	85.82
28	35.97	29.19	6.74	10.28	0.10	1.11	2.18	0.00	0.64	0.02	86.24
Overgrowth											
32	36.28	31.87	5.81	9.33	0.00	0.02	2.18	0.02	0.17	0.10	85.79
36	37.12	32.39	8.75	3.98	1.55	0.02	1.77	0.15	0.04	0.00	85.77
40	36.88	32.12	9.67	2.74	1.36	0.00	2.15	0.00	0.02	0.00	84.93
44	36.71	32.29	10.12	2.36	0.74	0.07	1.82	0.05	0.00	0.01	84.16
48	37.01	32.24	10.13	2.18	0.80	0.05	1.99	0.04	0.00	0.01	84.44
52	37.39	32.70	10.43	2.18	0.62	0.06	1.93	0.00	0.05	0.00	85.36

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
56	37.27	32.38	10.05	2.57	0.51	0.00	1.88	0.00	0.00	0.03	84.68
60	37.36	32.68	9.91	2.34	0.42	0.01	2.02	0.03	0.00	0.00	84.77
64	37.47	32.72	9.79	2.68	0.07	0.03	2.17	0.03	0.00	0.04	85.00
68	36.97	32.68	9.61	2.56	0.35	0.02	2.01	0.00	0.00	0.00	84.20
72	37.47	32.82	9.74	2.47	0.51	0.03	1.97	0.00	0.00	0.00	85.01
76	37.44	32.66	9.38	2.79	0.66	0.04	1.78	0.01	0.02	0.00	84.78
80	37.00	32.99	9.45	2.47	0.67	0.02	2.05	0.01	0.00	0.03	84.69
84	37.72	33.19	10.00	2.04	0.68	0.02	2.01	0.10	0.00	0.00	85.77
Aub4b											
Core											
0	36.59	26.34	11.11	6.87	0.00	2.42	1.54	0.05	1.23	0.02	86.16
4	36.04	26.36	11.00	7.22	0.10	2.59	1.59	0.00	1.24	0.13	86.26
8	35.90	26.15	10.72	6.84	0.03	2.54	1.62	0.11	1.25	0.01	85.18
12	36.25	25.87	11.01	7.13	0.00	2.60	1.64	0.07	1.15	0.00	85.72
16	36.08	25.56	11.05	7.43	0.15	2.72	1.51	0.02	1.39	0.03	85.94
20	36.31	25.52	11.24	7.66	0.06	2.60	1.61	0.02	1.30	0.11	86.43
Overgrowth											
24	37.43	31.88	10.11	2.96	0.85	0.20	1.81	0.01	0.03	0.01	85.27
28	37.69	32.50	10.07	2.81	0.19	0.03	1.93	0.02	0.00	0.03	85.27
32	37.61	32.60	9.51	3.20	0.58	0.00	2.10	0.05	0.00	0.00	85.65
36	37.32	32.86	9.84	2.77	1.06	0.02	2.20	0.00	0.00	0.00	86.07
40	37.77	32.70	10.35	1.96	1.22	0.00	2.11	0.01	0.00	0.03	86.16
44	37.75	33.06	11.46	0.12	1.23	0.01	2.14	0.05	0.00	0.00	85.83
48	37.53	33.18	11.37	0.01	1.52	0.00	2.15	0.10	0.00	0.00	85.87
52	37.77	32.76	11.35	0.03	1.33	0.01	2.20	0.03	0.03	0.00	85.50
56	38.00	33.02	11.53	0.09	0.56	0.00	2.21	0.22	0.03	0.09	85.75
60	37.75	33.26	11.79	0.02	0.62	0.01	2.21	0.10	0.00	0.00	85.74
64	37.86	33.33	11.64	0.03	0.59	0.02	2.21	0.15	0.04	0.01	85.88
68	38.15	32.94	11.68	0.07	0.70	0.00	2.15	0.15	0.01	0.00	85.85
72	38.06	32.98	11.58	0.10	0.40	0.01	2.25	0.18	0.02	0.00	85.59
76	38.01	33.17	11.44	0.01	0.45	0.02	2.18	0.15	0.09	0.04	85.56
80	37.81	33.02	11.43	0.03	0.83	0.00	2.13	0.00	0.00	0.00	85.25
84	37.72	33.07	11.19	0.00	0.82	0.05	2.08	0.07	0.00	0.06	85.06
88	37.68	32.67	11.56	0.10	0.95	0.00	2.09	0.15	0.06	0.02	85.27
92	37.54	32.52	11.67	0.00	0.93	0.03	2.16	0.06	0.02	0.08	85.02
96	37.29	32.51	11.54	0.00	0.99	0.00	2.26	0.09	0.00	0.01	84.70
100	37.32	32.41	11.55	0.07	1.10	0.02	2.24	0.03	0.00	0.03	84.77
104	37.07	32.06	11.35	0.06	1.12	0.04	2.13	0.08	0.00	0.08	84.00

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Austeel1											
Core											
0	35.8	27.3	9.03	9.4	0	3.46	0.99	0	0.4	0	86.35
4	35.9	27.4	9.04	10.2	0	3.41	1	0.02	0.5	0.06	87.51
8	35.7	27.2	8.95	9.46	0.14	3.32	0.92	0.07	0.64	0	86.46
12	35.8	26.9	9.05	9.65	0.06	3.45	0.98	0	0.55	0	86.44
16	35.4	27.6	9	9.66	0	3.54	0.92	0.07	0.68	0	86.89
Overgrowth											
20	36.1	29.5	7.2	7.58	1.83	0.1	1.98	0.98	0.06	0.04	85.31
24	38	32.4	9.61	3.08	1.02	0.03	2.04	0.35	0.04	0	86.50
28	37.7	32	9.64	3.39	1.53	0.03	2.26	0.52	0.02	0	87.07
32	37.2	31.3	9.7	2.98	2.26	0.05	2.38	0.67	0.06	0	86.60
36	37.3	31.1	9.98	2.92	2.82	0.04	2.39	0.63	0.07	0	87.19
40	37.4	31.7	10	2.72	2.17	0.02	2.43	0.94	0.01	0	87.34
44	37.4	31.2	10.3	2.43	2.31	0	2.4	0.98	0.02	0.03	86.98
48	37.3	31	10.4	2.34	2.17	0.01	2.26	0.84	0.07	0	86.37
52	37.6	31.4	10.3	2.08	1.66	0.01	2.25	0.92	0.04	0.04	86.36
56	37.6	30.9	11.3	0.02	1.73	0.03	2.31	1.94	0.04	0	85.79
60	37.8	31.3	11.6	0.03	1.81	0.02	2.31	1.99	0.01	0.04	86.86
64	37.9	31.5	11.5	0	1.55	0.04	2.29	1.47	0.03	0	86.36
68	37.6	31.5	11.8	0.04	1.86	0	2.31	1.3	0.04	0	86.47
72	38.3	32	11.8	0.03	1.71	0.01	2.27	0.97	0	0.03	87.15
76	38.1	31.4	11.5	0.03	1.58	0.08	2.22	1.46	0	0	86.37
80	37.9	31.7	11.7	0.07	1.94	0	2.2	1.19	0	0	86.77
84	37.8	31.6	11.8	0	1.68	0	2.32	1.44	0.01	0	86.65
88	37.7	31.5	11.7	0	1.97	0.02	2.31	1.55	0.1	0	86.84
92	38	31.2	11.7	0.03	1.73	0	2.28	1.34	0.07	0.08	86.44
96	38	31.7	11.7	0	1.73	0.03	2.19	1.43	0	0.09	86.94
100	37.9	31.8	11.6	0.02	1.44	0	2.27	1.47	0	0.08	86.64
104	38.1	31.6	11.6	0	1.5	0	2.18	1.15	0.01	0.06	86.14
108	38	31.6	11.6	0	1.42	0	2.24	1.15	0	0.07	86.06
112	38.1	31.9	11.7	0	1.65	0.03	2.22	1.3	0	0.11	86.97
116	38.2	31.9	11.7	0.01	1.67	0.03	2.3	1.37	0	0.04	87.14
120	37.8	31.9	11.7	0	1.84	0.03	2.29	1.11	0	0	86.64
124	38	31.9	11.6	0	1.77	0.01	2.29	1.17	0	0.06	86.85
128	37.9	31.4	11.6	0	1.46	0.04	2.3	1.31	0	0.04	85.96
132	37.6	31.4	11.7	0	1.51	0	2.3	1.22	0	0	85.73

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Austeel12-22b											
Core											
0	35	27	8.49	9.96	0	2.5	1.5	0.01	1.36	0	85.79
4	35	27.1	8.46	10.4	0	2.4	1.49	0.02	1.22	0	86.06
8	35	27.2	8.38	10.1	0	2.55	1.47	0	1.13	0	85.80
12	35	27.9	8.43	9.89	0	2.33	1.56	0	1.14	0.05	86.36
16	35.1	27.4	8.36	10.1	0.11	2.45	1.61	0	1	0	86.09
20	35.3	27.5	8.31	9.74	0.09	2.24	1.65	0.1	1.08	0.03	86.09
24	34.7	27.3	8.37	10	0.08	2.33	1.5	0.02	1.19	0.03	85.52
28	35.8	28.8	8.26	9.52	0	2.03	1.8	0	1.14	0.16	87.44
32	34.8	27.2	8.48	10.4	0.11	2.5	1.59	0	1.15	0.05	86.31
Overgrowth											
36	35.6	29.5	7.17	8.07	1.39	0.13	1.98	0.94	0.08	0	84.85
40	37.4	33.1	8.86	2.68	0.78	0.07	1.7	0.26	0.03	0	84.90
44	37.6	30.5	9.17	3.3	1.15	0.04	2.16	0.16	0.08	0	84.16
48	37.3	31.8	9.52	3.31	1.5	0	2.23	0.13	0.03	0.03	85.89
52	37	31.6	9.32	3.62	1.66	0.04	2.23	0.16	0.03	0.03	85.69
56	37.4	31.5	9.69	3.19	1.65	0.01	2.26	0.15	0	0.02	85.85
60	37	31.7	9.73	3.01	1.57	0.01	2.36	0.22	0.03	0.02	85.69
64	37	31.5	9.91	2.97	1.37	0.01	2.38	0.18	0	0	85.34
68	36.7	31.6	9.99	3.11	1.93	0	2.26	0.23	0.02	0	85.79
72	37.2	31.9	9.89	2.82	1.94	0.01	2.33	0.25	0.04	0	86.33
76	36.7	31.9	10	2.66	1.9	0.02	2.37	0.3	0	0	85.86
80	37	31.6	10.2	2.51	2.19	0.03	2.38	0.27	0.01	0	86.16
84	37.3	31.5	10.3	2.62	1.62	0	2.29	0.16	0.01	0	85.78
88	36.9	31.8	9.76	2.49	1.91	0.01	2.27	0.29	0	0.01	85.37
92	37.3	31.5	10.1	2.36	1.69	0.02	2.31	0.29	0.04	0.1	85.71
96	37.3	31.9	10.3	2.16	1.83	0.01	2.4	0.1	0	0.06	86.07
100	37.6	32.3	11.7	0.14	1.34	0	2.19	0.34	0	0	85.59
104	38	32.2	11.3	0.07	1.33	0	2.28	0.53	0.04	0	85.76
108	37.4	31.5	11.6	0.05	1.72	0.02	2.27	0.4	0	0.04	85.03
112	37.4	32	11.8	0.06	1.61	0.02	2.39	0.45	0	0.01	85.69
116	37.8	32.1	11.8	0.04	1.63	0.06	2.35	0.44	0.04	0	86.23
120	37.8	31.9	11.8	0.01	1.84	0.03	2.27	0.55	0.03	0.08	86.31
124	37.8	31.9	11.6	0.06	1.7	0	2.23	0.64	0.01	0	85.98
128	38	31.5	11.6	0.03	1.42	0.01	2.12	0.44	0.09	0.04	85.17
132	37.9	32	11.9	0	1.56	0.03	2.18	0.43	0	0.08	85.99
136	37.9	31.8	11.8	0.01	1.68	0.07	2.17	0.87	0.01	0.02	86.36
140	37.7	32	11.5	0	1.74	0.03	2.39	0.63	0	0	85.97

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
144	37.7	31.9	11.7	0.03	1.6	0	2.06	0.55	0.04	0.04	85.68
148	37.7	31.9	11.9	0.08	1.66	0.03	2.22	0.48	0	0.1	86.14
152	38	31.6	11.7	0.05	1.46	0.04	2.06	0.47	0	0	85.30
156	38	32.1	11.6	0	1.66	0.01	2.26	0.53	0.04	0.03	86.27
160	37.7	32.1	11.5	0.08	1.79	0	2.16	0.78	0	0.02	86.12
164	37.8	32.7	11.4	0.01	1.87	0	2.14	0.48	0.06	0	86.35
168	37.8	32.8	11.4	0	1.69	0	2.27	0.46	0.02	0	86.38
172	37.7	32.8	11.2	0.07	1.72	0	2.02	0.35	0	0.02	85.85
176	38.3	32.6	11.2	0	1.72	0.01	2.16	0.34	0	0	86.27
180	37.6	32.2	11.6	0	1.26	0	2.31	0.51	0	0	85.37
184	38	31.8	11.7	0.06	1.19	0	2.34	0.47	0	0	85.52
188	38	31.7	11.6	0.05	1.53	0.03	2.06	0.75	0.1	0	85.73
192	37.9	32.2	11.7	0	1.35	0.01	2.23	0.58	0	0.03	85.97
196	38	32.1	11.5	0	1.2	0	2.17	0.72	0.02	0.06	85.78
200	38.2	32.1	11.4	0.06	1.21	0.07	2.31	0.53	0	0.05	85.90
204	38.1	32.3	11.7	0	1.29	0	2.2	0.37	0	0.03	86.04
208	38.1	32.5	11.6	0.04	1.52	0.03	2.2	0.54	0.02	0.05	86.53
212	38.2	32.7	11.2	0	0.96	0	2.21	0.66	0.07	0	85.99
216	37.6	32.6	11.4	0	1.26	0	2.25	0.61	0	0.03	85.69
220	37.7	32.4	11.4	0	1.37	0	2.28	0.54	0.02	0.12	85.77
224	38.1	32.3	11.4	0.02	1.33	0	2.18	0.48	0	0.01	85.75
228	37.8	32.6	11.4	0.06	1.4	0.06	2.21	0.49	0	0.03	86.02
232	37.6	32.3	11.2	0	1.28	0	2.26	0.58	0	0	85.15
236	37.9	32.7	11.4	0	1.49	0	2.28	0.61	0	0	86.40
240	37.6	32.2	11.2	0.05	1.28	0.05	2.23	0.63	0.05	0	85.25
244	38.2	32.9	11.5	0.02	1.33	0	2.13	0.6	0.03	0.04	86.69
248	37.8	32.9	11.4	0.02	1.36	0.03	2.18	0.47	0.01	0	86.22
252	37.7	32.8	11.4	0.04	1.13	0.02	2.26	0.57	0.03	0	86.01
256	38.1	32.4	11.6	0.01	1.28	0	2.03	0.53	0	0	85.97
260	37.9	32.4	11.4	0	1.49	0.05	2.22	0.71	0	0	86.17
264	36.4	31.6	11.9	0.07	1.46	0.04	2.43	0.68	0	0	84.56
Austeel 3											
Core											
0	34.3	34	1.63	13.1	0	0.47	1.75	0.01	0.63	0.12	86.04
4	34.2	34.1	1.69	13.9	0.18	0.49	1.77	0	0.55	0.13	86.95
8	33.7	34.1	1.78	13.6	0.01	0.58	1.5	0.01	0.55	0.07	85.83
12	34.1	34.3	2.11	13	0.09	0.61	1.53	0	0.65	0.14	86.51
16	34.4	32.7	3.72	11.4	0.11	1.21	1.42	0.01	1.15	0.01	86.14

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Overgrowth											
20	37.4	31.7	9.58	3.68	1.67	0	2.08	0.25	0	0.02	86.40
24	36.9	31.6	9.78	3.1	1.44	0	2.12	0.22	0.03	0.01	85.18
28	37.1	31.6	9.72	3.36	1.46	0	2.12	0.13	0	0	85.47
32	37.6	31.4	9.5	3.4	1.73	0	2.24	0.19	0.01	0	86.12
36	37.4	31.4	9.83	3.11	1.59	0	2.09	0.22	0.07	0	85.64
40	37.5	31.4	9.82	3.25	1.45	0.05	2.17	0.23	0.05	0	85.86
44	37.3	32	9.78	3.16	1.62	0.01	2.29	0.19	0.04	0.13	86.54
48	37.7	32	9.58	2.64	1.69	0.02	2.27	0.35	0.04	0.04	86.30
52	37.6	32	9.53	2.58	1.72	0	2.17	0.43	0.05	0	86.15
56	37.5	31.8	9.48	2.8	1.58	0.04	2.3	0.25	0.02	0.04	85.81
60	37.7	32.3	9.92	2.49	1.56	0	2.36	0.35	0	0	86.63
64	37.2	32.2	9.92	2.19	1.67	0.02	2.35	0.54	0	0.02	86.08
68	37.5	32.2	9.71	2.27	2.08	0	2.08	0.67	0.03	0	86.56
72	36.9	32	10.1	2.08	1.9	0	2.2	0.45	0	0.03	85.66
76	38.2	32.4	11.2	0.13	1.38	0	2.28	0.67	0	0	86.25
80	37.6	32.6	11.1	0.08	1.81	0.05	2.28	0.76	0	0	86.30
84	37.8	32.4	11.1	0.1	1.78	0.02	2.35	0.7	0	0.08	86.40
88	37.5	32	11.2	0.07	1.45	0.05	2.38	0.68	0	0.07	85.32
92	37.6	32.6	11.2	0.03	1.6	0.04	2.21	0.67	0	0.01	85.94
96	38	32.4	11.2	0	1.56	0.06	2.26	0.85	0	0	86.28
100	37.8	32.5	11.3	0.01	1.68	0.02	2.16	0.69	0.01	0.08	86.15
104	37.9	32.3	11.2	0.07	1.52	0.02	2.25	0.78	0.01	0	86.06
108	37.9	32.3	11.3	0.07	1.35	0.04	2.08	0.67	0.04	0.03	85.67
112	37.9	32.2	11.3	0	1.47	0	2.23	0.84	0.01	0.1	86.08
116	38.1	32.2	11.5	0	1.4	0.07	2.27	0.79	0.02	0.08	86.42
120	37.8	32.2	11.5	0	1.36	0	2.21	0.74	0.01	0.19	85.92
124	38	32.5	11.2	0.04	1.07	0	2.34	0.8	0.02	0.07	86.00
128	38.2	32.8	11.3	0.06	1.13	0.02	2.11	0.69	0	0.03	86.25
132	38	32.4	11.5	0.01	1.33	0.02	2.36	0.78	0.01	0	86.48
136	37.8	32.4	11.3	0.08	1.09	0	2.1	0.87	0.01	0	85.61
140	37.8	32.3	11.5	0.01	1.31	0.02	2.04	0.94	0.01	0.08	85.97
144	38.1	32.7	11.3	0.04	1.27	0.01	2.24	0.95	0	0	86.51
148	38	32.2	11.1	0.04	1.14	0	2.12	0.94	0	0	85.54
152	37.8	32.2	11.2	0.01	1.2	0	2.2	0.92	0.02	0	85.52
156	37.5	32.4	11.5	0.03	1.16	0.06	2.31	0.74	0.04	0.03	85.74
160	38	32.4	11.1	0	1.57	0	2.08	0.81	0.08	0	86.01
164	38.1	32.7	11.4	0	1.15	0.02	2.19	0.85	0.02	0.04	86.46
168	37.8	32.3	11.5	0.01	1.33	0	2.18	0.98	0.08	0	86.20

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
172	38.2	32.3	11.4	0.01	0.85	0.01	2.25	0.84	0	0	85.88
176	38.3	32.4	11.2	0.13	1.09	0.03	2.18	0.77	0.01	0	86.17
180	38.2	32.5	11.3	0.03	1.07	0	2.03	0.99	0	0.02	86.14
184	35.7	32.5	10.6	0	0.92	0.01	2.05	0.58	0	0.03	82.31
188	38.2	32.5	11.5	0	0.94	0	2.19	0.74	0	0	85.97
192	38.2	32.5	11.6	0	1.07	0.01	2.14	0.66	0	0.02	86.10
196	37.9	32.5	11.5	0	1.26	0.02	2.17	0.67	0	0.09	86.05
200	38	32.4	11.6	0.03	1	0	2.19	0.43	0.07	0.04	85.77
204	37.6	32.6	11.3	0.01	1.17	0	2.06	0.53	0	0	85.30
208	38	32.6	11.2	0.01	1.18	0.03	2.04	0.73	0.01	0	85.75
212	38	32.9	11.4	0.02	1.02	0	2.14	0.54	0.05	0.03	86.06
Austellb											
Core											
0	35.7	33.4	5.43	8.16	0	0.89	1.69	0	1.14	0	86.36
Overgrowth											
4	35.8	31.3	6.67	7.78	0.99	0.3	2	0.49	0.43	0	85.76
8	36.9	32.1	9.25	3.39	0.89	0.03	1.99	0.24	0.08	0	84.85
12	37.5	32.6	9.42	3.79	0.97	0.03	2.09	0.17	0.03	0.13	86.65
16	37.5	31.9	9.52	3.19	1.21	0	2.19	0.16	0	0	85.60
20	37.5	31.9	9.86	2.93	0.89	0.01	2.04	0.19	0.01	0	85.33
24	37.6	31.9	9.61	3.05	1.12	0.02	2.27	0.18	0.03	0.08	85.89
28	37.4	32	9.75	3.44	1.76	0	2.25	0.23	0	0	86.85
32	37.2	32.1	9.52	3.41	1.66	0.02	2.11	0.19	0	0	86.23
36	37.2	31.6	9.55	3.43	1.86	0.07	2.29	0.14	0.04	0	86.21
40	37.3	31.6	9.96	3.43	2.01	0.02	2.4	0.15	0.06	0.08	87.06
44	37.7	32	9.8	2.98	1.44	0.02	2.33	0.31	0	0	86.49
48	37.3	32.1	9.71	2.89	2.25	0	2.21	0.19	0.04	0	86.63
52	37.5	32.1	9.79	2.86	1.97	0.01	2.22	0.31	0.04	0.09	86.92
56	37.7	32.5	9.8	2.74	1.75	0.01	2.34	0.27	0.08	0.07	87.21
60	37.7	32.3	9.69	2.68	1.52	0	2.27	0.34	0	0	86.51
64	36.4	30.1	10.2	2.76	2.06	0	2.21	0.49	0.06	0	84.36
68	37.2	32	10.2	2.39	1.79	0	2.38	0.32	0.03	0	86.31
72	37.8	32	9.71	2.24	1.81	0	2.34	0.44	0	0	86.26
76	37.4	31.7	10.1	2.07	1.95	0	2.34	0.44	0.16	0.08	86.23
80	38	32.6	11.3	0.24	1.95	0.01	2.18	0.7	0	0	86.87
84	38.3	32.5	11.4	0.08	1.52	0.03	2.37	0.71	0.08	0	87.02
88	38.1	32.1	11.7	0.13	1.69	0.03	2.21	0.6	0.01	0.08	86.61
92	38.4	32.1	11.7	0.01	1.9	0.01	2.2	0.54	0	0	86.87
96	38.2	31.8	11.6	0.08	1.72	0.02	2.46	0.7	0	0.03	86.53

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
100	37.9	32.2	11.3	0.05	1.78	0.01	2.3	0.76	0	0.05	86.43
104	38.4	32.3	11.5	0.07	1.72	0.02	2.25	0.7	0	0.03	86.94
108	37.8	32.4	11.5	0.07	1.51	0.04	2.28	0.54	0.02	0.03	86.12
112	37.5	32.2	11.5	0	1.97	0.02	2.22	0.45	0.01	0.06	85.93
116	38.3	32.6	11.7	0.02	1.88	0	2.23	0.61	0	0	87.30
120	37.8	32.4	11.5	0.03	1.7	0	2.18	0.39	0.03	0.05	86.10
124	37.9	32.2	11.8	0.02	1.75	0.03	2.45	0.68	0.08	0.06	86.97
128	37.7	32.1	11.7	0	1.9	0.01	2.27	0.43	0.09	0	86.13
132	38	31.9	11.6	0	1.52	0.01	2.07	0.46	0	0	85.48
136	38.1	32.1	11.8	0.03	1.75	0	2.3	0.66	0	0.05	86.75
140	38	32.3	11.7	0.05	1.62	0	2.07	0.49	0.01	0.02	86.15
144	38.1	31.9	11.5	0	1.72	0.02	2.19	0.57	0	0	86.01
148	37.8	32.4	11.4	0.02	1.74	0.04	2.31	0.93	0	0	86.66
152	38	32.5	11.3	0	1.4	0.02	2.25	0.86	0.01	0.06	86.40
156	38.4	32.4	11.5	0	1.49	0.01	2.17	0.62	0	0	86.65
160	38.2	32.3	11.4	0	1.45	0.05	2.24	0.67	0	0.02	86.27
164	38	32.5	11.5	0	1.35	0	2.19	0.64	0	0	86.10
168	38.1	32.5	11.1	0	1.68	0.01	2.26	0.52	0	0	86.17
172	37.8	32.9	11.2	0	1.34	0	2.21	0.63	0	0.01	86.07
176	38.1	33	11.3	0	1.33	0	2.21	0.6	0.05	0.01	86.54
180	38.1	33.2	11.3	0.02	1.33	0	2.33	0.76	0	0.08	87.06
184	38	32.5	11.4	0	1.29	0	2.25	0.66	0	0	86.09
188	37.9	32.9	11.4	0	1.42	0.01	2.3	0.72	0	0.02	86.60
192	37.8	33	11.2	0	1.34	0	2.24	0.71	0	0.12	86.39
196	37.8	32.4	11.5	0	1.37	0	2.26	0.62	0	0.06	85.97
200	38	32.7	11.5	0.02	1.42	0	2.27	0.64	0.06	0	86.61
204	38.1	32.7	11.5	0.07	1.18	0.05	2.18	0.54	0	0	86.35
208	37.9	32.8	11.4	0.01	1.12	0.04	2.4	0.49	0	0.15	86.36
212	38.2	32.6	11.3	0	1.1	0.02	2.42	0.58	0.02	0	86.26
216	38	32.6	11.2	0	1.13	0.01	2.4	0.42	0.02	0	85.80
220	38.3	32.6	11.4	0.05	1.17	0.05	2.31	0.63	0.01	0.07	86.52
224	38.4	33	11.4	0.01	1.17	0.01	2.18	0.62	0.08	0.02	86.76
228	38.1	32.8	11.4	0	1.23	0.02	2.34	0.85	0.03	0	86.74
232	37.9	32.8	11.4	0.02	1.31	0.01	2.25	0.68	0.03	0	86.33
Austeel2b											
Core											
0	35.1	33.3	4.74	9.15	0.05	0.95	1.95	0	1.1	0	86.31
4	34.5	33.3	4.7	9.19	0.15	0.95	1.85	0	0.98	0.07	85.71
8	34.9	33.2	4.88	9.43	0.05	0.92	1.76	0.02	0.99	0.04	86.24

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
12	34.7	33.4	4.87	9.18	0.08	0.88	1.71	0.05	0.96	0	85.82
16	34.6	33.3	4.91	9.1	0.15	0.88	1.88	0.02	1.1	0.05	85.95
20	34.4	33.2	4.91	9.1	0.1	0.85	1.76	0.06	1.12	0.11	85.62
24	34.9	33.5	4.97	8.69	0.05	0.86	1.73	0	1.02	0.1	85.82
Overgrowth											
28	35.7	30.2	6.72	7.47	1.05	0.25	1.87	0.94	0.17	0	84.36
32	37.1	31.3	9.26	2.95	1.45	0.06	2.25	0.89	0.01	0	85.23
36	37	31.4	9.31	3.52	1.85	0	2.24	0.94	0	0.03	86.23
40	36.7	31.6	9.46	2.76	1.73	0.01	2.19	1.25	0	0	85.65
44	37.2	31.7	9.58	2.13	1.66	0	2.43	1.48	0.01	0	86.12
48	37.5	32.1	10.9	0.02	1.72	0	2.32	1.55	0.04	0.03	86.22
52	37.2	32	10.7	0.06	1.41	0.01	2.25	1.3	0	0.08	85.03
56	37.7	32	10.8	0.07	1.45	0	2.19	1.53	0	0	85.71
60	37.3	32.2	10.8	0.08	1.49	0	2.18	1.38	0	0.09	85.52
64	37.3	32.4	11	0	1.58	0.03	2.13	1.42	0.12	0.08	86.06
68	37.6	31.9	10.9	0.09	1.41	0.01	2.15	1.33	0.08	0.03	85.54
72	37.7	32.2	11.1	0.09	1.21	0.01	2.26	1.32	0.03	0	85.97
76	37.7	32.1	11.2	0	1.24	0.01	2.18	1.35	0.05	0.08	85.92
80	37.5	31.8	11.1	0	1.3	0	2.05	1.16	0	0	84.97
84	37.1	32	11	0	1.32	0.02	2.17	1.09	0.02	0.03	84.76
88	37.6	32.3	11.2	0	1.2	0.03	2.14	0.87	0	0.02	85.24
92	37.5	32.2	11.1	0	1.27	0.02	2.09	0.87	0	0.03	85.08
96	37.4	32.4	11.2	0.06	1.14	0.03	2.25	0.97	0.03	0.03	85.45
100	37.8	32.2	11.1	0.02	1.1	0	2.23	1.1	0	0	85.55
104	37.6	32.2	11.2	0.07	1.21	0	2.2	0.85	0	0	85.23
108	37.6	32.3	11.1	0	1.07	0	2.1	1.03	0	0.06	85.20
112	37.6	32.4	10.9	0.04	0.86	0.07	2.25	1.31	0.05	0.13	85.62
116	37.6	32	11	0.01	0.99	0	2.28	1.2	0.02	0.01	85.00
120	38.1	32	11	0.05	0.96	0.05	2.47	1.18	0.02	0	85.80
124	37.6	32.3	11	0.03	1.14	0.01	2.46	1.01	0	0	85.45
128	37.4	31.8	11.2	0	1.03	0	2.38	1.28	0	0.07	85.12
132	37.6	32.7	11	0	1.04	0	2.38	1.16	0	0	85.90
136	37.8	32.3	11.1	0	0.85	0	2.37	0.9	0.1	0	85.45
140	37.9	32.1	11.1	0.01	0.87	0	2.26	1.25	0	0.09	85.62
144	37.3	32.4	11.2	0.07	1.02	0.01	2.23	1.14	0.03	0	85.36
148	37.3	32.2	11.1	0.01	0.85	0.01	2.43	1.09	0.02	0.06	85.05
152	37.3	32.6	11	0	1.02	0.03	2.48	0.87	0	0	85.21
156	37.7	32	11.3	0.02	0.83	0	2.36	1.04	0.03	0	85.24

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Austeel3b											
Core											
0	34.9	22	7.68	14.7	0	2.08	1.66	0.04	2.15	0.14	85.31
4	34.7	22	7.72	14.7	0.07	2.16	1.68	0.03	2.18	0.15	85.34
8	34.5	22.2	7.87	14.5	0.1	2.18	1.69	0.05	2.2	0.07	85.31
12	34.9	21.8	7.98	14.9	0.03	2.13	1.7	0	2.17	0.35	85.94
16	34.8	22	8.01	14.4	0	2.24	1.69	0.05	2.2	0.17	85.50
20	34.7	21.9	8.04	14.5	0.09	2.21	1.68	0	2.09	0.18	85.38
Overgrowth											
24	36.5	29.2	7.87	6.3	2.15	0.23	1.9	1.38	0.1	0	85.65
28	34.9	32.3	9.01	3.55	1.47	0	1.88	0.5	0.08	0	83.64
32	37.4	32.7	8.92	3.08	1.54	0.04	2.09	0.75	0.05	0	86.56
36	37.3	31.8	9.44	2.9	1.87	0.01	2.25	0.6	0	0.02	86.18
40	37	31.8	10.7	0.27	1.53	0.03	2.23	0.76	0.03	0.06	84.35
44	37.4	32.8	10.9	0.13	1.67	0	2.2	0.67	0	0	85.72
48	37.6	32.1	11.1	0.1	1.27	0.01	2.18	1.11	0.09	0.03	85.63
52	37.7	31.6	11.1	0.04	1.09	0	2.37	1.04	0	0.01	84.91
56	37.6	32.2	11.1	0.05	1.51	0	2.34	1.21	0.02	0.06	86.04
60	37.3	32.4	11.4	0.02	1.06	0.03	2.23	1.04	0.02	0.03	85.43
64	37.8	32.3	11.2	0.05	1.17	0	2.21	1	0	0	85.75
68	37.9	32.5	11.1	0	0.86	0.01	2.13	0.96	0.03	0.01	85.45
72	37.5	32.6	10.9	0.1	0.79	0	2.2	0.98	0.04	0.03	85.14
76	37.2	32.4	10.8	0.04	0.82	0	2.26	1.04	0.02	0	84.52
80	36.2	32.2	10.9	0.02	0.83	0.03	2.21	1.25	0	0	83.65
Austeel4b											
Core											
0	34	28.7	0.75	19.1	0.07	0.82	2.03	0.11	0.87	0.15	86.50
4	34	28.8	0.75	18.8	0.06	0.83	2.08	0.06	0.93	0.26	86.54
8	34.2	29.1	0.73	18.6	0.1	0.8	2.09	0	0.91	0.13	86.58
12	33.8	29	0.77	18.8	0.03	0.77	2.03	0.01	0.79	0.11	86.09
16	34	29	0.75	19.2	0.07	0.85	2.07	0	0.82	0.16	86.89
20	34	28.6	0.75	18	0.07	0.81	2.07	0.03	0.95	0.08	85.42
Overgrowth											
24	36.7	32.5	5.58	8.53	1.03	0.05	1.54	0.38	0.01	0	86.26
28	36.9	33	6.06	7.49	1.06	0.05	1.34	0.26	0.03	0.07	86.22
32	37	33.3	6.53	6.77	0.31	0.05	1.51	0.16	0	0	85.64
36	37.1	32.7	7.05	6.81	0.75	0	1.93	0.3	0.02	0.05	86.70
40	36.6	31.9	5.64	9.18	0.7	0.04	1.96	0.24	0.01	0.05	86.24
44	36.7	31.7	5.88	8.43	0.83	0	2.17	0.2	0	0	85.95

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
48	36.2	31.6	5.82	8.49	1.2	0.03	1.91	0.31	0	0	85.55
52	36.7	31.5	5.81	9.06	1.39	0.03	1.98	0.3	0.03	0.07	86.86
56	36.6	31.9	6.19	8.26	1.42	0	2.02	0.36	0.03	0	86.72
60	36.5	32.2	5.95	8.15	0.88	0	1.75	0.24	0	0	85.65
64	36.8	32.5	5.48	8.48	0.56	0	1.87	0.22	0.02	0	85.93
68	36.3	31.8	5.92	8.73	1.08	0	1.83	0.33	0.02	0.02	86.03
72	36.7	31.5	5.83	8.56	0.82	0.02	2	0.16	0.09	0.02	85.70
76	35.8	31.3	5.98	8.68	1.25	0.05	2.05	0.29	0.07	0.02	85.50
Austeel5b											
Core											
0	34.8	28.8	6	11.4	0	1.41	1.98	0	0.75	0.29	85.45
4	34.9	28.9	6.07	12.1	0.15	1.45	2.06	0.06	0.68	0.27	86.66
8	35.4	28.6	6.11	11.9	0.09	1.33	1.87	0.01	0.67	0.28	86.32
12	35.1	29.1	6.12	12.1	0.08	1.28	2.09	0.1	0.53	0.29	86.69
16	35	28.7	5.99	11.7	0.19	1.29	2.01	0	0.49	0.24	85.55
20	35.1	29	5.74	11.8	0.19	1.25	2.04	0.01	0.69	0.3	86.09
24	34.9	29	5.69	12.3	0.06	1.37	1.92	0.09	0.61	0.21	86.08
28	34.9	28.8	5.94	11.4	0.1	1.28	1.92	0.09	0.66	0.28	85.28
32	35.2	28.7	6.07	11.6	0.07	1.31	1.91	0	0.59	0.31	85.78
Overgrowth											
36	37	31.5	6.98	7.13	0.05	0.03	2.29	0.09	0.36	0.03	85.40
40	34.7	30.4	6.14	7.26	0.58	2.23	1.85	0.26	0.17	0.02	83.61
44	36.8	33.1	6.07	7.13	0.54	0.06	1.24	0.15	0.06	0.05	85.26
48	36.8	33.5	6.24	6.6	0.25	0	1.45	0.1	0	0.11	85.01
52	36.8	33.4	7.34	6.13	0.44	0	1.61	0.18	0.04	0	85.98
56	36.4	32.1	6.31	7.63	1.05	0	1.71	0.35	0.04	0	85.58
60	36.7	32.4	5.74	8.67	0.53	0	1.97	0.24	0	0.03	86.23
64	36.9	32.3	5.93	7.97	0.73	0.01	1.93	0.26	0.01	0	85.94
68	36.6	31.9	5.84	8.68	0.96	0.02	1.85	0.32	0.07	0	86.19
72	36.8	31.4	5.71	8.21	1.29	0	1.89	0.5	0	0.01	85.76
76	36.7	31.5	6.24	7.93	1.38	0	1.93	0.45	0	0	86.07
80	36.4	31.7	6.04	8.25	1.33	0	1.88	0.38	0.07	0	86.04
84	37	32.2	5.78	8.69	0.5	0.05	1.58	0.28	0.04	0	86.11
88	36.5	32	5.72	8.1	0.64	0.03	1.83	0.23	0.04	0.01	85.11
92	36.7	32	5.69	8.11	0.91	0	1.83	0.33	0.04	0	85.58
96	36.1	31.5	5.81	8.31	1.13	0	1.91	0.5	0.02	0.04	85.32
100	36.4	31.9	5.62	8.35	0.86	0	1.93	0.38	0	0.03	85.52
104	37.8	33.7	10.1	0.21	0.18	0	1.8	0.12	0.05	0.02	83.93

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Carrigan 1											
Core											
0	36.4	27.2	9.1	8.06	0.11	1.71	1.94	0.12	0.87	0.01	85.58
3	36.4	27.5	9.23	8.06	0.04	1.84	1.9	0.09	0.83	0.03	85.97
6	36.6	27.4	9.45	8.05	0.07	1.72	1.94	0.17	0.82	0.03	86.28
9	36.9	28.5	8.93	7.23	0	1.41	1.9	0.32	0.61	0.03	85.85
Overgrowth											
12	38.2	32.5	10.6	3.58	0.09	0.04	2.2	0.07	0.02	0	87.23
15	38.1	31.5	5.86	2.8	0.09	0	2.53	0.06	0.05	0	80.95
18	38.2	32	10.6	2.74	0.07	0.01	2.35	0	0.04	0	85.94
21	38	31.7	10.7	3.72	0.12	0	2.61	0.01	0.03	0	86.89
24	37.8	31.2	9.56	4.01	0.07	0.01	2.65	0.1	0.03	0	85.43
27	38	31.5	9.4	4.12	0.08	0.02	2.72	0.02	0.05	0.03	85.94
30	37.9	31.4	9.66	3.78	0.08	0	2.82	0.05	0.08	0	85.80
33	38	32	10.2	2.98	0.15	0	2.8	0	0	0.01	86.16
36	38.2	32.1	10.3	1.91	0.12	0.01	2.55	0.02	0.06	0	85.25
39	38.2	33.1	10.9	0.81	0.08	0.04	2.31	0.05	0.05	0.02	85.54
42	44	30.2	10.5	0.13	0.12	0.03	2.26	0	0.04	0.01	87.36
Carrigan 2											
Core											
0	35.9	27.7	6.71	10.6	0.03	1.26	2.14	0.09	0.87	0.07	85.49
3	35.9	27.9	6.7	10.9	0.04	1.22	2.09	0.08	0.82	0.09	85.79
6	35.8	27.9	6.47	10.8	0.07	1.22	2.17	0	0.91	0.05	85.36
9	35.8	27.9	6.8	10.6	0.06	1.27	2.1	0.07	1.02	0.08	85.66
12	36.2	27.8	6.46	10.7	0.01	1.27	2.17	0.01	0.9	0.07	85.64
15	36.8	28.3	7.11	8.59	0.04	0.91	2.13	0.08	0.62	0.02	84.59
18	37.2	28.5	7.01	9.08	0.04	0.86	2.08	0	0.62	0.03	85.43
21	37.5	29.5	7.61	6.87	0.09	0.57	2.15	0	0.42	0.02	84.79
Overgrowth											
24	38.4	31	9.2	3.76	0.06	0.15	2.13	0.2	0.07	0.03	85.02
27	38.8	31.3	9.43	3.63	0.11	0.06	2.34	0.15	0.04	0	85.89
30	38.8	31.6	9.18	3.22	0.07	0.08	2.04	0	0.06	0.01	85.01
33	38.8	31.4	9.74	2.27	0.02	0.08	2.18	0.14	0	0	84.67
36	38.4	31.4	9.58	2.3	0.09	0.09	2.12	0.08	0	0	84.07
39	38.7	31.4	9.41	2.95	0.08	0.14	2.21	0	0.02	0	84.85
42	37.5	30.5	9.26	3.43	0.05	0.51	2.45	0	0.05	0.02	83.81
Carrigan 3											
Core											
0	35.9	31.8	5.16	9.28	0	0.96	1.96	0.07	1.12	0.02	86.30

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
3	36	31.9	5.24	9.14	0.03	0.92	1.93	0	1.1	0.03	86.26
6	35.9	31.8	5.31	9.47	0.05	0.92	1.92	0.01	1.09	0.01	86.50
9	35.7	32	5.25	9.23	0.04	0.9	1.9	0	1.08	0.02	86.05
12	36.1	31.7	5.4	9.36	0.05	0.84	2.03	0	1.11	0.02	86.63
Overgrowth											
15	38	32.4	8.82	3.3	0.07	0.06	1.7	0.14	0.03	0	84.58
18	38.3	32.7	9.53	2.6	0.07	0.04	1.84	0.01	0	0	85.12
21	38	32.6	8.94	3.92	0.08	0	1.8	0.01	0.05	0	85.36
24	38.1	32.2	8.48	4.67	0.13	0.01	1.81	0	0.02	0	85.45
27	38.5	32.3	9.48	3.07	0.08	0.02	1.9	0.14	0.04	0	85.58
30	38.4	32.4	9.82	2.52	0.09	0.03	1.87	0.11	0.02	0	85.25
33	38.7	32	10.3	2.24	0.11	0	2.01	0.1	0.01	0	85.50
36	38.6	32.2	9.78	3.35	0.09	0	2.05	0.11	0.03	0	86.16
39	38.5	32	9.69	3.98	0.07	0	2.17	0	0.03	0.01	86.40
42	38.4	31.9	8.84	3.97	0.02	0	2.1	0	0.03	0	85.26
45	38.8	31.9	9.87	3.4	0.05	0	2.19	0.04	0.01	0	86.18
48	38.8	31.9	9.61	3.12	0.11	0	2.13	0	0.05	0.01	85.66
51	38.9	31.7	9.75	2.84	0.12	0	2.15	0.03	0.03	0.01	85.49
54	38.8	32	10	2.2	0.08	0	2.16	0	0	0.04	85.35
57	39.5	32.4	10.7	1.32	0.06	0	2.26	0.02	0	0	86.27
Carrigan 4											
Core											
0	35.6	28.7	8.29	8.16	0.03	1.61	1.86	0	0.77	0	85.10
3	35.7	28.1	8.15	8.23	0.01	1.44	1.88	0.04	0.81	0.01	84.35
6	35.8	28.8	8.34	8.18	0	1.53	1.87	0	0.82	0.03	85.42
9	35.7	28.9	8.2	7.85	0.02	1.49	1.93	0	0.85	0.03	84.91
12	35.6	28.8	8.29	7.95	0	1.49	1.85	0.02	0.82	0.02	84.87
15	35.7	28.5	8.24	7.84	0.05	1.51	1.9	0	0.79	0	84.52
18	36.2	29.5	8.36	6.71	0.08	0.99	1.81	0	0.49	0	84.09
Overgrowth											
21	36.8	31.6	8.9	3.95	0.07	0.07	1.7	0.14	0.09	0	83.32
24	37.3	32.5	9.64	2.73	0	0.04	1.74	0.15	0.03	0.02	84.13
27	37.3	32.4	9.51	2.64	0.07	0	1.8	0.14	0.01	0	83.89
30	37.4	32.1	9	3.87	0.09	0.03	1.68	0.01	0.05	0	84.25
33	37.6	31.7	9.92	2.51	0.07	0.04	1.83	0.27	0.05	0.02	84.04
36	37.4	31.9	10	2.44	0.05	0.03	1.89	0.18	0.04	0.01	83.92
39	37.6	31.8	10.1	2.19	0.07	0.03	1.88	0.11	0.07	0	83.82
42	37.3	31.7	10	2.32	0.05	0.02	1.98	0	0.05	0	83.43
45	37.6	31.3	9.96	2.44	0.06	0.01	2	0.06	0.03	0	83.50

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
48	37.2	31.9	9.56	2.93	0.07	0	2.14	0	0.01	0	83.86
51	37.2	31.6	9.93	3.37	0.07	0.01	2.32	0	0.05	0	84.55
54	37.3	31.3	8.99	3.59	0.05	0.04	2.31	0.07	0	0.01	83.71
57	37.6	30.7	9.19	3.53	0.05	0	2.33	0.11	0.02	0	83.51
Carrigan 5a											
Core											
	36.6	29.5	6.96	8.44	0.14	0.88	2.17	0.09	0.57	0.03	85.42
	36.7	28.7	6.84	8.42	0.16	1.05	2.16	0.17	0.57	0	84.71
	36.8	29.4	6.96	8.34	0.14	0.88	2.13	0	0.54	0	85.19
	36.5	29	6.64	8.44	0.13	0.9	2.2	0.12	0.53	0.01	84.51
	36.9	29.3	6.79	8.29	0.09	0.71	2.17	0	0.46	0	84.72
Overgrowth											
	37	31.3	8.38	3.2	0.02	0.03	1.64	0.11	0.03	0.01	81.69
	38.5	31.7	9.29	2.74	0.06	0.02	1.92	0.11	0.04	0.01	84.40
	38.5	31.4	9.41	2.72	0.06	0.04	1.89	0	0.02	0	84.05
	38.5	31.4	9.42	2.51	0.04	0	1.87	0.09	0.07	0.01	83.85
	38.5	30.8	9.43	2.33	0.09	0	1.93	0.07	0.06	0.01	83.22
	38.5	31.1	9.69	2.17	0.06	0	1.97	0	0.04	0	83.57
	38.7	31.2	9.69	2.27	0.06	0.03	1.98	0	0.07	0	84.07
	38.2	30.9	9.11	3.3	0.06	0	2.24	0.19	0.03	0	84.08
	38.2	31.4	9.11	3.67	0.03	0	2.12	0	0.02	0.02	84.64
	38.2	30.8	9.07	3.62	0.07	0	2.15	0	0.02	0	83.89
	38.1	31	9.17	3.5	0.04	0	2.16	0.05	0	0	84.00
	38.5	30.9	9.38	2.77	0.09	0	2.23	0.02	0.02	0	83.91
	38.5	30.3	9.58	2.48	0.16	0	2.09	0	0.01	0.03	83.16
	38.6	30.7	10	1.55	0.16	0	2.19	0.02	0.04	0	83.30
	38.7	31.2	10.1	1.21	0.1	0	2.07	0.05	0.04	0	83.45
	39.1	31.7	10.8	0.08	0.09	0.01	2.07	0.15	0.03	0.02	83.99
	39.1	31.6	10.6	0.02	0.06	0	2.07	0.04	0.02	0.01	83.52
	39.2	31.5	10.6	0.05	0.06	0	2.09	0.03	0.01	0	83.52
	39.1	31.1	10.5	0.05	0.09	0	2.04	0	0	0	82.80
	39	31.2	10.5	0.05	0.19	0	1.91	0	0	0	82.84
	39.1	30.6	10.5	0.04	0.18	0	1.97	0	0	0.01	82.39
	39	30.3	10.4	0.03	0.17	0.03	2	0	0	0.01	81.94
	38.9	31.1	10.4	0.03	0.14	0	2.04	0.06	0	0	82.66
	38.7	31.4	10.3	0	0.09	0.01	2.03	0.06	0.02	0	82.52
	38.1	31.2	10.5	0.04	0.09	0.03	1.99	0	0.01	0	81.94

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Carrigan 5b											
Core											
37.1	32.4	9.16	7.08	0.11	0.45	2.06	0	0.17	0		88.49
37.1	32.1	7.6	7.18	0.13	0.46	2.11	0	0.15	0		86.82
36.7	30.2	7.47	7.64	0.1	0.55	2.12	0.06	0.31	0		85.17
36.3	30.9	7.52	7.38	0.13	0.61	2.06	0	0.35	0.01		85.23
36.6	30.8	7.59	7.49	0.06	0.62	2.05	0	0.38	0.01		85.65
36.6	31.7	7.48	7.44	0.14	0.62	2.02	0.08	0.34	0		86.35
36.4	31.7	7.35	7.35	0.14	0.58	2.03	0	0.31	0		85.84
37.2	32.7	9.9	4.65	0.12	0.13	1.72	0.18	0.06	0.02		86.73
Overgrowth											
38.5	33	9.85	2.7	0.02	0	1.78	0.09	0.01	0		85.87
38.1	32.8	9.92	2.85	0.03	0	1.99	0.13	0	0		85.81
38	32.6	10.3	2.47	0.08	0	2.09	0.08	0.02	0.01		85.65
37.8	32.7	10.6	2.33	0.01	0	2.15	0.03	0.02	0		85.60
38.1	32.3	10.2	2.51	0.05	0	2.19	0.11	0.03	0.01		85.58
38	32.5	10.2	2.67	0.05	0.02	2.39	0.14	0.01	0		86.11
37.9	32	9.85	3.4	0.04	0.02	2.24	0.09	0	0		85.55
38	32.3	10.1	3.7	0.09	0	2.34	0	0.01	0.01		86.50
37.7	31.8	12.1	3.79	0.09	0.01	2.3	0.01	0.04	0		87.91
37.9	32.2	9.6	3.77	0.06	0.03	2.49	0.05	0.11	0.01		86.21
37.8	32	9.58	3.9	0.04	0.01	2.49	0	0.04	0		85.82
37.7	32	9.54	3.98	0.08	0.02	2.44	0	0.08	0		85.81
37.9	32.3	9.54	4.01	0.1	0.03	2.47	0.21	0.06	0		86.57
37.9	32.2	9.29	4.16	0.08	0	2.61	0.02	0.02	0		86.25
37.5	32.3	9.16	3.82	0.03	0	2.62	0	0.04	0		85.43
37.7	32.3	9.68	3.81	0.08	0.02	2.57	0.02	0.06	0		86.12
37.3	32.5	9.78	3.7	0.11	0.03	2.62	0.04	0.02	0		86.07
37.9	32.3	9.86	3.38	0.07	0	2.61	0	0	0		86.16
38.2	32.2	9.88	3.21	0.12	0	2.63	0	0	0.01		86.27
38.2	32.7	9.96	2.82	0.07	0.01	2.28	0	0.02	0		86.06
38	32.8	10.4	2.37	0.09	0	2.25	0	0.01	0		85.90
38.3	32.8	10.5	1.86	0.08	0	2.25	0.04	0.03	0.02		85.85
38.5	33.6	11.2	0.61	0.07	0	2	0	0	0		85.98
38.6	33.7	11.6	0.06	0.08	0.02	2.12	0	0.01	0.01		86.17
Crangr 3											
Core											
0	35.7	33.7	6.93	5.58	0.04	1.23	1.69	0.08	0.82	0.03	85.78
3	36	34.1	6.75	5.51	0.14	1.23	1.79	0.12	0.74	0.09	86.45

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
6	36	34.1	6.79	5.48	0.03	1.05	1.78	0.09	0.89	0.08	86.28
9	35.8	34	6.66	5.65	0.11	1.19	1.74	0.07	0.91	0	86.18
12	35.6	33.9	6.72	5.48	0.03	1.4	1.68	0.07	1.05	0.04	85.91
Overgrowth											
15	36.3	30.7	6.38	9.83	0.01	0.47	2.14	0.05	0.65	0.07	86.60
18	36.8	31.2	6.09	9.35	0.06	0.37	1.93	0.14	0.14	0.04	86.06
21	36.7	32	5.78	8.34	0.05	0.27	1.23	0.18	0.09	0.04	84.76
24	37.7	32.6	6.25	6.63	0.13	0.17	1.15	0.2	0.15	0.03	85.02
27	37.1	31.9	6.93	6.68	0.18	0.21	1.49	0.27	0.1	0	84.87
30	36.9	31.5	6.74	6.81	0.25	0.12	1.56	0.39	0.32	0.02	84.66
33	36.7	31.7	6.24	7.76	0.16	0.17	1.53	0.35	0.27	0.06	84.91
36	37	31.8	6.18	7.79	0.17	0.1	1.59	0.34	0.36	0	85.33
39	36.7	31.7	6.24	7.93	0.25	0.21	1.8	0.26	0.1	0	85.21
42	36.9	31.8	6.3	7.68	0.08	0.14	1.75	0.17	0.15	0	84.93
45	37.1	31.8	6.44	8.64	0.2	0.29	1.56	0.19	0.1	0.05	86.31
48	36.8	32	6.56	7.96	0.29	0.12	1.72	0.22	0.51	0	86.10
51	36.6	31.6	6.38	7.95	0.19	0.08	1.6	0.31	0.29	0.01	84.98
54	36.6	31.8	6.36	7.77	0.12	0.1	1.6	0.15	0.15	0.01	84.65
57	37.1	31.9	7.13	6.36	0.2	0.19	1.69	0.18	0.15	0	84.92
60	37	32	7.02	6.45	0.18	0.19	1.58	0.19	0.17	0.06	84.85
63	37.1	31.7	7	6.9	0.1	0.1	1.65	0.19	0.34	0.03	85.04
Crang4											
Core											
0	35.7	26	8.38	11.3	0.03	2.89	1.2	0.05	0.73	0.08	86.35
3	35.3	26.2	8.33	11.3	0.02	2.97	1.18	0.12	0.58	0.09	86.17
6	35.7	25.8	8.3	11.3	0.01	3.34	1.28	0.07	0.54	0.1	86.52
Overgrowth											
9	37.4	32.6	5.22	8.27	0	0.1	1.35	0.25	0.19	0	85.34
12	37.5	33.2	6.14	6.65	0	0.31	1.18	0.07	0.21	0	85.22
15	37.4	32.5	6.3	7.17	0.12	0.27	1.54	0.32	0.38	0	85.96
18	35.3	30.6	6.19	6.26	0.2	0.16	1.43	0.24	0.27	0.05	80.60
21	37.2	32	6.09	7.57	0.14	0.02	1.59	0.35	0.15	0.02	85.09
24	37.1	32	6.24	8.01	0.16	0.29	1.87	0.25	0.17	0	86.07
27	37.1	31.7	6.18	8.51	0.07	0.27	1.96	0.32	0.08	0.02	86.17
30	36.9	31.7	6.49	7.86	0.16	0.39	1.96	0.25	0.39	0.03	86.08
33	37.5	32.2	6.96	6.63	0.18	0	1.59	0.25	0.2	0	85.53
36	37.3	31.7	6.75	6.61	0.11	0.08	1.76	0.19	0.26	0	84.82
39	37.3	31.4	6.83	7.42	0.03	0.27	2.34	0.16	0.46	0.01	86.17
42	36.6	30.9	6.88	6.86	0.2	0.1	2.54	0.27	0.2	0	84.55

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Crang5											
Core											
0	35.5	29.7	4.4	13.5	0.1	0.33	2.38	0.11	0.5	0.14	86.53
3	34.8	28.2	3.51	15.6	0.07	0.57	2.3	0.13	0.85	0.2	86.25
6	34.6	28.4	3.45	16.3	0.07	0.82	2.37	0.08	0.77	0.18	86.95
9	34.9	28.5	3.68	15.1	0.09	0.75	2.42	0.08	0.77	0.21	86.51
12	35	28.9	3.59	15.2	0.11	0.56	2.47	0.09	0.79	0.14	86.84
Overgrowth											
15	36.7	32.5	5.49	8.48	0.12	0	1.6	0.12	0.24	0.04	85.35
18	36.7	32.5	5.5	8.47	0.12	0	1.55	0.12	0.24	0.04	85.27
21	36.6	34	5.53	7.5	0.2	0	1.25	0.17	0.31	0.13	85.67
24	37.1	33.2	6.34	7.17	0.14	0.06	1.3	0.15	0.22	0.06	85.73
27	37	32.8	6.58	7.07	0.29	0.22	1.57	0.33	0.29	0.08	86.22
30	37	32.5	6.92	6.66	0.42	0.12	1.64	0.35	0.27	0.03	85.90
33	36.6	32.3	6.34	7.57	0.29	0.12	1.57	0.3	0.1	0.08	85.28
36	37.1	32.6	6.2	7.87	0.3	0.1	1.51	0.29	0.19	0.08	86.15
39	36.7	32.6	6.18	8.28	0.26	0.04	1.56	0.31	0.24	0.05	86.19
42	37	32.5	6.32	7.81	0.21	0	1.47	0.31	0.32	0.06	86.00
45	36.9	32.3	6.36	7.74	0.23	0	1.65	0.26	0.29	0.06	85.85
48	36.6	32.3	6.26	7.94	0.28	0	1.64	0.17	0.14	0.06	85.37
51	36.8	32.3	6.42	7.88	0.19	0	1.6	0.15	0.26	0.04	85.67
54	36.6	32.5	6.43	7.75	0.26	0	1.55	0.15	0.12	0.01	85.32
57	36.2	32.4	6.4	7.13	0.28	0	1.53	0.19	0.17	0.06	84.36
60	37.1	32.3	7.11	6.52	0.15	0.1	1.59	0.21	0.29	0.1	85.45
63	37.1	32.8	6.78	6.47	0.22	0.08	1.61	0.14	0.21	0.04	85.45
66	37	32.4	6.99	6.99	0.15	0.18	1.44	0.21	0.07	0.09	85.54
69	36.6	31.8	6.5	6.89	0.13	0	1.46	0.18	0.38	0.11	84.02
72	37.2	33	6.45	7.58	0.16	0.25	1.4	0.12	0.39	0.07	86.70
75	37.2	32.9	6.44	7.4	0.22	0	1.47	0.18	0.19	0.1	86.05
78	36.9	32.7	6.55	7.14	0.16	0	1.43	0.16	0.26	0.11	85.40
81	37	32.7	6.53	7.02	0.19	0	1.53	0.15	0.15	0.03	85.30
84	37	32.6	6.46	7.33	0.27	0.08	1.45	0.12	0.29	0.1	85.69
87	36.9	32.9	6.72	7.14	0.14	0.24	1.38	0.14	0.21	0.09	85.80
90	37	32.7	6.57	7.3	0.18	0.2	1.53	0.18	0.21	0.03	85.86
93	37.1	32.6	6.56	7.76	0.14	0	1.5	0.19	0.14	0.1	86.04
96	36.7	32.6	6.53	7.33	0.17	0	1.5	0.21	0.27	0.05	85.37
99	37	32.4	6.3	7.37	0.18	0	1.55	0.17	0.32	0.1	85.32
102	36.6	32.3	6.49	7.46	0.21	0	1.43	0.18	0.32	0.08	85.05

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Crandall Estate Well #1											
Cran2g5 parallel to zoning											
Constant contrast innermost dark zone											
0	37	32.4	7.04	6.8	0.26	0.06	1.53	0.28	0.09	0.06	85.54
3	36.8	32.7	7	6.97	0.33	0	1.63	0.3	0.2	0.03	85.88
6	36.6	32.7	6.93	6.83	0.34	0.08	1.5	0.27	0.32	0.13	85.61
9	37.2	32.4	7	6.67	0.29	0.06	1.65	0.23	0.29	0.08	85.85
12	36.8	32.5	6.91	6.92	0.33	0	1.54	0.24	0.38	0.04	85.65
15	37	32.4	6.81	6.93	0.29	0.04	1.66	0.24	0.22	0.03	85.63
18	36.5	32.4	6.92	7.06	0.29	0	1.65	0.27	0.26	0.07	85.33
21	36.6	32.5	6.74	6.93	0.23	0	1.63	0.33	0.29	0.1	85.40
24	36.5	32.6	6.74	7.07	0.25	0.04	1.66	0.24	0.34	0.07	85.47
27	36.7	32.6	6.73	6.94	0.25	0	1.65	0.27	0.29	0.08	85.56
30	36.7	32.5	6.66	7.13	0.24	0.04	1.59	0.28	0.6	0.11	85.87
Cran2g5											
Central Light Zone											
0	36.8	32.7	6.21	8.02	0.21	0	1.5	0.22	0.29	0.03	85.94
3	36.8	32.7	6.26	8.31	0.25	0	1.58	0.38	0.27	0.08	86.65
6	36.8	32.5	6.18	7.61	0.21	0.1	1.66	0.32	0.19	0.08	85.63
9	36.8	32.6	6.16	8.15	0.38	0.14	1.6	0.28	0.15	0.06	86.32
12	36.4	32.2	6.23	8.32	0.32	0.18	1.55	0.2	0.27	0.04	85.72
15	36.7	32.5	6.16	8.05	0.21	0.04	1.65	0.26	0.48	0.05	86.11
18	36.4	32.5	6.11	7.88	0.28	0.14	1.59	0.27	0.15	0.09	85.46
21	36.5	32	6.15	7.81	0.2	0.21	1.69	0.16	0.22	0.11	85.01
24	36.4	32.3	6.21	8.03	0.27	0	1.74	0.3	0.1	0.17	85.46
27	35.9	32.4	6.12	7.81	0.25	0	1.67	0.17	0.32	0.02	84.68
30	36.4	31.8	6.26	8.17	0.25	0	1.75	0.26	0	0.07	84.97
33	36.1	32.1	6.2	8.29	0.23	0.06	1.7	0.21	0.22	0.1	85.13
Cran2g5											
Outer Dark Zone											
	36.9	32.7	6.52	7.21	0.1	0	1.58	0.17	0.32	0.12	85.58
	36.9	32.6	6.49	7.16	0.14	0.1	1.48	0.14	0.14	0.08	85.14
	36.7	33	6.55	7.22	0.12	0	1.5	0.12	0.29	0.06	85.56
	36.6	32.8	6.34	7.47	0.23	0.02	1.47	0.24	0.48	0.11	85.71
	36.5	32.4	6.4	7.61	0.14	0.04	1.57	0.17	0.07	0.1	85.02
	36.9	32.5	6.49	7.56	0.24	0.04	1.59	0.2	0.34	0.08	85.99
	36.8	32.5	6.48	7.27	0.12	0	1.56	0.16	0.22	0.12	85.27
	36.7	32.3	6.48	7.27	0.14	0	1.56	0.2	0.26	0.01	84.87
	36.3	32.3	6.49	7.65	0.22	0.27	1.52	0.2	0.2	0.03	85.24

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
	36.5	32.2	6.52	7.31	0.12	0	1.57	0.16	0.15	0.04	84.49
	32	29.4	5.9	6.16	0.17	0.08	2.08	0.09	0	0.04	75.96
Cran2g6											
Core											
0	34.8	29.7	7.02	10.5	0	1.99	1.63	0.04	0.87	0.23	86.78
3	35.1	29.7	6.9	10.2	0	1.72	1.8	0.02	0.8	0.25	86.42
6	37.1	32.6	5.87	8.22	0.03	0.04	1.25	0.14	0.21	0.04	85.54
9	37.3	32.6	5.97	8.44	0	0.2	1.38	0.06	0.27	0.01	86.18
12	37.1	32.8	5.62	8.43	0.06	0.14	1.19	0.15	0.39	0.07	85.87
Overgrowth											
15	37.2	33.2	6.46	7.13	0	0.02	1.24	0.05	0.38	0	85.62
18	37.1	33	6.26	7.22	0.14	0	1.48	0.17	0.34	0.05	85.74
21	37.3	32.7	6.78	6.7	0.16	0.15	1.66	0.25	0.36	0.11	86.16
24	37	32.4	6.53	7.1	0.17	0.08	1.69	0.2	0.51	0.03	85.69
27	36.9	32.1	6.27	7.7	0.11	0	1.54	0.26	0.48	0.06	85.41
30	37.2	32.4	6.11	7.79	0.11	0.12	1.65	0.18	0.51	0.06	86.09
33	37.1	32.6	6.11	7.9	0.18	0.17	1.68	0.28	0.36	0.02	86.35
36	36.8	32.3	6.14	7.78	0.17	0	1.67	0.26	0.48	0.05	85.69
39	37.3	32.4	6.07	8.42	0.08	0	1.73	0.16	0.29	0.01	86.40
42	36.8	32.4	6.29	7.74	0.13	0	1.75	0.14	0.37	0.06	85.72
45	37	32.5	6.31	8.15	0.08	0.17	1.65	0.18	0.54	0	86.50
48	37.2	32.6	6.41	7.83	0.1	0.04	1.73	0.13	0.29	0.02	86.32
51	37.1	32.7	7.08	6.55	0.12	0.04	1.81	0.11	0.55	0.06	86.13
54	37.1	32.8	6.98	6.95	0.11	0.06	1.65	0.11	0.43	0.02	86.13
57	37.4	32.7	6.79	7.07	0.09	0.25	1.71	0.14	0.32	0.06	86.49
60	37.3	32.8	6.63	6.85	0.09	0.27	1.64	0.19	0.34	0.05	86.10
63	37.4	32.6	6.33	7.71	0.12	0.04	1.57	0.07	0.27	0.08	86.10
66	37.2	32.9	6.15	7.77	0.08	0	1.54	0.08	0.41	0.03	86.20
69	37.2	32.6	6.41	7.89	0.04	0.1	1.49	0.09	0.27	0.01	86.13
72	37.3	32.8	6.49	7.44	0.1	0	1.46	0.1	0.21	0.04	86.01
75	37	32.7	6.37	7.71	0.12	0	1.52	0.14	0.33	0.02	85.94
78	37.4	32.9	6.15	7.64	0.1	0.04	1.51	0.16	0.39	0	86.37
81	37.2	33	6.47	7.37	0.07	0	1.59	0.1	0.26	0.04	86.02
84	37.4	32.3	6.48	7.16	0.06	0	1.55	0.14	0.41	0.05	85.60
87	37.4	32.3	6.42	7.44	0.08	0.04	1.62	0.11	0.24	0	85.60
90	37.1	32.8	6.43	7.69	0.05	0	1.55	0.19	0.39	0.04	86.21
93	37.3	32.7	6.42	7.23	0.01	0	1.62	0.14	0.26	0.05	85.69
96	37	32.8	6.41	7.64	0.04	0	1.61	0.1	0.15	0.02	85.78
99	37.4	32.4	6.42	7.51	0.06	0	1.63	0.11	0.22	0.09	85.76

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
102	37.4	33	6.56	7.04	0.05	0	1.64	0.05	0.2	0.01	85.90
105	37.3	33	6.59	6.92	0.06	0	1.59	0.17	0.22	0.12	85.92
108	35.1	30.4	6.12	6.88	0.06	0	1.49	0.09	0.38	0.04	80.51
111	37.2	33	6.93	6.45	0.07	0.21	1.68	0.09	0.31	0.08	86.08
114	37.6	33.1	6.86	6.43	0.1	0	1.69	0.12	0.34	0	86.29
117	37.3	33.1	7.01	6.24	0.03	0	1.75	0.06	0.45	0.04	85.90
120	37.7	33	7.06	6.48	0	0	1.6	0.06	0.24	0.04	86.18
123	37.5	32.5	7.05	6.24	0.05	0	1.71	0.09	0.48	0.04	85.71
126	37.6	32.9	7.01	6.37	0.05	0	1.57	0.09	0.27	0	85.87
129	38	33	6.77	6.73	0.06	0	1.56	0.07	0.17	0.1	86.39
132	38	33	6.58	6.89	0.01	0	1.57	0.06	0.29	0.06	86.49
Ned1											
Core											
0	34.6	26	4.47	16.9	0.02	1.31	2.24	0	1.14	0.3	86.99
4	34.2	26.2	4.58	16.6	0.01	1.35	2.15	0	1.11	0.32	86.54
8	34.6	26	4.52	16.2	0.04	1.27	2.11	0	1.03	0.37	86.14
12	34.6	26.2	4.48	16.6	0.08	1.22	2.15	0	1.2	0.4	86.91
16	34.7	26.1	4.48	15.9	0	1.28	2.06	0	0.98	0.23	85.82
20	34.3	26.1	4.38	16.8	0	1.28	2.14	0	0.93	0.29	86.3
Overgrowth											
24	37.3	31.8	9.22	4.44	1.75	0	2.23	0.15	0.05	0.09	87
28	36.9	31.8	8.68	4.59	1.91	0.02	2.21	0.21	0.05	0.1	86.5
32	37	31.7	8.52	4.67	1.97	0.35	2.13	0.21	0	0	86.54
36	37.1	31.6	8.54	4.35	2.41	0.03	2.32	0.41	0.06	0.08	86.88
40	37	31.6	8.91	4.04	2.52	0	2.28	0.27	0	0.03	86.66
44	37.4	31.4	9.21	3.46	2.43	0.02	2.23	0.31	0.01	0.05	86.53
48	36.9	31.7	9.98	2.55	2.3	0	2.16	0.31	0	0.04	85.9
52	37.6	31.8	10.9	1.56	2.03	0.05	2.29	0.17	0.06	0.1	86.49
56	37.7	32.3	11.1	0.84	1.95	0.02	2.17	0.19	0.09	0.05	86.42
60	37.9	32.2	11.5	0.2	1.65	0.04	2.22	0.17	0.01	0	85.91
64	37.6	32.5	11.9	0.17	1.47	0.03	2.14	0.19	0.04	0.03	86.03
68	37.8	32.5	11.6	0.06	1.47	0	2.34	0.19	0	0.07	85.95
72	37.5	32.2	11.5	0.09	2.19	0	2.21	0.19	0.01	0	85.99
76	37.6	32.6	11.8	0.05	1.74	0.05	2.13	0.2	0	0.02	86.22
80	37.1	32.3	11.6	0.01	1.9	0.02	2.27	0.17	0.03	0	85.44
Nedlagain											
Core											
0	33.9	24.1	4.57	18	0.07	1.31	2.07	0.01	1.36	0.42	85.87
4	34.4	24	4.47	17.8	0	1.45	1.99	0	1.39	0.37	85.91

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
8	34.2	24.1	4.52	17.7	0.07	1.23	2.14	0	1.5	0.33	85.76
12	34.4	24.3	4.43	17.8	0.02	1.34	2.28	0.09	1.6	0.4	86.65
16	34.6	25.8	4.65	16.7	0	1.16	2.14	0	0.97	0.21	86.2
Overgrowth											
20	37.1	31.6	9	4.24	1.47	0	2.23	0.17	0.02	0	85.86
24	37.1	31.9	8.69	4.69	1.86	0.02	2.09	0.28	0.07	0.07	86.74
28	35.9	31.2	8.51	4.6	1.89	1.08	2.17	0.28	0	0	85.59
32	37	31.5	8.64	4.49	2.15	0.01	2.17	0.38	0	0	86.33
36	37	32	9.13	3.99	2.44	0.02	2.22	0.37	0.04	0.07	87.26
40	37	31.4	9.37	3.48	2.11	0	2.22	0.23	0.03	0	85.83
44	37.2	31.9	9.95	2.83	2.19	0.02	2.2	0.29	0.02	0	86.54
48	37.4	32.1	10.6	1.74	1.81	0	2.12	0.24	0.03	0	86.05
52	37.3	32.4	11	0.81	1.95	0.01	2.16	0.29	0.07	0.03	86.03
56	37.9	32.4	11.6	0.29	2.07	0	2.2	0.25	0.01	0	86.66
60	38.1	32.8	11.7	0.06	1.83	0.01	2.13	0.13	0	0.04	86.71
64	37.4	32.4	11.7	0.04	1.47	0.02	2.14	0.23	0.06	0.03	85.49
68	37.4	32.6	11.9	0.07	1.96	0.04	2.19	0.32	0	0.05	86.47
72	37.7	32.7	11.8	0.05	1.84	0.06	2.17	0.24	0	0.14	86.76
76	37.7	32.5	11.7	0.06	1.6	0	2.25	0.17	0.03	0.02	85.97
80	37	32.1	11.5	0.06	1.48	0.04	2.28	0.22	0	0.02	84.63
Ned2											
Core											
0	34.5	24.2	4.43	17.9	0.06	1.32	2.03	0.04	1.35	0.35	86.22
4	34.8	24.3	4.42	17.9	0.03	1.29	2.01	0.01	1.5	0.39	86.63
8	34.6	24.5	4.43	17.5	0.03	1.17	2.06	0	1.45	0.42	86.11
12	34.6	24.5	4.39	18	0.11	1.3	1.96	0.02	1.4	0.46	86.76
16	34.8	24.4	4.58	17.8	0	1.28	2.06	0	1.62	0.46	87.05
20	35.3	24.8	4.55	17.3	0.02	1.18	2.08	0	1.9	0.45	87.59
Overgrowth											
24	36.8	32	8.62	4.92	2.39	0	2.21	0.09	0	0.08	87.11
28	37.1	31.6	8.81	4.23	2.11	0	2.17	0.08	0.07	0	86.22
32	37.1	32.3	9.11	3.89	2.16	0.02	2.19	0.05	0	0.06	86.92
36	37.5	32.1	9.14	3.65	1.91	0.02	2.15	0.04	0.04	0.06	86.6
40	37.8	32.6	9.81	2.82	1.67	0	2.21	0.07	0.03	0.03	87.02
44	37.7	32.7	10.4	1.72	1.61	0	2.23	0.03	0.03	0	86.41
48	37.8	32.5	11	1.06	1.7	0.01	2.17	0.01	0	0	86.22
52	38	32.9	11.3	0.39	1.67	0.02	1.99	0	0.06	0.03	86.35
56	38.3	33.2	11.1	0.08	1.28	0	2.06	0.03	0.07	0	86.08
60	38.1	33.8	11.1	0.09	1.35	0	2.1	0.03	0	0	86.59

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
64	38.3	33.7	11.7	0.09	0.38	0.02	2.28	0.01	0.02	0.07	86.58
68	38.7	34.1	11.5	0	0.38	0	2.49	0.07	0.05	0	87.35
72	38.8	34.1	11.3	0.04	1.03	0.02	2.34	0.01	0.03	0	87.67
76	39.3	34.4	11.7	0.11	1.6	0	2.75	0	0	0.09	89.97
Ned3											
Core											
0	36.3	26.9	11.2	6.32	0.23	3.27	1.2	0	1.94	0.04	87.32
4	36.5	26.8	11.3	6.05	0.09	3.12	1.22	0.09	1.81	0.03	87.08
8	36.5	27	11.2	6.06	0.02	3.38	1.1	0.07	1.83	0.04	87.21
12	36.6	26.7	11.5	6.14	0.21	3.45	1.08	0.08	1.74	0.06	87.53
Overgrowth											
16	37.1	33.3	4.38	10.3	0.05	0.27	1.69	0	0.3	0.04	87.34
20	37.6	32.8	8.54	4.42	2.26	0	2.07	0.33	0	0	87.96
24	37.9	32.6	8.5	4.16	2.1	0.03	2.08	0.27	0	0	87.62
28	37.9	33.4	8.84	3.98	2.31	0	2.14	0.25	0.05	0.06	88.92
32	38.2	33.6	9.34	2.92	1.87	0	2.14	0.03	0	0.07	88.16
36	38.4	33.8	9.92	1.75	1.43	0.03	2.18	0.05	0.05	0	87.56
40	38.9	34.3	10.8	1	1.34	0.05	2.07	0.07	0	0	88.55
44	38.9	34.5	11.1	0.34	1.74	0	2.09	0	0	0	88.74
48	38.7	34.6	11	0.06	1.63	0	2.13	0.02	0.05	0	88.14
52	38.7	34.5	11.1	0.07	1.66	0.03	2.14	0.07	0	0	88.3
56	39.1	33.4	11.2	0.04	1.83	0.02	2.35	0.54	0.01	0	88.48
NedC1											
Core											
0	36.7	27.6	9.01	9.56	0.16	1.86	1.76	0.03	0.82	0.08	87.56
4	36.6	27.5	9.11	9.36	0.07	1.89	1.77	0	0.92	0.08	87.29
8	36.5	28	9.2	9.66	0.17	1.91	1.86	0.02	0.88	0.08	88.31
12	36.4	27.9	8.84	9.41	0.01	1.78	1.97	0.04	0.97	0.01	87.34
16	37.1	28.5	9.16	8	0.23	1.37	2.13	0	1.02	0.06	87.62
Overgrowth											
20	37.8	32	8.93	4.63	1.68	0	2.17	0.36	0.07	0	87.58
24	37.2	31.4	8.99	4.52	1.92	0.74	2.34	0.27	0.04	0	87.34
28	37.9	32.3	10.2	2.93	1.04	0.6	2.65	0.08	0.1	0.11	87.87
32	38.7	33.3	11.4	0.98	0.53	0.03	2.48	0.02	0	0.06	87.36
36	38.4	32.8	11.8	0.48	0.85	0.02	2.31	0.12	0.07	0	86.83
40	37.1	31.9	11.1	0.8	1.24	0	2.33	0.2	0.12	0	84.68
NedC2											
Core											
0	36	23.8	8.1	14.5	0.14	2.51	1.58	0.01	1.67	0.04	88.26

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
4	36.2	23.8	8.25	15.1	0.17	2.45	1.5	0.06	1.78	0.12	89.36
8	36.3	24	8.14	13.9	0.12	2.46	1.47	0	1.83	0	88.22
Overgrowth											
12	38.3	31.1	9.13	5.87	1.33	0.53	2.25	0.19	0.31	0.05	89.04
16	38.2	33.9	9.01	4.31	1.47	0.04	2.35	0.25	0	0.07	89.62
Nedamnh1											
Core											
0	34.8	25.9	4.34	16.9	0.02	1.25	2.18	0.02	1.07	0.22	86.71
3	35.2	25.7	4.48	16.5	0.02	1.24	2.17	0.02	1.11	0.24	86.7
6	37.6	31.2	8.36	4.87	1.53	0	2.33	0.34	0.02	0	86.23
Overgrowth											
9	37.6	31.3	8.82	4.03	1.79	0.01	2.27	0.38	0.03	0	86.2
12	37.7	31.8	10	1.86	1.47	0.55	2.2	0.34	0.03	0	85.94
15	38.4	32.4	11	0.32	1.33	0	2.31	0.25	0.04	0	86.05
18	38.9	32.5	11.1	0.12	1.26	0.01	2.27	0.28	0.02	0	86.41
21	38.5	32.7	11.4	0.08	1.44	0.01	2.28	0.29	0.03	0	86.65
24	38.6	32.7	11	0.08	1.47	0	2.25	0.35	0.01	0	86.43
27	39.2	32.5	11.1	0.04	1.35	0	2.31	0.28	0.03	0	86.84
Nedamnh2											
Core											
3	36.2	34.1	3.43	11	0	0.42	1.94	0	0.56	0.03	87.68
Overgrowth											
6	38	31.9	8.37	4.63	1.33	0	2.19	0.25	0.04	0.01	86.68
9	37.2	31.3	8.38	4.85	1.47	0.04	2.36	0.35	0.05	0	85.95
12	37.7	31	8.83	4.25	1.68	0.03	2.81	0.45	0.06	0	86.78
Nedamnh3											
Core											
3	34.8	24	4.34	18.2	0.06	1.34	2.16	0	1.5	0.32	86.75
Overgrowth											
6	37.6	31.6	8.47	4.76	1.67	0	2.25	0.09	0.03	0.01	86.48
9	37.9	31.6	9.64	2.88	1.38	0	2.3	0.1	0.01	0	85.81
12	38.7	33.2	10.9	0.09	0.9	0	2.29	0.11	0.01	0	86.16
Nedamnh4											
Core											
82	35.3	28.5	3.75	14.5	0.07	1.57	1.89	0.03	1.28	0.09	86.94
Overgrowth											
83	36.7	30.6	8.18	4.41	1.57	0.04	2.24	0.3	0.23	0	84.27
84	38	31.4	8.43	4.7	1.65	0.02	2.4	0.4	0.05	0	86.98
85	37.9	31.1	9.34	3.72	1.93	0	2.35	0.28	0	0	86.54

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
86	39.5	32.3	11.3	0.15	1.31	0	2.31	0.24	0.01	0.01	87.18
87	35.1	37.4	10.8	0.13	1.77	0.05	1.69	0.16	0.01	0	87.21
Ofgl											
Core											
0	34.6	25.4	3.16	18.3	0.02	0.62	2.37	0	1.44	0.38	86.32
4	34.7	26	3.19	18.3	0.02	0.63	2.45	0.02	1.41	0.42	87.1
8	34.8	25.6	3.48	18.8	0	1.3	2	0	1.48	0.55	88.03
12	35.9	28.9	4.96	13.4	0.88	0.49	1.99	0.19	0.65	0.36	87.63
Overgrowth											
16	37	32.7	5.82	7.2	1.07	0	1.37	0.37	0.03	0.08	85.68
20	37.4	33.3	6.54	6.84	0.37	0.05	1.52	0.24	0.01	0	86.24
24	37.5	33.1	7.01	6.35	0.47	0.05	1.72	0.23	0	0.05	86.51
28	37	32.5	5.96	8.91	0.2	0	2.02	0.25	0	0	86.86
32	37.5	32.7	6.72	6.83	0.72	0	1.68	0.36	0	0	86.56
36	36.7	32.3	5.85	9.32	0.53	0.02	2.11	0.3	0	0.01	87.13
40	37	32.8	6.45	8.69	0.66	0.04	2.39	0.47	0.03	0	88.45
44	36.9	31.8	6.07	8.18	0.91	0	2.34	0.57	0.15	0.02	86.88
48	37	32.3	5.84	8.6	0.42	0	1.99	0.23	0	0	86.37
52	37.1	32.3	6.05	8.52	0.99	0.06	1.97	0.4	0.06	0.02	87.44
56	37.4	32	6.03	8.31	1.07	0.02	1.96	0.37	0.02	0.06	87.3
60	36.8	32.1	6.18	8.97	1.19	0	1.98	0.34	0	0	87.61
64	36.6	31.8	6.17	8.04	1.05	0	2.11	0.41	0.07	0	86.25
68	36.9	32.1	6.11	8.52	1.24	0	1.93	0.33	0.03	0.05	87.26
72	36.7	32.3	5.9	8.78	0.51	0	2.02	0.26	0	0	86.49
76	37	32.3	5.92	8.5	0.99	0.01	1.92	0.24	0.02	0	86.84
80	36.9	32.3	5.92	8.57	0.95	0	1.79	0.44	0	0.09	86.97
84	37.3	32.5	5.94	7.86	0.79	0	1.84	0.33	0.08	0.01	86.72
88	37.3	32.3	5.96	8.17	1.2	0	2.01	0.59	0	0.03	87.57
92	38.9	35.3	10.6	0.26	0.17	0.01	1.85	0.19	0.07	0	87.34
Oriskgl											
Core											
0	34.8	31.4	7.04	8.46	0	2.2	1.2	0	0.7	0.02	85.81
4	35.1	31.6	7	8.52	0.06	2.28	1.16	0	0.66	0.04	86.43
8	35.3	31.6	6.83	8.57	0.15	2.25	1.32	0	0.71	0.02	86.78
12	34.8	31.6	6.97	8.97	0.03	2.4	1.26	0.08	0.72	0.06	86.86
Overgrowth											
16	36.8	33.6	5.99	7.58	0.62	0	1.22	0.14	0.03	0.04	86.01
20	36.9	33.8	6.18	6.72	0.16	0.08	1.2	0.17	0	0.02	85.22
24	37	33.5	6.26	7.02	0.47	0.02	1.3	0.18	0	0.04	85.71

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
28	37.6	33	7.49	5.47	0.27	0.03	1.77	0.3	0.08	0	86.03
32	37	32.2	5.36	9.51	0.6	0.04	1.82	0.14	0.05	0.06	86.76
36	36.7	32.3	5.96	8.55	0.68	0.02	1.78	0.23	0.01	0	86.26
40	36.2	32.3	6.1	8.23	1.01	0.02	1.87	0.3	0.03	0.06	86.15
44	36.5	31.9	5.87	8.47	1.08	0.02	2.05	0.36	0	0	86.27
48	36.5	31.5	6.2	8.26	1.24	0	2.01	0.28	0.09	0.12	86.14
52	36.3	32.2	6.17	8.38	0.72	0.01	1.85	0.21	0	0	85.82
56	36.7	32.4	5.85	8.35	0.4	0	1.77	0.22	0.05	0.03	85.79
60	36.5	32.2	5.85	8.72	0.62	0.01	1.87	0.35	0	0.07	86.18
64	36.5	31.8	5.96	8.63	1.32	0.03	1.92	0.27	0.01	0.05	86.45
68	36.6	32.7	5.74	8.67	1.24	0	1.89	0.36	0.04	0.06	87.21
72	35.9	32.8	5.91	8.57	1.15	0	1.91	0.27	0.02	0.02	86.57
76	38	33.8	10.6	0.05	0.19	0.03	1.82	0.19	0.04	0.06	84.77
80	36.3	33.2	9.42	0.14	0.37	0.01	1.44	0.07	0	0.03	80.91
Oriskfg2											
Core											
0	35.5	32.2	6.7	8.77	0	1.08	2.1	0.06	0.65	0.02	87.09
4	35.9	32.4	6.6	8.57	0.05	1.1	2	0.01	0.43	0.13	87.22
8	35.7	32.1	6.68	8.7	0	1.06	2.04	0	0.56	0.07	86.96
12	35.7	32.1	6.78	8.66	0.07	1.1	1.94	0.03	0.56	0.09	87.12
16	35.6	32.2	6.59	8.35	0.31	0.87	1.96	0.13	0.41	0.02	86.43
Overgrowth											
20	35.2	34.3	5.65	7.32	0.68	0.03	1.14	0.16	0.05	0	84.57
24	37	33.8	6.27	6.96	0.4	0.05	1.21	0.07	0	0	85.73
28	37.3	33.3	6.54	6.73	0.46	0.05	1.33	0.07	0.04	0	85.86
32	37.8	33.3	6.55	6.78	0.34	0.06	1.4	0.07	0	0	86.25
36	37.2	32.9	7.66	6.15	0.27	0.07	1.8	0.3	0.03	0.06	86.5
40	37	32.8	7.02	6.65	0.73	0	1.92	0.3	0	0	86.41
44	37	32.3	5.91	8.07	1	0	1.75	0.24	0	0	86.22
48	36.5	31.6	5.34	9.71	0.67	0	1.94	0.14	0.07	0	86.02
52	36.9	32.5	5.71	8.44	0.33	0	1.75	0.26	0.07	0	86
56	36.6	31.8	5.94	8.5	0.46	0	1.98	0.39	0.04	0.02	85.67
60	36.6	32.5	6.03	8.05	0.53	0	1.85	0.27	0.03	0	85.79
64	36.6	32.2	5.99	8.69	0.61	0.01	1.88	0.22	0.04	0.07	86.22
68	36.7	32.3	6.07	8.1	0.95	0	1.87	0.31	0	0	86.37
72	36.6	32	5.82	8.51	1.16	0.02	1.93	0.4	0	0	86.39
76	36.8	31.7	6.08	8.68	1.33	0.01	1.85	0.44	0	0.04	86.91
80	36.8	31.8	6.24	7.85	1.49	0.01	1.96	0.27	0.01	0.03	86.41
84	37.1	32.3	5.98	8.17	0.71	0	1.77	0.18	0.09	0.07	86.33

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
88	36.7	32.5	5.8	8.39	0.56	0	1.69	0.19	0	0.04	85.88
92	36.3	32	5.93	7.71	1.13	0.03	1.87	0.35	0.01	0.08	85.36
96	36.5	31.8	6.05	8.27	1.04	0.01	1.89	0.4	0.06	0	85.94
100	36.6	32.1	6.15	8.05	1.22	0	2.05	0.29	0.05	0.03	86.6
104	36.5	32.5	7.3	6.16	0.73	0	1.69	0.24	0.02	0	85.15
108	37.4	34	10.4	0.03	0.42	0.02	1.54	0.21	0	0	84.07
Oriskfg3											
Core											
0	34.8	21.8	8.02	15.9	0.12	2.68	1.44	0	1.78	0.07	86.59
4	34.8	22.1	7.97	16	0.11	2.45	1.41	0.03	1.66	0.15	86.64
8	34.8	21.8	7.99	16	0	2.62	1.48	0.08	1.78	0.01	86.63
Overgrowth											
12	36.3	29.9	6.33	8.79	1.5	0.4	1.86	0.47	0.22	0.03	85.74
16	37	34.1	6.23	6.89	0.5	0.05	1.53	0.19	0.05	0.07	86.58
20	37.2	32.5	6.23	7.43	1.22	0.01	1.42	0.24	0	0.06	86.32
24	37	33.2	6.22	6.99	0.25	0.07	1.34	0.11	0.01	0	85.23
28	37.5	33.4	6.78	6.83	0.5	0.01	1.42	0.21	0	0	86.66
32	37.2	33.3	7.47	5.63	0.37	0.02	1.82	0.09	0.04	0.03	86.02
36	36.8	32.6	6.23	7.72	0.5	0.01	1.93	0.28	0	0	86
40	36.7	32.2	5.54	8.97	0.44	0.03	1.9	0.14	0.08	0.14	86.1
44	36.6	32.2	5.94	8.75	1.1	0	1.68	0.22	0.07	0	86.53
48	36.6	32.1	5.77	8.47	1.13	0	1.96	0.46	0.05	0.02	86.57
52	36.1	31.8	5.85	9.18	1.29	0.01	2	0.42	0.04	0	86.73
56	36.3	31.8	6.27	8.02	1.31	0.02	2.07	0.3	0.03	0.02	86.17
60	36.4	31.9	6.09	8.53	0.92	0	2.01	0.32	0	0.1	86.2
64	36.8	32.4	5.95	8.92	0.54	0.01	1.78	0.29	0.01	0.12	86.8
68	36.7	31.9	5.76	8.85	0.85	0	1.77	0.26	0	0.09	86.1
72	37.1	31.8	6.02	8.17	1.1	0.02	1.9	0.32	0.04	0	86.4
76	36.9	31.8	5.97	8.6	0.83	0.05	1.97	0.46	0	0.05	86.6
80	36.7	31.8	5.89	8.22	0.98	0	2.16	0.31	0.01	0	86.1
84	38.3	34.1	10.3	0.54	0.6	0	1.94	0.16	0	0.03	85.94
Of1c											
Core											
0	36.7	28.4	9.91	6.53	0.07	2.52	1.56	0	1.72	0	87.49
4	36.5	28.3	9.67	6.54	0.17	2.5	1.52	0	1.68	0.06	86.95
8	36.9	28.9	9.66	6.81	0	2.47	1.56	0.06	1.4	0	87.66
Overgrowth											
12	36.9	31.3	6.29	8.3	1.4	0.28	1.77	0.3	0.1	0	86.65
16	36.8	32.6	6.05	7.28	1.08	0.09	1.36	0.2	0.03	0.02	85.48

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
20	37.1	33.1	6.21	7.43	0.53	0.07	1.3	0.19	0.01	0.03	85.93
24	37.4	33.3	6.29	7.44	0.47	0.02	1.39	0.02	0.05	0	86.43
28	37.3	33.8	6.51	6.94	0.22	0.02	1.32	0.15	0	0.07	86.34
32	37.1	33.6	6.53	7.04	0.49	0.01	1.28	0.14	0	0	86.18
36	36.7	31.7	6.1	8.9	0.48	0.05	2.47	0.36	0.03	0.04	86.84
40	37.1	31.9	6.25	8.54	0.53	0	2.3	0.35	0.09	0.04	87.07
44	36.6	31.8	6.15	8.35	0.52	0	2.44	0.47	0	0.08	86.37
48	37.4	31.8	6.11	8.44	0.49	0.04	2.39	0.34	0	0	87.01
52	37.4	32.6	5.95	8.88	0.57	0	1.92	0.26	0	0	87.53
56	37.2	32.2	6.21	8.03	0.7	0	1.95	0.29	0.02	0.02	86.57
60	36.9	32	5.9	8.36	0.78	0	1.93	0.37	0	0	86.25
64	37.2	32.2	5.99	8.7	1.04	0.02	1.9	0.41	0.02	0.02	87.44
68	36.9	31.8	5.97	8.19	1.03	0.01	1.99	0.34	0.08	0.05	86.39
72	37.2	31.8	6.36	8.33	1.56	0.01	2.13	0.47	0.08	0.02	87.9
76	37	32.3	6.03	8.64	0.66	0	1.76	0.31	0	0	86.72
80	37.2	32.8	5.97	8.45	0.49	0.03	1.77	0.14	0	0.02	86.88
84	37.3	32.5	5.97	8.64	0.56	0.01	1.96	0.18	0.03	0	87.06
88	37.1	32.1	5.89	8.51	0.81	0	1.96	0.37	0.03	0	86.82
92	36.8	32	6.03	8.51	1.16	0.02	2.01	0.28	0	0.06	86.77
96	37.1	31.6	6.17	8.24	1.09	0.03	1.94	0.31	0	0.05	86.52
100	37	31.9	5.97	8.49	1.23	0.03	1.97	0.48	0.06	0.05	87.16
104	37.1	32.2	6.2	8.54	1.17	0.04	2.12	0.42	0.01	0.01	87.76
108	37.4	32.5	5.79	8.61	0.93	0	1.73	0.31	0	0	87.29
112	39.3	35.1	10.8	0.58	0.37	0	1.84	0.12	0.04	0	88.08
116	39.7	35.6	11	0.32	0.26	0	2	0.15	0.01	0.03	89
120	41.3	38.3	10.9	0.09	0	0	1.67	0	0	0.07	92.32
Of2c											
Core											
0	36.7	25.7	10.7	8.1	0.05	2.41	1.6	0	1.7	0.08	87.06
4	36.9	25.4	10.8	8.12	0.02	2.35	1.75	0	1.66	0.05	87.1
8	36.7	25.6	10.7	8.59	0.02	2.37	1.59	0	1.6	0	87.15
12	36.6	25.7	10.9	8.49	0.08	2.27	1.7	0.02	1.65	0.03	87.35
16	36.5	25.7	10.8	8.13	0.05	2.4	1.58	0	1.54	0	86.79
Overgrowth											
20	36.5	31.5	6.01	9.03	0.98	0.27	1.69	0.33	0.09	0	86.46
24	36.6	32.8	6.04	7.36	1.09	0.03	1.23	0.32	0	0	85.45
28	37.5	33.8	6.47	6.78	0.15	0.05	1.37	0.05	0.05	0	86.23
32	37.8	33.4	7.56	5.44	0.14	0.02	1.9	0.16	0	0	86.4
36	36.8	31.8	6.24	8.4	0.62	0.03	2.11	0.33	0.02	0.04	86.34

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
40	37.1	32	6.12	9.08	0.47	0	2.25	0.57	0	0.05	87.61
44	36.8	31.7	6.02	8.62	0.58	0.01	2.3	0.43	0.02	0	86.53
48	37	32	6.22	8.3	0.48	0	2.29	0.45	0.07	0	86.78
52	36.7	31.5	6.2	8.34	0.96	0.03	2.17	0.4	0.05	0.02	86.41
56	36.6	31.4	5.99	8.52	1.17	0.03	2.39	0.52	0.07	0	86.73
60	37.1	31.9	6.48	8.61	0.9	0.01	2.1	0.43	0.04	0	87.57
64	36.8	32.2	6.19	8.01	0.81	0.05	1.95	0.36	0	0	86.35
68	37.1	32.6	6.02	8.52	0.5	0	1.79	0.33	0.13	0	86.97
72	36.9	32.1	5.84	8.35	0.54	0	1.92	0.26	0.03	0.05	85.93
76	37.2	31.9	6.3	8.34	0.95	0.05	1.99	0.4	0	0	87.09
80	37.1	32.1	6.1	8.5	1.05	0.01	2.03	0.39	0.05	0	87.35
84	37.3	32.3	6.19	8.41	1.04	0	1.96	0.42	0	0	87.58
88	38.4	34.5	10	1.2	0.28	0.03	1.84	0.15	0	0.01	86.35
92	40.5	36.3	10.6	0.12	0.07	0	1.58	0.14	0.01	0.05	89.22
Of3c											
Core											
0	37.9	28.4	13.7	1.42	0	2.93	1.34	0.09	1.08	0.11	87
4	37.8	28.2	13.6	1.32	0.12	2.72	1.52	0.07	1.01	0.06	86.49
8	37.5	28.3	13.5	1.47	0.1	2.79	1.41	0.07	1	0.04	86.12
12	37.8	28.4	13.9	1.35	0.14	2.75	1.39	0.05	0.87	0	86.65
16	37.8	28.6	13.9	1.56	0.13	2.77	1.59	0	0.85	0.14	87.32
Overgrowth											
20	36.1	30.7	5.76	8.92	1.33	0.44	1.87	0.24	0.36	0	85.63
24	36.9	32.7	5.92	7.32	1.38	0.06	1.31	0.4	0.01	0.06	86.12
28	36.9	33.6	6.83	6.39	0.48	0.08	1.34	0.24	0.09	0	86.01
32	37.4	32.3	6.55	7.77	0.57	0.04	1.94	0.32	0.01	0	86.91
36	36.9	32	6.04	8.65	0.56	0.05	1.84	0.31	0.03	0	86.4
40	37.1	31.8	6.28	8.09	0.5	0.04	1.94	0.35	0.03	0	86.18
44	36.5	31.5	5.85	8.71	0.87	0.01	2	0.37	0	0	85.81
48	36.8	31.4	6.24	8.16	0.78	0.03	1.97	0.38	0	0.07	85.9
52	36.2	31.5	6.28	8.13	1.07	0	2.1	0.4	0	0	85.71
56	36.8	32.4	6.03	8.49	0.44	0.02	1.88	0.2	0	0	86.28
60	36.1	32	5.86	8.28	0.6	0	1.76	0.37	0	0	84.92
64	35.5	31.1	5.93	8.4	1.07	0.03	1.93	0.53	0	0.08	84.56
68	36.8	31.5	6.01	8.28	1.12	0	1.86	0.37	0.09	0.01	85.93
72	36.4	31.9	5.55	8.71	0.9	0	1.79	0.3	0	0.05	85.54
Of4c											
Core											
0	35.8	26.1	9.2	9.72	0.02	2.51	1.49	0.11	0.84	0.06	85.83

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
4	35.5	26.4	9.22	9.67	0.16	2.46	1.56	0.02	0.91	0.04	85.98
8	35.6	26.2	9.25	9.78	0.01	2.93	1.27	0	1.06	0.09	86.23
12	35.6	25.8	9.32	10.2	0.13	3.07	1.32	0.02	1.38	0.02	86.87
16	35.9	26.9	8.49	9.16	0.3	2.11	1.41	0.11	0.8	0.05	85.28
20	36.5	32.7	6.24	7.23	0.7	0.08	1.34	0.29	0.04	0	85.12
24	36.1	31.9	6.86	6.28	0.38	1.13	1.95	0.29	0.05	0.04	84.99
Overgrowth											
28	35.4	32	6.16	7.69	1.18	0.7	2.23	0.38	0.11	0	85.8
32	36.5	31.5	6.33	7.93	0.98	0.01	2.19	0.42	0.08	0.05	86
36	36.5	31.6	5.81	7.96	1.4	0.06	1.98	0.56	0.03	0.04	85.94
40	36.3	31.6	6.35	7.94	1.4	0.04	1.99	0.56	0.07	0	86.21
44	36.6	31.9	6.24	7.91	0.89	0.01	1.76	0.27	0.03	0	85.56
48	36	31.7	6.06	7.88	0.74	0.04	1.89	0.31	0.02	0	84.65
52	36.5	31.9	6.27	8.1	0.86	0	2.02	0.35	0.01	0	85.98
56	36.6	31.6	6.81	7.68	1.03	0.04	2.23	0.49	0.05	0.03	86.57
60	35.8	32	7.08	7.36	1.32	0.02	2.47	0.47	0.12	0	86.6
64	36.6	32.2	8.87	4.12	0.41	0.04	1.85	0.09	0	0	84.16
Of5c											
Core											
0	36.5	31.7	8.45	6.08	0	1.45	1.76	0.11	0.13	0	86.2
4	36.8	31.7	7.9	6.16	0.24	1.21	1.98	0.1	0.02	0.01	86.14
Overgrowth											
8	37.3	32.5	6.05	7.48	0.74	0.15	1.61	0.43	0	0	86.25
12	37.2	33.5	6.55	6.51	0.33	0.01	1.29	0.19	0.03	0.03	85.69
16	37.2	33.2	6.77	6.47	0.41	0.06	1.29	0	0	0	85.39
20	37.5	33.3	7.67	5.15	0.3	0.04	1.69	0.23	0.02	0	85.89
24	37.6	33.3	7.52	5.4	0.41	0.04	1.58	0.16	0.05	0.05	86.04
28	37	32	5.7	9.1	0.61	0	1.85	0.35	0	0	86.58
32	37	31.8	5.82	8.12	0.64	0	1.68	0.28	0.01	0	85.31
36	37	31.7	6.13	8.44	0.65	0	1.85	0.32	0	0	86.03
40	36.5	31.4	5.88	8.64	1.17	0	2.11	0.3	0	0	85.98
44	36.9	31.5	6.27	8.41	0.97	0.02	1.95	0.35	0	0	86.31
48	36.7	31.7	6.24	7.91	1.06	0	1.82	0.48	0.01	0.05	85.91
52	36.9	32.4	6	8.83	0.44	0	1.89	0.26	0.04	0	86.76
56	37.1	32.1	5.85	9.2	0.5	0.05	2.17	0.3	0.08	0	87.32
60	37	31.8	6.1	8.21	0.85	0.06	2.11	0.3	0	0.05	86.46
64	38	34.4	5.96	7.09	0.87	0.04	1.95	0.62	0.06	0	88.94
68	36.7	32.2	6	8.67	0.85	0.01	2.07	0.28	0.05	0	86.8
72	37.5	33.6	9.71	1.48	0.49	0	1.92	0.25	0.02	0	85

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
76	38.4	35.2	11	0.02	0.23	0.03	1.81	0.15	0	0.03	86.88
Of31c											
Core											
0	36	26.1	8.05	12.2	0.12	2.51	1.37	0	1.3	0.09	87.71
4	35.6	25.6	8	13.1	0.15	2.78	1.33	0.01	1.24	0.16	87.89
8	35.8	25.4	8.08	12.5	0.09	2.78	1.34	0.06	1.29	0.11	87.51
12	35.5	25.6	7.99	12.6	0	2.68	1.3	0	1.14	0.19	87.01
16	35.8	25.6	7.83	12.6	0.15	2.6	1.25	0.06	1.23	0.2	87.38
20	36	25.4	7.93	12.9	0.06	2.75	1.33	0.06	1.22	0.14	87.78
24	36	25.4	8.1	12.7	0.03	2.68	1.25	0	1.27	0.08	87.41
28	35.9	25.4	8.11	12.4	0.02	2.73	1.37	0.02	1.3	0.08	87.44
32	35.8	25.7	8.03	12.7	0.07	2.74	1.3	0.01	1.21	0.17	87.64
Overgrowth											
36	36.9	30.8	6.11	9.04	1.32	0.38	1.81	0.39	0.17	0	86.86
40	37.3	32.9	5.8	7.9	0.93	0.06	1.34	0.25	0.06	0.05	86.63
44	37.5	33.4	5.99	7.49	0.43	0.05	1.3	0.17	0.06	0	86.35
48	37.9	33.1	7.18	6.42	0.61	0.04	1.67	0.18	0.01	0	87.13
52	37.4	32.6	5.9	9.07	0.6	0.02	1.81	0.3	0.05	0	87.82
56	37.3	32.5	6.01	8.08	0.83	0	1.87	0.3	0.05	0	86.93
60	37.6	32	6.09	8.03	0.86	0.02	1.96	0.37	0.07	0	86.97
64	37.5	31.9	5.91	8.06	1.64	0	1.89	0.51	0.02	0	87.4
68	37.6	32.2	6.23	7.9	1.23	0	1.99	0.43	0	0	87.51
72	37.8	32.4	6.15	8.05	0.98	0.02	1.81	0.25	0	0	87.46
76	37.6	32.9	5.8	8.57	0.7	0	1.89	0.3	0.06	0	87.78
80	37.9	32.5	6.28	8.43	0.97	0	1.87	0.32	0.02	0	88.22
84	37.9	32.7	6.22	8.67	1.11	0.01	1.99	0.38	0.06	0	89.01
88	38.4	32.7	6.34	8.95	1.4	0	2.04	0.42	0.04	0.02	90.3
Of31c2											
Core											
0	35.9	25.4	7.98	12.5	0.15	2.84	1.29	0.02	1.19	0	87.24
4	36.4	25.8	8.04	12.7	0.04	2.77	1.31	0	1.31	0.14	88.48
8	36.6	29.1	6.67	10.8	0.43	1.4	1.72	0.18	0.84	0.1	87.86
Overgrowth											
12	37.8	33.2	6.06	7.8	0.95	0.07	1.59	0.3	0.06	0.03	87.82
16	38.2	34	6.47	6.56	0.34	0.01	1.38	0.05	0.03	0.1	87.22
20	38.6	33.5	7.16	6.64	0.47	0.01	1.79	0.12	0	0	88.32
24	38	32.6	6.11	8.6	0.51	0	1.94	0.36	0.05	0	88.16
28	37.8	32.8	6.2	8.43	0.6	0.02	1.94	0.33	0	0.02	88.18
32	37.9	32.7	6.13	8.58	0.48	0	1.89	0.31	0.03	0	87.99

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
36	38	32.2	6.2	8.21	0.53	0.02	2.06	0.28	0.02	0	87.44
40	37.7	32.5	6.26	8.9	0.96	0.08	2.07	0.43	0.03	0	88.96
44	38.2	32.1	6.22	8.81	1.14	0.01	2.14	0.33	0.02	0.02	89.05
48	37.7	32.3	6.53	7.73	0.95	0.05	2.08	0.48	0	0.08	87.92
52	38.2	32.7	6.34	8.39	0.74	0	2.01	0.39	0.01	0	88.79
56	38.2	32.9	5.98	8.56	0.63	0.01	1.78	0.28	0.04	0	88.37
60	38.1	33.1	5.89	8.74	0.45	0.01	1.89	0.28	0.04	0	88.55
64	38.3	32.7	6.25	8.5	0.79	0	2.11	0.45	0.03	0	89.19
68	38.3	33.2	6.4	8.19	1.01	0.01	2.11	0.35	0	0.06	89.6
72	38.7	33	6.41	8.87	1.21	0.03	2.02	0.43	0.05	0.01	90.7
76	40	35.6	9.67	3.42	0.73	0	1.84	0.21	0	0	91.52
80	41.7	36.7	11.7	0.08	0.09	0	2.13	0.13	0.01	0	92.49
Of32c											
Core											
0	35.6	25.2	8.09	12.7	0.09	2.37	1.53	0.09	1.2	0.08	86.94
4	35.8	24.9	8	12.3	0	2.18	1.65	0.07	1.25	0.29	86.45
8	35.9	24.9	7.99	12.6	0.17	2.16	1.59	0	1.23	0.13	86.6
12	35.8	26.6	7.4	11.1	0.49	1.69	1.62	0.21	0.91	0.08	85.87
Overgrowth											
16	37.2	32.3	5.62	8.42	0.84	0.06	1.46	0.36	0.02	0.06	86.4
20	37.8	32.8	6.38	7.08	0.5	0.03	1.33	0.21	0.01	0	86.15
24	37.9	33	6.6	6.89	0.42	0.02	1.35	0.14	0.05	0	86.34
28	37.4	32.3	6.11	8.05	0.54	0	1.9	0.21	0.05	0	86.52
32	36.9	31.9	6.05	8.44	0.59	0	1.91	0.42	0.03	0.03	86.3
36	36.9	32.1	6.11	8.41	0.7	0.04	1.97	0.29	0	0.06	86.56
40	36.8	31.5	5.85	8.63	1.19	0	1.98	0.4	0.06	0.03	86.47
44	37.1	31.5	6	8.13	1.22	0.02	2.02	0.39	0	0.02	86.39
48	36.9	31.5	6.37	7.93	1.23	0	1.98	0.5	0.01	0.03	86.46
52	37.4	31.9	6.08	8.13	0.73	0	1.78	0.22	0.02	0	86.15
56	36.8	32	6	8.31	0.58	0.01	1.76	0.31	0.02	0	85.81
60	36.8	31.9	5.98	8.44	0.68	0.04	1.79	0.25	0.02	0.02	85.85
64	36.9	31.7	5.97	8.4	1.13	0	1.86	0.4	0.06	0	86.37
68	36.6	31.2	5.96	8.19	0.96	0.01	1.99	0.39	0	0	85.35
72	36.4	31.3	5.82	8.71	0.99	0	1.84	0.45	0.04	0.06	85.58
76	37.6	33.4	10.5	0.32	0.34	0	1.77	0.2	0	0	84.09
Of33c											
Core											
0	37.1	32	5.99	7.61	0.91	0.18	1.68	0.29	0.06	0	85.83

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Overgrowth											
4	37.2	33.1	6.38	6.78	0.41	0.03	1.59	0.14	0.09	0.03	85.77
8	37.4	32.4	6.52	7.31	0.43	0.04	2.02	0.18	0.01	0	86.34
12	36.6	32.6	6.26	7.58	0.42	0.01	1.95	0.27	0.12	0.02	85.77
16	37	32.1	6.58	7.19	0.79	0.06	2.05	0.31	0.06	0.01	86.1
20	36.9	32.2	6.17	8.81	0.71	0.01	2.07	0.32	0.07	0	87.2
24	36.4	32	6.02	8.15	0.82	0	2	0.12	0.01	0	85.52
28	36.5	31.3	5.94	8.51	1.5	0	2.07	0.35	0.07	0.09	86.34
32	35.9	31.5	5.87	8.39	1.06	0.01	1.91	0.43	0.05	0.04	85.22
36	36.5	31.3	6.25	7.98	1.07	0.01	1.93	0.28	0	0.08	85.45
40	36.3	31.8	5.97	8.14	0.56	0	1.77	0.12	0	0	84.64
44	36.1	31.8	5.72	8.46	0.69	0.04	1.82	0.14	0	0	84.78
48	35.9	31.6	5.85	8.27	1.16	0.04	1.94	0.35	0.02	0	85.16
52	35.8	30.7	5.82	8.32	1.28	0	1.98	0.32	0	0.08	84.26
Of34c											
Core											
0	35.6	23.8	8.1	13.7	0.2	2.69	1.38	0.05	1.57	0.3	87.44
4	35.5	25.5	7.41	12.3	0.76	1.97	1.58	0.06	1.1	0.09	86.26
Overgrowth											
8	37	32.2	5.43	8.51	0.91	0.05	1.53	0.36	0	0	86.04
12	37.8	33.6	6.4	6.81	0.99	0.02	1.42	0.17	0.09	0.08	87.35
16	39	34.3	6.63	6.7	0.17	0	1.51	0.19	0.11	0.01	88.53
20	38.1	33.4	6.12	8.54	0.49	0.04	1.73	0.13	0	0	88.56
24	37.2	32.5	6.34	8.61	0.94	0.05	1.8	0.23	0.12	0	87.82
28	37	31.7	6.1	8.56	0.88	0	1.91	0.42	0.03	0.1	86.65
32	37.9	32.2	6.19	8.63	1.11	0	2.12	0.42	0.06	0	88.7
36	37.7	31.6	6.34	8.38	1.22	0	2.2	0.28	0.06	0.06	87.81
40	38.1	32.3	6.25	7.92	1.07	0.03	2.02	0.41	0	0	88.18
44	37.1	32.4	6.17	8.41	0.51	0.04	1.78	0.17	0.02	0.06	86.66
48	37	31.8	5.9	8.73	0.65	0.02	1.88	0.19	0	0.04	86.19
52	37.1	31.3	5.92	8.7	0.98	0.01	2.07	0.33	0.01	0.15	86.53
56	36.9	31.2	5.82	8.07	1.15	0.02	2.12	0.36	0	0.01	85.55
60	36.9	31.2	6.16	7.53	0.7	0.03	1.82	0.24	0.05	0.07	84.68
Of34c											
Core											
0	35.9	23.9	7.78	14.5	0.05	2.56	1.38	0.01	1.38	0.29	87.74
4	36.2	29.5	6.17	9.35	1.62	0.58	1.67	0.54	0.29	0.09	86.02
Overgrowth											
8	37.4	32.3	5.97	7.04	0.65	0.01	1.52	0.22	0.09	0	85.22

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
12	37.5	31.8	6.75	6.78	0.73	0.01	1.86	0.26	0	0	85.69
16	37.9	35.3	6.52	9.09	0.64	0	1.88	0.14	0	0	91.5
20	37.1	30.8	5.67	8.68	0.72	0	2.04	0.18	0.05	0.07	85.35
24	37.7	31.5	5.97	8.92	1	0	2.03	0.29	0.03	0.05	87.42
28	35.6	31	5.87	8.47	1.33	0.06	1.87	0.37	0	0	84.56
32	36.1	31.3	5.83	8.3	0.48	0	1.76	0.26	0.05	0	84.07
36	36.4	32.8	5.91	8.4	0.82	0.01	1.71	0.26	0.01	0.03	86.39
40	35.5	28.4	5.37	8.22	1.21	0.02	1.87	0.18	0.06	0	80.83
44	38.9	33.5	6.26	9.17	1.37	0.05	2.02	0.33	0.05	0.05	91.71
48	38.3	31.7	5.79	8.59	1.41	0.04	2.11	0.31	0.02	0.03	88.28
52	37.5	33.4	6.31	7.97	0.93	0	1.94	0.27	0	0	88.27
56	39.6	34.8	11.3	0.11	0.27	0.02	1.79	0.03	0.06	0	88.04
Of34cagain											
Core											
0	35.2	23.7	7.83	13.6	0.02	2.8	1.35	0.03	1.53	0.15	86.16
4	35.4	24.4	7.92	13.3	0.13	2.62	1.43	0.09	1.6	0.2	87.04
Overgrowth											
8	37.2	32.1	5.67	8.65	0.92	0.08	1.62	0.22	0.01	0.02	86.47
12	37.7	32.8	6.21	7.02	0.8	0.04	1.45	0.29	0.07	0.06	86.44
16	37.5	33.3	7.01	6	0.31	0.03	1.56	0.2	0.04	0	85.93
20	37.2	32.6	5.67	8.6	0.75	0	1.84	0.23	0	0.06	86.92
24	36.8	32.1	6.12	8.54	0.81	0	1.87	0.24	0	0	86.54
28	37.4	31.9	6.02	8.37	1	0.01	2.05	0.52	0.04	0.03	87.34
32	37.3	31.6	5.9	8.9	1.08	0.01	2.04	0.42	0.02	0	87.35
36	37.4	31.7	6.27	7.64	1.11	0.01	2.03	0.37	0	0	86.52
40	37.1	32.2	6.23	7.99	0.86	0.02	1.93	0.22	0	0	86.53
44	37.1	32.3	5.76	8.35	0.34	0.03	1.77	0.2	0.08	0.04	85.93
48	37.5	32.3	5.82	8.63	0.54	0.03	1.91	0.18	0	0.07	87.01
52	37.1	31.9	6	8.25	0.98	0.05	1.83	0.27	0.03	0	86.38
56	37.1	31.9	5.97	7.79	0.91	0	2.01	0.32	0	0	85.94
60	37.2	32.4	6.33	7.14	0.77	0.01	1.94	0.19	0	0	86.02
64	40.2	34.2	10.3	0.07	0.29	0	1.66	0.16	0.03	0.01	86.93
Of34cagain											
Core											
0	35.3	23.9	8.02	14	0.02	2.66	1.4	0	1.57	0.07	86.99
4	36.4	30.1	6.34	9.07	1.61	0.44	1.87	0.36	0.29	0.04	86.44
Overgrowth											
8	37.1	33	6.02	7.3	0.88	0.01	1.62	0.22	0	0	86.18
12	36.2	32	6.43	6.22	0.56	0.07	1.8	0.26	0.03	0.02	83.56

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
16	37.1	32.1	5.7	8.51	0.36	0.02	1.85	0.18	0.05	0	85.92
20	36.8	32	5.95	8.88	0.62	0.02	1.83	0.15	0.05	0.08	86.38
24	36.7	31.8	6.25	8.33	0.87	0.02	1.9	0.27	0	0	86.11
28	36.3	31.6	6	8.76	1.2	0.06	1.99	0.37	0.06	0	86.31
32	36.6	31.8	6.04	8.43	1.55	0	1.97	0.35	0.04	0.06	86.84
36	37	31.6	6.15	8.09	1.48	0.01	1.92	0.41	0.03	0	86.62
40	37	32.3	6.07	8.05	0.74	0.01	1.82	0.13	0.04	0	86.22
44	37.2	32.2	5.8	8.46	0.56	0.01	1.86	0.15	0	0.07	86.29
48	36.7	32.2	6.1	8.15	1.01	0	1.92	0.23	0.05	0	86.32
52	37.3	31.8	5.94	8.37	1.06	0	1.88	0.31	0.05	0	86.68
56	37.4	31.9	6.02	8.44	0.87	0.03	1.99	0.3	0.01	0.04	87.02
60	36.9	32	6.06	8.26	0.91	0.03	1.85	0.26	0	0	86.19
64	38.6	34.1	11	0.24	0.34	0.04	1.84	0.05	0.03	0.06	86.3
68	38.9	35.2	11	0.16	0.18	0	1.69	0.11	0	0	87.19
Of35c											
Core											
0	35.9	28.7	6.33	12.3	0.04	0.38	2.45	0.09	0.38	0.15	86.7
4	35.9	28.5	5.9	12.6	0.03	0.41	2.47	0	0.43	0.01	86.21
8	35.5	28.2	5.95	11.9	0.01	0.46	2.44	0.06	0.41	0	84.98
12	35.9	28.6	5.96	12.7	0.06	0.41	2.56	0.02	0.46	0.16	86.76
16	35.7	28.9	6.29	12.3	0	0.43	2.49	0	0.41	0	86.48
20	35.8	28.9	6.01	12.6	0	0.53	2.54	0.07	0.37	0	86.73
Overgrowth											
24	36.1	30.8	5.91	8.98	1.33	0.09	1.95	0.47	0.07	0	85.68
28	36.7	32.6	4.9	9.71	0.65	0.03	1.42	0.3	0.01	0	86.3
32	37.2	32.5	5.91	7.29	1.65	0.02	1.39	0.34	0	0.05	86.32
36	37	32.6	6.24	7.49	0.78	0.02	1.34	0.22	0	0	85.7
40	36.9	33.5	6.39	7.23	0.35	0.03	1.35	0.19	0	0	85.89
44	36.7	33.2	6.34	6.66	0.36	0.02	1.25	0.11	0	0.02	84.66
48	36.8	33.8	6.2	6.58	0.35	0	1.41	0.28	0.05	0.01	85.51
52	37.2	33.3	7.06	6.04	0.42	0.03	1.57	0.19	0.04	0	85.81
56	37.8	32.2	6.98	6.48	0.54	0	1.79	0.24	0.11	0.01	86.18
60	37.4	32.2	5.7	8.4	0.67	0.01	1.85	0.24	0.02	0	86.44
64	37	32.5	5.88	8.33	0.82	0	1.9	0.23	0	0.03	86.66
68	36.7	32	5.68	8.36	1.23	0.02	1.91	0.39	0	0	86.28
72	36.3	31.6	5.77	8.5	1.42	0.01	1.89	0.36	0	0	85.79
76	37.4	31.8	6.23	8.13	1.29	0	2.06	0.45	0	0	87.43
80	37.4	32	6.16	8.12	0.89	0.03	1.86	0.35	0.01	0	86.82
84	37.2	32.7	6.14	8.63	0.37	0.03	1.87	0.23	0.05	0	87.22

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
88	37.7	32.2	6.03	7.96	0.59	0	1.97	0.37	0.03	0.07	86.86
92	37.5	32.6	6.03	8.45	1.07	0.04	1.85	0.42	0.04	0.01	87.92
96	37.9	32.3	6.28	8.39	1	0	1.99	0.31	0.08	0	88.21
100	38.6	33.7	7.87	5.83	0.65	0	1.94	0.28	0.01	0	88.88
Ofamnh1											
Core											
0	36.9	25.1	10.3	8.24	0.02	2.42	1.7	0.02	1.71	0	86.42
4	36.7	25.4	10.5	8.62	0.06	2.43	1.61	0.02	1.63	0.01	87.01
8	34.6	23.6	10.2	7.83	0.05	2.41	1.59	0	1.66	0.04	81.89
12	36.5	25.4	10.6	8.38	0.07	2.38	1.65	0.01	1.64	0	86.64
Overgrowth											
16	36.4	30.6	5.86	8.83	1.48	0.18	1.96	0.51	0.11	0	85.9
20	37.5	33	5.74	7.34	0.39	0.05	1.46	0.23	0.06	0	85.71
24	38	33.4	6.49	6.71	0.28	0.01	1.28	0.1	0.04	0	86.27
28	38	32.9	7.42	5.76	0.23	0	1.78	0.19	0.02	0	86.23
32	37.5	32.2	5.96	8.39	0.39	0	1.96	0.28	0.02	0.01	86.71
36	37.4	32	6.06	8.53	0.48	0	2.03	0.33	0.01	0	86.82
40	37.2	31.8	5.9	8.59	0.8	0	2.03	0.42	0.04	0.01	86.8
44	37.1	31.7	5.88	8.57	0.82	0	2.13	0.52	0	0.01	86.71
48	37.4	31.5	6.04	8.06	0.85	0	2.12	0.44	0.04	0	86.38
52	37.3	32	5.79	8.29	0.42	0	1.87	0.25	0.03	0	85.97
56	37.1	32.2	5.81	8.37	0.35	0	1.88	0.23	0.04	0	85.99
60	37.3	31.8	5.82	8.46	0.58	0	1.93	0.38	0.03	0	86.3
64	37.5	31.5	5.91	8.38	0.79	0	2.02	0.39	0.02	0	86.55
68	37.1	31.3	5.96	8.6	0.78	0	2.12	0.42	0.03	0	86.26
72	37.5	31.6	6.2	8.3	0.69	0	2.27	0.36	0.01	0	86.97
76	38.6	33.2	9.19	2.33	0.38	0	2.18	0.26	0.01	0	86.11
Orisk gr l rose											
Outermost Dark											
0	38.9	34	9.92	2.29	0.33	0	1.89	0.16	0.33	0.03	87.92
4	39	34.4	10.9	0.55	0.24	0	1.91	0.25	0.03	0.04	87.38
8	39.4	34.1	10.6	0.81	0.35	0	1.82	0.16	0.24	0.07	87.6
12	39.5	34.4	10.8	0.64	0.38	0	1.85	0.2	0.17	0	87.88
16	39.2	34.2	10.1	1.81	0.28	0	1.89	0.16	0.19	0.04	87.79
20	39.2	34.4	10.3	1.67	0.33	0	1.79	0.15	0.28	0.01	88.13
24	39.4	34.3	10.2	1.65	0.4	0	1.75	0.18	0.05	0	87.82
28	39.3	34.4	10.1	2.18	0.31	0	1.8	0.18	0.31	0	88.55
32	39.1	34.2	9.98	2.1	0.36	0	1.76	0.24	0.35	0.06	88.2
36	38.9	34.2	10.1	1.84	0.24	0	1.75	0.12	0.26	0.03	87.41

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
40	39	34.2	9.54	2.88	0.4	0	1.73	0.19	0.31	0.02	88.26
44	38.7	33.8	9.69	2.39	0.37	0	1.71	0.16	0.38	0.04	87.21
48	38.8	34.1	9.44	2.81	0.3	0	1.86	0.21	0.07	0.01	87.51
52	38.8	33.9	9.91	2.25	0.33	0	1.84	0.17	0.22	0.01	87.41
56	38.8	33.7	10.1	1.83	0.29	0	1.88	0.21	0.38	0.04	87.21
60	38.6	33.8	10.1	1.97	0.3	0.02	1.83	0.17	0.14	0	86.97
64	38.8	34.1	9.54	3.07	0.54	0	1.82	0.18	0.29	0	88.27
68	38.6	33.6	9.34	3.07	0.34	0	1.7	0.26	0.15	0.06	87.11
72	38.4	34.2	9.79	2.05	0.45	0	1.83	0.25	0.31	0.07	87.33
76	38.9	34	9.87	1.81	0.34	0	1.77	0.23	0.31	0.03	87.26
80	38.8	34.1	9.6	2.23	0.37	0	1.75	0.2	0.16	0.12	87.25
84	38.7	33.9	9.23	3.23	0.41	0	1.8	0.26	0.26	0.03	87.84
88	38.9	33.7	9.49	2.56	0.3	0	1.77	0.21	0.31	0.03	87.31
92	38.9	33.6	9.87	2.33	0.34	0	1.81	0.19	0.14	0.07	87.27
Orisk gr 1 rose											
Outer Light											
0	37.5	31.9	6.25	8.79	0.75	0	2.14	0.32	0.39	0.1	88.13
4	37.3	31.7	6.09	8.31	0.73	0	1.98	0.39	0.24	0.09	86.84
8	37.3	31.6	6.51	8.19	0.63	0	1.98	0.46	0.24	0.04	86.94
12	37.4	31.9	6.2	8.25	0.65	0	1.99	0.5	0.36	0.04	87.22
16	37.1	31.8	6	8.41	0.67	0	1.94	0.43	0.19	0.03	86.61
20	37.4	31.6	6.04	8.4	0.65	0	2.03	0.42	0.2	0.01	86.72
24	37.5	31.8	5.98	8.51	0.71	0	1.92	0.45	0.36	0.06	87.33
28	37.1	31.7	6.24	8.51	0.72	0	1.96	0.43	0.31	0.15	87.07
32	37.1	31.9	6.1	8.47	0.72	0	1.99	0.41	0.42	0.03	87.1
36	37.2	31.6	6.27	8.31	0.76	0	1.88	0.34	0.22	0	86.59
40	37	31.3	6.01	8.58	0.75	0	1.85	0.35	0.42	0.04	86.32
44	37.1	31.5	5.94	8.7	0.83	0	1.91	0.44	0.36	0	86.8
48	36.9	31.6	5.85	8.82	0.92	0	1.93	0.38	0.37	0.04	86.82
52	37.2	31.1	6.01	8.92	0.87	0	1.98	0.38	0.37	0.05	86.87
56	37.1	31.2	6.01	9.02	0.9	0	2.03	0.4	0.32	0.06	87.05
60	37	31.3	6.05	8.68	0.99	0	1.94	0.34	0.1	0.01	86.42
64	36.9	31.5	6.03	8.59	0.84	0	1.97	0.45	0.29	0.04	86.56
68	37.1	31.6	6.04	8.68	0.75	0	1.99	0.36	0.25	0.07	86.9
72	37	31.4	5.97	8.79	0.75	0	2.01	0.49	0.2	0.05	86.67
76	37.2	31.3	6.02	8.59	0.88	0	1.95	0.38	0.36	0	86.71
80	36.9	31.6	6.13	8.28	0.8	0	1.94	0.3	0.29	0.07	86.27
84	37	31.4	5.94	8.73	0.82	0	1.98	0.41	0.42	0.1	86.78
88	37.2	31.6	6.19	8.55	0.74	0	1.94	0.43	0.39	0.01	87.12

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
92	37.1	31.4	6.07	8.49	0.81	0	1.96	0.51	0.29	0.06	86.67
96	36.9	31.4	6.17	8.42	0.68	0	1.98	0.38	0.19	0.01	86.12
100	37.1	31.6	6.11	8.39	0.77	0	2	0.41	0.31	0.07	86.73
104	37.3	31.4	6.09	8.34	0.66	0	1.97	0.42	0.26	0.03	86.38
108	37.4	31.5	6.04	8.35	0.69	0	1.87	0.34	0.39	0.06	86.66
Orisk gr 1 rose											
Inner Dark											
0	37.4	32.5	6.28	7.03	0.47	0.08	1.36	0.17	0.39	0.02	85.63
4	36.9	33.3	6.35	6.5	0.26	0	1.41	0.17	0.32	0.01	85.22
8	36.7	33	6.12	7.23	0.25	0	1.46	0.17	0.41	0.04	85.35
12	37	32.8	6.36	7.1	0.24	0.04	1.26	0.13	0.24	0.09	85.19
16	37.4	33	6.63	6.93	0.24	0	1.4	0.16	0.2	0	85.93
20	37.2	33.2	6.56	6.62	0.11	0	1.39	0.12	0.24	0.08	85.54
24	37.1	33.5	6.08	6.86	0.13	0	1.22	0.16	0.24	0.01	85.24
28	37.4	33.2	6.31	6.55	0.24	0	1.22	0.09	0.31	0.11	85.4
32	37.1	32.8	6.56	6.95	0.15	0	1.27	0.09	0.29	0.05	85.3
36	37.4	32.8	6.5	6.66	0.17	0	1.25	0.13	0.24	0.1	85.26
Senlg2											
Core											
0	35.5	25.4	8.39	11.7	0.22	2.64	1.45	0.08	1.36	0	86.66
4	35.7	25.6	8.44	11.5	0.11	2.53	1.48	0.1	1.26	0.13	86.79
8	35.9	25.5	8.31	11.6	0.16	2.58	1.51	0.1	1.22	0	86.82
12	35.7	25.1	8.43	11.3	0.15	2.6	1.42	0.1	1.2	0.1	86.04
16	35.5	25.1	8.4	11	0.06	2.65	1.42	0.16	1.16	0.12	85.52
20	35.7	25.4	8.51	11.5	0.17	2.66	1.41	0.12	1.12	0.07	86.63
Overgrowth											
24	37.5	33.4	8.84	4.36	0.37	0.04	1.89	0	0.03	0	86.41
28	37.9	33.1	10.4	1.92	0.19	0.03	1.94	0.01	0	0.03	85.55
32	37.6	33.1	9.1	3.54	0.15	0	1.71	0.09	0.04	0	85.33
Senlg3											
Core											
1	35.2	24.1	7.35	13.9	0.18	2.14	1.63	0.03	1.68	0.1	86.22
2	35.3	24.1	7.43	13.9	0.11	2.14	1.68	0	1.61	0.11	86.4
3	35.1	24.3	7.36	13.4	0.12	2.16	1.71	0.01	1.73	0.17	85.98
4	35	24.1	7.52	13.7	0.09	2.07	1.64	0	1.56	0.09	85.77
5	34.9	24.3	7.6	14.1	0.09	2.18	1.77	0	1.58	0.17	86.62
6	35.2	24.1	7.44	13.7	0.01	2.1	1.69	0	1.61	0.2	86.07
7	35	24.5	7.59	13.5	0.05	2.17	1.74	0	1.71	0.12	86.25
8	35	24.2	7.5	13.8	0.03	2.2	1.62	0.01	1.53	0.04	85.92

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
9	35.6	24.2	7.31	13.3	0.1	2.02	1.72	0.05	1.47	0.13	85.93
10	35	24	7.52	13.1	0.05	2.06	1.71	0.04	1.6	0.24	85.32
11	35	24.3	7.58	13.9	0.12	2.12	1.74	0.05	1.62	0.09	86.44
12	35	24.2	7.5	13.4	0.06	2.16	1.74	0.09	1.51	0	85.64
13	35	24.2	7.76	13.5	0.07	2.09	1.7	0.05	1.64	0.06	86.03
14	35	24.3	7.54	13.6	0.06	2.09	1.77	0.04	1.54	0.19	86.08
15	35.1	24.8	7.75	13.7	0.33	2.01	1.72	0	1.45	0.18	87.03
Overgrowth											
16	37.4	32.8	9.29	2.9	0.2	0.1	1.87	0	0.07	0	84.64
17	38	33.3	10.1	2.02	0.18	0.07	2.03	0.04	0.02	0	85.78
18	37.7	33.3	10.1	2.07	0.14	0.05	1.95	0.06	0.05	0	85.47
19	37.4	33.5	10.1	2.11	0.22	0.04	2.06	0.05	0	0.03	85.53
20	37.7	33.5	9.45	3.12	0.14	0.01	1.87	0.03	0	0.02	85.81
21	37.5	33.4	8.77	3.78	0.23	0.06	1.87	0	0.01	0.03	85.63
22	37.3	32.9	8.77	4.31	0.22	0.02	2.03	0.07	0.03	0.12	85.76
23	37.6	32.9	9.3	3.31	0.44	0.02	2	0.12	0.03	0.07	85.75
24	37.6	33.2	9.88	2.46	0.64	0.02	2.07	0.17	0	0	86.08
25	37.6	33.4	10.2	2.14	0.51	0	2.06	0.32	0	0.03	86.26
26	38.1	33.2	10.5	1.55	0.33	0	2.08	0.23	0.02	0.03	86.04
27	38.1	33.7	11.1	0.37	0.32	0	1.93	0.12	0.02	0	85.68
28	38.4	33.8	11	0.39	0.36	0	1.88	0.15	0	0	85.96
29	38.5	33.8	11	0.41	0.11	0.01	1.77	0.16	0	0.01	85.75
30	38.3	33.6	10.8	0.49	0.26	0	1.83	0.27	0.04	0	85.66
31	38.4	34.4	11	0	0.11	0.02	1.73	0.22	0.05	0.06	86.09
32	38.4	34	11.2	0.11	0.23	0.04	1.73	0.09	0	0.01	85.84
Senlg4											
Core											
0	36.8	27.7	12.6	3.79	0.04	3.86	0.88	0.06	1.01	0.08	86.89
4	37	27.7	12.6	3.57	0.06	3.9	0.88	0	1.08	0.07	86.84
8	37.1	27.7	12.6	3.4	0.15	3.79	0.92	0	1	0	86.59
12	36.8	27.8	12.6	3.54	0	3.92	0.89	0.04	1.05	0.1	86.75
16	37.2	27.7	12.7	3.4	0.05	3.69	0.89	0.02	0.98	0.13	86.74
20	36.6	27.9	12.6	3.62	0	3.79	0.9	0.02	0.95	0.17	86.6
24	37	27.8	12.5	3.59	0.05	3.94	0.91	0.05	0.97	0.13	86.89
28	37.1	28	12.5	3.46	0.02	3.76	0.85	0.06	0.99	0.12	86.78
Overgrowth											
32	38.4	33.5	9.86	2.31	0.19	0.05	2.16	0.04	0.05	0	86.53
36	38.2	32.8	10.3	2.42	0.08	0.01	2.11	0.07	0.01	0	86.06
40	38	32.9	9.61	2.96	0.19	0.02	2.11	0.2	0	0.02	86

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
44	37.8	32.9	9.25	3.67	0.21	0.04	1.91	0.16	0	0.05	85.93
48	37.9	33.3	8.99	3.56	0.21	0	1.92	0.14	0	0	86
52	38.1	33.9	8.88	3.74	0.18	0.03	1.84	0.06	0.01	0.02	86.78
56	38.1	33.5	8.76	3.99	0.05	0	2.02	0.04	0.06	0	86.51
60	38.1	33	8.54	4.18	0.04	0	2.16	0.06	0.07	0.09	86.28
64	35.8	38.5	7.49	3.87	0.26	0.03	1.87	0.13	0.05	0.02	88.03
68	38.1	32.8	8.89	4.32	0.27	0	2.27	0.21	0.01	0	86.87
72	37.9	32.8	8.78	4.37	0.27	0.01	2.28	0.14	0.02	0.04	86.56
76	37.5	32.8	8.97	3.99	0.33	0	2.19	0.15	0.02	0.11	86.06
80	37.6	32.8	9.61	3.09	0.6	0.04	2.4	0.3	0.08	0.04	86.5
84	37.9	32.6	9.9	2.55	0.56	0	2.43	0.3	0	0.01	86.23
88	38	32.7	10.1	1.93	0.54	0.02	2.52	0.42	0.03	0.11	86.39
92	38.1	32.9	10.2	1.72	0.52	0.02	2.35	0.29	0.03	0	86.17
96	38.1	33.2	10.4	1.42	0.6	0.01	2.36	0.3	0	0.08	86.39
100	38.5	33.2	10.6	1.11	0.27	0	2.32	0.28	0	0	86.36
104	38.6	33.3	11.3	0.2	0.3	0	2.26	0.33	0.01	0	86.29
108	38.8	33.8	11.1	0.25	0.31	0.06	2.37	0.27	0	0.04	86.94
112	38.8	33.5	11.1	0.4	0.44	0.01	2.11	0.25	0	0	86.56
Senlg5											
Core											
0	35.4	33.4	6.28	6.4	0.27	1.44	1.69	0.08	1.31	0.01	86.26
4	35.4	33.8	6.23	6.62	0.12	1.44	1.62	0.01	1.34	0.06	86.71
8	35.1	33.8	6.26	6.4	0.12	1.44	1.65	0	1.37	0	86.06
12	35.5	33.8	6.33	6.65	0.12	1.39	1.62	0.03	1.26	0	86.71
16	35.2	33.5	6.06	6.15	0.31	1.51	1.68	0	1.34	0.19	85.93
Overgrowth											
20	37.5	33.1	8.77	3.81	0.3	0.02	1.75	0.19	0	0.02	85.46
24	37.3	33.4	8.46	3.97	0.07	0	1.73	0.02	0	0.09	85.1
28	37.1	33.2	9.68	2.18	0.05	0.02	1.89	0.05	0.05	0	84.23
32	38	32.7	10.5	1.61	0.12	0.01	1.92	0.02	0.01	0.02	84.9
36	37.4	32.3	9.45	2.96	0.28	0	1.79	0.13	0	0	84.34
40	37.2	33.1	8.73	3.65	0.2	0	1.66	0.14	0.08	0	84.84
44	37.6	32.7	8.85	4.12	0.25	0	1.89	0.07	0	0	85.55
48	37.6	33	10.7	0.46	0.12	0.05	2.39	0	0.03	0.12	84.45
52	38	33.5	10.7	0.12	0.07	0.02	2.44	0	0	0.07	84.86
56	38.2	33.6	10.9	0	0.07	0.01	2.54	0	0	0.03	85.35
60	38.1	33.6	10.8	0.05	0.07	0.02	2.49	0.01	0.08	0.05	85.22
64	38	33.1	11.1	0.05	0	0.01	2.36	0.04	0.01	0	84.6
68	39	34	11.6	0.04	0	0.01	2.62	0.04	0.03	0	87.26

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
72	37.7	33	11.3	0.02	0.09	0.03	2.47	0.02	0.03	0	84.65
76	37.1	32.4	11.2	0.08	0.08	0.01	2.47	0.05	0	0	83.45
Senlg6											
Core											
0	35.5	26.8	5.67	14	0	1.43	2.04	0	1.29	0.06	86.72
4	35.4	26.8	5.64	14.2	0.07	1.39	2.06	0.09	1.31	0	86.89
8	35.2	26.7	5.66	13.8	0.15	1.32	2.03	0	1.39	0.1	86.32
12	35.5	26.9	5.65	13.9	0.1	1.39	2.08	0.09	1.37	0.07	87.02
16	35.4	27.3	5.65	13.9	0	1.46	1.94	0.05	1.38	0.06	87.16
20	35.3	26.9	5.62	13.9	0	1.41	2.03	0.03	1.36	0.17	86.69
Overgrowth											
24	37.6	33	8.88	4.24	0.28	0.13	1.82	0.17	0.15	0	86.23
28	37.9	33.4	8.34	4.11	0.28	0.01	1.59	0.01	0.05	0	85.64
32	37.3	32.5	9.93	2.45	0.21	0.07	1.82	0.01	0	0	84.29
36	38.1	33.2	9.62	2.78	0.32	0	2.12	0.09	0.02	0	86.27
40	38	33.6	9.14	3.33	0.13	0.03	1.75	0.08	0.02	0	85.98
44	37.6	33.1	8.64	4.05	0.15	0	1.81	0.07	0.01	0.06	85.52
48	37.9	32.8	8.82	4.34	0.28	0.02	1.93	0.13	0.06	0.07	86.33
52	37.5	32.8	9.01	4.09	0.18	0	2.14	0.13	0	0	85.87
56	37.5	33.1	9.16	3.58	0.27	0.02	2.06	0.15	0.01	0.11	85.95
60	38	33	9.58	3.03	0.59	0.02	2.22	0.2	0	0	86.57
64	37.9	32.9	9.9	2.28	0.56	0.04	2.04	0.26	0	0.06	85.87
68	38.1	33.5	10.1	1.97	0.62	0	2.02	0.29	0.01	0	86.62
72	37.9	33.5	10.5	1.64	0.6	0.01	1.94	0.24	0	0	86.34
76	37.9	33.7	10.8	1.01	0.49	0.01	2	0.2	0.07	0.08	86.15
80	38.8	33.7	11.5	0.13	0.27	0	1.99	0.12	0	0	86.45
84	38.2	33.3	11.2	0.36	0.4	0.01	1.96	0.15	0	0.03	85.55
88	38.2	33.9	11.3	0.5	0.35	0.04	2.05	0.19	0.06	0.12	86.61
Senlg7											
Core											
0	34.9	27.6	6.89	11.2	0	1.02	2.25	0	0.9	0.19	84.91
4	35.3	27.5	6.89	11.4	0.03	1.05	2.18	0	0.83	0.05	85.13
8	35	27.4	6.89	11.2	0.02	1.06	2.18	0.01	0.94	0.09	84.8
12	35.1	27.6	6.98	10.8	0.13	1.15	2.25	0.05	0.82	0.09	84.9
16	35.6	27.4	6.91	11	0.1	1.1	2.26	0	0.82	0.1	85.28
20	35.1	27.1	6.78	11.1	0.1	1.12	2.24	0	0.85	0.04	84.41
24	35.3	27.2	6.98	11.1	0.14	1.24	2.14	0	0.82	0.08	84.98
28	35	27.3	7.16	10.9	0	1.21	2.22	0	0.89	0.12	84.81

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Overgrowth											
32	37.6	31.9	10.3	1.97	0.09	0.02	1.88	0.1	0.11	0.03	84.06
36	37.4	32.4	9.08	3.06	0.36	0.02	1.84	0.04	0.03	0.06	84.25
40	37	32.8	8.59	3.8	0.11	0	1.77	0.11	0.06	0	84.21
44	36.9	32.4	8.6	4.07	0.39	0	2.01	0.07	0	0	84.38
48	37	32.4	8.75	3.79	0.25	0.04	2.02	0.13	0	0.04	84.46
52	37.3	32.2	9.5	2.87	0.5	0	2.01	0.12	0	0	84.5
56	37.1	32.6	9.92	2.05	0.66	0	1.91	0.22	0.02	0	84.47
60	37.3	32.4	10.1	1.64	0.45	0	2.17	0.27	0	0	84.36
64	37	32.9	10.6	0.73	0.58	0.01	2.1	0.14	0.07	0	84.07
68	37.1	33.2	11	0.21	0.31	0	2.21	0.19	0.1	0.08	84.38
72	37.5	32.9	10.8	0.53	0.17	0	1.91	0.16	0.03	0.05	84.02
76	38.1	33.3	10.7	0.51	0.3	0.01	2.18	0.19	0.02	0	85.36
80	37.8	33.9	10.7	0.16	0.17	0	1.95	0.02	0.02	0	84.7
84	38.5	33.8	11.2	0.1	0.17	0	1.84	0.22	0	0	85.81
88	38	33.4	10.9	0.03	0	0.01	1.83	0.09	0.04	0	84.22
92	37.7	33.6	10.9	0.02	0	0	2.04	0.01	0	0.08	84.32
96	37.3	33.5	10.6	0.07	0.01	0.02	1.91	0.05	0.03	0	83.5
Senlg8											
Core											
0	36.9	29.1	10.7	3.92	0.04	1.36	2.08	0.01	1.46	0	85.48
4	36.4	29.1	10.8	4.38	0	1.52	2.01	0	1.44	0.07	85.64
8	36.6	29.4	10.7	4.16	0	1.53	2.05	0.05	1.69	0.08	86.22
12	36.8	29	10.6	4.45	0	1.53	2.11	0.03	1.75	0.02	86.33
16	36.2	28.9	10.8	4.52	0.01	1.62	2.08	0.03	1.67	0.04	85.9
20	36.5	28.8	10.8	4.22	0.01	1.65	2.08	0.03	1.75	0	85.74
24	36.9	29.2	10.8	4.7	0.06	1.79	2.04	0.01	1.75	0.07	87.34
28	36.7	29	10.8	4.62	0	1.64	2.09	0.07	1.64	0.08	86.64
Overgrowth											
32	36.8	32.1	9.13	4.18	0.47	0.5	1.84	0.08	0.49	0.02	85.52
36	37.5	32.9	8.55	4.08	0.3	0.07	1.76	0.03	0.06	0.04	85.22
40	37.8	32.9	10.4	1.73	0.04	0.06	1.96	0.07	0.07	0	85.05
44	38	33	10	2.06	0.21	0.02	1.95	0.15	0.05	0.06	85.52
48	38.3	32.8	10.4	1.73	0.22	0.02	1.93	0.1	0.04	0	85.51
52	38.3	32.6	10.2	2.27	0.2	0.04	1.85	0.06	0.06	0.1	85.64
56	38	32.2	9.96	2.47	0.23	0.02	1.96	0.08	0.02	0.02	85
60	37.9	32.2	9.99	2.52	0.33	0	1.88	0.25	0.03	0	85.06
64	38.2	32.5	9.47	3.12	0.22	0.05	1.79	0.21	0	0.02	85.57
68	38.2	33	8.99	3.22	0.11	0	1.57	0.01	0.09	0.06	85.23

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
72	37.9	32.8	8.7	4.09	0.09	0.02	1.84	0	0	0	85.45
76	37.8	32.6	9	3.88	0.18	0.01	1.78	0.07	0	0	85.29
80	37.6	32.5	8.84	3.94	0.35	0	1.97	0.07	0	0.12	85.34
84	37.5	32.8	9.24	3.53	0.41	0.03	1.93	0.24	0.06	0	85.66
88	37.8	32.9	9.78	2.75	0.63	0	1.97	0.24	0	0.06	86.09
92	37.9	32.8	10.2	2.08	0.49	0.01	2.01	0.43	0.01	0	85.88
96	37.9	33.3	10.4	1.38	0.44	0	1.87	0.22	0.02	0.01	85.51
100	38.2	33.8	10.6	0.47	0.55	0.02	1.76	0.22	0	0	85.68
104	38.3	33.7	11	0.19	0.27	0	1.83	0.17	0.01	0.08	85.45
108	38.3	34.1	10.7	0.37	0.28	0.01	1.74	0.15	0	0.09	85.61
112	38.4	33.9	10.8	0.41	0.48	0.03	1.89	0.12	0.02	0	86.04
116	38.1	34.2	10.9	0.14	0.17	0.02	1.66	0.1	0.01	0	85.2
120	37.9	33.9	10.8	0.01	0.2	0.03	1.7	0.16	0	0.03	84.79
Senile Core											
0	36.7	32.5	7.6	6.16	0.01	0.64	2.21	0.68	0.31	0.02	86.74
4	36.6	32.7	7.69	5.68	0.08	0.62	2.19	0.49	0.32	0.01	86.35
8	36.6	32.9	7.58	5.99	0.02	0.68	2.24	0.57	0.31	0	86.97
12	36.6	32.7	7.68	5.92	0.16	0.76	2.13	0.59	0.27	0.02	86.88
16	36.8	32.8	7.55	6.05	0.04	0.7	2.06	0.6	0.21	0.03	86.86
20	36.8	32.9	7.49	5.84	0.13	0.73	2.21	0.48	0.34	0.11	87.04
24	36.7	32.5	7.49	5.93	0	0.71	2.21	0.43	0.34	0	86.3
28	36.9	32.7	7.69	6.12	0.07	0.7	2.04	0.44	0.33	0.11	87.11
Overgrowth											
32	38.3	33.3	9.04	3.87	0.25	0.08	1.78	0.06	0.09	0.02	86.81
36	38.4	33.3	10.4	1.93	0.13	0.05	2.08	0.01	0.03	0.06	86.32
40	38.2	33	9.49	3.23	0.18	0	2.25	0.04	0.04	0.01	86.4
44	38.3	33.4	8.99	3.53	0.08	0.03	1.83	0.09	0.03	0.05	86.34
48	38.1	33.4	8.88	3.8	0.13	0.02	2.09	0.12	0	0.1	86.64
52	38.1	33.3	8.87	4.72	0.12	0	2.1	0.17	0.01	0.01	87.35
56	37.8	32.6	8.95	4.79	0.25	0	2.22	0.17	0.01	0	86.84
60	38	32.6	8.91	4.04	0.3	0	2.39	0.18	0.04	0.05	86.46
64	37.4	32.9	9.32	4.05	0.33	0.01	2.42	0.16	0	0	86.52
68	38	32.3	9.73	2.83	0.32	0.01	2.43	0.31	0.01	0	85.91
72	38	32.6	9.99	2.7	0.64	0	2.47	0.35	0	0	86.72
76	38.2	32.5	10.3	2.03	0.56	0	2.39	0.24	0.01	0.07	86.3
80	38.2	32.8	10.3	1.93	0.45	0.02	2.44	0.27	0.03	0.16	86.53
84	38.3	33.1	10.9	1.29	0.57	0.05	2.64	0.41	0.03	0.04	87.29
88	38.8	33.7	11.3	0.3	0.42	0.02	2.62	0.2	0.01	0.04	87.39

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
92	38.4	33.4	11.3	0.53	0.29	0.03	2.64	0.27	0	0.05	86.9
Sen2c											
Core											
0	37.1	29.4	9.95	6.47	0.06	1.65	2.03	0.04	0.12	0.05	86.88
4	36.8	29.4	9.83	6.92	0.06	1.83	2.02	0.02	0.09	0	86.94
8	36.3	29.2	9.35	7.77	0.08	1.83	1.99	0	0.13	0.01	86.68
12	36.7	28.8	9.38	8.18	0.08	1.8	2.11	0.08	0.09	0.03	87.2
16	36.9	29.5	9.92	7.03	0.04	1.76	2.01	0.05	0.11	0.13	87.42
Overgrowth											
20	37.8	33.5	8.82	4.26	0.17	0	1.81	0.09	0	0	86.42
24	38.3	33.2	10.4	1.86	0.08	0.06	2.09	0.18	0.05	0.04	86.32
28	38.1	33.3	10.6	1.92	0.15	0.01	1.91	0.17	0.05	0	86.2
32	38.1	34.1	9.99	2.48	0.12	0.04	2.06	0.12	0	0.08	87.01
36	37.1	33.8	10.1	2.94	0.33	0.01	2.04	0.09	0	0.03	86.43
40	38.2	33.1	9.61	2.97	0.34	0.02	1.71	0.04	0	0.07	86.05
44	38.4	33.3	9.56	3.15	0.34	0.01	1.69	0.15	0	0.05	86.65
48	38	33.6	9.1	3.01	0.15	0.04	1.54	0.12	0.06	0.05	85.68
52	38.5	33.4	8.87	3.69	0.17	0	1.6	0.06	0.01	0	86.26
56	37.9	33.1	8.75	4.3	0.07	0	1.79	0.01	0.04	0.04	85.97
60	38	33.4	8.99	4.01	0.18	0	1.93	0.01	0.09	0	86.56
Sen3c											
Core											
0	35.5	24.4	6.73	15.2	0.14	1.17	2.19	0	0.86	0.29	86.46
4	35.3	24.1	6.93	16	0.02	1.64	1.93	0.01	0.82	0.39	87.16
8	34.9	24	6.77	16	0.09	1.7	2.04	0.08	0.83	0.16	86.62
12	35.3	23.9	6.67	15.7	0.1	1.68	1.79	0.06	0.73	0.19	86.02
16	35.6	23.9	7.01	15.7	0.06	1.61	1.92	0.01	0.75	0.35	86.93
Overgrowth											
20	38.1	32.8	9.19	3.45	0.53	0.04	1.94	0.1	0	0	86.06
24	38.3	33.1	10.5	1.82	0.07	0.03	2.05	0.15	0.02	0	86.04
28	38.1	33	10	2.5	0.27	0.06	2.1	0.1	0	0.05	86.26
32	37.9	33	9.47	3.07	0.3	0.02	1.91	0.1	0.01	0.04	85.81
36	38.3	33.2	8.95	3.9	0.08	0.04	1.84	0.07	0	0.04	86.44
40	37.6	33.1	9.1	4.31	0.26	0.02	2.14	0.18	0	0.05	86.76
44	37.7	32.7	8.98	4.09	0.28	0	2.09	0.07	0.01	0.04	85.96
48	37.6	32.7	9.61	3.61	0.35	0.02	2.12	0.22	0.02	0	86.18
52	38	32.9	10.2	2.53	0.5	0.01	2.25	0.26	0.02	0.17	86.79
56	37.7	32.4	10.4	2.21	0.57	0	2.21	0.29	0	0	85.77
60	38	33.1	10.6	1.36	0.32	0	2.24	0.29	0	0.08	85.92

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
64	38.5	33.3	11.2	0.37	0.25	0	2.04	0.21	0.06	0	85.9
68	38.9	33.3	11.2	0.47	0.17	0	1.99	0.13	0.02	0	86.21
72	38.4	33.6	11.1	0.57	0.26	0	2.2	0.15	0.02	0.04	86.39
76	38.4	33.8	11.4	0.67	0.3	0.04	2.03	0.12	0	0.13	86.82
80	38.6	34.2	11.4	0.16	0.13	0.03	1.86	0.13	0.05	0.04	86.51
84	38.7	33.8	11.5	0.09	0.14	0.04	1.96	0.25	0.03	0.05	86.54
88	38.6	34	11.4	0.11	0.18	0.04	1.87	0.22	0	0.06	86.43
92	38.5	34.1	11.5	0.21	0.07	0	1.95	0.19	0	0.04	86.48
96	39	33.9	11.5	0.07	0.12	0	2.01	0.18	0.06	0.07	86.86
100	39.2	34.6	11.4	0.09	0.11	0.02	1.79	0.2	0	0	87.31
104	38.9	37.2	9.84	0.4	0.02	0.08	1.72	0.04	0.02	0.01	88.25
Sen5c											
Core											
0	36.7	26.4	9.71	9.19	0.13	2.28	1.62	0.03	1.4	0	87.41
4	35.9	26.8	9.49	9.13	0.21	2.65	1.62	0	1.23	0.09	87.11
8	36.2	26.6	9.65	8.9	0.15	2.37	1.75	0.05	1.29	0.1	86.99
12	36.5	26.3	9.62	8.89	0.13	2.5	1.6	0.01	1.18	0.04	86.82
16	36.3	26.6	9.68	9.14	0.14	2.31	1.69	0.07	1.23	0.06	87.23
20	36.5	26.3	9.79	9.06	0.05	2.33	1.59	0.06	1.27	0.03	86.96
24	36.4	26.4	9.68	8.64	0.09	2.23	1.58	0.07	1.27	0	86.34
28	36.2	26.8	9.6	8.62	0.15	2.1	1.76	0.06	1.23	0.06	86.66
Overgrowth											
32	37.4	32.5	9.36	2.82	0.19	0.07	2.18	0.03	0.01	0.01	84.61
36	38.2	32.6	10.1	2.69	0.18	0.01	1.9	0	0.03	0	85.72
40	37.9	33	9.12	4.2	0.22	0	1.8	0.09	0.01	0	86.39
44	37.9	33.5	9.06	4.05	0.11	0	2.09	0.01	0.01	0.03	86.72
48	38	33.4	9.86	2.43	0.2	0.06	2.18	0.03	0.01	0.05	86.19
52	38.4	33.6	10.3	1.64	0.07	0.02	2.16	0.07	0.03	0	86.31
56	38.1	33.8	10.7	1.11	0.24	0.02	2.24	0.04	0.01	0	86.28
60	38.5	33.6	11.5	0.13	0.29	0.01	2.15	0.06	0	0.05	86.38
64	38.8	33.8	11.2	0.48	0.22	0.03	2.1	0	0.02	0.05	86.66
68	38.9	33.9	11.3	0.49	0.13	0.06	1.92	0	0	0	86.7
72	38.5	34	11.2	0.08	0.13	0.02	1.8	0	0	0.04	85.8
76	38.6	34	11.6	0.03	0.22	0	1.88	0.08	0.03	0	86.34
80	38.7	34	11.5	0.03	0.11	0	1.93	0.08	0.02	0	86.3
84	38.8	33.8	11.4	0.06	0	0.01	2.05	0.06	0	0	86.24
88	38.6	33.8	11.4	0.03	0.1	0.05	1.78	0.13	0	0.02	85.93
92	39.9	35.4	11.7	0	0.13	0.05	2.02	0.07	0.03	0	89.29

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Sen1d											
Core											
0	35.8	24.9	8.03	12.5	0.24	0.91	2.09	0	1.32	0.02	85.77
4	36.1	24.9	8.27	12.5	0.34	0.95	2.3	0.08	1.29	0.17	86.86
8	34.5	29.5	8.27	11.8	0.11	0.83	2.4	0.03	1.14	0.11	88.59
12	30.5	26.2	7.26	11.3	0.18	0.75	2.13	0	1.16	0	79.45
Overgrowth											
16	36.4	30.4	8.94	6.72	0.26	0.36	2.07	0.09	0.44	0.06	85.79
20	38	32.7	10.3	1.9	0.12	0	2	0.08	0.03	0	85.15
24	37.6	33.1	10.4	2	0.07	0.01	2.04	0.17	0.03	0	85.38
28	38.9	33	10.2	2.08	0.17	0.06	2.1	0.15	0.05	0.09	86.7
32	38.1	32.9	10.2	1.89	0.19	0.03	2.09	0.18	0.02	0	85.55
36	37.4	32.9	10.4	1.99	0.11	0.03	1.9	0.11	0.02	0.09	84.91
40	37.6	32.9	9.97	2.33	0.12	0.01	1.86	0.11	0	0.09	85.02
44	36.9	31.9	9.87	2.59	0.15	0	1.9	0.09	0.07	0	83.41
48	37.9	32.9	9.17	2.99	0.2	0	1.72	0	0.01	0.04	84.9
52	37.5	33	8.96	4.11	0.11	0.02	1.77	0.07	0.09	0	85.56
56	37.2	33.2	8.84	3.85	0.15	0.02	2.05	0.14	0.02	0	85.49
60	37.4	32.9	9.08	3.79	0.31	0	2.02	0.05	0	0.03	85.58
64	37.9	32.9	9.44	2.82	0.39	0	2.02	0.2	0	0.05	85.75
68	38.2	32.8	9.95	2.54	0.38	0.03	2.12	0.25	0.03	0.1	86.39
72	37.6	32.7	10.1	1.9	0.67	0.02	2.09	0.2	0	0	85.3
76	38.3	32.7	10.5	1.74	0.48	0	2.07	0.17	0	0	85.9
80	38.7	33.1	10.9	0.71	0.52	0.04	2.02	0.19	0.01	0	86.24
84	38.5	32.7	11	0.33	0.41	0.05	2.1	0.23	0	0	85.31
88	38.2	33.5	10.9	0.41	0.32	0.02	1.84	0.11	0.02	0.07	85.33
92	38	33.4	10.7	0.41	0.53	0	1.94	0.25	0	0	85.27
96	38.4	34.3	10.9	0.13	0.39	0.04	1.82	0.09	0.04	0	86.06
100	38.4	33.5	10.8	0.12	0.06	0	1.75	0.14	0.05	0	84.82
104	38.5	34	10.8	0.11	0.09	0	1.78	0.07	0.02	0	85.39
108	38.5	34	11.1	0.1	0.08	0.05	1.8	0.13	0	0	85.82
112	37.9	34.6	10.4	0.07	0	0	2.05	0	0.02	0.02	85.11
116	39.3	35.9	11.2	0.06	0.01	0.04	1.93	0	0	0	88.35
Sen2d											
Core											
0	34.9	24.2	8.63	11.9	0.05	2.66	1.35	0.05	1.99	0.12	85.85
4	35	24.3	8.58	11.5	0.1	2.66	1.38	0.01	2.01	0.07	85.64
8	35.1	24.3	8.52	11.7	0.15	2.68	1.37	0.08	1.81	0.03	85.8
12	35.1	25.6	8.56	10.3	0.1	2.17	1.61	0.04	1.48	0	84.84

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Overgrowth											
16	37.3	32.4	9.98	2.95	0.22	0.11	1.89	0	0	0.03	84.89
20	36.9	32.7	9.27	3.3	0.12	0.01	1.97	0.02	0.03	0	84.3
24	37.4	33.1	8.64	3.95	0.05	0	1.88	0.07	0.05	0	85.16
28	37	33.1	8.93	4.5	0.3	0	2.15	0.11	0.08	0.12	86.24
32	36.8	33.1	9.09	3.37	0.04	0.02	2.09	0.05	0	0	84.61
36	37.8	32.8	9.9	2.22	0.43	0	2.06	0.03	0	0	85.28
40	37.4	32.9	10	1.78	0.4	0	2.03	0.19	0.02	0	84.74
44	37.5	33.7	10.3	1.39	0.28	0.01	1.94	0.09	0	0	85.22
48	37.5	32.8	10.4	0.28	0.28	0.01	1.83	0.16	0	0	83.26
52	38.2	34.1	10.9	0.42	0.11	0.01	2.07	0.1	0.02	0.1	85.96
56	38.6	33.7	11	0.55	0.18	0	1.99	0.08	0	0.04	86.05
60	38.3	33.5	11	0.68	0.2	0.02	2.18	0.21	0.01	0	86.05
64	37.8	34.3	10.7	0.02	0.1	0.03	1.78	0.12	0.01	0	84.88
68	38.3	33.7	11.1	0.1	0.17	0.04	2.21	0.18	0.07	0	85.82
72	37.5	34.1	11	0.02	0.14	0.05	1.82	0.13	0	0.09	84.84
76	38.1	33.6	11.2	0.07	0.01	0.01	2.05	0.04	0	0	85.04
80	37.8	33.7	11.1	0.07	0.04	0	2.12	0.03	0	0	84.86
84	37.7	33.5	11.1	0	0.06	0	1.95	0.09	0	0	84.35
88	38	33.5	10.9	0.05	0.13	0	1.95	0.08	0	0	84.66
92	37.9	33.6	10.8	0	0	0.03	2.04	0.03	0	0	84.39
Sen3d											
Core											
0	35.1	35.2	5.85	6.65	0.13	2.28	0.92	0.01	0.7	0	86.84
4	35.1	35.3	5.86	6.68	0	1.99	1.01	0.07	0.73	0	86.72
8	35.6	35	5.72	6.8	0	2.02	1.01	0.03	0.72	0.08	86.91
12	35.4	34.3	6.1	6.66	0.03	1.76	1.17	0.07	0.74	0	86.27
16	35.2	35.1	5.93	6.57	0.01	2.03	1.05	0.07	0.78	0.01	86.74
Overgrowth											
20	38	33.3	8.87	3.96	0.08	0.1	1.78	0.16	0.01	0.08	86.25
24	38.4	33	9.77	2.24	0.2	0.03	1.9	0.11	0.02	0.09	85.75
28	38.2	33.1	10.3	1.83	0.27	0	2.07	0.12	0.04	0.01	85.91
32	37.9	32.9	10	2.47	0.33	0.01	1.98	0.07	0.07	0	85.75
36	37.7	33.4	9.16	3.06	0.08	0	1.83	0.03	0	0.06	85.31
40	37.6	33	8.72	3.96	0.14	0.04	1.74	0	0	0	85.27
44	38.6	33	9.13	4.07	0.24	0.04	2.01	0.17	0.01	0	87.26
48	37.9	34.1	9.46	3.9	0.07	0.03	2.16	0.08	0.02	0	87.72
52	36.9	33.6	9.74	3	0.27	0	2.22	0.24	0.05	0	86.02
56	38.2	33.1	10.1	1.86	0.46	0.03	2.21	0.21	0	0	86.17

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
60	38	33.8	10.6	1.8	0.52	0.01	2.28	0.27	0	0	87.3
64	38.6	33.5	10.4	1.26	0.48	0	2.18	0.18	0.03	0.06	86.68
68	38.7	33.6	11.3	0.24	0.29	0	2.07	0.21	0.04	0.01	86.43
72	39.4	33.5	11.1	0.46	0.23	0.01	2.04	0.17	0.05	0	86.93
76	39	34	11.1	0.48	0.17	0.02	1.99	0.15	0	0.02	86.92
80	38.9	34	11.1	0.42	0.06	0.02	1.98	0.15	0	0.03	86.62
84	39.1	33.9	11.2	0.02	0.12	0.03	1.93	0.03	0	0	86.3
88	38.7	34.2	11.2	0	0.15	0.02	1.9	0.1	0	0	86.25
92	39.1	34.2	10.9	0.04	0	0.05	1.96	0.07	0	0	86.23
96	38.9	34.1	11.2	0.05	0.03	0	1.96	0.16	0	0	86.43
100	38.7	34.1	11.1	0.04	0.07	0.02	1.93	0.18	0.03	0	86.2
104	38.9	33.9	11.2	0.02	0	0	2.11	0.13	0	0.03	86.3
108	38.7	34.1	11.1	0.09	0.01	0.04	2.07	0.14	0.06	0	86.3
Sen3d-2nd run											
Core											
0	35.4	35.2	5.83	6.61	0.1	1.64	1.13	0.01	0.95	0	86.88
4	35	35	6	6.66	0.04	2.07	1.11	0.07	0.69	0	86.64
8	35	35	5.84	6.25	0.07	2.08	1.07	0.05	0.76	0	86.19
Overgrowth											
12	38	33.1	8.56	3.62	0.31	0.22	1.8	0.16	0.09	0	85.82
16	37.9	32.8	10.4	2.22	0.19	0.02	1.98	0	0	0	85.46
20	37.8	33	9.51	3.19	0.2	0.01	1.73	0.13	0	0	85.54
24	37.6	33.1	8.92	3.71	0.13	0.02	1.81	0.09	0	0	85.38
28	37.6	33	8.75	4.06	0.26	0	2.2	0.09	0	0	86.01
32	37.9	33	9.07	3.9	0.16	0.05	2.1	0.14	0.05	0.02	86.42
36	37.5	32.9	9.64	2.6	0.5	0.01	2.15	0.2	0	0.03	85.53
40	37.8	32.9	10.1	2.03	0.35	0.01	2.15	0.27	0	0	85.54
44	38	32.9	10.2	1.57	0.4	0.06	2.11	0.19	0.03	0	85.46
48	38	33.2	10.6	0.83	0.31	0.02	2.05	0.2	0.06	0.01	85.26
52	37.9	33.7	11.1	0.13	0.27	0.05	1.94	0.11	0	0.06	85.26
56	38.2	33.7	10.8	0.48	0.3	0	1.82	0.18	0.01	0.11	85.58
60	37.8	33.9	10.9	0.37	0.32	0.04	1.9	0.16	0	0.08	85.4
64	38.2	34.2	11	0.03	0.27	0	1.79	0.06	0.03	0	85.55
68	38.7	34.2	11.2	0.03	0.13	0	1.84	0.21	0	0	86.35
72	38.6	33.9	11.2	0.07	0.17	0	1.75	0.07	0	0.06	85.72
76	38.5	33.7	11	0	0	0	1.82	0.2	0.03	0.02	85.18
80	38.3	34.6	10.7	0.04	0.16	0.01	1.79	0.15	0.03	0	85.74
84	35.4	35.6	10.9	0.06	0.04	0.02	1.88	0.07	0.04	0.03	84.02
88	35.9	35.5	9.94	0.07	0.09	0.02	1.61	0.21	0	0	83.34

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
92	35.9	34.1	10.6	0.07	0.12	0	1.89	0.05	0	0	82.69
Senlamnh											
Core											
0	36.1	32.7	8.1	5.39	0.08	2.09	1.59	0.09	0.9	0	87.07
Overgrowth											
4	38.2	32.8	8.71	3.74	0.23	0.08	1.97	0.14	0.03	0.04	85.92
8	38.5	32.7	10.4	1.85	0.19	0.02	2.08	0.09	0.02	0.02	85.8
12	38.5	32.3	9.86	2.85	0.21	0	2.1	0.06	0.03	0	85.86
16	38.6	33.1	8.72	3.72	0.08	0.03	1.8	0.07	0.01	0.01	86.07
20	38.3	32.6	8.79	4.04	0.15	0.01	2.12	0.06	0.02	0	86.13
24	37.9	32.4	8.75	4.42	0.26	0	2.36	0.16	0.01	0	86.25
28	38.3	32.5	9	3.7	0.25	0	2.16	0.21	0.03	0.02	86.2
32	38.2	32.4	9.56	3.07	0.38	0	2.35	0.25	0.02	0	86.23
36	38.5	32.4	9.96	2.15	0.43	0	2.28	0.26	0.02	0	85.99
40	38.9	32.7	10.1	1.71	0.36	0	2.39	0.28	0.03	0	86.37
44	38.6	33.1	10.4	1.27	0.4	0	2.31	0.3	0	0	86.35
48	39.1	33.3	11.1	0.17	0.24	0	2.21	0.21	0.01	0	86.35
52	38.9	33.3	10.7	0.53	0.24	0.01	2.08	0.18	0.03	0	85.96
56	38.9	33.5	10.8	0.41	0.19	0.01	2.19	0.13	0.01	0.01	86.1
60	39.2	33.5	10.7	0.52	0.24	0.01	2.12	0.2	0.01	0	86.42
64	39.2	33.9	10.9	0.06	0.12	0	1.97	0.15	0.01	0	86.35
68	39	37	11.7	0.07	0.08	0.01	2	0.12	0.01	0	89.96
Sen2amnh											
Core											
107	36.9	33	6.5	7.11	0.05	0.54	2.28	0	0.71	0.02	87.13
Overgrowth											
108	38.4	32.5	8.59	3.84	0.34	0.02	1.95	0.15	0.04	0.01	85.89
109	39	32.9	9.97	1.97	0.13	0.01	2.17	0.09	0.03	0.03	86.28
110	38.6	32.8	9.72	2.75	0.15	0	2.13	0.13	0.04	0.01	86.25
111	38.3	33.1	8.58	3.65	0.08	0	1.87	0.02	0.02	0	85.56
112	38.5	33	8.64	4.12	0.15	0	2.21	0.03	0.02	0.01	86.59
113	38.2	32.7	8.68	4.01	0.2	0	2.24	0.01	0.01	0	86.03
114	38.5	32.7	9.49	2.89	0.32	0	2.31	0.04	0.02	0.05	86.31
115	38.3	32.9	9.88	2.08	0.39	0.01	2.29	0.03	0.01	0	85.84
116	38.4	33.1	10.3	1.65	0.31	0	2.28	0.07	0.01	0.02	86.19
117	38.8	33.3	10.8	0.13	0.21	0	2.13	0	0	0.01	85.49
118	39	33.2	10.6	0.46	0.18	0	2.11	0	0.02	0	85.66
119	39.3	33.5	10.8	0.42	0.18	0	2.11	0.01	0	0	86.27
120	39	33.6	10.7	0.31	0.14	0	2.07	0	0.01	0.02	85.82

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
121	39.1	33.7	10.9	0.04	0.12	0.01	1.99	0.12	0.02	0	86.01
122	39.5	33.5	10.7	0.02	0.05	0	2.02	0.12	0.01	0.01	85.93
123	41.4	32.7	10.6	0.02	0.07	0	2.31	0.04	0.02	0	87.09
Sen3amnh											
Core											
0	35.6	24.3	7.48	13.9	0.07	2.08	1.75	0	1.7	0.09	86.94
4	36.5	28.5	8.35	9.47	0.11	1.34	1.8	0.09	1.07	0.05	87.36
Overgrowth											
8	38.9	33.1	10.1	2.15	0.12	0.03	2.03	0.03	0.04	0.03	86.51
12	38.1	32.8	9.47	3.07	0.14	0.01	2.16	0.03	0.06	0.03	85.89
16	38.1	33.3	8.54	4.13	0.12	0.01	1.95	0.05	0.02	0	86.26
20	38.2	32.8	8.78	4.56	0.2	0	2.15	0.07	0.03	0	86.76
24	38.4	32.8	9.07	3.76	0.23	0	2.21	0.1	0.01	0	86.58
28	38.7	32.8	9.59	2.47	0.4	0	2.14	0.21	0.05	0	86.41
32	38.6	32.6	9.96	1.95	0.43	0	2.14	0.26	0.02	0	86.05
36	38.7	33	10.3	1.64	0.43	0	2.18	0.24	0.03	0	86.47
40	38.6	33.6	10.9	0.17	0.3	0	1.96	0.18	0	0	85.61
44	39	33.5	10.7	0.5	0.28	0	2.11	0.18	0.02	0	86.35
48	38.9	33.5	10.8	0.44	0.22	0	1.96	0.15	0.01	0	85.99
52	38.8	33.7	10.8	0.45	0.31	0	1.96	0.2	0	0	86.25
56	38.9	33.9	10.6	0.02	0.11	0	1.82	0.17	0	0	85.57
60	38.7	34.1	10.9	0.05	0.08	0	1.92	0.13	0	0	85.92
64	38.6	34.4	11.3	0.02	0.09	0	1.89	0.06	0.03	0	86.38
Sen gr 6											
Core											
0	36.3	32.4	7.79	6.34	0	0.43	2.1	0.47	0.33	0.09	86.23
3	36.3	32.1	7.71	6.23	0.02	0.66	2.2	0.49	0.41	0.05	86.24
6	36.5	32.4	7.62	6.42	0.07	0.39	2.13	0.44	0.53	0.11	86.57
Overgrowth											
9	37.9	32.6	10.1	2.84	0.11	0	2.15	0.09	0.21	0	85.87
12	37.6	32.2	9.88	2.72	0.16	0	2.33	0.11	0.17	0.05	85.16
15	37.7	32.8	9.39	3.24	0.21	0	2.01	0.11	0.17	0.09	85.67
18	37.7	32.6	9.17	3.43	0.05	0	1.99	0.14	0.31	0.05	85.4
21	37.7	32.7	8.75	3.76	0.07	0	1.98	0.05	0.15	0	85.22
24	37.5	32.4	8.8	4.46	0.05	0	2.09	0.15	0.24	0	85.67
27	37.4	32.2	8.86	4.25	0.07	0	2.23	0.14	0.17	0.1	85.42
30	37.4	31.9	8.91	4.23	0.12	0	2.23	0.14	0.14	0.11	85.21
33	37.5	32.1	8.95	4.4	0.16	0	2.38	0.24	0.17	0.04	85.98
36	37.5	31.9	8.98	4.36	0.18	0	2.36	0.14	0.17	0.07	85.67

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
39	37.5	32.1	9.34	3.8	0.13	0	2.38	0.2	0.28	0.04	85.71
42	37.5	31.5	9.46	3.37	0.24	0	2.34	0.32	0.07	0.05	84.81
45	37.7	32	9.99	2.69	0.45	0	2.39	0.38	0.24	0.06	85.84
48	37.8	32.1	10.5	2.17	0.32	0	2.54	0.37	0.47	0.04	86.3
51	37.7	31.9	10.2	2.22	0.3	0	2.61	0.44	0.09	0.04	85.49
54	37.9	32.2	10.6	1.74	0.29	0	2.59	0.39	0.24	0.06	86.07
57	37.6	32.7	11.1	0.64	0.32	0	2.58	0.42	0.31	0.03	85.69
60	38	32.7	11.3	0.31	0.22	0	2.64	0.3	0.17	0.05	85.74
63	38.2	33.3	11	0.61	0.14	0	2.58	0.17	0.31	0.01	86.23
66	38.2	32.6	10.9	0.53	0.23	0	2.56	0.26	0.35	0.05	85.67
69	38.2	33.3	11.2	0.05	0.17	0	2.57	0.17	0.24	0.03	85.95

Sen gr 6

Outer Dark Zone

0	38.4	32.7	11.3	0.28	0.21	0	2.5	0.26	0.26	0.03	85.94
3	37.8	32.8	11.3	0.22	0.15	0	2.47	0.3	0.14	0	85.11
6	38.4	32.6	11.5	0.19	0.2	0	2.42	0.35	0.19	0	85.83
9	38	32.7	11.4	0.23	0.21	0	2.54	0.28	0.28	0.01	85.65
12	38.3	32.6	11.4	0.26	0.26	0	2.46	0.35	0.12	0.04	85.85
15	37.9	32.6	11.5	0.22	0.29	0	2.56	0.33	0.24	0.05	85.74
18	38	32.8	11.3	0.25	0.3	0	2.48	0.29	0.07	0	85.46
21	38.1	32.7	11.3	0.22	0.25	0	2.45	0.25	0.21	0	85.39
24	38.1	32.7	11.2	0.15	0.22	0	2.53	0.23	0.31	0.01	85.37
27	37.9	32.8	11.2	0.22	0.22	0	2.61	0.25	0.35	0.03	85.61
30	38	32.5	11.2	0.25	0.18	0	2.58	0.26	0.26	0.04	85.35
33	37.9	32.5	11.2	0.23	0.21	0	2.6	0.28	0.14	0	85.03
36	38.2	32.7	11.1	0.27	0.31	0	2.65	0.28	0.29	0.01	85.78
39	38.1	32.3	11.2	0.3	0.19	0	2.56	0.31	0.17	0.04	85.17
42	37.9	32.8	11.2	0.47	0.25	0	2.65	0.32	0.17	0.09	85.88
45	38.3	32.7	11.1	0.4	0.18	0	2.63	0.29	0.17	0.04	85.8
48	37.9	32.8	11	0.43	0.23	0	2.56	0.2	0.24	0.05	85.33
51	38	32.7	11.1	0.6	0.12	0	2.48	0.2	0.19	0.08	85.4
54	37.9	33	11	0.59	0.23	0	2.58	0.23	0.21	0.08	85.77

Sen gr 6

Inner Light

0	38	31.9	10.4	2.24	0.28	0	2.47	0.4	0.16	0.04	85.9
3	38.1	32.4	10.6	2.07	0.29	0	2.45	0.51	0.28	0	86.71
6	37.7	32	10.3	2.23	0.22	0	2.46	0.34	0.28	0.08	85.68
9	37.8	32.2	10.4	2.07	0.23	0	2.44	0.45	0.15	0.04	85.8
12	37.6	32	10	2.31	0.33	0	2.39	0.22	0.16	0.04	85.07

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
15	37.6	32.3	10.2	2.58	0.35	0	2.38	0.45	0.36	0	86.19
18	37.6	32.1	9.99	2.56	0.36	0	2.47	0.42	0.28	0.06	85.8
21	37.7	31.8	9.85	2.45	0.36	0	2.43	0.47	0.14	0	85.14
24	37.2	31.8	9.99	2.43	0.32	0	2.36	0.34	0.45	0.1	84.99
27	37.5	31.7	9.95	2.88	0.26	0	2.36	0.34	0.21	0.04	85.2
30	37.3	31.8	9.79	2.95	0.34	0	2.37	0.29	0	0	84.79
33	37.4	32	9.53	3.11	0.34	0	2.48	0.32	0.31	0.04	85.59
36	37.2	32.2	9.68	3.25	0.26	0	2.5	0.44	0.24	0.04	85.81
39	37.4	31.9	9.42	3.46	0.16	0	2.3	0.2	0.19	0	84.97
42	37.8	31.7	9.27	3.69	0.14	0	2.38	0.24	0.28	0	85.5
45	37.6	32.3	9.29	3.98	0.12	0	2.39	0.28	0.33	0.01	86.29
48	36.9	32.2	9.18	4.22	0.08	0	2.46	0.15	0.26	0	85.45
51	37.6	31.9	9.17	4.18	0.18	0	2.44	0.23	0.34	0	86.06
54	37.2	32.2	9.21	4.22	0.13	0	2.37	0.18	0.26	0	85.85
57	37.6	32	9.08	4.2	0.12	0	2.38	0.2	0.24	0	85.78
60	37.3	32.2	9.28	4.21	0.11	0	2.4	0.15	0.16	0.02	85.87
63	37.5	32.2	9.09	4.27	0.16	0	2.3	0.21	0.38	0.06	86.15
66	37.5	32.3	9.04	4.27	0.16	0	2.28	0.1	0.24	0	85.82
69	37.3	32.3	8.97	4.48	0.13	0	2.37	0.18	0.1	0.06	85.85
72	37	32.2	8.94	4.2	0.18	0	2.37	0.14	0.19	0.05	85.2
75	37.2	31.8	8.91	4.34	0.17	0	2.35	0.19	0.17	0.03	85.09
78	37.4	31.9	9.18	4.19	0.22	0	2.42	0.3	0.29	0.02	85.86
81	37.2	31.9	9.21	4.01	0.17	0	2.45	0.16	0.27	0.02	85.39
84	37.4	32.1	9.17	4.3	0.18	0	2.53	0.18	0.24	0.05	86.11
87	37	32.2	9.65	3.24	0.35	0	2.67	0.33	0.43	0	85.9
90	37.1	32.5	9.84	2.6	0.5	0	2.72	0.41	0.31	0	85.99
93	37.4	32.4	9.86	2.23	0.41	0	2.65	0.47	0.4	0.02	85.78
96	37.4	32.4	9.96	2.35	0.44	0	2.73	0.47	0.26	0.03	85.97
99	37.1	32.6	9.89	2.27	0.5	0	2.74	0.38	0.26	0.04	85.78
Skani											
Core											
0	35.3	26.2	9.01	10.7	0.09	2.43	1.56	0.02	0.05	0.06	85.49
4	35.6	26.3	9.01	10.8	0.01	2.37	1.57	0	0.08	0.08	85.85
8	35.5	26.4	9.05	10.9	0.1	2.42	1.6	0.01	0.01	0.09	86.16
12	35.4	27.2	8.94	10.5	0.14	2.01	1.7	0.01	0.03	0.02	86.17
Overgrowth											
16	36.6	32.1	9.46	4.21	0.76	0.02	2.26	0.22	0.06	0.05	86.95
20	37	32	9.57	3.87	0.75	0.05	2.28	0.16	0.02	0.02	86.93
24	36.6	32.4	10	2.81	0.9	0	2.07	0.25	0.02	0	86.43

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
28	36.7	31.8	10	3.25	0.84	0.04	2.29	0.19	0	0.05	86.57
32	36.2	31.8	9.95	3.27	1.2	0.05	2.22	0.25	0.02	0	86.83
36	36.1	31.9	9.64	3.08	1.33	0.06	2.35	0.22	0.05	0	86.85
40	37	32.5	9.89	2.8	0.91	0.04	2.21	0.14	0.04	0.02	86.96
44	37.6	32.2	10.1	2.82	1.09	0.02	2.55	0.31	0	0.09	88.47
48	36.6	31.8	10.1	2.77	1.18	0.07	2.43	0.24	0.03	0.03	87.09
Skan2c											
Core											
0	36.6	33.9	5.71	7.99	0.1	0.59	1.83	0.16	0.74	0.03	87.78
4	36.6	33.8	5.79	8.15	0.08	0.53	1.91	0.04	0.58	0.02	87.56
8	36.4	33.8	5.81	8.14	0.08	0.54	1.84	0.09	0.5	0.03	87.38
Overgrowth											
12	36.7	30.7	6.67	9.29	0.63	0.08	1.97	0.51	0.19	0	87.72
16	37.6	32.6	10	3.05	0.67	0.01	2.2	0.11	0.05	0	87.37
20	38.1	33.4	10.3	2.94	0.81	0.18	2.22	0.03	0	0.01	89.19
24	38.4	32.8	10.1	2.97	0.61	0	2.18	0.12	0	0.02	88.08
28	37.7	32.9	9.99	3.15	0.75	0	2.25	0.09	0.05	0	88.14
32	38.2	33	10	3.03	0.67	0.02	2.28	0.06	0.02	0	88.32
36	37.9	33	10.1	3.05	0.96	0.01	2.12	0	0	0	88.62
40	37.9	32.9	9.66	2.91	0.64	0.01	2.08	0.07	0.06	0	87.24
44	37.8	33.3	10	2.83	0.77	0.02	2.29	0.04	0	0.08	88.34
48	38.2	33.2	10	2.89	0.68	0.02	2.23	0.11	0.03	0	88.42
52	37.8	33.3	10.2	2.97	0.77	0.05	2.21	0.08	0.08	0.02	88.59
56	37.3	27.9	8.31	2.37	0.72	0.1	2	0.26	0.02	0.04	80.14
Skan3											
Core											
0	35	30	7.18	8.98	0	2.12	1.54	0	2.25	0.04	87.08
4	35	29.8	7.2	8.95	0.12	2.15	1.53	0.03	2.11	0.06	87.21
8	34.8	29.6	7.16	8.67	0.14	2.34	1.45	0.03	2.12	0	86.53
12	34.8	29.7	7.07	8.52	0.09	2.15	1.41	0.05	2.14	0.01	86.12
16	35.1	29.8	7.05	8.57	0	2.14	1.47	0	2.01	0.01	86.09
Overgrowth											
20	36.3	29.5	7.1	8.64	1.43	0.1	2.04	0.51	0.12	0.04	87.98
24	36.9	31.6	9.62	3.66	1.12	0.02	2.29	0.34	0.01	0.01	87.31
28	37.3	31.4	9.67	3.67	1.56	0.07	2.18	0.32	0.1	0.04	88.81
32	37.4	31.7	10.4	3.03	1.62	0.01	2.13	0.21	0.03	0.03	89.06
36	37.3	31.7	10.1	3.34	1.41	0.02	2.18	0.19	0.04	0	88.44
40	37.2	31.9	10.2	3.39	1.49	0.01	2.2	0.07	0.01	0.01	88.77
44	37.1	31.7	9.99	3.26	1.2	0	2.07	0.15	0	0	87.4

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
48	38	31.2	9.97	3.16	1.38	0	2.13	0.08	0	0	88.05
52	39	31.7	9.96	3.1	1.45	0	2.14	0.04	0	0	89.65
56	37.9	31.5	9.69	3.13	1.3	0	2.07	0.04	0	0.01	87.58
60	37.1	31.9	10.1	2.75	1.43	0.01	2.08	0.05	0	0	87.64
64	36.9	31.6	10.2	2.91	1.36	0.02	2.25	0.05	0.03	0	87.38
68	37.2	31.4	10.2	2.69	1.35	0.02	2.23	0.1	0.07	0	87.27
72	36.7	31.6	10.2	2.91	1.58	0.02	2.25	0.01	0.04	0.01	87.73
76	35.9	31	10.1	2.64	1.31	0.02	2.22	0.08	0	0.04	85.32
Skan4											
Core											
0	35.2	22.3	8.66	15.4	0.16	2.75	1.3	0	1.05	0.15	87.22
4	33.9	24.2	7.95	15.4	0	2.75	1.24	0	1	0.12	86.58
8	35.2	23	8.68	15.9	0.15	2.81	1.28	0	1.11	0.13	88.45
12	35.7	25.1	8.03	13.1	0.03	1.44	1.78	0.06	0.61	0.07	85.95
Overgrowth											
16	35.9	28.8	7.1	8.37	2.97	0.07	1.95	1.22	0.07	0.07	91.18
20	37.6	32.9	9.41	3.69	0.92	0.06	1.91	0.52	0.02	0.01	88.46
24	37.7	33.4	9.82	3.25	0.61	0.05	1.94	0.07	0.06	0	87.87
28	38	33.4	9.74	3.68	0	0.01	2.08	0	0	0	86.98
32	37.8	33.4	10.1	3.14	0.26	0.04	2.14	0	0	0.09	87.37
36	94.8	0.42	0.14	0.55	0.07	0.01	0.01	0.02	0	0	96.08
40	51	14.1	6.85	0.7	0.29	0.08	1.79	0.1	0	0	75.3
44	40	33.2	11.2	0.57	0.47	0.03	2.65	0.02	0	0	88.9
48	37.7	33	9.94	3.43	0.13	0.04	2.46	0	0.04	0	86.92
52	37.7	32.4	10.3	3.26	0.13	0.02	2.59	0.06	0.03	0	86.65
56	37.7	32.4	10.2	3.43	0.31	0.04	2.52	0	0.08	0.05	87.11
60	37.6	32.7	9.9	3.49	0.42	0.01	2.44	0.14	0.03	0	87.37
Skan5											
Core											
0	35.6	32.8	3.04	13	0	0.44	1.89	0	0.23	0.1	87.05
4	35.1	32.5	3.01	12.9	0.01	0.39	1.9	0.03	0.22	0.16	86.27
8	35.4	32.6	2.92	12.5	0	0.46	1.82	0	0.28	0.23	86.19
Overgrowth											
12	36.9	30.8	8.14	5.38	1.91	0.01	1.97	0.98	0	0.01	89.03
16	37.3	31.6	9.57	3.44	1.51	0.01	2.43	0.32	0.03	0	88.54
20	37.2	32.6	9.65	2.93	1.71	0	2.05	0.2	0	0.02	89.02
24	37.4	32	9.74	3.17	1.38	0	2.1	0.17	0	0.01	88.13

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Skan7C											
Core											
0	35.7	33.9	4.63	9.2	0.04	0.36	1.94	0.05	0.55	0.07	86.5
4	35.7	33.7	4.46	9.3	0.02	0.31	1.92	0.07	0.48	0.12	86.2
8	36.1	33	5.24	9.19	0.13	0.29	1.96	0.07	0.45	0.02	86.71
Overgrowth											
12	36.5	31.4	8.22	5.42	1.35	0.11	1.98	0.43	0.04	0.04	87.57
16	37.5	32.4	9.29	3.5	1.23	0.05	2.04	0.53	0	0.02	88.47
20	38	32.7	9.62	3.94	0.88	0	2.26	0.24	0.05	0.04	89.13
Skan8											
Core											
0	35.8	34	5.02	9.09	0.01	0.45	1.93	0.02	0.63	0.1	87.01
4	36.3	33.7	5.1	8.9	0.03	0.45	1.9	0.06	0.65	0.03	87.22
8	35.8	33.8	5.01	9.05	0.05	0.59	1.84	0	0.8	0	87.06
12	35.7	33.8	5.06	9.17	0.09	0.75	1.82	0.02	0.94	0.1	87.53
16	36.8	31.7	6.72	8.79	0.05	0.28	2.52	0	0.66	0.12	87.76
20	37.7	33	9.64	3.04	0.92	0.04	2.09	0.4	0	0.03	88.33
24	37.8	32.7	9.82	3.02	0.9	0.03	2.23	0.37	0.02	0	88.29
28	37.8	32.2	9.7	3	1.29	0.02	2.31	0.39	0.01	0.01	88.74
32	37.5	32.2	9.82	2.96	1.31	0.01	2.29	0.63	0	0.03	88.8
36	37.7	32.4	9.81	2.7	1.11	0.04	2.33	0.44	0.1	0	88.3
40	37.6	32.7	10.1	2.55	1.22	0.01	2.29	0.46	0.02	0	88.93
44	38	33.2	10.3	2.55	1.18	0	2.28	0.24	0.04	0.06	89.68
48	38.5	33.6	11.5	0.12	0.59	0.02	2.31	0.27	0	0.03	87.83
52	35.8	35.8	10.9	0.15	0.86	0.06	2.13	0.32	0	0	87.26
56	38.8	33.8	12	0.09	0.18	0.06	2.36	0.02	0.01	0.04	87.65
60	38.2	33.3	11.9	0.13	0.91	0.03	2.25	0.38	0	0	88.55
64	38.1	32.9	12	0.15	0.9	0.06	2.47	0.45	0	0.01	88.42
68	37.9	32.7	11.9	0	0.88	0.02	2.49	0.4	0.07	0.01	87.8
Skan9											
Core											
0	36.4	31.3	9.56	4.68	0	1.99	1.6	0	0.93	0	86.47
Overgrowth											
4	36.5	32.3	4.82	11.4	0.03	0.06	1.99	0.04	0.19	0.06	87.39
8	36.2	31.3	4.7	12	0.01	0.06	2.22	0.06	0.18	0.08	86.81
12	36	31.1	4.62	11.7	0.07	0.04	2.3	0	0.27	0.05	86.23
16	36.3	31	4.71	11.5	0.11	0.1	2.21	0.02	0.25	0.07	86.46
20	36.3	30.6	5.73	11.4	0.14	0.15	2.31	0.02	0.41	0.12	87.32
24	37.3	32.2	9.98	3.81	1.12	0	2.1	0.2	0.01	0.06	88.51

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
28	37.6	32.1	10.3	2.99	1.22	0	2.23	0.11	0	0	88.46
32	37.5	32	10.1	3.26	1.47	0.02	2.24	0.08	0	0.03	88.95
36	37.6	32.4	10.4	2.89	1.24	0	2.21	0.16	0.06	0.05	88.86
40	37.5	32.8	10.1	2.9	1.51	0.04	2.14	0.23	0	0.03	89.64
44	37.3	32.4	9.93	2.78	1.24	0	2.25	0.22	0	0	88.02
48	37.7	32.4	10	2.99	1.29	0.03	2.31	0.2	0.03	0	88.98
52	37.4	32.3	9.88	2.93	1.14	0.12	2.05	0.2	0.05	0	87.91
56	37.8	32.7	10.1	2.69	1.19	0.02	2.26	0.2	0.01	0	88.82
60	37.2	32.5	10.1	2.76	1.38	0.05	2.21	0.26	0	0	88.64
64	38	32.6	10.3	2.5	1.46	0	2.29	0.19	0	0	89.68
68	37.8	33	10.4	2.56	1.42	0	2.3	0.28	0.05	0.07	89.98
72	38.9	33.8	10.7	2.38	1.19	0.02	2.44	0.29	0.04	0	91.52
76	38.6	33.5	11.9	0.02	0.91	0.01	2.18	0.22	0.04	0.02	88.83
80	38.1	33.1	11.8	0	0.89	0.03	2.11	0.27	0.01	0	87.7
Skan10-1c											
Core											
0	36	28.6	11.1	6.54	0.02	3.73	0.7	0.05	0.68	0.08	87.55
4	36.1	28.5	10.9	6.47	0.04	3.86	0.67	0	0.61	0	87.21
8	36.4	28.4	11	6.56	0	3.75	0.68	0.05	0.64	0	87.41
12	36.5	29.1	10.5	6.73	0.36	3.22	1.01	0.09	0.61	0	88.72
Overgrowth											
16	37.6	31.8	9.15	4.19	1.58	0.06	2.02	0.77	0.05	0.02	89.66
20	37.7	32.5	9.7	3.37	1.52	0.05	2.16	0.31	0	0	89.63
24	38.1	32.9	9.94	3.27	1.33	0	2.2	0.19	0.04	0	89.98
28	37.9	32.6	10	3.29	0.9	0.05	2.32	0.4	0	0	88.9
32	38.1	33.5	9.74	3.1	0.91	0.02	2.02	0.19	0	0	88.97
36	38.2	33.3	9.91	3.24	1.37	0.01	2.21	0.3	0.01	0	90.75
40	38	32.9	9.93	2.82	1.08	0.07	2.18	0.31	0	0.05	89.03
44	38.1	33	9.65	2.93	1.2	0	2.13	0.22	0.01	0	89.15
48	38.1	32.6	10.1	3.1	1.51	0.04	2.35	0.37	0	0.04	90.45
52	37.9	32.2	9.86	3.06	1.44	0.02	2.44	0.49	0	0	89.63
56	38	31.9	9.93	2.9	1.44	0.01	2.57	0.53	0	0.01	89.47
60	36.6	30.6	9.6	2.69	1.58	0.04	2.42	0.7	0.02	0.04	86.76
64	37.6	32.1	9.92	2.9	1.42	0	2.41	0.69	0.01	0.02	89.25
68	37.5	32.3	10.2	2.79	1.78	0.02	2.38	0.52	0	0.04	90.38
72	38.3	32.5	10.1	2.51	1.61	0.03	2.31	0.43	0.01	0	90.23
Skan10-2c											
Core											
0	36.2	27.9	11.2	6.59	0.12	3.86	0.65	0.01	0.59	0.09	87.32

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
4	36.2	27.7	11.1	6.55	0.1	3.82	0.69	0.03	0.59	0	86.99
8	36.2	27.9	11.3	6.61	0.09	4.03	0.65	0.01	0.63	0.07	87.69
12	36.4	28.1	11	6.29	0	3.84	0.69	0.04	0.6	0.02	87.02
16	36.2	28	11.3	6.56	0.06	3.78	0.64	0.01	0.57	0.07	87.35
20	36.2	27.9	11.2	6.4	0.13	3.84	0.68	0	0.59	0.06	87.11
Overgrowth											
24	36.9	30.8	8.01	6.4	1.89	0.1	1.96	0.76	0.03	0.06	89.88
28	37.5	32	9.6	3.59	1.54	0.04	2.12	0.39	0.02	0.01	89.25
32	37.5	32.1	10	2.72	1.62	0.03	2.05	0.33	0.01	0.07	89.02
36	37.8	32.5	10	3.11	1.57	0	2.23	0.24	0.01	0	89.9
40	38.1	32.5	9.82	3.01	1.58	0.02	2.15	0.31	0.01	0.04	90.05
44	38.6	33.7	11.9	0.34	0.41	0.02	2.61	0	0.02	0	88.28
Skanel-1c											
Core											
0	36.2	34.4	5.75	9.09	0.05	0.37	2.07	0	0.08	0.11	88.16
4	36.3	34.4	5.75	8.79	0	0.42	2	0.02	0.08	0.01	87.72
8	36.2	34.3	5.82	9.13	0.04	0.47	2.09	0	0.05	0.12	88.26
12	36.4	34.2	5.73	8.87	0	0.53	1.99	0.02	0.12	0.09	87.97
16	36	34.7	5.67	8.76	0	0.49	1.98	0.04	0.12	0.08	87.77
20	36.5	34.7	5.62	8.85	0.03	0.48	1.89	0.05	0.12	0.1	88.37
24	36.9	34.3	6.38	8.06	0.21	0.37	1.99	0.05	0.07	0.15	88.89
Overgrowth											
28	38	32.9	9.75	3.81	0.78	0.03	2.52	0.22	0.05	0.05	89.28
32	38.1	32.5	10.1	3.13	0.95	0.05	2.35	0.1	0	0	88.73
36	37.8	32.8	10.3	3.33	0.83	0.03	2.3	0.2	0	0.02	88.93
40	38	32.9	10.2	3.37	1.07	0	2.33	0.24	0	0	89.7
44	38.2	32.9	10.3	3.09	0.88	0.01	2.35	0.17	0	0	89.27
48	38.2	32.8	10	3.05	1.22	0.05	2.4	0.22	0.02	0.04	89.94
52	38.2	32.7	10.2	3.12	1.31	0	2.25	0.21	0	0.01	89.92
56	38	32.7	10.2	3.1	1.14	0	2.4	0.15	0	0	89.47
60	37.9	32.3	10.3	3.18	1.18	0.02	2.28	0.2	0.03	0.01	89.22
64	38.2	32.6	10.2	3.3	1.43	0	2.25	0.23	0.03	0	90.36
68	38.1	32.6	10.1	2.94	1.31	0.01	2.26	0.26	0	0.02	89.73
Skanel-2c											
Core											
0	35.8	33.2	5.89	8.56	0.01	0.33	2.1	0.01	0.04	0.13	86.01
4	36	32.7	6	8.54	0.02	0.32	2.1	0.01	0.13	0.11	86.04
8	35.9	33.3	5.84	8.88	0	0.4	1.97	0.05	0.12	0.1	86.57
12	35.6	33	5.75	9.05	0.01	0.36	2.05	0	0.14	0.12	86.07

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
16	35.9	33.1	5.78	8.53	0.04	0.36	2	0.04	0.12	0.14	86.06
Overgrowth											
20	36.9	32.2	9.12	3.8	0.85	0.02	1.97	0.28	0.02	0.05	86.58
24	37	32.2	9.69	3.31	0.78	0.03	2.23	0.21	0	0.06	86.69
28	37.7	32.4	9.69	2.77	0.96	0	1.79	0.14	0.01	0.03	86.97
32	37.2	31.9	10.1	3.34	0.98	0.01	2.14	0.14	0	0	87.39
36	37	31.2	9.96	3.34	1.14	0.03	2.5	0.18	0	0.09	87.23
40	37.4	31.2	9.7	3.18	1.17	0.14	2.15	0.22	0	0.01	87
Skani2-1c											
Core											
0	35.5	34.1	3.07	12.1	0.05	0.37	1.88	0	0.58	0.12	87.8
4	35.7	34.1	3.06	12	0.07	0.35	1.84	0.05	0.63	0.09	87.92
8	36.1	33.8	3.58	11.9	0.15	0.3	1.91	0.02	0.53	0.08	88.59
12	36	33.9	3.57	11.5	0.11	0.29	2	0.04	0.52	0.15	88.35
Overgrowth											
16	37.6	32.1	9.8	4.15	1.33	0.01	2.43	0.36	0.05	0.08	89.99
20	37.7	32.2	10.2	3.09	1.15	0.04	2.32	0.26	0.02	0.07	88.8
24	37.7	32.1	10.1	3.46	1.44	0.02	2.52	0.3	0	0.04	89.94
28	37.5	31.6	10.1	3.65	1.22	0	2.58	0.32	0	0.03	88.88
32	37.6	31.8	9.96	3.5	1.28	0	2.65	0.38	0	0.08	89.26
36	37.7	31.3	9.97	3.65	1.58	0.02	2.63	0.28	0.04	0.07	89.69
40	37.5	32.1	9.9	3.7	1.7	0	2.78	0.21	0	0	90.54
44	38	32	10.3	3.25	1.39	0.02	2.43	0.16	0.01	0.01	89.69
48	37.9	32.1	10.2	3.53	1.46	0.02	2.7	0.22	0	0.06	90.46
52	37.2	31.6	10.1	3.09	1.67	0.02	2.59	0.25	0	0.03	89.15
56	36.7	30.6	10	3.38	1.64	0.02	2.68	0.27	0.05	0.04	87.9
60	37.9	31.9	10.5	3.06	1.77	0.01	2.43	0.21	0.02	0.03	90.53
64	38.6	33	10.6	2.98	1.28	0.01	2.3	0.15	0	0.01	91
Skani2-2c											
Core											
0	35.6	34	2.78	11.8	0.03	0.22	1.78	0.05	0.64	0.08	87.03
4	35.5	33.5	2.69	11.5	0.05	0.25	1.73	0.02	0.69	0.08	86.06
8	35.8	33.7	2.77	11.7	0.07	0.23	1.67	0.04	0.63	0.09	86.81
12	35.7	33.7	2.76	11.8	0.05	0.22	1.68	0	0.75	0.23	86.88
16	35.8	33.9	2.78	11.8	0.05	0.22	1.8	0.03	0.65	0.07	87.09
20	35.8	33.9	2.79	11.8	0.14	0.24	1.72	0.04	0.63	0.1	87.33
24	37	32.9	5.43	9.23	0.67	0.17	1.91	0.42	0.38	0.11	89.24
Overgrowth											
28	36.8	30.7	10.1	3.9	1.31	0.1	2.26	0.35	0	0.07	87.69

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
32	34.5	29.5	8.51	2.79	1.6	0.02	2.02	0.63	0.09	0.05	82.19
36	37.7	31.9	10.1	3.18	1.34	0.03	2.14	0.26	0	0.03	88.74
40	37.6	31.6	10.1	3.39	1.12	0.02	2.16	0.42	0	0.02	88.03
44	37.3	32	9.97	3.25	1.44	0.01	2.14	0.22	0	0.04	88.56
48	37.5	31.4	9.91	3.23	1.44	0.01	2.12	0.14	0	0.06	88.04
52	37.5	31.8	9.95	3.32	1.32	0	2.08	0.13	0	0.06	88.22
56	37.4	31.9	9.91	3.44	1.3	0.01	2.09	0.11	0	0.05	88.27
60	37.6	32.1	9.83	3.4	1.37	0.01	2.16	0.17	0	0.03	88.76
64	37.5	31.3	9.8	3.17	1.54	0	2.11	0.09	0	0.04	87.95
68	37.4	31.4	9.99	3.2	1.43	0.03	2.11	0.17	0	0.03	87.99
72	37.8	31.5	10.1	3.1	1.52	0.02	2.16	0.15	0	0.03	88.68
76	37.3	31.9	10.1	3.01	1.39	0	2.2	0.15	0	0.06	88.28
80	37.6	31.8	10.1	3.01	1.24	0	2.2	0.16	0	0.07	88.14
84	37.8	31.9	9.99	2.95	1.41	0.02	2.2	0.11	0	0.02	88.6
88	37.4	31.7	10	3.04	1.45	0.03	2.27	0.26	0.01	0.04	88.51
92	37.6	31.5	10	3.21	1.37	0	2.18	0.2	0	0.08	88.25
96	37.1	31.4	10.1	2.89	1.75	0	2.09	0.26	0	0.04	88.3
Skani3-1c											
Core											
0	35.7	26.9	7.29	12	0.08	1.47	2.01	0	0.49	0.09	86.25
4	35.7	26.9	7.15	12.4	0.06	1.34	2.11	0	0.48	0.13	86.31
8	35.3	27.1	7.31	12.2	0.08	1.37	2.06	0	0.47	0.03	86.03
12	35.6	27.5	7.36	12.5	0.11	1.36	2.12	0	0.47	0.07	87.19
Overgrowth											
16	36.6	31.1	8.65	4.4	2.07	0.06	1.84	0.48	0	0.01	88.49
20	37.7	32.6	9.7	2.96	1.19	0.02	1.99	0.27	0	0	88.31
24	37.3	31.9	9.62	3.27	1.19	0.22	2.36	0.25	0.01	0.06	88
28	37	31.8	9.64	3.22	1.3	0.03	2.11	0.31	0.08	0	87.55
32	37.5	31.9	9.87	2.86	1.13	0.04	2.38	0.36	0.1	0	87.97
36	37.6	31.7	9.89	3.1	1.37	0.02	2.35	0.46	0.01	0.12	88.7
40	39.2	31.7	9.44	3.1	1.1	0.03	2.32	0.3	0	0.06	89.02
44	35.3	34.2	9.3	2.87	1.32	0.07	2.23	0.3	0.05	0.08	87.79
48	37.1	32.3	10	3.19	1.29	0.01	2.57	0.23	0	0	88.66
52	38	32.8	10.2	2.46	0.86	0.02	2.58	0	0.03	0	88.32
Skani3-2c											
Core											
0	35.7	27.4	7.49	12.2	0.14	1.29	2.09	0.01	0.47	0.11	87.06
4	35.4	27.4	7.51	12	0.12	1.5	2.05	0	0.47	0.07	86.67
8	35.3	27.9	7.65	11.4	0.09	1.29	2.08	0	0.45	0.06	86.44

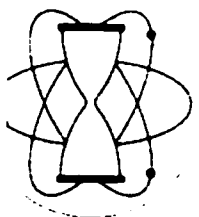
Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
12	35.3	26.8	7.6	12.1	0.08	1.43	2.05	0	0.44	0.13	86.1
16	35.2	26.5	7.57	12.8	0.11	1.56	2.03	0	0.6	0.12	86.66
20	35.5	26.6	7.5	12.6	0.08	1.55	2.03	0	0.64	0.05	86.65
24	36.1	24.9	7.48	10.9	0.15	1.29	2.15	0.09	0.48	0.05	83.83
28	35.6	26.7	7.64	12.5	0.1	1.39	2.18	0	0.54	0.06	86.88
Overgrowth											
32	36.9	32.1	9.35	3.34	1.14	0	1.85	0.35	0	0	86.83
36	36.8	32.4	9.31	3.42	1.18	0.02	1.96	0.24	0	0.02	87.17
40	38.2	31.7	9.91	3.04	1.04	0.03	2.23	0.19	0	0.1	88.08
Yag1											
Core											
1	35.2	25.4	7.84	12.1	0.01	2.47	1.44	0.01	1.01	0.12	85.66
2	35.5	25.3	7.84	12	0.16	2.5	1.46	0.06	1.05	0.11	85.95
3	35.6	25.8	8.11	12.2	0.07	2.54	1.53	0.02	0.9	0	86.83
4	35.9	25.3	8.13	11.9	0.15	2.57	1.5	0.02	0.94	0.06	86.56
5	35.7	25.6	8.25	11.6	0.13	2.51	1.46	0.12	0.91	0	86.33
6	36.2	25.9	8.19	11.7	0.05	2.53	1.53	0	0.95	0	87.1
Overgrowth											
7	31.5	30.2	8.91	1.8	0.45	0.34	2.17	0.25	0.03	0	75.66
8	37.6	32.7	10.9	0.25	0.38	0.05	2.24	0.3	0.01	0.02	84.36
9	32.7	28.8	9.53	0.45	0.34	0.05	1.93	0.34	0	0.06	74.1
10	37.7	33.1	9.69	3.22	0.28	0.01	2.33	0.15	0.03	0.08	86.66
11	37.9	33.2	9.92	2.14	0.48	0	2.62	0.11	0.02	0	86.41
12	38	33.2	10.6	1.36	0.62	0.04	2.37	0.36	0.04	0	86.55
13	38.4	33.4	11.5	0.05	0.38	0	2.14	0.3	0	0.06	86.29
14	38.3	33.6	11.2	0.05	0.31	0.01	2.01	0.17	0	0	85.59
15	38.3	33.6	11.4	0.09	0.45	0.01	2.09	0.15	0.06	0.03	86.15
16	38.1	33.4	11.6	0	0.34	0	2.03	0.28	0	0.16	85.95
17	38.4	33.6	11.3	0.04	0.29	0	2.03	0.22	0.01	0.04	85.95
18	38.7	33.4	11.6	0.08	0.31	0	2.02	0.27	0	0	86.37
19	38.5	33.5	11.7	0.07	0.39	0	2.07	0.21	0.01	0.04	86.49
20	38.3	33.9	11.6	0	0.26	0.06	2.05	0.26	0	0	86.48
21	38.3	33.9	11.5	0	0.28	0.01	2.08	0.23	0.08	0.05	86.52
22	38.8	33.7	11.7	0.09	0.22	0.02	2.12	0.16	0.01	0.02	86.88
23	37	32.8	12	0.04	0.11	0.04	2.03	0.12	0.01	0	84.19
24	31.5	29.7	10.7	0.5	0.31	0	1.8	0.07	0	0.04	74.7
25	38.3	34	11.8	0.04	0.26	0	2.07	0.13	0	0	86.6

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
Yag2											
Core											
1	35.8	26.6	7.83	11.7	0	2.21	1.65	0.1	0.76	0.17	86.83
2	35.7	26.7	7.82	11.7	0.11	2.26	1.4	0	0.65	0.14	86.45
3	36	26.8	7.79	11.6	0	2.29	1.72	0	0.67	0.17	87.05
4	35.6	26.9	7.97	11.7	0.03	2.23	1.63	0.01	0.62	0.21	86.91
5	35.6	26.9	7.82	11.8	0.01	2.29	1.55	0.02	0.77	0.06	86.88
6	35.4	26.8	7.91	11.7	0.03	2.31	1.56	0	0.62	0.16	86.4
7	35.6	26.5	7.94	11.9	0	2.29	1.52	0.04	0.6	0.03	86.46
Overgrowth											
8	36.4	29.7	8.3	8.27	0.25	1.46	1.66	0	0.38	0.16	86.56
9	38.2	32.8	10.3	1.72	0.48	0.02	1.93	0.21	0	0	85.69
10	38.1	33.2	9.69	3.01	0.49	0.02	1.8	0.09	0.03	0	86.42
11	38	33.1	9	3.65	0.35	0.01	1.81	0.11	0.01	0.03	86.11
12	37.9	33.1	9.27	3.56	0.34	0.05	1.87	0.2	0.06	0	86.39
13	38.1	33.2	9.39	2.97	0.3	0.03	1.8	0.07	0.04	0.06	86.04
14	38.3	33.2	9.88	2.53	0.46	0.01	1.9	0.19	0.05	0	86.46
15	38.8	33.6	10.2	1.76	0.61	0.03	1.98	0.19	0.03	0	87.2
16	38.5	34.3	11	0	0.67	0.03	1.81	0.17	0	0	86.49
17	38.8	34.1	11	0	0.21	0	1.86	0.04	0	0.03	86.09
18	38.5	34.3	11	0.03	0.35	0.03	1.72	0.11	0	0.06	86.18
19	38.6	33.6	11.3	0.04	0.47	0	1.88	0.11	0.02	0.07	86.2
20	38.5	33.8	11.2	0.06	0.42	0.04	1.8	0.09	0	0.03	86.01
21	38.9	34.2	11.3	0.07	0.25	0	1.77	0.04	0.01	0.04	86.43
22	38.6	34.1	11.3	0.03	0.52	0.01	1.88	0	0.06	0	86.48
23	38.8	34.2	10.9	0.04	0.2	0	1.84	0.05	0.03	0.01	85.96
Yag3											
Core											
1	36.8	30.7	8.96	6.68	0	0.8	2.31	0.01	0.47	0.02	86.69
2	36.9	30.1	9.12	6	0.02	0.67	2.37	0	0.42	0.05	85.68
3	36.9	30.1	9.32	6.12	0.12	0.72	2.48	0.05	0.53	0.09	86.43
4	37.2	29.9	9.39	6.26	0.13	0.76	2.37	0.08	0.54	0.01	86.64
5	37.2	30.3	8.86	6.53	0.16	0.74	2.45	0	0.5	0.1	86.88
6	36.6	30.9	4	12.5	0.02	0	2.41	0.01	0.16	0.09	86.76
7	35.9	31.6	5.9	9.03	0.17	0.92	2.18	0.04	0.3	0.02	86.1
Overgrowth											
8	37.7	33	9.87	2.24	0.39	0.19	2.28	0.18	0.13	0.05	86.07
9	38	33	10.4	2.43	0.54	0.02	1.91	0.15	0.04	0.05	86.51
10	38.1	33.4	9.98	2.54	0.62	0.04	1.96	0.18	0.09	0.03	86.9

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
11	38	33.1	9.76	2.77	0.42	0.05	1.74	0.16	0	0	85.97
12	37.9	33.6	9.61	2.72	0.19	0.02	1.82	0.15	0	0	85.97
13	38.2	33.3	9.3	3.16	0.26	0.06	1.99	0.14	0.03	0.03	86.46
14	38.2	33.7	8.91	3.84	0.27	0	2.08	0	0.06	0	87.03
15	37.9	33.7	9.29	3.54	0.25	0.03	1.97	0.13	0.01	0	86.86
16	37.8	33.5	9.18	3.73	0.26	0	2.07	0	0	0.11	86.7
17	38.1	33	9.23	3.75	0.41	0.03	2.17	0.23	0.06	0	86.95
18	38.1	33.5	9.3	3.49	0.42	0.02	2.11	0.24	0.01	0.05	87.21
19	38.2	33	9.51	3.08	0.28	0	2.28	0.15	0	0	86.49
20	38.2	33.5	9.67	2.72	0.41	0	2.36	0.18	0.03	0	87.04
21	38.2	33.6	11.1	0.46	0.66	0.01	2.72	0.35	0.05	0.03	87.16
22	38.8	33.9	11.5	0.09	0.47	0.03	2.48	0.22	0	0.05	87.46
23	38.5	33.8	11.4	0.04	0.39	0.01	2.55	0.23	0	0.05	86.99
24	38.4	33.5	11.6	0.04	0.41	0.06	2.57	0.35	0	0	86.88
25	34.8	32.7	12.2	0.02	0.47	0.01	3.13	0.25	0	0	83.47
Yaglc											
Core											
1	35.6	33.4	4.84	9.1	0.07	0.99	1.71	0	1.31	0.03	86.95
2	35.4	33.1	4.91	9.18	0	0.93	1.81	0	1.26	0.06	86.69
3	35.5	33.1	4.87	8.87	0	0.91	1.82	0.04	1.22	0.04	86.31
4	35.7	33.6	4.91	8.78	0.07	1.06	1.77	0.08	1.19	0	87.19
Overgrowth											
5	38	33.2	8.78	3.76	0.37	0.04	1.66	0.26	0.01	0	86.03
6	37.8	33.1	10.5	2	0.31	0	2	0.23	0.08	0.05	85.95
7	38.3	33	10.8	1.86	0.56	0.01	2.03	0.2	0	0	86.71
8	38.1	32.5	10.8	1.88	0.68	0.02	2.01	0.25	0.05	0.08	86.35
9	37.6	32.7	10.6	2	0.41	0.04	1.9	0.39	0.05	0.03	85.69
10	37.5	32.9	10.5	1.95	0.49	0.04	1.88	0.16	0.01	0	85.42
11	37.6	32.9	9.81	2.94	0.32	0.02	1.88	0.14	0.04	0.02	85.67
12	37.4	32.9	9.26	3.49	0.36	0.05	2	0.14	0.07	0.01	85.73
13	37.6	32.8	9.36	3.38	0.26	0.01	1.9	0.04	0	0	85.37
14	37.6	32.6	9.44	3.58	0.32	0.01	2	0.22	0.03	0.02	85.83
15	37.6	32.8	9.72	3.21	0.57	0.02	2.19	0.24	0	0	86.42
16	37.5	33.1	10.2	2.48	0.62	0	2.04	0.17	0.03	0	86.1
17	37	33.6	10.6	1.67	0.42	0.02	2.09	0.21	0	0.02	85.58
18	37.9	33.4	11.7	0.16	0.72	0	1.97	0.27	0	0.04	86.16
19	38.2	33.8	11.8	0.02	0.46	0.01	2.24	0.24	0.06	0	86.84
20	38.7	34.4	12	0.11	0.46	0.02	1.98	0.27	0	0	87.96
21	28.1	41.7	9.24	2.2	0.43	0.05	1.63	0.18	0	0.06	83.62

Distance	SiO ₂	Al ₂ O ₃	MgO	FeO	V ₂ O ₃	CaO	Na ₂ O	Cr ₂ O ₃	TiO ₂	MnO	Total
22	3.36	4	0.77	0.4	0.02	0.07	0.17	0.01	0	0	8.805
Yag2c											
Core											
1	34.5	29.9	4.05	14.2	0	0.33	2.57	0.01	0.39	0.22	86.08
2	34.7	30.2	3.91	14	0.07	0.42	2.53	0	0.19	0.09	86.14
3	34.8	29.8	3.97	14.1	0	0.38	2.38	0	0.28	0.12	85.84
4	35	29.6	4.11	13.7	0	0.24	2.61	0	0.43	0.06	85.67
5	36.5	32.1	10.5	1.92	0.45	1.31	1.98	0.22	0.09	0.11	85.19
Overgrowth											
6	37.5	32.8	10.1	2.22	0.38	0.03	1.66	0.18	0.03	0	84.87
7	37.5	33	9.83	2.82	0.56	0.02	1.79	0.2	0.06	0.03	85.83
8	37.4	33.3	9.16	3.67	0.39	0	1.8	0.12	0	0.02	85.88
9	37.6	33.1	9.19	3.47	0.23	0.05	2.01	0.22	0.02	0	85.9
10	37.5	32.8	9.62	3.54	0.38	0.02	1.96	0.09	0.04	0	85.86
11	37.3	32.6	9.98	2.68	0.29	0	2.05	0.14	0	0	85.08
12	37.4	32.6	10.1	2.19	0.45	0.02	1.96	0.18	0.01	0.06	84.92
Yag3c											
Core											
1	35.4	25.1	8.73	11.7	0.07	2.83	1.3	0.02	1.39	0	86.56
2	35.8	25.2	8.65	11.8	0.06	2.96	1.33	0.09	1.46	0.11	87.51
3	35.9	25.2	8.84	12	0.1	2.86	1.34	0.04	1.5	0.09	87.87
4	37.6	30.4	9.23	6.74	0.33	1.27	1.73	0.2	0.58	0	88.05
Overgrowth											
5	37.8	33	10.4	2.38	0.43	0.05	1.98	0.08	0	0.02	86.12
6	37.9	33.2	9.97	2.85	0.57	0.08	1.87	0.08	0.01	0	86.5
7	38.4	33.2	9.38	3.44	0.15	0.03	1.79	0.08	0.02	0.02	86.49
8	38.4	33.3	9.53	3.39	0.37	0.06	2.03	0	0.04	0	87.09
9	38.5	33.1	10	2.44	0.36	0.03	2	0.09	0.06	0.08	86.68
10	38.5	33.5	11.2	1.18	0.44	0	2.03	0.3	0	0	87.09
11	39.1	34.3	11.9	0.1	0.4	0	2.19	0.21	0.08	0.05	88.33
12	39.4	34.2	11.9	0.11	0.3	0	2.01	0.07	0	0.1	88.01
13	39.7	34.3	11.9	0.02	0.4	0.06	2.21	0.17	0	0.02	88.72

APPENDIX 5
ZIRCON AGE DATES



GEOCHRON LABORATORIES

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711 CONCORD AVENUE ♦ CAMBRIDGE, MASSACHUSETTS 02138-1002 ♦ U S
TELEPHONE: (617)876-3691 TELEFAX: (617)661-0148 E-MAIL: staff@geochronlabs.com

September 17, 1998

Mr. Roland Scal
Dept. of Geology
Brooklyn College
2900 Bedford Avenue
Brooklyn, NY 11210

Dear Mr. Scal,

Enclosed are the results of the U/Pb age determinations on the zircon samples you sent to us in July. While you asked for only two analyses, and are being charged for only two, Sam Bowring thought it best to analyze all four zircons; a Concordia plot of the four zircons is enclosed.

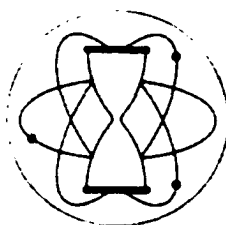
According to Sam, he would interpret zircons Z1 and Z2 as essentially concordant and being about 408 Ma. Z1 and Z4 are discordant, but Sam thinks they could well belong to the same suite of grains and be about 408 Ma. Because the grains were quite small and contained small amounts of radiogenic Pb, the error ellipses on the Concordia plot are a little larger than usual, although the ellipses for the $^{207}\text{Pb}/^{206}\text{Pb}$ dates for Z1, Z2 and Z4 overlap.

Sam has digital images of the air abraded grains if you would like to have them.

Enclosed is our invoice for this work. We have already billed you for the previous two K-Ar analyses, and we have sent you an "AB" invoice for all the work. Our "AB" invoices are pro forma invoices, and don't show up on our books unless they are paid. You can pay either the one "AB" invoice or the two regular invoices and we will sort out the details on this end. Please do not hesitate to contact me if you should have any questions about the enclosed results or the invoices.

Best regards,

Richard Reesman
General Manager/K-Ar Laboratory Manager



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TELEPHONE: (617)876-3691 TELEFAX: (617)661-0148 E-MAIL: staff@geochronlabs.com

U-Pb ISOTOPIC ANALYSES ON ZIRCONS

Our Sample No.: SS-2510 Date Received: 7/13/98

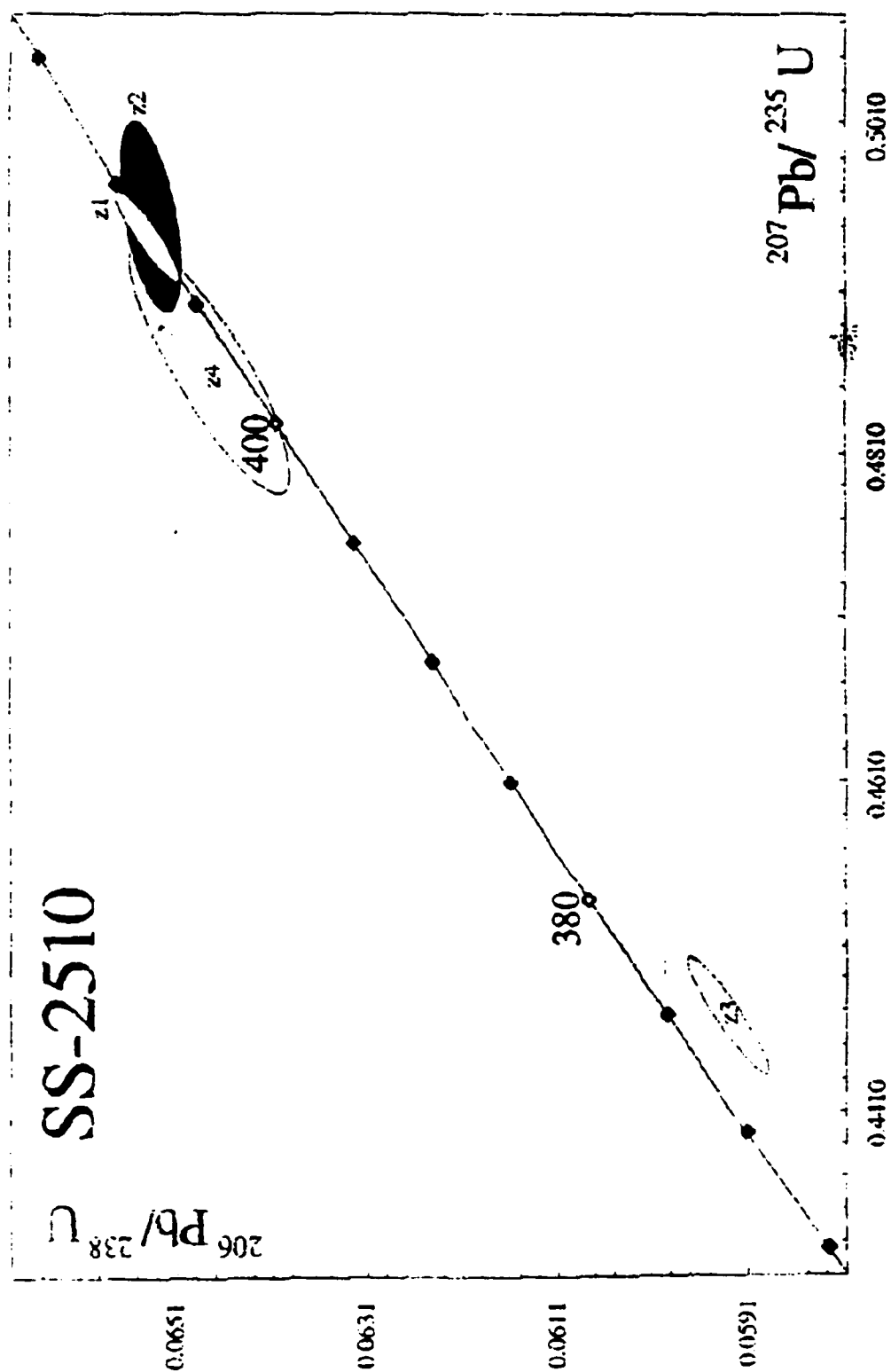
Your Reference: Letter July 10 Date Reported: 9/16/98

Submitted By: Roland Scal
Dept. of Geology
Brooklyn College
2900 Bedford Avenue
Brooklyn, NY 11210

Sample Description: Handpicked zircons

	Z2	Z1	Z4	Z3
Weight (mg)	0.0012	0.0099	0.0019	0.0034
Concentrations				
U (ppm)	270.52	82.95	158.83	177.75
Pb (ppm)	18.01	5.83	12.70	11.81
Atomic Ratios				
$^{206}\text{Pb}/^{204}\text{Pb}$	429.59	765.56	193.01	404.92
$^{208}\text{Pb}/^{206}\text{Pb}$	0.130	0.172	0.167	0.170
$^{206}\text{Pb}/^{238}\text{U}$	0.06532	0.06535	0.06471	0.05929
% error	(.49)	(.49)	(1.28)	(.72)
$^{207}\text{Pb}/^{235}\text{U}$	0.49544	0.49434	0.48627	0.44679
% error	(1.15)	(.55)	(1.57)	(.79)
$^{207}\text{Pb}/^{206}\text{Pb}$	0.05501	0.05486	(.05450)	0.05466
% error	(.98)	(.23)	(.85)	(.31)
Ages (Ma)				
$^{206}\text{Pb}/^{238}\text{U}$	407.9	408.1	404.2	371.3
$^{207}\text{Pb}/^{235}\text{U}$	408.6	407.9	402.4	375.0
$^{207}\text{Pb}/^{206}\text{Pb}$	412.7	406.6	391.8	398.3
corr. coef.	0.530	0.904	0.841	0.919
Total Common Pb (pg)	3.3	4.6	7.1	5.9
Blank (pg)	3.3	3.5	3.5	3.5

SPECIALISTS IN GEOCHRONOLOGY & ISOTOPE GEOLOGY



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