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**Diagenesis: Cementation, dolomitization, and dedolomitization,
including petrophysical characteristics of carbonate rocks**

Guo, Baiying, Ph.D.

City University of New York, 1994

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**DIAGENESIS: CEMENTATION, DOLOMITIZATION,
AND DEDOLOMITIZATION, INCLUDING PETROPHYSICAL
CHARACTERISTICS OF CARBONATE ROCKS**

**by
Baiying Guo**

A dissertation submitted to the Graduate Faculty in Earth and Environmental
Sciences in partial fulfillment of the requirement for the degree of Doctor of
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1994

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ABSTRACT

A detailed field- and laboratory study of the stratigraphy-, lithofacies-, diagenesis (emphasizing the origin of the dolostones), gas prospects and petrophysical properties of the Sauk Sequence (Cambro-Ordovician carbonates) in eastern New York has been completed. Beachrocks were selected as modern counterparts in order to compare the petrophysical characteristics between non-buried- and buried carbonates,

The Sauk carbonates were deposited on the Early Paleozoic passive margin of the North American continent. The former carbonate shelf can be divided into two subprovinces: (1) central (Wappinger Group), confined to the Appalachian fold-thrust belt, and (2) western [Beekmantown Group (of Fisher 1977)], underlying the Saratoga Platform. Facies study indicates that both subprovinces were deposited in a former tropical-coastal complex involving supratidal flats, intertidal flats, and adjacent subtidal zones. The central shelf was submerged beginning in the Early Cambrian. The water was deeper, the supply of terrigenous sediment less, and the accumulation rate was rapid (thickness 1000 to 1300 m). In the western-shelf subprovince, deposition did not begin until the Late Cambrian. The water depth was shallow, supply of terrigenous sediment abundant, and the accumulation rate was lower (thickness 500 to 700 m). These contrasts may have resulted from different rates of basin subsidence. In the central-shelf subprovince, clear water, proper subsidence rate and water depth were more favorable for accumulating a thick carbonate succession than in the Western shelf. The peritidal setting, which peaked in the Late Cambrian, was transformed into a normal shallow-marine environment at the end of the Early Ordovician.

In the Wappinger Group, I recognize seven fabric categories of dolomite that are products of three stages of dolomitization: (1) early, syndepositional; (2) second, shallow

burial; and (3) late, deep burial. Preserved early dolomite includes very-fine crystalline dolomite, in cores of some rhombs and as micrite ooids which formed during penetemporaneous deposition ($\delta^{18}\text{O}$ -5.6 to -6.7 ‰). The shallow-burial dolomitization altered most early dolomite into second-stage dolomite, which constitutes 80 to 90% of the massive regional-scale dolostones. Second-stage dolomites include fine to coarsely crystalline dolomite and some cement ($\delta^{18}\text{O}$ -6.1 to -7.4 ‰). Late-stage dolomite includes non-saddle dolomite (fracture filling) and saddle dolomite characterized by fracture- and pore filling ($\delta^{18}\text{O}$ -8.5 to -12.2 ‰). Saddle dolomite, which is virtually absent from the uppermost three formations of the group, is widespread in the underlying Upper Cambrian Pine Plains Formation. The estimated paleotemperature of the early- to second-stage dolomite is 35 to 45°C, and the late dolomite is higher than 125° C

Secondary calcite (dedolomite), which crosscut and replaced second-stage dolomite, is confined to the topmost three formations, especially, but is abundant only in the Halcyon Lake Formation. The secondary calcite displays progressive degrees of replacement from intercrystalline through pseudomorphic to massive. Its bright-yellow CL color easily distinguishes it from the dull precursor calcite and dull veinlet calcite, and from the reddish-CL-colored dolomites. The mean $\delta^{18}\text{O}$ of dedolomite is -7.9 ‰. The estimated paleotemperature of the dedolomite is 25°C.

Geological- and geochemical evidence proves that dedolomite formed during post-Early Ordovician emergence (post-Sauk, pre-Tippecanoe surface of unconformity). Because second-stage dolomite is older than the dedolomite; it must have formed even earlier--during the initial episode of subsidence (maximum possible amount of a few hundred meters to 1 km) associated with the passive-margin tectonic regime. Under this shallow- to intermediate burial, most early dolomite had been modified and the second-

stage dolomite formed. During the ensuing convergent-margin episode(s), and subsequently, the Wappinger Group was deeply buried (to estimated maximum depths of 5 to 7 km) and the late-stage saddle dolomite filled remaining spaces such as interparticle pores, vugs, and fractures. Neither the shallow-burial second-stage dolomites nor the dedolomites were significantly altered by subsequent deep burial.

During such deep burial, kerogen was altered to mature and to supermature states (beyond crude oil, but still within the conditions for thermogenic methane). In samples of the cuttings from the Finnegan boring, I found residue of oil in the pores of some sandstone- and dolostone layers in the Galway Formation (Upper Cambrian). These residues prove that during shallow burial, oil and gas were generated and migrated. The estimated average porosity at the time of oil migration is about 10%. After deeper burial, most primary- and secondary porosity was lost and the Sauk strata became very tight (porosities from 0.1% to 4.64% and recovery efficiency from 0 to 25% depending on rock texture and lithologies). Relatively porous rocks are oolitic dolostone, vug dolostone, calcdolostone, and ribbon dolostone. No matter how diagenesis destroyed primary porosity, the petrophysical properties of the studied Sauk rocks still show a clear relationship with depositional facies as in the studied beachrocks. As in modern beachrocks, oolitic dolostone presents the best porosity, skeletal grainstone follows, and fine- to very-fine dolostones show very low porosity.

Two borings found gas shows: Columbia Gas No. 1 Finnegan and the Crom-Wells No. 1 Fee (in the Sauk Sequence). In another boring ARCO No. 1 Susi, two intervals of vaterite have been found, which formed when drilling mud reacted with methane. Study of the stratigraphic sequences and associated surfaces of unconformity also implies that the general geologic requirements for forming subtle hydrocarbon traps have been fulfilled.

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CONTENTS

ABSTRACT

ACKNOWLEDGEMENTS

CONTENTS

TABLES

ILLUSTRATIONS

PART I INTRODUCTION AND PURPOSE. 1

CHAPTER 1: RESEARCH MATERIALS AND METHODS 3

1.1 Materials	3
1.1.1 Modern beachrock.	3
1.1.2 Carbonates of the Sauk Sequence.	3
1.2 Field study.	8
1.3 Analytical methods.	9
1.3.1 Petrography.	9
1.3.2 Cathodoluminescence.	9
1.3.3 Electron Microprobe.	10
1.3.4 X-ray diffraction.	10
1.3.5 Isotope composition (Oxygen and Carbon).	11
1.3.6 Carbon dating.	11
1.3.7 Mercury-porosimetry analysis.	11

PART II CEMENTATION: TURNING CARBONATE SEDIMENTS INTO CARBONATE ROCK: CASE HISTORY OF HOLOCENE DIAGENESIS IN BEACHROCKS. 13

CHAPTER 2: PETROGRAPHY AND CEMENTATION IN SOME HOLOCENE BEACHROCKS. 13

2.1 Group A-- oolitic grainstone	14
2.2 Group B-- Skeletal grainstone.	20
2.3 Group C-- Packstone.	21
2.4 Group D-- Skeletal-peloidal dolostone	25
2.5 Group E-- Terrigenous beachrock.	25
2.6 Group F-- <i>Halimeda</i> -grainstone.	30

CHAPTER 3: PETROPHYSICS OF HOLOCENE BEACHROCK. 33

3.1 Porosity.	34
3.2 Recovery efficiency.	40

3.3 Median throat size.	40
3.4 Normalized throat size.	44
3.5 Capillary-pressure curves.	45
3.6 Discussion and conclusion.	49

PART III DOLOMITIZATION AND DEDOLOMITIZATION: CASE HISTORY OF ANCIENT (CAMBRO-ORDOVICIAN) CARBONATE ROCKS OF PASSIVE MARGIN, EASTERN NEW YORK. 55

CHAPTER 4: GEOLOGIC SETTING OF EASTERN NEW YORK.	55
4.1 Geologic setting.	55
4.2 Stratigraphy	60
4.2.1 Sauk Sequence.	60
4.2.1.1 Beekmantown Group.	65
4.2.1.2 Wappinger Group.	68
4.2.2 Taconic Sequence	81
4.3 Post-Sauk, pre-Tippecanoe surface of unconformity.	88
4.4 Inferred burial history of the Sauk Sequence	90

CHAPTER 5: DEPOSITIONAL ENVIRONMENTS AND FACIES.	93
5.1 Western shelf (Fisher's Beekmantown Group).	93
5.1.1. Microlithofacies.	93
5.1.2. Interpretation of ancient environment.	106
5.2 Central shelf (Wappinger Group).	110
5.2.1 The best choice for facies study: Pine Plains Formation.	111
5.2.2 Depositional cycles- parasequences and facies relationships.	113
5.2.2.1 Facies.	114
5.2.2.2 Parasequences.	125
5.2.2.3 Example of sequence-stratigraphic analysis in cores of bore hole 73-91, Clinton Point Quarry.	126
5.2.3 A brief summary of environment evolution during deposition of the Wappinger Group.	129
5.3 Western shelf vs. Central shelf.	133

CHAPTER 6: DIAGENESIS: DOLOMITIZATION AND DEDOLOMITIZATION IN SAUK SEQUENCE.	136
6.1 Introduction.	136
6.2 Fabric- and composition components of carbonate rocks.	138
6.2.1 Calcite.	141
6.2.1.1 Precursor calcite.	141
6.2.1.2 Veinlet calcite.	141
6.2.2 Dolomite.	142
6.2.2.1 Early-stage dolomite.	146
Early dolomite (a) in the top of the Wappinger Group.	146
Early dolomite in the Pine Plains Formation.	147
6.2.2.2 Second-stage dolomite	151
Dolomite (b),(c),(d),(e) in the Top of the Wappinger Group.	151

Second-stage dolomite in the Pine Plains Formation	153
6.2.2.3 Late-stage dolomite.	158
Dolomite (f): non-saddle dolomite fracture filling.	158
Dolomite (g): saddle dolomite.	159
6.2.2.4 CL color of dolomite.	161
6.2.3 Dedolomite and -related calcite.	162
6.2.3.1 Dedolomite.	162
6.2.3.2 Extents and replacement fabrics of dedolomite.	163
6.2.3.3 Dedolomite-related calcite	169
6.3 Diagenetic paragenesis.	169
6.4 Geochemistry.	175
6.4.1 Major-ionic constituents.	175
6.4.2 Trace elements.	176
6.4.2.1 Precursor calcite.	179
6.4.2.2 Veinlet calcite.	179
6.4.2.3 Dolomite.	179
6.4.2.4 Dedolomite and -related calcite.	179
6.4.2.5 Interpretation of trace-element data.	182
6.4.3 Ratios of stable isotopes.	184
6.5 Discussion: Origin of dolomite and dedolomite of the Wappinger Group.	188
6.5.1 The dedolomitization and the conditions under which it is inferred to have taken place.	188
6.5.2 Geological relationship of post-Sauk, pre-Tippecanoe subaerial weathering and dedolomitization.	192
6.5.3 Burial history and diagenetic paragenesis.	193
6.5.4 Interpretation of oxygen-isotope ratios	197
6.5.5 Massive dolomite of the Wappinger Group: a product of shallow burial that survived deep burial	200
6.6 Conclusions.	201

CHAPTER 7: PETROPHYSICAL CHARACTERISTICS OF THE ROCKS OF THE SAUK SEQUENCE

7.1 Results from Finnegan boring, western-shelf subprovince.	205
7.1.1 Visual observation of pores.	206
7.1.2 Porosity from analysis of well logs.	206
7.1.3 Porosimetry results.	207
7.1.3.1 Procedure.	209
7.1.3.2 Results.	211
7.1.3.3 Discussion	215
7.1.3.4 Conclusion.	217
7.2 Results from the Wappinger Group, central shelf	218
7.2.1 Samples from Clinton Point and Cedar Cliff quarries studied by Liang <i>et al.</i>	218
7.2.2 Samples from outcrops and cores measured by Guo	221

CHAPTER 8: IMPLICATIONS FOR PETROLEUM PROSPECTING IN THE SAUK SEQUENCE.	224
8.1 Petroleum in Cambro-Ordovician rocks	224
8.2 Direct indications of petroleum in the Finnegan boring.	226
8.3 Depth of burial: Diagenesis, petrophysics of potential reservoir rocks, and maturation of organic matter	226
8.3.1 Diagenesis.	228
8.3.2 Petrophysical characteristics of selected rock types.	230
8.3.3 Results from organic geochemistry.	233
8.4 Potential petroleum traps.	234
8.5 Conclusions.	239
APPENDIX I: THIN-SECTION LISTS.	241
APPENDIX II: THE DATA OF THE MICROPROBE ANALYSIS.	249
REFERENCES.	262

TABLES

Table 1-1	Location and lithology of beachrocks studied	6
Table 1-2	Thin-section samples from the Sauk Sequence.	7
Table 2-1	Three cement forms related to porosity in oolitic beachrock	19
Table 2-2	Relationship of cement and porosity to radiocarbon age in Group F.	31
Table 3-1	Petrophysical data of beachrocks.	35
Table 3-2	Relationships among petrophysical parameters of the beachrocks	39
Table 3-3	Categories of capillary-pressure curves of beachrocks	44
Table 3-4	Number of capillary-pressure curves of the beachrocks	46
Table 3-5	Petrofacies of the beachrocks.	52
Table 4-1	Names and relative geologic spans of three sequences	58
Table 4-2	Stratigraphy of Ordovician-Cambrian in northeastern NY (western shelf)	59
Table 4-3	Names of formations within the Sauk Sequence on Saratoga Platform and in the Appalachian fold-thrust belt.	62
Table 4-4	Schematic columnar section of Wappinger Group showing formations	68
Table 5-1	Microlithofacies (Mlf) summary of the Sauk Sequence in Finnegan boring	96
Table 5-2	Western shelf (Beekmantown Group) v. central shelf (Wappinger Group)	135
Table 6-1	Fabric components of carbonate in the Wappinger Group	140
Table 6-2	Geochemical data of carbonates from the top of the Wappinger Group	177
Table 6-3	Summary of geochemical data of dolomite from the Wappinger Group.	178
Table 6-4	Isotopic composition of samples from Crom-Wells No.1 Fee (top of the Wappinger Group).	185
Table 6-5	Isotopic composition of samples from the Wappinger Group, various localities.	186
Table 6-6	Comparison between the Halcyon Lake and the Pine Plains formations	195
Table 7-1	Porosity of selected typical interval from well logs of Finnegan boring	209
Table 7-2	Summary of porosimetry data from cuttings of Finnegan boring	210
Table 7-3	Some petrophysical parameters of Briarcliff and Pine Plains formations by Liang <i>et al.</i>	220
Table 7-4	Mercury porosimetry results from the Wappinger Group by Guo	222
Table 7-5	Results of porosity and permeability measurements	223

ILLUSTRATIONS

Figure 1-1 Location map of studied beachrock samples	4
Figure 1-2 Sketch map showing sampling locations from the Sauk Sequence.	5
Figure 2-1, a, b, c, d, e, f Oolitic beachrock. Photomicrographs.	15-17
Figure 2-2, a, b, c, d, e, f Beachrocks of Group B, C, and D, photomicrographs.	22-24
Figure 2-3, a, b, c, d, e, f Terrigenous and <i>Halimeda</i> beachrock, Photomicrograph.	27-29
Figure 2-4 profile sketch of <i>Halimeda</i> beachrock prograding sequence.	32
Figure 3-1, a, b, c, d Graphs of recovery efficiency (RE) v. porosity.	37-38
Figure 3-2, a, b, c, d Bivariate plot of all studied beachrock samples.	41-42
Figure 3-3, a, b Bivariate plot showing groups and petrofacies.	43
Figure 3-4, a, b, c A series of concave capillary-pressure curves for oolitic grainstone (Group A).	47
Figure 3-5, a, b, c, d Capillary-pressure curves.	50-51
Figure 4-1 Index map showing major tectonic components of study area and locations of samples	56
Figure 4-2 Reconstructed paleogeomorphologic profile-section across the Early Paleozoic passive margin of North America.	61
Figure 4-3 Columnar section of strata penetrated in the Finnegan boring.	64
Figure 4-4 Map of eastern New York showing county outlines and locations of bore holes.	66
Figure 4-5 Graphic presentation of microlithofacies of western-shelf carbonate, Sauk Sequence from Finnegan boring.	69
Figure 4-6, a, b Lithology and stratigraphy from Crom-Wells No. 1 Fee.	70
Figure 4-7 Columnar sections of the Sauk Sequence penetrated in ARCO No. 1 Susi compared with Crom-Wells No. 1 Fee.	71
Figure 4-8 Graphic summary of microlithofacies results of strata from Taconic Sequence penetrated in the Finnegan boring.	82
Figure 4-9, a, b, c, d, e Enlarged views of petrographic thin sections from Taconic- and Tippecanoe sequences.	84, 86-87
Figure 4-10, a, b Stages in development of post-Sauk, pre-Tippecanoe surface of unconformity.	89
Figure 4-11 Schematic geohistory curve of the top of the Halcyon Lake Formation.	92
Figure 5-1, a, b, c, d, e, f Microlithofacies shown by photomicrographs.	98,100,102
Figure 5-2, a, b, c, d, e, f Microlithofacies shown by photomicrographs.	104-105,107
Figure 5-3 Outcrop view of cyclic features of Pine Plains Formation	112
Figure 5-4 Views of Facies A and B in Upper Pine Plains Formation.	115
Figure 5-5 Facies A (a) intraclasts; (b) oolitic.	116
Figure 5-6 Facies A (a) well-preserved ooids; (b) sandy grainstone.	117
Figure 5-7 Facies B (a) small channel; (b) wavy bedding.	120
Figure 5-8, a, b Vug dolostone: (a) loose block; (b) enlarged view.	121

Figure 5-9, a, b Facies C, close view of algal stromatolites.	123
Figure 5-10 a, b Paleokarst breccia, sink-hole breccia.	124
Figure 5-11 Columnar section of cored boring 73-91 showing results of sequence- - stratigraphic analysis results.	127
Figure 5-12 A summary of facies and environment analysis of the Wappinger Group.	131
Figure 6-1, a, b, c, d Enlarged views of calcite in precursor limestone, calcdolostone, dolomite(a), and dolomite(d).	144,145
Figure 6-2, a, b, c, d Enlarged views of very fine dolomite and different steps of modification of ooids.	149-150
Figure 6-3, a, b, c, d Enlarged views showing relic texture of grainstone and various occurrences of saddle dolomite.	154-155
Figure 6-4, a, b, c, d Enlarged views showing dolomite(b),dolomite (e), dolomite (d) and pseudomorphic dedolomite, stained thin section or CL light . . .	156-157
Figure 6-5, a, b, c, d Enlarged views showing fracture-filling dolomite (f), Saddle dolomite (g), and intercrystalline replacement dedolomite, stained thin section or CL light.	164-165
Figure 6-6, a, b, c, d Enlarged views showing pseudomorphic dedolomite, massive dedolomite, dedolomite related-calcite veinlet, and late dull-calcite vein, stained thin section or CL light.	167-168
Figure 6-7 Sketch of diagenetic paragenetic succession of the Wappinger Group . . .	171
Figure 6-8, a, b Plots of manganese versus iron in dolomite and dedolomite.	180
Figure 6-9, a, b Graphs of manganese plotted against carbonates in dedolomites . . .	181
Figure 6-10 Graphic presentation of Fe, Mn content in zoned dolomite (f).	183
Figure 6-11 Stable-isotope ratio of samples from the Wappinger Group.	187
Figure 7-1 Graph of porosity v. recovery efficiency, samples from Finnegan boring .	212
Figure 7-2 Three kinds of capillary-pressure curves (from Finnegan boring).	213
Figure 7-3 Bivariate plot of recovery efficiency (RE) v. porosity for sample from Liang <i>et al.</i>	218
Figure 8-1 Enlarged views showing oil residue, samples from Finnegan boring.	227
Figure 8-2 Diagenesis summary of the Sauk Sequence from Finnegan boring	229
Figure 8-3 Photomicrograph showing compacted pellets and deformed twinning	231
Figure 8-4 Porosity v. depth in Finnegan boring.	232
Figure 8-5 Overlapping relationships between- and within sequences, northern NY . .	237

PART I

INTRODUCTION AND PURPOSE (HOW AND WHY I CHOSE THIS TOPIC)

It is well known that of the world's petroleum reservoirs, 40% are composed of carbonate rocks; in North America, the proportion of carbonate reservoirs is 60%. In many cases, because of their distinct pore systems, carbonate reservoirs produce more oil and at higher rates than terrigenous reservoirs. In recent years, numerous studies on the sedimentary environments-, lithofacies-, and the petrophysical consequences of diagenesis of carbonates have been carried out to meet the needs of the petroleum industry.

Recently, the Sauk Sequence has become a target unit for renewed interest in petroleum exploration in Oklahoma (Arbuckle Group), Texas (Ellenburger Group) (Brown and Georgia 1988; Hook 1990; and Suneson and Campbell 1989) and elsewhere in the world. For eastern New York, Keith and Friedman (1977) argued that the former carbonate-shelf deposits of the Sauk Sequence should be worthy petroleum-exploration targets. As a result, the Columbia Gas Company in 1983 drilled the No. 1 Finnegan at the eastern edge of the Saratoga Platform. The boring found a show of gas that was judged to be noncommercial. For the gas potential of the Sauk Sequence in eastern New York, two research projects* have been carried out in the Northeastern Science Foundation.

Fortunately, I have been involved in the two research projects whose main focus was on the stratigraphy-, lithofacies-, diagenesis-, and petroleum prospects of the Sauk

* 1. "Pre-drilling geologic work in connection with proposed Albany basin, New York, deep scientific test hole to test gas potential of Paleozoic formations", which was co-funded by NYGAS, the Northeastern Science Foundation, Hofstra University, and John E. Sanders.

2. "Geology and gas potential of Paleozoic strata in the eastern overthrust belt of New York and Vermont" which was supported by the New York State Gas Association (NYGAS) and the New York State Energy Resources Development Authority (NYSERDA).

Sequence in eastern New York State. In addition, in order to understand and explain the diagenetic processes that have affected the Sauk strata and to compare petrophysical properties between modern- and ancient carbonates, I chose beachrock as a modern counterpart of carbonate to carry out the petrographic and petrophysics study**. This is because beachrock represents the first step in the transition from unconsolidated sediment to lithified rock. Beachrock has not been subjected to burial diagenesis; its primary pore system is much better preserved than that of ancient rocks. Most of above research results I have obtained are the basis of this dissertation.

I have emphasized diagenesis- and petrophysics of carbonates because these are the most-important factors for evaluating the petroleum potential of carbonate rocks. Moreover, the origin of regional-scale massive dolostones, as in the Sauk Sequence, is still in debate. No such dolomite deposit of this scale is found on modern shelves. Neither can synthetic dolomite be made in the laboratory under normal temperature and pressure. The study of diagenesis of Sauk dolomite will be of great help for understanding the origin of regional-scale massive dolostones.

The purposes of this study are to understand: 1) how pore systems evolve from various carbonate sediments to carbonate rocks and how lithology controls the petrophysics of various carbonate rocks (beachrock represents a product of early diagenetic process, which has not involved burial diagenesis); 2) how diagenetic processes (cementation, dolomitization, and dedolomitization) have affected such modern carbonates as beachrocks and such ancient carbonate rocks as those in the Sauk Sequence of Cambro-Ordovician of eastern New York; 3) how the diagenetic history of the Sauk Sequence in eastern New York is related to burial-

** "Petrophysics of Holocene beachrocks" which was supported jointly by the Education Committee of China, Huainan Mining Institute, and the Northeastern Science Foundation.

uplift-, and tectonic events and then summarize the model of its dolomitization and dedolomitization; 4) the prospective gas potential of the Sauk Sequence in northeastern New York State based on comprehensive studies of the stratigraphy-, lithofacies-, petrophysics and burial history of the Sauk Sequence.

CHAPTER 1: RESEARCH MATERIALS AND METHODS

1.1 Materials

1.1.1. Modern beachrock

I studied 51 samples of samples that Prof. G. M. Friedman had previously collected from the Holocene deposits along the coasts of the Bahamas, the Red Sea, the Mediterranean, the Persian Gulf, the Great Barrier Reef of Australia and the southern Caribbean (Figure 1-1, Table 1-1).

1.1.2. Carbonates of the Sauk Sequence

The samples of the Sauk Sequence for the study of stratigraphy, facies, and diagenesis are from three bore holes (the Columbia Gas Co. No. 1 Finnegan and the ARCO No. 1 Susi, rotary samples collected at 10-foot intervals; and the Crom-Wells No. 1 Fee, cable-tool cuttings collected at irregular intervals when the bit had to be changed, usually 2 to 5 ft in the Sauk carbonates), some outcrops, and the Clinton Point Quarry (Figure 1-2, Table 1-2). Thin sections have been made from two different kinds of samples. One is specimens from outcrops or cores. Another is chips from well cuttings of boreholes. Using a binocular stereomicroscope, I first identified and separated selected chips that were sent for thin sections.

Altogether, I studied 718 thin sections. Of these, about 256 were covered regular thin sections cut from shallow cored borings made in the Clinton Point Quarry and collected by Barnard College students working under Dr. J. E. Sanders in 1983. I myself selected

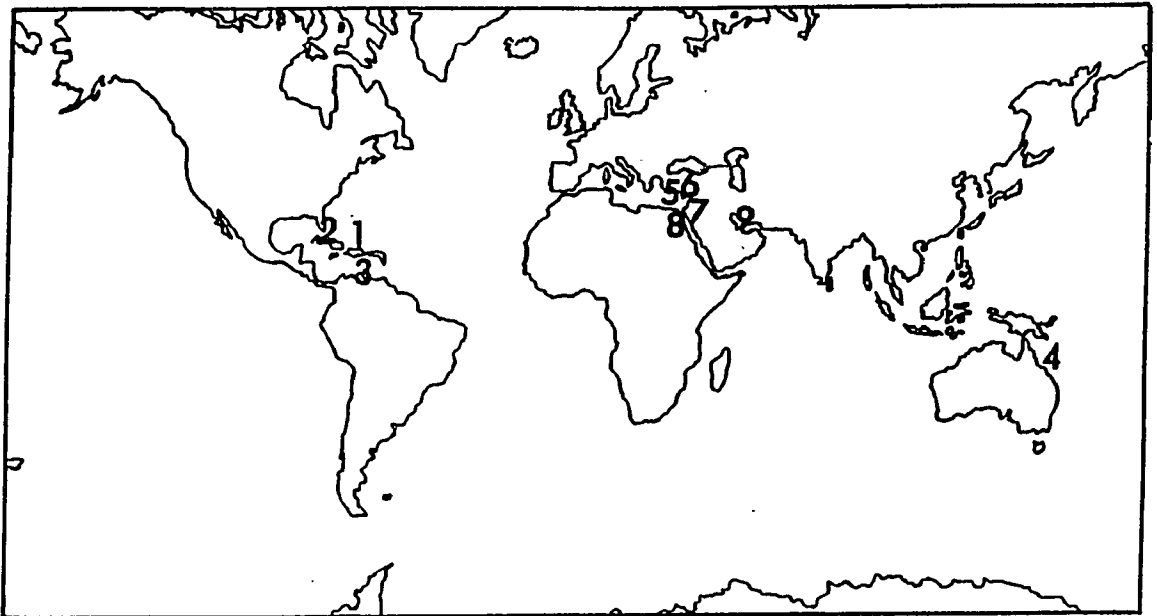


Figure 1-1. Location map of studied beachrock samples: 1. Bahamas; 2. Florida; 3. Venezuela; 4. Great Barrier Reef; 5. Bardawil, Mediterranean; 6. Kharube, Mediterranean; 7. Gulf of Elat, Red Sea; 8. Gulf of Suez, Red Sea; 9. Persian Gulf.

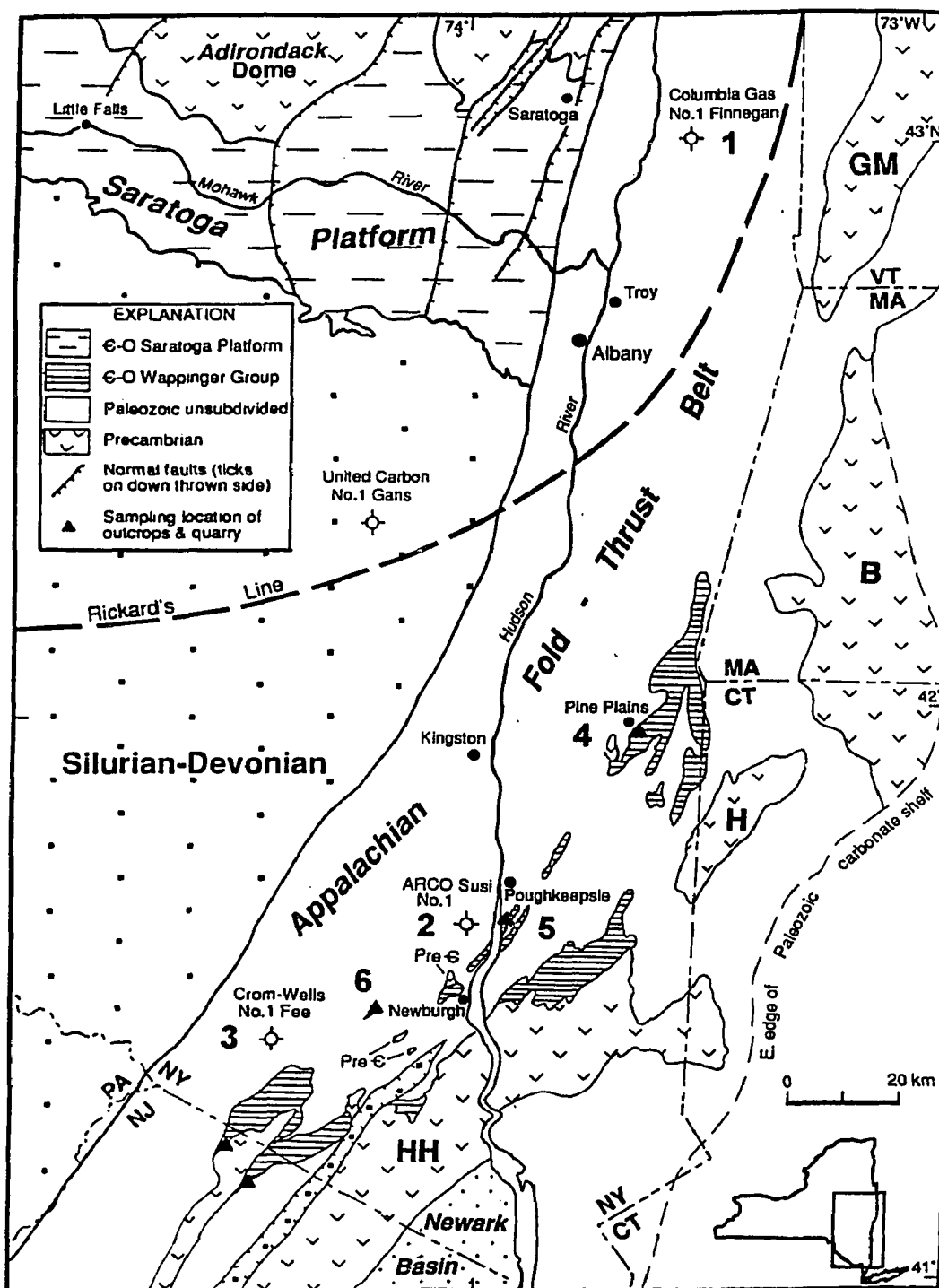


Figure 1-2. Sketch map showing major sampling locations of the Sauk Sequence. Borings: 1. Finnegan; 2. ARCO Susi; 3. Crom-Wells. Outcrops and Quarries: 4. Pine Plains, Halcyon Lake; 5. Clinton Point Quarry and vicinity; 6. Maybrook Quarry.

Table 1-1 LOCATION AND LITHOLOGY OF BEACHROCKS STUDIED

Location	Number of samples	Lithology	Group
Florida	1	Oolitic grainstone	A
Bahamas 1, Bimini	1	Skeletal grainstone	B
Joulters Cay	2	Oolitic grainstone	A
Cockroach Cay	1	Oolitic grainstone	A
Schooner Cay	6	Oolitic grainstone	A
Schooner Cay	1	Skeletal grainstone	B
Bahamas 2, Williams Island	2	Packstone	C
Andros Inland	4	Packstone	C
Mediterranean, Bardawil	4	Skeletal-peloidal Dolo- stone	D
Mediterranean, Kharube	3	Skeletal grainstone	B
Red Sea, Gulf of Elat	6	Terrigenous beachrock	E
	1	Packstone	C
Red sea, Gulf of Suez	4	Terrigenous beachrock	E
	2	Oolitic grainstone	A
Great Barrier Reef, Australia	2	Terrigenous beachrock	E
Southern Caribbean, Venezuela, Francisqui Cayo	5	<i>Halimeda</i> grainstone	F
Vaper Cayo	2	<i>Halimeda</i> grainstone	F
Persian Gulf, Abu Dhabi	1	Oolitic grainstone	A
	1	Packstone	C
	2	Skeletal grainstone	B
Total number of samples	51		
Distribution: Group A: 13; Group B: 7; Group C: 8; Group D: 4; Group E: 12; Group F: 7			

Table 1-2 Thin-section samples from the Sauk Sequence

Locations	Sample-type	Stratigraphy assemblage	Regular	Polished	Total
Colum. Gas #1 Finnegan	Chips	Western shelf slope, basin	150	5	155
Crom-Wells #1 Fee	Chips	Central shelf	78	25	103
ARCO #1 Susi	Chips	Central shelf	10	17	27
Clinton Point Quarry	Cores & walls	Central shelf	12	15	27
	Cores (JES collection)	Central shelf	256		256
Outcrops many loc.	Hand specimen	All	129	21	150
Total			635	83	718

the materials for 462 thin sections. Some thin sections were stained for distinguishing calcite, dolomite and iron-rich dolomite (G. M. Friedman, 1959). Of all sections, 83 were polished for cathodoluminescence and microprobe study (Table 1-2). A detailed list of the studied thin sections is in Appendix A.

On the basis of petrographic study, I selected suites of samples for analysis using electron-beam microprobe, X-ray diffraction, isotopic composition, carbon dating, mercury porosimetry, and permeability, accordingly. I describe the samples and present the results of these analyses in the following chapters. For additional comparisons, I examined the cuttings under binocular microscope and compared them with the gamma-ray logs from the New York Natural Gas Co., No. 1 Lum boring in the collection of the New York State Museum.

1.2 Field study

I made field studies mostly of rocks belonging to the Sauk Sequence. I did so not only to collect samples, but also to study stratigraphic- and structural relationships and macro-lithofacies features. To examine the Sauk carbonates in the western-shelf subprovince in New York, I made a couple of field trips to the Saratoga Platform, and to the well site of the Finnegan borehole in Washington County. At the Finnegan well site, the top of the Sauk Sequence lies about 5000 feet below the surface. The strata exposed at the well site are deposits from the Northern Appalachian Ordovician foreland basin (Austin Glen and Mt. Merino formations). Accordingly, I made several field trips to study these foreland-basin strata, including a visit to the type section of the Mt. Merino Formation at Mt. Merino, south of Hudson, NY; to the section of the Austin Glen Formation exposed at the west end of the Rip Van Winkle bridge, Catskill, NY; and to Rushor's Quarry, in Troy.

For studying the Sauk rocks in the central-shelf subprovince--the Wappinger Group,

in addition to the type location, Pine Plains and Stissing Mountain area (Knopf, 1967), I paid most of my attention to the outcrops and walls in and nearby the Clinton Point Quarry (See Figure 1- 2.), as well as to roadcuts in Newburgh, Orange County, NY and in Sussex County, NJ.

1.3 Analytical methods

With the exception of determining the isotope ratios (oxygen and carbon), and the radiocarbon dates, I performed all other methods of sample identification and -measurement. I carried out the electron-beam microprobe analyses at RPI (Rensselaer Polytechnic Institute) and all the rest at the Rensselaer Center of Applied Geology of the Northeastern Science Foundation, Troy, NY.

1.3.1. Petrography

My first step was to examine all cuttings under the binocular microscope. I carried out the binocular study in conjunction with well logs available to me. For the No. 1 Finnegan boring, I had a complete suite of geophysical logs, including gamma ray, neutron, sonic, and dipmeter. For the other borings, only the gamma-ray logs were available. At the same time, I picked out chips for preparation of petrographic thin sections. Then, I studied the thin sections that had been cut from the selected chips.

I studied all thin sections using a petrographic microscope (Leitz Ortholux, equipped with a Leitz Orthomat automatic camera system for high-resolution photography). I noted basic petrographic characteristics, such as mineral composition, texture, structure, and diagenesis.

1.3.2. Cathodoluminescence

Altogether 83 thin sections were polished and left uncovered for study under luminescence microscope (Nuclide luminoscope, Model ELM-2). The operating conditions for cathodolumines-

cence (CL) petrography and photomicrography were: beam voltage, 12 to 15 Kv; and the beam current, 0.4 to 0.6 mA in a 50- to 70-mTorr vacuum under an air atmosphere.

1.3.3. Electron Microprobe

I also analyzed selected polished thin sections using a fully automated JEOL 733 electron-beam microprobe. The operating conditions for the microprobe were: 15 to 45 kv accelerating voltage; 25 na beam current; beam diameter approximately 10 microns; and maximum counting times of 60 seconds.

I have carried out 450 point analyses to determine the geochemical characteristics of various fabric components of the Wappinger Group (from the central-shelf subprovince). Of these, I had selected 300 from the top three formations (Lower Ordovician) and 150 from the Pine Plains Formation (Upper Cambrian). The microprobe analyses were intended to determine the geochemical characteristics of the very different depositional- and diagenetic fabrics I found in the Wappinger Group. I hoped that these data would be helpful for explaining the dedolomitization in the top of the Wappinger Group and for interpreting the different diagenetic characteristics between the Halcyon Lake Formation (Lower Ordovician) and the Pine Plains Formation (Upper Cambrian).

I keystroked all numerical data into spreadsheets using Quattro-Pro software. Then, I used graphic methods to search any trends existing between each of the main- and trace elements. I present the detailed results in Chapter 6.

All analytical data from microprobe are listed in Appendix B.

1.3.4. X-ray diffraction

I used qualitative- and semi-quantitative analyses mainly for beachrocks to determine mineral composition and relative proportions of each mineral and to confirm the petrographic study.

1.3.5. Isotope composition (Oxygen and Carbon)

I submitted 21 samples for analysis by Geochron Laboratories, of Krueger Enterprises, Inc., Cambridge, Massachusetts, to determine ratios of the stable isotopes of oxygen and carbon. The analytical techniques involved in mass spectrometry are discussed in Faure (1977).

All samples are from the Wappinger Group.

1.3.6. Carbon dating

I selected two samples from a vertical succession of beachrocks from Francisqui Cayo, Venezuela, Southern Caribbean to check their ages. The purpose was to relate the rock age to the porosity of the beachrocks.

1.3.7. Mercury-porosimetry analysis

I used mercury porosimetry for petrophysical analysis of beachrock. In mercury porosimetry, mercury is forced into small voids of rocks. The higher the imposed pressure, the smaller are the voids that the mercury can intrude. Hence, a graph of cumulative mercury-intrusion volume versus capillary pressure is also a graph of cumulative mercury-intrusion volume versus throat size (Purcell 1949). The following equation expresses the relationship of throat size to pressure:

$$r = \frac{-2\gamma \cos\theta}{P},$$

where:

γ = interfacial tension (485 dynes/cm for Hg/vacuum),

θ = contact angle (130° is used because it is cited most frequently),

P = pressure,

r = the radius of tubular throats.

Because, during near-surface diagenesis, neither the particles nor the cement in beachrocks have been extensively recrystallized or deformed, a tubular model of throat shape is appropriate for use with beachrock.

Sampling, cleaning, and experimental procedures follow Ghosh and Friedman (1987), and Kopaska-Merkel and Amthor (1988). Most samples were exposed to pressures up to 20,000 psia.

The intrusion of Hg into some samples ceased at a pressure below 20,000 psia. If this happened, the test run was terminated. In a few samples, intrusion continued to increase at pressures above 20,000 psia. These samples were subjected to pressures up to 30,000 psia. Such high pressures covered the full range of porosity and provided comparison with similar data derived under high pressure for subsurface reservoir rocks (Amthor *et al.* 1988; Kopaska-Merkel and Friedman 1989).

Several samples were not sufficiently consolidated to permit standard cylindrical core plugs to be made by drilling, but yielded data comparable to that obtained from standard core plugs. (See Kopaska-Merkel 1988.) Samples were watched closely for any phenomena that might indicate fabric change or damage under high pressure (Amthor *et al.* 1988). Neither abrupt increase in intrusion at high pressure nor apparent extrusion at decreased pressure were observed. These relationships indicate that, even at high pressures, the samples kept their original fabric.

PART II

CEMENTATION: TURNING CARBONATE SEDIMENTS INTO CARBONATE ROCK: CASE HISTORY OF HOLOCENE DIAGENESIS IN BEACHROCKS

CHAPTER 2: PETROGRAPHY AND CEMENTATION IN SOME HOLOCENE BEACHROCKS

Of all modern cemented rocks, beachrocks have been studied most extensively. Geologists have studied Holocene beachrocks to determine their mineral compositions, lithologies, cementation, diagenesis, and origin (Ginsburg 1953, Illing 1954, Russell 1963, Stoddart and Cann 1965, Gavish and Friedman 1969, Taylor and Illing 1969, Bricker 1971, Friedman and Gavish 1971, Helsinger 1973, Helsinger and Friedman 1973, Friedman 1975, Krumbein 1979, Flügel 1982, H. M. Meyers 1987, Dunkel *et al.* 1988, Schillings and Richter 1989, Amieux *et al.* 1989). But, I know of no published reports detailing the petrophysical studies of beachrock.

The purpose of this chapter was to determine the different lithologic characteristics of beachrocks, their diagenesis (cementation), and pore systems. My study has shown that the sedimentary environment-, sediment properties-, and diagenetic history of a given beachrock have determined the characteristics of both lithology and pore systems. In fact, petrographic characteristics provide an explanation of the petrophysical results to be discussed in Chapter 3. Thus, the petrographic study of beachrocks can be used to predict their petrophysical characteristics, as well as to find out how diagenesis controls pore systems and to recognize some petrofacies of Holocene beachrocks.

I used lithologic- and petrophysical characteristics to classify beachrocks from the Bahamas, Red Sea, Persian Gulf, Mediterranean, southern Caribbean, and Great Barrier

Reef (Australia) (See Figure 1-1.) into six groups, as follows: Group A--oolitic grainstone, Group B--skeletal grainstone, Group C--Packstone, Group D--dolostone, Group E--terrigenous beachrock, and Group F--*Halimeda* grainstone. Because for most purposes, groups B and F can be merged, this study recognizes five beachrock petrofacies (petrophysical facies).

2.1 Group A--Oolitic grainstone

Most samples in this group were from the Bahamas (Joulter's Cay, Cockroach Cay, and Schooner Cay). The rest were from Florida, the Red Sea, and the Persian Gulf. All of the samples in Group A are white, weakly consolidated, similar-looking rocks. But the samples differ in degree of consolidation and in cement styles. As a result, even among samples belonging to the same lithology and coming from the same environment, petrophysical properties differ.

In general, the rocks of Group A are composed almost entirely of ooids, with ooids constituting more than 95% of their particle volume. Locally, a few skeletal fragments and intraclasts are associated. The diameters of the ooids range from 0.2 mm to 1.2 mm; most are 0.3 to 0.6 mm. The ooids are well sorted and spherical or ovoid in shape. Three kinds of ooids are present: (1) normal, (2) micritized, and (3) superficial (Figure 2-1-e, a, b)

Cementation: Based on cementation related to porosity, I recognize three styles of cement that affected the porosity of the beachrocks: (1) discontinuous pore rimming; (2) continuous pore-rimming; (3) granular (Figure 2-1-a, c, d, e, f; Table 2-1).

(1) Discontinuous pore-rimming cement includes both discontinuous fringe microcrystalline cement and meniscus cement. In rocks with discontinuous fringe cement,

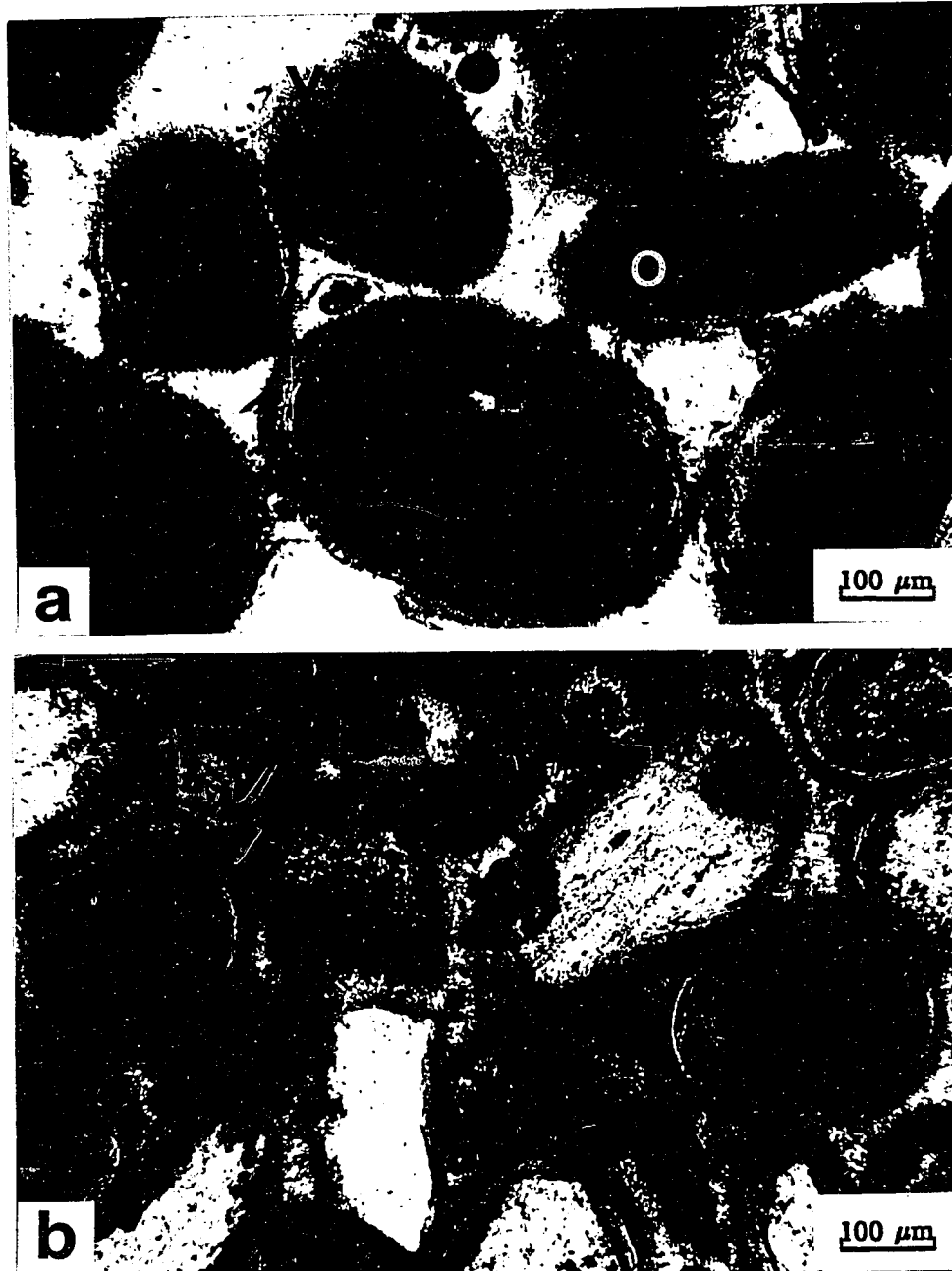


Figure 2-1. Oolitic beachrock. Photomicrographs, plane-polarized light, except as otherwise noted. a). Micritized ooids, from the Bahamas. Despite the alteration of the nuclei, the thin, concentric laminae are still visible. The boundary between nuclei and concentric laminae is transitional. One ooid (O), at right, retains obscure internal concentric laminae. A little acicular aragonite cement discontinuously rims pores. Some of the ooids (at top left, V) have been partially dissolved, thus increasing the porosity. b). Superficial ooids from Persian Gulf show large nuclei and clear boundaries between nuclei and one or more laminae of coating.

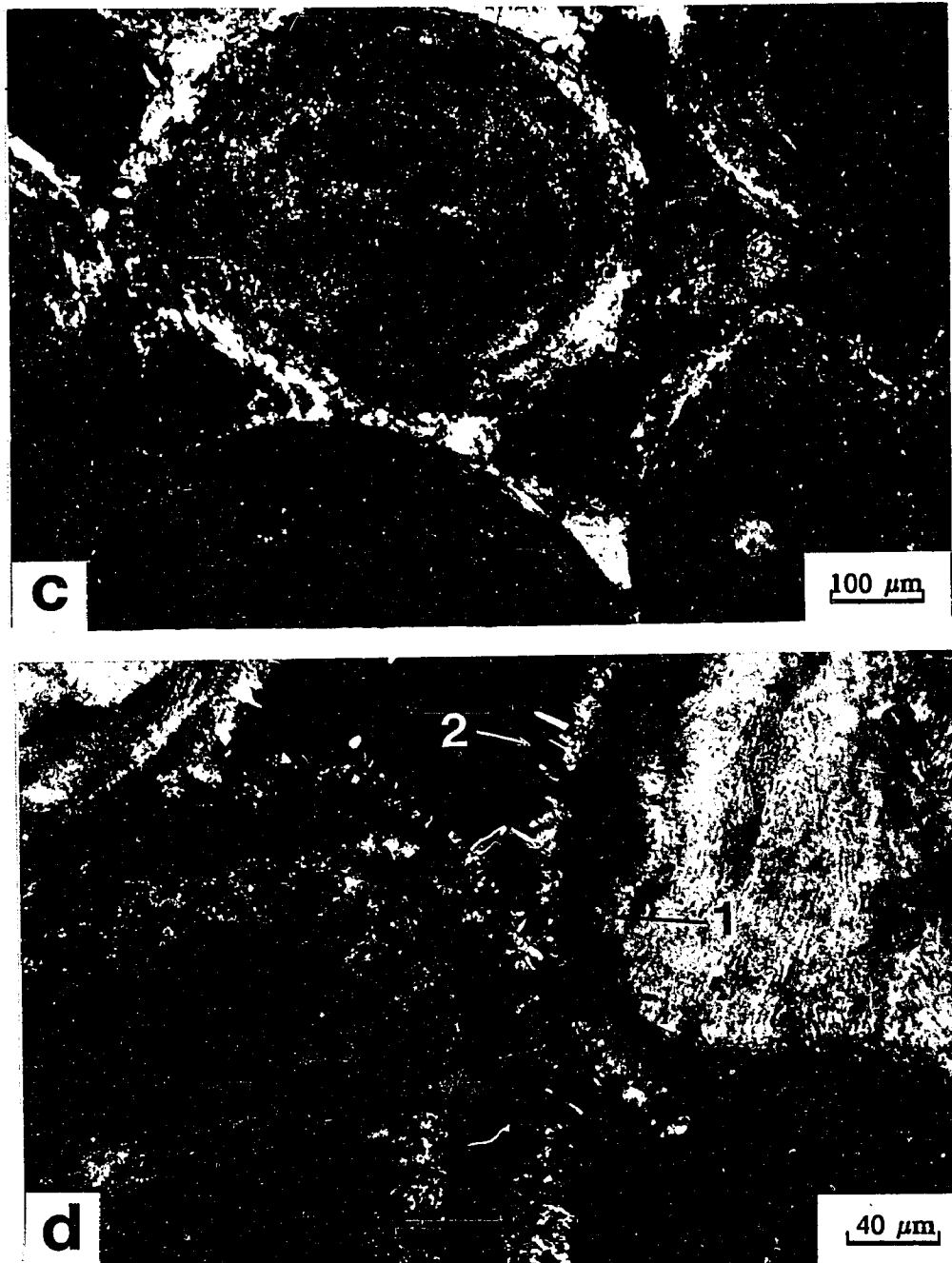
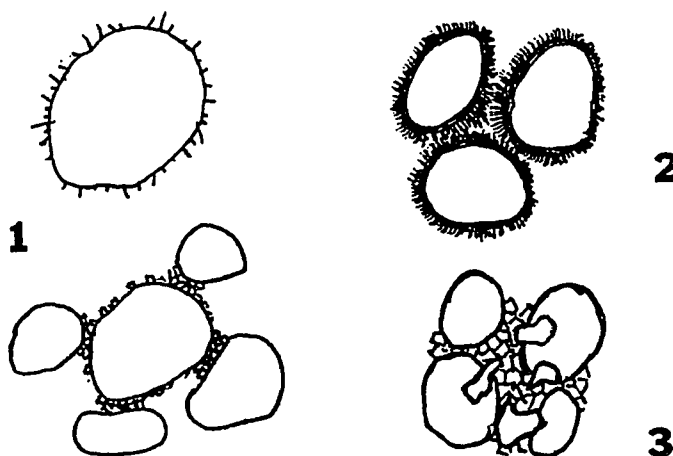
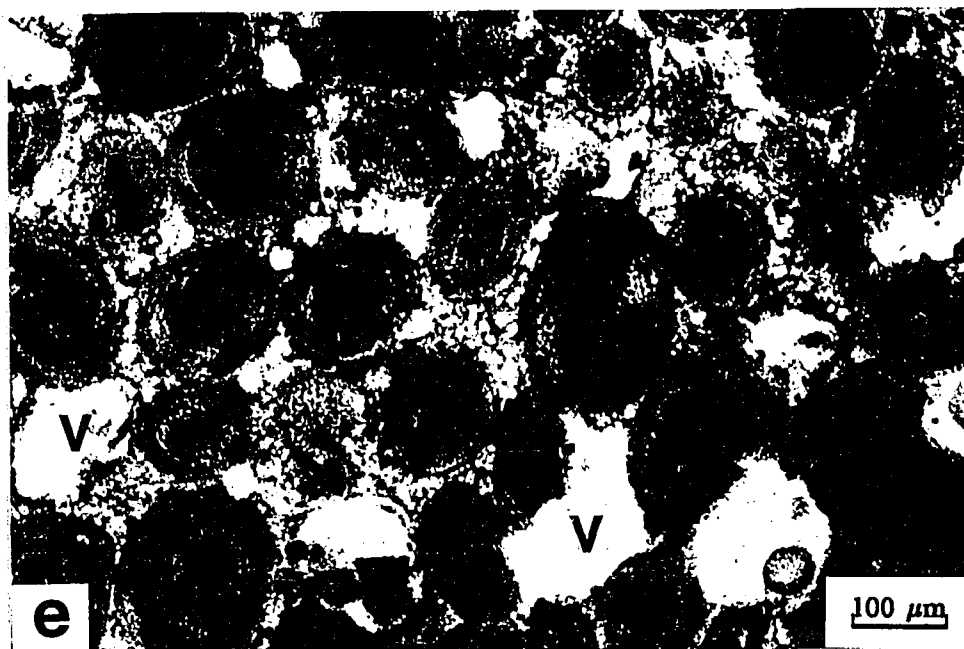


Figure 2-1. c). Microcrystalline meniscus cement from the Bahamas, crossed-polarized light. Pore space is less than "a". The ooid at right bottom displays a tiny intraparticle pore (white area). d). Two-generation continuous pore-rimming cement from the Persian Gulf, crossed-polarized light. The first generation (cement 1) is a thin, dark cryptocrystalline layer (Mg-calcite). The second generation 2 consists of acicular aragonite needles growing perpendicularly to particle surfaces.



f

Figure 2-1. e). Normal ooids from the Bahamas. Most primary interparticle pores have been filled by granular low Mg-calcite. As a result of dissolution of both ooids and earlier cement, many secondary vugs (v) have formed. f). Sketches of three kinds of cement styles related to porosity in oolitic beachrock. 1a, discontinuous fringe (see Fig. 2-1, a) in which acicular aragonite is slightly aligned, and 1b, meniscus cement (see Fig. 2-1, c); microcrystalline cement was concentrated at the corners of pores. 2, two-generation continuous pore-rimming cement (see Fig. 2-1, d). By contrast with 1a, acicular aragonite was arranged densely; 3, granular low-Mg calcite cement with large amount of secondary vugs. (See Fig. 2-1, e.)

needles of different sizes are loosely arranged on the surfaces of the ooids. The aragonite needles range in length from 2 μm to 5 μm and may be perpendicular to the surfaces of the ooids. Much primary pore space is preserved (Figure 2-1-a). Meniscus cement (low-Mg calcite) mainly fills the corners of the pores; e.g., at the contact points of the particles. The effect is to round off the sharp corners (Figure 2-1-c). So, the rocks with this kind of cement also preserve most of the primary interparticle pores. The clear and transparent crystals of meniscus cements are finely granular, euhedral, and from 6 μm to 20 μm in size. Rocks with cement type (1) consist of less than 10% cement and thus their retained porosities are large (from 27 to 32.6%). These samples occupy the lower right position on the bivariate graph of porosity versus recovery efficiency (Figure 3-1-b).

(2) Continuous pore-rimming cement. This cement covers particle surfaces continuously, and sometimes fills the pores completely; commonly it is composed of two generations. These are cryptocrystalline, thin rim cement (high-Mg calcite) covered by acicular aragonite crystals perpendicular to particle surfaces (Figure 2-d). Microcrystalline high-Mg calcite cement may occur between cryptocrystalline- and acicular layers. This kind of cement style occupies more than 15% of total sample volume and is associated with lower porosities than cement of type (1); porosity ranges from 15.5 to 19.7%. From Figure 3-1-b, it is clear that by increasing the amount of cement, from discontinuous pore-rimming- to continuous pore-rimming cement of two generations, the porosity is decreased and recovery efficiency is increased.

(3) Granular cement (Figure 2-1-e). Euhedral- to subhedral low-Mg calcite crystals fill most of the interparticle pores. The crystals are 20 to 60 μm in size and are distributed without preferred orientation (Flügel 1982). Also, no pore-rimming cement is

observed. This kind of cement, occupying more than 20% of sample area in thin sections, was possibly formed by recrystallization of other cement types, such as acicular or cryptocrystalline aragonite/high-Mg calcite. The rock with this cement type is characterized by having many secondary vugs and few primary pores. More vugs and smaller primary pores are present in this sample than in any of the other samples. Porosity of this sample is 37.7%, the highest of all the samples studied. It is located at the upper right on the bivariate graph (Figure 2-4-a, b), far away from the other oolites. This fact resulted from the special texture and origin. After it had been cemented in beach zone, the rock was obviously affected by fresh water.

Table 2-1 THREE CEMENT FORMS RELATED TO POROSITY IN OOLITIC BEACHROCK

Cement forms	Description	Porosity (%)	Capillary -pressure curves
Dis-continuous pore rimming	Microcrystalline cement crystals are loosely arranged on surfaces of particles, or meniscus cement fills the corners of pores. Much primary pore space has been preserved. See Figure 2-i,a.	Primary pores 27.0-32.6	Concave "a" See Figure 3-4-a
Continuous pore rimming	More than two generations of cement, commonly the first is dark and cryptocrystalline; and the second, acicular. Occasionally, cement from a third generation fills the remaining pores. See Figure 2-1,c.	Primary pores and few vugs 15.5-19.7	Concave "b" & "c" See Figure 3-4-b,c
Granular cement	Most of interparticle primary pores are filled by granular calcite cement. Many vugs have formed. See Figure 2-1,e.	Numerous vugs, less primary 37.7	Bimodal See Figure 3-5-d

As mentioned above, the intensity- and style of cement strongly controlled the pore system of the oolite beachrock. (See discussion in Chapter 3.)

2.2 Group B--Skeletal grainstone

This group includes all grainstones except for oolitic and *Halimeda* grainstones. Included in this group are 7 samples from the Mediterranean, Persian Gulf, and the Bahamas. Although all 7 samples are grainstones, different particles, cements, and textures are present.

Three samples from the Mediterranean contain particles of mollusks, brachiopods, and quartz, feldspar, and rock fragments. Most skeletons have been broken but some are perfectly preserved. An important property of the Mediterranean samples is their bedding structure, which results from a parallel orientation of bladed skeletons. In one sample, most of the larger skeletons are convex upward with big shelter pores formed underneath. However, in the other two samples, platy- or bladed skeletons are very tightly packed. Accordingly, porosity in these samples ranges from 7.0 to 16.8%. Microcrystals of high-Mg calcite and bladed high-Mg calcite are found in these samples, respectively. These cements commonly rim pores or form menisci; in some, they fill pores (Figure 2-2-a, b).

Grainstones from the Bahamas consist of intraclasts and ooids, and their lithologic characteristics are similar to those of the oolite group. In grainstones of the Persian Gulf, oncolites and intraclasts are found separately. The lithologic properties of these grainstones are diverse. This leads to their different pore systems.

Compared with oolites, both porosity and recovery efficiency are lower. This is because the blade-like shapes of skeletal particles, and their poorer sorting, do not permit

packing to be as efficient as in oolites.

2.3 Group C--Packstone

Eight samples of pellet packstone from the Bahamas were studied. Some calcisiltite and a few skeletal fragments are associated; pellets and peloids occupy from 50 to 80% of the volume of the samples. The pellets and peloids are dark brown, spherical, ovoid or irregular, and their diameters range from 0.05 to 0.2 mm. Commonly the pellets are connected to one another or have even been incorporated into micrite (Figure 2-2-d). It is possible that these pellets were deposited by biochemical processes as fecal pellets (Friedman and Sanders 1978). Peloids have been observed in place, which present a clear outline, like any particles deposited mechanically (Figure 2-2-c). Micrite and microcrystalline cement, whose proportion of each sample ranges from 20 to 50% by volume, are important constituents in packstones.

The pores formed between pellets and micrite are of different shapes and -sizes. The pellet packstones are characterized by two sizes of interparticle pores, one smaller, the other large than pellets. Pores of the smaller size are ordinary primary interparticle pores, but the larger pores are unusual. Individually, the larger interparticle pores look like fenestrae (Chilingar *et al.* 1967). However, the shapes- and sizes of the larger pores are variable; they are distributed randomly. These large pores are present because cementation stopped compaction of the sediments. Vugs and intraparticle pores can also be seen. Cement, constituting a little more than 15% of the rock, is mainly microcrystalline, rarely needle-form, and is transparent or semi-transparent.

This group possesses the best petrophysical properties of all samples; e.g., high porosities and the highest recovery efficiencies.

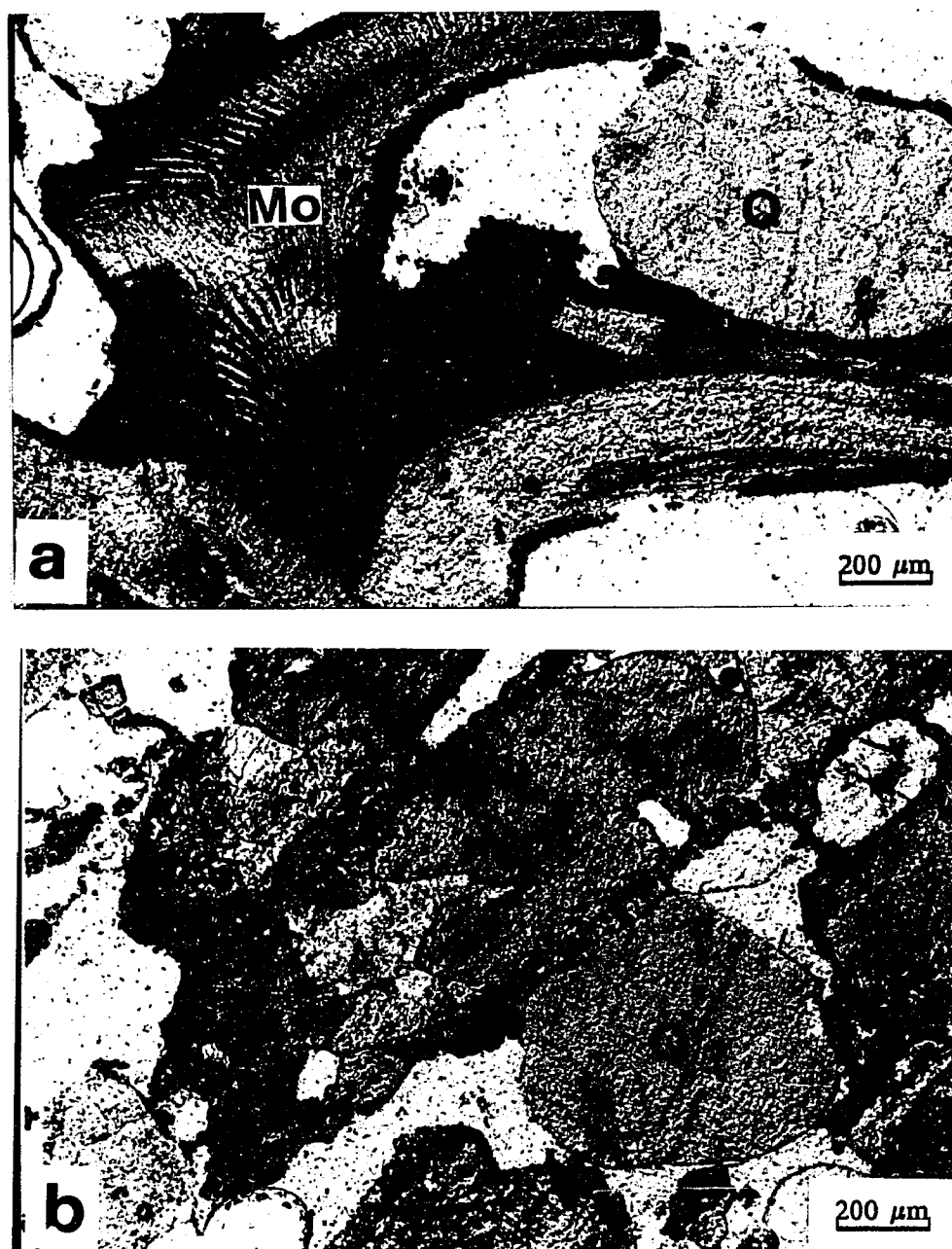


Figure 2-2. Beachrocks of Group B, C, and D. a). Skeletal beachrock from Kharube, Mediterranean. Particles include brachiopods (Br) and quartz (Q). Cement is microcrystalline high Mg-calcite (black). Note large remaining interparticle pores (white). b). Skeletal beachrock in which mollusk skeletal debris (Mo) predominates, Kharube, Mediterranean. Note oriented fabric of elongate skeletal debris in which initial porosity was small compared with Figure 2-2,a. Bladed Mg-calcite crystals on the particle surface are aligned.

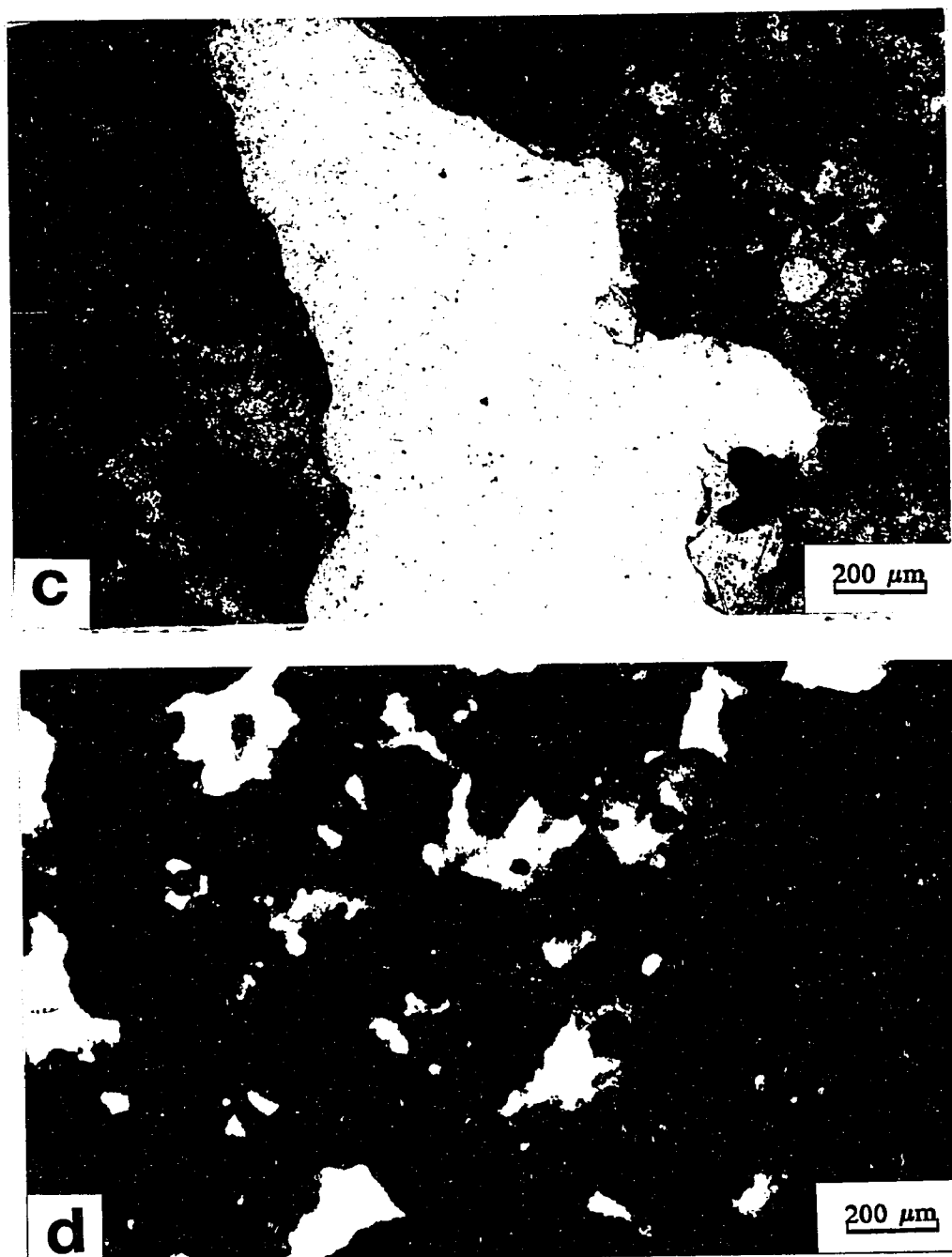


Figure 2-2. c). Peloid-packstone beachrock from the Bahamas. Spaces between peloids are filled by cryptocrystalline cement and tiny skeletal particles. White area at center is a large vug. d). Pellet-packstone beachrock from the Bahamas. Pellets, smaller than peloids in Figure 3-C, have been connected one to another or even incorporated into micrite. Note bimodality in sizes of pores. The large pores look like fenestrae. The diameters of the smaller pores are smaller than those of the pellets.

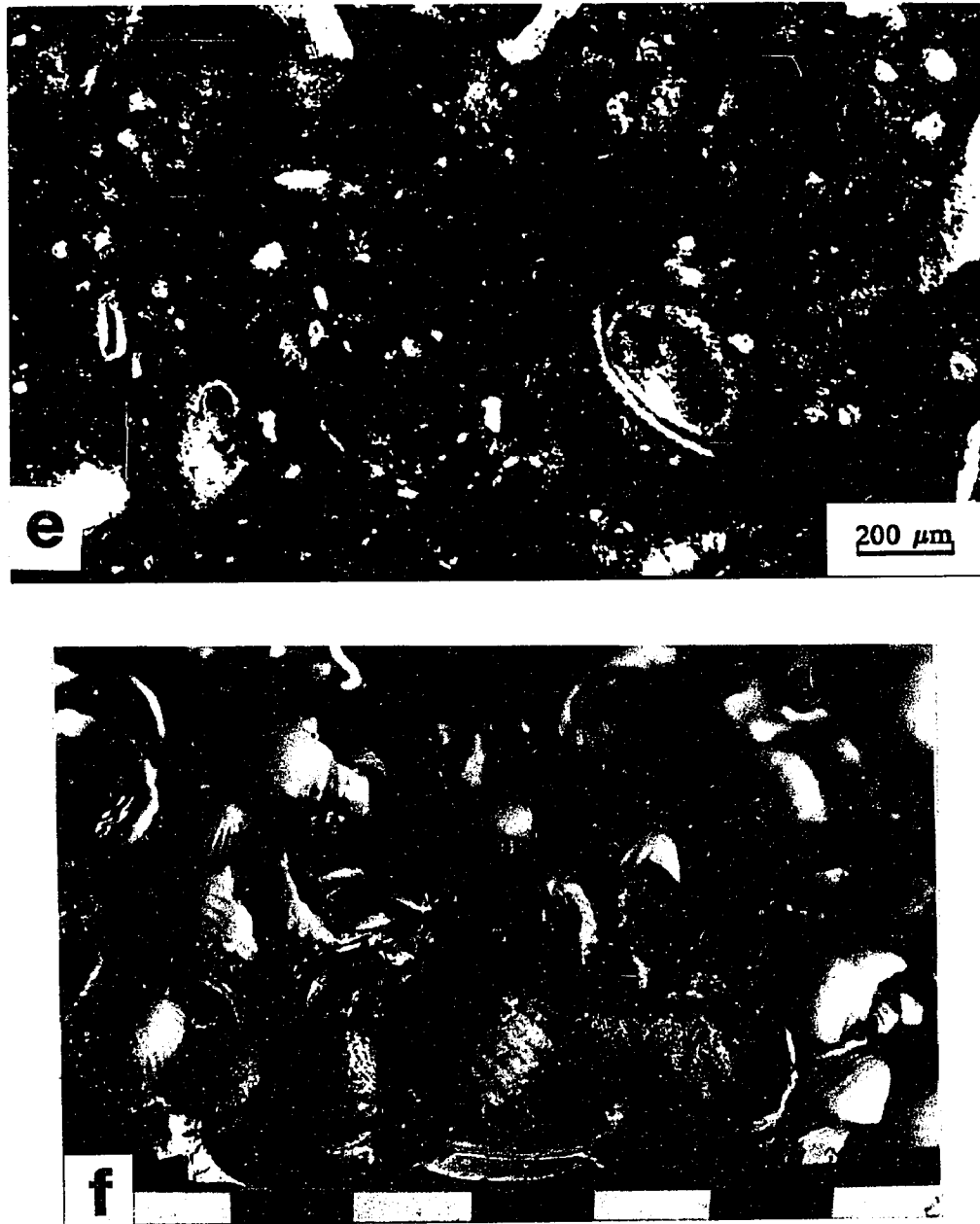


Figure 2-2. e) and f). Skeletal-peloidal dolostone beachrock from Bardawil, Mediterranean. Photomicrograph "e" shows the fine-textured particle size of sample "f" which consists of molluscan- and bryozoan debris, peloids, silt particles and micrite, cement. A few small pores are visible. Scale = 1 cm.

2.4 Group D-- Skeletal-peloidal dolostone

Four samples were collected from Bardawil, Mediterranean, from the shore of the lagoon. They are classified as dolostone because the main constituent is dolomite, although texturally, they are wackestones or packstones (Figure 2-2-e, f). Particles are mainly skeletal and/or peloidal, mixed with a little siliciclastic silt. Mollusks are the most-common skeletal constituents; bryozoans are next in abundance. Most skeletons are 1 to 2 cm in size, have not been broken, and are well sorted. Other tiny skeletons, such as mollusks and ostracods, and peloidal particles can be identified only under the microscope. Both micrite and microcrystalline cement exist between particles, which consist of dolomite based on X-ray-diffraction analysis. The cements occupy most of interparticle spaces so that primary pores are hardly seen.

2. 5. Group E-- Terrigenous Beachrock (Figure 2-5-c)

These calcipebblestones and calcisandstones were collected from the northern gulfs of the Red Sea (Gulfs of Elat and Suez) and the Great Barrier Reef of Australia. Most are light brown with reddish tints and are well consolidated; some are weakly consolidated. Terrigenous particles predominate; their diameters range from 0.4 mm to 5 mm, and they consist of rock fragments, quartz, orthoclase, microcline, and plagioclase. The rock fragments, many of which are larger than 2 mm, include quartzite, quartz sandstone, basalt, andesite, granite, granite gneiss, calcisandstone, and limestone. Calcareous skeletons are a minor constituent, ranging from 2 to 30%. They include foraminiferans, ostracodes, and bryozoans. The particles are well sorted and, because of their coatings, their shapes are sub-rounded or even rounded.

Coated particles can be seen in every thin section from the Red Sea samples,

especially on particles less than 3 mm in diameter. Most coarse particles have been thinly coated with partial concentric laminae, but on finer particles, the coatings are thick and perfect. In general, quartz particles possess more-ideal coatings than do feldspar particles. The thickness of coated layers ranges from 10 μm to 60 μm . Oolitization always begins from the concave surface of the particles. Because the concentric laminae form on the concave sides of the particles, the particles tend to be subspherical or even spherical (Figure 2-3-a, b). Every step of oolitization may be observed in thin sections (Figure 2-3-f). In these samples, the products of steps 1 (partially coated particles) and 2 (superficial ooids) are abundant.

Two types of cement are observed. The first type, which consists of aragonite, is 2- or 3-generation cement. The first generation consists of dark cryptocrystalline aragonite rimming the pores. The second generation is formed by transparent acicular aragonite that grew towards the centers of pores (Figure 2-3-b). After the acicular aragonite had been precipitated, microcrystalline vadose silt filled some residual pores (e.g., Figure 2-3-c).

The other type of cement is pelletal-cryptocrystalline in form, and is composed of high-Mg calcite. Commonly, through gradual disappearance of the pelletal texture, this type is often observed to grade into cryptocrystalline cement. In some cases, the edges of particles have been dissolved during the cement-precipitation process or were affected by the activity of boring sponges (Figure 2-3-d).

Almost all pores are primary interparticle; vugs are rare. The porosities of weakly consolidated samples range between 13.8 and 28.3%. The porosities of terrigenous beachrocks that are well consolidated range from 3.6 to 11.3%. Preserved porosity in well-consolidated beachrocks is lower for two reasons: (a) a significant amount of cement

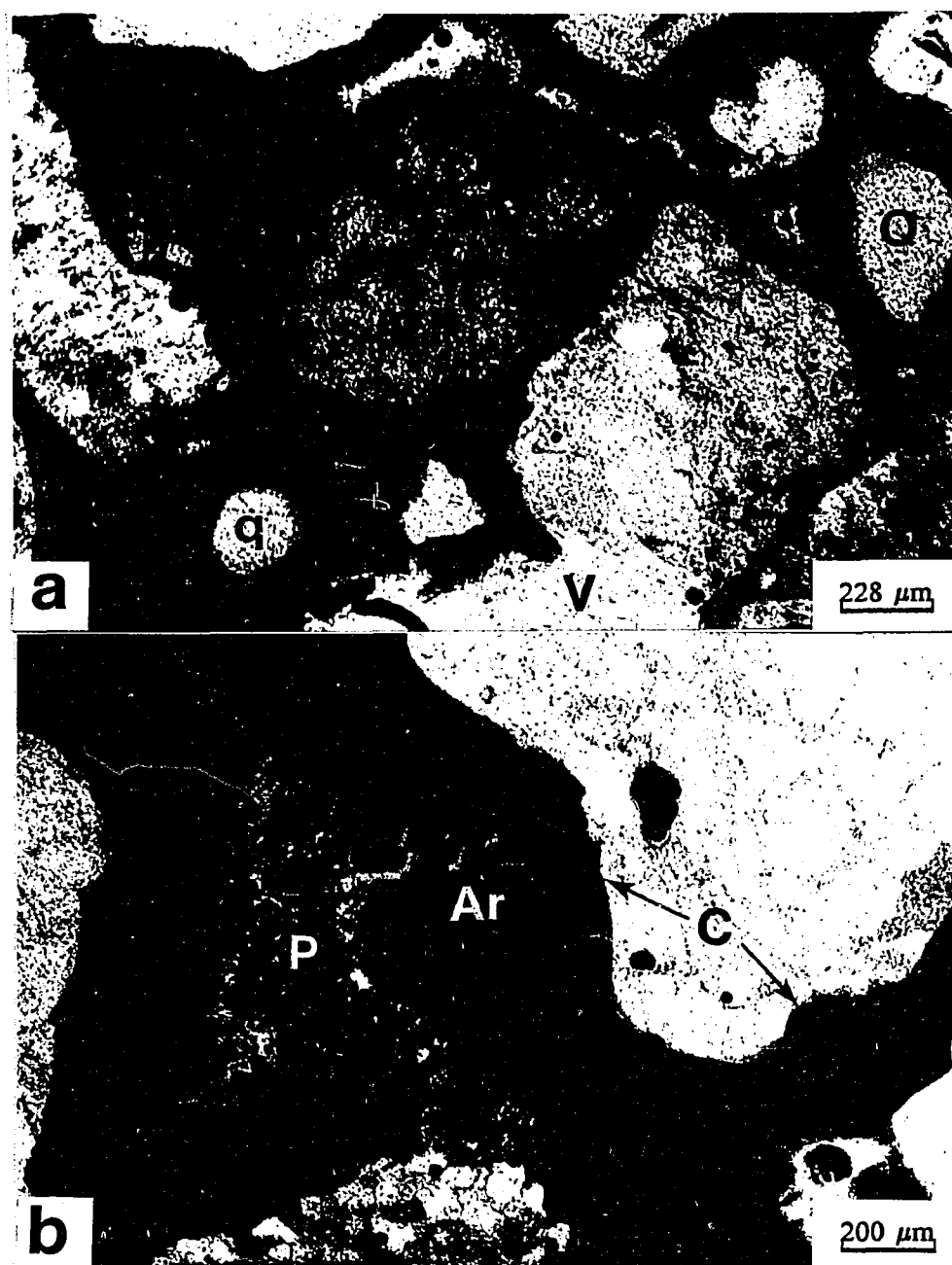


Figure 2-3. Terrigenous beachrocks, Red Sea area (a,b,c,d), *Halimeda* beachrock, southern Caribbean (e), and ooid development (f). a). Coated particles in specimen from Gulf of Suez. The coating on the quartz particle (Q) is thicker than that on the feldspar (Pl). The particle at lower left is a normal ooid with quartz nucleus (q). Two-generation cement has obliterated most of the interparticle porosity. At bottom, V is a secondary vug. b). Two-generation cement in specimen from Gulf of Elat, crossed-polarized light. The first cement is dark cryptocrystalline aragonite (Ar); the second, transparent acicular aragonite. Only a small triangular primary pore is preserved (P). Note oolitized coating (dark gray, C) has formed on the concave surface of the particle at the right top.

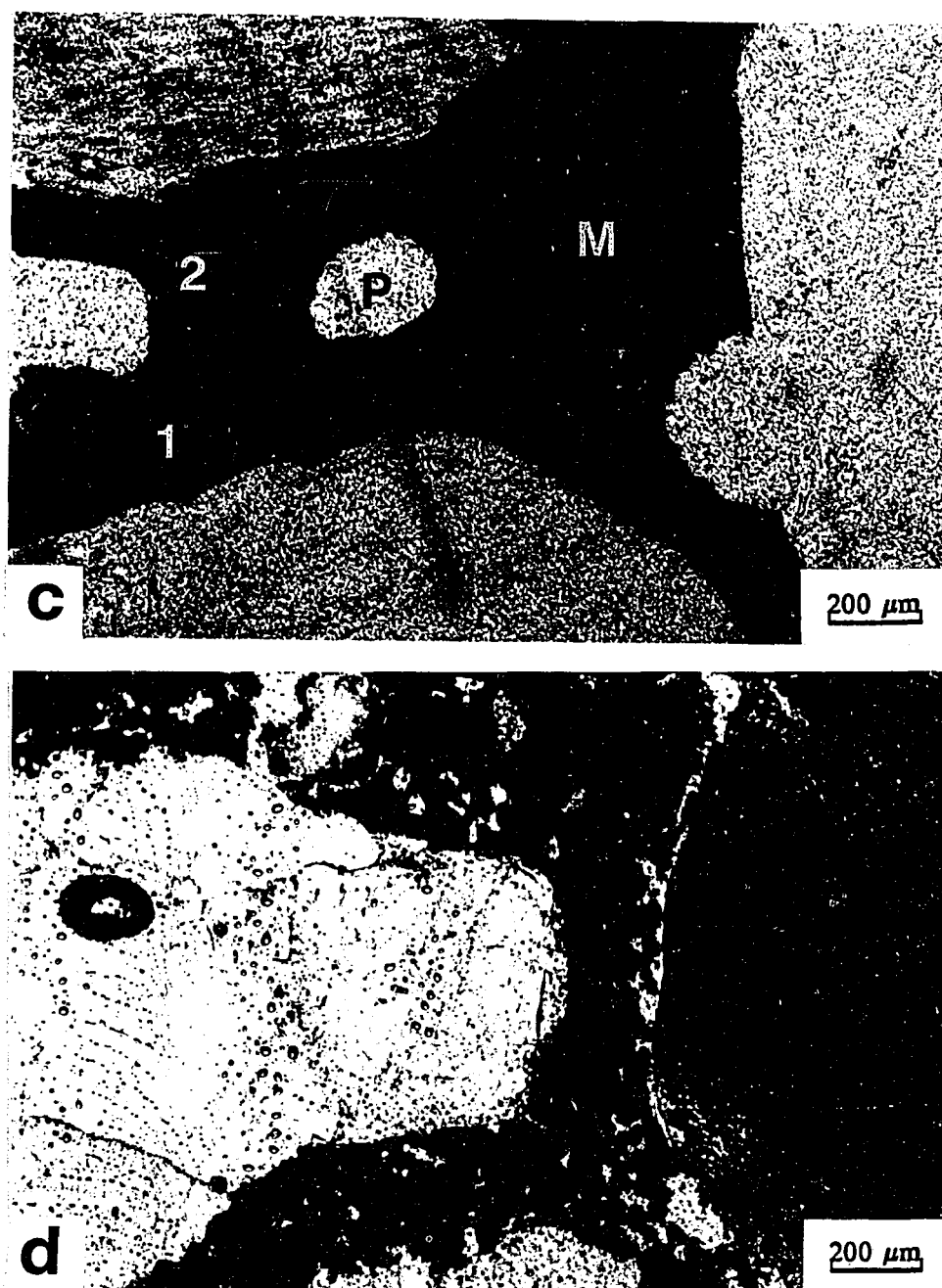
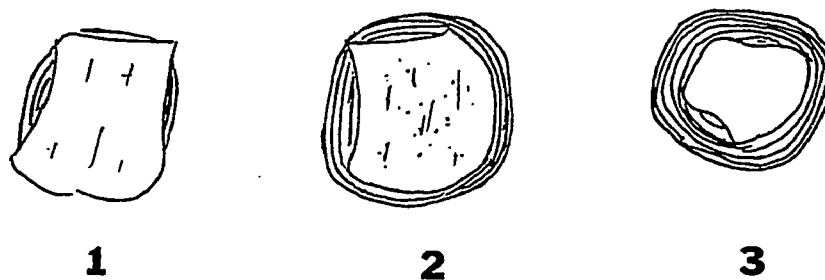


Figure 2-3. c). Two-generation cement in specimen from Gulf of Elat. After the two generations (1 and 2) of cement had formed, dark vadose silt (M) filled most of remaining pores so that only a small pore (P) is preserved. d). Pelletal-cryptocrystalline cement from Gulf of Elat. High-Mg calcite cement occupies most primary interparticle pores.



f

Figure 2-3. e). *Halimeda* grainstone beachrock from southern Caribbean. Partial section of a *Halimeda* particle, showing dark calcified plates with abundant irregular holes that were originally filled with organic matter. A large proportion of the primary porosity has been preserved. f). Sketches of the stages of oolitization. 1, partially coated particle; 2, superficial ooid; and 3, normal ooid. Further description in text.

formed in multiple generations, and (b) micrite filled most of the residual pore space.

2. 6 Group F-- *Halimeda*-grainstone

Seven samples were collected from southern Caribbean island, off the coast of Venezuela. Again, the lithologic characteristics of the samples are similar, but their petrophysical properties are different. Five of these samples form a prograding sequence from B51 (oldest), to B55 (youngest) (Table 2-2; Figure 2-4).

The particles consist mainly of the green alga, *Halimeda*, accounting for 60% (based on point counting). Coral fragments follow with 27% on the average. Red alga (possibly *Lithophyllum*), mollusks, foraminifera, and echinoderms are less common. Variable sections of *Halimeda* are perfectly preserved, as seen under the microscope (Figure 4-e). *Halimeda* debris consists of dark calcified plates with abundant irregular holes that were originally filled with organic matter; intercept areas of individual particles average 0.5 x 2 mm. Broken coral particles displaying fibrous biocrystalline texture average 0.4 mm in size.

From oldest to youngest in the prograding sequence, the quantity of cement increases and its style changes, from an early equant Mg-calcite cryptocrystalline cement, to a two-generation cement consisting of an equant cryptocrystalline cement covered by acicular aragonite rim cement. Correspondingly, porosity declines from 29.8 to 10.7% and the sizes of primary pores decrease. This significant change of porosity occurred over the course of only 225 years. Obviously, porosity in these samples is controlled by the quantity of cement.

Table 2-2 RELATIONSHIP OF CEMENT AND POROSITY TO RADIOCARBON AGE IN GROUP F

Samples	Porosity (%)	Cement (%)	Cementation	Radiocarbon age (year BP)
B51	29.8	8	Cryptocrystalline, equant high-Mg calcite	1135 $\pm$ 70
B52	20.5	10	Cryptocrystalline, equant high-Mg calcite	
B53	17.3	12	First, cryptocrystalline; second, acicular aragonite, >24 μ m	
B54	13.9	13	Same as B53	
B55	10.7	18	Similar to B53, but lengths of acicular crystals may be more than 30 μ m. Crystals extend to center of pores.	910 $\pm$ 70

From oldest to youngest, porosity and primary pores decrease; cement increases and cementation style changes from one generation to two generations.

A possible cause for increasing cementation with age is a rapid epeirogenic rise of the island. The oldest unit escaped cementation because of rapid emergence. In contrast, the younger units were kept in contact with sea water for a longer time and hence were subject to longer periods of cementation.

This sequence suggests that among all diagenetic processes affecting beachrocks, cementation is the most-significant process in reducing porosity.

In summary, based on their lithologic characteristics, I have classified beachrocks into six groups. Cementation is the most-important diagenetic process that controls porosity preservation. In the following chapter, I will present the data derived from porosimetry measurements and show how the petrographic properties control the petrophysics of the beachrocks.

Conclusion comments are interacted in Chapter 3

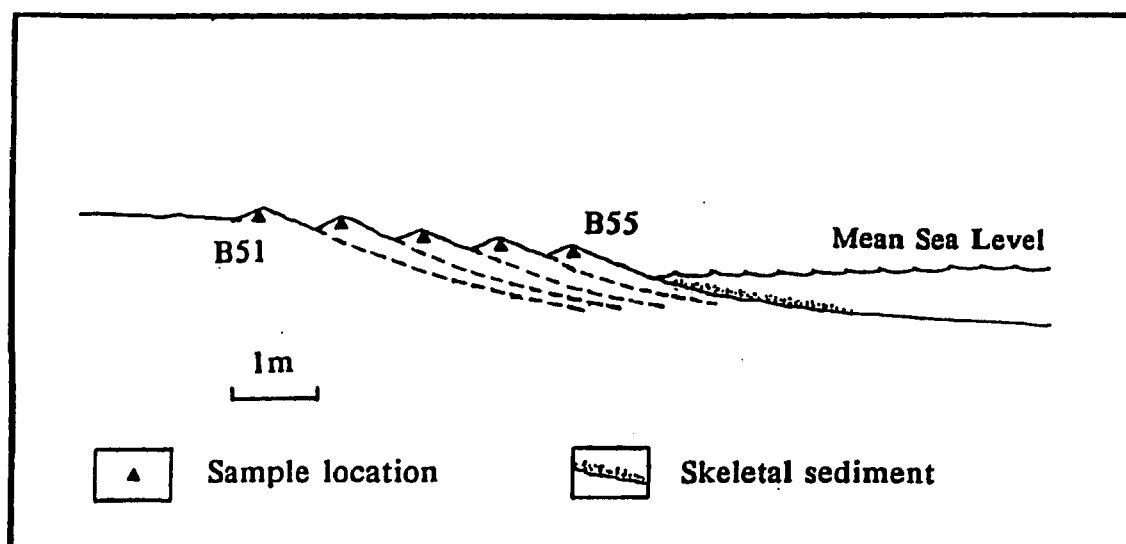


Figure 2-4. Profile sketch of *Halimeda* beachrock of prograding sequence from Francisqui Cayo, southern Caribbean. Vertical scale is exaggerated. Oldest layer (B51) is located landward and youngest (B55) seaward.

CHAPTER 3: PETROPHYSICS OF HOLOCENE BEACHROCK

Mercury porosimetry is widely used in the study of petroleum reservoirs. Data obtained through porosimetry include volume distribution of pore throats, fluid-recovery efficiency, pore-size distribution, and even oil-column height and permeability (e.g., Purcell 1949, Dullien and Dhawan 1974, Schowalter 1979, Wardlaw 1980, Friedman *et al.* 1981, Jennings 1987, Etris *et al.* 1988, Kopaska-Merkel and Amthor 1988, Wardlaw *et al.* 1988, Friedman *et al.* 1990). Some authors have found that petrophysical parameters and lithology are related. They have attempted to derive petrophysical classifications related to petrography (Ghosh and Friedman 1989).

Some petrofacies (petrophysical facies) have been classified based on mercury-porosimetry analysis and interacted with lithologic information (Kopaska-Merkel and Friedman 1989). Kopaska-Merkel and Friedman have mapped subsurface units using petrofacies that could predict the distribution of reservoir- and seal units. Hence, in the evaluation of reservoir units petrofacies study is an important technique.

On the basis of previous studies, the same lithofacies may belong to different petrofacies because petrofacies rely largely on diagenesis which has changed depositional petrophysical properties of sediments. Accordingly, some questions will be raised: How do petrophysical properties relate to different kinds of original sediments before they were buried? How does diagenesis affect changing pore systems? I hoped that the study of petrophysics of modern cemented rock would provide answers to these questions.

I chose Holocene beachrock as a study objective of petrophysics because beachrock represents the first step in the transition from unconsolidated sediment to lithified rock. Beachrocks have not been subjected burial diagenesis; their primary pore system are much better preserved than are those of ancient rocks. The relationship

between the petrophysical properties and lithology of beachrock should actually prove to be more straightforward than that of ancient rocks. It is important to establish modern petrofacies of carbonate rocks, such as beachrocks, which could be used to compare with the petrofacies of ancient carbonate reservoir unit.

Many important petrophysical parameters of reservoirs related to their pore systems are derived from porosimetry. Of these parameters, porosity, recovery efficiency (RE), median throat size, normalized throat size, and kind of capillary-pressure curve are regarded as the most significant (Amthor *et al.* 1988, Ghosh and Friedman 1989, Jennings 1987, Kopaska-Merkel and Amthor 1988, Kopaska-Merkel and Friedman 1989, Wardlaw 1976, Wardlaw and McKellar 1981, Wardlaw *et al.* 1988).

3.1 Porosity

The porosity of the beachrocks varies greatly from one group to another. Even among samples collected from the same area and of the same lithology, significant differences in porosity exist. I attempted to discover what porosities characterize beachrocks, how many porosity ranges and what kinds of pores exist, as well as how lithological properties control the porosity of beachrocks.

From Table 3-1 and Figure 3-3-a, I know that Group--A (oolitic grainstone) possesses the highest average porosity of all groups, 24.2%. The porosity of Group--C (pellet packstone) is 22.7%; followed by Group--B (skeletal grainstone), 17.8%; Group--F (*Halimeda* grainstone), 17.2%; Group--E (terrigenous beachrock), 12.1%. The least-porous group is Group--D (dolostone); on the average, its porosity is only 4.2%.

Factors Controlling the Porosity of Beachrock: The porosities of the sediment matrix, the sedimentary environment, and diagenetic processes affect the pore systems of rocks.

Table 3-1 **PETROPHYSICAL DATA OF BEACHROCKS**

Group	Porosity (%)	Recovery efficiency (%)	Median throat size (microns)	Normalized throat size	Numbers of sample
A	$\frac{24.22}{15.52-37.69}$	$\frac{21.30}{7.91-42.67}$	$\frac{15.69}{0.47-33.17}$	$\frac{6.19}{0.9-50.60}$	13
B	$\frac{17.79}{7.01-23.34}$	$\frac{20.48}{4.20-35.80}$	$\frac{12.37}{2.59-19.16}$	$\frac{2.81}{1.88-4.13}$	7
C	$\frac{22.72}{18.63-26.20}$	$\frac{42.71}{28.20-56.30}$	$\frac{1.7}{0.14-6.38}$	$\frac{6.12}{0.68-15.52}$	8
D	$\frac{4.16}{3.07-5.35}$	$\frac{9.66}{3.23-15.71}$	$\frac{0.01}{0.01-0.015}$	$\frac{65.14}{12.40-202.4}$	4
E	$\frac{12.11}{3.63-26.94}$	$\frac{20.98}{9.52-36.08}$	$\frac{7.45}{0.15-26.95}$	$\frac{15.96}{1.64-99.47}$	12
F	$\frac{17.19}{10.70-29.75}$	$\frac{29.32}{11.88-63.83}$	$\frac{11.35}{0.48-26.81}$	$\frac{2.96}{1.25-5.83}$	7
*	$\frac{24.22}{15.52-37.69}$	$\frac{\text{average}}{\text{minimum-maximum}}$			

Compared with other grainstones, the largest primary interparticle pores have been preserved in oolites because of their high particle sphericities and good sorting. In pellet packstones, two kinds of primary interparticle pores are present. One is smaller than the pellets, whereas the other, which formed between micrite particles and/or pellets, is larger than the pellets. These large pores resemble fenestral pores, and are responsible for the high porosities of the wackestones, which are greater than the porosities of the grainstones studied. Terrigenous beachrocks are less well sorted and initially packed tightly. Therefore, they have retained lower porosities. In summary: shape, size, sorting

of sedimentary particles, and their arrangement or packing style determined the primary porosity. The primary pores created by the deposition of sediments are the predominant pore type in beachrocks.

Sedimentary environments control the properties of sediments, including those found in beachrocks. For example, every sedimentary realm contains a predominant particle type. Further, samples of a single lithology collected from areas with differing sedimentary environments may possess different porosities (e.g., terrigenous Group, Figure 3-1-c) - the porosity of sandstones from the Gulf of Suez is much greater than that of those from the Gulf of Elat although both gulfs are northern extensions of the Red Sea. Finally, consider the dolostone of Group D. This rock formed in an unusual environment near a sea-marginal lagoon. As a result of dolomitization, the porosity of this beachrock is very low.

Diagenesis is an important controlling factor for porosity. The beachrocks described here were consolidated principally by cementation. The effects of compaction were negligible. The oolitic group (Group A) illustrates how porosity is controlled by cementation (Figure 3-1-b). Rocks with high porosities (generally more than 25%), are weakly cemented with discontinuous fringe- and/or meniscus cement. Well-cemented rocks with continuous pore-rimming and/or two-generation cement are less porous (porosity commonly less than 20%). Consequently, as cement increases, porosity decreases.

Dissolution or boring was a significant factor locally, as in a sample from the Bahamas, whose porosity is the highest of all samples described here. In this rock, vugs are the dominant pores and primary interparticle pores are less important.

Similarly, on the basis of consolidation, the terrigenous beachrock group (Group E) can also be subdivided into subgroups. One subgroup, showing less porosity, has

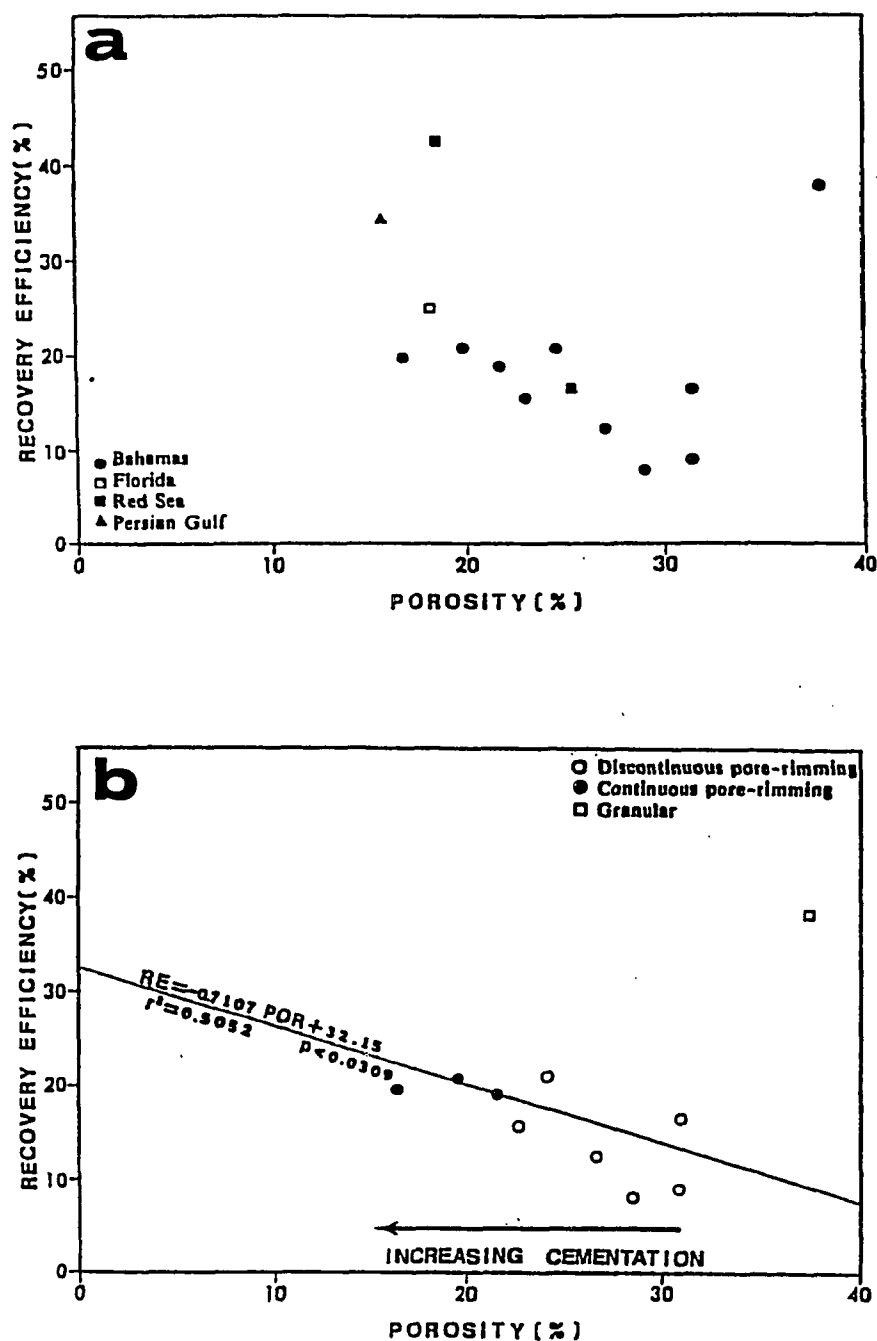


Figure 3-1. Graphs of recovery efficiency (RE) vs. porosity. a). 14 samples of group A are from Bahamas, Florida, Red Sea, and Persian Gulf. Porosity is inversely proportional to RE. b). Bahamas oolitic beachrocks. Graph shows discontinuous pore-rimming cement, continuous pore-rimming cement, granular cement. The line and formula in the graph express the multiple-regression results. Porosity is related to cement type.

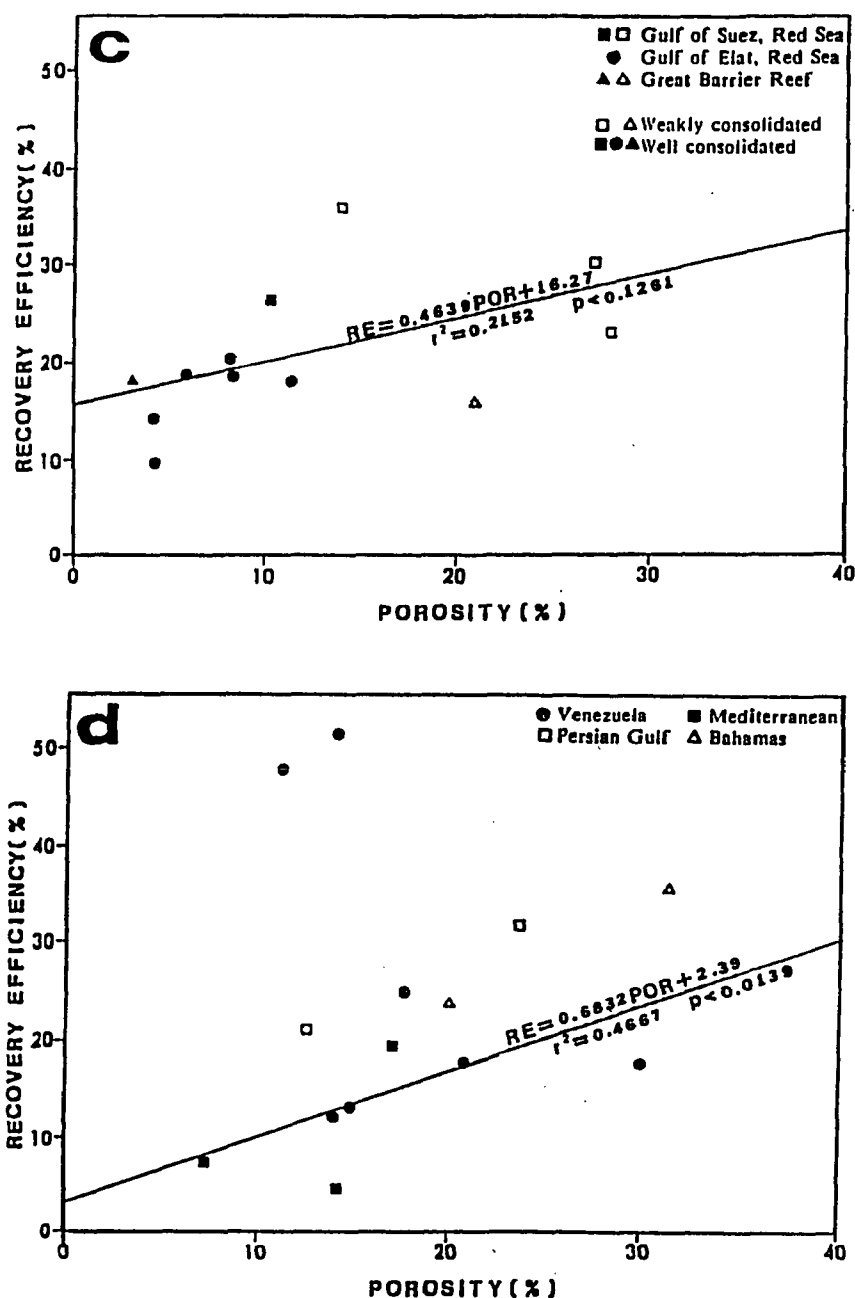


Figure 3-1. Graphs of recovery efficiency(RE) vs. porosity. c). Group E--terrigenous beachrock. Samples are from Gulf of Suez, Red Sea, the Great Barrier Reef, and the Gulf of Elat, Red Sea. The graph shows that petrophysical properties are controlled by the degree of consolidation or cementation. The well-consolidated samples with more cement exhibit smaller porosity and RE. Porosity is a positively related to RE (based on multiple-regression statistics). d). Group B and Group F. Samples are from southern Caribbean (Venezuela), Mediterranean, Persian Gulf, and the Bahamas. These samples are all grainstones, but display divergent porosities and recovery efficiencies, because they are of a different particle type and texture, and originated in different areas. RE and porosity are positively related.

Table 3-2 RELATIONSHIPS AMONG PETROPHYSICAL PARAMETERS OF BEACHROCKS

Group	Parameters	Recovery efficiency	Median throat size	Normalized throat size
A	Porosity	-	+	
B		+	-	
C		+	-	
D		+	?	
E		+	?	
F		-	?	
Total		+	+	
A	Recovery efficiency		-	?
B			-	?
C			-	-
D			-	?
E			?	-
F			-	?
Total			-	-

+ represents positive relationship

- mean inverse relationship

? relationships are not clear

been well consolidated; it contains two- or three generations of cement. The other, which is much more porous, is weakly consolidated and contains little cement (Figure 3-1-c).

Porosity Related to other Petrophysical Parameters (Table 5): Data on the relationship of porosity to recovery efficiency from research on reservoir rocks are divergent (Wardlaw and Taylor 1976, Wardlaw 1976 and 1980, Amthor *et al.* 1988, Kopaska-Merkel and Friedman 1989). In this study, porosity is roughly proportional to recovery efficiency (RE) for all samples (Figure 3-2-b). Correspondingly, on the bivariate graph of porosity versus RE, most groups show a positive relationship (Figure 3-1-c, d, 3-3-a), but Group A (oolite grainstone, Figure 3-1-a) and Group F (*Halimeda* grainstone) does not. Although Wardlaw (1976 and 1980) explained the changing relationship

between porosity and RE by different pore geometry, it is not clear whether this interpretation is valid for these beachrocks.

Considered as a whole, a positive relationship between porosity and median throat size exists for all samples (Figure 7-b). However, groups B and C display a negative relationship, and groups D, E and F show no clear relationship between porosity and median throat size.

3.2 Recovery efficiency

Recovery efficiency (RE) is the percentage of trapped hydrocarbons which may be withdrawn from a reservoir rock under a particular set of conditions. In mercury porosimetry, RE is the percentage or fraction of mercury intruded at maximum pressure which is extruded during pressure reduction to final minimum pressure (14-15 psia or atmospheric pressure)

The mean recovery efficiency of each group is shown in Table 3-1. The RE values of the packstone group are the highest. The *Halimeda* grainstone group is next. Groups A, B, and E yielded similar RE values. Group D (dolostone) had the lowest RE values. This can also be seen from Figure 3-3-a.

Clearly, recovery efficiency is inversely proportional to median pore-throat size both for each group and for all samples (Figure 3-3-b & 3-2-c). The data are consistent with previous work (Wardlaw 1976, Amthor *et al.* 1988, Kopaska-Merkel and Friedman 1989).

3.3 Median throat size

In order from largest to smallest median throat size, the groups are: A, B, F, E, C, and D. Group D is an exception to the general trend, having both low RE values and small median throats; the RE values of group C are the highest.

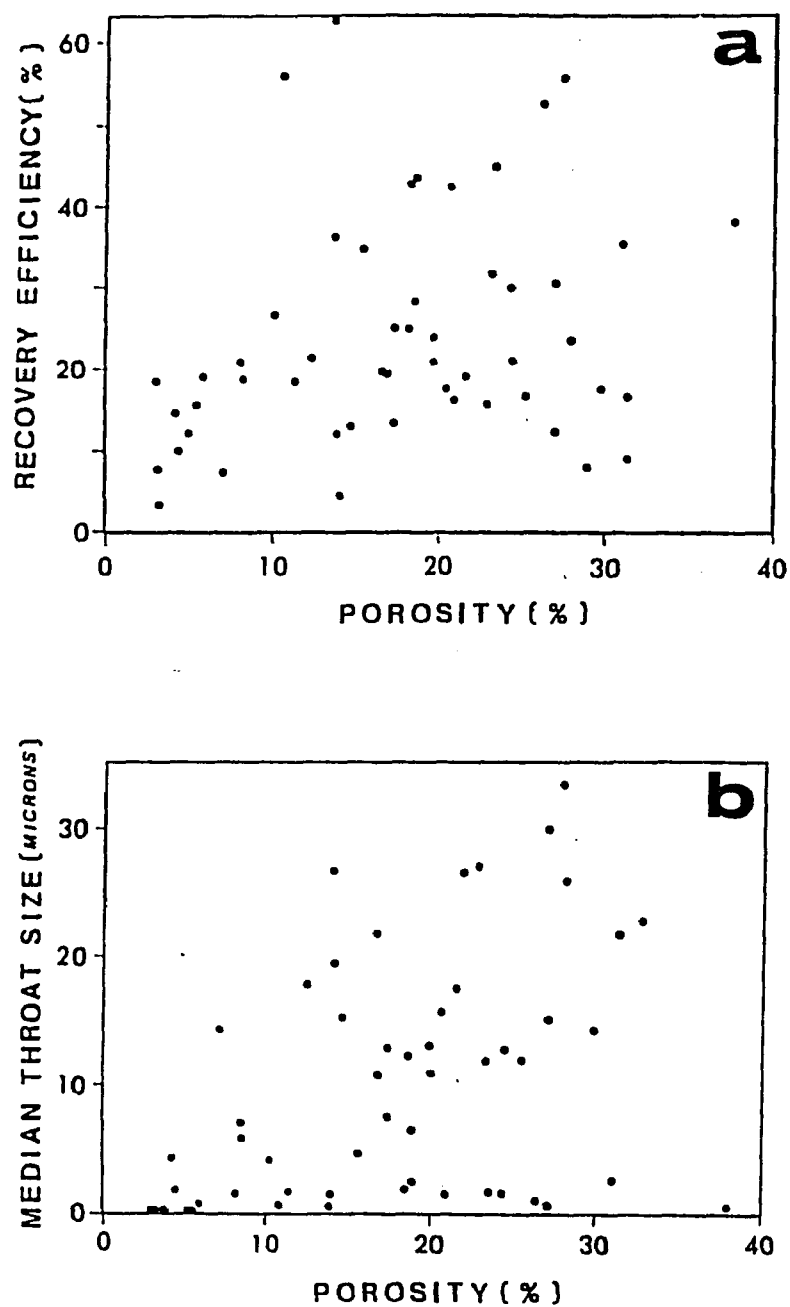


Figure 3-2. Bivariate plot of all studied beachrock samples. a). Bivariate plot of recovery efficiency versus porosity; a weak positive relationship is indicated between RE and porosity. b). Bivariate plot of median throat size versus porosity shows an approximate positive relationship between them.

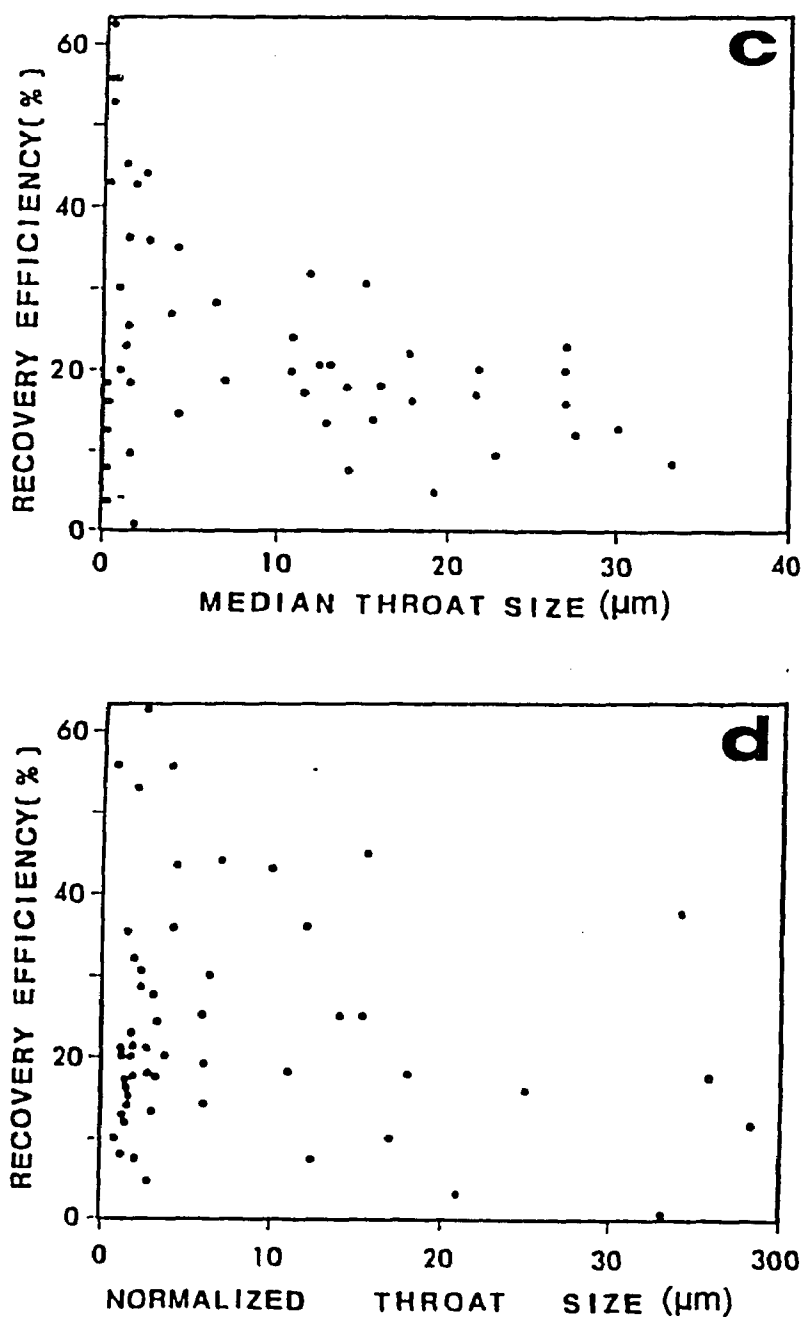


Figure 3-2. Bivariate plot of all studied beachrock samples. c) Bivariate plot of recovery efficiency versus median throat size. An obvious inverse relationship exists between them. d). Bivariate plot of recovery efficiency versus normalized throat size; a weak inverse relationship exists between RE and normalized throat size. Note that the normalized throat size of most samples is less than 10.

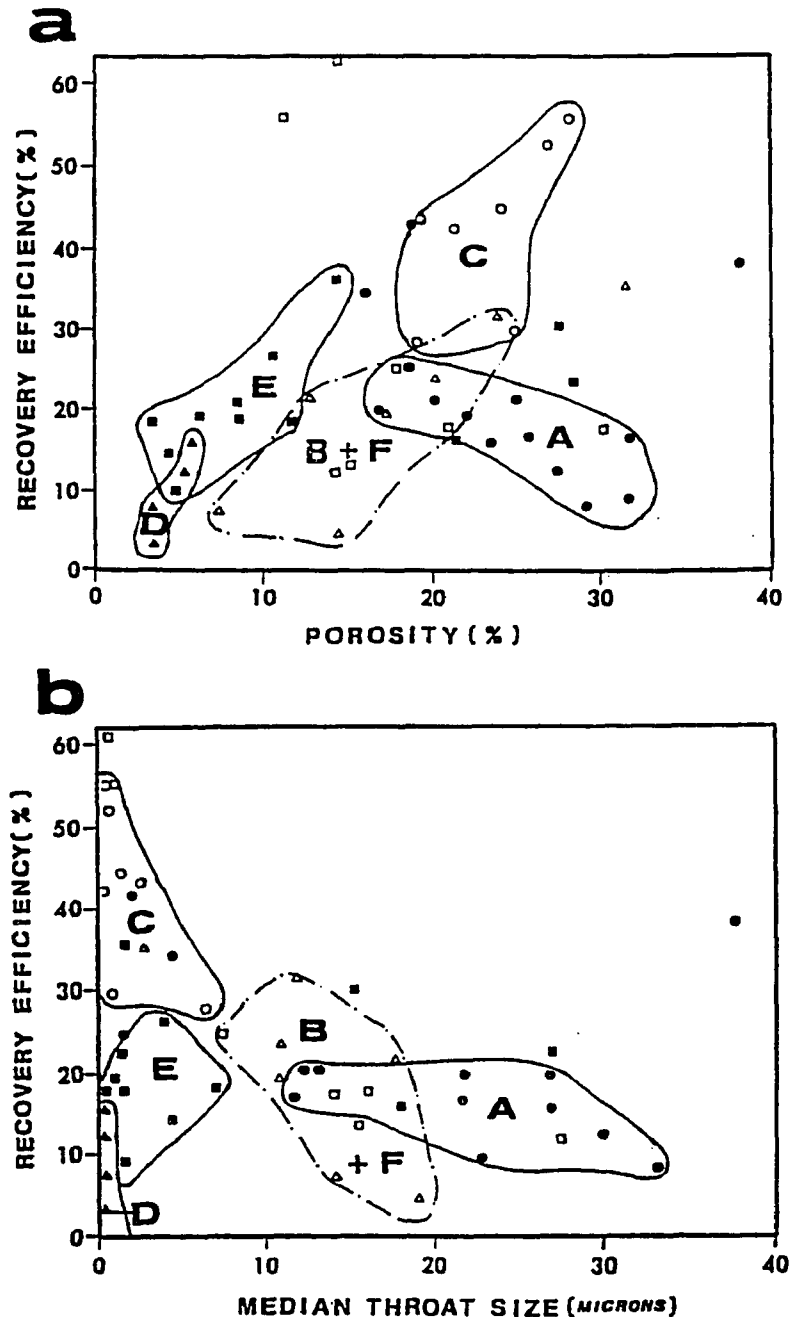


Figure 3-3. Bivariate plots of (a) recovery efficiency and porosity, and (b) recovery efficiency and median throat size for beachrocks of five different kinds of petrographic and petrophysical characteristics, as follows: Group A (oolitic grainstone petrofacies from Bahamas, Red Sea and Persian Gulf), Group B and F (skeletal-grainstone petrofacies from Mediterranean and southern Caribbean, Venezuela), Group C (pelletal packstone petrofacies, Bahamas), Group D (dolostone petrofacies, Mediterranean lagoon), and Group E (carbonate-cemented terrigenous petrofacies, Red Sea). Filled circle--Group A, open circle--Group C, filled square--Group E, open square--Group F, open triangle--Group B, filled triangle--Group D. Note that, in both plots, groups A, C and E are distinct from one another, whereas groups D and B+F overlap other groups.

Table 3-3 CATEGORIES OF CAPILLARY-PRESSURE CURVES OF THE BEACHROCKS

Curve type	Porosity	Recovery efficiency	Median throat size	Normalized throat size	Low-pressure intrusion	High-pressure intrusion
Concave	a High	Low	Large	Low	Large	Small
	b					
	c Moderate	Moderate	Moderate		Moderate	Moderate
Convex	Low	Low	Very low	High	Low	Moderate
Gently sloping	Low	Low	Low	Moderate --high	Low --->	Moderate
Inter-mediate	High	High	Low	Low	Low	High
Polymodal	Variable					

3.4 Normalized throat size

Many previous workers paid much attention to the sorting of throat size and took it to exert a strong affect on recovery efficiency. Normalized throat size represents throat-size sorting (Wardlaw *et al.* 1988, Kopaska-Merkel and Friedman 1989).

Normalized throat size

$$= \frac{(\text{throat size } 20\% - \text{throat size } 80\%) \text{ mercury saturation}}{\text{Throat size at } 50\% \text{ mercury saturation}^*}$$

* throat size 20% means the throat size that is measured from the incremental capillary-pressure curve when 20% of the maximum intrusion volume has occurred.

Figure 3-2-d and Table 3-1 present the characteristics of normalized throat size in the beachrocks. First, the average values of each group are very different and therefore,

they are separated widely on Figure 3-2-d. Second, a general inverse relationship exists between RE and normalized throat size for all samples. This relationship is not clear within individual groups because values for normalized throat size among the samples of each group are similar.

3.5 Capillary-pressure curves

Five kinds of capillary-pressure curves are classified (Table 3-3). This classification is derived from that of Amthor *et al.* (1988), but with two important differences. First, convex curves are associated with low RE values. The extrusion curves are not subparallel to intrusion curves for this convex capillary-pressure curves. So, this kind of curve is different from any documented by Amthor *et al.* (1988). Second, I found a series of concave curves that can be subdivided into three sub-categories based on the shapes of the curves and the intrusion volumes under high pressure. The distribution of each kind of capillary-pressure curve in each group of beachrock is shown in Table 3-4.

(1) *Concave Curves*: Most samples of groups A, B, and F, and one samples of group E, 28 in all, yield concave curves (Table 7). Compared with other curves, concave curves coincide with higher porosities, moderate recovery efficiencies, higher intrusion under low pressure and low- to moderate intrusion at high pressure. According to the shapes of incremental curves and the amounts of intrusion at high pressure, three sub-categories of concave curves are recognized (Figure 3-4-a, b, c.).

Concave "a" curves are steep and indicate little intrusion at high pressure. Samples with concave "a" curves possess larger median throats and lower recovery efficiencies compared to samples with concave "c" curves. The slope of concave "c"

curves are gentle and indicate moderate intrusion under high pressure. Thus the median throats of samples having concave "c" curves are smaller, and their RE values are higher. Concave "b" curves are intermediate.

This classification corresponds well to petrographic information. The samples of Group A in which the cement is discontinuous (such as sample B36) yield curves of sub-category concave "a". As the amount of cement increases (one- or two-generation continuous pore-rimming), and porosity and median throat size decrease, concave "a" curves are replaced by concave "b" or, even concave "c" curves.

Table 3-4 NUMBER OF CAPILLARY-PRESSURE CURVES OF EACH KIND IN EACH GROUP OF THE BEACHROCKS

Group	a	Concave b	c	Convex	Gently sloping	Inter- mediate	Polymodal
A	3	4	5				2
B	1	5	1				
C		1	1			2	3
D				4			
E			1		7		4
F		2	4				1
Subtotal	4	12	12				
Total		28		4	7	2	10

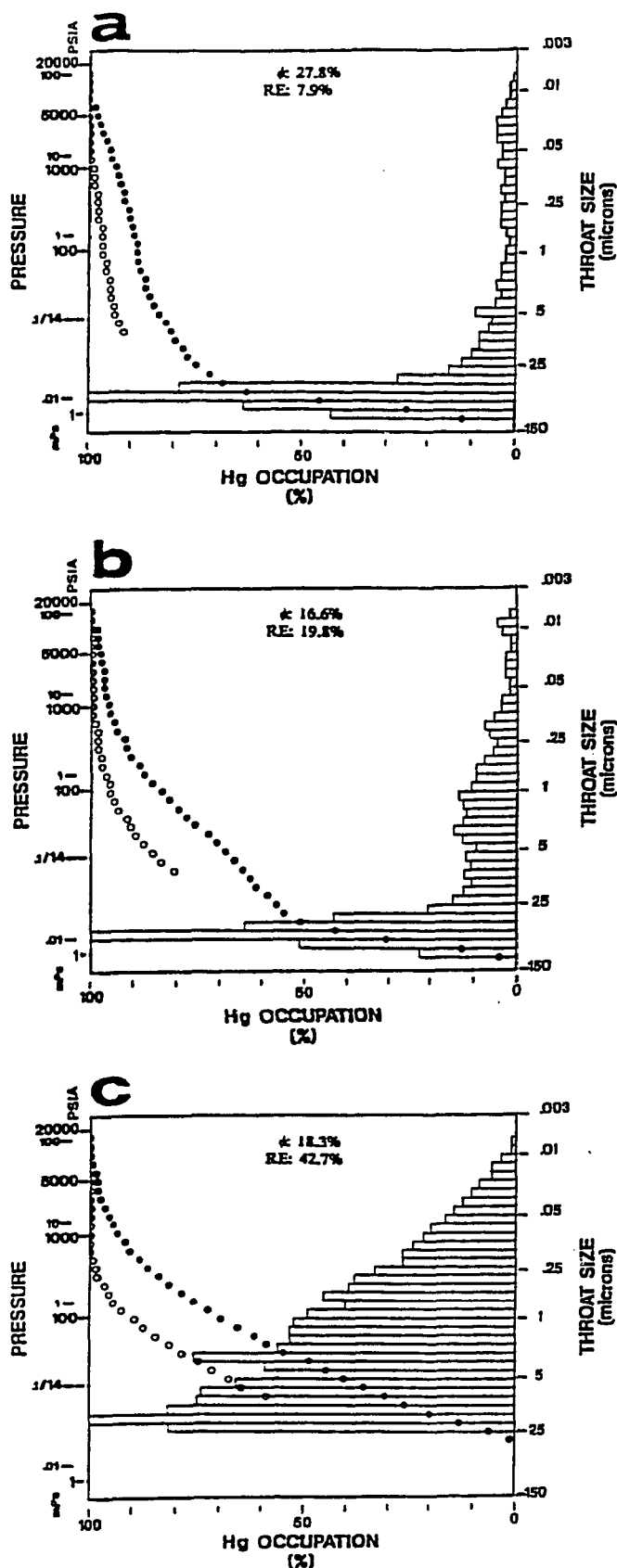


Figure 3-4

A series of concave capillary-pressure curves for oolitic grainstone (Group A). Filled circles represent cumulative mercury intrusion curve; open circles represent extrusion; open bars of histogram show incremental intrusion. ϕ : porosity; RE: recovery efficiency.

a). Graph for Bahamas oolitic beachrock. Note steep slope of curve and small RE. At high pressures, only a little mercury has been intruded. The samples with this kind of capillary-pressure curves contains discontinuous pore-rimming cement.

b). Graph for Bahamas oolitic beachrock. Note decreasing slope, more intrusion at high pressure and larger RE compared with figure 9-a. The samples present thin continuous pore-rimming cement.

c). Graph for Red Sea oolitic beachrock from Gulf of Suez. Note gently sloping intrusion curve. Compared with Figures 3-4-a and 3-4-b, it presents the largest intrusion at high pressure and the largest RE. The samples possess two-generation continuous pore-rimming cement.

(2) *Convex curves (Figure 3-5-a)*: Only four samples of Group D show convex curves and they are from Bardawil, Mediterranean. The porosities- and recovery efficiencies of these samples are low; median throat sizes are small. Their normalized throat sizes are large. These convex curves differ from those of Amthor *et al* (1988).

(3) *Gently sloping curves (Figure 3-5-b)*: I have seven samples with gently sloping curves, which are from Group E (terrigenous beachrocks). They are characterized by low porosities, low RE values, and small median throats but moderate- to high normalized throats.

(4) *Intermediate curves (Figure 3-5-c)*: Only two samples, pellet packstones of Group C from the Bahamas, are assigned to this type. They are characterized by good "sorting" of throat size and a leptokurtic throat-size distribution. They keep high RE values, relatively high porosities, small median throats and small normalized throats. This is the "ideal" curve for reservoir rocks.

(5) *Bimodal- and polymodal curves (Figure 3-5-d)*: Ten samples in groups E, C, A, and F belong to the bimodal- or polymodal types. Actually, the curves of many of these samples are intermediate between concave- and typical polymodal curves. Their throat-size distribution shows more than one peak and their cumulative curves are more or less "S"-shaped. The samples with polymodal curves present variable petrophysical characteristics, which often depend on what group they belong to.

In summary, the shapes of the incremental- and cumulative-intrusion curves for each group of beachrocks are characteristic. Most samples of groups A, B, F (all grainstones but with different particle types) are concave. Group D yields special, convex curves. Most of the curves of Group E are gently sloping, although a few samples yield polymodal curves. Group C curves are intermediate and polymodal (Table 3-4).

3.6 Discussion and conclusion

Although the petrophysical characteristics of the beachrocks vary, the lithologic- and petrophysical properties are related. First, I found that the petrophysical parameters of each group are distinct from those of the others (Table 3-1). Second, on bivariate graphs, samples collected from the same environment (or realm) and of similar lithologic nature plot close to one another (Figure 3-3-a, b). On these graphs, samples of group A, C, and E always occupy different areas although group D and groups B + F overlap with others. Finally, each group possesses its own specific type of capillary-pressure curve (Table 3-4). These findings uphold the conclusion that environment and lithologic characteristics exert substantial control on petrophysical properties; diagenesis is a secondary, but quite important factor.

Because the lithologic characteristics- and petrophysical properties of samples from a single group are similar, they may be assigned to a common petrofacies (Kopaska-Merkel and Friedman 1989). Groups B and F exhibit similarity in characteristics (Table 3-1, Figures 3-3-a, b) such that it is appropriate to merge them into a single petrofacies. Hence, among the samples studied, five petrofacies are recognized (Table 3-5).

Petrofacies can be distinguished by both the kinds of capillary-pressure curves and the bivariable plots of petrophysical parameters (Table 3-5 and Figure 3-3). Oolitic- and skeletal grainstone petrofacies present concave curves; packstone petrofacies, intermediate and polymodal; dolostone petrofacies, convex curves; terrigenous beachrock petrofacies, gently sloping and polymodal curves.

A few samples are not inclosed in the area of the groups on the Figure 3-3, that these sample should belong to, this has resulted from the different localities of sampling

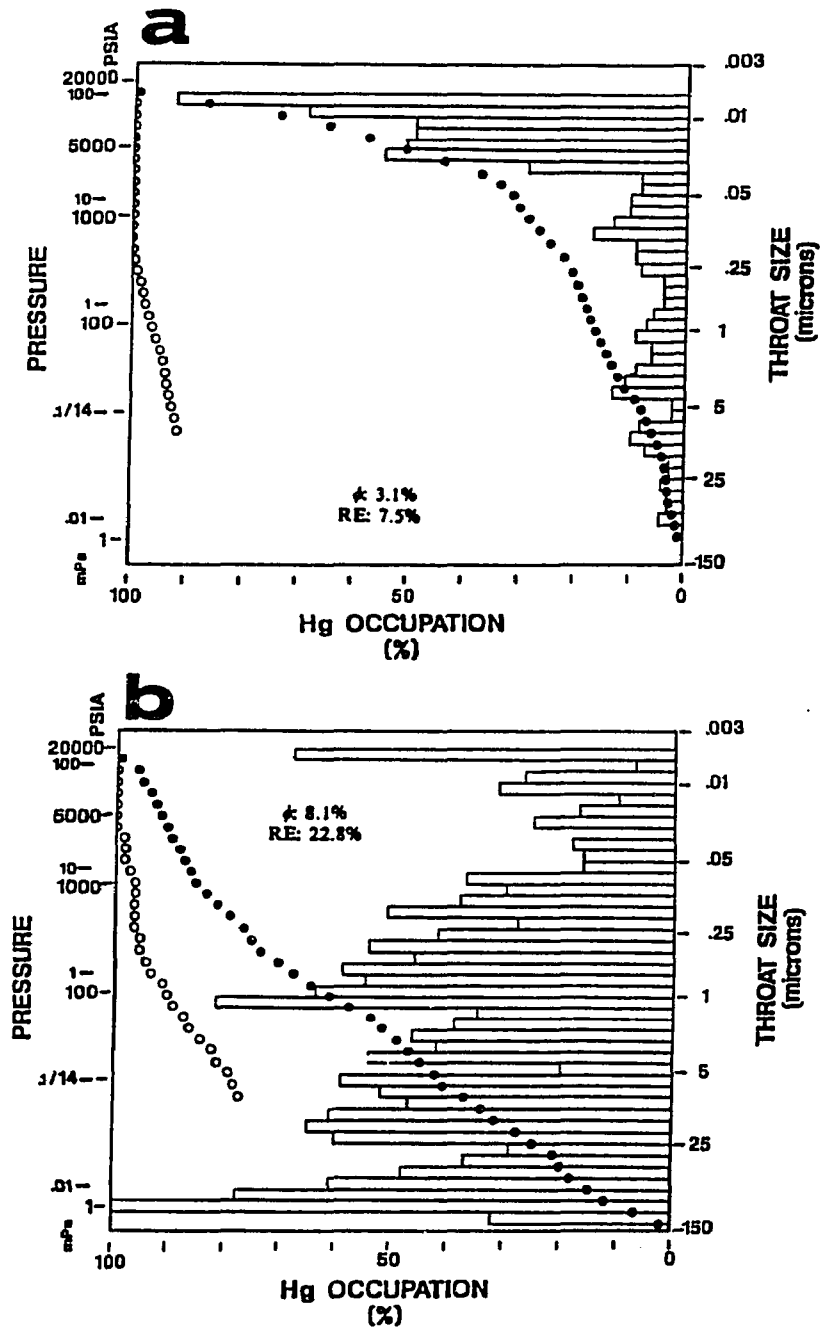


Figure 3-5. Capillary-pressure curves. Filled circles represent cumulative mercury intrusion; open circles extrusion; open bars of histogram are incremental intrusion. ϕ : porosity; RE: recovery efficiency. a). Convex capillary-pressure curve of dolostone (Group D) from eastern Mediterranean. Graph shows low recovery efficiency and much more intrusion under high pressure than under low pressure. b). Gently sloping capillary-pressure curves of carbonate-cemented beachrock whose particles are mostly terrigenous (Group E) from Gulf of Elat, Red Sea. A similar quantity of intrusion occurred at both high- and low pressure. The RE and porosity are low.

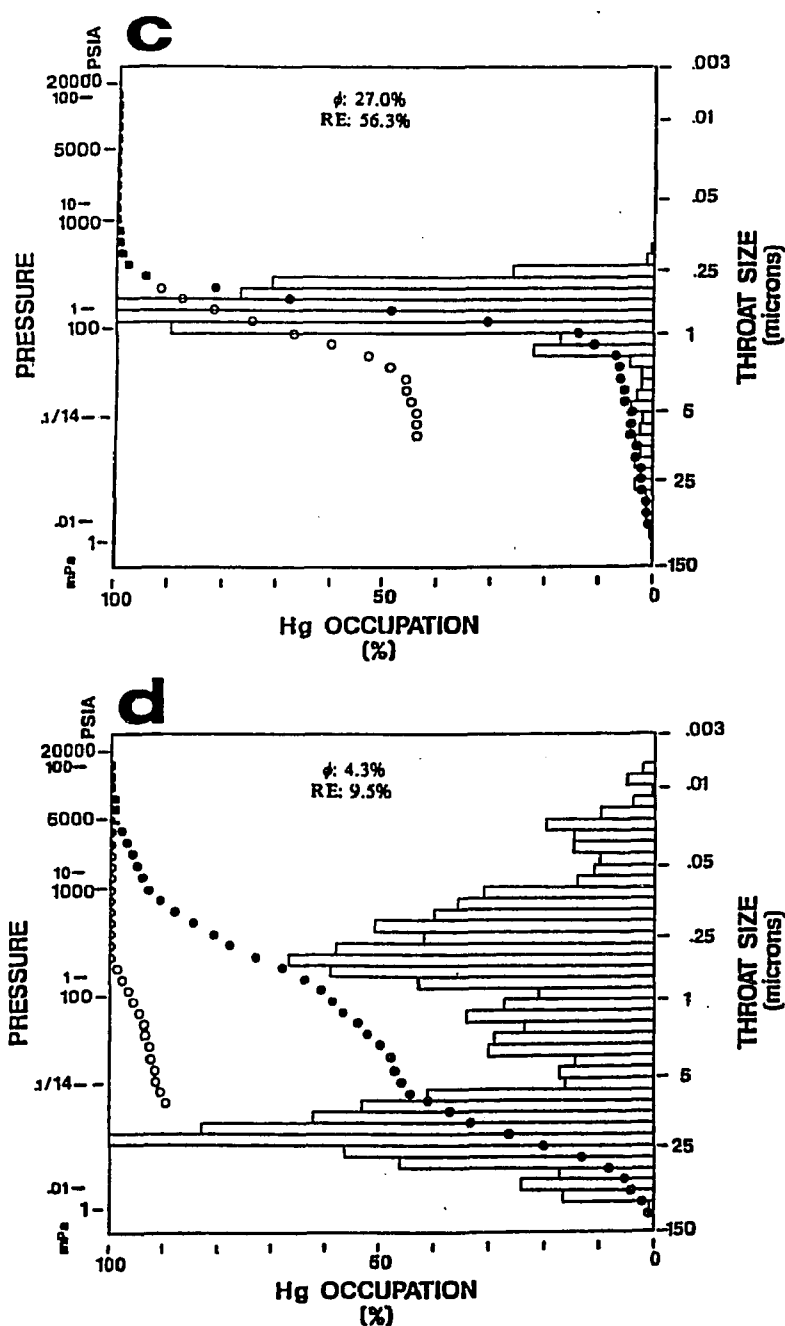


Figure 3-5. c). Intermediate capillary-pressure curves of pellet wackestone beachrock (Group C) from the Bahamas. It is characterized by good sorting of pore-throat size and large RE. The porosities of the rocks displaying this curve are high; of all the beachrocks studied, their petrophysical properties are the best. d). Bimodal capillary- pressure curves of carbonate-cemented beachrock whose particles are mostly terrigenous from Group E, Gulf of Elat, Red Sea. Incremental curve displays more than two peaks; such curves are for those samples having variable porosity and recovery efficiency.

Table 3-5 PETROFACIES OF THE BEACHROCKS

Petrofacies	Group	Lithology	Porosity	RE	Capillary pressure curves
Oolitic grainstone	A	Oolitic grainstone	Highest	Low-moderate	Concave
Grainstone	B & F	Skeletal & intraclast grainstone	Moderate	Variable	Concave
Wackestone	C	Pelletal packstone	High	Highest	Intermediate Bimodal
Dolostone	D	Skeletal-peloidal dolostone	Low	Low	Convex
Terrigenous	E	Sandstone, granule-stone	Moderate -low	Low	Gently sloping Polymodal

and the variability of the petrophysical properties of the beachrock studied. However, it is true for the samples in same petrofacies to possess similar, consistent petrophysical characteristics.

I also note that both oolitic-grainstone petrofacies and skeletal-grainstone petrofacies display concave curves and their bivariable plots overlap. The reason for this is that in the skeletal-grainstone group are various kinds of grains such as skeletal, oolitic, intraclastic, etc. Thus the lithologic- and petrophysical properties of some of samples from the skeletal grainstone group may be similar to those in the oolitic group. But, as mentioned before, the oolitic group is characterized its own nature.

CONCLUSIONS

1. Beachrocks from different realms possess divergent petrophysical properties resulting from their different sedimentary environments, -lithologies, and -diagenetic histories. In all of these, lithology is a first controlling factor. Lithofacies- and petrophysics of beachrocks are related. Even though there is some variation of petrophysical properties among the samples of each group, the properties of a group's samples are still proximate when contrasted with those of samples from other groups. I recognized five petrofacies: oolitic- and skeletal grainstones, packstone, dolostone, and terrigenous beachrocks.

2. In beachrocks, cementation has been the most-important diagenetic process. It commonly controls the evolution of the pore system. In oolite and *Halimeda* beachrocks, as cementation progresses (from scarce, discontinuous pore-rimming cement to one- and two-generation continuous pore-rimming cement), porosity and median throat size decreases but recovery efficiency increases. Meanwhile, with increasing cementation, capillary-pressure curves change from concave "a" to concave "c".

3. A prograding sequence of beachrocks from an island off the coast of Venezuela was included in this study. The beachrocks exhibit regular beds dipping gently seaward, with the oldest bed farthest from the sea. All five Venezuelan samples are lithologically similar, but differ in cement type and cement quantity, with resulting differences in pore systems. As the age of the beds decreases, their porosity drops from 29.8 to 14.6%; RE increases from 17.2 to 63.8%; and median throat size is reduced from 13.9 μm to 0.5 μm . This sequence displays porosity that is directly proportional to median throat size and inversely proportional to RE, a finding in accordance with those of Wardlaw (1976, 1980).

My results also confirm that beachrocks (and possibly shallow-marine carbonates)

are basically consolidated by cementation, and the effects of compaction can be ignored. Correspondingly, cementation, rather than compaction, controls the petrophysical properties of beachrocks. So rock age, which is often correlated with a rock's degree of compaction, does not determine the porosity in beachrocks.

4. Primary interparticle pores are the most-abundant type of pores in beachrocks. Dissolution vugs are not common. Intraparticle pores are very small and rare.

5. Most beachrocks show a positive relationship between porosity and RE, but oolitic- and *Halimeda* grainstone do not. Also, a rough positive relationship exists between porosity and median size. But recovery efficiency is inversely proportional to median throat size.

6. The dolostones from the Mediterranean exhibit peculiar petrophysical properties. Both porosity and recovery efficiency are very small, and the dolostones yield special, concave, capillary-pressure curves. These peculiarities could be the result of early diagenetic dolomitization in which most of the primary pores were lost.

**PART III DOLOMITIZATION AND DEDOLOMITIZATION:
CASE HISTORY OF ANCIENT (CAMBRO-ORDOVICIAN) CARBONATE
ROCKS OF PASSIVE MARGIN, EASTERN NEW YORK**

CHAPTER 4: GEOLOGIC SETTING OF EASTERN NEW YORK

4.1 Geologic setting

The area of interest contains a positive area within which Precambrian basement complex is exposed to the north (Adirondack Dome); and two areas within which Cambrian-Ordovician strata are exposed: (1) a block-faulted area lying south of the Adirondacks, the **Saratoga Platform**, where the basement is overlain by comparatively thin Lower Paleozoic rocks that are nearly horizontal; and (2) the **Appalachian fold-thrust belt**, in which Paleozoic, including Sauk, and Taconic sequences and Precambrian rocks are exposed. In the Catskills, younger, also nearly horizontal Paleozoic strata (Silurian-Devonian) are present to west of the thrust belt (Figure 4-1). The folded- and overthrust strata of the Appalachian fold-thrust belt have been thrust over the strata of the Saratoga Platform. In the Green Mountains, Berkshires, Housatonic Highlands, and Hudson Highlands, Precambrian basement rocks are exposed; they have been thrust over the Lower Paleozoic.

From late in the Cambrian Period to the medial Ordovician, a systematic pattern of contrasting facies was established. This pattern governed the deposition of all strata. To the west lay a shallow tropical shelf on which carbonates were deposited. Farther east, in the deeper water, mostly fine-textured terrigenous strata accumulated on a slope that connected basinward with a former continental rise. By applying the concept of stratigraphic sequences, I have arrived at a "non-standard" view of the relationships between the Taconic formations and their correlations with the shelf strata. Apart from

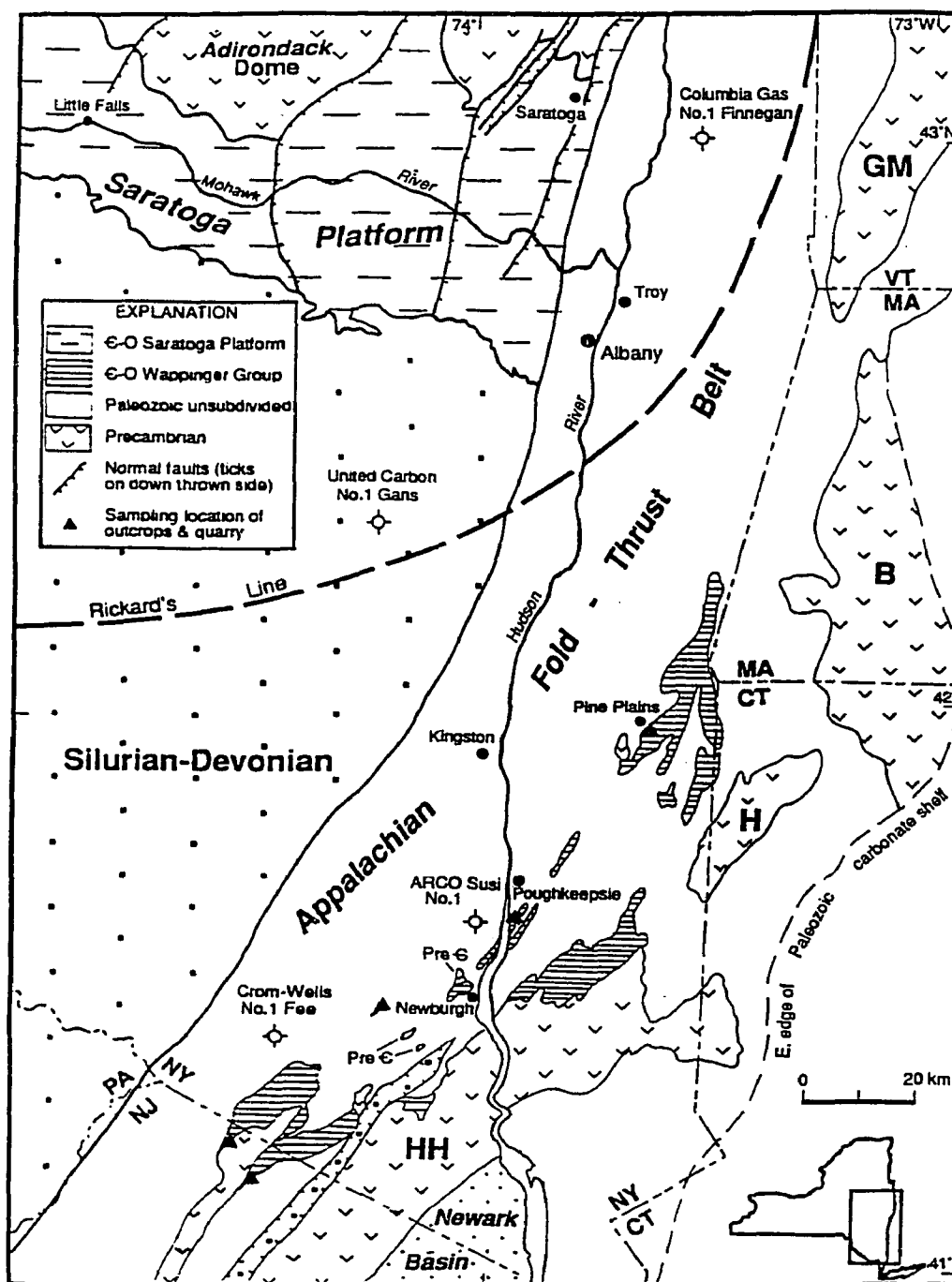


Figure 4-1. Index map showing major tectonic components of study area and locations of outcrop samples (solid triangles) and of bore holes mentioned in text. Abbreviations for major highland outcrop areas of Precambrian rocks in Appalachian fold-thrust belt are: GM, Green Mountains; B, Berkshires; H, Housatonic Highland; HH, Hudson Highland. Nonpatterned areas in fold-thrust belt include all Paleozoic rocks other than the Wappinger Group, whether metamorphosed (and including metamorphosed Sauk equivalents) or not. Except for the normal faults cutting the Saratoga Platform, most faults have been omitted; Taconic allochthon not shown. (Compiled from Rickard, 1973; 1970 geologic map of New York State, and Highway geology map of New York.)

these particular problems of Taconic geology, a general consensus prevails that the Taconic strata were deposited in the basin and then overthrust onto the shelf strata whose age span is generally the same as that of the Sauk strata.

I have assigned the strata in the region into three sequences: Sauk Sequence and lower part of the Tippecanoe Sequence (Sloss 1963) for the shelf strata; and Taconic Sequence, for the basin strata (Table 4-1).

The Sauk Sequence includes "strata that overlie an interregional conformity (*sic*) cut on late (*sic*) Precambrian and older rocks and underlie an interregional unconformity at the base of the succeeding Tippecanoe Sequence" (Sloss, 1963, p. 95-96). The Tippecanoe Sequence designates "strata of the craton that rest upon an interregional unconformity cut on Sauk and older rocks and that underlie an interregional unconformity at the base of the overlying Kaskaskia Sequence" (Sloss, 1963). I infer that the Taconic Sequence is the stratigraphic equivalent of all of the Sauk Sequence plus the lower part of the Tippecanoe Sequence.

Table 4-2 shows the stratigraphic formations of the region studied, in northeastern New York. The names shown for the (Western) shelf * strata follow Rickard (1973), and those of the basin strata are after Platt (1960) and Metz (1967, 1980). Note the "Beekmantown Group" of Rickard (1973) and many others represents Lower Ordovician strata (part of the Sauk Sequence). But, Fisher (1977) proposed to expand the "Beekmantown Group" to include all the strata from base of the Potsdam Sandstone (Upper Cambrian) to the top of the Lower Ordovician (thus to make "Beekmantown" equal to the entire Sauk Sequence on the Saratoga Platform).

* The shelf strata of the Sauk Sequence include three parts (A Keith 1933): western shelf (Beekmantown Group in Saratoga area), central shelf (Wappinger Group, SE New York) and eastern shelf. Table 4-2 shows only shelf strata underlying the western shelf.

Geologic Age	Sequences	
M. Ord.	Tippecanoe	Taconic
Post-Sauk, pre-Tippecanoe surface of unconformity	Sauk	
L. Ordovician		
U. Cambrian		
M. Cambrian		
L. Cambrian		? ? ? ?
Precambrian		

Table 4-1. Names and relative geologic time spans of the three sequences applicable to the Lower Paleozoic rocks of eastern New York State. (After Guo, Sanders and Friedman, 1993 ms)

Shelf strata (Rickard, 1973)		This study		Basin strata (Platt, 1960; Metz, 1980)		
System	Group/Formation	Sequence		Formation	System	
	Utica	Tippecanoe Sequence	Taconic Sequence			
	Trenton					
O 2	Black River					
	Chazy					
	Knox unconformity					
O 1	Beekmantown	Sauk Sequence				
	Little Falls					
	Galway					
e 3	Postdam					
	Uncomformity					
	Precambrian basement					
				Pawlet		
				Mt. Merino	O	
				Poultney		
				Hatch Hill	e 3	
				West Castleton		
				Bull Formation	e 1	

Table 4-2. Stratigraphy of Ordovician-Cambrian in northeastern New York State (Western-shelf subprovince).

4.2 Stratigraphy

4.2.1 Sauk Sequence

Paleotectonic Settings: During the developmental history of the Sauk Sequence, two paleoplate-tectonic settings were present: (1) the former passive eastern margin of the North American continent that subsided slowly to moderate depths (Figure 4-2), and (2) a convergent-margin setting (Dewey and Bird 1970; Bird and Dewey 1970, 1975) within which large-scale overthrusts from the ocean toward the continental interior created a foreland basin within which subsidence was rapid and deep (Quinlan and Beaumont, 1984). This contrast will become apparent from a consideration of the burial history of the Sauk strata.

The Sauk Sequence was deposited when most of North America was functioning as an enormous tropical-carbonate platform surrounded on both east and west by deep-ocean basins. The Sauk rocks in eastern New York State have been interpreted as products of a subsiding carbonate shelf that was situated on the eastern passive continental margin. (See Figure 4-2.)

In eastern New York State, the Sauk Sequence (predominantly dolomitic carbonates) crops out in two discrete subprovinces separated by Rickard's line (See Figure 4-2, Table 4-3): (1) the western-shelf Sauk Sequence in the Saratoga Platform (Guo, Sanders, and Friedman 1990), and (2) the central-shelf Sauk Sequence in the Appalachian fold-thrust belt. The Saratoga Platform coincides with the western-shelf subprovince of Arthur Keith (1932, 1933). The Sauk Sequence of the Appalachian fold-thrust spans Keith's central-shelf- and eastern-shelf subprovinces. The strata of the central-shelf subprovince have been thrust over those of the western-shelf province. In

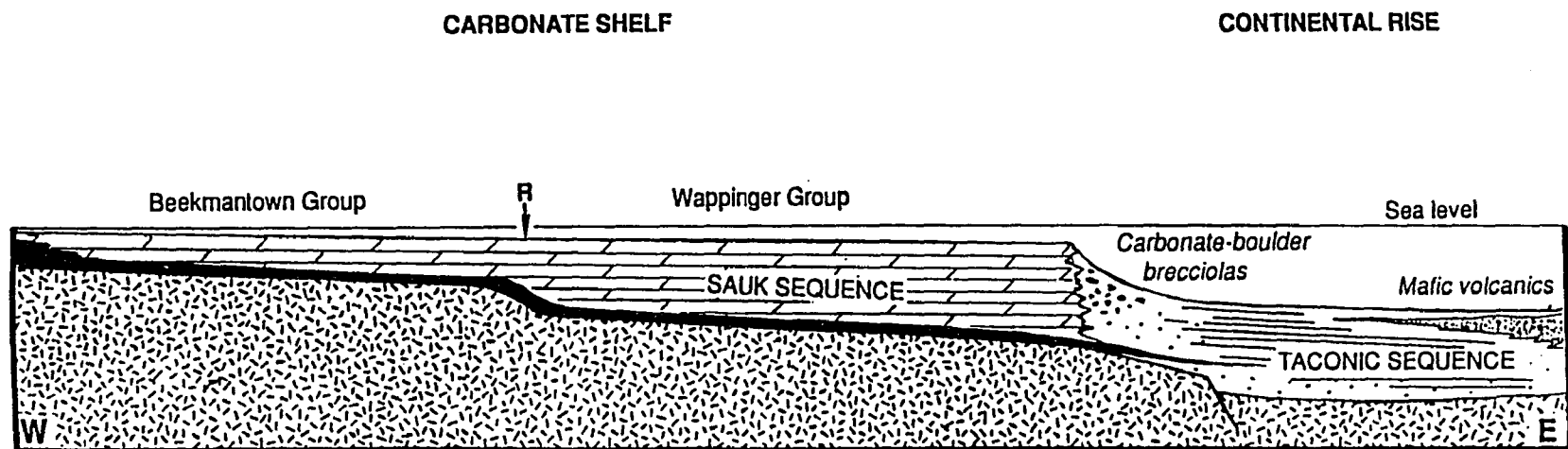


Figure 4-2. Reconstructed paleogeomorphologic profile-section across the Early Paleozoic passive margin of North America. Use of Beekmantown for all of the Sauk Sequence W of Rickard's Line (R) is based on Fisher, 1977. The nature of the change of level between the base of the Wappinger Group and that of the Beekmantown Group is not known and is shown here schematically. Short line segments in random pattern, Precambrian basement; black, basal quartzose sandstone (Potsdam on the W, Poughquag on the E). Dolostone pattern for Sauk Sequence includes limestones (now calcite marbles) in the eastern part of the former carbonate shelf.

SARATOGA PLATFORM:		APPALACHIAN FOLD-THRUST BELT:	
Tippecanoe Sequence			
M. Ord.	Various limestones	Balmville Ls.	M. Ord.
~~Post-Sauk, pre-Tippecanoe surface of unconformity~~~~~			
L. Ord.	Beekmantown (Rickard)	WAPPINGER GR.	L. Ord.
U. Camb.	Little Falls Fm.		
	Galway Fm.		
	Potsdam Ss.		
~~			
Precambrian "basement"			

Table 4-3. Names of formations within the Sauk Sequence on Saratoga Platform (left) compared with those in the Wappinger Group in the Appalachian fold-thrust belt.

turn, the strata of the central-shelf subprovince have been overthrust by those of the eastern-shelf subprovince. The strata of the eastern-shelf subprovince have been metamorphosed; I do not consider them further here.

In the western-shelf subprovince, the Sauk carbonates (the Beekmantown Group in usage of Fisher 1977) are relatively thin, their basal quartz-sandstone unit is the Upper Cambrian Potsdam Sandstone, which rests nonconformably on Precambrian basement. And the strata, although cut by numerous normal faults, have not been repeated by overthrusts. The Sauk carbonates are extensively exposed in the Saratoga Platform and have been studied by many generations of New York geologists. Steep normal faults have broken the Saratoga Platform into numerous fault blocks. Although exposures are numerous, the stratigraphic span of each is limited. The entire succession of the Sauk Sequence from the Saratoga Platform, 356 m (1176 ft) thick, has been penetrated in the Columbia Gas No. 1 Finnegan boring (Figure 4-3).

The Sauk strata of the central-shelf subprovince, named the Wappinger Group, are exposed in the fold-thrust belt. They are relatively thick (3785-4800 feet, from Knopf 1962 and this study) their basal unit is the Lower Cambrian Poughquag Quartzite, which rests nonconformably on Precambrian basement. East and south of Rickard's line, during the pre-Taconic deformation of mid-Ordovician age, the thicker Sauk strata were thrust westward over the mid-Ordovician shales. And they have been cut by normal faults (but the normal faults are not so conspicuous as they are on the Saratoga Platform). In southeastern New York State, in Dutchess, Ulster, and Orange counties, the Wappinger Group is exposed many scattered localities. The top three quarters of the Wappinger strata have been penetrated by two exploratory borings: (1) the Crom-Wells No. 1 Fee, near Middletown, Orange County; and (2) the ARCO No.1 Susi, near Marlborough, Ulster

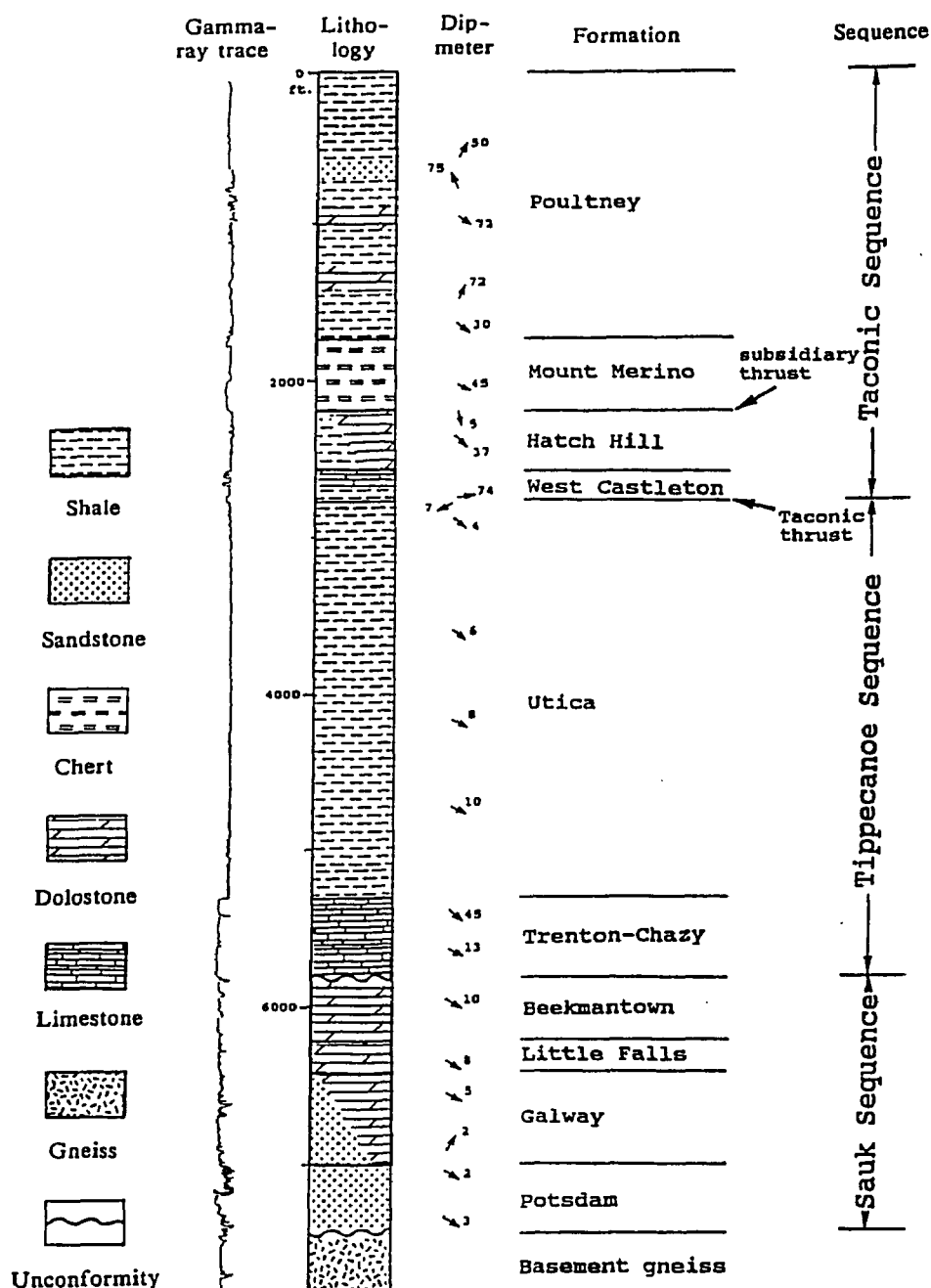


Figure 4-3. Columnar section of strata penetrated in the Finnegan boring. Compare the strata of the Taconic Sequence cut by this boring with the full succession shown Table 4-2 in which the Mt. Merino Formation overlies the Poultney Formation and the Hatch Hill and West Castleton formations underlie the Poultney. The finding of Poultney above Mt. Merino is inferred to indicate that some of the strata have been overturned; the absence of any overturned Austin Glen beneath the inverted Mount Merino and presence of Hatch Hill and West Castleton formations in apparent normal order implies a fault at a depth of 2190 feet. The finding of the typical platform strata (Utica Shale to Precambrian basement gneiss) beneath West Castleton Formation starting at a depth of 2764 feet is the basis for recognizing the Taconic thrust.

County (Figure 4-4).

4.2.1.1. Beekmantown Group

According to the proposal of Fisher (1977), "Beekmantown Group" includes Upper Cambrian through Lower Ordovician strata in the Champlain and Mohawk valleys. But, Rickard (1973) and many others have used Beekmantown for only the Lower Ordovician part of the subsurface New York carbonate rocks. At one time, Fisher proposed but later abandoned "Saratoga Spring Group" for the Upper Cambrian strata near Saratoga. In my study of the Finnegan boring (Guo, Sanders, and Friedman, 1990, 1991), I have followed Rickard's use of Beekmantown. Now, I need a term that includes the whole Sauk Sequence in the western shelf, which can be comparable to the Wappinger Group in the central shelf of the Sauk Sequence. I have applied Fisher's "Beekmantown Group" for this purpose.

The following data about the Beekmantown Group (sense of Rickard, 1973) are derived from my study of the cuttings and logs from the Columbia Gas Co. No. 1 Finnegan boring. In the absence of fossils or limestones that have been used by some workers (for example, Fisher and Hanson 1951; Fisher and Mazzullo 1976; Fisher 1977; Mazzullo, Agostino, Seitz, and Fisher 1978) to revise the outcropping formations, I lack the bases for recognizing the latest stratigraphic units these workers have established. From top downward, I adopt Beekmantown, Little Falls, Galway, and Potsdam. (See Figure 4-3.)

Viewed broadly, the strata in the Finnegan boring assigned to the Sauk Sequence consist of dolostone (upper part), sandy dolostone/dolomitic sandstone (middle part), and quartz sandstone (lower part). Because the lithologic characteristics change gradually and transitionally from the top to the bottom, the strata belonging to this sequence are difficult

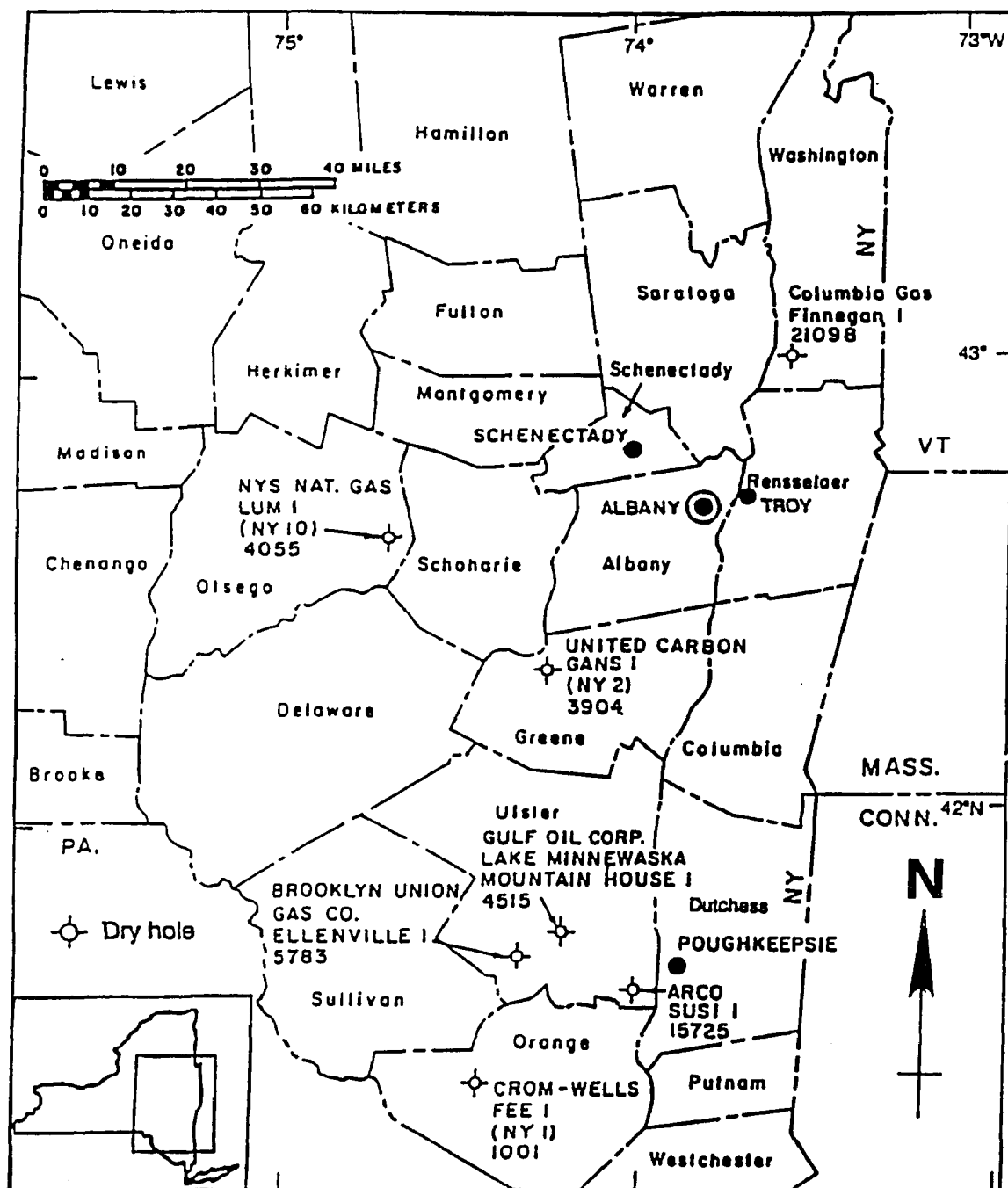


Figure 4-4. Map of eastern New York showing county outlines and locations of outcrops and bore holes that penetrated the Sauk Sequence rocks. Insert map shows regional location.

to subdivide. As Rickard (1973) wrote: "The rocks of the carbonate shelf consist of.... The great thickness of relatively uniform lithologies and subtle lateral changes from one rock type to another have made this sequence very difficult to subdivide and correlate." The only way to help this problem is to study the lithofacies.

On the basis of detailed lithologic characteristics (Figure 4-5), and following previously published descriptions of the characteristics of each formation (Fisher 1977, Rickard 1973) one may subdivide the Sauk Sequence more easily. From 6244 to 6320 feet, in the Finnegan boring, abundant chert occurs with the dolostone; quartz sands are rare; and dolomite crystals are finer as contrasted with the upper strata. Accordingly, this depth serves as a boundary between the overlying Beekmantown (Rickard 1973) and underlying strata that I assign to the Little Falls. Following the same line of reasoning, I distinguish a boundary at 6430 feet. Below this level, the dolostone possesses medium gray color, finer crystals, and the sandstones often contain black organic material (oil residue). Undoubtedly, 6430 feet marks the top surface of the Galway Formation. However, the boundary between the Galway and the underlying Potsdam could logically be placed at either one of two levels: (a) 7000 feet, where sandstone becomes the chief constituent, or (b) 7252 feet below which no dolostone is interbedded with the sandstone. "Potsdam sandstones are gradually replaced upwards by quartzose dolostones and dolostones of Galway..." "...sandstones in the lower part of the Galway in the south probably are fingers of the Potsdam in the north" (Rickard, 1973). Because Potsdam and Galway interfinger with each other, both boundaries are reasonable. I have selected 7000 feet as the level for the Galway/Potsdam boundary because under this level, the dolostone in the interval 7200-7252 feet is the only small "finger".

4.2.1.2. Wappinger Group

Table 4-4 shows the formations within the Wappinger Group, with thickness figures that were determined by E. B. Knopf (1962) from outcrop mapping in Dutchess County. The most-complete information available about the lithologic characteristics of the upper part of the Wappinger Group is based on my detailed restudy of the cuttings from the Crom-Wells No. 1 Fee boring (Figure 4-6) and ARCO No.1 Susi (Figure 4-7).

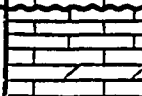
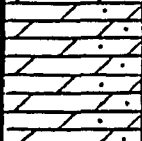
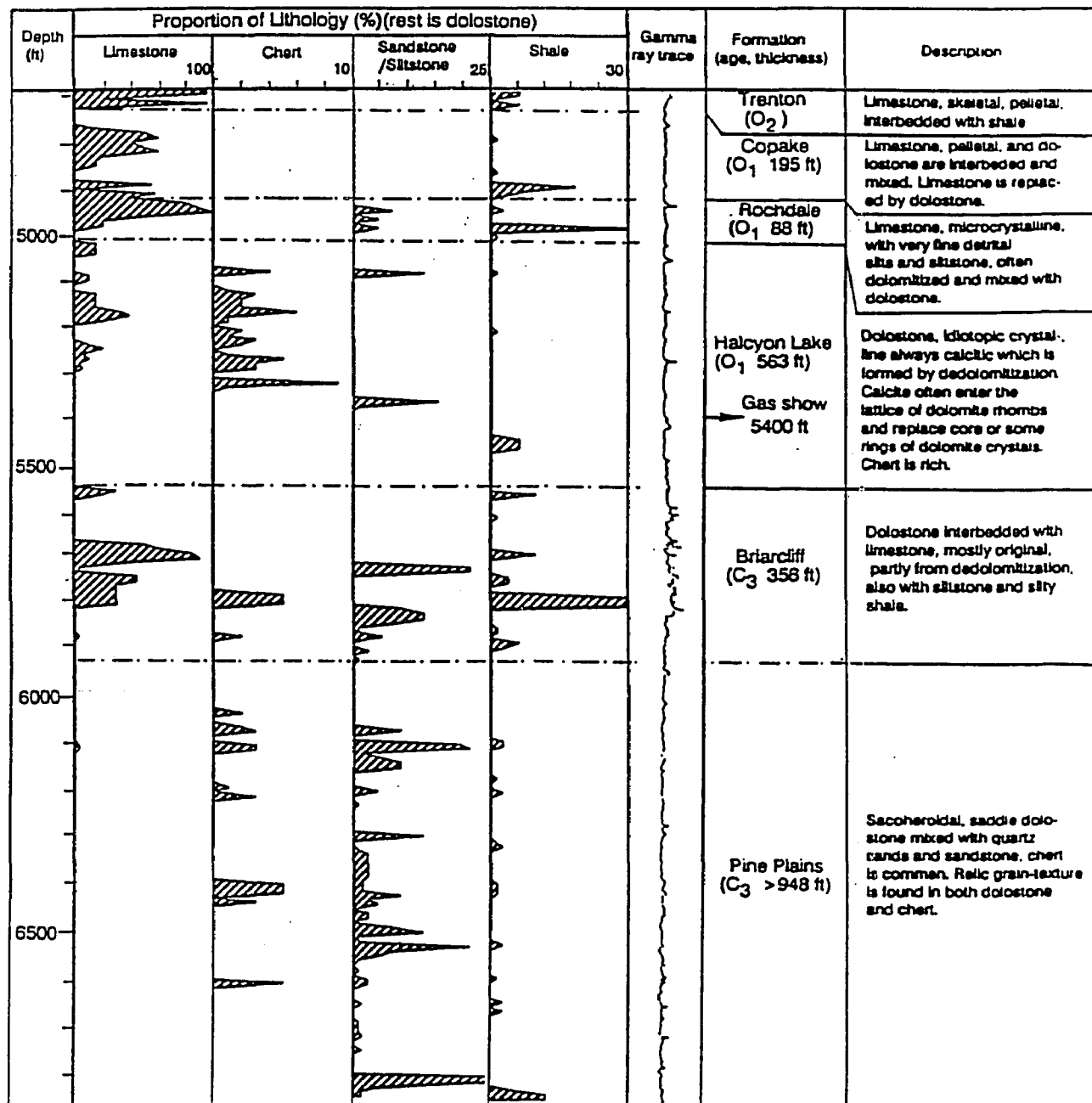
Age	Lithology	Sequence	Formation (Group)	Thickness (ft.) (Knopf, 1962)		
M. Ord.		Tippecanoe	Balmville Ls.	0 to ?		
Post-Sauk Unconformity						
L. Ord.		Sauk	(Wappinger Group)	Copake Ls.	0 to 500	
				Rochdale Ls.	750	
Halcyon Lake Fm.	350					
U.E	Briarcliff Fm.			700		
	Pine Plains Fm.			1475		
M.E			(Wappinger Group)	Stissing Dol.	500	
L.E					Poughquag Quartzite	10 to 75
					Nonconformity	
Precambrian basement						

Table 4-4. Schematic columnar section of the Wappinger Group showing named formations within it (based on outcrop studies in northern Dutchess County, NY, by Knopf, 1962)

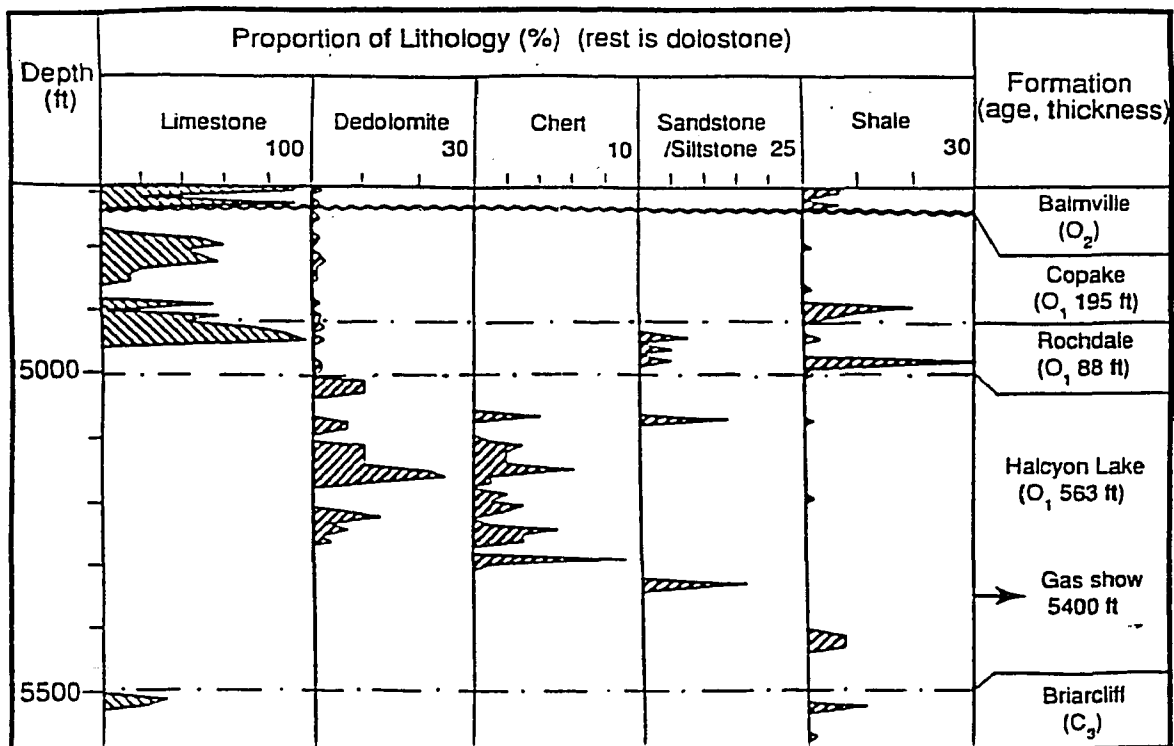
Figure 4-5. Graphic presentation of microlithofacies of western shelf-carbonate assemblage of Sauk Sequence, Finnegan boring (5824 to 7440 feet). Abbreviations are as follows: Lithologic composition: Dls. = dolostone; ss. = sandstone; sts./sh. = siltstone/shale. (The width of the lithology column indicates 100 percent; widths of patterns within this column display the estimated proportions by volume of the three individual lithologic components listed.) The color column shows three shades of gray, darkening toward the right, with three steps indicated by tick marks as follows: light gray, gray, and dark gray. In the column headed Dolostone Mlf, XI. size refers to sizes of dolomite crystals, with abbreviations: Mic. = microcrystalline; F. = fine crystalline; and M. = medium crystalline. In the Sandstone Mlf column, particle sizes are abbreviated as follows: S. = silt; F. = fine sand; and M. = medium sand (Udden-Wentworth grade scale). No quantity of ooids is indicated by the width of the column headed ooids; only their presence or absence is shown. Cement abbreviations are: Arg. = argillaceous; Dol. = dolomite; Si = silica; and Org. = organic matter.

[illegible]

Figure 4-6. a). Lithology and stratigraphy of the Wappinger Group penetrated by Crom-Wells No.1. Fee, based on my detailed studies of the cable-tool cuttings from the Crom-Wells Fee No.1 boring, Orange County, New York (in collection of New York State Museum, Albany). b). Lithology and stratigraphy of the basal limestone of the Tippecanoe Sequence (=Balmville) and of the upper part of the Wappinger Group (Sauk Sequence), revised from Figure 4-6, after dedolomite had been recognized.



a



b

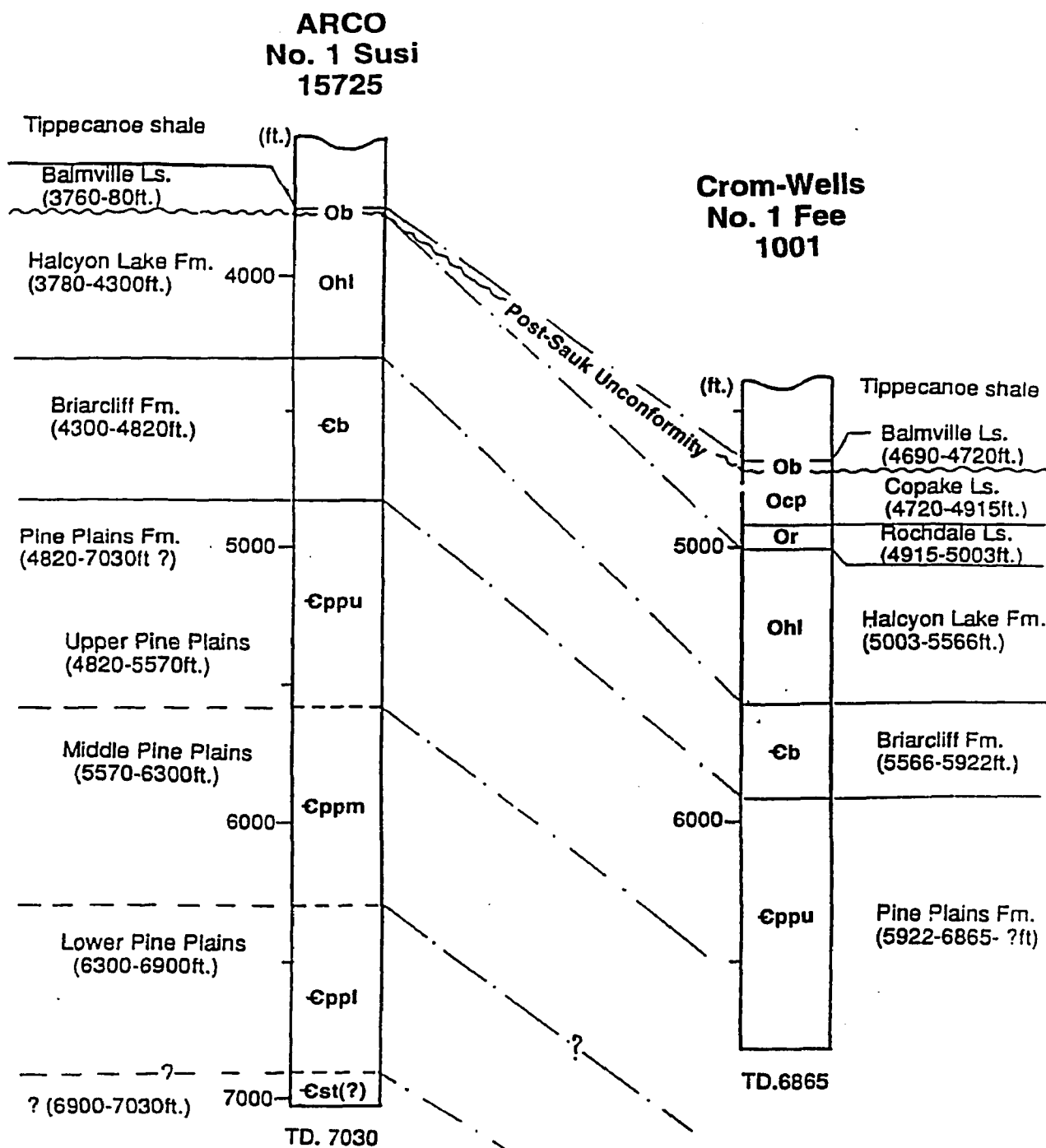


Figure 4-7. Columnar sections of the Sauk Sequence penetrated in ARCO No. 1 Susi compared with Crom-Wells No. 1 Fee. Notice that in the Susi boring at left, the post-Sauk, pre-Tippecanoe surface unconformity cuts out the Copake and Rochdale limestones that are present in the Fee boring, and that the Susi boring penetrated more of the Pine Plains Formation than did the Fee boring.

As can be seen from the columnar section of the Crom-Wells No. 1 Fee boring, the predominant rock constituent of the Wappinger Group is carbonate (limestone, dolostone, and dedolomitized dolostone). Limestone decreases downward and the proportion of terrigenous material (quartz) increases downward. For example, in the Rochdale and Copake formations, limestone predominates. No dolostone is present above the top of the Copake. Limestone and dolostone are interbedded or mixed in the Halcyon Lake and Briarcliff. But, in the Halcyon Lake Formation, the distinctive calcdolostone is a product of dedolomitization of a precursor dolostone. Limestone is not present in the Pine Plains Formation. Calcite is present in limestone or dolomitic limestone as of original calcium-carbonate sediment, as discrete interbeds, and as replacement products of some of the dolomite (hence is dedolomite). Note that the dedolomite is best developed in the Halcyon Lake Formation but is also present in the overlying two formations (Figure 4-6, b).

Chert is most abundant in the Halcyon Lake Formation and is also common in the Pine Plains Formation. But it is present only rarely in the Briarcliff Formation and is absent above to top of the Halcyon Lake Formation. The admixed terrigenous quartz is present only as silt-size particles in the Rochdale and Briarcliff formations, but is present in the form of numerous rounded, sand-size particles in the Pine Plains Formation. In the Crom-Wells Fee No. 1, shale is rare.

The results from Crom-Wells are, basically, correspond to those from the cuttings from the ARCO No. 1 Susi, and from the Clinton Point Quarry and numerous outcrops. A summary description for each formation of the Wappinger Group follows.

1. *Poughquag Quartzite.* The Poughquag Quartzite was named by J. D. Dana (1872, p. 250-256) for the even-bedded quartzite at Poughquag, Dutchess County, New

York, that rests unconformably on the "Archean" and is overlain by the Stockbridge limestone.

The Poughquag was not penetrated by either of the two exploratory borings in the Appalachian fold-thrust belt. On the basis of outcrops, such as in the cut along the S. side of I-84, Newburgh, Orange Co., Poughquag Quartzite is massive, white pure quartz sandstone (orthoquartzite).

A thin section collected from this I-84 locality shows that the rock is composed of 98% transparent quartz with most of the particles in the size range of medium- to coarse sand. The texture is clastic and the fabric, particle supported. Among the sand-size framework particles, monomineralic quartz, many showing wavy extinction shadows, forms an estimated 80%. Quartzite (metamorphic rock) fragments form about 10%. The framework also includes little amount altered feldspars, now consisting of sericite, that are slightly rounded and well sorted in the size range of medium- to coarse sand. The cement consists mostly of sericite but includes illite and a trace of pyrite that is always associated with sericite.

In terms of above observations, I infer that the parent area of the Poughquag sand contained abundant metamorphic quartzite. The highly mature composition and excellent roundness of the particles imply intense decomposition and vigorous physical transport. Although the sand was probably deposited near a coast, I think its mud content indicates that it is not a typical beach deposit. Finally, the lack of recognizable fresh feldspar implies that the parent area was subjected to intense chemical decay.

2. *Stissing Dolostone.* The Stissing Formation was named by E. B. Knopf (1927, p. 429-458) for the Middle Cambrian unit. Type section is located N. of Pine Plains and Stissing Mountain (Knopf, 1962). From Knopf's descriptions, the Stissing consists of pale

gray- or white, fine- to aphanitic dolostone. Two particular points about the Stissing stand out: (1) much of the dolostone contains secondary pores ("drusy cavity", vugs lined with quartz crystals; the "diamonds" of local usage); and (2) her unit No. 04 contains shale, some pale green and the basal part deep red.

In the ARCO No.1 Susi boring, the interval from 6300 to 6900 ft. that I assign to the lower Pine Plains Formation possibly belongs to the Stissing. The samples in this interval are characterized by pale gray with greenish or pinkish color, abundant mixed silts/siltstone, very fine, even texture, and lack of cyclic features. The facies in this interval is definitely different from the overlying typical cyclic Pine Plains Formation.

3. *Pine Plains Formation.* The Pine Plains Formation was named for the village of Pine Plains, Dutchess County, NY (E. B. Knopf, 1962).

The Pine Plains Formation is a major part of the Wappinger Group. Its thickness is large (1475 feet measured on outcrops in the type area, northern Dutchess County by Knopf, 1962; >1350 feet in the Clinton Point Quarry, Poughkeepsie, Johnson, 1987, source report; Roy Budnik, report on 1991 cores), more than one third of the thickness of the whole Wappinger Group (3785 to 4250 feet, Knopf, 1962; a maximum 4800 feet computed by Sanders and me, 1993 ms.). Moreover, the uppermost formations, such as the Copake and Rochdale, and the lower formations, such as Stissing and Pouqhqaug are rarely exposed. Hence, in the study area, the Pine Plains, Briarcliff, and Halcyon Lake formations are most likely to be exposed. Of these, the Pine Plains Formation can be recognized easily by its various lithologic- and cyclic features.

Compared with other formations, the Pine Plains Formation shows its unique features, such as:

(1) Lithofacies is stable, and comparable from New Jersey (Allentown Formation

in Kittatiny Group) to eastern New York. Throughout this large area, the Pine Plains Formation shows uniform lithology from both outcrops and bore-hole samples.

(2) In the Pine Plains Formation, most depositional features are well preserved. In this respect, none of the other massive dolomite formations matches it. Hence, despite total dolomitization, the Pine Plains Formation perfectly preserves its depositional characteristics. It would obviously be a good objective to be used to study its ancient depositional environment and the origin of dolomite.

(3) Cyclic features. Small-scale cycles (parasequences) in the Pine Plains Formation are well developed. These are fifth- or sixth-order cycles and can be used to study sea-level changes.

(4) The formation consists of fine- to medium crystalline ("sucrosic") dolostones including saddle-dolomite vein- and pore-fillings. Extrabasinal sand-size particles in the form of rounded quartz are present both as scattered admixtures and as discrete beds of sandstone. Chert pods are common but of little total volume. Other features include intraclasts and relic ooids.

From a comprehensive study, especially, from detailed study of the cuttings from the ARCO No. 1 Susi boring, I recognize three units of this formation: lower, middle, and upper.

The lower part of Pine Plains Formation consists of fine dolostone, silty dolostone and dolomitic siltstone. On outcrop, these different lithologies show "ribbed" appearance. Compared with the two overlying units, its beds are thinner and its precursor carbonate did not contain sand-size particles. All of these indicate a lower rate of deposition and a lower-energy environment. I infer that they are products of deeper water than are the upper two units.

Both middle- and upper parts of Pine Plains Formation possess cyclic features that consist of alternating layers of very fine- to medium crystalline, pale gray or white to dark-gray- colored dolostone. In general, finer crystalline dolostone is associated with darker color and coarser dolostone shows pale-gray color. But, the fine- to medium crystalline oolitic dolostone in the Pine Plains Formation is dark gray .

The important difference between the middle- and upper units of the Pine Plains Formation is that oolitic dolostone is not as well developed in upper part as in the middle part. This feature is also can be seen in the cuttings from the Crom-Wells No. 1 Fee and from the rock faces- and cores in the Clinton Point Quarry. It is even comparable to the cuttings from the Finnegan boring in the western-shelf subprovince. (See Figure 4-5.)

Hence, from lower unit to upper unit, an overall shallowing upward is indicated: from deeper water offshore for the lower unit, to nearshore oolite shoals for the middle unit, and to a peritidal complex in the upper unit in which the facies varied systematically with the numerous fluctuations of sea level.

The cyclic features are interpreted as *parasequences* (Friedman, Sanders, and Kopaska-Merkel 1992, Friedman 1992c, d; 1993a, b) that formed by deposition at the margin of a tropical sea in an arid- or semiarid climate. In such settings, contrasting sediments are deposited in the various environments defined by tidal levels. As a first approximation, three such environmental settings are subtidal, intertidal, and supratidal. A detailed facies and environmental analysis will be discussed in Chapter 5.

I have found that in the Crom-Wells No. 1 fee boring and in the Clinton Point Quarry, a distinct change in the size of the quartz particles from sand abundant in the Pine Plains to silt only in the Briarcliff, which may be regionally significant.

4. Briarcliff Formation. The Briarcliff Formation was named by E. B. Knopf

(1962) for Briarcliff Farms south of Pine Plains, Dutchess County. The most-complete exposures of the Briarcliff Formation are in the Clinton Point Quarry with thickness more than 1295 ft. I assign a depth interval of 356 ft in the Crom-Wells No.1 Fee and the 350 ft. depth interval in the ARCO No. 1 Susi borings to the Briarcliff Formation.

The Briarcliff Formation is characterized by its pale- to medium gray, fine crystalline, even texture, always mixed with terrigenous silts, and thin- to massive beds. In the Briarcliff Formation, the cyclic changes in color, texture, and composition are vague. In general, the Briarcliff is more uniform than the Pine Plains. I estimate that in the Briarcliff, most dolostones are devoid of internal layer structures and are present in thick- to medium beds; only a minority (estimated 20%) consists of laminated layers.

The Briarcliff Formation in the Crom-Wells No. 1 Fee boring consists predominantly of dolostone but includes some interbedded limestones. I found that a special characteristic of the Briarcliff Formation is the abundance of silt-size terrigenous quartz in the form of admixed silt in dolostone, in siltstone, and silty shale. Hence, silty dolostone, argillaceous dolostone, dolomitic siltstone, and dolostone are intermixed. Mrs. Knopf (1962) also mentioned calcdolostone in Briarcliff Formation in Briarcliff Farm, Dutchess County. However, I did not find any calcdolostone in the Briarcliff Formation in the Clinton Point Quarry or in the cuttings from the ARCO No. 1 Susi bore hole.

Comparison between the Briarcliff and Pine Plains formations.: 1) The Pine Plains Formation exhibits cyclic patterns more clearly than the Briarcliff. 2) More kinds of lithofacies are present in the Pine Plains Formation. 3) Features of the original calcium-carbonate sand-size sediment, such as oolites, skeletal particles, and intraclasts, are more numerous and better preserved in the Pine Plains Formation. 4) In the Pine Plains Formation, "floating" rounded particles of sand-size quartz and sandstone beds are

common. Most of the quartz in the Briarcliff is of silt size (which is difficult to see in field study). 5) In some places, such as in Briarcliff Farms (Knopf 1962) and the cuttings from the Crom-Wells No. 1 Fee boring, limestones or calcdolostones are interbedded in the Briarcliff Formation. No such calcdolostone was reported in the Pine Plains Formation.

The above-cited evidence indicates that the environment in which the Briarcliff Formation was deposited differed from that of Pine Plains Formation. I infer that during the period of Briarcliff deposition, the water was deeper, more quiet, and sea-level fluctuations were not significant as in Pine Plains. Most of the Briarcliff carbonates were deposited in subtidal- and intertidal zones; deposits of the supratidal zone, which are so common in the Pine Plains Formation, are not present. (See Chapter 5.)

5. *Halcyon Lake Formation.* The Halcyon Lake Calcdolostone was named by Knopf (1946, 1962) for Halcyon Lake south of Pine Plains, Dutchess County. The type locality is on the northeastern shore of Halcyon Lake. The formation is 350 feet thick and consists of "interbedded calcdolomite and dolomite with subordinate sandstone" (Knopf 1962).

The common features of the Halcyon Lake Formation as described by Knopf (1962), by Offield (1967) and confirmed in this study are medium- and light gray, fine- to coarse crystalline, medium- to massive beds dolostone and calc-dolostone with abundant chert nodules and -lenses.

Knopf (1962) described the Halcyon Lake Dolostone as being "the most elusive of the Wappinger carbonates to find and identify. Where known it is a calcitic dolostone, slightly quartzose and with chert pods...medium-thick bedded..coarse-medium textured...". Warthin and Pack (1956 ms.) described the strata in the Crom-Wells Fee No. 1 boring that they assigned to the Halcyon Lake as: "Gray finely crystalline limestone, containing up

to 50% dolomite rhombs...". As a result of his mapping of the Goshen-Greenwood Lake area, Offield (1967) stated that the following were distinctive aspects of this formation: calc-dolomite layers (in sub-equal amounts); a definite very fine-sandpaper texture; abundant chert in scattered nodules, lenses, and discontinuous layers; and an unmistakable fetid odor of hydrogen sulfide when freshly broken.

My study of the cuttings from the Crom-Wells No. 1 Fee and ARCO No. 1 Susi borings, the type locality at Halcyon Lake, and samples collected by Russell Such from Winfarm (SE of Pine Plains) shows that the Halcyon Lake consists of dolostone and calcdolostone with abundant chert. A striking new result of my investigations is that the calcdolostones are products of dedolomitization. (See Chapter 6.) Calcite has replaced dolomite, not only on fracture fillings but also by entering the lattice of dolomite rhombs and in cores or some zones of concentrically zoned dolomite crystals. Stained thin sections in which calcite appears as red show these relationships (Figure 6-6, a). The maximum proportion of calcite in these idiomorphic "calcdolostones" (dedolomites) ranges between 30 and 40%. Therefore, although they display characteristic dolostone textures, they effervesce vigorously with dilute hydrochloric acid. In fact, Knopf's (1962, p. 32) description: "By calcdolomites I mean not interbedding of calcitic with dolomitic layers but rocks in which many individual constituents are made up of calcite and dolomite in an intimate intermixture" matches my new results.

I assign an interval of 563 ft in the Crom Wells No. 1 Fee and 690 ft in the ARCO No. 1 Susi to the Halcyon Lake Formation.

6. Rochdale Formation. The Rochdale Limestone was named by Dwight (1887, p. 32) for the fossiliferous rocks of the "Calciferous" (Lower Ordovician, Beekmantown of many authors but not Beekmantown of Fisher 1977). Knopf (1927) restricted the term

Rochdale to the lower part of the strata assigned by Dwight to the "Rochdale group."

On the basis of study of outcrops on Cedar Valley Road, at Bethel, and the cuttings from the Crom Wells No. 1 Fee boring, I describe the Rochdale Formation as consisting of light-gray, thin-bedded, fine crystalline dolostone interbedded with pelletal- or micritic limestones and dolomitic limestones.

Copake and Rochdale limestones have been found from the Crom-Wells No. 1 Fee boring. Between 4720 and 5003 feet in the Crom-Wells No. 1 Fee, limestone and dolostone are interbedded. I recognize two units: pelletal limestone between 4720 and 4914.5 feet which I assign to Copake Limestone, and micritic limestone with very fine silts and siltstones from 4914.5 to 5003 feet that I assign to the Rochdale Limestone. However, based on his examination of the cuttings, Rickard (1973) put all of the interval from 4720 to 5003 feet into the Rochdale Limestone and inferred that a fault exists in between the two units. In his idea, these two units are the same stratigraphic unit, Rochdale, which was repeated by a fault.

7. Copake Limestone. The Copake Limestone was named by Dana (1879). Dwight included Dana's Copake within his "Rochdale group." Knopf (1927) subdivided the Lower Ordovician "Rochdale group" of Dwight into two units. She applied the term Copake limestone to the mottled gray-and-white limestone containing *Ophileta* sp., white limestone, and gray quartzose dolostone that forms a thick quartzose weathered coating, is riddled with *Scolithus* borings, and contains a large *Ophileta*. This unit is underlain by the Rochdale limestone and overlain unconformably by the basal limestones (mid-Ordovician ages) of the Tippecanoe Sequence. Weaver (1957) mapped the Copake quadrangle and measured several sections of the Copake limestone.

In outcrops, the Copake Limestone is rare. It is present in Crom-Wells No. 1 Fee

boring (See above description.); not present in ARCO No. 1 Susi. It consists of pelletal/micritic limestone interbedded with finely crystalline dolostone.

In the old limestone quarry northeast of Copake village, the Copake Limestone consists of gray well-laminated silty limestones and burrow-mottled silty limestones. These limestones overlie, perhaps disconformably, some massive dolomite sedimentary breccias, not mentioned by Weaver.

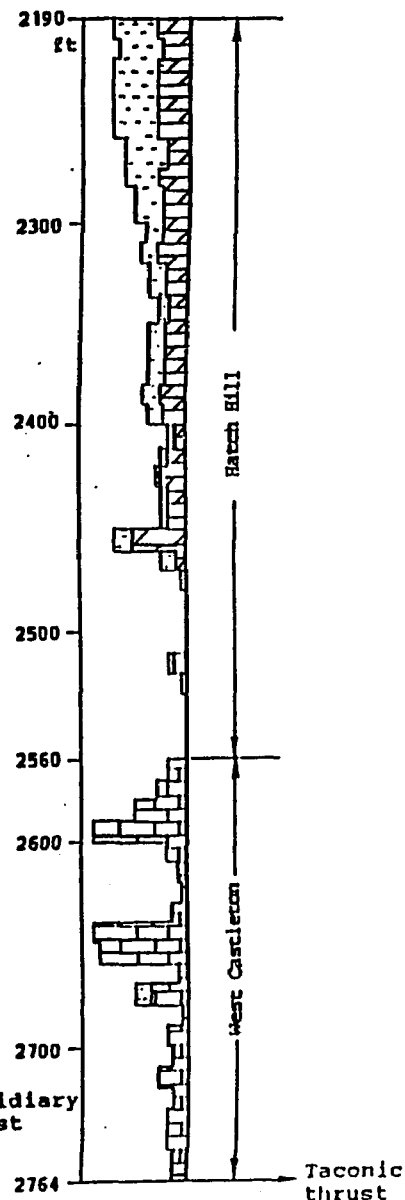
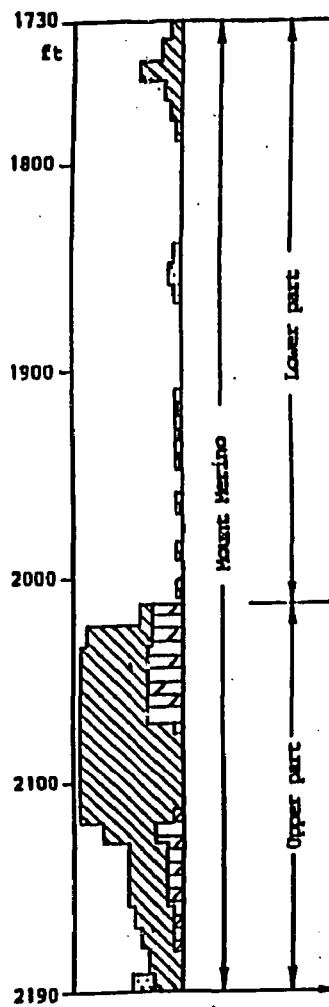
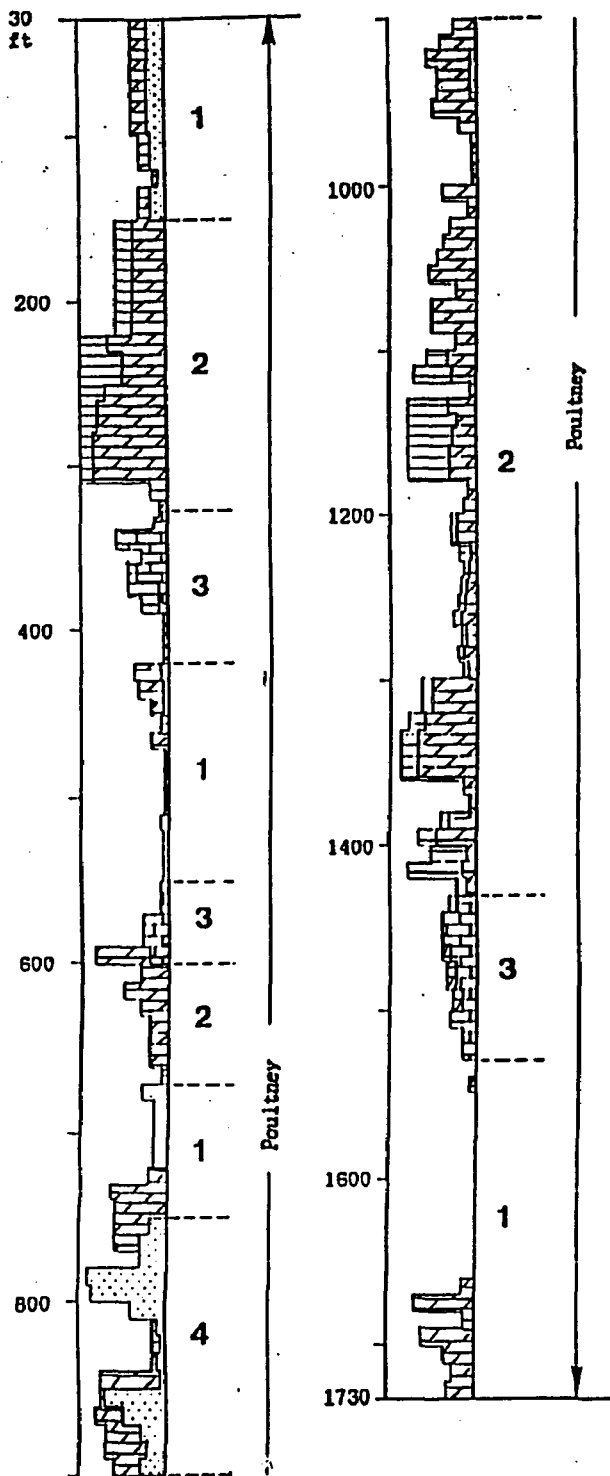
The Sauk Sequence everywhere is characterized by a consistent mineral change downward. At the top, calcite prevails, but downward, calcite decreases and dolomite increases. This mineralogical transition implies not only that depositional conditions changed during the Late Cambrian and Early Ordovician, but it may also indicate that these formations may have been subjected to a systematic series of diagenetic processes.

4.2.2. Taconic Sequence (Figure 4-8)(named by Arthur Keith 1932)

From exposures in northeastern New York, western Vermont, and especially, in southern Washington County, New York, near the Finnegan boring, Ruedemann (1901a, 1914, 1930), Cady (1945, 1960), Cady and Zen (1960), Bird (1963), Platt (1960), Theokritoff (1964), Metz (1967 ms., 1980), Rowley *et al.* (1979), and Bosworth (1980, 1980 ms.) have described the features of the various formations of the Taconic succession. Although no one had presented an entire description of all the subdivisions and thicknesses of each of the formations, summary descriptions and approximate thicknesses of every formation are available.

The following paragraphs present the results of my study of the Taconic Sequence in the cuttings from the Columbia Gas. Co., No. 1 Finnegan boring. According to my interpretation, the strata of the Taconic succession penetrated by the Finnegan boring include from top downward: Poultney Formation and Mount Merino Formation (overturn-

Figure 4-8. Graphic summary of microlithofacies results of strata from Taconic Sequence penetrated in the Finnegan boring. The width of the column represents 100 percent; the widths of the patterns within this column display the estimated proportions by volume of the various microlithologies shown. Present are the inverted Poultney (depth interval 30 to 1730 feet) + Mount Merino formations (depth interval 1730 to 2190 feet) and right-way-up Hatch Hill and West Castleton formations (depth interval 2190 to 2764 feet). The contact of the inverted younger strata with right-way-up older strata and absence of any graywacke (Austin Glen or Pawlet) is the basis for inferring the subsidiary thrust indicated at 2190 feet.



EXPLANATION

	Limestone		Dolostone		Chert
	Shale/Slate		Sandstone		Siltstone
	Dolomitic slate		Microlithofacies of Poultney		

subsidary thrust

Taconic thrust

ed); and Hatch Hill Formation and West Castleton Formation (in normal order).

Poultney Formation. Previous workers who have studied the Poultney Formation, have reported that it contains a variety of rocks with multiple colors. Despite the variety, the predominant lithologic types are slates and interbedded quartz arenites, quartzites, and limestones. The slates are hard, light gray, or gray with greenish color. From Willard Mountain (the well site) in northern Washington County, to the Cambridge Quadrangle, southern Washington County, the lithologic characteristics of the Poultney change.

In the Finnegan boring, I was able to recognize four microlithofacies in the Poultney Formation; (1) dark-gray shale and black mudstone, commonly with interbeds of gray calc-siltstone or fine sandstone and sandy calc-dolostone; (2) light-gray, gray, greenish, microcrystalline dolostone mixed with shale (or slate); (3) dark gray shale and skeletal limestone interbedded; (4) gray crystalline quartz-dolostone (Figure 4-9-a) and light-gray dolomitic quartzite interbedded with gray shale and -siltstone. Of these, microlithofacies 1 and 2 predominate.

Based on a comparison with published descriptions of the Poultney, I infer that the rocks in the depth interval 30 to 1730 feet are equivalent to the upper part and the lower part of the Poultney Formation of Metz, Platt, and Rowley, or Poultney members A and B of Theokritoff. But the Poultney Formation in the Finnegan boring most closely resembles that from the Cambridge Quadrangle (Metz, 1967 ms., 1980). The exception is that in my study, I have found much microcrystalline dolostone. The petrographic identification of dolomite is confirmed by X-ray analysis. Because it is microcrystalline (dolomicrite), mixed with slate, and possesses a very fine texture, the dolostone has not been recognized previously.

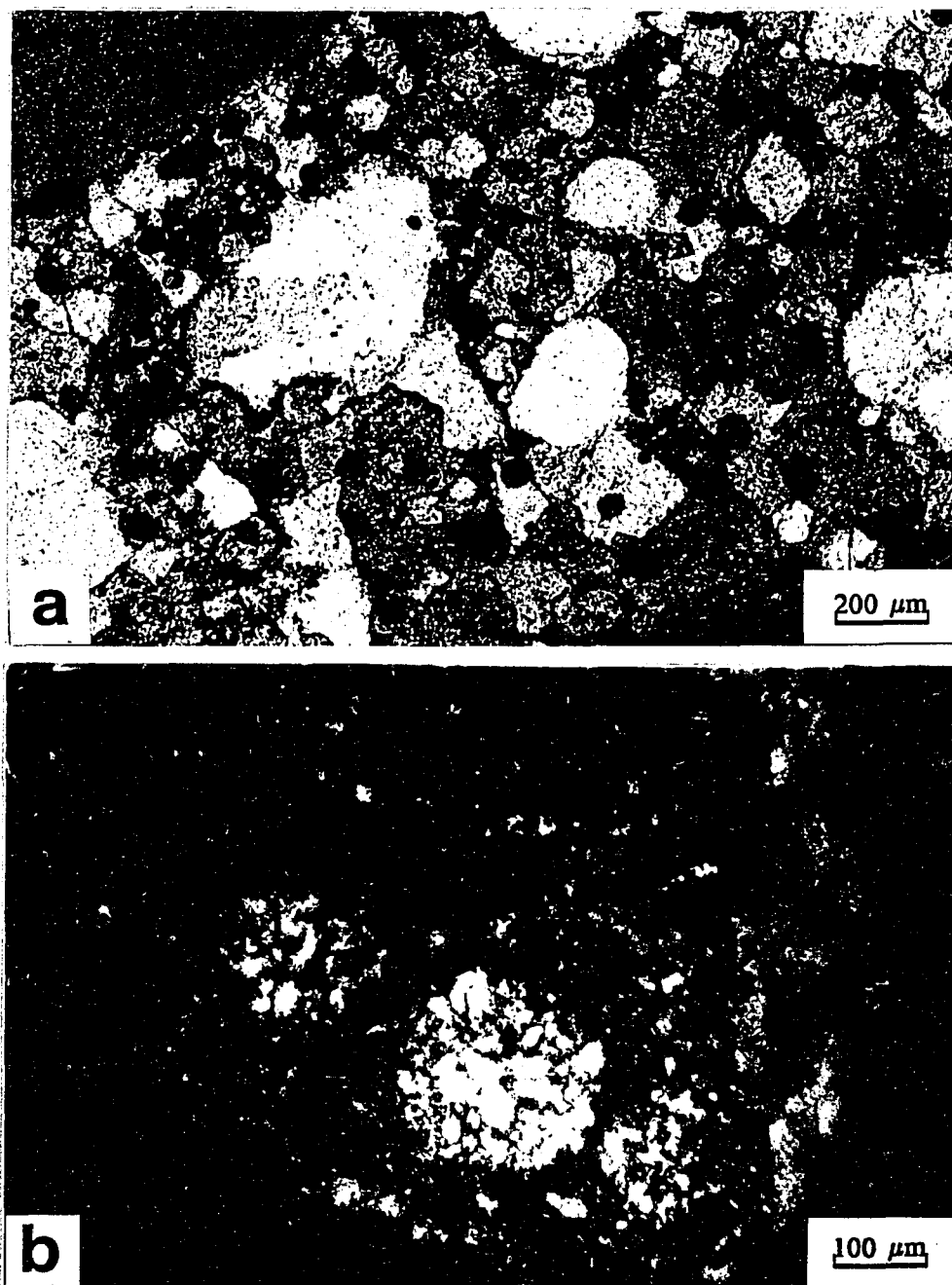


Figure 4-9. Enlarged views of petrographic thin sections prepared from selected samples of cuttings from the Taconic- and Tippecanoe sequences; photomicrographs taken in plane-polarized light except as otherwise noted. (a) Sandy dolostone, Poultney Formation (760 to 770 feet). Rounded sand-size quartz particles are scattered among the xenotopic- and hypidiotopic dolomite crystals. During diagenesis, the edges of the quartz particles were corroded and/or replaced by dolomite crystals. (b) Chert, consisting of microcrystalline chalcedony, Mount Merino Formation (2040 to 2050 feet), crossed-polarized light. Three pseudomorphs of radiolaria are preserved in which the crystals of chalcedony are larger than those in the surrounding chert.

Mount Merino Formation. I have divided the strata I assign to the Mount Merino into two parts: an upper part and a lower part. The upper part consists of chert (Figure 4-9-b), siliceous slate, dolomicritic chert, and dolomicrite. The chert is best developed in the middle part of this interval. Both the lithologic characteristics and sequential patterns of this interval are almost the same as those from the type locality, Mount Merino, south of Hudson, NY. The lower part includes mostly dark shale and rare interbeds of chert, of limestone, of siltstone, and of fine sandstone.

Hatch Hill Formation. In the Finnegan boring, the strata that I have assigned to the Hatch Hill Formation include mixed medium-gray dolostone (Figure 4-9, c) and -siltstone interbedded with dark-gray shale, -siltstone, and -slate. Mixed dolostone and siltstone decrease from 70% at top to 0% at bottom. In both lithology and thickness, the strata cut by the Finnegan boring that I assign to the Hatch Hill Formation match those described from this formation in adjacent areas. The correspondence between the Hatch Hill in the Finnegan boring and Bosworth's (1980 ms.) description of exposed Hatch Hill is especially close.

West Castleton Formation. The strata in the Finnegan boring that I have assigned to the West Castleton Formation consist of dark gray- to black shale and -siltstone and interbedded pelletal limestone that is medium gray. This identification agrees with all previous descriptions of "West Castleton" (Platt 1960; Zen 1961; Jacobi 1977 ms.; Metz 1967 ms., 1980).

Previous study of the surface structure of Willard Mountain indicates that the Poultney Formation is inverted (Bosworth and Rowley 1984). The fact that in the Finnegan boring, the chert of the Mount Merino underlies the Poultney slate proves that the strata are overturned. Barring other complications, underneath overturned Mt. Merino

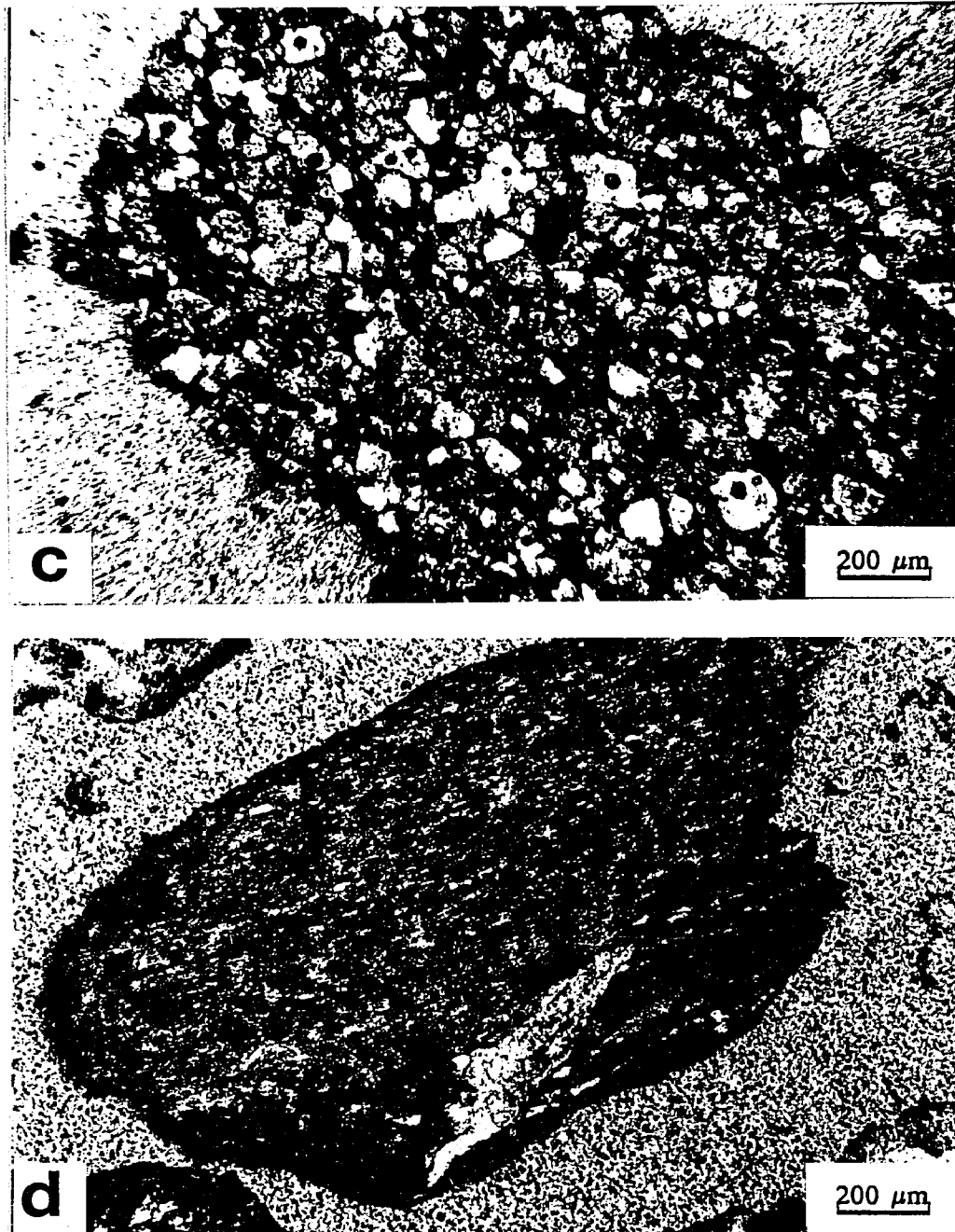


Figure 4-9. (c) Silty dolostone, Hatch Hill Formation (2310 to 2320 feet). The well-sorted, subrounded- to subangular, silt-size quartz particles are mixed with dolomite crystals. A small amount of argillaceous matrix is present. (d) Shale, Utica Formation (2720 to 2730 feet). Clay minerals have been recrystallized and display oriented arrangement.

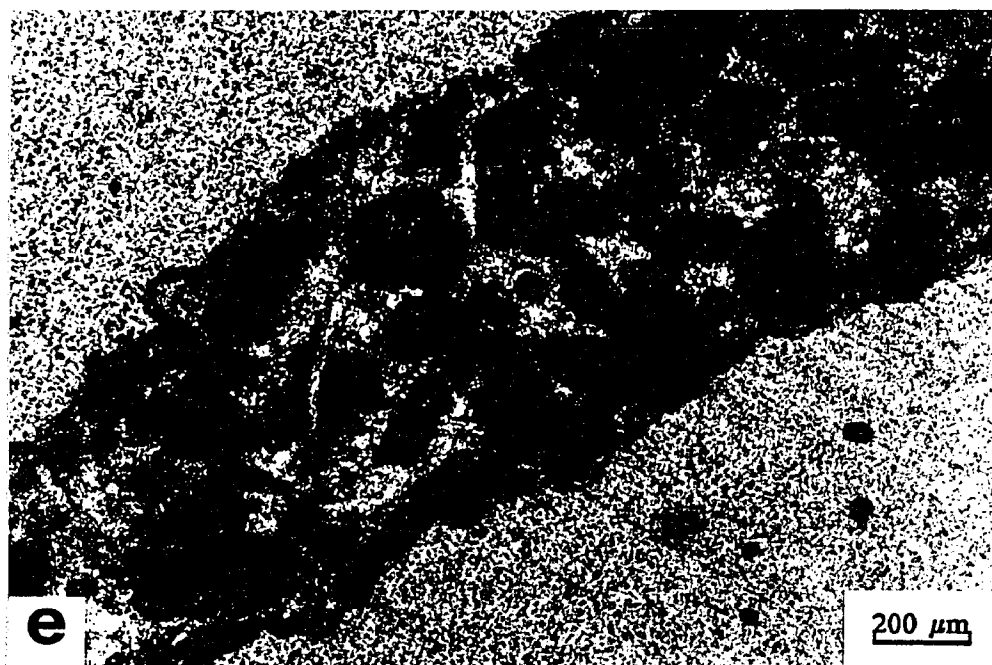


Figure 4-9. (e) Peloidal limestone, Trenton/Chazy formations (5720 to 5730 feet). Well-sorted peloids having various shapes (dark areas) cemented with sparry calcite are a typical product of a shallow-water submarine shelf environment.

chert should be the Austin Glen (or Pawlet) graywacke. In fact, in the cuttings from the Finnegan boring, no graywacke is present. Below the overturned Mount Merino are right-way-up Hatch Hill and West Castleton formations. This relationship leads me to infer that the Finnegan boring cut a thrust fault between the lowest Mount Merino strata and the highest Hatch Hill. More evidence of such a fault can be derived from the gamma-ray traces and the dipmeter log. Except for an abrupt lithologic change, the dip is only 5° at a depth of 2190 feet. This contrasts with steeper dips above (45°) and below (37°).

The Figure 4-9, d, e are samples from Tippecanoe Sequence in the Finnegan boring.

4.3 Post-Sauk, pre-Tippecanoe surface of unconformity

In southeastern New York, wherever the appropriate rocks are exposed, the top of the Wappinger Group, consisting of Lower Ordovician and/or older strata of the Sauk Sequence (Offield 1967; Fisher 1977) can be seen to be truncated by the post-Sauk, pre-Tippecanoe surface of unconformity (*as mentioned, equals the "post-Knox unconformity" in the usage of Churnet, Misra, and K. R. Walker 1982, p. 77 and the "Knox unconformity" of Rickard 1973 and as widely applied informally among petroleum-exploration geologists*) above which is the basal Middle Ordovician limestone of the Tippecanoe Sequence (the Balmville Limestone in the region of interest). Deposits of early Middle Ordovician age are not present (Fisher 1977). In many parts of the region, one or more of the formations at the top of the Wappinger Group (Sauk Sequence), the Copake or Rochdale limestones and locally, even part of the Halcyon Lake Calcdolostone, were completely removed (Figure 4-10, a, b). In Columbia and Dutchess Counties, evidence from study of the Balm-

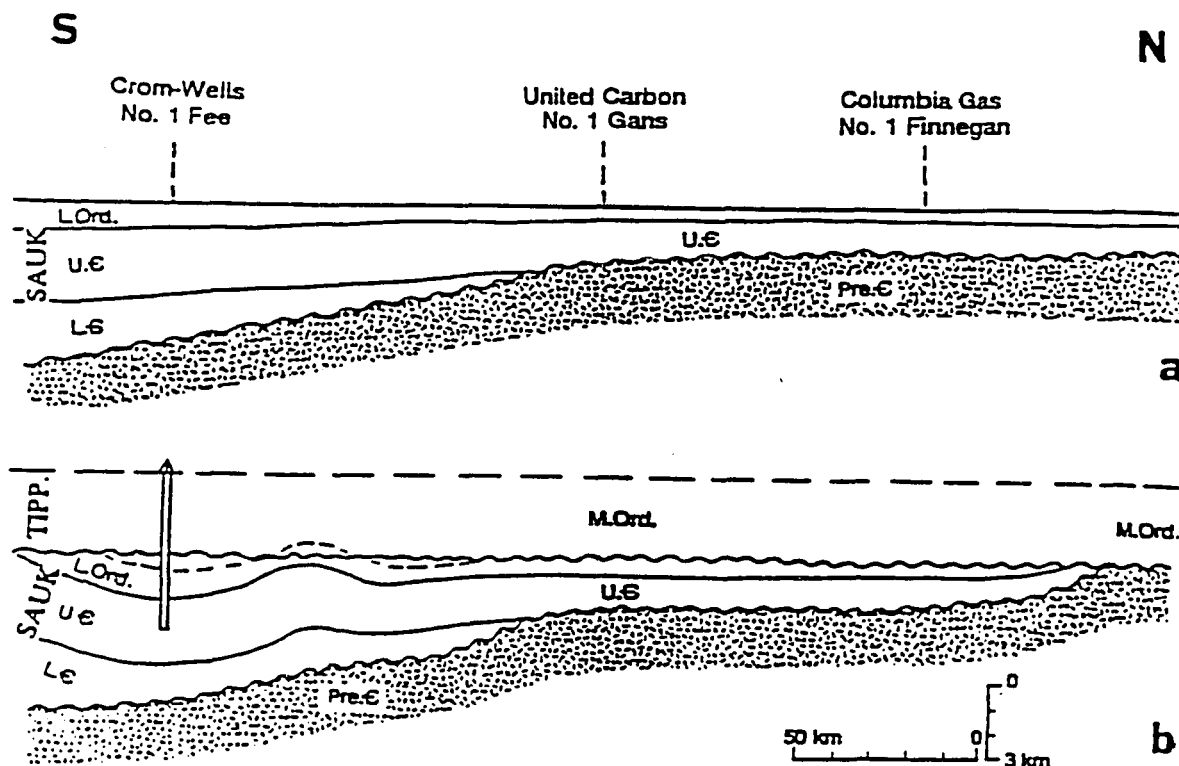


Figure 4-10. Stages in development of post-Sauk, pre-Tippecanoe surface of unconformity as seen along N-S profile from Crom-Wells No. 1 Fee boring to Adirondacks in latitude of Colombia Gas Co. No. 1 Finnegan boring.

a. Sauk sequence deposited. Notice that the Lower Cambrian and lower part of the Upper Cambrian pinch out to the N in the middle of the profile.

b. Sauk sequence folded and truncated by post-Sauk, pre-Tippecanoe surface of unconformity, preserving Copake and Rochdale formations in synclines only. Dashed line shows the contact between Rochdale and Halcyon Lake formations. The Halcyon Lake Formation comes to the land surface in crests of anticlines. (Location of pinchout of Lower Cambrian based on Rickard, 1973.)

ville Limestone and underlying Sauk strata suggests that the post-Sauk, pre-Tippecanoe surface unconformity was an irregular karst surface. It developed on the older dolomitic carbonate rocks of the Sauk Sequence

The results from the Crom-Wells No. 1 Fee are anomalous with respect to the pattern derived from surface exposures, described above. This boring is located in the midst of the region where in outcrops, the Balmville Limestone, only a few feet thick, rests on the Halcyon Lake Calcdolostone. In this boring, the Halcyon Lake is overlain not by a few feet of Balmville as in the outcrops, but by 88 feet of Rochdale Limestone, 195 feet of Copake, and 40 feet of Balmville. (See Table 4-4.) In the ARCO No. 1 Susi boring, the post-Sauk, pre-Tippecanoe surface unconformity at 3780 ft. is absolutely clear cut (Figure 4-7); above this level, the characteristic skeletal limestones of the Balmville are present. No limestone exists below 3780 feet, and the dolostone is associated with some chert nodules, a characteristic of the Halcyon Lake Formation. Hence, neither Copake nor Rochdale are present beneath the Balmville Limestone.

Above- and below the post-Sauk, pre-Tippecanoe surface of unconformity, the depositional style of the carbonate rocks differs markedly. Below this surface of unconformity, the carbonate rocks consist mostly of dolostones. Above this surface, the carbonates are mostly limestones.

The post-Sauk, pre-Tippecanoe surface unconformity affected profoundly the burial and uplift history of the Sauk strata and their diagenetic paragenesis.

4.4. Inferred burial history of the Sauk Sequence.

Figure 4-11 displays the inferred history of burial and -uplift of the top of the Halcyon Lake of the Wappinger Group. After the Sauk Sequence had been deposited,

at least three times of downward- and upward movements are known. Thus, the diagenesis of Sauk Sequence was largely affected by these burial-uplift events. The initial subsidence of the top of the Wappinger Group, which was not very deep, started in Early Cambrian time and continued as the predominant situation until the end of the Early Ordovician. The total initial subsidence amounted from a few hundred meters to less than one kilometer which is estimated by the preserved total thickness of Copake, Rochdale, and Halcyon Lake formations, 260 meters. After that, during the Early Middle Ordovician, the Sauk strata were elevated and subaerially eroded; the post-Sauk, pre-Tippecanoe surface of unconformity formed.

Later in the Middle Ordovician, the second subsidence, one that was more extensive than the first, commenced and the Tippecanoe Sequence was deposited. The amount of the second subsidence equalled the thickness of the Tippecanoe Sequence terrigenous strata [the Martinsburg Formation, shown by Drake and Epstein (1967) to be about 3 km] plus that of one or more overthrust sheets (possibly another 3 km). The third, most-prolonged, subsidence started early in the Silurian Period and continued until late in the Paleozoic Era (Pennsylvanian to Early Permian). This subsidence affected all Paleozoic rocks and subjected them to deep burial. Estimates of the former depth of burial of the Devonian strata of the Catskills lie in the range of 4 to 7 km (temperatures of 150° to 200°C; Friedman and Sanders 1982; Friedman 1987a, b) for as long as 200 ma. The post-Paleozoic burial situation is not recorded in any strata preserved within the region, but is inferred to have consisted of elevation.

Notably, during the post-Sauk, pre-Tippecanoe unconformity, the middle- and lower parts of the Wappinger Group were not elevated to the Earth's surface. Their diagenetic paragenesis was different from the top formations. Detailed discussion is in Chapter 6.

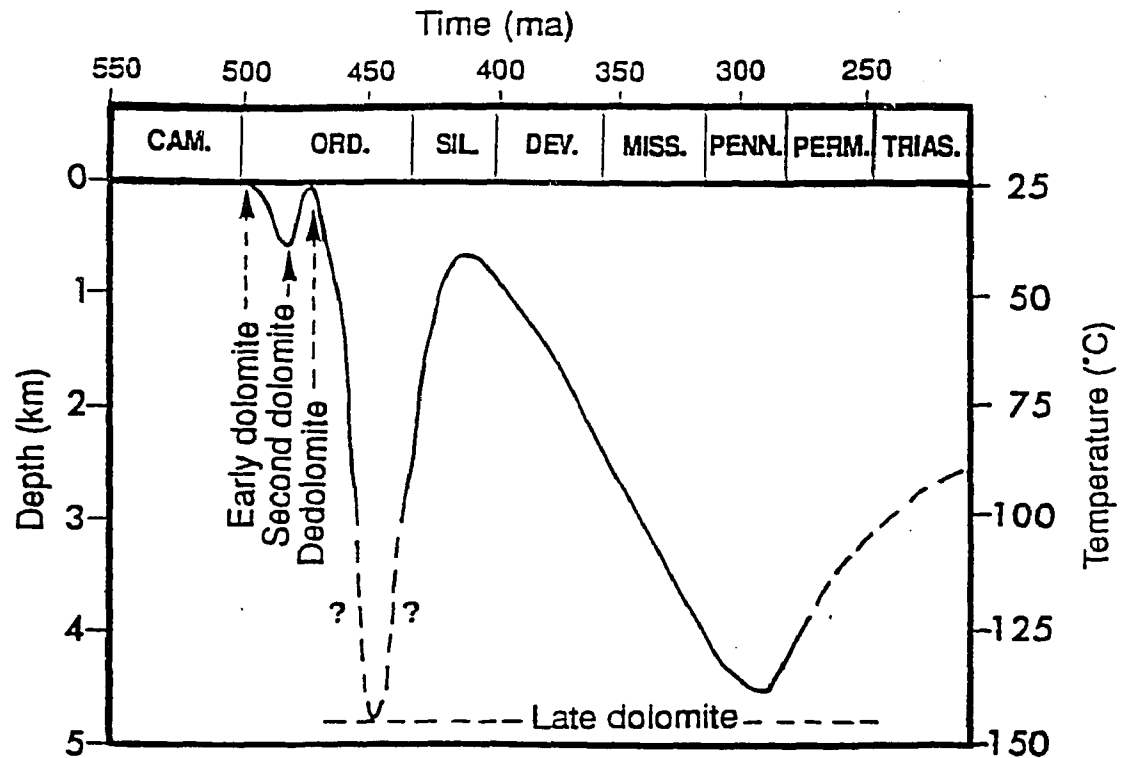


Figure 4-11. Schematic geohistory curve showing time history of burial of the top of the Halcyon Lake Formation. Further explanation in text. Compare with sedimentation diagram in Siever (1986, fig. 5, p. 245.)

CHAPTER 5: DEPOSITIONAL ENVIRONMENTS AND FACIES

Many generations of investigators have studied the paleoenvironments- and facies of the Sauk Sequence in New York State. Most of them limited their studies to the strata belonging to the western-shelf subprovince, the Saratoga Platform. As for the strata of the central-shelf subprovince, the only studies have been by Ervilus and Friedman (1991), who gave a brief description of the facies characteristics based on study of two outcrops of the Pine Plains Formation (located at Limekiln Road, East Fishkill, in the Hopewell Junction 7.5-minute quadrangle).

In this study, I mainly present: 1) a microlithofacies analysis of the Sauk strata from the western-shelf subprovince based on information from the Finnegan boring including well cuttings and well logs; and 2) the parasequences and facies studies of the Pine Plains Formation of the Wappinger Group which are deposits from the central-shelf subprovince. The information is from outcrops, cores, well cuttings, and well logs.

The most-complete section of the Sauk strata was penetrated by the Finnegan boring; no other outcrops or cores can be compared with it. As mentioned before, in the Saratoga Platform, post-Taconic normal faults have cut the Sauk strata into many pieces. Thus no complete (or even half complete) sections will ever be found.

5.1 Western shelf (Fisher's Beekmantown Group)

5.1.1. Microlithofacies

Much previous work on lithofacies analysis of the Sauk Sequence (Upper Cambrian through Lower Ordovician) in northeastern New York has been carried out by

Prof. Friedman and his former students (Conway and Friedman, 1984; Curl 1983 ms.; Curl, Zagorski, and Friedman 1984; Friedman and Keith, 1983; Mazzullo and Friedman, 1975; Mazzullo, Agostino, Seitz, and Fisher, 1978; Rubin, 1975 ms.; Rubin and Friedman 1977, 1981; Zagorski, 1981 ms.). Lithofacies study is regarded as an effective way to get the information of sedimentary environments and diagenetic history of potential reservoir strata and it provides useful background data for evaluating reservoir rocks.

The difficulty of using well cuttings to do lithofacies analysis is obvious. No macrofossils nor macro-sedimentary structures, such as bedding, ripples, desiccation cracks, and contact relationships between different kinds of rocks, are available. Therefore, lithofacies derived from outcrops and cores and those based on well cuttings will probably differ. For this reason, I define the information derived from well cuttings as microlithofacies (Fairbridge 1954) instead of lithofacies.

In studying the samples from the Finnegan boring, I have based the identification- or classification of microlithofacies on: (1) megascopic properties of well cuttings that can be observed under a binocular microscope, such as color, rock type, texture, mineral composition, and proportions of various kinds of rocks within a given depth interval; (2) petrographic examination of thin sections cut from carefully selected chips from the samples of cuttings that provide complete and precise information about microlithofacies, including detailed composition- and texture of every kind of rock and associated relationships among them, such as constituent type of carbonate, cement, and kinds of detritus in sandstones, as well as effects of diagenetic changes; and (3) instrumental bore-hole logs, including gamma-ray, Dual Laterolog, and compensated neutron-litho-density, which are used to determine rock type and relative content of various types of rocks, and to prove and correct the depth interval in which samples of cuttings were

collected. Furthermore, the instrumental well logs are helpful in locating the correct *in-situ* depths of layers from which allochthonous chips were derived.

As mentioned above, microlithofacies differ from lithofacies established from study of outcrops and of cores. However, both microlithofacies and lithofacies are closely related. Microlithofacies is a part of lithofacies and the characteristics of microlithofacies are absolutely contained in lithofacies. In general, microlithofacies are simplified from lithofacies and lack important macro properties. I have tried to connect and compare lithofacies and microlithofacies in order to interpret sedimentary environments and diagenesis and to establish a model of microlithofacies encountered in the Finnegan boring.

Microlithofacies analysis has proved useful in subdividing the stratigraphic succession, especially that within the Sauk Sequence. Moreover, in subsurface geological study where large amounts of well cuttings and logs are available, microlithofacies analysis may be particularly important.

Based on lithologic characteristics, I recognize five microlithofacies (Table 5-1). (See also Figure 4-5.) Three are dolostones, and two are sandstones. I identify submicrolithofacies by their admixed constituents, such as chert, sands or sandstones, ooids, and so forth.

Microlithofacies (Mlf) 1

Microlithofacies 1 is light gray, medium-fine crystalline dolostone. On the basis of associated constituents, I recognize four sub-facies.

Mlf 1-a (in Beekmantown Group)

The chief dolostone of Mlf 1-a is medium crystalline and its color is light gray and

**Table 5-1 MICROLITHOFACIES (Mlf) SUMMARY OF SAUK SEQUENCE
IN FINNEGAN BORING**

Mlf no.	Description	Sub-Mlf	Remarks
1	Light gray, medium-fine crystalline dolostone	1-a 1-b 1-c 1-d	Little chert Cherty Sandy Pure
2	Medium gray, fine-micro-crystalline dolostone	2-a 2-b	With sandstone, pores of some layers filled with oil residue With relict ooids interbedded with sandstone
3	Dark gray, microcrystalline dolostone		With little calcite
4	Quartz sandstone and ortho-quartzite		
5	Feldspathic quartzite		

white. Crystals (perfect rhombs) display zoning with "cloudy" cores surrounded by clear rims. Chert is light gray, with orangish color, cryptocrystalline, and occurs as a matrix among the dolomite crystals (Figure 5-1, a); it forms about 5% of the volume of the rock. In addition, a small amount of argillaceous matrix also can be seen between some dolomite rhombs (Figure 5-1 b). In Mlf 1-a, sand-size quartz is very rare.

The diagenetic fabric of Mlf 1-a suggests that the initial carbonate sediment consisted of a lime mud. During early diagenesis, scattered dolomite rhombs grew and incorporated inside the rhombs the original fabric of the lime mud. Later, silica replaced locally the remaining non-dolomitized parts of the original lime mud to form cryptocrystalline chert.

Mlf 1-a is often associated with gray, microcrystalline dolostone and silty microcrystalline dolostone, in which the crystals of dolomite are hypidiotopic and not isogranular, less than 0.05 mm in size, and commonly contain a small amount of relict calcite. Mlf 1-a is partially similar to Lithofacies 1-a, b of Mazzullo and others (1978).

Mlf 1-b (in Little Falls Formation)

The chief rocks of Mlf 1-b are dolostone that is fine- to medium crystalline (0.3 mm); xenotopic and hypidiotopic, light gray or gray. In addition, associated light gray, orangish chert composes about 10% by volume. Very few rounded, fine-sand-size quartz particles are scattered in the dolostone. Microcrystalline dolostone is rare. the chert is mostly cryptocrystalline, but locally microcrystalline (Figure 5-1, c).

Mlf 1-b differs from Mlf 1-a by its abundant chert and fine, xenotopic dolomite crystals. Medium- to fine crystalline texture is common to both.

Mlf 1-c (in Beekmantown)

The typical rocks of Mlf 1-c are dolostone and sandy dolostones. The dolostones



Figure 5-1. Enlarged views of petrographic thin sections prepared from selected samples of cuttings from the Sauk Sequence, Columbia Gas Co. No.1 Finnegan boring, showing microlithofacies; photomicrographs taken in plane-polarized light, except as otherwise noted. (a) Mlf 1-a, Beekmantown group (5930 to 5940 feet). Dolomite crystals (dark areas) in a "matrix" of cryptocrystalline chert. The dolomite rhomb in top center clearly displays an internal zoned texture. Some dolomite rhombs stopped growing when silica began to form. At the bottom of this field of view is microcrystalline dolomite. (b) Mlf 1-a, Beekmantown Group (5930 to 5940 feet). Perfect medium crystalline dolomite rhombs set in a small amount of cryptocrystalline (probably argillaceous) matrix (black).

are characterized by fine crystals (0.08-0.2 mm) that are idioblastic or hypidioblastic. The sandy dolostones (<90%) are mixed with white- and light-gray fine quartz sandstone (10 to 30%). All of these may be transitional from sandstone to sandy dolostone and to dolostone. The sandstone (Figure 5-1, d) consists of quartz, and a few feldspars which include rare plagioclase, orthoclase, and microcline. Interparticle spaces are occupied by fine detrital matrix or by cements. The matrix typically consists of pelitic material that either rims the framework particles or fills pores. The authigenic siliceous cement mainly forms syntaxial overgrowths around detrital quartz. Dolomite also is a kind of cement that replaced earlier cement.

Mlf 1-c is in places associated with medium-gray, silty microcrystalline dolostone.

Mlf 1-d (in Little Falls Formation)

Mlf 1-d is characterized by pure fine crystalline dolostones, most of which are light gray, but a few of which tend toward dark gray. Small amounts of rounded sand-size quartz particles are sporadic between dolomite crystals that are mostly xenoblastic and hypidioblastic.

Mlf 1-d is associated with microcrystalline calc-dolostone.

Microlithofacies 2

Microlithofacies 2 consists of medium-gray, fine-microcrystalline dolostone. I have recognized two sub-facies.

Mlf 2-a (Upper part of Galway Formation)

This microlithofacies consists of fine-microcrystalline dolostone with variable amounts of fine sandstone whose proportion increases from 2 % at the top to 30 % at the bottom. In contrast to all the other light-gray dolostones, that overlie it, the dolostone of Mlf 2-a is mainly medium gray. Most crystals range in diameter from 0.03 to 0.2 mm; the

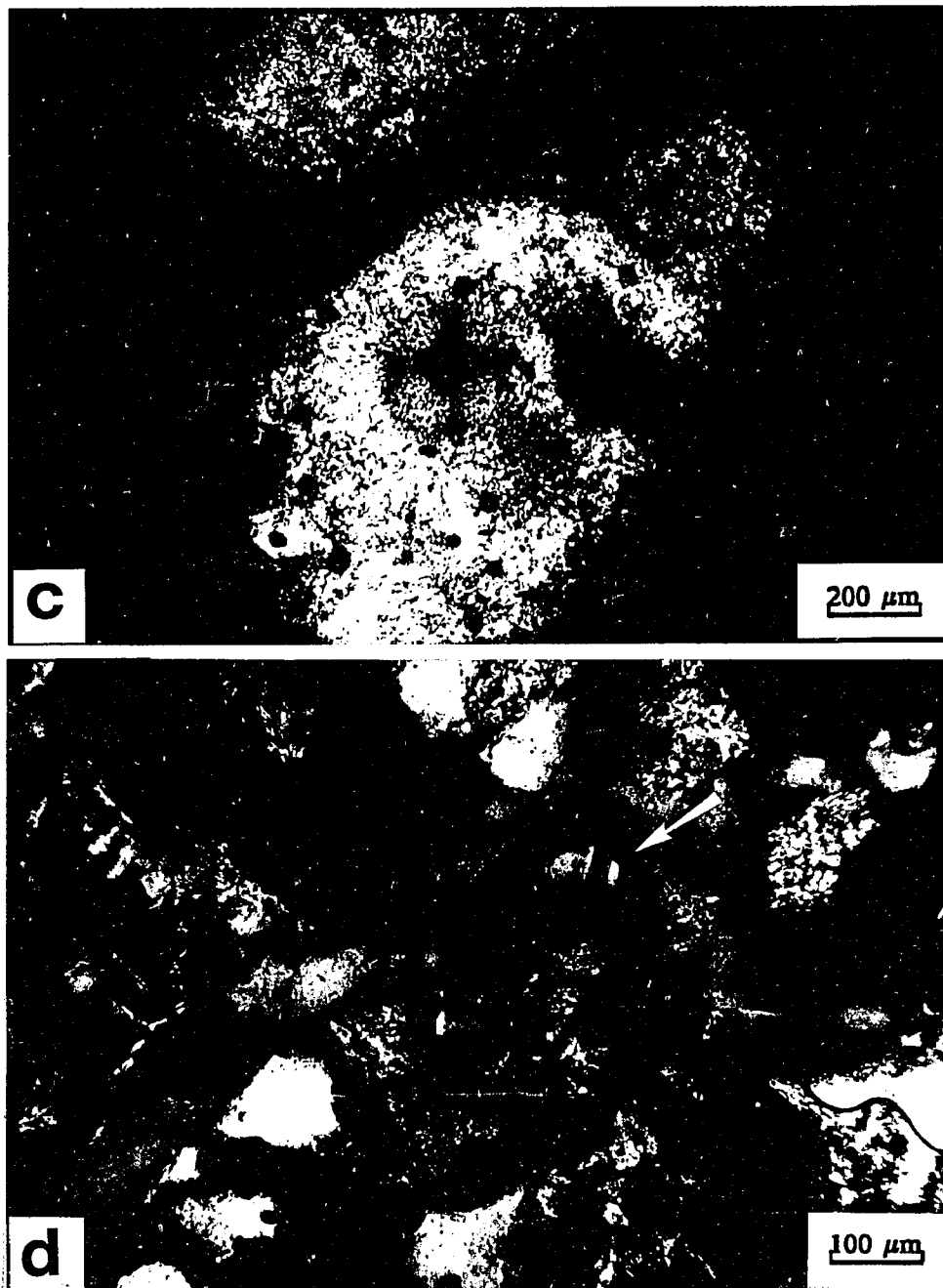


Figure 5-1. (c) Mlf 1-b, Little Falls Formation (6270-6280 feet), crossed-polarized light. The small circular area displaying a dark cross is a filled vug (probably a pseudomorph of a radiolarian). (d) Mlf 1-c, Beekmantown Group, (5970 to 5980 feet), crossed-polarized light. Fine sandstone containing several kinds of feldspar. Overgrowths of both quartz and feldspar are present. The optical orientation of the feldspar overgrowth on the plagioclase particle (indicated by arrow) differs from that of the particle that was enlarged.

diameters of a few are more than 0.25 mm. A little relict calcite is sporadic in the dolostone. An interesting fact is that in the medium crystalline dolomite are found only very few rounded quartz particles; the fine crystalline dolomite contains abundant sand-size quartz; and the microcrystalline dolomite, almost no quartz sand or -silt.

The particles of the sandstones consist of fine, mainly subangular particles at 6430 to 6600 feet; or of medium-, mostly rounded particles below 6600 feet, and with rare feldspar. Overgrowths of quartz and feldspar are widely developed. Both argillaceous matrix and dolomite cement exist. A distinctive feature is the black organic material (oil residue) present in the intergranular pores (Figure 5-1, e) and stylolites of some sandstone chips (Figure 5-2, a), and also in some dolostones (Figure 5-1, f).

The proportion of sandstone increases from top to bottom. In addition, the particle sizes grade from fine to fine-medium at the top to medium at the bottom.

Mlf 2-a is found associated with dark gray- and black shale and shaly siltstone (<5% by volume), which is found scattered throughout the whole interval from 6430 to 6700 feet. In some places in the lower part, however, its proportion becomes more than 20%.

In summary, the Galway Formation can be distinguished from the Beekmantown and Little Falls by color (medium gray); texture (isogranular, fine-microcrystalline); and associated with fine-medium sandstone, in which organic material commonly is present, and with rare dark-gray siltstone and -shale.

Mlf 2-b (lower part of Galway Formation)

The properties of microlithofacies 2-b are similar to those of Mlf 2-a. The differences are: (1) Sandstone has increased in volume to about 50% or more. Two kinds of sandstones are present: very clear, medium- to coarse, quartz sandstone and dolomitic



Figure 5-1. (e) Mlf 2-a, upper part of Galway Formation (6460 to 6470 feet). Fine sandstone composed of well-sorted quartz with interstitial pores filled with oil residue. (f) Mlf 2-a, upper part of Galway Formation (6560 to 6570 feet). Crystalline dolostone in which intercrystalline pores contain oil residue. On the basis of the textural relationship between dolomite rhombs and the pore spaces (rhombs projecting into pores; small rhombs "floating" in the pores), these pores are inferred to have formed by dissolution of nonreplaced original calcium-carbonate mud and thus are of secondary origin.

fine sandstone (Figure 5-2, b). (2) Within the dolostone, which is fine- to microcrystalline and sandy in places, a few relict intraclasts and ooids are observed (Figure 5-2, c, d). (3) Locally, the proportion by volume of the associated siltstone-shale may attain more than 20%.

I consider that Mlf 2-b is a transitional facies between Mlf 2-a and Mlf 4.

Microolithofacies 3

Microolithofacies 3 consists of pure, gray, microcrystalline dolostone that contains a small amount of admixed silt. The dolostone contains a little calcite; some chips effervesce obviously with dilute HCl. The sizes of dolomite crystals range from 0.02 to 0.05 mm. The crystals are isogranular. Hence, the rock fabric is homogeneous, and thus differs from that of Mlf 2-b. But both of them are medium gray and microcrystalline. Accordingly, Mlf 3 may be regarded as a small "finger" of the dolostone correlated with the Galway dolostones.

Microolithofacies 4, quartz sandstone (upper Potsdam)

Microolithofacies 4 includes white, very clear, medium-textured quartz sandstone associated with dolostone and siltstone and shale. The particles in the sandstone range in diameter from 0.1 to 1 mm; they are rounded or subrounded and well sorted. Only a small amount of feldspar is present. Where syntaxial silica overgrowths on the clasts are well developed, this kind of quartz sandstone is termed an orthoquartzite (Figure 5-2, e). Commonly, the crystal sizes of dolomite cement reach 0.01 to 0.04 mm; such cement accounts for an estimated 15% of the total volume of the sandstone.

Microolithofacies 4 is associated with coarse siltstone/very fine sandstone whose proportion reaches 15% by volume. The silt particles are subangular. Both argillaceous- and dolomitic cement are important. Syntaxial overgrowths of cement on detrital particles

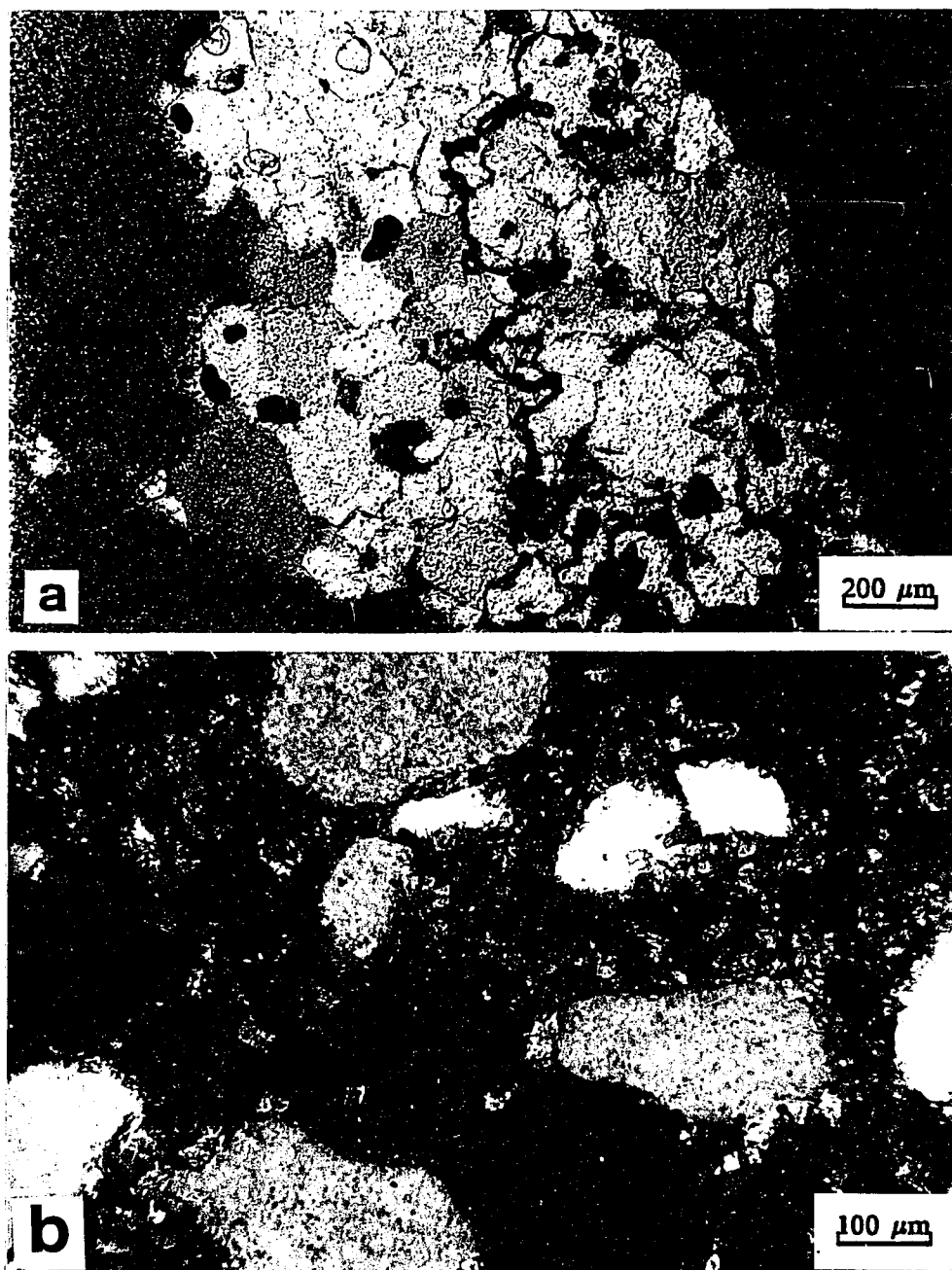


Figure 5-2. Enlarged views of petrographic thin sections prepared from selected samples of cuttings from the Sauk Sequence, Columbia Gas Co. No. 1 Finnegan boring, showing microlithofacies; photomicrographs taken in plane-polarized light except as otherwise noted. (a) Mlf 2-b, Galway Formation, (6820 to 6830 feet). Medium quartz sandstone displaying well-developed quartz overgrowths and stylolite seam filled by oil residue. (b) Mlf 2-d, Galway Formation (6920 to 6930 feet), crossed-polarized light. Dolomitic fine sandstone with interparticle spaces filled by microcrystalline idioblastic-hypidioblastic dolomite crystals some of which have replaced the outer parts of some quartz particles.

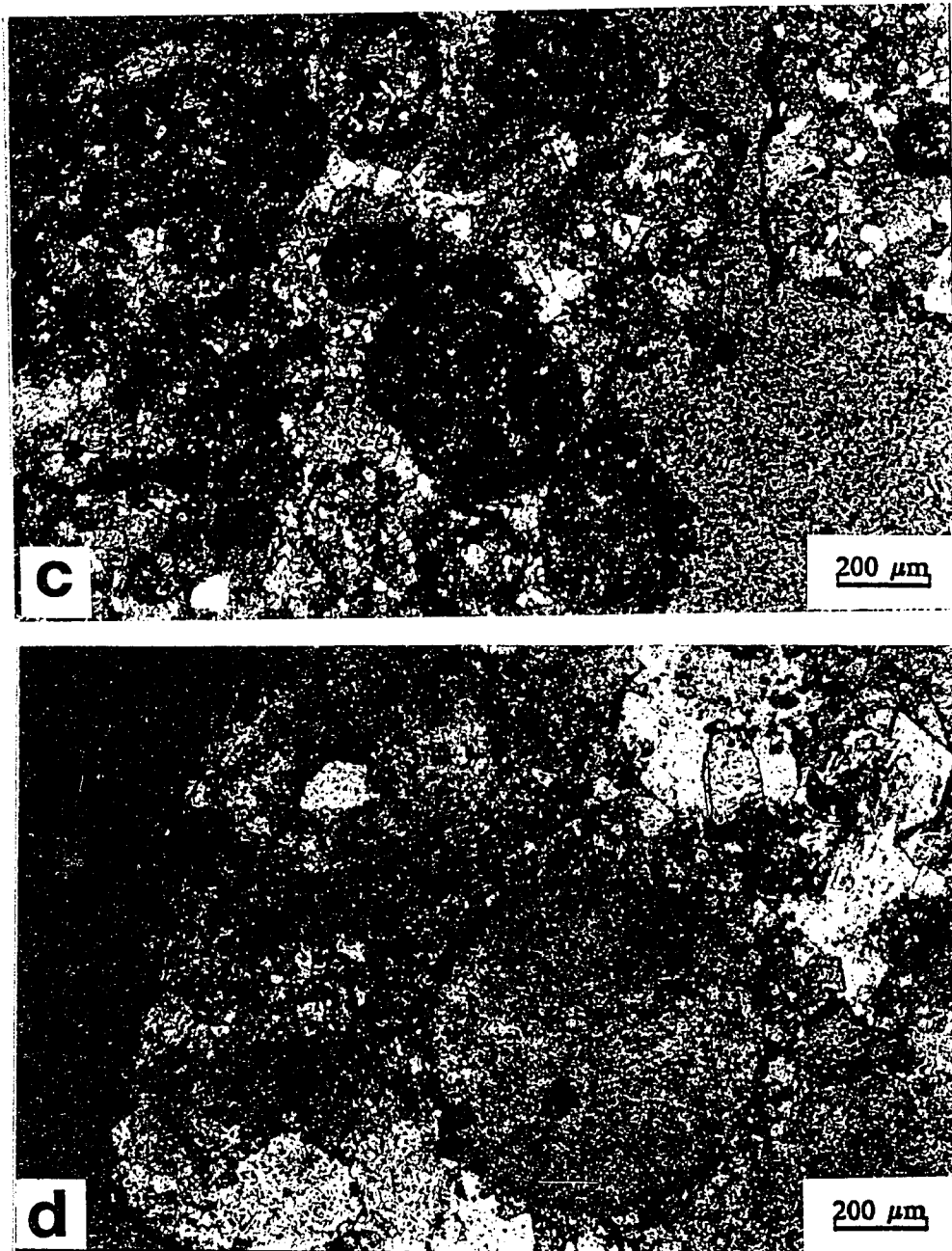


Figure 5-2. (c) Mlf 2-b Galway Formation (6820 to 6830 feet) crossed-polarized light. Relict intraclast dolostone in which cryptocrystalline intraclasts exhibit ovoid- or irregular, subrounded shapes. (d) Mlf 2-b Galway Formation (6920 to 6930 feet), crossed-polarized light. Relict oolitic dolostone in which two of the three ooids in view have preserved their original nuclei and concentric coatings.

are also present.

Dolostone that is gray- to light gray, microcrystalline, and containing calcite locally, forms about 10% by volume. In such dolostone, peloids are observed in places.

Microlithofacies 5: Feldspathic quartzite (lower Potsdam)

Microlithofacies 5 consists of feldspathic white quartzite interbedded with black shale and -siltstone. The clasts of the quartzite are mostly 0.2 to 0.6 mm in diameter; they are rounded to subrounded. In addition to the predominant quartz, feldspar is a normal constituent, accounting for 10%. Orthoclase is the dominant feldspar, but microcline is also present (Figure 5-2, f). Cement consists of pelite (chlorite, less) and of silica overgrowths (more).

In summary, vertically, from top to bottom of the Sauk Sequence of the western-shelf subprovince, (1) dolostone facies is gradually replaced by sandstone facies; the Galway Formation is a transitional zone; (2) the color of the dolostone changes from light gray to dark gray, and the crystal size of the dolomite from medium, fine, to microcrystalline; (3) the particle sizes of the sandstone increase from fine to medium and the content of associated silty shale increases. All of these imply the alternation of depositional environments from shallow marine to transitional, and even to nonmarine.

5.1.2. Interpretation of ancient environment

In addition to the papers cited about lithofacies and depositional environment, these topics have been the subject of papers by Braun and Friedman (1969), Buyce and Friedman (1975), Dolfi and Friedman (1983), Friedman and Radke (1979) and Friedman and Sanders (1984).

As mentioned previously, from the cuttings collected out of the Finnegan boring,

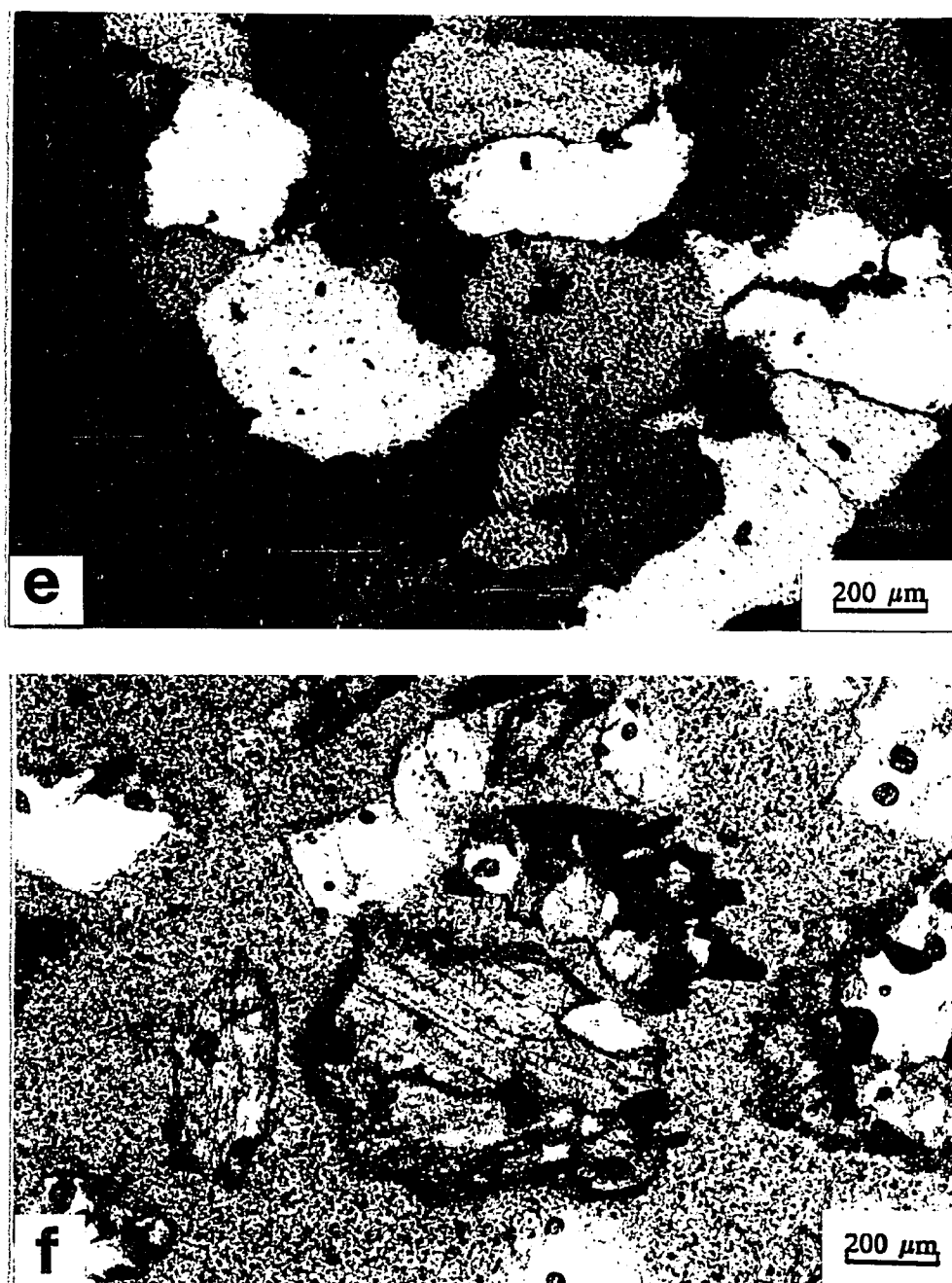


Figure 5-2. (e) Mlf 4, Potsdam Formation (7070 to 7090 feet), crossed-polarized light. Orthoquartzite in which well-developed quartz overgrowths in optical continuity with the original particles have coalesced to form mosaic contacts. (f) Mlf 5, Potsdam Sandstone (7300 to 7310 feet), feldspathic quartz sandstone in which during drilling, the original particles have become separated into chips consisting of individual particles. At center are plagioclase particles.

only limited information for inferring the ancient sedimentary environments is available. First of all, diagenetic processes have partially, in some cases, totally obliterated the original fabric of the rocks. Secondly, cuttings alone cannot provide information about macro-sedimentary structures and paleobiological information. But I can obtain a general indication of ancient environments from microlithofacies analysis to compare with previous studies of lithofacies in adjacent areas. Fortunately, much previous work of ancient depositional environments in northeastern New York State of the Upper Cambrian to lower Ordovician strata has been based not solely on outcrops but included cores as well. In attempting to compare the results from the Finnegan boring with those of previous workers, I confine ourselves to generalized inferences concerning sedimentary environments.

Mazzullo, Agostino, Seitz, and Fisher (1978) based their analysis of depositional environments of the Upper Cambrian-Lower Ordovician (from the Potsdam Sandstone through the Gailor Formation) in the Saratoga Springs area on samples from a long continuous core. They concluded that the depositional environments had ranged from shallow marine to subaerial sea-marginal flats. They identified eight kinds of lithologies. Of these, their Lithologies 1, 2, and 8 closely resemble most of the microlithofacies from the Finnegan boring.

Petrographically, the light-gray, medium crystalline, xenotopic dolomite crystals with multiple-zoned texture and so on of both Lithology 1-a and Mlf 1-a, are very similar. But in Mlf 1-a from the Finnegan boring, no vugs have been seen. Possibly pervasive dolomitization of the strata cut by the Finnegan boring has obliterated all vugs and caused the crystals to be larger and their shapes, more perfect (hypidiotopic or isotopic) than in the rocks near Saratoga Springs. That a little chert has replaced original carbonate may

indicate that the values of the pH alternated between acid and alkaline. The SiO_2 could have come from dissolution of detrital quartz. This implies a semiarid, evaporite setting. Accordingly, I infer that Mlf 1-a, like Mlf 1-a, is of supratidal-intertidal origin.

Mlf 1-b is much more cherty than Mlf 1-a. It implies more- intense evaporitic environment, possibly a supratidal flat.

Mlf 1-d is comprised of pure dolostone that matches Lithology 1-b (Mazzullo and others, 1978) or nondescript dolostone of Mazzullo and Friedman (1975). Because Mlf 1-d was associated with Mlf 1-a, b and contains neither chert nor sand-size quartz, I regard it as the product of intertidal- or subtidal zones.

Mlf 1-c, 2-a, and 2-b are sandy dolostone or dolomitic sandstone. They are equivalent to Lithology 1-d of Mazzullo and others (1978). I infer that they are products of intertidal flats and tidal currents. I interpret the well-rounded- and well-sorted sand-size quartz particles in this facies as being of eolian origin. In the pores of some rocks of Mlf 2-a, oil residues have been preserved. Some relic ooids and intraclasts in Mlf 2-a indicate the primary texture of limestone; they indicate deposition on small ooid shoals.

Mlf 3 is characterized by darker color, finer crystals, and a small amount of calcite. These properties imply that their original equivalent could have been homogeneous carbonate sediment deposited in a marine environment.

Mlf 4 and Mlf 5 are equal to Lithology 8 of Mazzullo and others (1978). The particles of the sandstone of Mlf 4 possess good compositional maturity, and are well rounded and well sorted. They may be products of a nearshore marine environment. But, Mlf 5 sandstones include a certain amount of feldspar, and chlorite cement rims some detrital particles. In contrast to Mlf 4, this environment has been interpreted as a lower-energy nearshore marine setting.

Consequently, I infer that the similarities of the Mlf and the Lithologies of Mazzullo and others (1978) enable me to make projections about the depositional environment: a tropical coastal complex involving intertidal flats, supratidal flats, and low-energy adjacent subtidal (marine). An important lithologic difference between the lithofacies of the Saratoga Springs area and samples from the Finnegan boring is the lack of limestone facies among the chips. Several possibilities may have been responsible for this difference. It could have resulted from a difference of original environment. Or, differential dolomitization may have been involved. All former limestones in the strata cut by the Finnegan boring may have been converted into dolostone, whereas some original calcareous strata near Saratoga Springs may have escaped such conversion. The relict ooids and intraclasts found in chips from the Galway Formation are good examples which indicate dolostone that formed by replacement of an original calcium-carbonate sediment.

Moreover, I can also compare the Mlf of the Beekmantown with the lithofacies of the Tribes Hill [as determined from study of cores from the Mohawk Valley by Curl, Zagorski and Friedman (1984)]. I found similar dolostone- and chert facies in both units. From this similarity, I also infer a supratidal- and intertidal depositional environment for the strata cut by the Finnegan boring.

5.2 Central shelf (Wappinger Group)

In Chapter 4, I have presented a summary description of the strata-, lithology-, and depositional environment of the Wappinger Group. The change in lithofacies from bottom to top is obvious: orthoquartzite (Poughquag); pale-gray to white-, fine- to very fine dolostones (Stissing and lower unit of Pine Plains), cyclic sandy fine- to medium dolostones (middle and upper units of Pine Plains); vague cyclic silty fine- to medium

dolostone (Briarcliff); massive medium- to fine calcdolostone (Halcyon Lake), and fine dolostone and limestone interbedded (Rochdale and Copake). Of these dolomitized formations, the dolostones of the Pine Plains Formation have best preserved the original textures and depositional structure. From facies analysis of the Pine Plains Formation, I can determine the ancient environments and then infer the depositional environments of the other formations. Finally, I discuss the environmental evolution of the Wappinger Group from Early Cambrian to Early Ordovician and also make a comparison between the variations in depositional environments of the Sauk strata of the central-shelf- and the western-shelf subprovinces.

5.2.1 The best choice of facies study: Pine Plains Formation

The Pine Plains Formation constitutes a major part of the Wappinger Group, because its thickness is large, more than one third of thickness of the whole Wappinger Group. Moreover, the uppermost formations, such as the Copake and Rochdale, and the lower formations, such as Stissing and Pouqhqaug, are rarely exposed. In the study area, the Pine Plains Formation can be recognized easily by its various lithologic- and cyclic features.

Compared with other formations, the Pine Plains Formation shows its unique features, such as: (1) Its lithofacies is stable, and comparable from New Jersey (Allentown Formation of the Kittatinny Group) to eastern New York. (2) Most of the depositional features of the precursor calcium-carbonate sediment are well preserved. (3) Cyclic features. Small-scale cycles in the Pine Plains Formation are notably preserved (Figure 5-3).

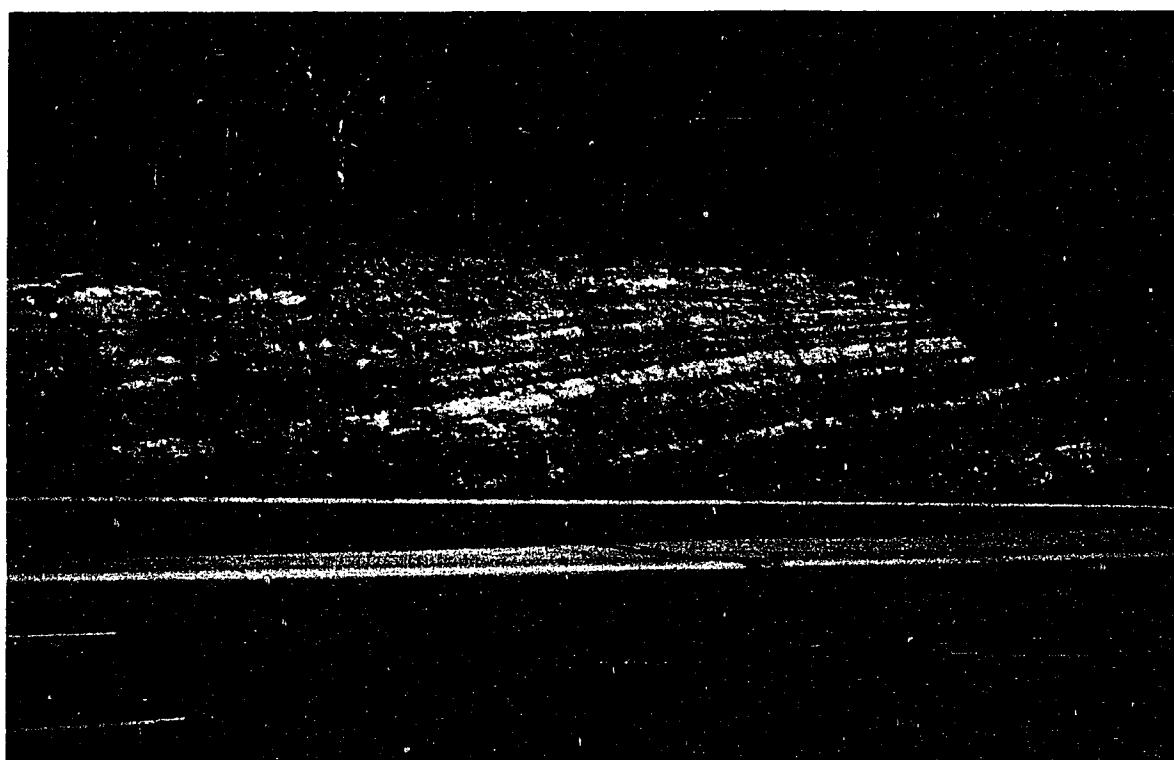


Figure 5-3. Outcrop view of cyclic features of Pine Plains Formation exposed in roadcut on U. S. Route 9, junction with Spackenkill Road, Town of Poughkeepsie, Dutchess County, New York. View eastward of the cut, opposite Friendship Motel. Repeated repetitions of light gray- and dark gray dolostones are expressions of parasequences.

5.2.2 Depositional cycles- Parasequences and Facies Relationships

In the middle- and upper part of the Pine Plains Formation, the basic motif of the strata is represented by distinctive kinds of cyclically repeated layers, or facies. I interpret these cycles as parasequences (Friedman, Sanders, and Kopaska-Merkel, 1992; Friedman, 1992c) that formed by deposition at the margin of a tropical sea in an arid (or semi-arid) climate. In such settings, contrasting sediments are deposited in the various environments defined by tidal levels. As a first approximation, three such environmental settings are subtidal, intertidal, and supratidal.

All kinds of sedimentary characteristics, many of which are products of distinctive environmental settings, can contribute to the cyclic features of a formation. These include color, texture (crystal- or particle-size, particle type, such as micrite, pellet, ooids, etc.), composition (carbonate, terrigenous sands and mud, etc.), primary sedimentary structures (bedding, laminae, biturbation structures, etc.).

The initial event in the deposition of each parasequence was a rapid submergence. Beneath the lowest tide level of the newly risen sea, subtidal sediments were deposited. Given the large quantity of carbonate sediments that can be formed along a tropical coast in an arid climate and a relatively stable sea level following the initial rapid submergence, with time, the abundant carbonate sediments will accumulate near shore and will prograde the shoreline seaward. The abundant carbonate sediments will convert parts (or all) of the former shallow sea floor into dry land. As the intertidal/supratidal zone migrates seaward, at first intertidal sediments and then supratidal sediments cover the earlier-deposited subtidal sediments. After the supratidal zone has become established, a stretch of territory, formerly submerged, becomes subaerially exposed. If sea level dropped for any considerable length of time before the next rapid submergence

reestablishes the conditions for deposition of a new parasequence, the effects of emergence may be intensified. If during emergence, the hydrologic regime were to change from arid to humid, then conditions would be established for developing karst features, such as dissolution-enlarged cracks, caves, and sinkholes (Friedman, 1992b, c, d, 1993a, b).

5.2.2.1 Facies

As a result of these conditions and continuing subsidence, a succession of parasequences would be deposited, each ideally consisting of three facies, and always forming the same pattern of layers. From bottom to top the facies formed are designated as: A (subtidal); B (intertidal); and C (supratidal). Because of variations in the depositional environment, not every parasequence contains all three facies. In most cases, however, at least two of these facies, always in the same fixed order where the shoreline has prograded seaward, are present in each individual cycle in the patterns (from bottom upward): ABC-ABC; AB-AB; or some variant thereof (Figure 5-4). Some of the characteristics of these three facies are summarized below. I illustrate these with selected examples from both the middle- and upper parts of the Pine Plains Formation.

Facies A- subtidal

Facies A can be subdivided into subfacies consisting of A₁, massive fine- to medium dolostone formed from calcium-carbonate grainstones, many oolitic and containing rounded intraclasts (Figure 5-5 a, b); sandy dolomitic grainstones; and dolomitic sandstones; and A₂, finer, very fine massive dolostones. Coarser grainstones may overlie finer massive dolostones to constitute an upward-coarsening parasequence, which is the opposite to the usual variety mentioned previously.

Most of the medium dolostones display ghosts of precursor carbonate sand-size

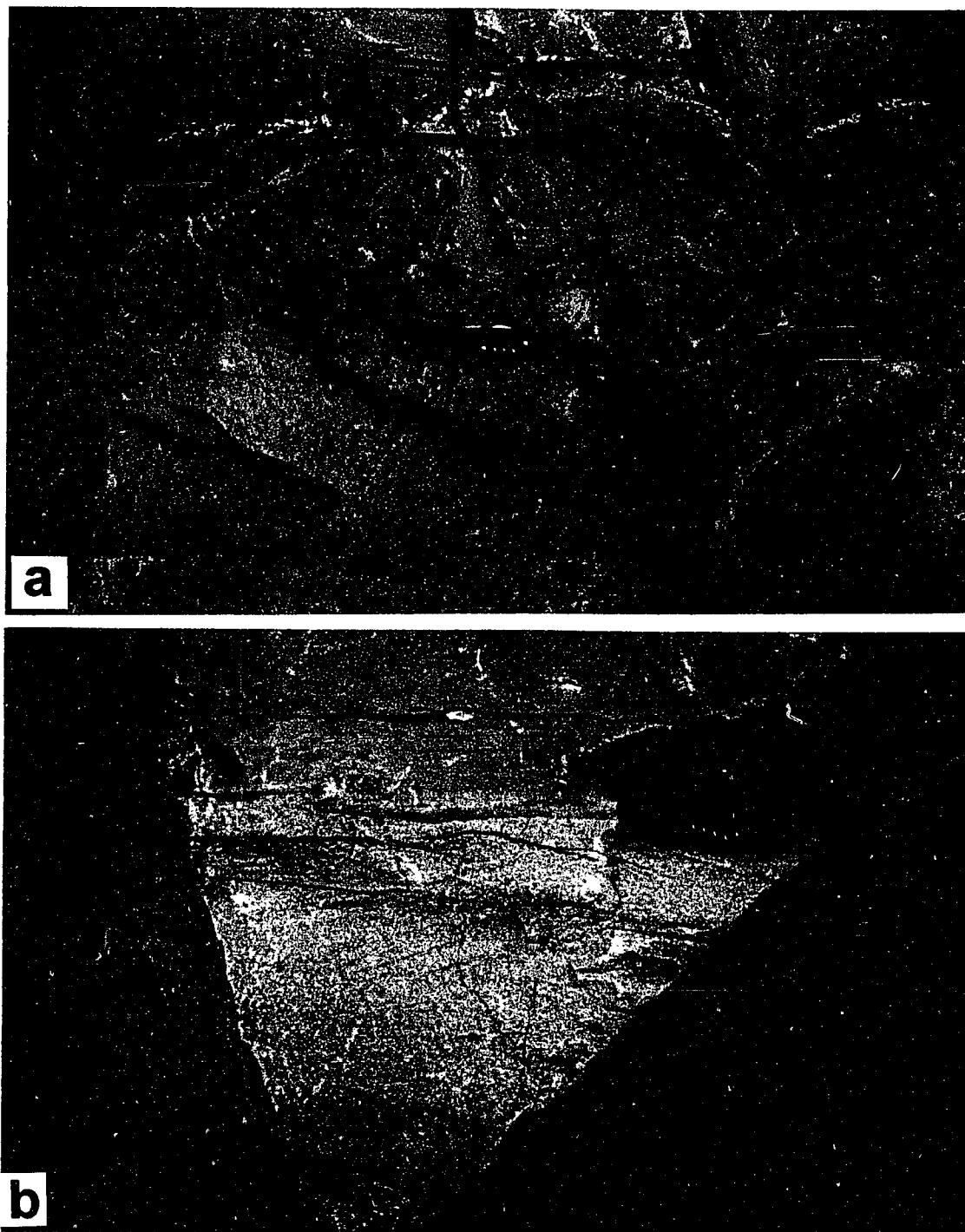


Figure 5-4. Views of Facies A and B, Upper Pine Plains Formation, loose quarried blocks on W face of Clinton Point Quarry. (a) Close view of parasequence consisting of Facies A (below knife, coarser and lacking well-developed layer structure) and B (above knife, finer and displaying prominent layers). (b) Close view of Facies A (below) showing sets of oppositely dipping small-scale cross strata. The overlying layer consists of Facies B, fine crystalline dolostone.

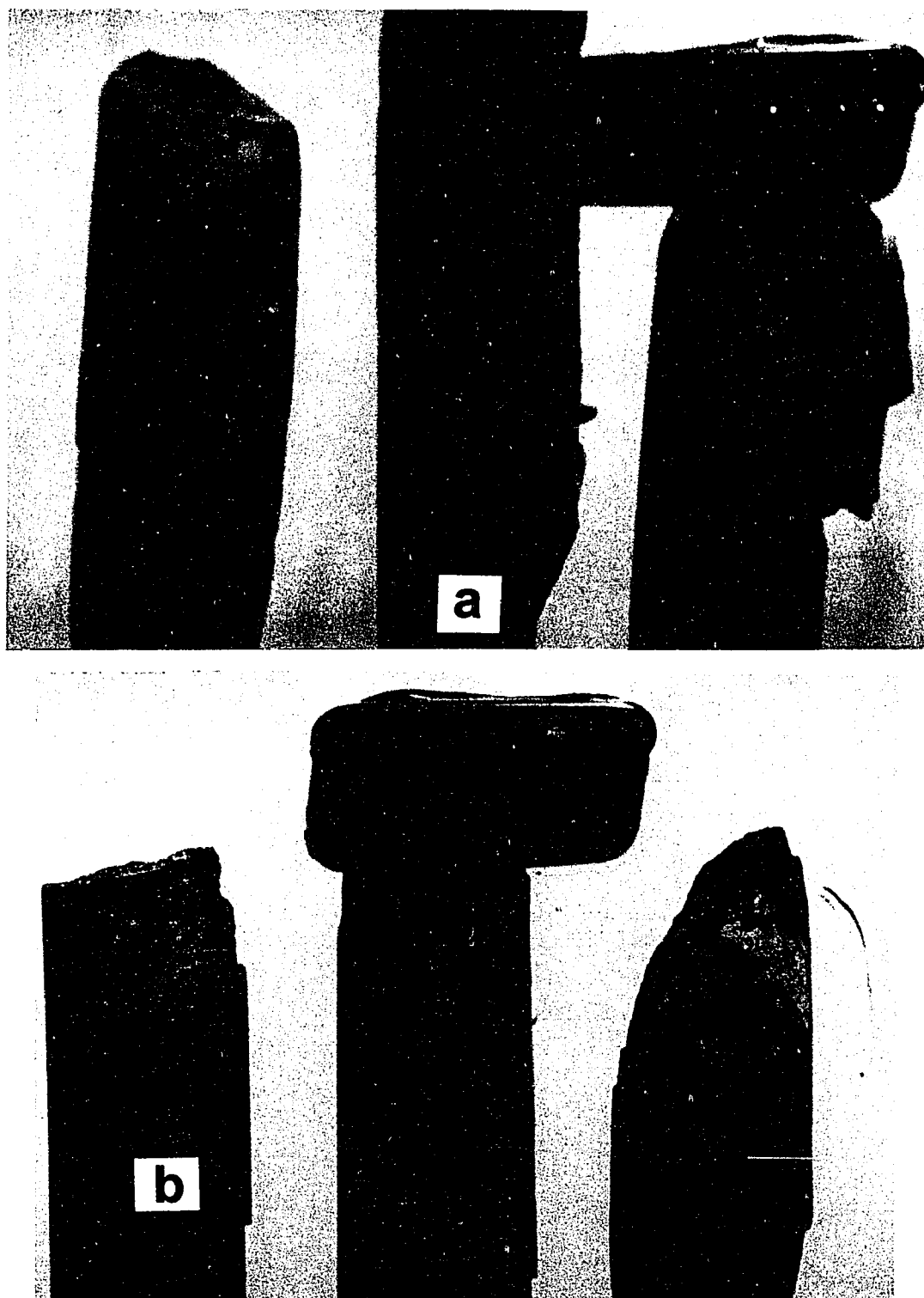


Figure 5-5 Facies A, core 73-91, Pine Plains Formation, Clinton Point Quarry: (a) medium to coarse dolostone with intraclast; (b) dark-colored oolitic dolostone.

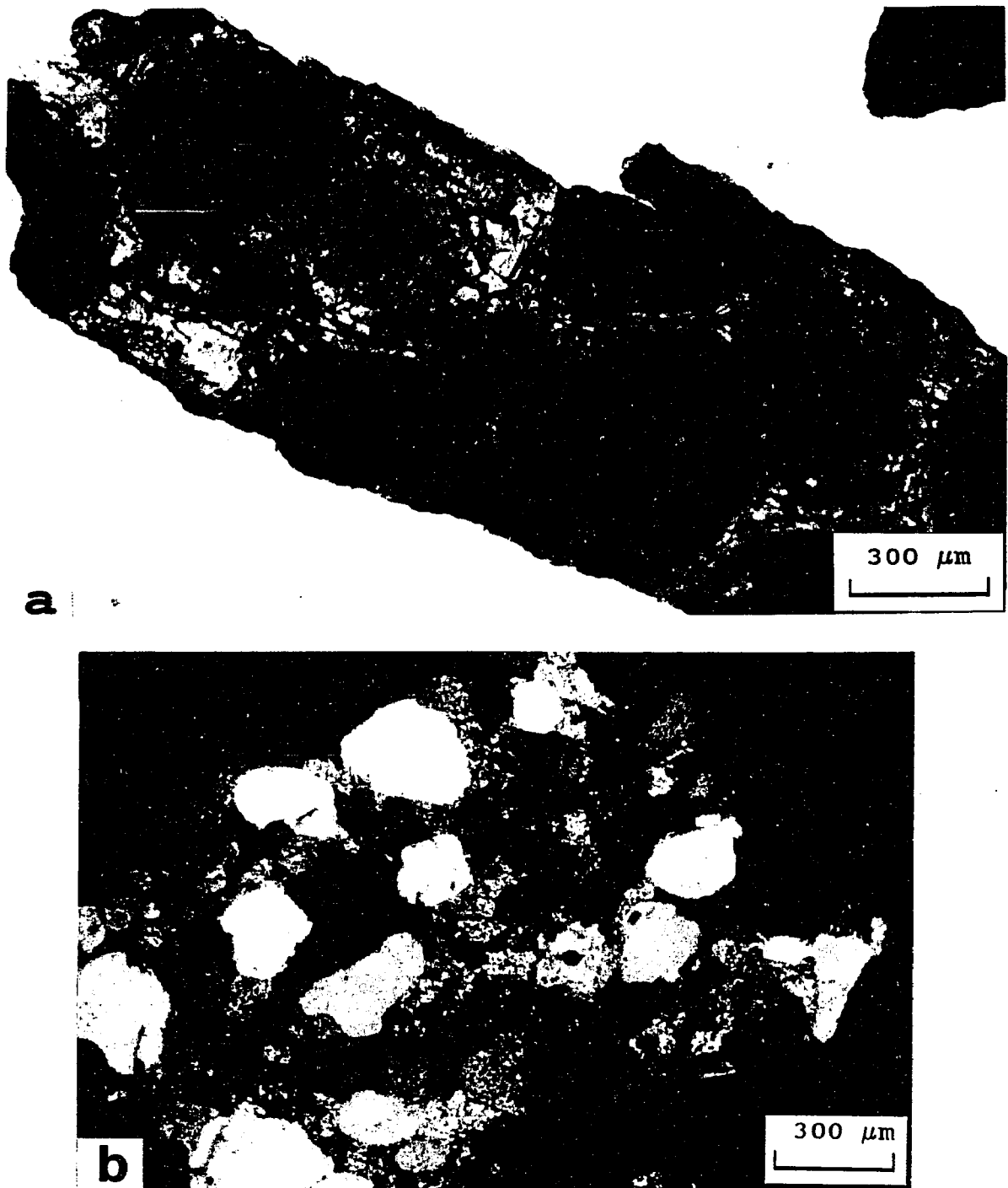


Figure 5-6 Facies A: (a) oolitic dolostone with well-preserved fabrics from precursor carbonate, ARCO No. 1 Susi, depth 6120 to 6130 ft. (b) sandy grainstone from Pine Plains Formation, Crom-Wells No. 1 Fee boring, Orange County NY.

particles (137', 148', CP1-b from Clinton Point Quarry Core 73-91). The true- or relic particles include intraclasts, algal debris, ooids, pellets, and various skeletal materials whose state of preservation is a function of recrystallization. In places, the original oolitic texture has been preserved perfectly (Figure 5-6, a and 6-2, b). Both the original nuclei as well as the concentric laminae of such ooids can be recognized and, under crossed-polarized light, an extinction cross is visible. In partly recrystallized ooids, the crystal sizes of the dolomite within the ooids increases from interior to margin.

Commonly, the oolitic grainstones are dark gray and fine- to medium crystalline, unimodal planar-s texture. By contrast, skeletal grainstones are gray to light gray, fine- to medium crystalline, unimodal or polymodal planar-s texture, and may be bioturbated.

In the grainstones, rounded sand-size quartz particles are common (Figure 5-6, b). The amount of these sand-size quartz particles increases towards the western-shelf subprovince. In the Columbia Gas No. 1 Finnegan boring, the proportion of sandy dolostone and sandstone ranges between 5 and 80 %, and the average is 30%; in the Crom-Wells No. 1 bore hole, about 5 %; and in the ARCO No. 1 Susi bore hole, rare. By contrast, grainstone (especially, oolitic) increases from west to east.

The thickness of facies A₁ in a parasequence typically ranges from 10 cm to >1 m, or even a few meters. The rocks may or may not be cross stratified or display burrow mottling from extensive bioturbation. I interpret this facies as deposits of subtidal shoals or -bars, even tidal inlets.

Facies A₂ consists of gray, fine- to very fine massive dolostone, rarely with laminae. I infer that this facies is a product of a subtidal environment not influenced by wave action, currents, or burrowing organisms.

Facies B (intertidal)

In contrast to the massive aspect of Facies A, the rocks of Facies B are distinctively layered on a small scale, and display various sedimentary structures. In vertical section, from bottom to top, facies B could consist of the following subfacies.

B₁: Intraclasts (or edgewise) dolostone consisting of intraformational sharpstone breccias (Figure 5-7, a), or flat-pebble intraclast conglomerates. These represent the deposits of small channels, or local scour lags.

B₂: Small-scale-cross-bedded packstones and -wackestones. Both B₁ and B₂ represent intertidal-channel deposits.

B₃: Well-layered wackestone or mudstone displaying wavy bedding, flaser bedding, lenticular bedding and/or fenestral fabric. B₃ is the most-abundant intertidal facies and includes three varieties: (1) wavy beds, with lighter- and darker laminae in about equal amounts (Figure 5-7, b); (2) Gray, fine-, with sparse very fine, dark laminae; (3) and dark gray, fine- or very fine laminae that may be interlayered with sparse fine, gray laminae.

The crystal sizes vary in different laminae. The thicknesses of the laminae range from < 1 mm to centimeters. In very thinly laminated rocks, regarded as a typical intertidal facies, some argillaceous- and quartz silts are mixed with dolomite; in a few laminae, these noncarbonates form the majority constituent.

In facies B₃, ripple marks, burrow mottles, and geodes are common. I interpret this facies as deposits of intertidal flats, tidal creeks, or possibly even of upper subtidal environments of a backbarrier complex.

B₄: Light-gray vuggy fine crystallized dolostone. This particular facies is characterized by its unique, readily visible vugs (Figure 5-8, a, b). The shapes of the vugs are spherical, which indicates an origin by dissolution; they postdate the shallow-burial

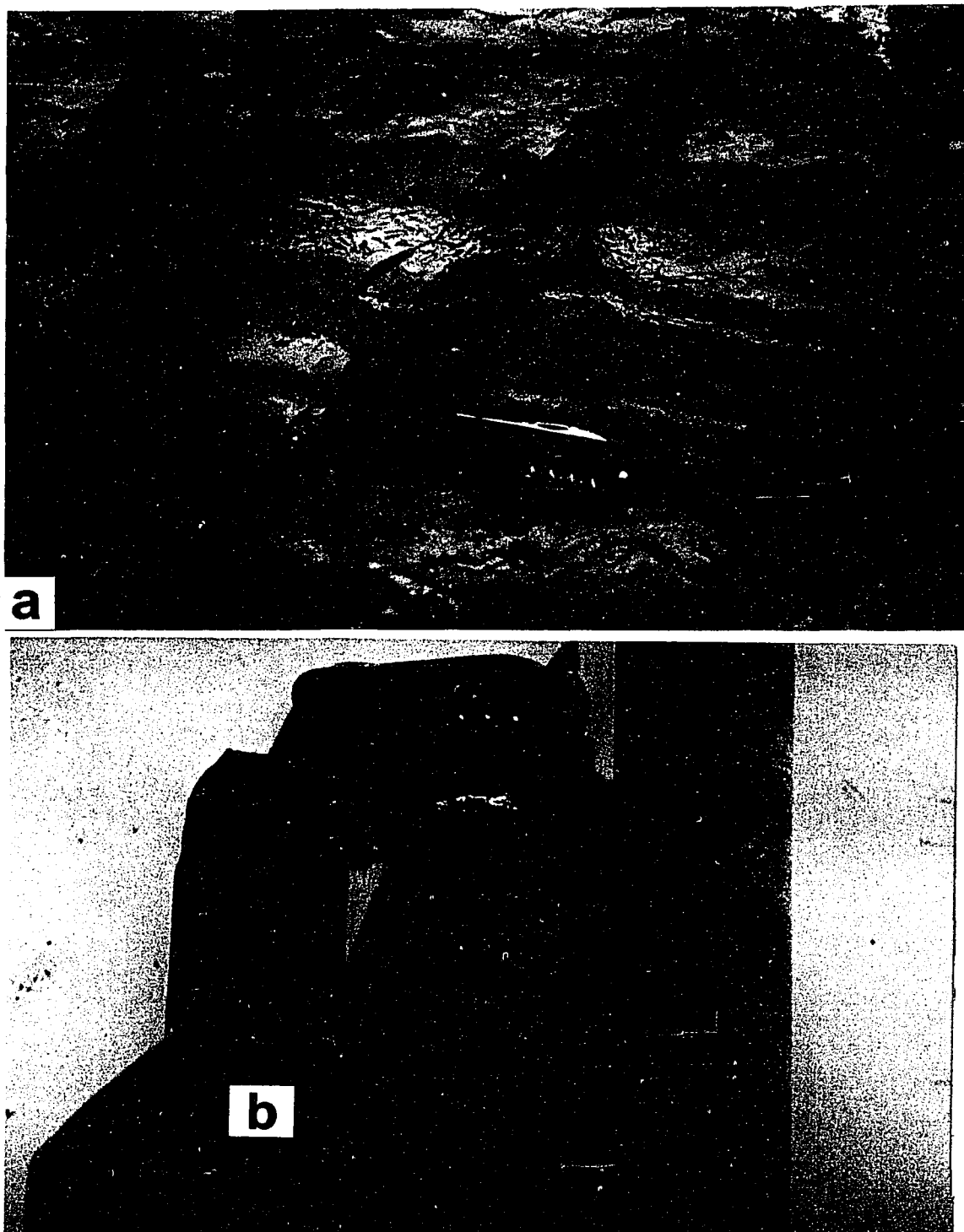


Figure 5-7 Facies B: (a) close view of intraformational sharpstone conglomerate, which represent small channel deposits; W face of Clinton Point Quarry; (b) wavy-bedded dolostone with lighter- and darker laminae in about same amount, core 73-91, Clinton Point Quarry.

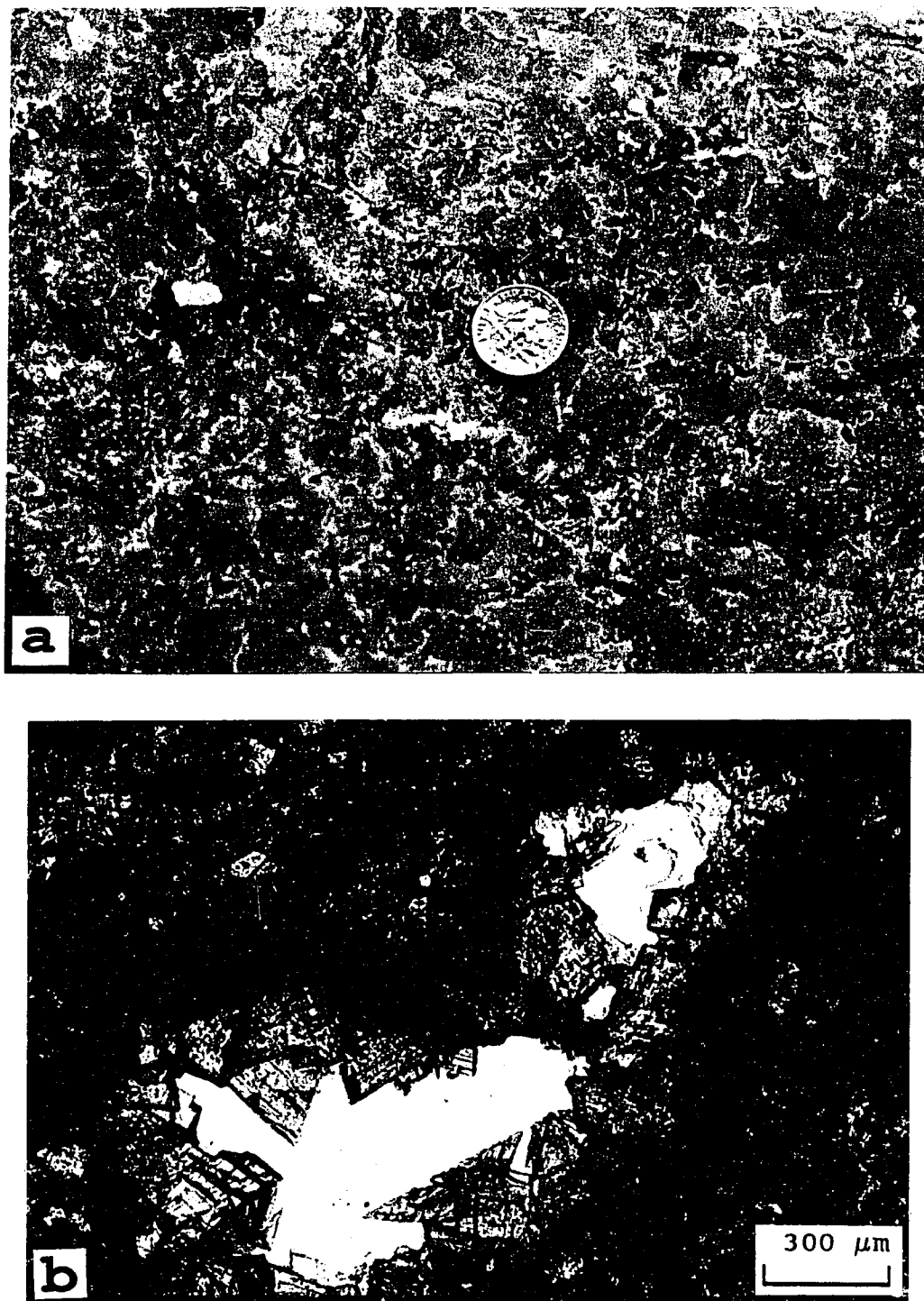


Figure 5-8 Vug dolostone: (a) close view of a loose block, W wall of Clinton Point Quarry; (b) enlarged view, plane polarized light.

dolomite. The vugs formed during earlier diagenesis are rimed/filled with late-diagenetic products, such as quartz and saddle dolomite. As the vugs are limited only to certain layers, I infer that the dissolution was related to surface water instead of formation water. The vuggy dolostones are not laminated. Therefore this kind of dolostone may be initially subtidal carbonate and later dolomitized. Then, they were exposed near the Earth's surface and underwent dissolution.

Facies C (supratidal)

The diagnostic features of Facies C include algal stromatolites, mudcracks, and features formed by subaerial exposure such as karst-depression breccias (Friedman 1992 b, c, d). I recognize two subfacies.

Subfacies C₁ are stromatolites; these are very distinctive and clearly visible in both fresh- and weathered exposures (Figure 5-9, a, b). They are present at the top of the intertidal-supratidal cycle.

Subfacies C₂ includes various sedimentary breccias. Of these, karst breccias are common. Many consist of angular clasts of all sizes jumbled together (Figure 5-10, a). In some, light-gray clasts are set in a dark-colored matrix which closely resembles the dark nonsoluble material that accumulates along stylolites. The order of abundance of the clasts in the karst breccias is: grainstones, fine-crystalline dolostones, and oolitic dolostones.

Although Knopf recognized using a widespread layer-parallel variety of sedimentary breccia as a marker for the base of the Pine Plains Formation, discordant karst-type breccias have not been reported by any previous investigators of the Pine Plains Formation. As illustrated in following sections, I have found karst breccias in many localities. By karst breccias I mean breccias filling sinkholes. In some cases, these repre-

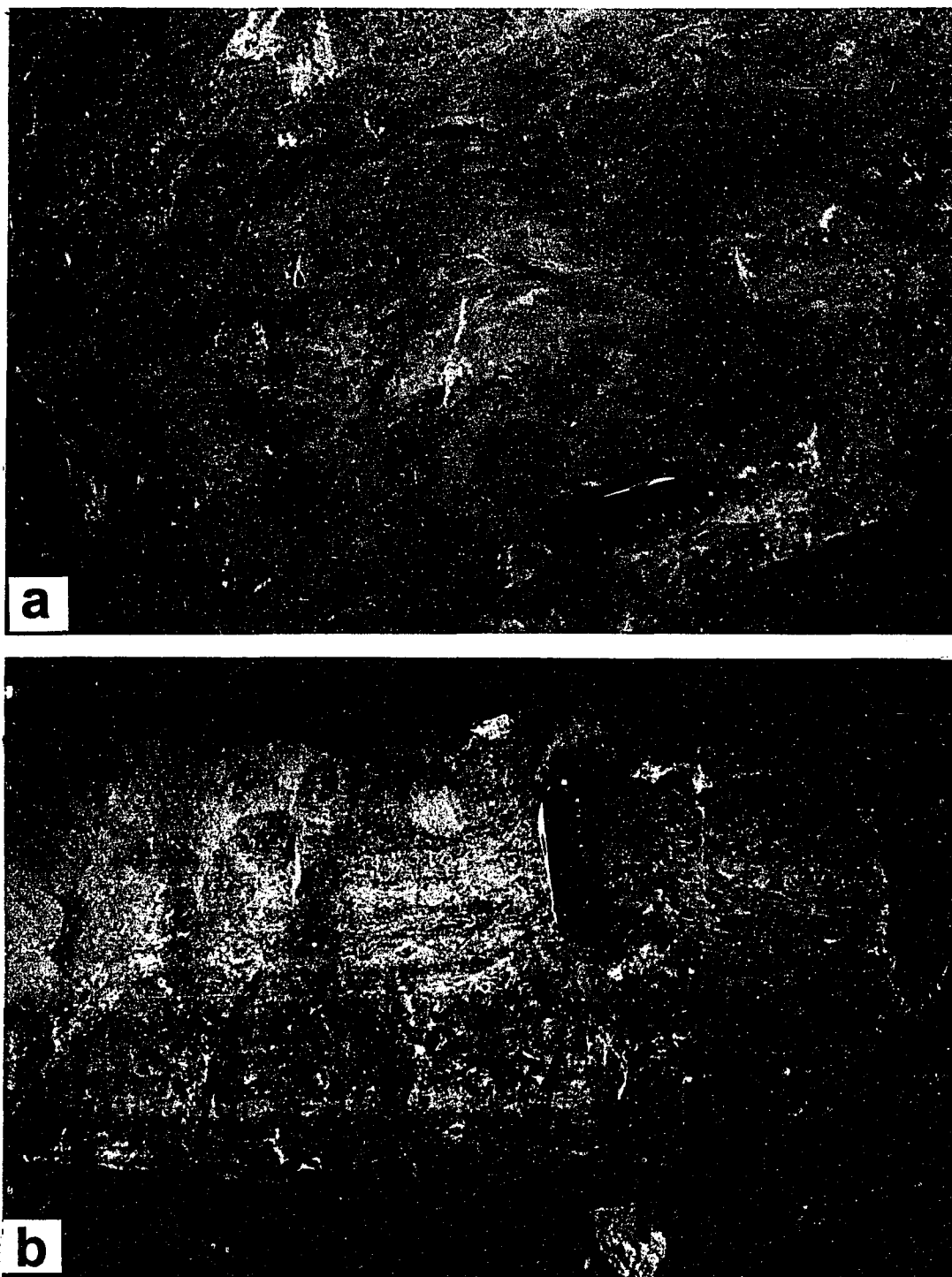


Figure 5-9 Facies C, close view of algal stromatolites: (a) shows convex-up domal- and columnar structure. The largest "dome" is just above the knife; the one at left shows the columnar structure most clearly; (b) algal laminae. Loose blocks from W wall of Clinton Point Quarry.

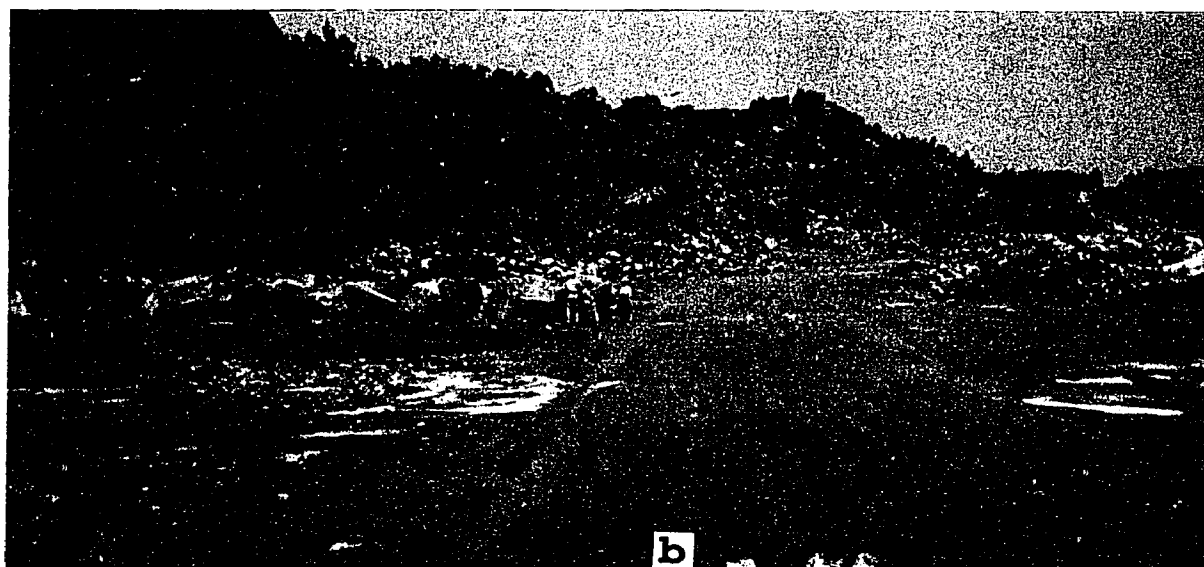
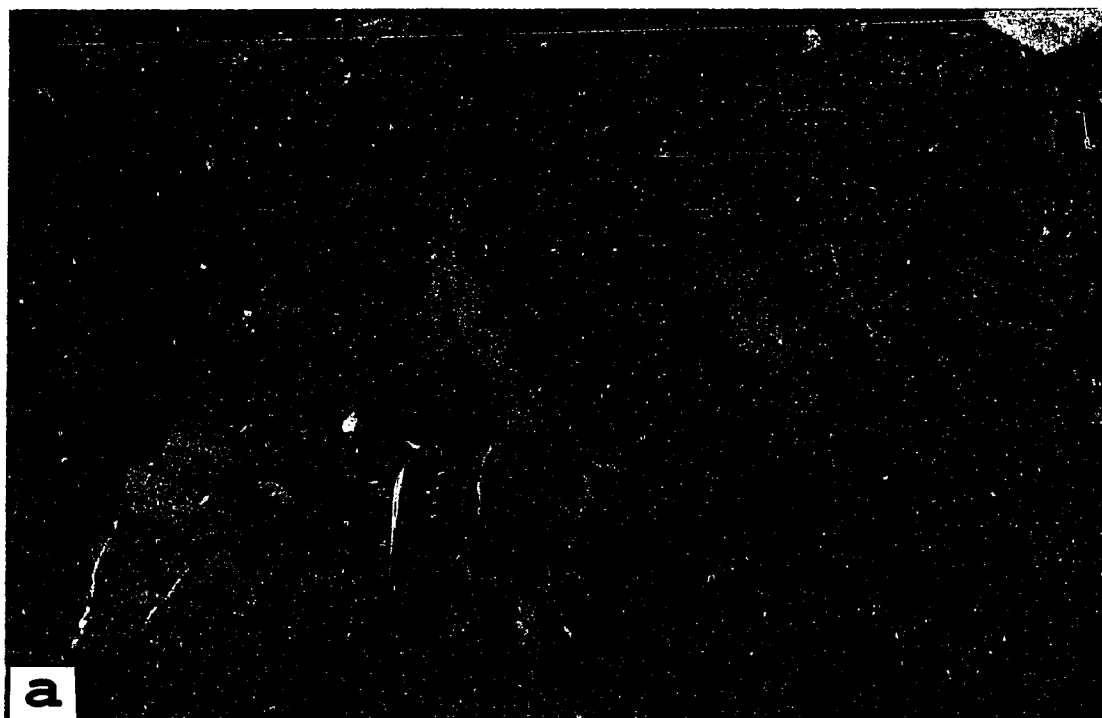


Figure 5-10 Karst breccia : (a) close view of massive paleokarst breccia including a large block of well-bedded dolostone above knife; (b) massive, coarse paleokarst breccia filling steep-sided sinkhole (wall marked by dashed red lines). Clinton Point Quarry, W face.

sent collapsed roofs of caves and the material is *in situ*. In other cases, brecciated material may have been reworked by the transgressing sea and washed into open cracks in the rocks below. The key relationship in either of these situations is a steep (vertical- or even overhanging) contact between breccia and other kinds of rocks (Figure 5-10, b). Layer-parallel breccias may form where karstification formed *in situ* and even overlie stromatolites.

5.2.2.2. Parasequences

The facies and subfacies described in the previous section may have been deposited in lateral continuity with one another. Laterally adjacent facies can be superposed in vertical patterned successions as a result of the forward growth of depositional slopes (such as on fans or at the shore) and/or changes of base level. Thus, they follow the principles elucidated by Lavoisier [for the cases related to changing sea levels (more commonly known as Walther's law; Friedman, Sanders, and Kopaska-Merkel, 1992, p. 7-9, 177-181)]. I have found the most-common parasequences to consist of the following combinations:

- (1) A_1/A_2 , subtidal deposits, upward coarsening.
- (2) B/A , subtidal- and intertidal deposits, upward fining.
- (3) B_3/B_{1-2} , intertidal channel and -flat, upward fining.
- (4) B_3/C_2 , intertidal-supratidal, upward fining.
- (5) $C_1/B_1/B_2/B_3$, intertidal-supratidal.

Hence, ideally, one single sequence of events including submergence, progradation, and emergence should cause a entire parasequence to be deposited consisting of A, B, C, facies from bottom to top. Its subfacies order should be A_1 , A_2 , B_1 , B_2 , B_3 , C_1 , C_2 . However, I never found such an ideal parasequence involving all subfacies

in outcrops or in cores.

5.2.2.3. Example of sequence analysis in cores of bore hole 73-91, Clinton Point Quarry

Clinton Point Quarry bore hole 73-91 was continuously cored in 1991 by the Lone Star Industries Corporation. The purpose of this hole is to penetrate a stratigraphic interval within the Pine Plains Formation that is likely to be quarried in the future but that former cores did not penetrate. Based on a comparison with the cuttings from ARCO No. 1 Susi borehole, I infer that the strata penetrated by core 73-91 belong to my newly recognized middle unit of the Pine Plains Formation.

Core 73-91 cuts parts of the Pine Plains Formation that are not exposed in the existing quarry facies. The average dip of the strata cut by core 73-91 is about 40 to 50°; this means that the 245-foot core cut 150 stratigraphic feet of the formation. Many varieties of dolostone and breccia are present.

Core- and related thin-section study and description of bore hole 73-91 provide sufficient information for recognizing facies and carrying out sequence-stratigraphic analysis. Figure 5-11 shows the result of facies study and sequence-stratigraphic analysis. First, I studied the lithologic composition and sedimentary structures to classify the facies. After I had organized the facies, I could recognize parasequences and find the parasequence boundaries, or **parasequence surfaces** (defined as surfaces resulting from erosion or nondeposition, or the correlative conformable surfaces. Abrupt facies changes are regarded as good criteria for recognizing parasequence surfaces. Several similar parasequences can constitute a parasequence set (PS set).

In Core 73-91, I have used karst-type breccias to recognize four upward-shoaling units (larger than parasequence sets) and above a possible fifth such unit, because each layer of karst-type breccia indicates an interval of erosion. In the hierarchy of sequence-

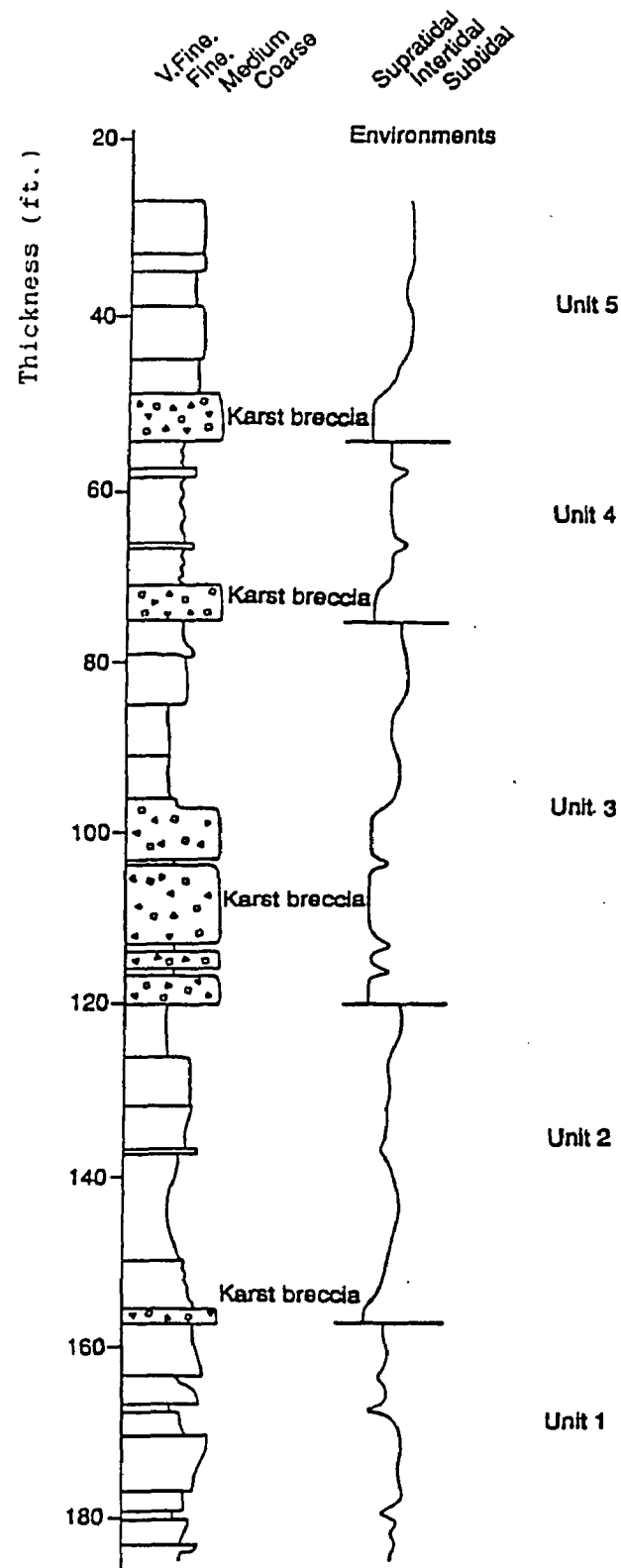


Figure 5-11 Columnar section of cored boring 73-91 through middle part of Pine Plains Formation, Clinton Point Quarry, Poughkeepsie, NY, showing results of sequence-stratigraphic analysis results.

stratigraphic terms, the designation for the unit of next-higher rank above parasequence set is **facies tract**. I do not think these "units" in Core 73-91 are the same as "facies tracts"; hence, I avoid using that term.

I have numbered these units starting with 1 at the bottom and increasing upward. As discussed below, each unit possesses its own distinctive depositional products.

Unit 1: Above the base in Unit 1, oolites prevail. These are the inferred products of subtidal oolite shoals or -bars. In this interval, upward-coarsening parasequences are typical. In the upper part of Unit 1, the depositional products of tidal channels are present. Here, upward-fining (typical) parasequences prevail. This upward change from subtidal shoal- or -bar- to intertidal settings, indicates that Unit 1 is a progradational unit (one that accumulated while the position of the shoreline was shifting progressively seaward).

Unit 2: The base of Unit 2 is marked by a karst breccia 2 feet thick. This breccia indicates that after Unit 1 had been deposited, an episode of emergence followed during which karst features were developed. During the next submergence, the karst products were deposited as a breccia and the region returned to being a submerged carbonate shelf. Because the clasts in this breccia seem not to have moved far away from their original positions, I infer that the duration of the episode of subaerial exposure was short and the total erosion, slight. In this unit, I define 4 parasequences. Near the bottom of Unit 2 are products of lower intertidal flats. These pass upward successively into products of upper-subtidal settings; lower-subtidal settings; and finally, to products of shoals and bars of a subtidal setting. This progression indicates that Unit 2 is a retrogradational parasequence set (one that accumulated while the position of the shoreline was shifting progressively landward).

Unit 3: The lower part of Unit 3 consists of a zone 18 feet thick in which 4 breccias are

interbedded with wackestone or mudstone deposited on intertidal flats, thus forming 4 parasequences. This juxtaposition implies that sea level oscillated often. Each breccia-mudstone pair implies a change from emergence to submergence and back again to emergence. Thus, these four parasequences consist of a parasequence set which represents a supratidal-intertidal setting. The upper part of Unit 3 consists of subtidal deposits. Hence, unit 3 also represents a retrogradational set.

Unit 4: Unit 4 starts with a karst-type breccia, 4 feet thick, that is overlain by characteristic depositional products of intertidal flats and tidal creeks. I found wavy bedding typical of intertidal flats in this unit. Vertically through Unit 4, the facies do not change significantly. I infer that Unit 4 is an aggradational parasequence set (one that built upward while the shoreline remained in about the same place as time passed).

Unit 5: Because of tectonic activity, most of the rocks in Unit 5 have been broken. Thus, it is difficult to establish parasequences. Despite the tectonic effects, most of facies are oolitic which represent subtidal-zone deposits. At the base is a karst breccia as below.

5.2.3 A brief summary of environmental evolution during deposition of the Wappinger Group

Many depositional signals can be used to determine ancient environment (paleogeography, water depth, sediment supply, water energy, water salinity, etc.). The most-important signals include depositional texture, structure, lithology, fossils, vertical sequence, and lateral morphology of the depositional bodies (Reading 1986; Friedman and Sanders 1978; Friedman, Sanders, and Kopaska-Merkel 1992). Unfortunately, few fossils were found by Knopf (1962) in the Wappinger Group. Moreover, dolomitization wiped out depositional signals seriously. These create difficulties for reconstructing

original depositional environments. In this section, I summarize briefly the evolution of environment for the Wappinger Group on the basis of the results of the Pine Plains Formation (former section) and the study of the other formations.

I have used the following signals (characteristics) to determine water depth, water energy, and environmental zone (supratidal, intertidal, subtidal, shallow marine, etc.), as shown in Figure 5-12.

1) Depositional structure: various cross strata, ripple marks, breccia, bioturbation features, etc. are well-known features used in facies analysis.

2) Carbonate sands (or allochems, such as skeletons, ooids, pellets, intraclasts, etc.) are products of the high-energy zone (intertidal and upper subtidal). Silt-size pellets/peloids are also abundant in lower-energy zones.

3) Crystal size of dolomite. As discussed in Chapter 4, an interesting general fact I found is that the crystal size of dolomite is intimately controlled by the original depositional fabric. In dolostones preserving sand-size carbonate particles, the crystals are always fine to medium, even coarse. In fine- to very-fine crystalline dolostones, rarely any relic allochems can be seen and the texture is even and homogeneous. This indicates that fine- to very-fine crystalline dolostones resulted from replacement of original lime mud. Hence, in general, coarser crystalline dolomite was recrystallized from carbonate sands and finer crystalline dolomite from carbonate silts or -mud.

4) Limestone proportion in carbonate sequence. Many studies suggest that a large quantities of ancient regional massive dolostones are peritidal deposits from the margins of ancient tropical seas under an arid- or semi-arid climate. Hence, dolomite is a kind of evaporate mineral (Friedman 1980). In the Sauk Sequence, dolomite is much more developed in the western- and central-shelf subprovinces than in the eastern-shelf sub-

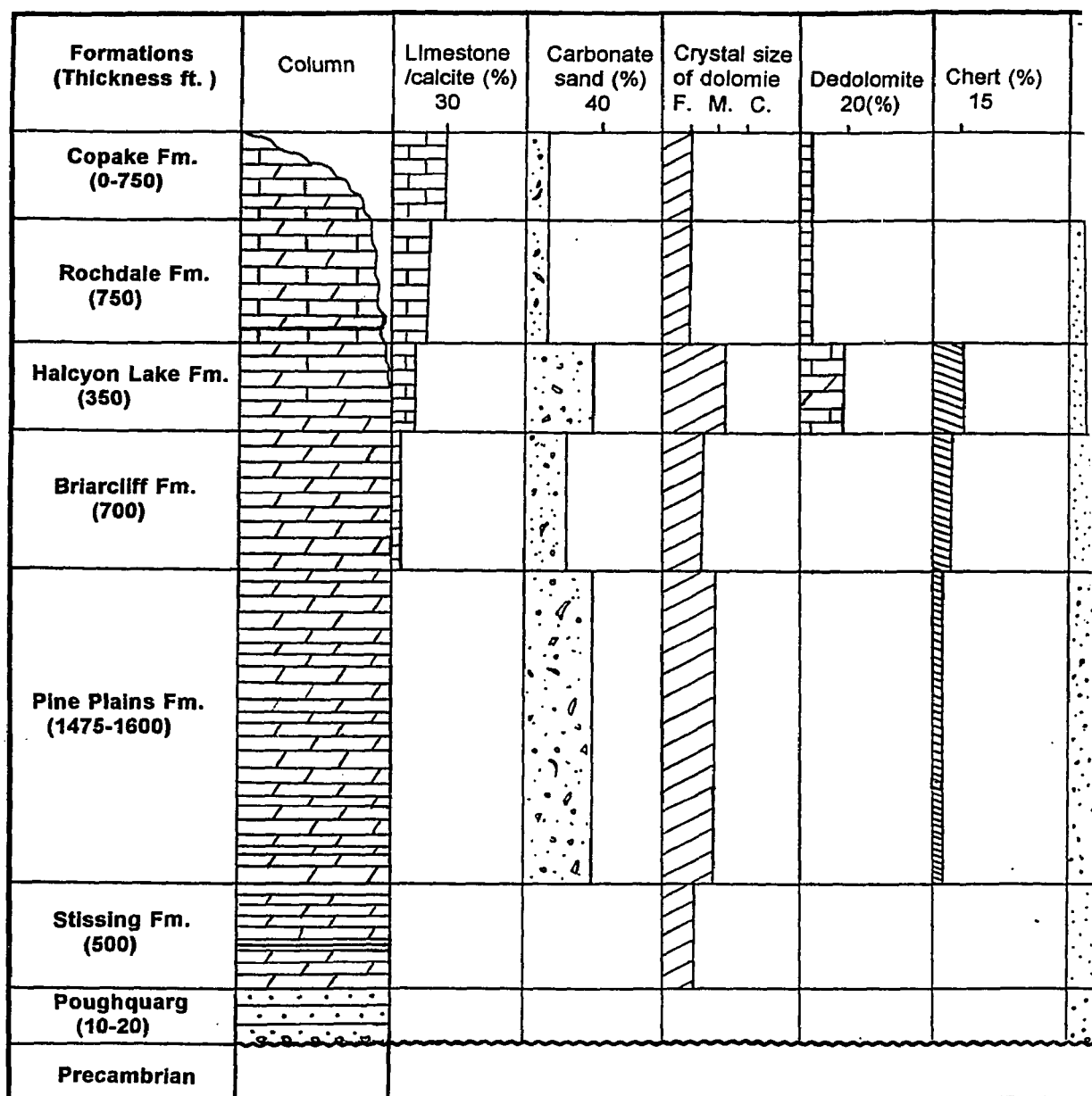
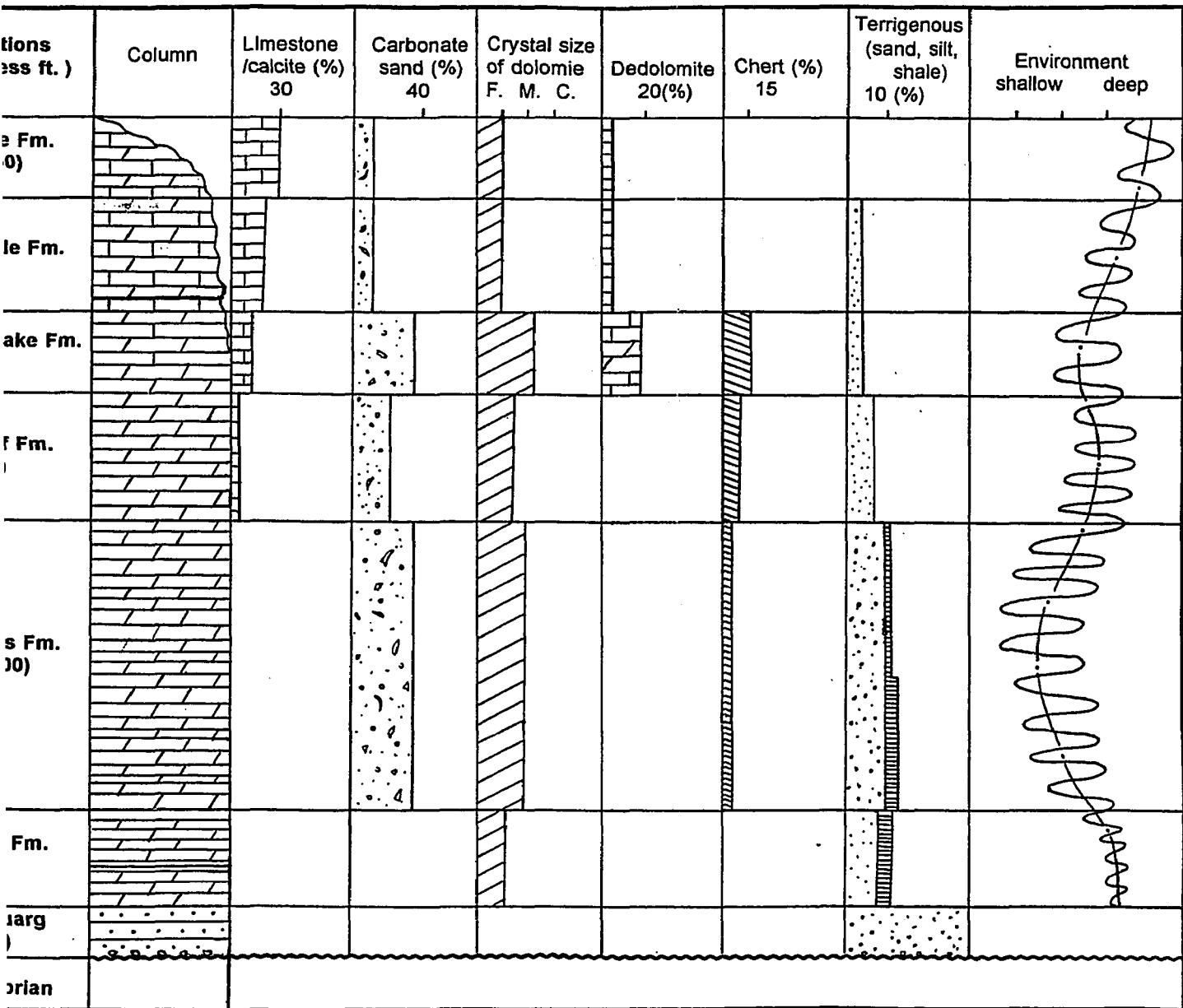


Figure 5-12 A summary of facies and environment analysis of the Wappinger Group



ary of facies and environment analysis of the Wappinger Group

province (also cf. Dunbar and Rodgers, 1957). Because the western-shelf and central-shelf subprovinces were situated on the former continent side of a huge shallow epeiric sea, and the eastern-shelf lay on the side of the former ocean that included a normal shallow-marine zone, thus, I infer that the limestone portion in a carbonate sequence represents a deposit of a normal shallow sea, where water depth was deeper than in an epeiric sea and water salinity was normal.

5) Chert and dedolomite portion. Chert that is associated with dolomite is regarded as a product of arid or semi-arid environment (Rubin 1975 ms.; Rubin and Friedman 1981) or a product of termination of a parasequence when the carbonate sediments were subaerially exposed (Friedman, 1992b, c, d). The concentration of chert may represent climate and how frequently a carbonate shelf or -platform was subaerially exposed. Dedolomite is also a product of subaerial exposure when precursor dolomite was processed by meteoritic water. Dedolomite could represent a termination surface of a parasequence (Friedman, 1992b, c, d) or relate to a long-term exposure associated with a surface of an unconformity. (See Chapter 6.)

6) Terrigenous clasts content- sands, silts, and shale. Although the content of terrigenous material in a carbonate succession depends on the supply of extrabasinal sediment, if such sediment supply were stable, terrigenous clasts would accumulate on the basis of water energy. Sands would be found in higher-energy zones where carbonate sands were being deposited, and silts would be found in lower-energy zones where lime mud accumulated.

Figure 5-12 shows the distribution of all of these environmental signals in the entire Wappinger Group. Note the most right column, the sea-level curve, represents both the range of the water depth and fluctuation of the water. From the bottom (early) to the top

(late), the Poughquag represents a coastal zone of initial submergence of sea water. The Stissing Dolostone was deposited in a lower-energy subtidal zone, where terrigenous silts were abundant. The Pine Plains Formation represents a typical peritidal deposit on carbonate platform. But, the upper part of the Pine Plains Formation was deposited in shallower water than was the lower part of the Pine Plains Formation. The Briarcliff Formation continued a peritidal setting, but the water depth was deeper than that in the Pine Plains, and the supratidal level was not reached. The Halcyon Lake Formation must have been deposited in a high-energy setting according to its medium- to coarse crystalline, abundant chert and well-developed burrow mottles. The Rochdale and Copake formations indicate that the epeiric-sea setting changed; the sea submerged most of area to greater depths than previously. Therefore limestone is developed in these two formations. In summary, during the period of deposition of the Wappinger Group, the carbonate platform was well developed during the episodes of deposition of the Pine Plains, Briarcliff, and Halcyon Lake formations. However, the water depth, the energy, and fluctuation of the sea were more-or-less different for each of these units.

5.3 Western shelf vs. Central shelf

As discussed in former sections, both the Beekmantown Group (of Fisher 1977) (Western shelf) and the Wappinger Group (Central shelf) were deposited on a subsiding passive margin of the North American continent. Facies study indicates that both subprovinces were part of a former tropical coastal complex involving supratidal flats, intertidal flats, and adjacent subtidal zones. Both groups present similar facies changes from early quartzite, to predominant dolostone and later, transferred to limestone. However, because of the different position of paleogeographic boundaries, -time of

submergence and different rate of basin subsidence, some important contrasts exist between the western-shelf- and central-shelf subprovinces. The Central shelf was submerged from Early Cambrian and developed a peritidal setting the best in Late Cambrian and transferred from peritidal setting to normal shallow marine at the end of the Early Ordovician. The water was deeper, the supply of terrigenous sediment less, and the accumulation rate was rapid (thickness 1000 to 1300 m). In the Western-shelf subprovince, deposition did not begin until the Late Cambrian. The water depth was shallow, supply of terrigenous sediment was abundant, and the accumulation rate was slower (thickness 500 to 600 m). Obviously, in the Central-shelf subprovince, clear water, proper subsidence rate, and water depth were more favorable for accumulating a thick carbonate succession than in the Western shelf.

The differences are summarized in the Table 5-1.

**Table 5-1 Western shelf (Beekmantown Group) versus
Central shelf (Wappinger Group)**

	Western shelf Beekmantown Group (of Fisher 1977)	Central shelf Wappinger Group
Time span	U. €- L. Ord.	L. €- L.Ord
Thickness	500-700 m	1000-1300 m
Cyclic	Supratidal-subtidal carbonate-clastic	Supratidal-subtidal carbonate
Supply of terrigenous sediment	Rich	Poor
Water depth	Shallower	Deeper
Accumulation rate	Slow	Fast
Speed of basin downwarp	Slow	Fast

CHAPTER 6: DIAGENESIS: DOLOMITIZATION AND DEDOLOMITIZATION IN SAUK SEQUENCE

6.1 Introduction

The problem of the origin of burial-type dolostones, which became something akin to "geologic orphans" during the sabkha stampede, is attracting renewed interest. Current emphasis has centered on attempts to understand how a given burial-type dolostone is related to the burial history of a region. Investigators have found, in Hardie's (1987) words, "dolomites and dolomites." Some burial-type dolostones originated in the shallow subsurface; some, in the deep subsurface. Various geochemical approaches have been applied in the hopes that each possible dolomitizing fluid would yield some unique geochemical "fingerprint." But as yet, we have not reached a common acceptable result.

The burial-type dolostones in the Cambro-Ordovician Sauk Sequence (Sloss 1963) exist on a world-class scale in North America. Any advance in understanding the origin of the Sauk burial dolostones in one area offers potential for advances in many localities. Studies of the origin of regional-scale dolomite in the Sauk Sequence elsewhere based on the burial history have yielded mixed results (Amthor and Friedman 1992, Barnaby and Read 1992, Friedman 1992, Gao and Land 1991, Kupecz and Land 1991, Lee and Friedman, 1987, Mountjoy and Halim-Dihardja, 1991). Lee and G. M. Friedman (1987) contended that much of the dolomite in the Sauk Sequence in West Texas and southeastern New Mexico (Lower Ordovician Ellenburger Group) originated in the deep subsurface with the Mg being supplied from basinal brines. More recently, Amthor and G. M. Friedman (1991) inferred a somewhat-more-complex history of dolomite in the Ellenburger Group, West Texas. They found evidence for multiple stages of dolomitization ranging from early shallow subtidal to late deep burial. By contrast, after studying the

local representatives of the Sauk Sequence in SW Oklahoma (Lower Ordovician Cool Creek Dolostone of the Arbuckle Group), Gao and Land (1991) proposed that the dolomite had been modified by meteoric water probably when the carbonate shelf was emerged during later Paleozoic erosion intervals when surfaces of unconformity of regional extent formed. Friedman (1992) disagreed with this interpretation.

In this chapter, I approach the origin of a regional-scale S-type (Dunbar and Rodgers 1957) burial dolostone from the viewpoint of dedolomite. I have tried to relate not only the dolomitization but also the products of a widespread dedolomitization to the diagenetic- and burial history of the rocks. I have tried to view the problem of Hardie's (1987) "dolomites and dolomites" from the point of view of "calcites and calcites."

The section of the Sauk Sequence that I have examined is known in southeastern New York as the Wappinger Group. (See Table 4-1.) At the top of the Wappinger Group, particularly in the Halcyon Lake Formation (E. B. Knopf 1962), are widespread mixed calcite-dolomite rocks known as **calcdolostones**. Such rocks are usually identified on the outcrop by the fact that they look like dolostones yet effervesce freely in cold dilute hydrochloric acid (thus testing positively for calcite). Mixed calcite-dolomite rocks can be products of incomplete dolomitization of a calcium-carbonate sediment or of incomplete calcitization (dedolomitization) of a dolostone. Recent investigations have shown that most of the calcdolostones at the top of the Wappinger Group are products of dedolomitization (Guo, Sanders, and G. M. Friedman 1992a).

Petrographic evidence proves that more than 95% of the regional-scale burial-type dolostones in the upper part of the Wappinger Group formed prior to dedolomitization. I ascribe this episode of calcitization of former dolomite to the interval of subaerial exposure accompanying the conditions that gave rise to the post-Sauk, pre-Tippecanoe surface of

unconformity (= "Knox unconformity" of Rickard 1973, Mussman and Read 1986, and many other authors; and "post-Knox unconformity" of Churnet, Misra, and Walker 1982).

A comparison study of dolomite in the Pine Plains Formation (lower part of the Wappinger Group) proves that no dedolomite is present in the Pine Plains Formation but saddle dolomite is widely distributed. This has resulted from different diagenetic history between the Halcyon Lake and the Pine Plains formations. During the subaerial exposure associated with the post-Sauk, pre-Tippecanoe surface of unconformity, the Pine Plains Formation was not brought to the Earth's surface.

If my interpretation that dedolomitization was related to post-Sauk, pre-Tippecanoe unconformity is correct, then I have established a valuable benchmark in the burial history of these rocks in the top of the Wappinger Group. From the benchmark position in the burial history of the dedolomite, I infer that the widespread burial dolostones formed in the shallow subsurface (depths of a few hundred meters at most). The evidence I present strongly supports the view that even though they were deeply buried starting in the Late Ordovician, both the regional-scale burial dolostones (of inferred shallow-burial origin) and the dedolomite (which I conclude formed at- or near the Earth's surface) survived prolonged deep burial without being significantly modified.

By contrast, the formations, such as the Pine Plains which were not exposed to subaerial conditions during the post-Sauk, pre-Tippecanoe unconformity were not subjected to a long-term near-surface diagenesis and much more of their pore space was left for deep-burial diagenetic processes. Hence, deep-burial products, such as saddle dolomite, are relatively abundant.

6.2 Fabric and composition components of carbonate rocks

Megascopically, the rocks in the upper part of the Wappinger Group consist of limestones,

calcdolostones, and dolostones. The Copake contains mostly limestones interbedded with calcdolostones and dolostones. The kinds of limestone include microcrystalline, pelletal, and skeletal. The Rochdale includes both limestones and dolostones. The Halcyon Lake consists of calcdolostones and dolostones but lacks limestones. The dolostones consist of very fine-, fine-, medium-, and coarse crystalline varieties. Notice that from the top downward, calcite decreases and dolomite increases. Noncarbonate constituents, such as chert, silt-size quartz, and shale are present, but they never predominate. (See Figure 4-6, a.)

However, in the lower part of the Wappinger Group, such as in the Pine Plains Formation, I did not find any relic original calcite nor dedolomite. The rocks have been totally dolomitized. (See Figure 4-6, b.)

As a result of pervasive dolomitization, most of the precursory calcium-carbonate sediment became transformed into dolostone. Later, some of the dolomite was replaced by calcite (dedolomitization, or calcitization) and at the same time, dedolomite-related calcite was deposited in open spaces (as veinlet- or pore fillings). Finally, a few late dolomite- and calcite veinlets crosscut all previous **components**. In the following sections, I describe the microscopic features of these rock components.

Based on mineral composition and CL characteristics, I recognize three first-order components: (1) calcite, (2) dolomite, and (3) dedolomite. Based on textural data (crystal size, size distribution, and shapes of crystal boundaries, Sibley and Gregg 1987), CL colors, and genetic categories, I have made second-order subdivisions of each (Table 6-1). The classification of crystal sizes (very fine, fine, medium, coarse) follows Friedman (1965), basically. But, because most dolomite crystals lie in the range of 50 to 200 μm (approximately in the medium-size class of Folk 1962, whose boundaries he placed at 62 μm to 200 μm), I have lowered Friedman's recommended size very fine/fine boundary from 100 μm to 50 μm .

Minerals category	Texture	Origin	CL patterns
Calcite	Very fine-fine Veinlets	Precursor Early & late diagenetic	Dull tan & brown
Dolomite	a Unimodal planar-s fine to very fine	Early stage (1)	Very dark (reddish)
	b Unimodal planar-s fine	Main stage (2)	1. Very dark (reddish) 2. Orange red 3. Dark tannish red or non-luminescent
	c Unimodal planar-e fine		
	d Unimodal planar-s medium-coarse		
	e Cement (non-Sd)		
	f Vein filling (non-Sd)	Late Stage (3)	1. Zoned, orange or red 2. Very dull red or non-CL
	g Saddle dolomite (Sd)		
Dedolomite	Replacement Dedolomite-related calcite veinlets	Diagenetic after stage (2) dolomite	Bright yellow

Table 6-1. Fabric components of carbonate in the Wappinger Group, southeastern New York

6.2.1. Calcite

Calcite displaying dull CL color is present in two forms: as precursor calcite composing limestone or dolomitic limestone and as veinlets.

6.2.1.1 *Precursor calcite*

The precursor calcite is very fine to fine (Figure 6-1, a). The sizes of the calcite crystals generally are less than 50 μm . The particles forming the original carbonate sediment include peloids and skeletal debris, mostly from echinoderms but including some sponge spicules. Noncarbonated constituents include quartz in the fine-silt-size range and some clay laminae (especially in the Rochdale Formation).

The original calcium-carbonate sediment has been selectively dolomitized by fine dolomite rhombs to yield dolomitic limestone, calcitic dolostone, and even dolostone. Evidence of the selective replacement includes echinoderm fragments that still preserve their original shapes and calcite monocrystal fabric (Figure 6-1, b); irregularly spaced aggregates of dolomite rhombs; and restriction of dolomite to particular laminae. Selective replacement has been controlled by differences of original composition and texture. For instance, micrite is a favored site for nucleation and thus is easily dolomitized.

The CL color of precursor calcite is dull tan to dark brownish (Figure 6-4, a). Such dull calcite is easy to distinguish from the dolomites (mostly reddish CL colors) and from the dedolomite and dedolomite-related calcite (bright-yellow CL color).

Precursor calcite is the main constituent of the limestones and dolomitic limestones that are present only in the Copake and Rochdale formations.

6.2.1.2 *Veinlet calcite*

Veinlet calcite is of two generations. Most of them are earlier than the dedolomite-related

calcite veinlets. The others came later than the dedolomite and the dolomite veinlets. Of these, dark-gray to black calcite from the Halcyon Lake and the Pine Plains formations is very special.

The dark-gray calcite fills irregular openings in the formations or irregular veins (widths may be more than 2 cm) or pockets (whose diameter may be more than 5 cm). Under the microscope, the calcite can be seen not only to simply fill the void but also to replace precursor dolomite which is often associated with some organic matter between crystals. Because it replaces dolomite, this calcite falls into the category of dedolomite. However, the CL color of the dark-gray calcite is tannish rather than the bright yellow of the rest of the dedolomite (See later section.)

6.2.2. Dolomite

As mentioned, based on their textures, I recognize seven categories of dolomite, which formed during three different stages.

Dolomite components (a) through (d) are replacement products: the dolomite replaced a calcium-carbonate precursor. Although, in most cases, the exact precursor carbonate component cannot be recognized, or only a textural ghost remains, a typical feature of dolomites (a) through (d) is that commonly they constitute a crystalline framework of the rocks. The other dolomites, (e), (f) and (g), grew into empty space as cement or fracture filling. In other words, the dolomites (e), (f), and (g) were directly precipitated from a certain fluid instead of replacing some precursor crystal(s). Dolomites (e), (f), (g) generally form subordinate components of the rocks, but are important burial-diagenetic products.

The importance of making the distinction between dolomite that replaced a pre-existing crystal and dolomite crystals that grew into empty space has been emphasized by nearly

all authors since Bruno Sander (1936, 1951), including Amthor and Friedman (1991, 1992).

Many kinds of empty spaces are available into which dolomite (and/or other mineral) crystals can grow. Some are initial pores among the primary framework constituents (such as skeletal debris, ooids, non-skeletal sands, pellets, and intraclasts) of the carbonate sediment. Others are secondary pores surrounding dolomite crystals that grew by replacement in a carbonate sediment but during diagenesis, became a **secondary framework**. Still-other pores form by dissolution of framework constituents. Finally, pore space is created when fractures form.

According to Bathurst (1975, p. 416) **cement** "is taken to include all passively precipitated, space-filling carbonate crystals which grow attached to a free surface". Under this definition, even a fracture filling qualifies as cement. In this discussion, I shall apply the term **cement** only to any mineral precipitated either in (1) spaces among the primary framework constituents of a sedimentary deposit during early diagenesis; or into (2) the pores among any secondary framework of crystals during later diagenesis. For crystals that grew into other openings that cut across framework constituents, I shall use **fracture filling** for the veinlets that fill fractures; and **pocket filling**, **vug filling**, or **pore filling** for scattered fillings of irregular openings of various sizes.

I have avoided the term "void-filling" dolomite as defined by Sibley and Gregg (1987). They modified the general term "void filling" by restricting it to mean only "cement and dolomite that replaced a precursor cement." As thus used, "void-filling" dolomite includes not only dolomite that grew into empty space but also dolomite that **replaced precursor cement**, i. e. is **replacement dolomite**. Accordingly, this usage blurs the important distinction among replacement- and nonreplacement dolomites. By contrast, Amthor and Friedman (1991, 1992) applied the term "void filling" in quite a different way. They included not only "cement

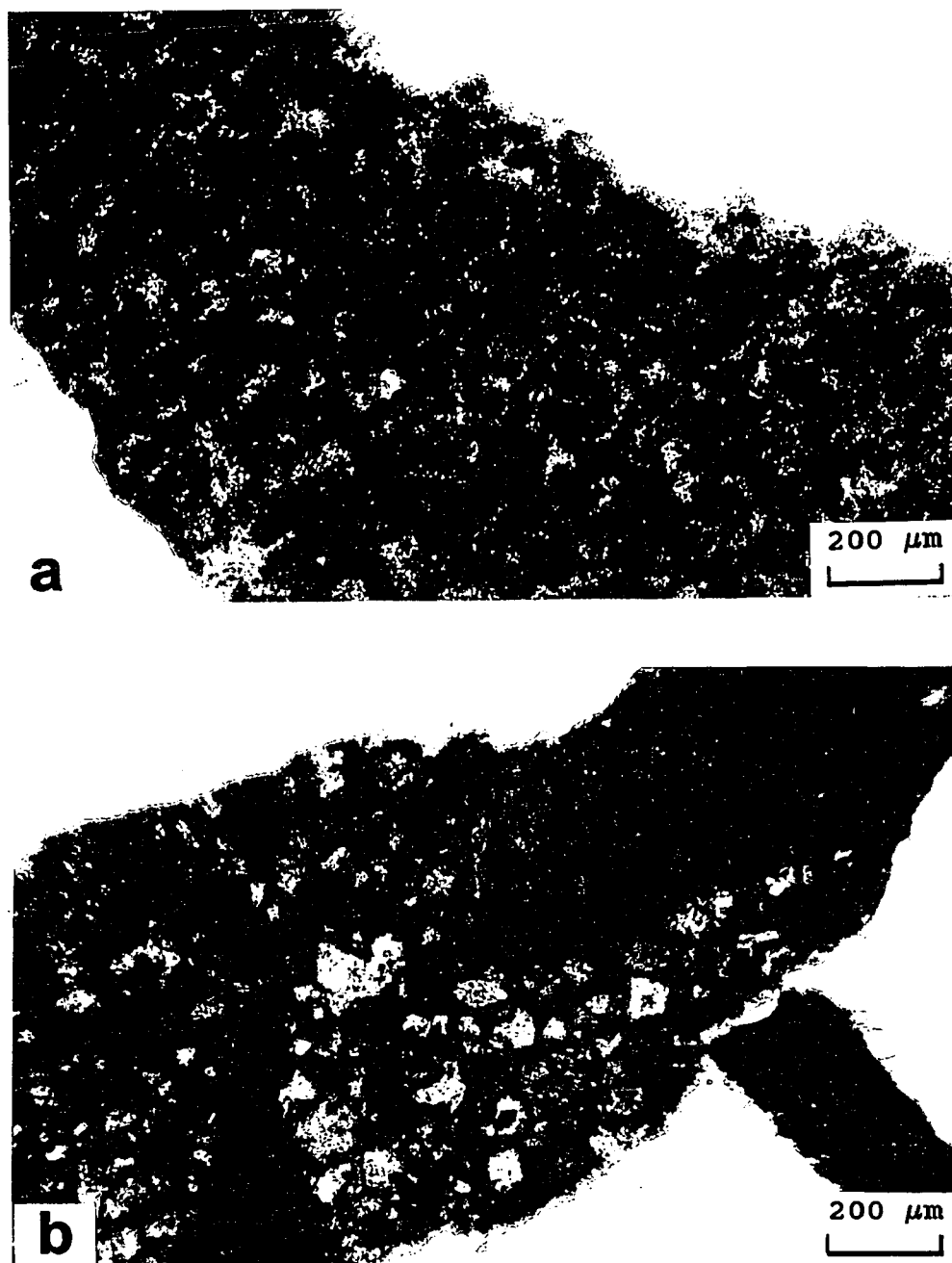


Figure 6-1. Enlarged views in plane-polarized light of limestones and dolomites from the top of the Wappinger Group, Crom-Wells No. 1 Fee boring. a). Precursor pelletal limestone, Copake Limestone at depth 4765 to 4770.5 ft. b). Selective dolomitization has preserved the original texture of an echinoderm fragment in a calcdolostone, Rochdale Formation at depth 4914.5 to 4917 ft.

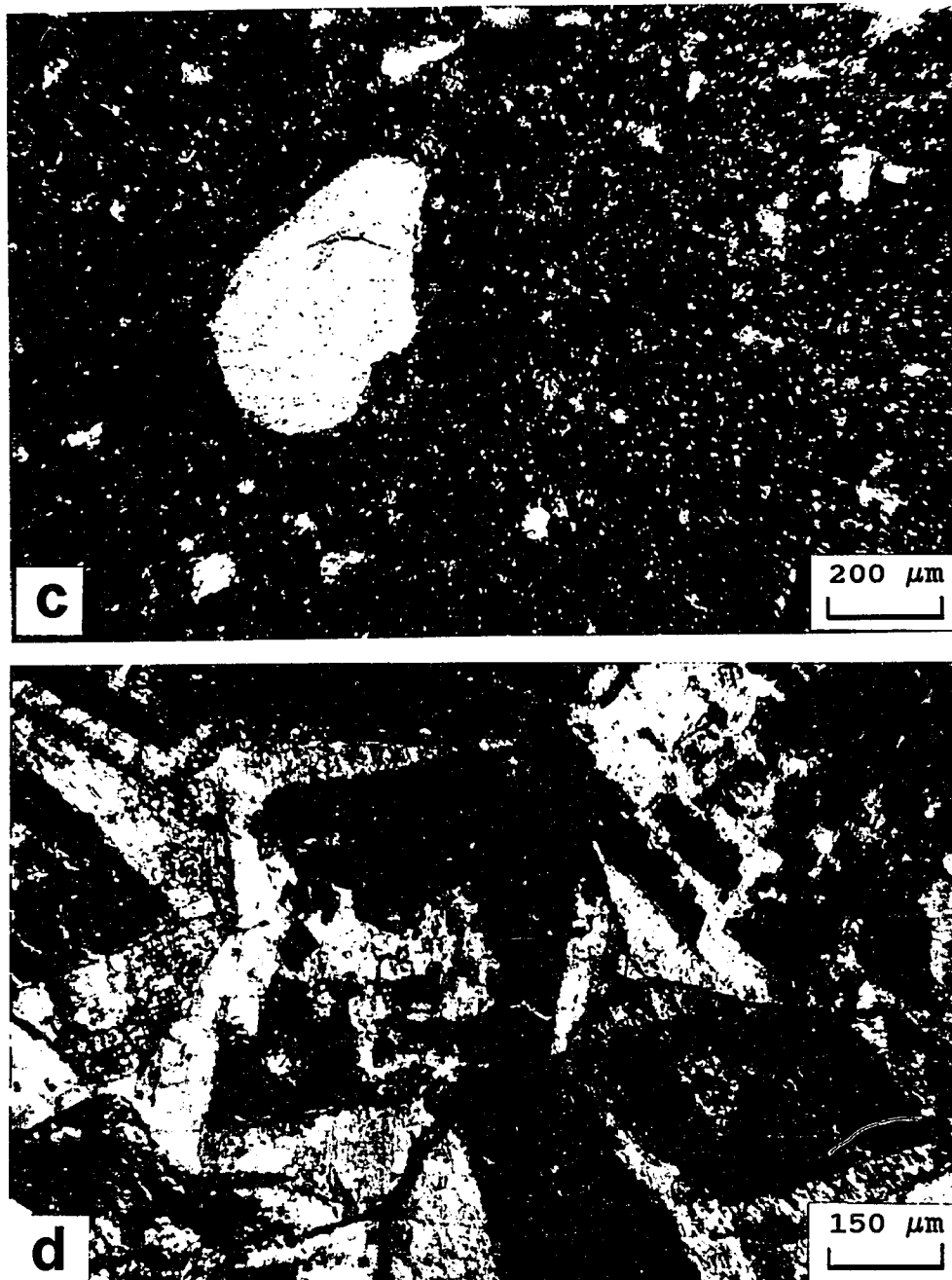


Figure 6-1. c). Unimodal planar-s very-fine-crystalline early-stage dolomite (a) showing an admixed single rounded sand-size particle of quartz and many angular silt-size particles. Halcyon Lake Formation at depth 5076 to 5078 ft, Crom-Wells No. 1 Fee. d). Unimodal planar-s medium- to coarse dolomite (d) that has been pseudomorphically replaced by dedolomite calcite (dark color; stained by alizarin red-S dye). The late-stage dolomite (e) cement (light color; transparent) that fills the pore spaces between the larger dolomite rhombs has not been dedolomitized. Halcyon Lake Formation at depth of 5232 to 5242 ft.

and dolomite that replaced a precursor cement" but also dolomite that grew into empty space formed by fractures.

In the classification, dolomite (e) is cement, and dolomite (f) is fracture filling. Both dolomite (e) and (f) are non-saddle dolomite. Dolomite (g) is saddle dolomite, which in the top of the Wappinger Group, is rare to absent. However, in the underlying Pine Plains Formation, saddle dolomite is quite abundant as fracture fillings, pocket fillings, or scattered pore fillings (could be as a last generation of cement).

6.2.2.1 Early-stage dolomite

Early dolomite (a) in the top of the Wappinger Group

Dolomite (a) is unimodal, planar-S very fine crystalline dolomite. The sizes of most crystals are less than 40 μm . (See Figure 6-1, c.) A few indications of original skeletal debris remain; a small amount of silt-size quartz, and rare rounded sand-size quartz are mixed in with the carbonate minerals.

The CL color of dolomite (a) is very dark red; in places, the red is mixed with a small amount of very-dark tan. Evidence that dedolomitization has affected dolomite (a) is scattered, possibly because of the tight texture. Some tiny dedolomite-related calcite veinlets, displaying the bright-yellow CL color of the calcite from the dedolomitization episode, cut across dolomite (a).

I have never found dolomite (a)(very fine crystalline) associated with precursor calcite nor with dolomite (b)(fine crystalline). I have never seen precursor calcite replaced by very fine-crystalline dolomite ($>20 \mu\text{m}$) nor dolomite (a) replaced by dolomite (b). This means that dolomite (a) is not a precursor of fine-crystalline dolomite (b) and may not be a replacement product of precursor calcite. Based on its very-fine-crystalline texture and paragenetic relationship, I infer that dolomite (a) is a product of penecontemporaneous neomorphism or very

early postdepositional diagenesis.

In addition, I have found the very dark CL color that typifies dolomite (a) in the cores of rhombs of dolomite (b) (easily distinguished from the red-orange CL color of the rims; See Figure 6-4, a). I think that these cores in euhedral rhombs of dolomite (b) resulted from the same early stage as the very-fine crystalline dolomite; I assign them both to the early-stage dolomite.

The distribution of dolomite (a) is very limited in the top of the Wappinger Group. I have found it only in a few samples of the Halcyon Lake and Rochdale formations.

Early dolomite in the Pine Plains Formation

Three types of relic texture indicate their very early (syndepositional) origin. These early products have survived late-diagenetic modification as follows: 1) Very fine dolomite (laminated or non-laminated); 2) Cores of some crystals; 3) Non-recrystallized ooids that preserve a depositional texture.

1. Very fine dolomite:

1) Non-laminated or with stromatolitic laminae. In very fine dolomite (cryptocrystalline dolostone), the texture is unimodal, planar-e. Most crystals are smaller than 12 μm ; the predominant crystal size is less than 8 μm . In the light-colored stromatolite laminae, some crystals may be larger than 20 μm . But, in the dark-colored stromatolite layers, crystals are very small, < 8 μm , even < 2 μm (8%)(Figure 6-2, a). According to Folk (1965) and Land (1985), crystal size of modern calcium-carbonate mud is a few μm (normally < 4 μm). After neomorphism, the crystal size of micrite in modern- and ancient analogues enlarges to 10 μm to 50 μm . Hence, most of preserved very fine dolomite in this study is similar to neomorphosed micrite. During burial-diagenetic processes, they did not recrystallize further. However, some signals that indicate burial diagenesis, such as veinlets and small-nodule

saddle dolomite and late dolomite veinlets formed within the non-laminated very fine dolomites are still present.

2) Laminated very-fine- to fine dolomite: The crystal sizes vary in different laminae. The thicknesses of the laminae range from < 1 mm to centimeters.

In thick-laminated rocks, textures are planar-s or planar-e. Some saddle dolomite, fracture-filling dolomite, and stylolites are associated.

In very thinly laminated rocks, regarded as a typical intertidal facies, some argillaceous- and quartz silts are mixed with dolomite. In a few laminae, these noncarbonates form a majority constituent. Most of dolomite crystals are planar-e, but some of them are planar-s.

A significant feature of thinly laminated dolostone is the absence of saddle dolomite and rarity of fractures and stylolites. Accordingly, among all rock types/facies in the Pine Plains Formation, deep-burial diagenesis has modified this one the least.

2. Cores in some dolomite crystals. As in the top of the Wappinger Group, the CL colors of some cores of dolomite crystals are darker and these are different from that of the rims. This may indicate the early origin of the cores.

3. Non-recrystallized ooids. In oolitic dolostone, in places, notably where the space between ooids has been filled with dark-colored, organic-rich argillaceous material, the original oolitic texture has been preserved perfectly. Both the original nuclei as well as the concentric laminae of such ooids can be recognized (Figure 6-2, b) and, under crossed-polarized light, an extinction cross is visible. Compared other recrystallized ooids, these ooids have preserved their original texture perfectly. Hence, they probably represent the product of early-stage dolomitization and almost have not affected by deep-burial diagenetic processes.

On the basis of outcrop-, specimen-, and thin-section study, I estimate that the proportion of survived early dolomite in the Pine Plains Formation is 10 to 15%. By contrast, in the

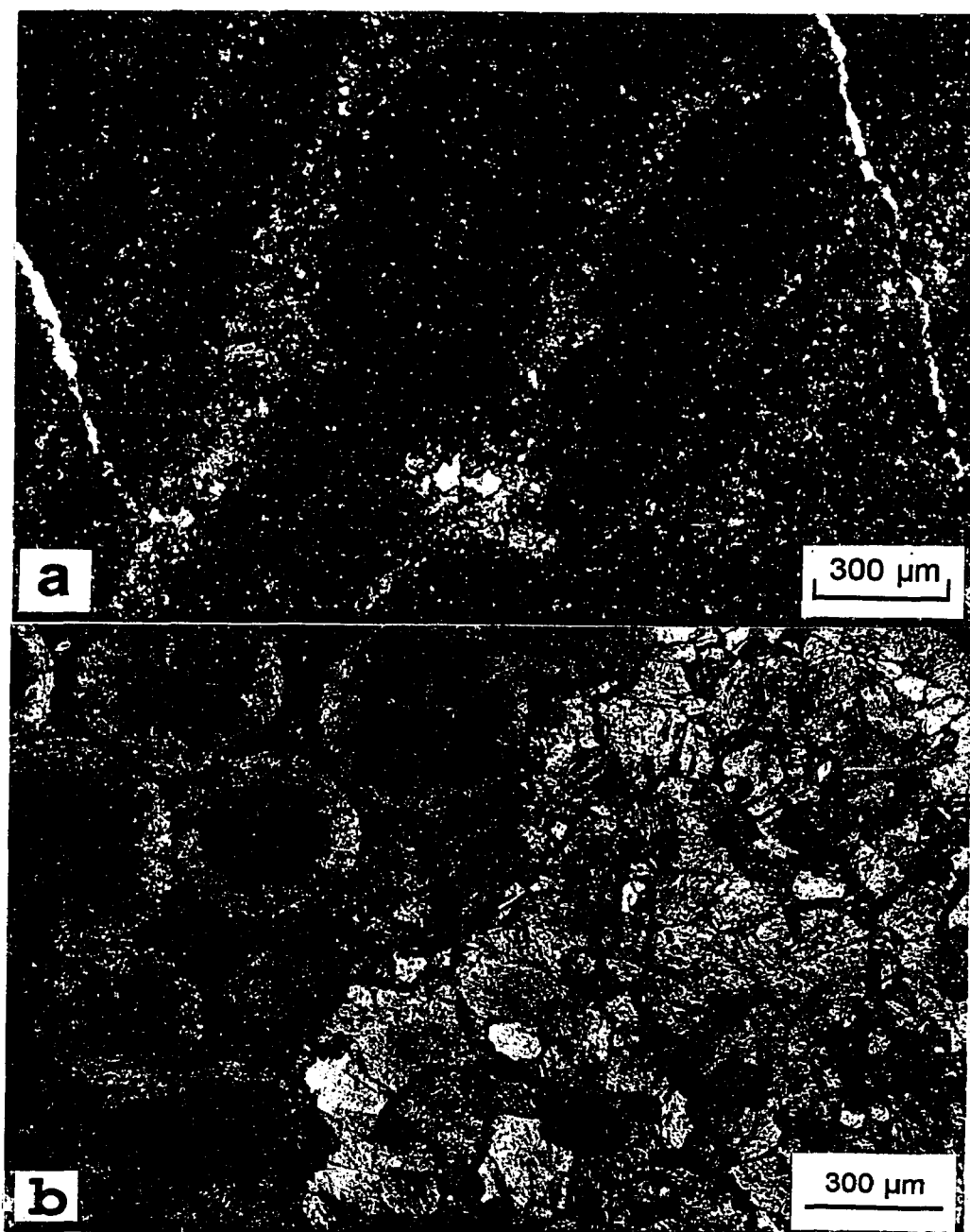


Figure 6-2. Enlarged views in plane-polarized light of dolomites. a. Dolomite (a), very-fine dolomite constitutes stromatolites which consists of light- and dark laminae. Light laminae are coarser than dark laminae. A little amount of saddle dolomite (white) has been found within the light laminae. Late quartz veinlets (white) crosscut laminae. Pine Plains Formation, Clinton Point Quarry, 73-91 hole, 91'. b. Non-recrystallized ooids. Upper left part shows non-recrystallized ooids. The cores and rims have clearly been preserved. Black organic-rich mud filled interooid pores. Within these ooids, primary texture has been preserved perfectly. It is possible that the organic mud has protected ooids from recrystallization. It can be assumed that both mud and ooids were deposited together and that no interooid pores were left. Therefore, diagenetic water had no chance to enter this specific area and to recrystallize the primary ooids. Plane-polarized light, Pine Plains Formation, CP Quarry, 73-91 hole, 241'.

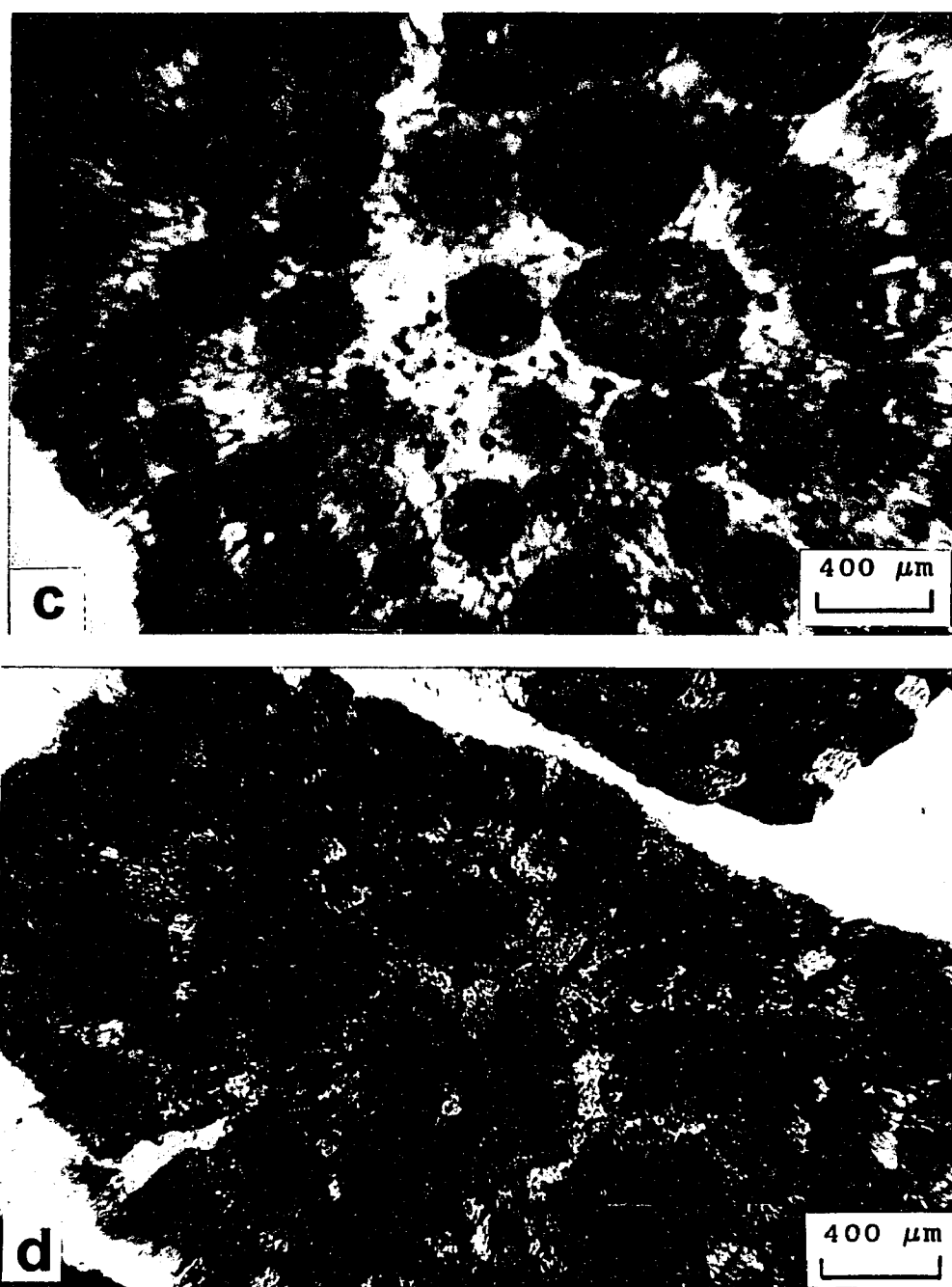


Figure 6-2. c). Slightly recrystallized ooids and associated two generations of cement. Within the ooids, white spots are recrystallized dolomite crystals. First-generation cement surrounds the ooids. Later cement which presents larger crystal-size than earlier cement, filled the rest of the pores. Under CL, later cement shows non-CL color, which is saddle dolomite. Plane- polarized light, Pine Plains Formation, ARCO No. 1 Susi boring. d). Recrystallized dolomite with ooid ghosts. Pine Plains Formation, ARCO No. 1 Susi.

top of the Wappinger Group, early dolomite (dolomite a) is rare.

6.2.2.2 *Second-stage dolomite*

Dolomite (b),(c),(d),(e) in the Top of the Wappinger Group

Dolomite (b).-- I recognize dolomite (b) by its unimodal, planar-s, fine crystalline texture. The sizes of the crystals range from 50 to 200 μm . This is the most-important kind of dolomite; it forms 60% of the Halcyon Lake Formation and is a major variety of the dolomite in the Copake and Rochdale formations (Figure 6-4, b). (See also Figure 6-4, a.)

Noncarbonate constituents including chert and silt-size quartz are associated in dolomite (b). Both dedolomite and veinlet dedolomite-related calcite are common in dolomite (b). As is explained in following paragraphs, all three dolomite CL colors are found in dolomite (b).

Dolomite (c).--I recognize dolomite (c) because it is unimodal, planar-e, and fine crystalline. Dolomite (c) is a subordinate fabric component in which euhedral dolomite rhombs are surrounded by dolomite (e) (Figure 6-2, c), chert nodules, or dedolomite. This indicates that euhedral dolomite crystals grew in the precursor calcite sediment. Next came an episode of dissolution and the creation of pore space. This pore space was later filled, either by further enlargement of dolomite crystals or by other material [discussed under dolomite (e)].

The fabric of dedolomitization products found in dolomite (c) is (l) intercrystalline replacement (defined in a following section).

Dolomite (d).--The crystals of dolomite (d) are unimodal, planar-s, and medium to coarse. Because of their large sizes, dolomite-(d) crystals can be recognized easily even by visual inspection of outcrops. Dolomite (d) is especially common in the middle part of the Halcyon Lake Formation; in it the effects of dedolomitization are well developed (Figure 6-1, d). Two replacement fabrics of dedolomitization products predominate in dolomite (d):

(II) pseudomorphic and (III) massive (discussed in a following section).

Dolomites (b), (c), and (d) constitute the main bulk of the dolostones in the three formations of interest. In each of these kinds of dolomite crystals, early-stage cores displaying dark CL colors are jacketed by second-stage rims showing medium-bright orange-red CL colors. This is the basis of my assignment of dolomites (b), (c), and (d) to the second-stage of dolomitization. The difference in the CL colors indicates that the crystals forming the rims were crystallized from a fluid unlike the one from which the dolomite forming the cores crystallized. The crystals of dolomite (d) are larger than those in the other categories; this is presumed to indicate slower- and longer crystallization (Sibley and Gregg 1987).

Dolomite (e); cement.-- What I designate as dolomite (e) consists of dolomite (transparent in thin section) that fills open space formed among a secondary framework of dolomite rhombs (Figure 6-4, c; also, See Figure 6-1, d.). In Figure 6-4, c, dolomite that grew into the empty space displays a cement texture similar to that found in early diagenetic cement. The very dull CL color of dolomite (e) cement differs from that of the enclosed dolomite crystals.

Most dolomite (e) cement grew in optical continuity with the enclosed framework-dolomite crystals. Thus, the contrast between "framework" dolomite and later "cement" dolomite is not visible under plane-polarized light or under crossed-polarized light. The cement texture of dolomite (e) can surely be recognized **only** under CL light. Two key distinguishing features are: (1) the CL colors of the cement differ from those of the framework crystals; and (2) under plane-polarized light, the cement crystals are relatively clear and transparent. In addition to the CL color of the example shown in Figure 6-4, c, an overgrowth that I assign to dolomite (e), cement, can also be non-CL (Figure 6-4, d) or dull red (such as the sample from the Crom-Wells No. 1 Fee boring, depth 5304 to 5307), which is similar to the CL color in the core of the framework crystals, but contrasts with the brighter CL zone of the rim. In either

case, the CL color contrast between cement dolomite (e) and framework-dolomite crystals indicates that the chemical composition of the fluids from which the overgrowth portion (cement) was precipitated, obviously differed from that in which the framework crystals formed.

I infer that the first dolomite crystals grew as scattered individuals within lime mud. At some later time, the nondolomitized lime mud between the scattered dolomite rhombs was dissolved and this dissolution converts the dolomite rhombs into a secondary framework. The dolomite cement then filled in the spaces among the secondary framework of dolomite crystals. The evidence that proves dolomite (e) formed in a free space rather than by replacing an unknown precursor material is that even between the boundaries of dolomite (e) crystals, some pore space ("P" in Figure 6-4, c) may remain. The transparency of dolomite (e) in thin section also suggests the crystals grew into free space. Nevertheless, whether or not one can prove that dolomite (e) formed by growing into free space (as cement) or by replacing older crystals that occupied the space (as a replacement product), dolomite (e) formed later than the dolomite crystals of the secondary framework. I do not know how much time elapsed between the time when the framework dolomite crystals formed and the dolomite (e) cement was precipitated. However, dolomite (e) is closely related to the framework crystals it jackets. Dolomite (e) always filled the pores passively and rarely eroded, truncated, or crosscut the framework crystals. Hence, dolomite (e) probably formed under the same general conditions and during the same diagenetic event, the second stage, as the framework.

Second-stage dolomite in the Pine Plains Formation

Most of dolomite (more than 80%) in the Pine Plains Formation is the product of second-stage, shallow- to medium-burial conditions.

The second-stage dolomite is characterized by its fine crystalline (less medium and very fine), unimodal- or polymodal, planar-s (less planar-e, and planar-a) and more-or-less

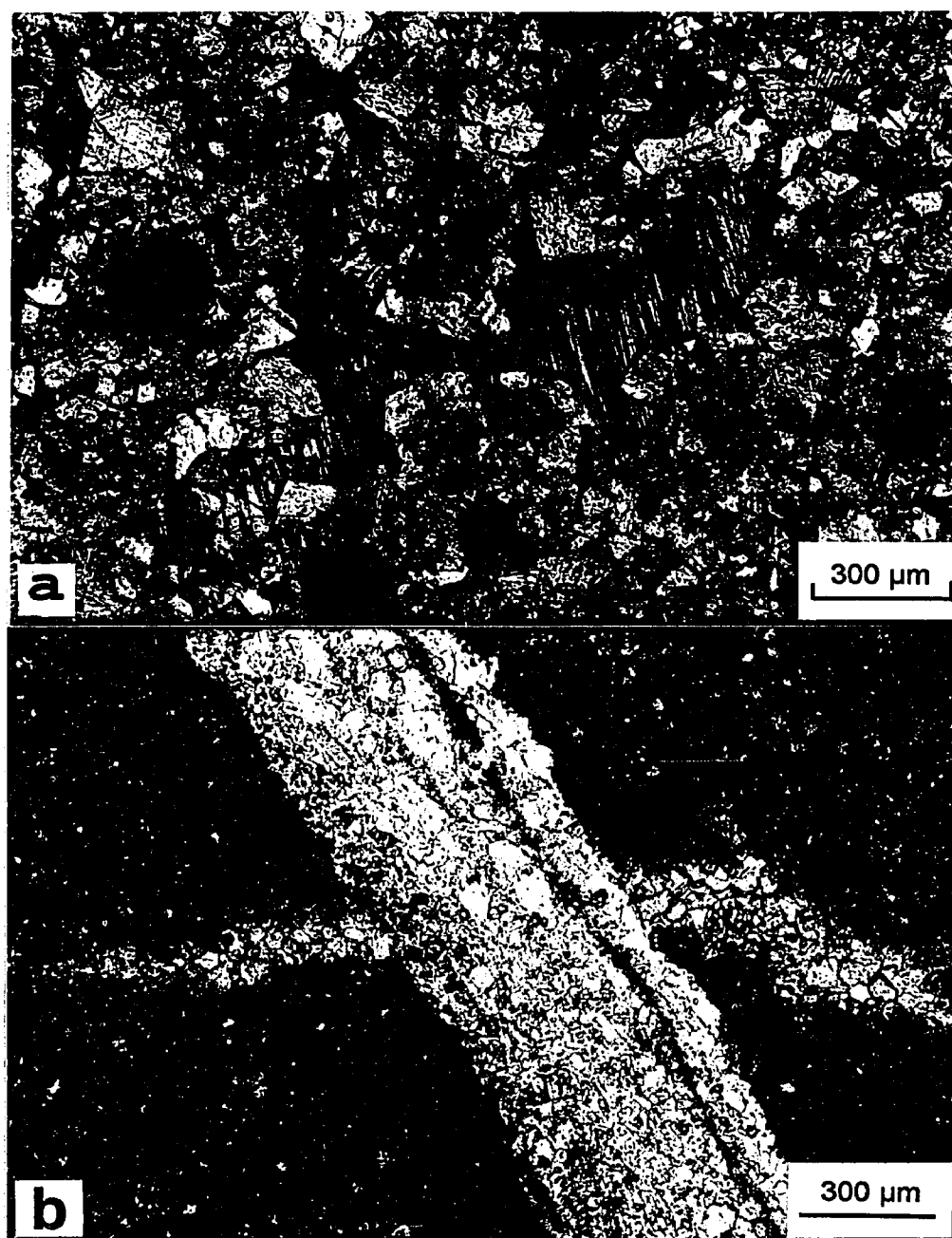


Figure 6-3 Enlarged views of dolomites (a, b, c) and outcrop view of hydrothermal saddle dolomite (d). a). Relic texture of grainstone. Only a few allochem ghosts can be recognized. In most cases, relic texture is very vague in recrystallized grainstones. In the center, an irregular calcite filling is present and recrystallized late dolomite growth toward to calcite. Plane-polarized light, Pine Plains Formation, Clinton Point Quarry, 73-91 hole, 53'. b). In very fine dolomite, quartz vein (thick, white) cuts through saddle dolomite vein (thinner). Plane-polarized light, Pine Plains Formation, Clinton Point Quarry, 73-91 hole, 100'.

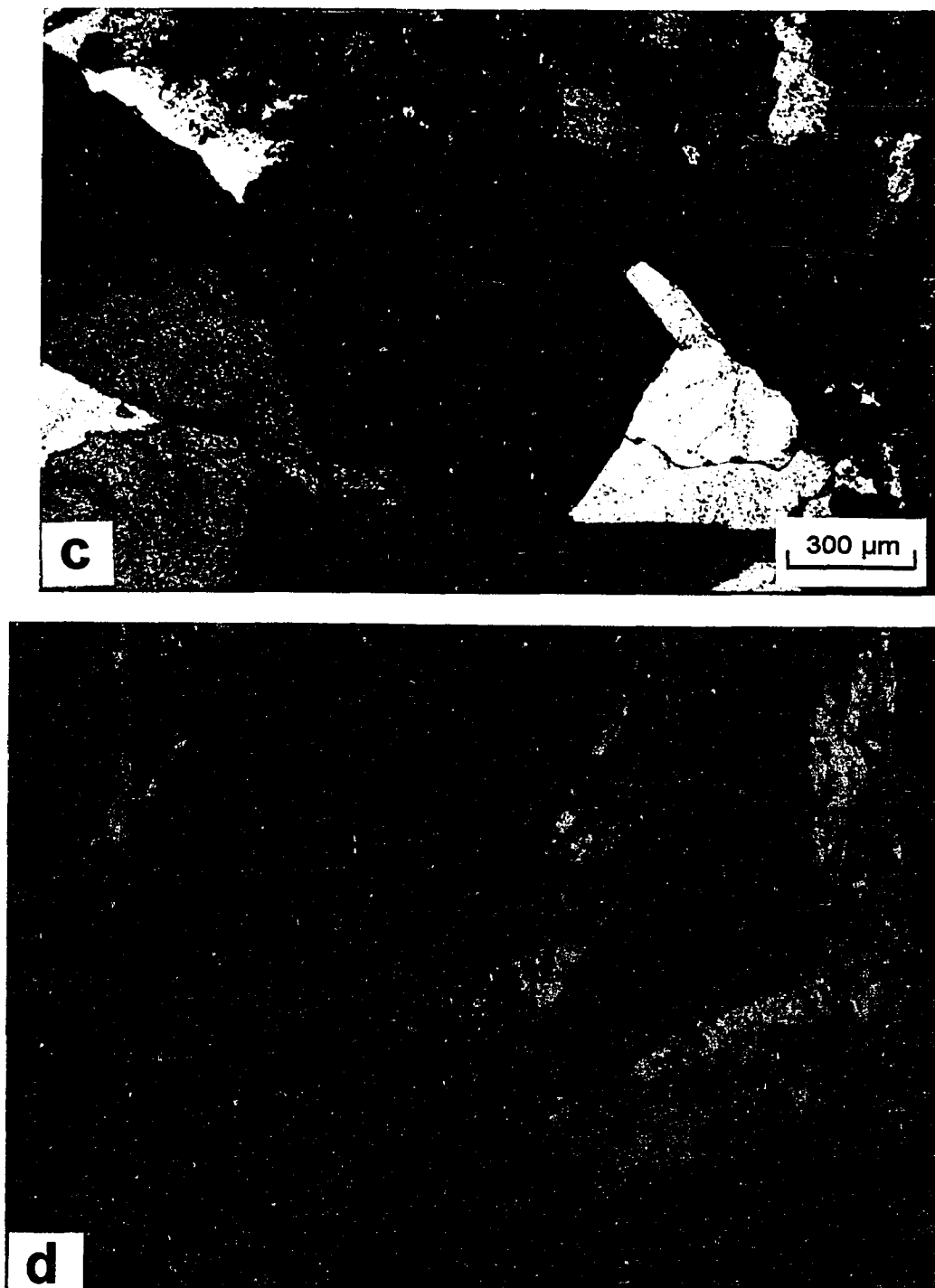


Figure 6-3. c). Saddle dolomite (gray, wavy extinction) is associated with late pore-filling quartz (white). Cross-polarized light, Pine Plains Formation, Clinton Point Quarry, 73-91 hole, 148'. d). Hydrothermal saddle-dolomite-filled fractures near faults on W side of entrance ramp from NY 32 to westbound lanes of I-84, Newburgh, Orange Co., NY.

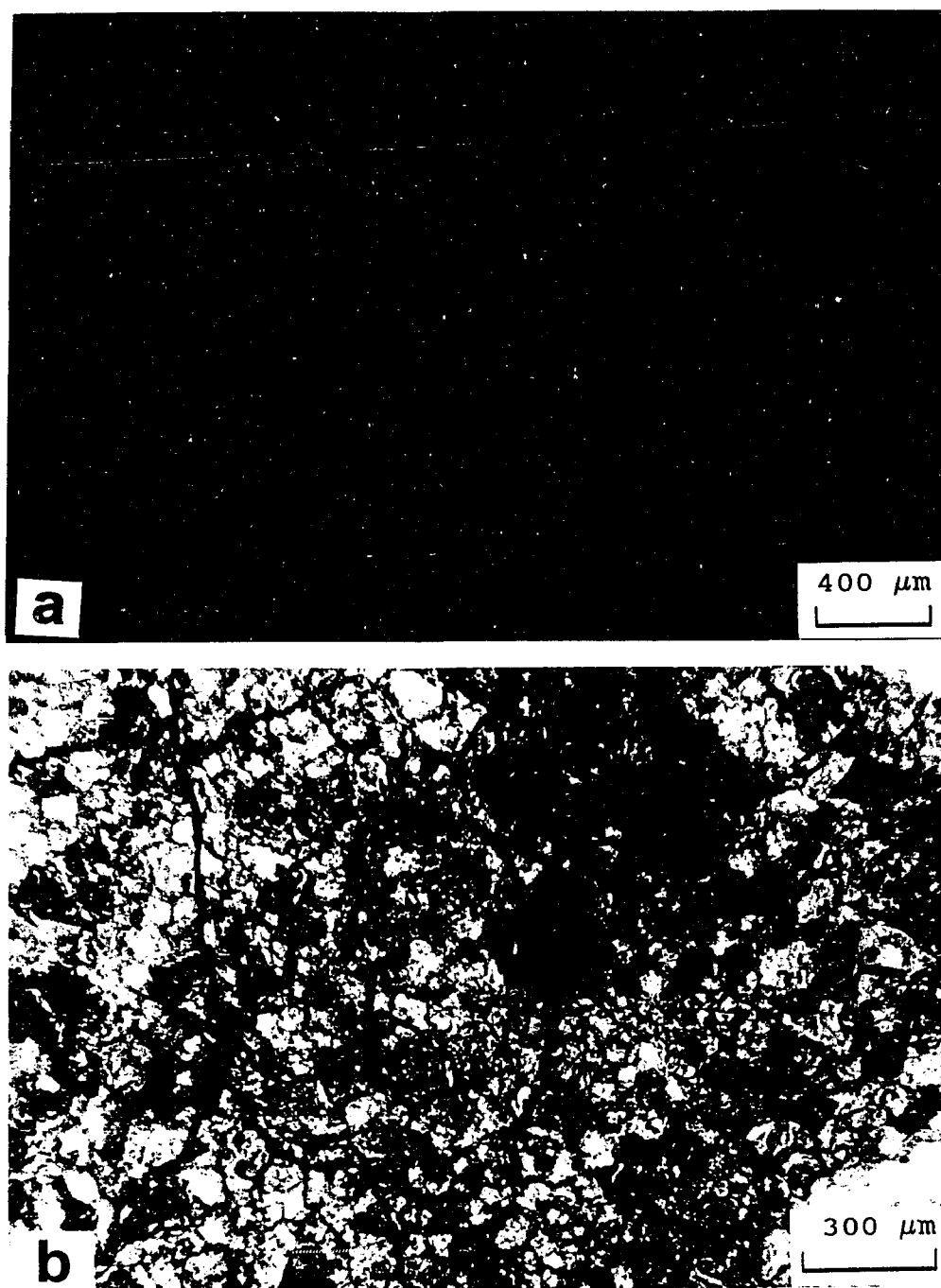


Figure 6-4. Photomicrographs in plane-polarized light and in CL showing stain- and/or CL colors of various fabric components. (The differences in color between figures 6-4, a and 6-4, b and the other color prints is a function of photographic film and -paper used.) a). Very-fine precursor calcite (dull brown CL color) that has been replaced by fine-crystalline euhedral dolomite (b) rhombs, each consisting of non-luminescent cores and medium-bright-orange CL-colored rims. Rochdale Formation at depth of 4915 to 4920 ft. b). Fine crystalline dolomite (b) viewed in plane-polarized light. Red color is from pseudomorphic-replacement dedolomite. Rochdale Formation at depth 5003 to 5006 feet, Crom-Wells No. 1 Fee.

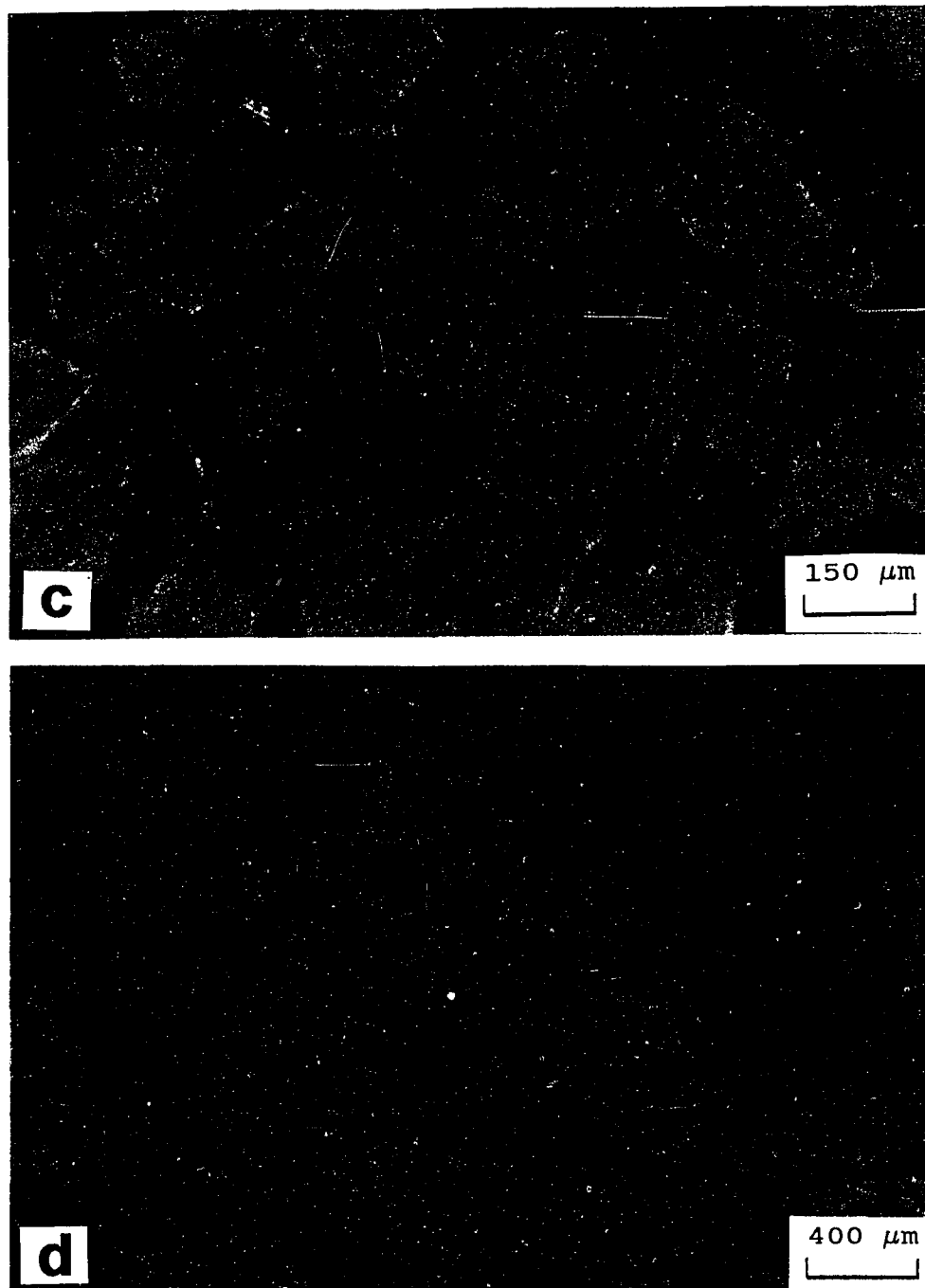


Figure 6-4. c). View under CL showing CL colors of zoned euhedral rhombs of dolomite (c) with dull-CL cores, possibly of dolomite (a) that have been cemented by dolomite (e) having very dull brownish CL. P indicates pore space not filled by dolomite (e) cement. Copake Formation at depth of 4740 to 4752 ft. d). View under CL of framework composed of dolomite (d), medium- to coarse dolomite displaying vague zoned texture, cemented by non-CL dolomite (e). Halcyon Lake Formation ARCO No. 1 Susi, depth 4140 to 4160 ft.

preserved relic depositional texture, such as allochem particles. Coarser very-fine dolomite (20 to 50 μm) shows even texture, unimodal planar-s, rarely preserves any relic allochem particles which probably indicates that their primary sediments were lime mud.

Evidence that these dolomites were modified under shallow- to medium-burial diagenesis includes: (1) compared with very-fine, first-stage dolomite, crystal sizes are larger, which indicates they were subjected a recrystallization under burial conditions; (2) different range of recrystallized allochem (ooids, skeletons, etc.) from almost without change to totally recrystallized can be seen commonly (Figure 6-2, c). And ghost allochems can be seen even in totally recrystallized dolomite (Figure 6-2, d). In general, oolitic dolostone has preserved its original texture better than other grainstone (Figure 6-3, a). Hence, although some fine- to medium planar-s dolomite do not show any ghosts, I know that most of their precursors must have been grainstones; (3) the second-stage dolomites crosscut by late-stage dolomite, such as saddle dolomite; (4) the isotope $\delta^{18}\text{O}$ value is between the values from the early- and late dolomites; (5) trace-element evidence (discussed in later section). The above-mentioned petrographic evidence supports the view that most of dolomite which formed during the early stage was modified in shallow-burial conditions. Because in burial conditions a source of Mg^{2+} is limited (Land 1985), Mg replacement must be rare. Recrystallization of early dolomite into coarser dolomite (second stage) did not need any extra Mg^{2+} .

6.2.2.3 Late-stage dolomite

Dolomite (f): non-saddle dolomite fracture filling

The dolomite forming veinlets that have filled fractures is dolomite (f). In some cases, such dolomite not only filled the fracture but also slightly replaced precursor dolomite that was adjacent to the walls of the fractures (Figure 6-5, a). The crystal sizes of the fracture-filling dolomite are larger than those of the adjacent precursor dolomite. What is more, the fracture-filling

dolomite displays a distinctive zoned texture that is an expression of contrasting chemical compositions and associated orange-red CL color. The zoned-dolomite veinlets crosscut second-stage dolomites, and dedolomite. Therefore, the fracture-filling dolomite occupies the latest position in the diagenetic paragenesis.

The evidence that supports the classification of dolomite (f) as a late-stage product includes: (1) The fracture-filling dolomite always cuts across one or more precursor dolomites, such as dolomite (a), (b), (c), and (d); (2) The fracture-filling dolomite more or less replaced or eroded earlier dolomite; (3) On the basis of their different CL colors, one can infer that the chemical composition of the fluid from which dolomite (f) was precipitated differed notably from that of the fracture-host dolomite. Thus, the time of origin of the fracture-filling dolomite (f) must have been significantly later than that of the fracture-host dolomite. Because dolomite (f) is later than all components of second-stage dolomite, I place it in the late stage.

The dolomite (f) of my classification is similar to dolomite textures 3 and 5 discussed by Amthor and G. M. Friedman (1991, 1992) and the "sucrosic dolomite" of Mountjoy and Halim-Dihardja (1991, p. 599, Figure 9c). As noted previously, Amthor and G. M. Friedman classified all fracture-filling dolomite under the heading of "void-filling dolomite."

Dolomite (g): saddle dolomite

It is noteworthy that I have not proved that any true saddle dolomite (Radke and Mathis 1980) formed within the uppermost three formations of the Wappinger Group. In a dubious category is a small amount of non-CL fracture-filling dolomite which may be saddle dolomite. By contrast, I have found that in the underlying the Pine Plains Formation, true iron-rich saddle dolomite is abundant in nodules, in veinlets, or in scattered pore fillings (Figure 6-5, b) and as last generation of cement (Figure 6-2, c).

Late-stage diagenetic saddle dolomite includes: (1) deep-burial saddle dolomite that

has been found in different kinds of dolostones facies as nodules (Figure 6-3, b), scattered pore fillings (See Figure 6-2, c), and veinlet fillings (Figure 6-3, c); (2) tectonic vein-filling hydrothermal saddle dolomite (Figure 6-3, d).

The common features of saddle dolomite I examined are its milky white, saddle shape of crystal surface, and medium- to coarse crystalline texture. These features are visible in nodule (0.5-1.5 cm in diameter) saddle dolomite, thicker vein-filling (>2 mm in wideness) saddle dolomite and bigger pore-filling (>2 mm in diameter) saddle dolomite. Under the microscope, I have recognized much tiny vein-filling- and pore-filling saddle dolomite that can not be distinguished megascopically. Under the microscope, saddle dolomite is more transparent than the other dolomite components, its crystals are larger, and its Fe content higher (thus stained with potassium chlorite). A sweeping extinction feature is unique compared with other dolomites. The most-distinctive characteristic of saddle dolomite results from its high Fe content: its non-CL (black) color or very dark CL color.

In fine- to very-fine dolostone facies, saddle dolomite occurs as tiny vein fillings (with fine to coarse crystalline) or nodules (medium to coarse crystalline). In fine- to medium relic grainstones, saddle dolomite presents scattered pore fillings(cement). In oolitic dolostone, saddle dolomite formed as last generation of cement following earlier generations of cement.

The content of saddle dolomite ranges as high as 10 to 15% in medium relic grainstones. In other facies of dolostone, saddle dolomite was found widely but in general, with its proportion is lower (5%).

A very special variety of saddle dolomite is tectonic-fracture-filling saddle dolomite or hydrothermal saddle dolomite. (See Figure 6-3, d.) The vein I sampled is exposed on the N side of I-84 in the cuts for the new ramps for entrance from and exiting to NY Route 32 and US 9-W, Newburgh. The veins extend completely across the exposure (for a distance

of at least 25 m). The vein I sampled is more than 25 cm wide, and is one of a group of closely spaced irregular veins. Hence, the dolomite postdates the tectonic fracturing of the rock and probably was precipitated from hydrothermal fluids.

These fracture fillings consist of coarsely crystalline **saddle dolomite**. Crystals range in length from 0.5 to 1.5 mm, but the lengths of most of them are about 1.0 mm. Under cross-polarized light, the saddle dolomite shows typical sweeping extinction. Under the cathodoluminescence (CL) microscope, the color of this kind of saddle dolomite is dull red rather than the non-CL color that characterizes most of the saddle dolomite in the Pine Plains Formation that fills scattered voids or tiny veinlets.

In terms of oxygen isotopes, the $\delta^{18}\text{O}$ of this tectonic fracture-filling saddle dolomite is -12.2‰ (PDB), is much more depleted than in the scattered saddle dolomite from the Pine Plains Formation (average -8.8‰). Thus, this hydrothermal-type saddle dolomite (characterized by very negative oxygen-isotopic ratio, very coarse crystals, dull red CL color, and occurrence in tectonic fractures) differs from the non-luminescent saddle dolomite that fills scattered voids or tiny veinlets in the Pine Plains Formation. Obviously, among all saddle dolomites, the hydrothermal fracture-filling dolomite is the latest product.

6.2.2.4 CL color of dolomite

I have identified three luminescence colors that prevail in all dolomites. (See Table 6-1.) These are (1) dark- and very dark red; (2) medium-bright orange red; and (3) dark tannish-red or non-luminescent.

(1) Dark- and very dark red. Dark-red CL colors are common in first-stage dolomite (a) and in the cores of crystals of dolomites (b), (c), and (d). (See Figure 6-4, a.) Dark-red CL colors are in second-stage dolomite (b) that has not been dedolomitized. Dark red is the predominant dolomite CL color (Figure 6-5, c).

(2) Medium-bright orange red. Some dolomite displaying medium-bright orange-red CL color is found in close association with dedolomite; Figure 6-5, c). Other dolomite displaying orange- to red CL color is found in zoned-dolomite veinlet fillings. (See Figure 6 -5, a.)

(3) Dark tannish-red or non-luminescent. Dolomite displaying dark tannish-red or non-luminescent color is found in cement (e) that filled intercrystalline space in dolomites (b) and (d) dolomite having medium-bright orange color. (See Figure 6-4, c.) Non-luminescent CL is typical in saddle dolomite.

The dedolomitization products associated with all dolomites display bright CL colors. I have found two contrasting fabrics discussed in the next section.

6.2.3. Dedolomite and -related calcite

Among the calcites having the same distinctive bright-yellow CL color and identical chemical compositions, I can distinguish two fabric components: (1) calcite that has clearly replaced a precursor dolomite (=dedolomite); and (2) calcite that mostly filled in open space along cracks (to make veinlets) and that shows only rare fabric evidence that any of it replaced a precursor dolomite. Because of the fabric evidence that much of this material filled open space and only a small amount of it replaced antecedent dolomite, I think it is not appropriate to use dedolomite nor the term "dedolomite vein," which has appeared widely in the dedolomite literature. Instead, I propose to refer to this calcite as **dedolomite-related calcite**. I infer that both the dedolomite and the dedolomite-related calcite are products of the dedolomitizing fluid.

6.2.3.1 *Dedolomite*

The dedolomite is common in dolomites (b), (c), and (d); and rare in dolomite (a). Basically, dedolomite is a subordinate fabric component associated with all kinds of dolomite.

If any dedolomite is present, its volume ranges between 5% and 50% of whatever dolomites were affected. Locally, however the proportion of dedolomite may exceed 50% of the volume, thus converting the affected dolostone back into a "limestone."

The products of dedolomitization are especially well developed in dolostones of the Halcyon Lake Formation but also are found in the Rochdale and Copake formations. (See Figure 4-6, a)

6.2.3.2 Extents and replacement fabrics of dedolomite

The dedolomite that has replaced dolomites (b), (c), and (d) displays three contrasting fabrics that I infer are the results of progressive dedolomitization. These fabrics are: (I) intercrystalline; (II) pseudomorphic; and (III) massive.

(I) Intercrystalline. In rocks displaying dedolomite belonging to fabric (I), the lattices of the larger dolomite rhombs have not been affected, only the dolomite forming the "background" among these rhombs (secondary framework) (Figure 6-5, d). The margins of a few large dolomite rhombs have been corroded, but most of them have not. Individual dolomite rhombs appear to be "floating" within a single giant crystal of dedolomite calcite. Proof that this calcite texture resulted from dedolomitization is its identity of CL color with that of dedolomite that is pseudomorphic after the large dolomite rhombs. Moreover, the $\delta^{18}\text{O}$ value of a sample of dedolomite-replacement fabric (I) lies within the dedolomite field (discussed in "Geochemistry").

I surmise that dedolomite-replacement fabric (I) indicates an initial stage of dedolomitization. Possibly the precursor material between the larger rhombs was rich in Ca and thus tended to be dedolomitized first. The fate of the larger dolomite rhombs, whether not they were affected or corroded, may have been determined by the degree of saturation of the solution with respect to dolomite.

Rocks displaying dedolomite-replacement fabric (I) are similar to those in which isolated

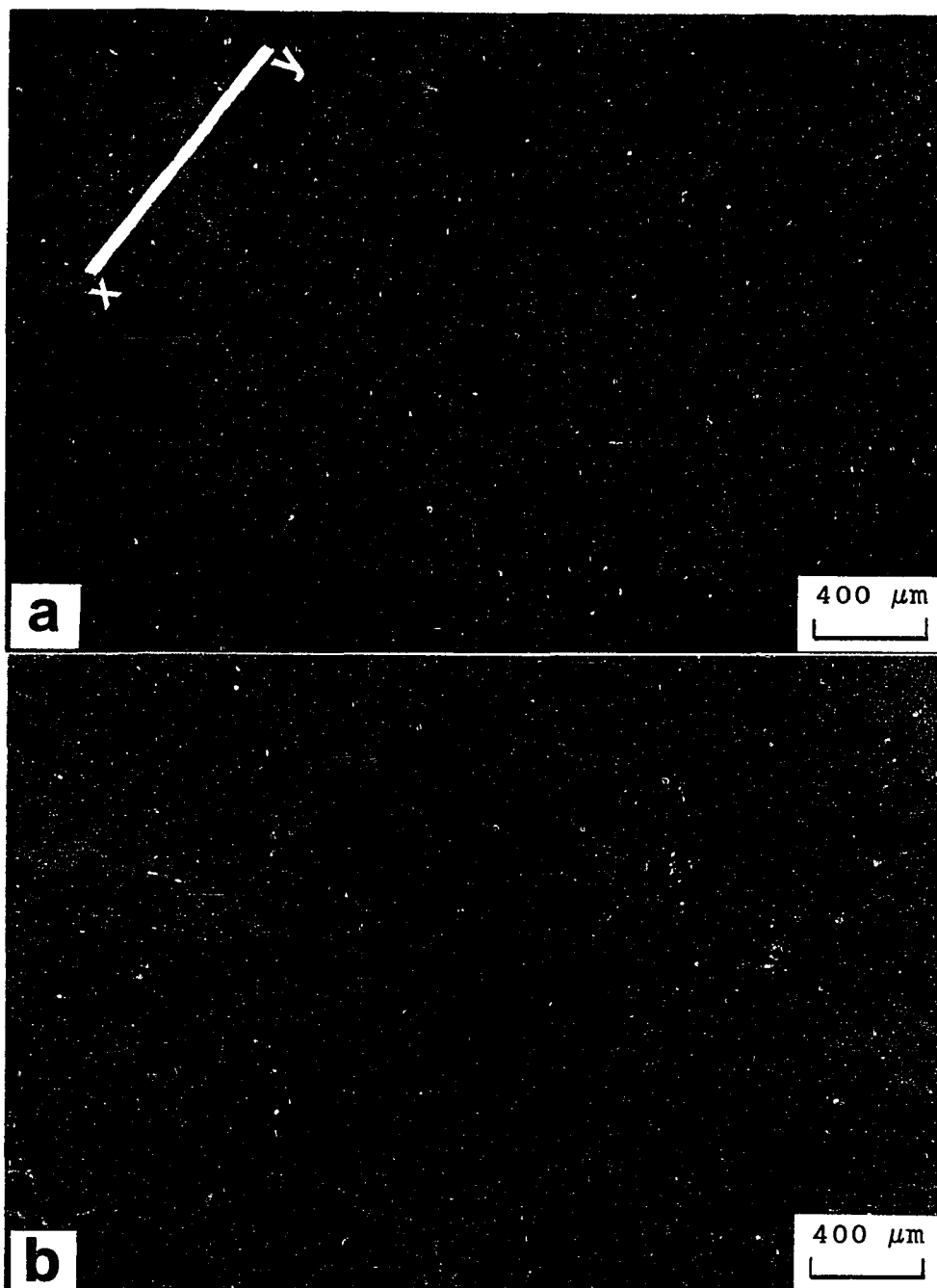


Figure 6-5. Photomicrographs in plane-polarized light and in CL showing stain- and/or CL colors; enlarged views showing CL colors of dolomite and dedolomite. a). Zoned fracture-filling dolomite (f) in which reddish cores are encased in brighter-colored rims. The brighter color of these rims is characteristic of late-stage dolomite (also visible in Figure 6-6, d). Line X-Y indicates the line of the microprobe traverse shown in Figure 6-10. Halcyon Lake Formation at depth of 5304 to 5307 feet, Crom-Wells No. 1 Fee. b). Second-stage dolomite (b) (dull red) and later-stage dolomites, (f) and (g) (=saddle dolomite). Dolomite (f), bright-orange color, fills hair-line cracks and also constitutes the initial lining of the vug. Non-CL saddle dolomite (black) forms final vug filling. Pine Plains Formation, Clinton Point Quarry, Hole 73-91, depth 58 ft.

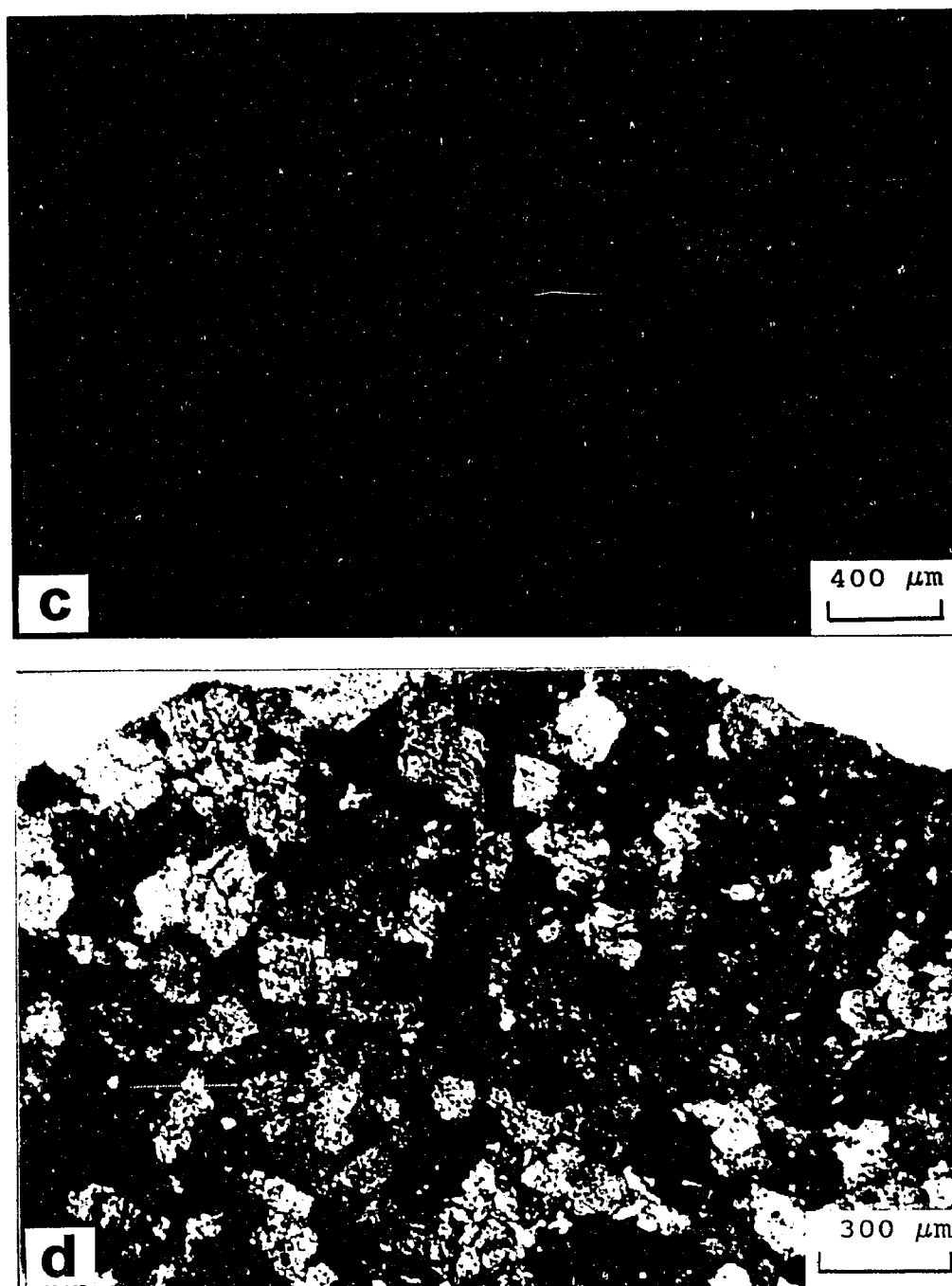


Figure 6-5. c). Dolomite CL colors (1) dark red and (2) medium-bright orange-red in the elongate chip just above the center that has been cut by a veinlet of dedolomite-related calcite having bright-yellow CL color. Halcyon Lake Formation at depth of 5043 to 5045 ft, Crom-Wells No. 1 Fee. d). Intercrystalline-replacement dedolomite viewed in plane-polarized light in which the dedolomite (red stain) is confined to parts of the "background" and scarcely affected the euhedral dolomite rhombs (white). Copake Formation at depth of 4820 to 4833 ft, Crom-Wells No. 1 Fee.

euohedral rhombs of dolomite are scattered within nondolomitized original lime mud. (See Figure 6-1, b.) The euohedral dolomite crystals within an incompletely dolomitized original lime mud should not be corroded. No dolomite would invade the outlines of these rhombs. However, during recrystallization of such calcite, the dolomite rhombs may be slightly corroded. The distinctive CL colors provide the best evidence for distinguishing dedolomite (bright light yellow) from precursor calcite (dull tan).

(II) Pseudomorphic. In dedolomite fabric (II) that I designate as pseudomorphic, the dedolomite partly (in some zones) or completely (in other zones) replaced euohedral dolomite rhombs. The bright light-yellow CL color of crystals that have been pseudomorphically replaced is characteristic. Such crystals are easily distinguishable from all other minerals that show dark- and dull CL colors. Pseudomorphic texture is the best evidence proving that the calcite is of secondary origin (thus is dedolomite; Evamy 1967, Friedman and Sanders 1967, Shearman, Khouri, and Taha 1961, Theriault and Hutcheon 1987).

Dedolomite of the pseudomorphic-replacement style occupies less than 50% of the volume of the affected rock. This conversion of dolomite crystals into dedolomite forms a calcdolostone (Figure 6-6, a).

I infer that dedolomite of fabric (II) forms an intermediate step between that of fabric (I) and of fabric (III).

(III) Massive. In this category I include dedolomite that forms irregular masses that occupy large proportions of the affected rock (Figure 6-6, b). Both the "background" dolomite [fabric (I)] and the larger rhombs [fabric (II)] have been replaced. A typical result is masses of dedolomite of the common calcdolostones of the Halcyon Lake Formation or even the reconstituted dolomitic "limestones" mentioned above (confined to the Halcyon Lake Formation)

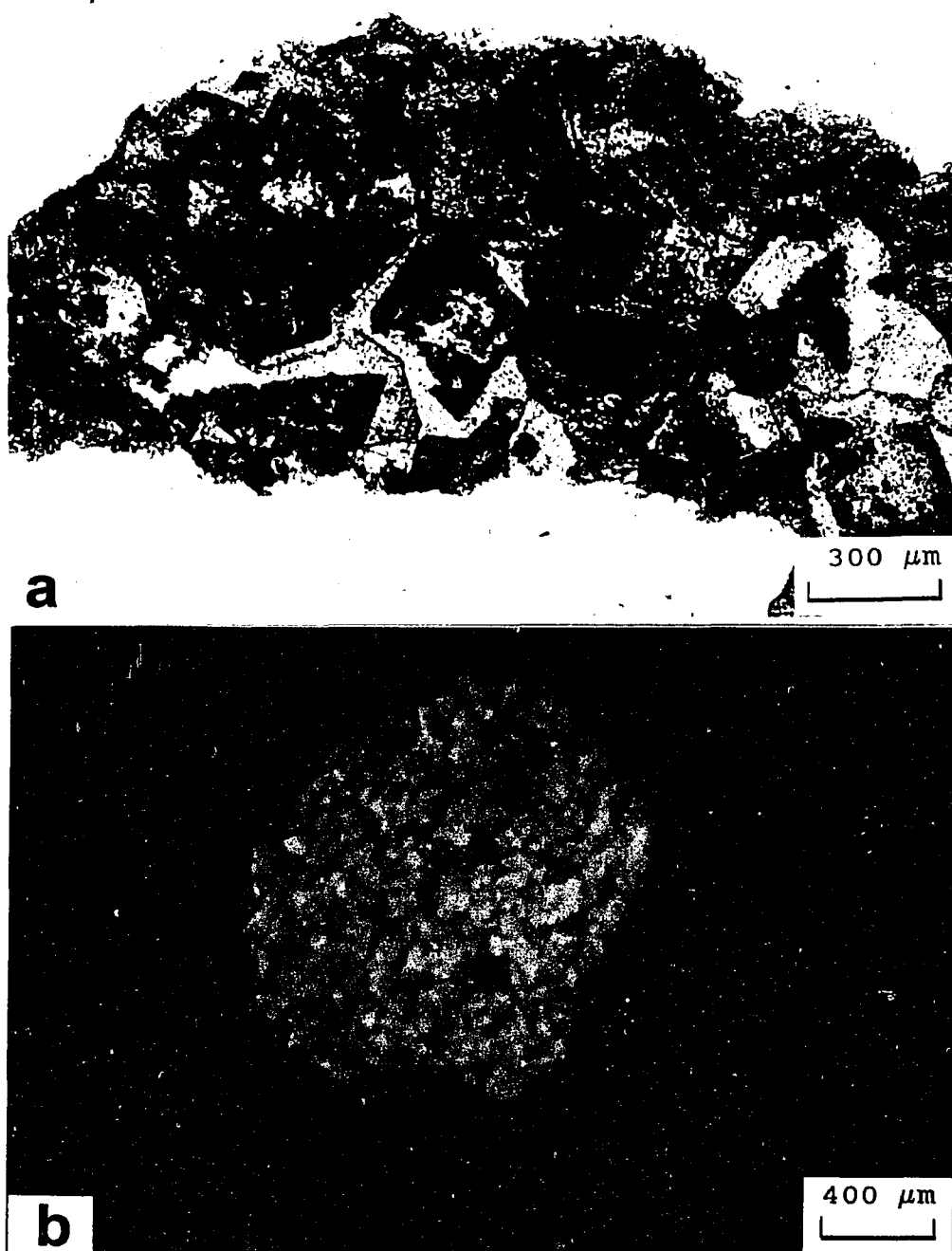


Figure 6-6. Photomicrographs in plane-polarized light and in CL showing stain- and/or CL colors; enlarged views showing CL colors of CL of dolomite, dedolomite, and veinlets of bright (dedolomite-related) calcite and of dull calcite (Crom-Wells No. 1 boring). a). View in plane-polarized light of stained thin section of pseudomorphically replaced dedolomite (red stain) formed from medium- to coarse euhedral rhombs of dolomite (d) that have been cemented by late-stage dolomite (e) (white). Halcyon Lake Formation at depth of 5232 to 5242 feet. b). Result of pervasive massive-replacement dedolomite in larger, circular chip. The CL color of dolomite is red; that of dedolomite, bright yellow. Halcyon Lake Formation at depth of 5129 to 5135 ft.

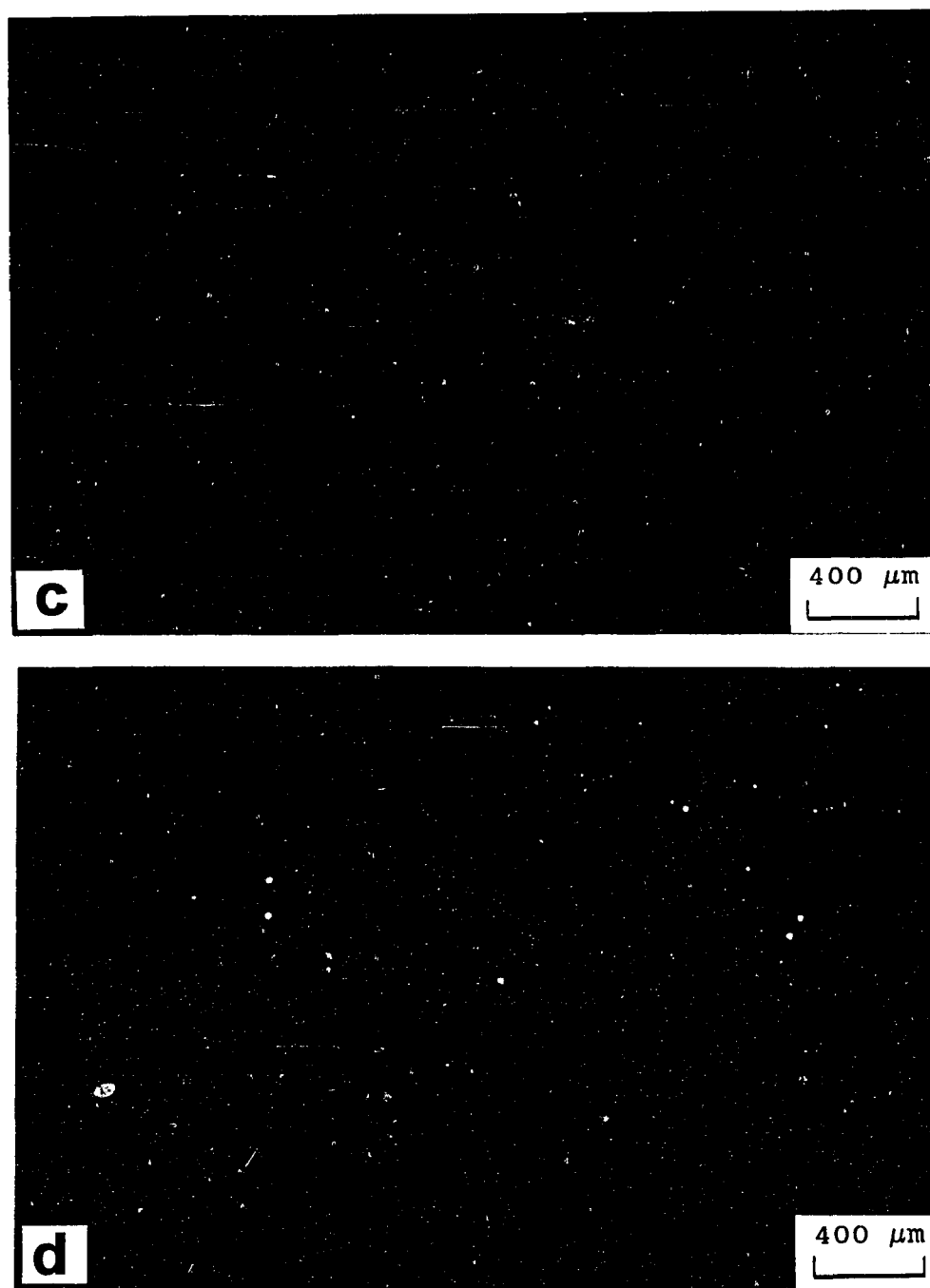


Figure 6-6. c). View under CL of small remnant of a composite veinlet (along L side of large chip at center) consisting of dull early calcite (tan color along the veinlet wall) and of bright yellow dedolomite-related calcite (interior of veinlet). Rochdale Formation at depth of 4996 to 4999 ft. d). Second-stage dolomite (b), dull red at bottom, cut by late-stage fracture-filling dolomite (f) that is brighter colored and zoned. Final fracture filling consists of late dull calcite (triangular remnant at top). Halcyon Lake Formation at depth of 5283 to 5288 ft.

whose calcite content may be as much as 60%.

In general, I consider that massive-replacement dedolomite of fabric (III) resulted from a continuation of dedolomitization of the pseudomorphic-replacement stage of fabric (II). Expressed in another way, I consider that the massive-replacement dedolomite (III) is the product of the most-advanced stage of dedolomitization.

6.2.3.3 *Dedolomite-related calcite*

In many cases, veinlet(s) consisting of dedolomite-related calcite coexist(s) with replacement dedolomite displaying all three of the dedolomite fabrics mentioned above. Petrographic evidence that the calcite of such veinlets belongs to the dedolomitization episode (thus is dedolomite-related calcite) is their physical continuity with dedolomite that has replaced dolomite rhombs. Lacking such evidence of physical continuity, it is not possible from petrographic observations alone to determine whether the calcite of veinlets is or is not a product of dedolomitization. Under the cathodoluminescence (CL) microscope, however, thin veinlets of dedolomite-related calcite are easy to recognize because the veinlet mineral shows the same bright light-yellow CL color as the dedolomite. (See Figure 6-5, c; and Figure 6-6, c.)

In some cases, both dull early veinlet calcite and bright dedolomite-related calcite coexist in the same fracture, but the early veinlet calcite is confined to the walls of the fracture and the dedolomite-related calcite occupies the central space of the fracture. (See Figure 6-6, c.) In some examples, the calcite of late veinlets has truncated dolomite (f) consisting of bright-zone CL color (Figure 6-6, d).

6.3 Diagenetic paragenesis

In terms of cross-cutting relationships of various mineral- and fabric components, obtained from petrographic- and CL studies, I have assembled a 10-step diagenetic history

for the three formations at the top of the Wappinger Group and for the Pine Plains Formation. Included are three stages of dolomitization; the dedolomitization took place after the second (or main) stage of dolomitization. However, because of different burial- and uplift histories between the top three formations and the Pine Plains Formation (details in "Discussion" section), their diagenetic products of the second- and late-stage are quite different as shown in Figure 6-7, a and 6-7, b separately.

The diagenetic history begins with the neomorphism of the original lime mud and extends through late calcite veinlets. Because some of the stages overlap (Figure 6-7, a, b), the following list is a generalized summary and should not be considered as a strict chronological sequence of discrete, non-overlapping steps.

(1) Neomorphism and/or lithification of previously deposited lime carbonates to form micrite, pelletal, skeletal, and oolitic limestone. This step includes the initial changes, such as from aragonite or high-magnesium calcite, to the precursor calcite. The precursor calcite may have been subjected to later diagenetic modification.

(2) Early-stage dolomitization. At some time late in or after step 1, the lime mud or precursor calcite was subjected to dolomitization to form very fine crystals of dolomite (a). Meanwhile, small euhedral rhombs of dolomite grew in the lime mud. In some dolomitic limestones, the cores of some euhedral dolomite crystals display a dark, dull CL color that may imply early-stage dolomite. Early dolomitization also affected large amounts of carbonate sands, such as ooids. Preserved non-recrystallized oolitic dolomite indicates early-stage origin. Early dolomitization could form dolomitic limestone, calcdolostone, or dolostone having various textures.

(3) Dissolution of remaining lime mud and conversion of early dolomite rhombs into secondary "framework". Evidence indicating dissolution is the relationship of dolomite (e) cement to

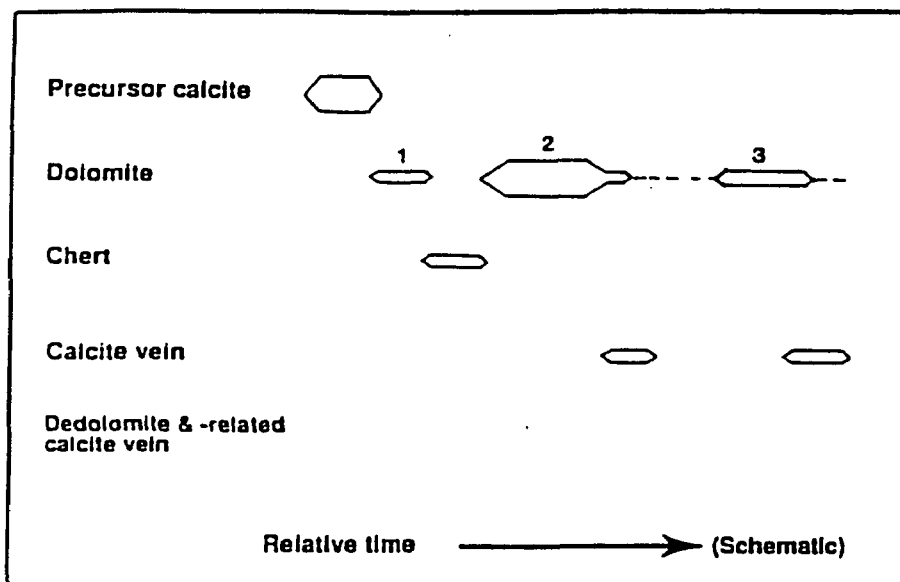
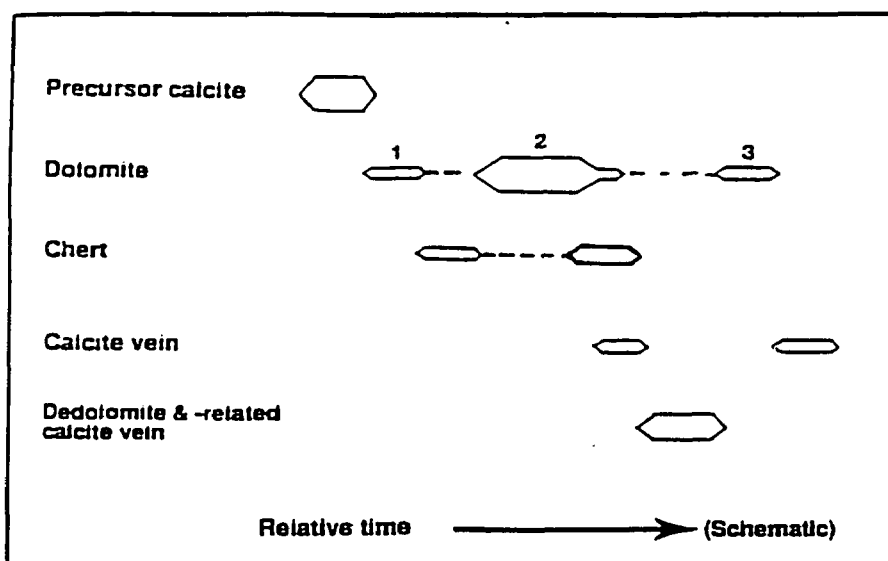


Figure 6-7. Diagenetic paragenetic succession in the of Wappinger Group, (a) Halcyon Lake Formation and (b) Pine Plains Formation. Note the three stages of dolomitization (numbered 1, 2, 3) are present in both formations. However, late-stage dolomite (mainly saddle dolomite) is more abundant in the Pine Plains Formation. And the dedolomite that follows the second-stage dolomite is only found in the Halcyon Lake Formation.

dolomite (c)(fine euhedral). Dolomite (e) grew as overgrowth cement into empty space that resulted from dissolution of precursor lime mud. In some cases, between the boundaries of dolomite (e) crystals, some pore space remains.

(4) Second-, or main-stage of dolomitization: In most wackestones and packstones, early dolomite replaced precursor calcite only partly(selectively). And in the second stage, dolomite may still replace precursor calcite or grew continuously around cores of early-formed rhombs. For the lime mud and micrite ooids, the dolomitization had almost been completed in the early stage and during the second stage, they were mainly recrystallized and may accompany some replacement products. Later in the second stage, new dolomite can also fill the interparticle-and/or intercrystalline pores as cement. As a result, fine-, medium-, or coarse crystals formed [dolomite (b), (c), (d), and (e)], respectively. Because during the first stage, the greatest volume of calcium carbonate had already been dolomitized, during the second-stage of dolomitization, the most-important processes would have been a kind of replacement-recrystallization (recrystallization more important than replacement).

In the Finnegan boring, I found some oil residues in the upper part of the Galway Formation (which is equivalent of the Pine Plains Formation). The oil residue has filled in some intercrystal/interparticle pores of sandy dolostone (Guo, Sanders, and Friedman, 1990). I assign a second-stage origin to host fine-crystalline dolomite containing the oil residues. Thus, I infer that the oil formed and migrated during shallow- to intermediate burial associated with the second-stage dolomitization. As well known, gas can be produced much later than oil. The origin of the thermogenic methane probably started at the end of the second-stage dolomitization.

The following steps (5), (6), (7) formed during or after the second-stage dolomitization.

(5) Silicification and origin of chert nodules. Silica may replace nondolomitized lime mud

between dolomite rhombs and locally replaces dolomite rhombs. Although some chert may have formed during the early stage, most of the chert was produced during or after the second-stage dolomitization.

(6) Precipitation of early-calcite veinlets: The early-veinlet calcites fill fractures some of which were later cut by veinlet(s) of dedolomite-related calcite.

(7) Dedolomitization: At some time after the second-stage dolomite formed, large amounts of Ca- and Mn-rich fluid circulated within the formations. This solution was not saturated with respect to dolomite, but saturated with respect to calcite. Hence, dedolomite replaced precursor dolomite. Partial- and even whole rhombs were affected. Some bright-CL-colored calcite did not replace precursor dolomite, but filled open spaces, in fractures and in pores.

During shallow- to intermediate burial (second stage of dolomitization), the diagenetic processes within the top three formations were very different from those within the Pine Plains Formation. In the top three formations, the second-stage dolomite that formed at a depth of around 600 feet was dedolomitized after uplift during the post-Sauk, pre-Tippecanoe unconformity. The dedolomitization and silicification affected only the top three formations, and was especially pronounced in the Halcyon Lake Formation. By contrast, the Pine Plains Formation did not reach the surface or near surface; and it underwent normal shallow- to intermediate burial processes. Hence, no dedolomite and only a few chert nodules are to be found. I infer that the depth of intermediate burial of the Pine Plains Formation may have been as much as 1 km maximum.

(8) Stylolitization: In the Wappinger Group, stylolites are widespread features. They are products of important diagenetic reactions. Most of the stylolites are parallel to bedding, but a few are nearly normal to bedding. The time(s) of origin of the stylolites is (are) later than the second-stage dolomite and earlier than the deep-burial saddle dolomite.

(9) Late-stage dolomitization: This stage includes all dolomite that is later than the main-stage dolomite. Within this generalized category, I lack evidence for determining how much later or for identifying possible discrete episodes of dolomite formation. Examples include dolomite (f), the zoned fracture filling (See Figure 6-4, d.), saddle dolomite; and vein-filling dolomite associated with quartz in late fractures that are abundant in the Pine Plains Formation. Of these, saddle dolomite is most abundant.

As mentioned, during shallow- to intermediate burial, the Halcyon Lake and the Pine Plains formations underwent quite different diagenetic processes. In the Halcyon Lake Formation, some near-surface processes, such as dedolomitization and silicification were strongly involved. Because of those near-surface processes, most primary- and secondary pores were eliminated. Not much pore space was left for later dolomite to fill. Hence, in the Halcyon Lake Formation, late-stage dolomite is rare. Only small amount of dolomite (f) filled some fractures; no saddle dolomite is to be found. Conversely, in the Pine Plains Formation, late-stage saddle dolomite is abundant.

(10) Precipitation of late dull-calcite veinlets: These veinlets crosscut all previously formed fabric components. As with the late-stage dolomite, the time(s) of formation of the late dull calcite veinlets is (are) not well constrained.

The oxygen-isotope ratios of the dark-gray calcite are very close to those in the other dedolomite, but the carbon-isotope composition of the dark-gray variety is much depleted (Figure 6-11). During microprobe analysis, a current of 45 nA damaged the black calcite immediately. Even a current as low as 15 nA caused slight damage (no other components were damaged). This indicates that the black calcite formed under very low temperature and -pressure. It is thus distinct from all other components that underwent deep-burial conditions. On the basis of its low tolerance for the electron-beam current, widespread occurrence, higher

organic content (black or dark gray color), and its distinctive isotope composition, I infer that black calcite may have been precipitated near the Earth's surface by fresh water. This may have taken place after the entire basin had been uplifted after the Late Paleozoic deformation.

Among the three stages of dolomite, the distributions of early dolomite (a) and late-stage dolomite are limited (4% and 1% in the top three formations and 13% and 7% in the Pine Plains Formation). By contrast, the second-stage dolomites (b), (c), and (d) constitute the predominant volume of massive dolomite in the top three formations (95%) and in the Pine Plains Formation (80%).

6.4 Geochemistry

I have supplemented the petrographic- and CL investigations by obtaining data on the (1) major ionic constituents (2) contents of the trace elements Fe, Mn, Sr, and Na in the minerals forming the different fabric components using an electron-beam microprobe (Table 6-2, 6-3); and (3) ratios of stable isotopes of oxygen and of carbon. Both the main constituents of the CaCO_3 and MgCO_3 and also the contents of the trace elements Fe and Mn show that different fabric components form distinctive chemical groups.

6.4.1 Major ionic constituents

Most of the calcite samples analyzed were from the precursor calcite, but some samples were of relic calcite spots found within euhedral dolomite rhombs and some from early- and late calcite veinlets. The mean composition of precursor calcite is: CaCO_3 98.6% and MgCO_3 1.1%. As shown in Table 6-2, the composition of the relic calcite spots within some dolomite crystals is similar to that of precursor calcite. But, in these relic calcite spots, the content

of MgCO_3 is much higher (3.6%) than that of the precursor low-magnesium calcite (1.1%).

As shown in Table 6-2, the MgCO_3 content of the dedolomite averages 5.2%. Thus this is a kind of Mg-rich calcite (but is not high-magnesian calcite). The Ca contents of dedolomite-related calcite in veinlets and of the early calcite veinlets is almost identical.

The mean composition of the dolomites is nonstoichiometric; they are quite rich in Ca. In dolomite of the top three formations (Table 6-2), the CaCO_3 : MgCO_3 ratio is 57:43. However, this ratio is somehow variable among different components and -formations as shown in Table 6-3.

Consider the most-common component, fine crystalline dolomite (b). It becomes more stoichiometric from the Rochdale Formation (58/42), to the Halcyon Lake Formation (57/43), and to the Pine Plains Formation (54/46) if we treat Fe^{2+} as a substitute of Mg^{2+} . This fact may indicate the slight differences of original dolomitizing fluids when these formations deposited or represents the progressive stabilization from younger- to older formations (Land, 1985).

Within an individual formation, later-stage pore-/fracture-filling products, dolomite (e), (f) and (g), are always slightly richer in Ca and poorer in Mg than the earlier replacement dolomite (a), (b), (d). This relationship contributes to the source of later-stage dolomitizing fluids, which probably were related to the dissolution of earlier products. As is well known, metastable Ca-rich dolomite is more soluble than Ca-poor dolomite (Land 1985). Earlier-stage, Ca-rich constituents which are the first to dissolve provide ions for the fluid that precipitated late-stage pore/fracture filling.

6.4.2 Trace elements

I measured the trace elements Fe^{2+} , Mn^{2+} , Sr, and Na in the minerals. Of these trace elements, only Fe^{2+} and Mn^{2+} are present in significant amounts; only small amounts of Na

Minerals	Components	Fe ppm	Mn	CaCO ₃	MgCO ₃ %	SiO ₂
Calcite	Precursor	236	72	98.6	1.1	0.2
	Relic in dolomite	141	0	95.9	3.6	0.5
	Early calcite vein	711	120	97.3	1.4	0.8
Dolomite	Mean dolomite	1969	50	56.5	41.8	1.1
	Dolomite (a)	2118	0	55.7	43.5	0.3
	Dolomite (b), (c)					
	Related to dedolomite	2254	256	55.6	43	0.8
	No relation with dedol.	3217	119	55.1	43.3	0.9
	Others	1748	16	57.4	40.3	1.9
	Dolomite (d)	653	16	57.6	41.6	0.5
	Dolomite (e)	255	58	57.9	41.4	0.5
	Dolomite (f)	2844	132	56.3	41.5	1.6
Dedolomite	Mean dedolomite	435	561	92.8	5.2	1.9
	Replacement	673	429	90.2	7.8	1.8
	Veinlet	70	843	96.9	1.1	2

Table 6-2 Geochemical data of carbonate components in the top of the Wappinger Group

Formation Component	CaCO ₃ / MgCO ₃ (%)	Fe (ppm)	Mn (ppm)	SiO ₂ (%)	FeCO ₃ (%)	Trends		
						Ca/Mg	Fe/Ca	Fe/Mn
Copake & Rochdale Dol. (b) (39)	57.0/40.6	1983	43	1.7	0.4	(-)		
Halcyon Lake Fm.						(-)		
Dol. (a) (5)	55.7/42.6	1902	0	1.2	0.3			
Dol. (b), (d) (68)	55.9/42.4	1268	122	1.6	0.3			
Dol. (e) ARCO (3)	55.3/41.1	11999	135	0.7	2.5			
Crom (8)	57.9/41.4	255	58	0.5	0.1			
Dol. (f) ARCO (7)	57.3/40.8	463	81	2.5	0.1			
Crom (22)	56.3/41.5	2844	131	1.6	0.5			
Pine Plains Fm.								
Dol. (a) (5)	55.7/44.3	7237	189	5.8	1.5	(+)	(-)	
Dol. (b) (40)	54.0/46.0	2258	172	1.2	0.5	(+)	(-)	
Saddle dol. (40)	55.3/44.7	9560	405	0.2	2.0	(-)		(+)

Keys: Dol. (a)--very fine dolomite; dol. (b)--fine dolomite; dol. (d)--medium to coarse dolomite; dol. (e)--cement dolomite; dol. (f)--fracture-filling dolomite; ARCO-- ARCO Susi bore hole, Crom--Crom-Wells #1 Fee hole; (39)-- numbers of analysis; (+)-- proportional relationship; (-)-- inverse relationship.

Table 6-3 Summary of geochemical data of dolomite components from the Wappinger Group

and Sr are present in a few samples.

6.4.2.1 Precursor calcite --The mean trace-element content of Fe^{2+} in the precursor calcite is 236 ppm and that of Mn^{2+} , 72 ppm. The composition of the spots of relic calcite within some dolomite crystals is similar to that of the precursor calcite.

6.4.2.2 Veinlet calcite --The veinlet calcite that preceded the dedolomitization contains much higher Fe^{2+} (710.6 ppm) and Mn^{2+} (119.5 ppm) than does the precursor calcite. The veinlet calcite is the only mineral component that contains a little Sr, 106.6 ppm.

6.4.2.3 Dolomites --The mean values of the contents of Fe^{2+} in all dolomites sampled are greater than those in the precursor calcite (Table 6-2). This relationship indicates that the Mg-rich dolomitizing fluid also brought along Fe^{2+} . By contrast, the content of Fe^{2+} (0 to 4500 ppm) is higher in dolomite than in the dedolomite (from 0 to 2000 ppm), but the amount of Mn^{2+} is smaller in dolomite (0 to 400 ppm) compared with 0 to 2000 ppm in dedolomite (Figure 6-8 a, b). During dedolomitization, Fe^{2+} decreased dramatically, and Mn^{2+} increased.

Trace elements Fe^{2+} , and Mn^{2+} in most late-stage components [dolomite (e), (f), (g)] are much higher than in host earlier components (Table 6-3). The samples containing the most Fe are cement between rhombs in the Halcyon Lake Formation, which is not saddle dolomite. As expected, all saddle dolomite samples are very rich in Fe^{2+} .

6.4.2.4 Dedolomite and dedolomite-related calcite --The Mn^{2+} content in dedolomite is proportional to CaCO_3 and inversely proportional to MgCO_3 (Figure 6-9 a, b). Moreover, in the dedolomite-related calcite in veinlets, the content of Mn^{2+} commonly is greater than it is in replacement dedolomite.

Although, as mentioned, the Ca contents of the dedolomite-related calcite veinlets and of the early calcite veinlets are almost the same, their amounts of Fe^{2+} and Mn^{2+} are not the same. The Fe^{2+} content is higher and Mn^{2+} content lower than in the dedolomite-related calcite.

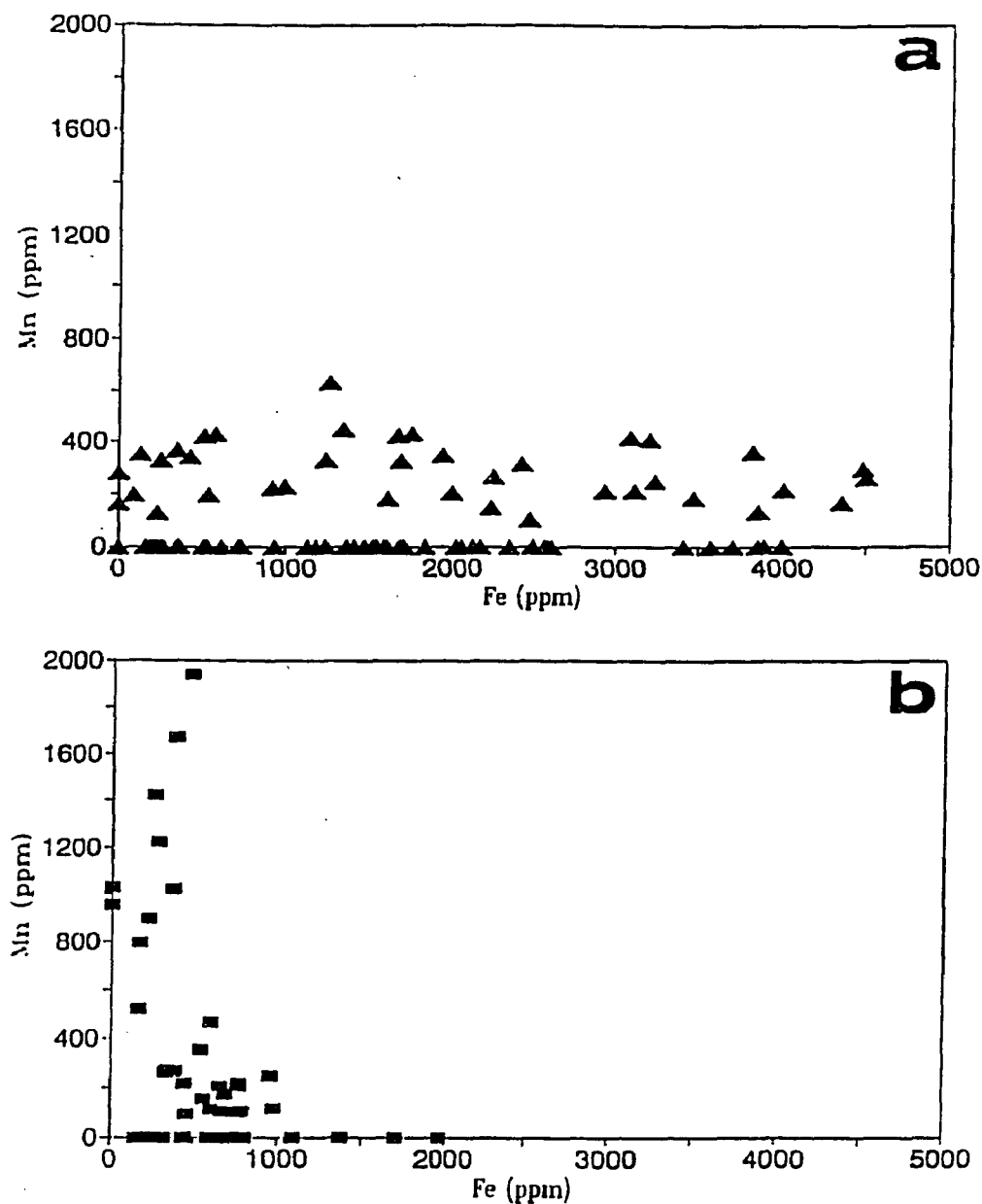


Figure 6-8. Plots of manganese versus iron, based on microprobe results, show the changes that accompanied dedolomitization. During dedolomitization, Fe decreased dramatically; in 25% of the samples of dedolomite, Mn increased. a). Dolomite. b). Dedolomite.

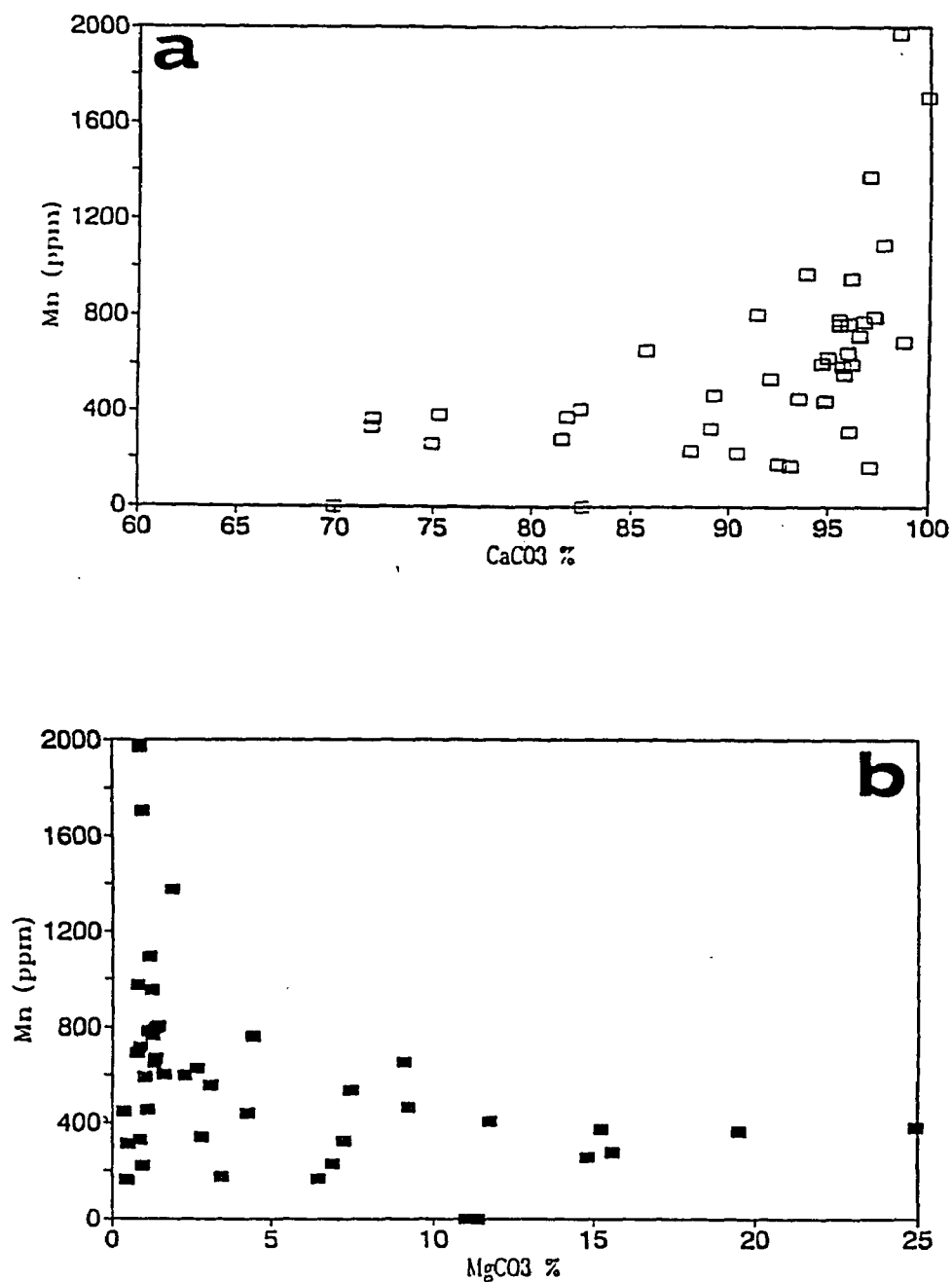


Figure 6-9. Graphs of manganese plotted against carbonates in dedolomites. Manganese is proportional to CaCO_3 and inversely proportional to MgCO_3 . a). Manganese versus CaCO_3 . b). Manganese versus MgCO_3 .

6.4.2.5 Interpretation of trace-element data --Chemical data satisfactorily explain various CL colors of the calcites, the dolomites, and the dedolomite and dedolomite-related calcite. The CL colors of precursor calcite and calcite veinlets are dull tan and brown. The dolomites display red CL colors with different brightness. And the CL colors of the dedolomite and dedolomite-related calcites are bright yellow. The intensity- and color of luminescence depend not only on the respective contents of Fe^{2+} and Mn^{2+} but also on the $\text{Fe}^{2+}/\text{Mn}^{2+}$ ratio. These results between CL colors and trace elements are the same as those found by several previous investigators (Meyers and Lohmann 1978, Frank and others 1982, and Barnaby and Rimstidt 1989).

The different dolomites of the various diagenetic stages, recognized by their textures and CL colors, also display distinctive chemical differences. Dolomite (a), the very-fine-crystalline product of early-stage dolomitization, gives a very dull-red CL color that is consistent with its high Fe^{2+} and with low Mn^{2+} . (See Table 6-2, 6-3.) In dolomites (b), (c), and (d), the products of the second (main)-stage of dolomitization, the CL color varies with Mn^{2+} content, which is related to association with dedolomite. The CL color of dolomite lacking any dedolomite is dark red (Mn^{2+} low or absent). The CL color of dolomite associated with dedolomite is medium-bright red (higher Mn^{2+} , 256 ppm). The CL color of dolomite (f), the late-stage fracture filling clearly displaying a zoned texture, is relatively bright orange red. The zoned texture is obviously an expression of variations in trace quantities of Fe^{2+} and Mn^{2+} (Figure 6-10). And because its high concentration of Fe^{2+} , late-stage saddle dolomite shows very dull CL color or non-CL color.

The lower Fe^{2+} and higher Mn^{2+} concentrations of the dedolomite than in the replaced dolomite strongly suggest that the dedolomitizing fluid was meteoric water that most likely entered these rocks during post-early Middle Ordovician erosion. As is well known, in fresh

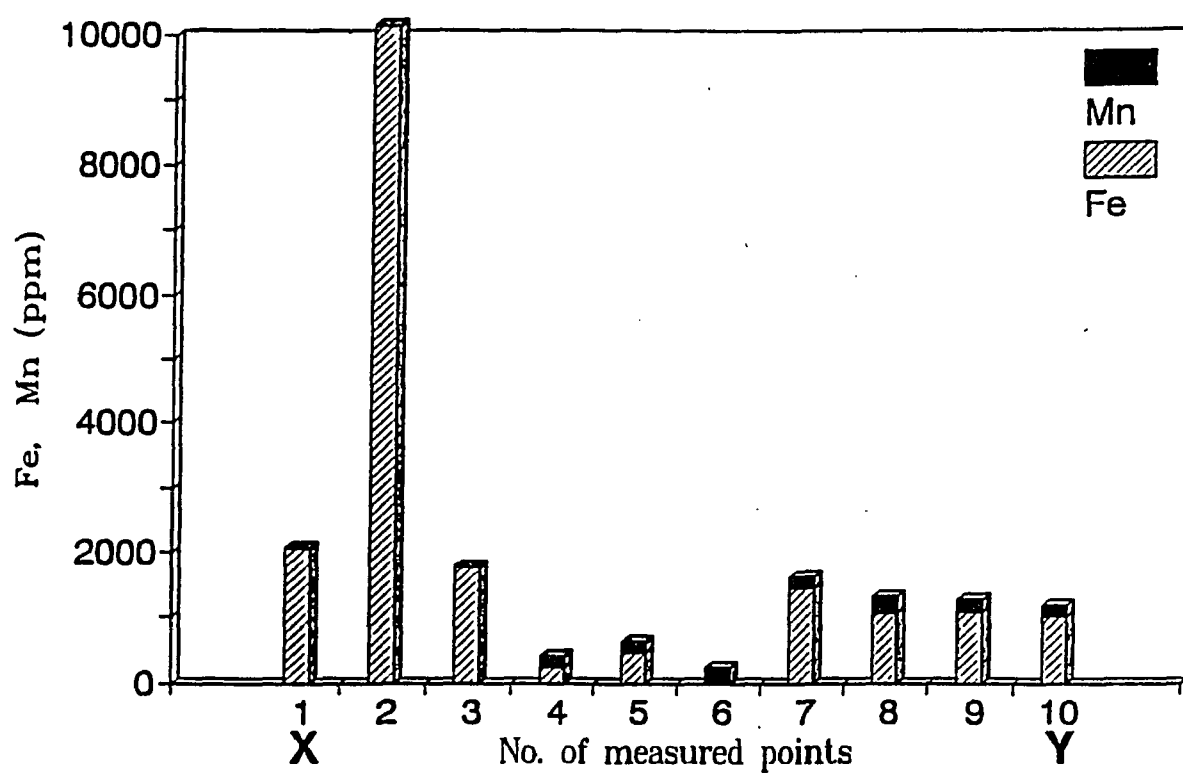


Figure 6-10. Graphic presentation of Fe and Mn contents of individual zones within the late-stage zoned fracture-filling dolomite (f) crystals based on point-traverse analyses by electron microprobe. X and Y points match that X and Y position within a measured crystal in Figure 6-5,a, each bar represents the results at a single point along the traverse line from the core of a crystal (rich in Fe and lacking Mn, at left) to a rim (much lower Fe and containing Mn, at right).

water, the Mn^{2+} content is an order of magnitude higher than that of the Fe^{2+} (Churnet and others 1982; Wedepohl 1978; Livingstone 1963). The similarity of both the chemical composition and CL colors of the dedolomite samples from the Copake, the Rochdale, and the Halcyon Lake formations implies that they were precipitated from the same kind of dedolomitizing fluid.

Land (1985) contends that dolomite undergoing diagenesis resulting from progressively deeper burial becomes more stoichiometric (gradual increase in Mg^{2+}) and its contents of the trace elements Fe^{2+} and Mn^{2+} increase. Amthor and Friedman (1992) established similar trends. As discussed above, in this study, I found the same trend. However, in the top three formations, dolomitization was interrupted by dedolomitization. As a result of such interruption, the trace-element composition of dolomite that co-exists with dedolomite is higher in Mn^{2+} , as in the trends cited above, but lower in Fe^{2+} , which is just the opposite of the cited trends.

6.4.3 Ratios of stable isotopes

The isotope results are based on the 21 samples from different fabric components which are calcite precursor, early calcite veinlets, dolomite (a)(early-stage), dolomite(b)(d)(second-stage), late-stage (saddle dolomite), and dedolomite] that I submitted to Geochron Laboratories Division of Krueger Enterprises, Inc. of Cambridge, Massachusetts, to be analyzed for stable-isotope ratios of carbon and oxygen. These samples not only represent different petrographic components but also within the dedolomite, represent different textures which include inter-crystalline-, pseudomorphic- and massive-replacement dedolomite.

Tables 6-4, and 6-5 and Figure 6-11 present the results. From Tables 6-4, and 6-5 and Figure 6-11 the important point to be seen is that calcite, dolomite, and dedolomite show

	Depth (ft.)	Lithology	Minerals	Formation	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
1	4738- 4788	Dolzed. Ls.	Precursor calcite	Copake Ls.	-2.4	-10.3
			Dolomite(b)	a.a.	-1.6	-6.5
2	4848- 4851	Dedolzed fine XL Dls	Dedolomite Intercrys- talline	Copake Ls.	-1.6	-7.4
			Dolomite(b)	a.a.	-1.0	-5.9
3	4848- 4851	Calcite vein	Calcite	Copake Ls.	-2.6	-10.0
			Dolomite(b)	a.a.	-1.0	-6.7
4	5173- 5184	Calc. Dls. fine-medium	Dedolomite Massive	Halcyon Lake	-2.3	-8.7
			Dolomite(b)	a.a.	-1.1	-7.4
5	5003- 5006	Calc. Dls Micro. xl.	Pseudomorphic dedolomite	Halcyon Lake	-2.1	-7.5
			Dolomite(b)	a.a.	-1.0	-6.2
6	5232- 5237	Calc. Dls. Medium-coarse	Pseudomorphic & irregular Dedolomite	Halcyon Lake	-2.0	-8.0
			Dolomite(d)	a.a.	-0.9	-6.8
7	5565- 5568	Micrite Ls.	Precursor calcite	Briarcliff?	-2.3	-10.0

* All samples of dolomite that co-exist with dedolomite represent the products of second stage of dolomitization, see the text.
Dolzed.= Dolomitized; Calc.= Calcitic; XL= Crystalline; Dls.= Dolostone; Ls.= Limestone.

Table 6-4 Isotopic composition of samples from Crom-Wells No. 1 Fee (top of the Wappinger Group)

Sample No.	Location (Formation)	Description	Isotope Ratios (per mil; ppt)	
			$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
1	Crom-Wells No. 1 Fee, 5045-5070: (Halcyon Lake)	V. fn. dolostone ; early stage, crypto-crystalline dolomite.	-0.8	-5.6
2	CP Quarry, Hole 73-91, 153': (Pine Plains)	V. fn. dolomite , (early dolomite?)	-0.2	-6.7
3	ARCO No. 1 Susi, 5570-5580 ft.: (Pine Plains)	Oolitic dolomite , (main-stage dolomite)	-0.2	-6.1
4	CP Quarry outcrop: CP 7-b (Pine Plains)	Fn. dolomite , coexists w/no. 6; (main-stage dolomite)	1.2	-6.3
5	CP Quarry, Hole 73-91, 25': (Pine Plains)	Saddle dolomite , (irregular vein and pore-filling); 3rd-stage dolomite.	-1.0	-8.5
6	CP Quarry outcrop; CP 7-a (Pine Plains)	Saddle dolomite , geode filling, late-stage dolomite	1.1	-9.0
7	I-84 cuts; Newburgh: (Pine Plains)	dolomite vein with quartz , hydrothermal, fills tectonic fracture, very late.	0.7	-12.2
8	Outcrop, type loc., S. of Pine Plains; Dutchess Co.: (Halcyon Lake)	Black calcite vein , late features; cross all Wappinger formations	-4.4	-7.9

Table 6-5 Isotopic composition of samples from the Wappinger Group, various localities

different values and occupy different areas on a plot of $\delta^{18}\text{O}$ versus $\delta^{13}\text{C}$. For $\delta^{18}\text{O}$, the mean value of calcite is -10.1 ‰, of dedolomite -7.9 ‰, and of second-stage dolomite, as precursor of dedolomite, -6.6 ‰.

Among dolomite samples, the oxygen-isotope composition becomes depleted from the early stage (-5.6 to -6.7 ‰), to the second stage (-6.1 to -7.4 ‰), and to the late stage (-8.5 to -12.2 ‰). But, the isotope compositions of early- and intermediate burial dolomite are pretty close, whereas $\delta^{18}\text{O}$ in saddle dolomite is much more depleted than is the early- and intermediate burial dolomite.

I will interpret the oxygen-isotope-ratio results in the Discussion section.

6.5 DISCUSSION: ORIGIN OF DOLOMITE AND DEDOLOMITE OF THE WAPPINGER GROUP

6.5.1 Dedolomitization and the conditions under which it is inferred to have taken place

One of the chief points of this chapter is that insights into the origin of dolomite can be found by analyzing the circumstances under which dolomite is destroyed (dedolomitized). Accordingly, it becomes necessary not only to prove that dolomite has been replaced by calcite but also to establish the circumstances under which this replacement happened.

My proof that dolomitization has taken place is entirely textural; characteristic dolomite fabrics are now composed of both calcite and dolomite. I have not found any distinctive magnesium-bearing minerals (for example, magnesite). Such mineralogical evidence indicates a closed system (C. B. Sclar, oral communication). I infer that the lack of Mg-reaction products implies that dedolomite in the top of the Wappinger Group formed in an open system where the Mg^{2+} ions freed from the former dolomite lattices were carried away in solution; I do not know their ultimate fate. (The dedolomitization-liberated Mg^{2+} might even have formed new

dolomite somewhere else.)

Since Von Morlot (1847) first recognized dedolomite, the subjects of dedolomite and dedolomitization have been much studied. Basing their arguments on chemical principles and experimental conditions, most authors argued that dedolomitization resulted from near-surface diagenetic processes (Schmidt 1965; Goldberg 1967; de Groot 1967; Braun and G. M. Friedman 1970; Scholle 1971; Mossler 1971; Chafetz 1972 G. M. Friedman and Radke 1979; Curl 1983 ms.; Curl, Zagorski, and G. M. Friedman 1984). They visualized that dolomite, formed in saline water, was subjected to the effects of fresh water (in which the dedolomite calcite formed). By contrast, others (Holail, Lohmann, and Sanderson 1988; Budai, Lohmann, and Owen 1984, for example) have cited evidence that dedolomitization has taken place in the subsurface, in deep- or shallow zones and even in contact-metamorphic aureoles, where temperature is higher and the fluid saltier than near the Earth's surface. I examine the Wappinger dedolomites in light of these ideas.

Near-surface dedolomitization might take place under three situations. These are: (1) at a surface of unconformity along which previously buried strata are elevated and eroded subaerially ; (2) at the termination of a cyclic peritidal-type parasequence (emergence and resulting subaerial exposure following the initial submergence and deposition of subtidal-, intertidal-, and/or supratidal carbonate sediments); and (3) as a result of modern weathering. The difference between the first two situations is one of degree only. Long-term emergence is implied by the surface of unconformity in contrast with a shorter-term emergence that is associated with each drop of sea level that creates a parasequence boundary. I propose to name the dedolomite that forms at the tops of parasequences as **parasequence-emergence dedolomite**.

Hypothetically, at least, the dedolomite in the top of the Wappinger could have formed

in all three near-surface situations. The Wappinger Group includes parasequences; the upper three formations were subjected to subaerial erosion during the post-Sauk, pre-Tippecanoe interval; and all of it has been subaerially weathered during the later part of the Cenozoic Era. Therefore, I must include all three possibilities.

Dedolomitization by modern weathering can be eliminated because the best developed dedolomite I found is in Crom-Wells No. 1 Fee, 4000 to 5000 ft below the surface. Obviously, this argument does not apply to the dedolomite that can be found in most outcrops.

The difficulties associated with trying to apply the concept of **parasequence-emergence dedolomite** are obvious. The main objection is that I have not found any relationship between dedolomite and parasequences. The best-developed parasequences in the Wappinger Group are in the Pine Plains Formations, where no dedolomite has been found. In addition, the dedolomite is confined to the topmost three formations of the Wappinger Group where parasequences are poorly developed. Moreover, the upper part of the Halcyon Lake Formation has been pervasively dedolomitized. I estimate that 60% of the strata of the Halcyon Lake Formation have been affected by dedolomitization. I think that this distribution of dedolomite in the topmost three formations of the Wappinger Group and absence of dedolomite in the Pine Plains parasequences effectively eliminates parasequence dedolomite as an explanation for the dedolomite in the upper part of the Wappinger Group.

In addition, the chemical identity of the bright calcites rich in manganese (both replacement dedolomite and the fracture-filling dedolomite-related calcite) indicates that both were formed by a fluid having the same composition. Moreover, the same veinlets filled by dedolomite-related calcite cut through all three formations. This suggests that these formations were dedolomitized during a single episode after all three formations had been lithified but whose textures were still open enough to allow fluids to circulate. I can not imagine that during the deposition/

dolomitization from the Copake to the Rochdale, and to the Halcyon Lake episodes, the dedolomitized fluid could have retained its chemical identity continuously for millions of years.

At least two arguments can be cited against the possibility that dedolomitization resulted from deep burial. (1) The widespread- and selective distribution in the top three formations and high concentration in the Halcyon Lake formation. (2) The chemical composition: all dedolomite samples are rich in Mn and poor in Fe. Such a composition implies that the dedolomitizing fluid was related to meteoric water.

Widely distributed dedolomite requires that tremendous quantities of Ca-rich fluid circulate through the formations, taking away Mg^{2+} and Fe^{2+} and bringing in Ca^{2+} and Mn^{2+} . As emphasized by Land (1985), the origin of dolomite requires that the dolomitizing fluid, bringing in the Mg^{2+} , be circulated extensively through the affected carbonate sediment. Analogously, dedolomitization requires that the active fluid, bringing in calcium and taking away magnesium, circulate extensively. This open-textural requirement implies that dedolomitization took place before the formations had been deeply buried. The textures of deeply buried carbonates are tight (Schmoker and Halley 1982; Scholle and Halley 1985) and the distribution of deep-burial dedolomite (Budai, Lohmann, and Owen 1984) is limited. Moreover, if dedolomitization formed under deep-burial conditions, it should be found in all formations rather being confined to the top three formations. The selective distribution of the dedolomite, therefore, precludes the possibility that the dedolomite was a product of deep-burial conditions.

In summary, I do not accept the interpretations that the dedolomitization of the topmost three formations of the Wappinger Group resulted from near-surface recent weathering, from deep burial, or from parasequence emergence. I think the evidence supports the inference that the top three formations of the Wappinger Group were dedolomitized in an open system associated with the episode of emergence that led to the post-Sauk, pre-Tippecanoe surface

of unconformity where a large amount of Ca-rich solution could circulate continuously and during a single diagenetic event.

6.5.2 Geological relationships of post-Sauk, pre-Tippecanoe subaerial weathering and dedolomitization

As mentioned, the post-Sauk, pre-Tippecanoe surface of unconformity truncates the top three formations of the Wappinger Group. As a result of such truncation, the Copake and Rochdale formations are rarely preserved. The parts of the Halcyon Lake Formation that were not removed were subjected to subaerial conditions. In many localities, the Balmville Limestone, the basal unit of the overlying Tippecanoe Sequence, rests unconformably on the Halcyon Lake Formation. The Balmville Limestone is characterized by variation in thickness, and is conglomeratic. These features suggest that the Balmville was deposited on a very irregular karst surface developed on the older carbonate rocks.

The distribution of dedolomite within the Wappinger Group coincides with the paleogeographic indications that during post-Sauk, pre-Tippecanoe erosion, only the top three formations were subaerially exposed and -eroded. In turn, this relationship implies that dedolomitization was a product of circulating meteoric water during post-early Ordovician erosion.

The effects of dedolomitization in the Copake and Rochdale formations are much slighter than they are in the Halcyon Lake Formation. My preferred explanation for this differential distribution is that the dedolomitization resulted from differential effects of the intensity- and processes of subaerial weathering. At the beginning of the early Middle Ordovician erosion interval, physical processes would have predominated. During the later stage, the effects of karst-type processes would have predominated and these effects would have been more pronounced in the Halcyon Lake Formation. Notably, the dedolomite is almost absent in

the lower part of the Halcyon Lake Formation that may indicate paleo-weathering did not reach such depth.

6.5.3 Burial history and diagenetic paragenesis

The study area was subjected a complex geological history and all the formations of the Wappinger Group have undergone a complex history of downward- and upward motions. (See Figure 4-11.) However, during the main episode of pre-Tertiary subaerial exposure, namely, the post-Sauk, pre-Tippecanoe interval, only the topmost three formations were affected.

1. Diagenesis in the top of the Wappinger Group

In the diagenetic paragenesis I have assembled, the second (main)-stage dolomite is earlier than the dedolomite. If I am correct in my contention that the dedolomite formed as a result of emergence during the formation of post-Sauk, pre-Tippecanoe surface of unconformity, then the second-stage dolomite, which antedates dedolomitization, must have formed during the first period of subsidence. Accordingly, the second-stage dolomite in the top three formations must have been the product of a shallow-burial environment (no more than several hundred meters).

I propose that the lithofacies and diagenetic paragenesis for the top three formations fit into the burial history as follows: (1) The precursor calcite and early-stage dolomite formed in the depositional- or syndepositional environment. (2) The second-stage dolomites, including replacement dolomites (b), (c), and (d); and cement (e), formed during the initial subsidence in a shallow-burial environment (depth from few to several hundreds meters). The massive dolomite of the top of the Wappinger Group originated in this environment predominantly. (3) Dedolomitization, which came after the second-stage dolomite, accompanied the karstifi-

cation associated with the Early Middle Ordovician uplift and post-Sauk, pre-Tippecanoe subaerial weathering. (4) Late-stage dolomite, such as fracture-filling dolomite, also some saddle dolomite (mostly found in underlying formations) probably are the products of a deep-burial environment associated with the second- or third subsidence, or even with the early-stages of final uplift.

2. The contrast in diagenetic history between the Halcyon Lake and the Pine Plains formations.

A significant finding in this study is the contrast in petrographic attributes and diagenetic paragenesis between the Halcyon Lake and the Pine Plains formations. In addition to the contrasts in depositional environment, other contrasts arise from their different burial histories: during the post-Sauk, pre-Tippecanoe erosion interval, the Halcyon Lake Formation was extensively exposed and the Pine Plains Formation was not. That is to say, when the Halcyon Lake Formation was subaerially exposed (affected by fresh water), the Pine Plains Formation remained deeply enough buried to be below the fresh-water table. Hence, the Halcyon Lake Formation was subjected to processes that began with shallow burial, and then included uplift and exposure, a second shallow burial, and a final deep burial. But, the Pine Plains Formation was subjected to only one cycle of gradual shallow burial and deep burial (Table 6-6). As a result, the duration of the time when the Halcyon Lake Formation was subjected to shallow-burial conditions may have been three times as long as that in the Pine Plains Formation. Moreover, parts of the Halcyon Lake Formation were subaerially exposed and eroded.

As a result of different burial and -uplift processes in the Halcyon Lake and the Pine Plains formations, their petrographic characteristics and the diagenetic histories are discrete, as shown in Table 6-6. The main points of difference between these two formations are the preservation of relic depositional textures (such as precursor sand-size carbonate sediment);

Table 6-6

A comparison of petrographic- and diagenetic characteristics between the Halcyon Lake and the Pine Plains formations

Halcyon Lake	Pine Plains
1. Original texture rarely preserved; predominant lithology is medium- to coarse dolostone lacking relic textures which either pervasive recrystallized after dolomitization or before.	Original textures (such as allochem) and sedimentary structures commonly visible; may be well preserved to perfectly preserved.
2. Chert abundant; dedolomite widespread. Chert antedates dedolomite and most dolomite (but some dolomite rhombs look to be later than chert; are 2 generations of chert present?)	Chert and dedolomite are virtually absent.
3. Cryptocrystalline dolomite not common	Common. Crystal sizes of $<8 \mu$ (very close to $4\text{-}\mu$ sizes of aragonite needles in modern lime mud). This size coincidence implies a lack of later recrystallization, no matter how deeply they were buried.
4. Saddle dolomite is rare or absent	Saddle dolomite distributed widely as pore fillings, vein fillings, nodules, etc.
5. Three stages of dolomitization	
1) Dolomite a	Cryptocrystalline dolostone
2) Dolomites b, c, d, e	Dolomite b, d
3) Dolomites f	Dolomite g
6. Burial- and uplift history during first subsidence, to post-Sauk, pre-Tippecanoe uplift, to early second subsidence	
Shallow burial, uplift to sub-aerial exposure, and deep burial	Shallow burial, uplift but not to fresh-water zone, intermediate burial, to deep burial

sedimentary structures (such as bedding); variation of dolomite texture; and the development of chert, dedolomite, and saddle dolomite.

Because the Halcyon Lake Formation remained in the near-surface environment for an estimated three times as long as the Pine Plains Formation, seawater and meteoric water could react readily with this formation. Hence, dolomitization, recrystallization, dedolomitization, and silicification were active processes. Under such long-term near-surface/shallow-burial conditions and all kinds of processes, original textures and -structures were modified completely, fine- to coarse planar-e or planar-s dolomites are perfectly developed, and chert and dedolomite well developed. Consequently, all primary- or secondary pores were obliterated.

How the two groups of formations reacted during subsequent deep burial was largely determined by what had happened to them during shallow burial. Formations that had already become impermeable (such as the Halcyon Lake Formation that had become impermeable before deep burial and the cryptocrystalline dolostones of the Pine Plains Formation) did not react much further on deep burial. Where permeability still existed prior to deep burial (as was evidently the case in much of the Pine Plains Formation), deep-burial processes gave rise to more deep-burial products, such as saddle dolomite.

I infer that the lack of saddle dolomite in the Halcyon Lake Formation resulted from a loss of porosity and permeability, which took place prior to the establishment of diagenetic condition favorable to saddle dolomite (deeper burial, higher temperature). As a result, instead of saddle dolomite, substitute products, dolomites "e" and "f", which occurred at shallower burial, and lower temperature than saddle dolomite, formed in the Halcyon Lake Formation. By contrast, saddle dolomite, which is regarded as typical late-diagenetic product, is rare to absent.

6.5.4 Interpretation of oxygen-Isotope ratios

Before I attempt to interpret the isotope ratios, I reemphasize my interpretation that the dedolomite in the three formations was formed during post-early Ordovician erosion under surface- or near-surface conditions and that the dedolomitizing fluid was mostly meteoric water. From this point of view, assuming that the $\delta^{18}\text{O}$ of Early Ordovician fresh water = -6 ‰ (SMOW) (Lohmann 1988), then one can use a formula (Frith and Smith 1971) or a graph (Land 1985), and a value of $\delta^{18}\text{O}$ -7.9‰ of dedolomite-related calcite to estimate the paleotemperature of the dedolomitizing fluid. The result is about 25°C, which represents a tropical surface temperature.

According to Land (1985), "dolomite is enriched in $\delta^{18}\text{O}$ relative to co-existing calcite by about 3 ppt...the CO_2 evolved from dolomite in H_3PO_4 is about 3.8 ppt heavier than CO_2 evolved from an equilibrium co-precipitate of calcite." In my data, the oxygen-isotope ratio of the second-stage dolomite is only 1.3 ‰ heavier than that in associated dedolomite. This implies that the second (main)-stage dolomites cannot be co-precipitates with the dedolomite. This relationship is consistent with the textural evidence that the second (main)-stage dolomite formed during the first subsidence in a shallow-burial environment. Notably, the differences in the isotope ratios of the second (main)-stage dolomite ($\delta^{18}\text{O}$ -6.6 ‰) and those of precursor calcite ($\delta^{18}\text{O}$ -10.1 ‰) match Land's estimated co-precipitated-delta value of 3.8‰. This indicates that both precursor calcite and the second (main)-stage dolomites may have been modified by the same diagenetic solution. This modification should have happened before the post-Sauk, pre-Tippecanoe uplift during first subsidence. Because the first subsidence of the top of the Wappinger Group has been constrained to only a few hundreds meters, the dolomitizing fluid in this depth should largely be related to modified sea water rather than to formation water. Because at (and above) this depth, carbonate was still kept very

porous and highly permeable, modified sea water could circulate easily through the formations.

The subject of the isotopic ratios in ancient sea water has been much disputed in the literature. Many studies suggest that the oxygen-isotopic ratio of early Paleozoic ocean water may have lighter than that of modern ocean water (James and Choquette 1983; Lohmann 1983, 1988; Popp, Anderson, and Sanderberg 1986; Veizer, Fritz, and Jones 1986).

Assuming that the ancient dolomitizing fluid (modified sea water) with $\delta^{18}\text{O}$ range 0 to -5‰ (SMOW) and using Frith and Smith's (1970) formula and Land's (1985) graph, I estimate that the $\delta^{18}\text{O}$ of -6.6‰ of the main dolomite in the top of the Wappinger Group implies a paleotemperature of formation in the range between 40° and 70°C

If the ancient surface temperature was 25°C, in the same range as today, and the geothermal gradient of 25°C/km, and a $\delta^{18}\text{O}$ of -6.6‰ in the dolomitizing fluid of 0‰ (SMOW, the same as modern sea water), then the reconstructed paleotemperature of formation of 70°C yields a maximum estimated depth of 2 km. However, as discussed earlier, I infer that the main dolomitization took place during the first subsidence, when the burial depth of the top of the Wappinger group would have been only a few hundred meters (preserved maximum thickness of 260 meters). In the first subsidence, the top of the Wappinger Group could not possibly have been buried to a depth of 2 km. Hence, the paleotemperature of the dolomitizing fluid could not have been as high as 70°. In addition, I doubt that Mg-rich waters could circulate freely within formations at a depth of 2 km. In carbonates, porosity decreases rapidly with depth. At a depth of 2 km, porosity is about one third of the porosity at the surface (Schmoker and Halley 1982; Scholle and Halley 1985).

If one assumes a $\delta^{18}\text{O}$ of -5‰ for the dolomitizing fluid (Land 1985, Gao and Land 1991, Amthor and Friedman 1992), then the inferred paleotemperature of formation of the main dolomite becomes ca. 40°C which corresponds to a burial depth of 0.6 km. This depth

and temperature correspond to the burial history discussed in a previous section. I think it is reasonable to infer that surface water can infiltrate porous, permeable buried sediments to depths of several hundred meters. Figure 6-11 shows that the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of the dolomite samples are relative close to estimated Early Ordovician paleomarine values (Amthor and Friedman 1992 cited from Lohmann 1988, and Stepanek 1988).

Note that second-stage replacement dolomite in the Pine Plains Formation possesses the same range of oxygen-isotope composition ($\delta^{18}\text{O}$ -6.5‰) as in the top of the Wappinger Group (Ervilus and Friedman, 1992). No doubt all second-stage massive dolomites that form the bulk of the Wappinger Group should be shallow-burial products (less than 1 km).

As described in a former section, late-stage dolomites [dolomite (f), (g)] always show fracture fillings, nodules, or scattered small pore fillings. They crosscut earlier dolomite frameworks. But, these late-stage dolomites are always a subordinate constituent (0 to 13 %) and never constitute any part of the framework of a body of dolostone. They represent a product of deep-burial processes because these late dolomites show very depleted oxygen-isotope compositions. The source of the fluid in which late-stage dolomite formed would have been related to formation water, basinal hot brines. If the $\delta^{18}\text{O}$ of the hot brine was +2 to +6‰, for the saddle dolomite with average $\delta^{18}\text{O}$ -9.9‰, an estimated temperature would be 125°C to 175°C which closely matches the result from the vitrinite reflectance, 155° (Ervilus and G. M. Friedman, 1992). This range of temperature indicates the late dolomite could have formed at a depth of 4 to 6 km.

In summary, the oxygen-isotope ratios determined on studied samples are consistent with the results of petrology, the diagenetic paragenesis, the occurrence of the precursor calcite, dolomite and -dedolomite, and the inferred burial history. My preferred interpretation is that the dedolomite in the top of the Wappinger Group is a product of paleo-exposure

to circulating meteoric water during the post-Sauk, pre-Tippecanoe interval and that it formed from meteoric water circulating within the precursor lithified- but still-porous dolomite at or near the Earth's surface. In turn, the precursor dolomite that was dedolomitized resulted from the second (main)-stage of dolomitization, which accompanied the first subsidence, and took place at an estimated depth of 0.6 km and an estimated paleotemperature of 40° C. I speculate that the dolomitizing fluid was downward-circulating decalcified seawater and that the "pump" was gravity operating on a fluid made denser than normal seawater as a result of evaporation. In contrast, late-stage dolomite formed at an estimated depth of 4 to 6 km and a paleotemperature of 125°C to 175°C during deep-burial diagenesis, and was precipitated from basinal brines.

6.5.5 Massive dolomite of the Wappinger Group: a product of shallow burial that survived deep burial

The petrographic evidence that the dedolomite is younger than the massive dolomite constrains the time of origin of the massive dolomite: it is of pre-mid Ordovician age. If my interpretation of the origin of the dedolomite is correct, then it not only the timing but also the conditions of origin of the massive dolomite are settled: shallow burial.

Deep burial of the Pine Plains Formation is demonstrated by values of vitrinite reflectance in the range of 1.87 to 1.92 from samples of black micrite, Hopewell Junction, southern Dutchess County, NY (Ervilus and G. M. Friedman 1992). This indicates the strata had been subjected to a temperature of 155° C, which implies an estimated depth of burial of 5 km. Urschel and G. M. Friedman (1984) and G. M. Friedman (1987 a, b) contended that the Lower Ordovician carbonates of the Northern Appalachian Basin acquired many of their observed characteristics as a result of burial in excess of 4- to 7 km. They found fluid-homogenization temperatures

that average 141°C to 223° C for various types of carbonate samples, and $\delta^{18}\text{O}$ of - 6.8 to -13.98‰ for dolomite. On the supposition that dolomites having these isotopic ratios crystallized from basin brine with $\delta^{18}\text{O}$ of 2 to 8‰ (SMOW), the corresponding estimated paleotemperature lies in the range of 78 to 193°C.

Did such deep-burial processes affect the dolostones at the top of the Wappinger Group? In this study of the Pine Plains Formation, late-stage dolomites, such as saddle dolomite, hydrothermal vein dolomite, and planar-a dolomite, are relatively abundant. The data confirm that deep-burial diagenetic dolomites are present in the Wappinger Group. However, these late-stage, deep-burial products never form a framework of the massive dolostone body. In the top three formations, deep-burial diagenetic dolomites are rare because the shallow-burial processes obliterated most of the pore space. Thus, during subsequent deep burial, the tight texture did not permit extensive through circulation of the hot deep-basinal brines that precipitated the ferroan- and saddle dolomites in spaces that were available.

No matter whether deep-burial modification is obvious or vague, the deep-burial modification did not change the framework of the massive dolostone body. In other words, the massive dolomite that formed at shallow-burial conditions (second-stage) survived deep burial. So did the dedolomite.

6.6 CONCLUSIONS

The regional-scale burial dolostones of the Sauk Sequence in southeastern New York, assigned to the Wappinger Group, were deposited on a tropical-carbonate shelf during Cambrian to Early Ordovician time. The carbonates in the Wappinger Group include limestones, dolomitic limestones, calcdolostones, and dolostones. From the top downward, the lithology changes gradually. Dolomite increases and calcite decreases. The calcdolostones are of two kinds.

One resulted from incomplete dolomitization of a precursor calcium-carbonate sediment. Dolomite replaced only part of the original calcite forming a mixed rock with relic calcite and replacing dolomite. Another is the product of dedolomitization (calcitization) in which dolomite was replaced by calcite of secondary origin (dedolomite).

The products of dedolomitization are distributed widely in the top of the Wappinger Group, but are found mainly in the Halcyon Lake Formation. Of the strata in the Halcyon Lake Formation 60% were subjected to dedolomitization. In the resulting calcdolostones, the proportion of dedolomite typically ranges from 10 to 30%; in some cases, it is more than 50%. The textures of dedolomites include intercrystalline-, pseudomorphic- and massive replacement. Identical in composition and CL color with the dedolomite, but not replacing a dedolomite precursor, are fracture fillings that I have designated as **dedolomite-related calcite**.

From detailed studies of the rock components, I recognize seven fabric categories of dolomite that are products of three stages of dolomitization: (1) early, syndepositional; (2) second, shallow burial; and (3) late, deep burial. Preserved early dolomite include very fine crystalline dolomite, core of some rhombs and micrite ooids which formed during penetemporaneous deposition ($\delta^{18}\text{O}$ -5.6 to -6.7 ‰). The shallow-burial dolomitization altered most early dolomite into second-stage dolomite, which constitute 80 to 90% bulk of massive regional-scale dolostones, includes fine- to coarsely crystalline dolomite and some cement ($\delta^{18}\text{O}$ -6.1 to -7.4 ‰). Late-stage dolomite includes non-saddle dolomite (fracture-filling) and saddle dolomite characterized by fracture- and pore filling ($\delta^{18}\text{O}$ -8.5 to -12.2 ‰). Saddle dolomite which is virtually absent from the uppermost three formations of the group, is widespread in the underlying Upper Cambrian Pine Plains Formation. The estimated paleotemperature of the early- to second- stage dolomite, 35-45°C, and late dolomite, higher than 125°C

Secondary calcite (dedolomite) which crosscut and replaced second-stage dolomite

is confined to the topmost three formations, especially, but is abundant only in the Halcyon Lake Formation. The secondary calcite displays progressive degrees of replacement from intercrystalline through pseudomorphic to massive. Its bright-yellow CL color easily distinguishes it from the dull precursor calcite and dull veinlet calcite, and from the reddish-CL-colored dolomites. The mean $\delta^{18}\text{O}$ of dedolomite is -7.9‰ . The estimated paleotemperature of the dedolomite is 25°C .

Petrographic evidence and identity of chemical composition of dedolomite and dedolomite-related calcite which cut through all three formations support the inference that the top three formations of the Wappinger Group were dedolomitized in an open system where a large amount of Ca-rich solution could circulate continuously and during a single diagenetic event. Dedolomite has been found only in the top three formations of the Wappinger Group, the ones that were subaerially influenced during post-early Ordovician time. This strongly suggests that dedolomitization was related to post-Early Ordovician uplift, exposure, and karstification, when meteoric water could circulate within the lithified- but still-porous dolostones at- or near the Earth's surface. Moreover, the oxygen-isotope composition of dedolomites also proves that dedolomites formed at near-surface temperatures.

Geological- and geochemical evidence proves that dedolomite formed during post-Early Ordovician emergence (post-Sauk, pre-Tippecanoe surface of unconformity). Because second-stage dolomite is older than the dedolomite, it must have formed even earlier--during the initial episode of subsidence (maximum possible amount of a few hundred meters to 1 km) associated with the passive-margin tectonic regime. Under this shallow- to intermediate burial, most early dolomite had been modified and the second-stage dolomite formed. During the ensuing convergent-margin episode(s) and subsequently, the Wappinger Group was deeply buried (to estimated maximum depths of 5 to 7 km) and the late-stage saddle dolomite filled remaining spaces,

such as interparticle pores, vugs, and fractures. Neither the shallow-burial, second-stage dolomites nor the dedolomites were significantly altered by subsequent deep burial.

I have recognize the products of three stages of dolomitization that I have designated by letters of the alphabet. The first-stage includes only dolomite (a). The second (main)-stages includes dolomites (b), (c), (d), and (e); and the late-stage, dolomites (f) and (g) (saddle dolomite). The dedolomite formed after the second (main)-stage of dolomitization.

Contrasts of petrographic attributes and diagenetic paragenesis between the top three formations and the Pine Plains Formation have resulted from different depositional-, burial-, and uplift histories. Because the top three formations were uplifted to the surface and subaerially exposed, surface- or near-surface processes, such as dolomitization, dedolomitization, and silicification were strongly involved and most of their porosity was eliminated. As a result, in the top three formations, after shallow-burial diagenesis, not much pore space which could serve as hosts for late-diagenetic- or deep-burial dolomite, was preserved. And well-demonstrated products of deep-burial dolomitization are rare. The evidence I have presented herein strongly supports a view that even though they were deeply buried starting in the Late Ordovician, both the regional-scale burial dolomite of inferred shallow-burial origin and the dedolomite that replaced it survived prolonged deep burial without being significantly modified.

CHAPTER 7: PETROPHYSICAL CHARACTERISTICS OF THE ROCKS OF THE SAUK SEQUENCE

In Chapter 3, I discussed the significance- and method of petrophysical analysis for reservoir rocks. Because commercial gas production has been obtained from the Sauk Sequence, such as from the Arbuckle Group in Oklahoma, and from the Ellenburger Group in New Mexico and Texas, also because some evidence (See Chapter 8.) indicates that the gas potential in the Sauk Sequence of eastern New York is quite good, in order to evaluate the gas prospects, it is necessary for an investigator to understand some basic, general petrophysical characteristics of the Sauk strata in eastern New York.

The completed studies of petrophysical characteristics of the rocks from the Sauk Sequence in eastern New York consist of three parts: (1) 21 samples of well cuttings from the Finnegan boring (Guo, Sanders, and Friedman 1991) which represent deposits of the western-shelf subprovince; (2) 52 core samples from the Clinton Point and Cedar Cliff quarries covering part of the Wappinger Group from the central-shelf subprovince (Liang, Friedman, Sanders 1992); and (3) 30 samples from outcrops and cores which represent most of the Wappinger Group (central-shelf subprovince) have been analyzed by me (Final report 1993).

7.1 Results from Finnegan boring, western-shelf subprovince

In the Columbia Gas Company No.1 Finnegan boring, the rocks encountered (from the surface downward) are the Taconic Sequence, Tippecanoe Sequence, Sauk Sequence, and Precambrian basement gneisses. (See Chapter 4, Figure 4-3 columnar section.) The most-likely potential reservoir rocks encountered in the Finnegan boring are the carbonate formations lying below the Taconic thrust and below the Ordovician shales,

starting at a depth of 5310 feet. Accordingly, in the program of petrophysical measurements, I concentrated my attention on these formations. By name, these are: Trenton to Chazy limestones (Tippecanoe Sequence); the Beekmantown Group (sense of Rickard 1973); the Little Falls Dolostone; the Galway Formation; and the Potsdam Sandstone.

In order to obtain data about the petrophysical properties of the rocks penetrated by the Finnegan boring, three approaches can be followed. First of all, from study of thin sections under a petrographic microscope, one can determine kinds, sizes, and textures of pores from direct visual observation. Also, study of thin sections can yield estimates of porosity. Second, from the neutron log and density log, one can determine useful data about the porosities of all strata penetrated. Finally, porosimetry measurements made from carefully selected well cuttings yield precise data about porosity, recovery efficiency, and distribution of the sizes of pore throats from individual lithologic varieties.

7.1.1 Visual observation of pores

Because all the formations of interest have been so deeply buried and subjected to pervasive diagenesis, neither primary pores nor secondary pores were visible in the thin sections of chips that were studied using a petrographic microscope. The only pores remaining were tiny micropores between particles or crystals. The few stylolites seams observed were filled with carbonized organic material. Accordingly, study of thin sections did not disclose much information about the pore systems.

7.1.2 Porosity from analysis of well logs

Not only lithology, but also porosity can be indicated by geophysical logs of bore holes. These include neutron logs, density logs, and sonic logs (Pirsson 1977, Asquith

and Gibson, 1982; Sternbach and Friedman, 1984, 1986; Schlumberger Limited 1972, 1987; Ghosh and Friedman, 1989). Porosity can be derived from either single logs or from combined neutron-density logs.

I used the combination neutron-density log from the Finnegan boring to calculate the porosity of selected formations. To obtain a numerical value for true porosity, one first reads the apparent limestone porosities from the neutron- and density curves of the well log. To find true porosity, one cross plots these values on a neutron-density chart. Table 7-1 shows the porosities thus determined for typical intervals of each of the formations of interest.

The porosities of the formations of interest (Trenton to Potsdam) as determined from the geophysical logs of the Finnegan boring are very low. These porosity data correspond with results from thin-section study and from porosimetry measurements.

7.1.3 Porosimetry results

Porosimetry measurements are a common laboratory method for determining porosity, recovery efficiency, and other important properties of reservoir rocks. Cylindrical cores (core plugs) are the most-used specimens for the petrophysical determination of porosities, volume distributions of pore-throat sizes, recovery efficiencies, and related petrophysical properties (Wardlaw, 1976; Wardlaw and McKellar, 1981; Jennings, 1987; Amthor, Kopaska-Merkel, and Friedman, 1988). Recently, small chips and well cuttings have also been used to make porosimetry measurements (Ghosh, Urschel and Friedman, 1987; Kopaska-Merkel, 1988).

In his pioneering work, Purcell (1949) suggested that small, irregularly shaped rock chips (he termed these cuttings) might be used to determine petrophysical properties.

Ghosh, Urschel, and Friedman (1987) established the validity of Purcell's hypothesis for a heterogeneous carbonate sequence. They compared petrophysical data obtained using chips (simulated cuttings) to data from core plugs. They concluded that petrophysical data derived from cuttings are as reliable as data from core plugs. The obvious advantages of using cuttings are not only that cuttings are by-products of the drilling operations (thus they do not require expensive extra rig time), but also because cuttings are derived from a thicker section of a formation rather than from a restricted part of it, cuttings are likely to be more representative of a formation than are core plugs.

Kopaska-Merkel (1988) also concluded well cuttings can yield mercury-porosimetry data that are nearly as accurate as can be derived from core plugs. Kopaska-Merkel measured the thickness of more than 2100 cuttings that were then analyzed using mercury porosimetry. He used statistics to evaluate the significance of the data, which he found to depend on sample size, size distribution of cuttings, and pore- and throat-size distribution as well as the amount and recognizability of cave. He found that three factors determine the validity of cutting-based mercury-porosimetry data: (1) the autochthonous- or allochthonous source of cuttings; (2) a sample size sufficient to ensure that total intrusion is greater than the detection and error limits of the machine; and (3) cuttings sufficiently larger than throat size to minimize boundary effects. He concluded that cuttings are suitable samples from any rock unit in which pore throats are narrower than 1/5th of the critical thickness (mean thickness minus 2 standard deviations) of the cuttings (typically cuttings with thickness 0.3 to 0.7 mm). However, Larson and Morrow (1981) suggest that reliable results require throats to be less than 1/30th of the thickness of the cuttings.

Samples from the Finnegan boring available to me include only chips. These well

cuttings are mostly thick enough (0.4 to 0.8 mm) to produce valid mercury-porosimetry data comparable with those samples used by Kopaska-Merkel. (An exception is part of the Potsdam Sandstone from the bottom of the boring; the cuttings are too small to be used in the porosimeter). Petrographic study revealed that as a result of pervasive diagenesis, only very small pores and pore throats remain in rocks at depths below 5310 feet. Therefore, I consider that the cuttings from the Finnegan boring fulfill Kopaska-Merkel's three requirements for obtaining valid mercury-porosimetry data. Thus, my results further test the validity of mercury-porosimetry measurements based on well cuttings.

**Table 7.1 Porosity of Selected typical intervals from well log
of Finnegan boring**

Depth (ft.)	Formation	Apparent porosity (from logs)		True porosity from	
		Density porosity (%)	Neutron porosity (%)	Formula* (%)	Chart* (%)
5380-5400	Trenton	-2	0	1.41	0.8
5490-5500	Trenton	-2	0	1.42	0.9
5730-5740	Chazy?	-1.5	0.7	1.17	?
5910-5930	Beekmantown	-0.5	0.2	0.38	1.2
6010-6020	Beekmantown	-5.2	1.2	3.77	0.5
6300-6310	Little Falls	-7.2	1	5.14	0.1
6510-6520	Galway	-2.5	1	1.9	1
6780-6800	Galway	-1	1	1	1.4
6940-6950	Galway	0	2	1.41	0.8
7070-7100	Potsdam	0.3	4.3	3.05	2

* See Schlumberger 1972, 1987.

7.1.3.1 Procedure

I prepared samples of cuttings for porosimetry as follows. Using a pair of fine tweezers, I picked chips of a single lithologic variety known to be autochthonous from samples collected at 10-foot intervals (or, as in a few cases, several such samples were

picked over to yield material that came from intervals of 20- or 30 feet). Altogether, from the Trenton-Potsdam interval, I selected 21 samples of well cuttings (Table-7.2).

I cleaned the samples successively in a 50/50 solution of toluene and acetone and pure acetone (Amthor, Kopaska-Merkel and Friedman, 1988; Ghosh and Friedman, 1989).

I reduced the data using a BASIC computer program from Micromeritics Corporation.

Table 7-2 Summary of Porosimetry Data From Cuttings of Finnegan Boring

Depth (ft)	Lithology	Formation	Porosity (%)	R.E. (%)	MTS (μ m)	Sample Weight (g)	Total Hg intrusion (cc/g, $\times 10^{-2}$)
5380-5400	Is.	Trenton	2.07	—	29.29	0.52	0.76
5480-5490	Is.	Trenton	2.35	5.62	33.77	0.56	0.89
5490-5500	Is.	Trenton	2.22	33.73	29.29	0.46	0.86
5660-5670	Is.	Chazy?	3.35	20.30	6.09	0.28	1.18
5730-5740	Is.	Chazy?	1.76	10.96	29.53	1.71	0.73
5890-5900	M.Dls.	Beekmantown	2.94	—	18.41	0.38	1.04
5910-5930	M.Dls.	Beekmantown	2.62	9.52	29.38	1.64	0.84
5950-5960	F.Dls.	Beekmantown	1.05	82.00	27.27	0.54	0.37
6010-6020	M.Dls.	Beekmantown	0.99	0.00	4.94	0.74	0.36
6190-6200	M.Dls.	Beekmantown	0.97	67.65	15.24	0.58	0.34
6190-6200	F.Dls.	Beekmantown	1.94	49.28	31.10	0.38	0.69
6300-6310	F.Dls.	Little Falls	1.91	4.35	34.38	1.81	0.69
6480-6490	F.Dls.	Galway	2.22	15.00	10.94	0.58	0.80
6510-6520	F.Dls.	Galway	2.49	15.39	35.18	1.88	0.91
6550-6560	F.Dls.	Galway	1.76	0.00	38.43	0.53	0.62
6780-6800	Sst.	Galway	2.48	—	14.22	1.13	0.93
6870-6880	O.F.Dls.	Galway	1.40	26.00	32.86	0.53	0.50
6920-6930	Sst.	Galway	2.48	37.80	28.92	0.57	0.92
6940-6950	Sst.	Galway	2.71	20.20	22.92	1.59	1.04
7070-7090	Sst.	Potsdam	2.36	19.78	35.62	0.36	0.91
7070-7100	Sst.	Potsdam	1.75	14.92	29.25	1.27	0.67

Summary of abbreviations:

Is.—limestone; M. Dls.—Medium-crystalline dolostone; F.Dls.—fine crystalline dolostone; O.F.Dls.—Oolitic F.Dls; Sst.—sandstone; R.E.—Recovery efficiency; MTS—Median throat size;

In all samples, the intrusion volumes were large enough to register on the instrument (a Micromeritics Pore sizer 9305) and greater than the instrumental error of measurement (>0.0015 cc; Kopaska-Merkel, 1988) (Table 7-2). In most samples from the Finnegan boring, both sample sizes and thicknesses of chips are larger than those used by Kopaska-Merkel (1988). Therefore, I consider that these samples were subject to minimal boundary effects.

7.1.3.2 Results

Table 7.2 presents sample weights, total volumes of mercury intruded, porosities, recovery efficiency values, and median throat sizes.

Of the samples measured, only small amounts of mercury penetrated into 10 samples only at low pressure (ca. 25 psia). Under high pressure (above 25 psia), very small amounts of mercury intruded 16 samples. This result corresponds to what one would expect from samples possessing very tight textures.

Porosity, which ranges from 0.97% to 3.35%, is related to lithologies and textures. Limestones of the Tippecanoe Sequence, averaging 2.35% porosity, are more porous than are the underlying rocks of the Sauk Sequence, in which porosities average 1.89%. The lowest porosities (1%) were measured in the dolostone microfacies Mlf 2-a (from a depth interval 5950 to 6130 feet; fine-microcrystalline dolostone). The porosities of all other microfacies of dolostone and sandstone are approximate. No obvious relationship exists between porosity and depth (Guo, Sanders, and Friedman, 1990, p. 259, Figure 13). In an overall sense, porosity tends to decrease downward from the top (Tippecanoe) to the bottom (Sauk).

Recovery efficiency ranges widely (Table 7-2); the average is 24%. Medium throat sizes are from 4.94 μm to 38.43 μm ; the average is 25.57 μm . Because of boundary

effects resulting from the small sample weights, these values are obviously overestimates.

Figure 7-1 shows scatter plots of porosity vs. recovery efficiency (RE). A weak inverse relationship is suggested but is not statistically significant. Similar relationships have been found in Lower Paleozoic carbonates from the Permian basin of Texas and New Mexico, and from the Anadarko basin of Texas and Oklahoma (Amthor, Kopaska-Merkel, and Friedman, 1988). No observable relationship exists between RE and median throat size (MTS) and between porosity and median throat size.

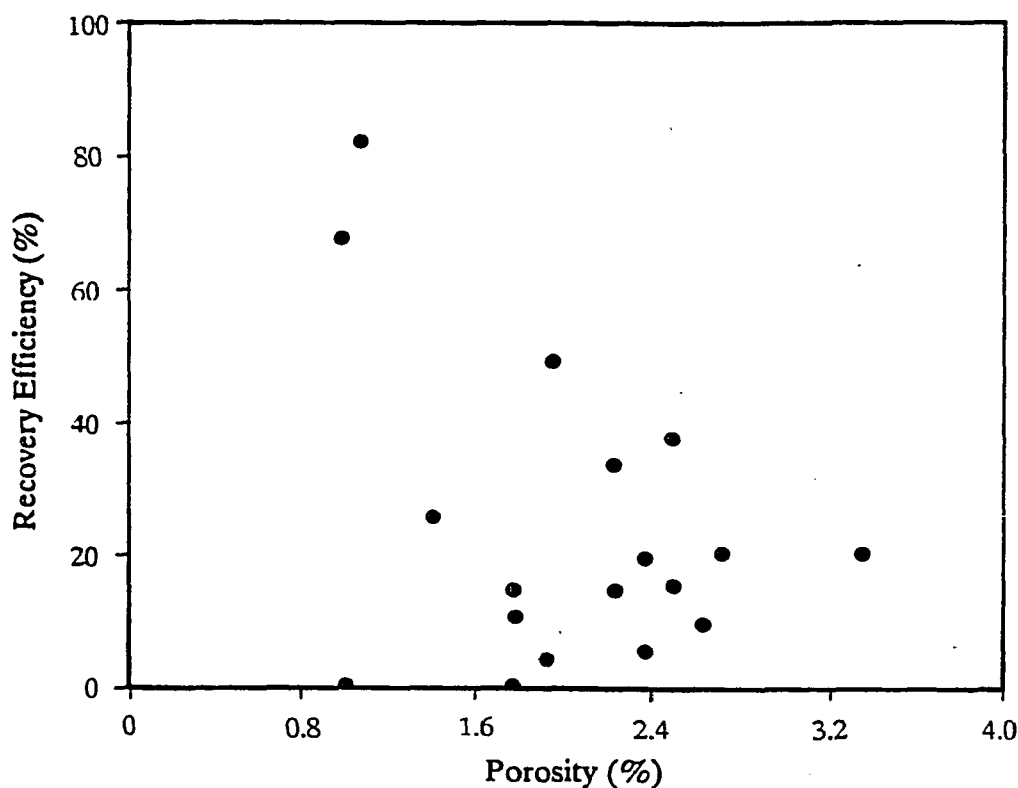


Figure 7-1. Graph of porosity versus recovery efficiency (RE). A weak inverse relationship is suggested.

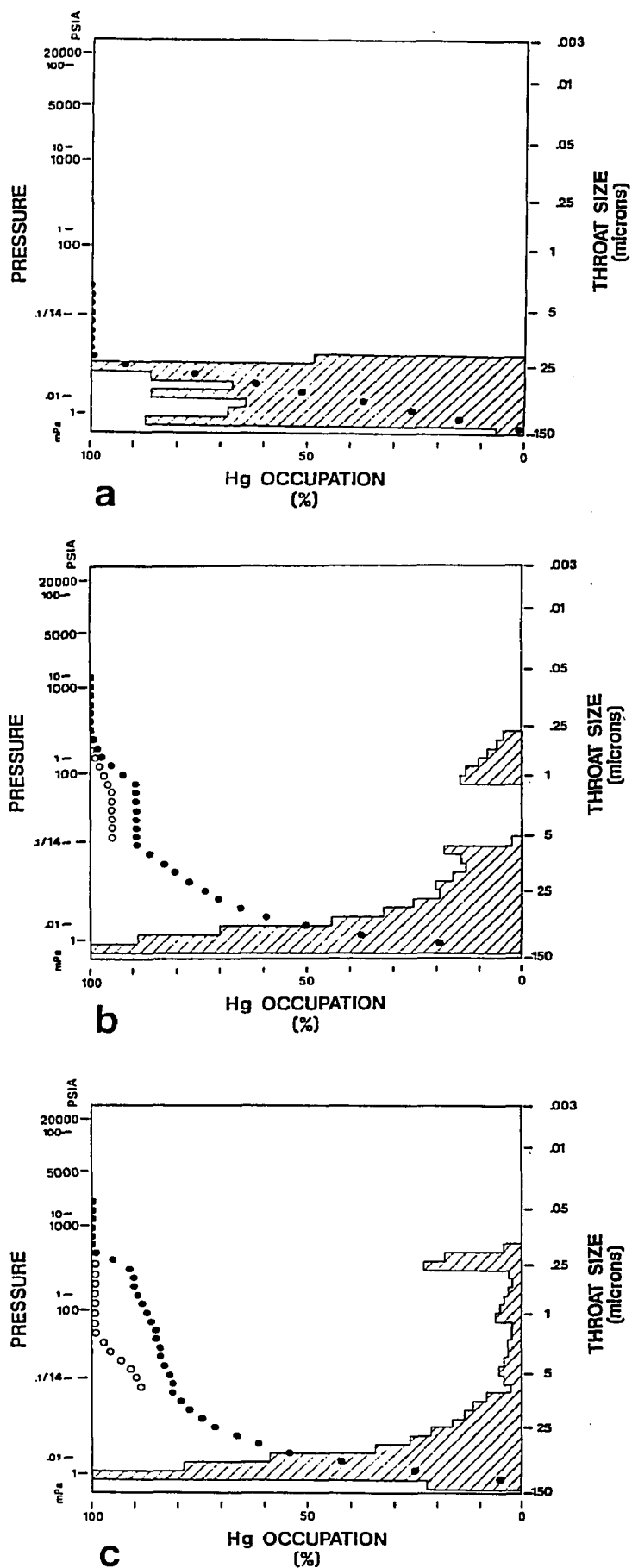


Figure 7-2. Three kinds of capillary-pressure curves.

a. Example in which no mercury is intruded at high pressure.

b. Example showing a stop interval between intrusion of mercury at low pressure and intrusion of mercury at high pressure.

c. Example of continuous intrusion of mercury as pressure is increased.

All capillary-pressure curves of measured samples belong to the "concave" type (Amthor, Kopaska-Merkel and Friedman, 1988; Kopaska-Merkel and Friedman, 1989; Guo and Friedman, 1990). But, based on the shapes of the curves and the intrusion situation at high pressure, they can also be subdivided into three kinds (Figure 7-2, a, b, c).

Figure 7-2, a displays the first kind of capillary-pressure curve, typical of 5 samples. The flat segment of the incremental curve means that mercury was intruded only at low pressure. The weights of these samples are less than 0.58 g. Accordingly, I consider that these samples with this kind of capillary-pressure curve were strongly affected by the "boundary effect" and that sample weight is an important factor which affects the data quality of mercury porosimetry.

Figure 7-2, b shows the second kind of curve which includes 8 samples. At high pressure, a little mercury penetrated. But between low- and high pressure, the incremental curve displays a vertical segment without intrusion. This indicates that mercury did not penetrate continuously. Rather, a stop interval, coinciding with the vertical line segment, exists between the two pressure levels. This characteristic is comparable to the result of Kopaska-Merkel (1988, figure 6).

The third kind of curve is typical of 8 samples. These incremental curves are smooth and their slopes change gradually (Figure 7-2, c). This means that as pressure was varied from low to high, mercury penetrated continuously. The weights of all these samples were more than 0.56 g.

A final important factor that should be taken into account is the effect of the high-pressure mud used during rotary drilling. The mud may penetrate porous parts of rocks and thus tend to break apart the chips into individual constituent particles. Less-porous rocks would not be subjected to this mud-prying effect. The effect is a

selective preservation of chips of rocks having tight texture. Hence, the porosity data derived from measuring rotary-drill cuttings tend to be biased toward smaller-than-normal values.

7.1.3.3 Discussion

In this study, the sizes of most cuttings fell within the range of 0.4 to 0.8 mm, and the mean throat sizes are small enough (4.9 to 38.4 μm) to yield satisfactory porosimetry data based on Kopaska-Merkel's results but are not smaller than the limit suggested by Larson and Morrow (1981). In 5 of my samples the "boundary effect" is pronounced (Figure 7-2, a). In other words, porosimetry data from these samples are suspect. In order to find the basis for these invalid capillary-pressure curves, I repeated several of these samples using larger sample weights. The weight of the sample from 5950 to 5960 was 0.54 g; the incremental-intrusion curve is type "a". By contrast, the weight of the sample from 5910 to 5930 was 1.64 g; it yielded a type-"c" curve. Comparable samples from depths 7070 to 7090 and 7070 to 7100 yielded "c" curves. Because these samples are very tight (the pores and pore-throat sizes are tiny), sample weight could have changed the characteristics of intrusion. Because of the limited amounts of chips in the smaller-size samples, too few throats and pores were measured. Only when enough material was used could the sample undergo measurable intrusion at high pressure. However, because some throats are exposed on the chip's surface and mercury surrounds the chips, at low pressure, mercury intrudes easily into these parts of the chips causing the boundary effect. If the rocks are not so tight, then curve "a" would never happen even if small samples are used as indicated by the better results Kopaska-Merkel got from more-porous samples. In summary, sample weight is an important factor for controlling

the intrusion process and shape of the capillary curve. For minimizing the boundary effect, I suggest that if one really needs porosimetry data from rocks having very tight textures, then the minimum sample weight should be at least 1.5 to 2.0 grams.

For checking the porosity data derived from porosimetry, I have used the combination neutron-density log from the Finnegan boring to calculate the porosities thus determined for typical intervals of each of the formations of interest. True porosities are calculated from the formula of Schlumberger Limited (1972, 1987). A comparison of Table 7-1 with Table 7-2 shows similar values for porosities but that the range of porosities derived from log calculations is larger than that measured from porosimetry.

I found oil residues in samples of the Galway Formation in the cuttings from an interval 410 feet thick extending from 6430 to 6840. (See Chapter 8.) I made petrophysical measurements on 4 petroleum-barren samples within this interval (Table 7-2; 6480 to 6490, 2.22%; 6510 to 6520, 2.49%; 6550 to 6560, 1.76%, all finely crystalline dolostones; and 6780 to 6800, 2.48%, sandstone). From study of thin sections of chips of the samples containing oil residues, my visual estimates of the porosity of the petroliferous layers are in the range of 10 to 15 percent. From this, I conclude that oil migrated at a depth of burial corresponding to a porosity of 10 to 15 percent. Where oil was present, such porosity was preserved ("fossil" porosity?). In the rest of the formerly porous rocks, post-oil deep burial resulted in almost total loss of porosity in all petroleum-barren rocks. Because they lacked oil, these potential reservoir rocks became "tight" rocks. I do not think it would be accurate to condemn the petroleum potential of the Cambro-Ordovician rocks of this area because so many potential reservoir- but petroleum-barren rocks lack porosity.

As noted, the porosities of petroleum-barren Trenton-Chazy limestones are slightly

larger than those of the petroleum-barren Galway rocks. In addition, the total organic carbon of a sample from the Trenton-Chazy interval is 0.36% compared with 0.11% for a sample from the Galway. I infer that these relationships imply that the Trenton-Chazy interval is more likely to have served as a source of gas (that would have migrated elsewhere) than the Galway.

7.1.3.4 Conclusion

Porosimetry measurements confirm visual observations and log indications that the porosity of petroleum-barren potential reservoir rocks in the Upper Cambrian and Lower Ordovician strata penetrated in Finnegan boring is low. The visual observations resulted from study under a petrographic microscope of thin sections cut from selected groups of drill cuttings. The log indications are based on calculations using data from the neutron-density log. By contrast, visual estimates of the porosity of the dolostones and sandstones within the Galway Formation that contain oil residues (samples within a zone 410 feet thick in the depth range of 6430 to 6840 feet) are 10 to 15%. From these relationships, I conclude that after the oil had formed and migrated, the region subsided to still-greater depths. The effects of this post-oil-migration deeper burial were to alter the oil to its current residue status and to destroy nearly all of the porosity in the oil-barren, otherwise potential reservoir rocks. In the petroliferous rocks, the oil preserved the porosity.

Because of their slightly greater porosities and higher contents of total organic carbon (0.36% vs. 0.11% based on only one sample from each interval), I infer that the limestones of the Trenton-Chazy interval are more likely to have served as sources of gas than the rocks in the Galway Formation.

7.2 Results from the Wappinger Group, central shelf

7.2.1 Samples from Clinton point and Cedar Cliff quarries studied by Liang *et al*

Liang, Friedman, and Sanders (1992) studied 52 core samples collected from the Cedar Cliff, and Clinton Point quarries, collected from unknown parts of the Briarcliff and Pine Plains formations. The results are shown in Table 7.3 (Liang *et al*'s Table 2) and Figure 7-3 (Liang *et al*'s Figure 3).

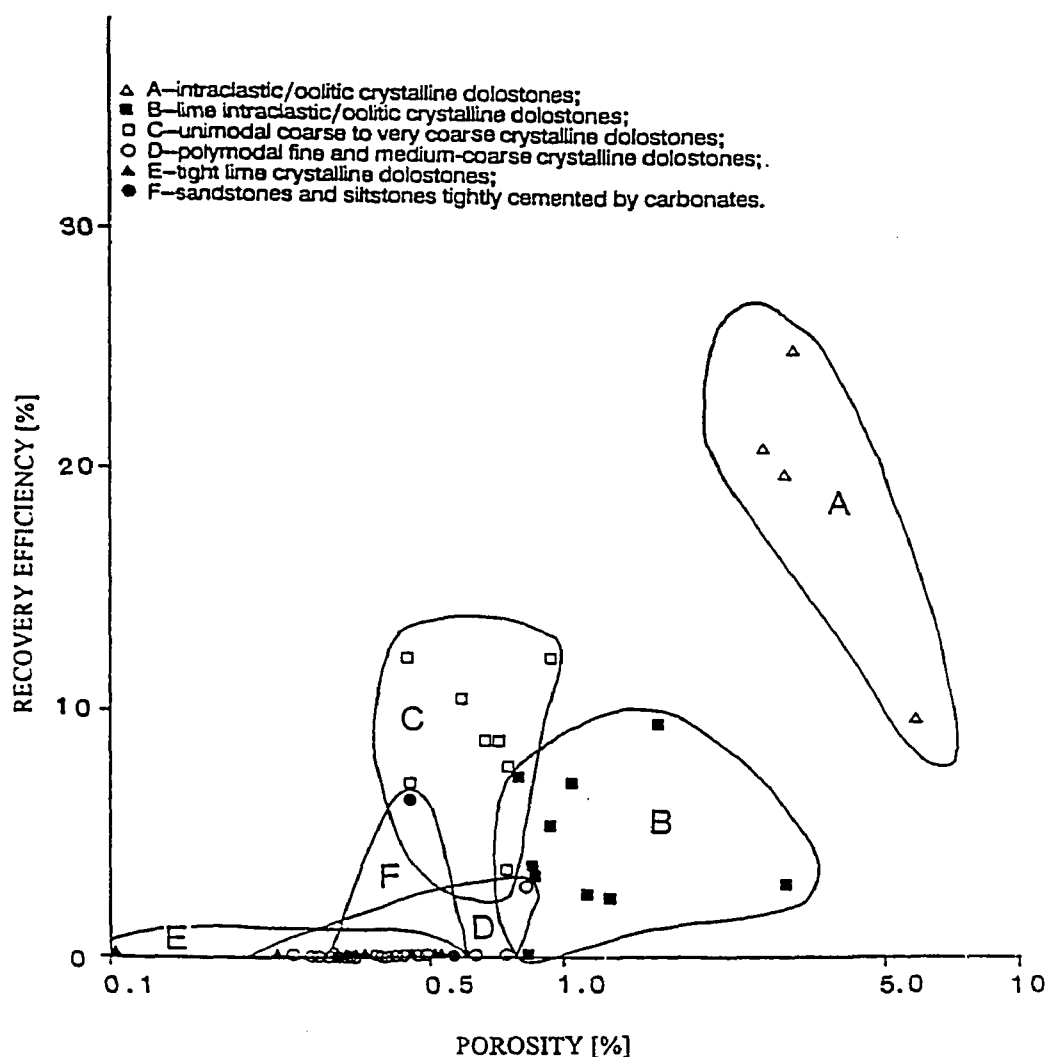


Figure 7-3. Bivariate plot of recovery efficiency (RE) vs. porosity for all studied samples (note the X-axis indicated by a logscale), which shows a weak positive relationship between RE and all samples, and a weak inverse relationship for Group A, and Groups B, C.

The results from Liang *et al* (1992) show "The porosities for most of the samples, about 80%, are less than 1%. For more than 50% of samples, porosity ranges from only 0.1% to 0.5%. No RE (recovery efficiency) have been obtained for many samples with low porosity...". Obviously, because most of samples show very low porosity and no recovery efficiency, the relationships between petrophysical parameters are not clear, and these authors' attempt to try to correlate different lithofacies with their petrophysical characteristics is very difficult for me to accept. However, at least two categories, relative porous and permeable dolostones (intraclast/oolitic, especially, with vugs) (in Liang *et al* figure 3, area A and B), and low-porous tight dolostone (area C, D, E) are recognized.

The results of Liang *et al* indicate that no matter how diagenesis destroyed primary porosity (compared with in beachrocks, oolitic limestone 24.22%, see Chapter 3, packstone 22.72%, and skeletal grainstone 17.79%), the petrophysical properties of the studied rocks still show a strong relationship with depositional environment and lithofacies. As in modern beachrocks, oolitic dolostones in the Sauk Sequence present the best porosity; skeletal grainstones and packstones follow. And fine-crystalline dolostones show very low porosity.

In addition, from the results of Liang *et al*, we know that no matter how many different lithofacies one can recognize in the rocks of the Sauk Sequence, most of them (80%) show very similar petrophysical properties: tight, low porosity, and no RE. The

*In terms of my studies of more samples from cores and outcrops, I would merge their lithofacies A, B, and C into one category. Because all transitional diagenetic steps from weakly recrystallized oolitic dolostone (lithofacies A, ooids clearly shown) to partly recrystallized (lithofacies B, only parts of ooid ghosts left), and to totally recrystallized dolostone (lithofacies C, ooid ghosts rare to absent) can be recognized, usually. In addition, vugs can be also found fine-crystalline dolostones.

only relatively porous rock is oolitic/skeletal dolostone, especially when vugs are included. In the Sauk Sequence, it is impossible for us to classify different petrophysical facies which depositional, diagenetic lithofacies, and petrophysical characteristics can be related, as I was able to do for beachrocks in Chapter 3. As a result, in later study (see 7.2.2), I did not make any detail calculations for all petrophysical parameters because they are not significant.

7.2.2 Samples from outcrops and cores measured by Guo

From my porosimetry results based on cuttings from the Finnegan boring and Liang *et al*'s results based on quarry cores, a general idea of petrophysical properties of the Sauk Sequence in New York has been derived.

Because Liang *et al*'s samples covered only the lower part of Briarcliff Formation and the upper part of Pine Plains Formation, I considered it necessary to pick up more samples from all formations of the Wappinger Group to measure their petrophysical parameters.

I have carried out porosimetry measurements on 32 samples (Table 7.4). The samples were selected from all different formations and facies. My objective was to correlate lithofacies with petrophysical properties. Unfortunately, overall, the results are very similar to that by Guo, Sanders, and Friedman (1991) from the Sauk Sequence, Finnegan boring, and by Liang, Friedman, Sanders (1992) from Briarcliff and Pine Plains formations in the Cedar Cliff and Clinton Point quarries.

Because of pervasive dolomitization and deep-burial diagenesis, most of samples show very tight textures. Relatively porous samples are from calcdolostone (average 2.9% in Rochdale Formation), ribbon dolostone (average 3.1% in Stissing Formation),

Table 7-4 Mercury porosimetry results from the Wappinger Group by Guo

Fm.	Lithology	Sampling	Porosity (%)	Recovery Efficiency (%)	Numbers
Ro.	Calc. dol.	E of Bethel pp 92 4-1	2.5 3.4 2.9	4.2 17.1 15.6	3
H.L.	Fine dol.	Halcyon Lake	0.5 0.7	0 0	
H.L.	Coarse dol.	Halcyon Lake	0.6 1.1	0 0	4
Br.	V. Fine dol.	CP 72-91 4'	0.4	0	
	Fine dol.	CP 72-91 65'	0.6	0	
	Medium dol.	CP 72-91 11.5'	0.3	0	3
P.P.	Very fine dol.	CP 73-91 91'	1.4	0	
		91'	1.2	0	
		123'	0.3	0	
		123'	0.4	0	4
P.P.	Fine dol.	CP 73-91 186'	0.4	0	
		126'	0.2	0	2
P.P.	Medium dol.	CP 73-91 95.5'	0.6	0	
		137'	0.3	0	
		199'	0.5	0	
		CP 1	0.5	0	4
P.P.	Breccia	CP 100'	0.3	44	
		CP 2	0.4	0	2
P.P.	Vuggy dol.	CP 4-1	1.1	0	
		CP 4-2	1.5	3.1	2
P.P.	Oolitic dol.	CP 73-91 34'	0.3	0	
		241'	1.3	0	
		241'	1.1	0	3
P.P.	Laminated dol.	CP 73-91 64'	0.2	0	1
St.(?)	"Ribbon" dol.	N 92 2d-01	3.4	15	
		Cold Spring	2.8	10	2
Total					32

Ro.- Rochdale Ls; H. L.- Halcyon Lake Fm.; Br.- Briaclyff Fm.
P.P.- Pine Plains Fm.; St.(?) - Stissing Fm.

and oolitic dolostone (1%), vuggy dolostone (1.3%) in the Pine Plains Formation. From Table 7-4, we can see that only 35% of the samples showed porosity of more than 1%. Seven samples showed withdrawal when the pressure was decreased (recovery).

In addition, vuggy dolostones showed smaller porosity (1 to 2%) than the results from OMNI Petrographic Lab (3 to 4%) (Table 7-5). Because the sample sizes used were not the same (my samples were much smaller than OMNI's), my samples did not include many vugs.

Table 7-5. Results of porosity and permeability measurements

Sample No.	Description	Permeability (Md)	Porosity (%)	Density (g/cm ³)
CP 1	Dark, medium dolostone with geodes	0.002	0.6	2.85
CP 2	Dolomitic karst breccia	13.752*	0.9	2.83
CP 3	Fine, laminated dolostone	0.003	0.5	2.83
CP 4-1	Light gray, vuggy dolostone	0.271	1.7	2.85
CP 4-2	Light gray, vuggy dolostone	0.793	2.5	2.85
CP 5-1	Light gray, vuggy dolostone	0.610	4.9	2.85
CP 5-2	Light gray, vuggy dolostone	1.663	4.8	2.85

* Fracture permeability

The results from OMNI Petrographic Services & Core Analysis, Houston, TX, for laboratory measurement of permeability of samples of the Pine Plains Formation were collected from faces of the CP Quarry. The measurements were carried out on cylindrical plugs 1 inch in diameter and 1.5 inches long.

CHAPTER 8: IMPLICATIONS FOR PETROLEUM PROSPECTING IN THE SAUK SEQUENCE

In this Chapter, I evaluate the implications for petroleum prospecting in Cambro-Ordovician strata in eastern New York State of the information from the study of the Finnegan boring, southern Washington County, and of the study of the Wappinger Group, southeastern New York. I begin with some general remarks about the Cambro-Ordovician rocks. I then summarize the direct indications of petroleum found in the Finnegan bore hole. From there, I move on to depths of burial and petroleum maturation. I conclude by discussing potential petroleum traps, including possible traps associated with surface structures, with overthrust sheets and with surfaces of unconformity throughout the region.

8.1 Petroleum In Cambro-Ordovician Rocks

Because the extent of deformation to which the strata have been subjected and to the numerous overthrusts in the area, most petroleum geologists prior to about 1970 considered that the petroleum potential of the northern Appalachians should be ranked as negligible. However, in 1972, the Columbia Gas Corporation supported a project proposed by Prof. G. M. Friedman for re-evaluating the petroleum potential of Lower Paleozoic rocks of eastern New York state. In a report delivered to Columbia Gas in 1973, B. D. Keith and Friedman used lithofacies analysis and environmental interpretation to identify several specific areas of economic potential for petroleum exploration in the Taconic region of the northern Appalachians. One of the targets they emphasized is oolitic shoals at the former shelf edge. [Part of this study has been published (B. D. Keith and Friedman, 1977; Friedman and B. D. Keith, 1983).] Because the Finnegan boring lies

at least 40 kilometers west of the former eastern edge of the carbonate platform, I do not consider that it tested the Friedman-B. D. Keith target of oolite shoals at the margin of the Early Paleozoic carbonate platform. A well to test this platform-margin target would have to be located in Vermont.

A further boost to the petroleum possibilities of the Appalachian region came from geological reactions to the discoveries made in the overthrust belt of the Rocky Mountain region. Now, for the very reason it had been previously rejected (i. e., being an overthrust belt), the Appalachians were looked upon as being petroleum prospective (as the Eastern Overthrust Belt, by analogy with the Western Overthrust Belt; Buyce, 1983). For these, and doubtless other reasons not known to me, Columbia Gas decided to drill the Finnegan test boring.

The Sauk Sequence is known to contain gas in southeastern New York (Crom-Wells Fee No. 1, SW of Middletown, Orange County, Sanders 1983). The gas was encountered in the Halcyon Lake Formation (Warthin and Pack 1953 ms.), in the upper part of the Cambro-Ordovician carbonates (now assigned to the Sauk Sequence).

Rickard (1973, p. 13) assessed the petroleum possibilities in the Cambro-Ordovician rocks as follows:

"Few wells have tested the Cambro-Ordovician carbonates. At present there is no oil production from these rocks but gas has been obtained from nearly all known formations or groups..."

Cambro-Ordovician rocks are known to be prolific petroleum reservoirs in Kansas and Oklahoma (the Arbuckle "limestone"). The Cambro-Ordovician carbonate rocks are the objects of great current- and active interest in the Arkoma basin, Oklahoma.

Sauk-Sequence carbonates have yielded oil in central Ohio (Calvert, 1964a, b, c).

8.2 Direct Indications Of Petroleum In The Finnegan Boring

The Finnegan boring found a show of gas that was judged to be noncommercial; hence, the hole was plugged and abandoned. My study of the cuttings has disclosed that oil residues are present in the pores of sandstones and dolostones of the Galway Formation in the lower part of the autochthonous platform carbonate/sandstone Sauk Sequence within an interval 410 feet thick (depth range 6430 to 6840 feet).

These residues prove that oil once migrated through the strata. I infer that such migration took place when the depth of burial of the strata was less than it ultimately became and, after entering some kind of trap, was altered by deeper-burial diagenesis. This is suggested both by the presence of the oil itself in a maturity zone beyond the oil limit and by the kinds and amounts of the pores. The texture of the residue-filled pore spaces implies a secondary origin (Figure 8-1, a, b). Oil migrated via these pores and pore throats. During later diagenesis, the original organic matter was decomposed (decarboxylation) and organic acids and carbonic acid generated. Such acids dissolve surrounding carbonate minerals (Schmidt and McDonald, 1979). My visual estimate of the amount of porosity at the time of oil migration is about 10 % on average with a possible maximum of 15 %.

8.3 Depth of burial: diagenesis, petrophysics of potential rocks, and maturation of organic matter

Petrographic-, petrophysical-, and organic-geochemical analyses indicate that the strata encountered in the Finnegan boring have been so deeply buried that nearly all

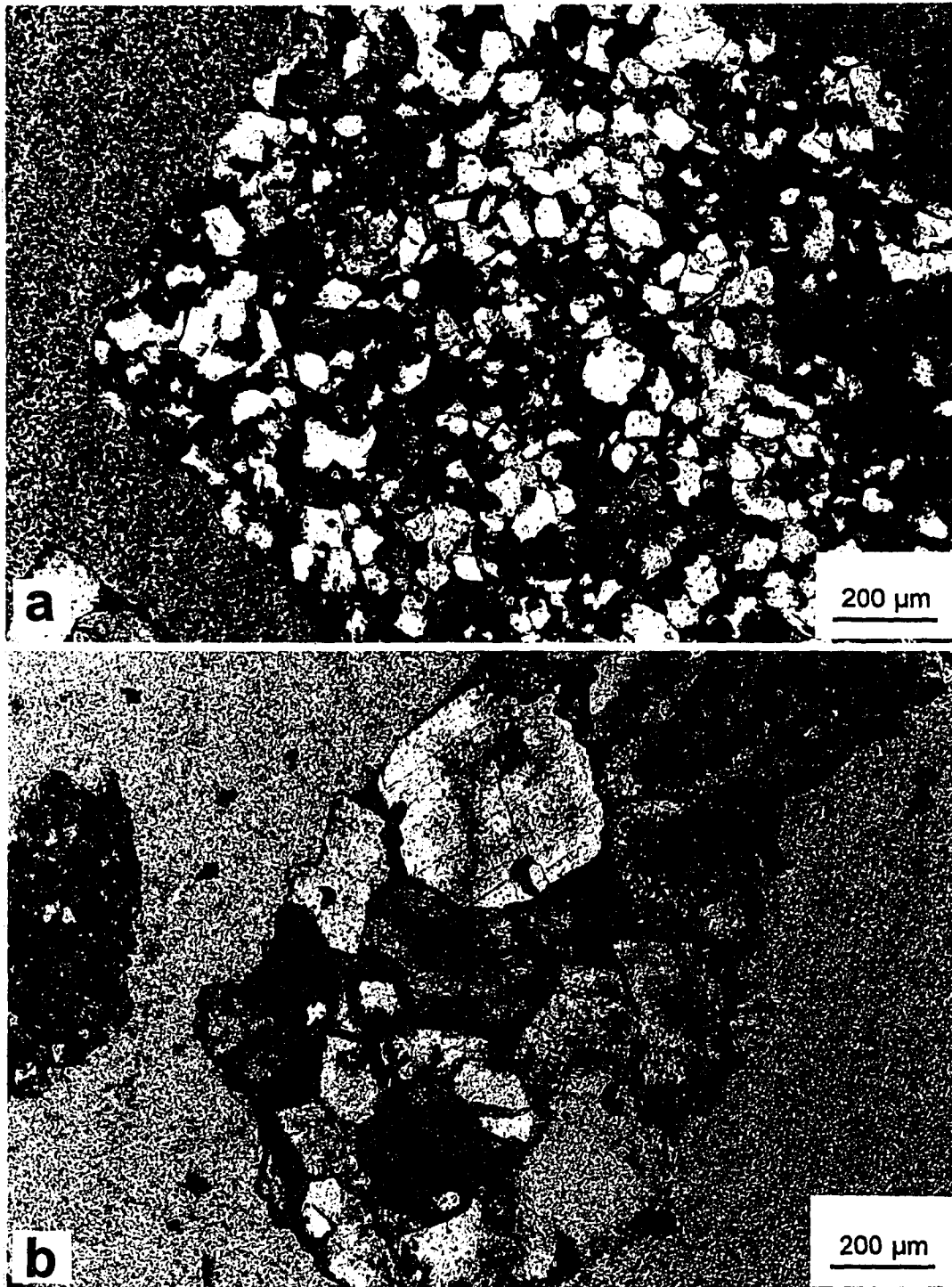


Figure 8-1. Enlarged view of petrographic thin sections prepared from selected samples of cuttings from Finnegan bore hole, plane-polarized. Oil residue found in upper part of Galway Formation. (a) Fine sandstone composed of well-sorted quartz with interstitial pores filled by oil residue, 6460-6470 feet. (b) Oil residue between dolomite crystals as secondary pores filling, 6560-6570 feet.

intergranular porosity of non-petroleum-bearing rocks has vanished and the kerogen altered to a state known as "superature" (beyond crude oil, but still within the conditions for thermogenic methane). I take this to imply that in northern New York State and vicinity, all rocks, even those now exposed at the Earth's surface, are mature enough to contain indigenous petroleum. Accordingly, the usual first question asked in assessing the petroleum situation in a region ("Have the solid hydrocarbons been deeply buried enough to have matured?") can be answered in the affirmative. In the following paragraphs of this section, I present the evidence related to diagenesis, to the petrophysical characteristics of selected rock types, and to maturation of organic matter. In the following section entitled petroleum traps, I discuss its geologic implications.

8.3.1 Diagenesis

My detailed study of thin sections has disclosed the rocks have undergone many diagenetic effects. These include compaction, recrystallization of clay, dolomitization, and silicification. A general diagenetic succession of sandstone and sandy dolostone from the Sauk sequence penetrated by Finnegan boring is shown graphically in Figure 8-2. After complicated and pervasive diagenesis, almost all primary pores have vanished. The diagenetic evidence from petrography is consistent with the GeoChem results based on organic geochemistry. The rocks have reached mature- to superature levels.

A typical kind of evidence showing compaction in the limestones consists deformed pellets; Figure 8-3, a shows an example from a depth range of 5720 to 5730 feet of the Finnegan bore hole. The initial shapes of some pellets can be elongate to begin with, but even allowing for such initial shapes, the examples from the Finnegan well suggest a flattening ratio of about 2 to 1.

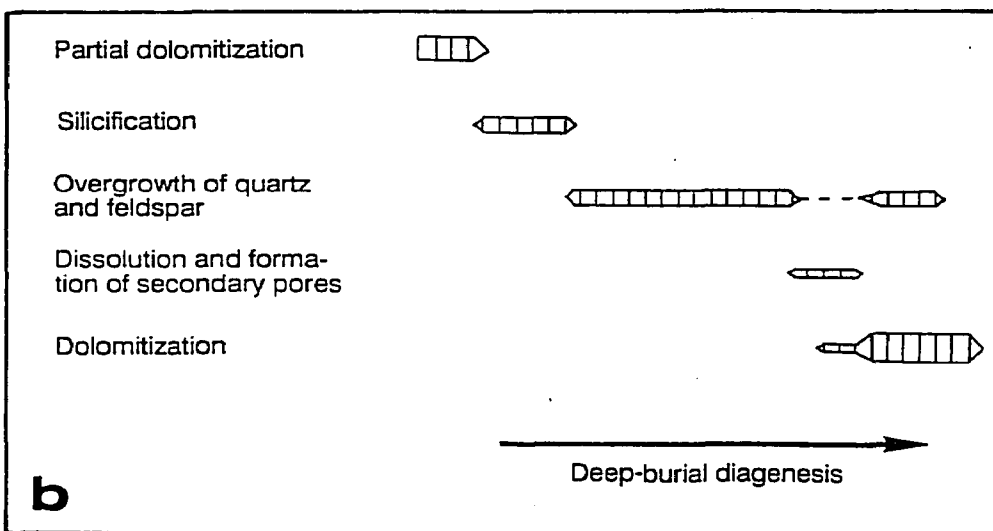
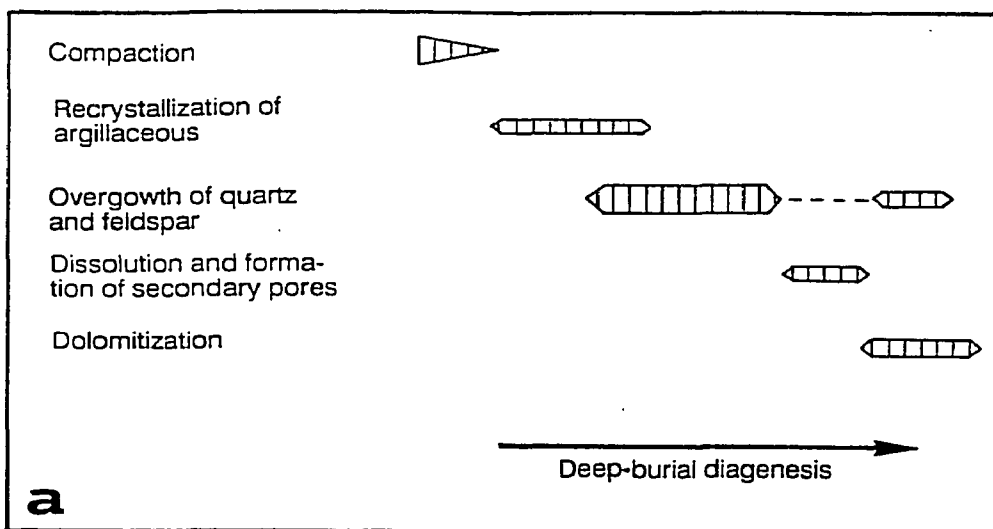


Figure 8-2, Diagenesis summary of sandstone (a), and sandy dolostone (b) of the Sauk Sequence in Finnegan boring.

Another kind of deep-burial evidence, distinctive twinning, is present in the thin sections of limestones (Tippecanoe Sequence) from the Finnegan bore hole (Figure 8-3, b). The distinctive twinning seen in the thin sections of calcite chips from a depth range of 5490 to 5500 matches that found in the Lone Star No. 1 Baden well in the Anadarko Basin, Oklahoma, between depths of 8.67 and 9.07 km (Friedman, Reeckmann, and Borak, 1981, p. T17). In specimens from the Baden well, the calcite twin planes, of which 2 or more are typical, are closely spaced, and have been bent or displaced. Glide planes along twin boundaries have acted as microfaults, displacing earlier twin planes in a stepwise fashion.

These indications of great former depths of burial are consistent with data from other localities in New York that also suggest former deep burial. Examples include the Devonian strata of the Catskills (Friedman and Sanders, 1982, 1983), the Silurian, and Devonian carbonates of western and central New York, as well as the carbonates of the Sauk and Tippecanoe strata of eastern New York (both reviewed in Friedman, 1987a, b).

8.3.2 Petrophysical characteristics of selected rock types

The most-likely potential reservoir rocks encountered in the Finnegan boring are the carbonate-quartzite formations lying below the Taconic thrust and the Utica Shale. I concentrate my attention to the following formations: Trenton-Chazy limestones, Beekmantown Group (sense of Rickard 1973 not of Fisher 1977), Little Falls Dolostone, Galway Formation, and Potsdam Sandstone in Finnegan boring and the Sauk rocks in the Wappinger Group.

Because all the formations of interest have been so deeply buried and subjected to pervasive diagenesis, neither primary pores nor secondary pores are visible in thin

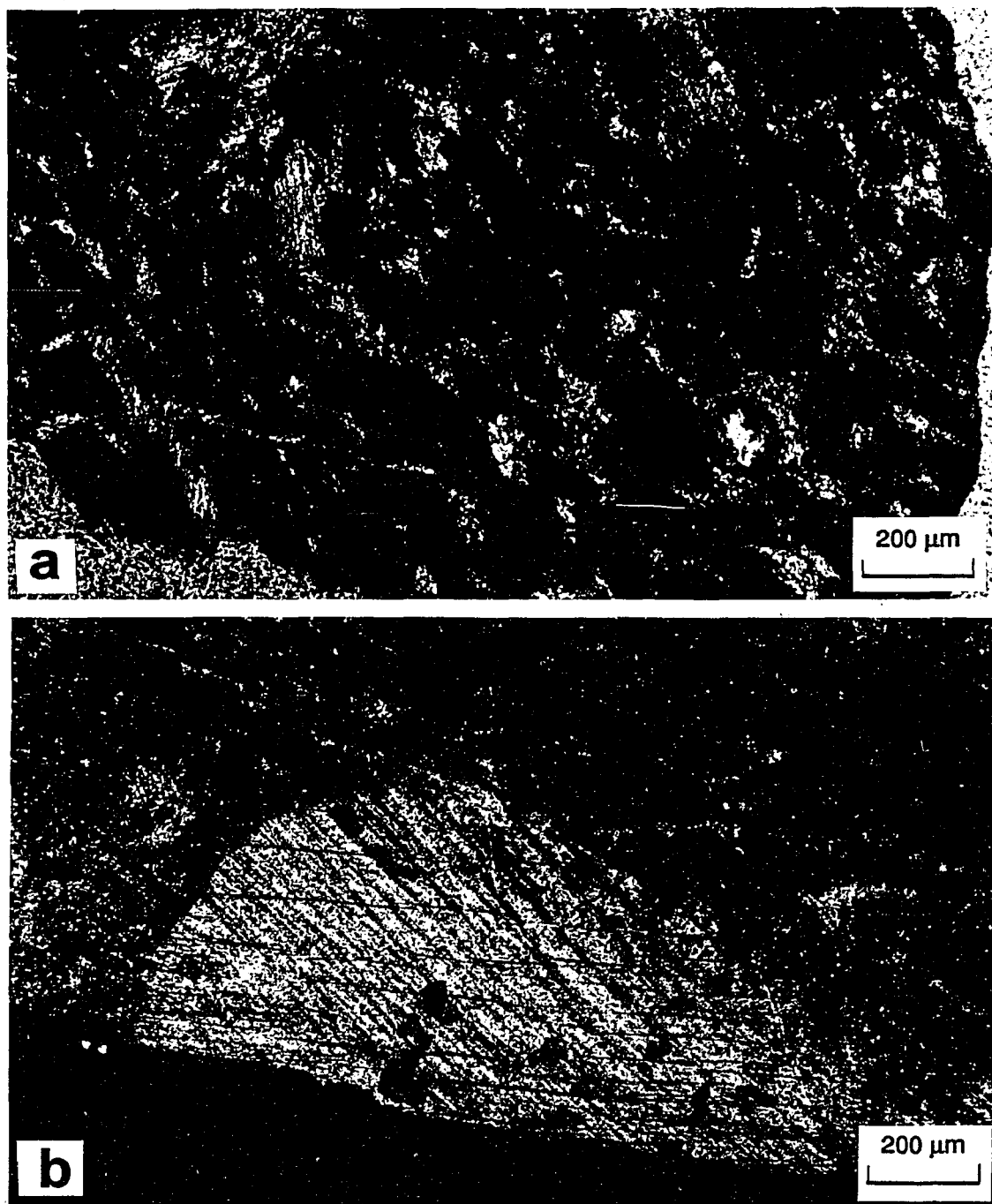


Figure 8-3. Enlarged views of petrographic thin sections showing diagenetic textures; photomicrographs in plane-polarized light, except as otherwise noted. (a) Pelletal limestone Trenton/Chazy formations (5720 to 5730 feet). These elongated pellets obviously have been subjected to oriented pressure during compaction diagenesis. (b) Deformed twin lamellae (indicated by arrow) in calcite crystals (skeletal fragments of an echinoderm), Trenton/Chazy formations (5490 to 5500 feet), crossed-polarized light. Comparable deformed twin lamellae have been found from a depth of 8.67 and 9.07 km in the Baden boring, Anadarko Basin, Oklahoma. Further explanation in text.

sections. Some secondary pores and a few stylolite seams observed were filled with oil residue. The intragranular porosities of the formations of interest as determined from porosimetry measurement are very low (Figure 8-4, and also see Chapter 7). These porosity data correspond with the results from thin-section study and from the geophysical logs of the Finnegan well.

Although the number of samples was limited, the porosity data suggest some general impressions. The Trenton-Chazy (Tippecanoe Sequence) limestones are more permeable than the rocks of the Sauk Sequence. In the Sauk Sequence, porosity correlates with lithology. The sandy dolostones of microlithofacies 1-c in the Beekmantown Group show the lowest porosities. In the Galway Formation, sandstones are more porous than the dolostones.

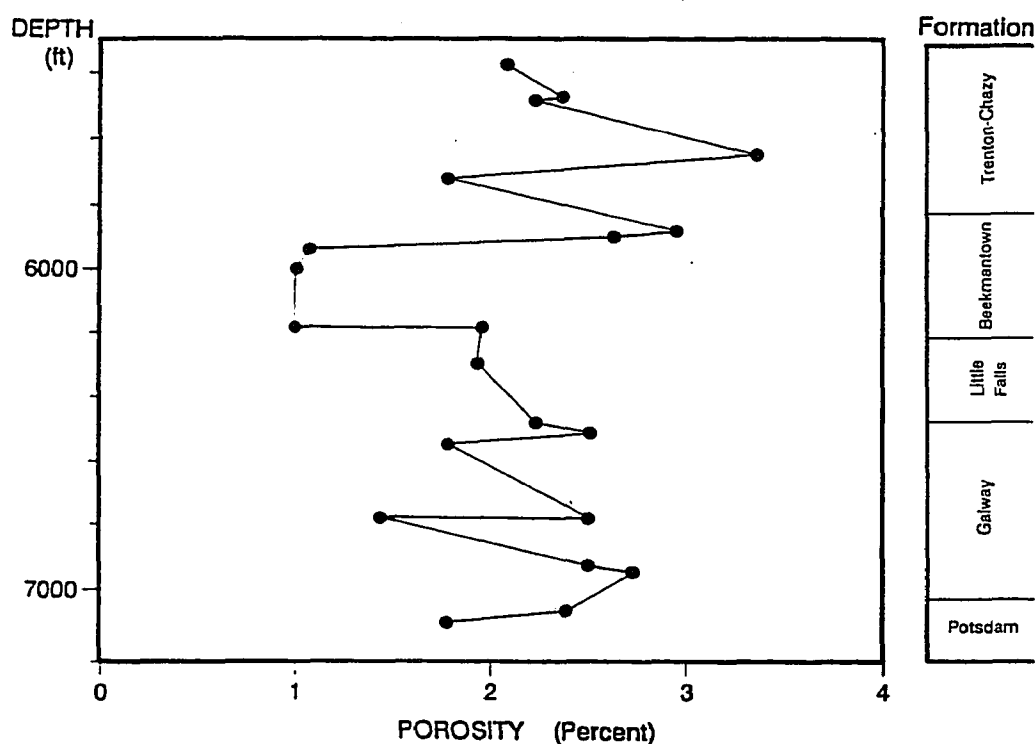


Figure 8-4. Plot of porosity versus depth in Tippecanoe and Sauk sequences. Despite the great fluctuations, typical porosity decreases slightly downward from a little more than 2 percent in the Trenton/Chazy unit (at top) to a little less than 2 percent in the Potsdam (bottom).

8.3.3 Results from organic geochemistry

Four samples were submitted to Geochem Laboratories, Houston, Texas for study of organic matter. The requested analytical work included: (1) Total Organic Carbon (TOC), and (2) analysis of kerogen [expressed as Thermal Alteration Index (TAI) and approximate equivalent vitrinite reflectance (AEVR)]. Table 8-1 gives the Geochem results.

The kerogen is the amorphous algal variety that is regarded as being oil prone, but the TAI indicates that the samples are "mature to very mature;" that is, they have been subjected to burial time/temperature relationships that would have converted any oil to thermogenic natural gas.

Table 1 RESULTS OF THE GEOCHEMICAL ANALYSES

Sample	Formation	Depth (ft.)	TOC [#]	TAI ^{\$} (percent)	AEVR [*]
Shale	Poultney	1540-1570	0.4	3.0	1.0
Shale	Utica	4000-4030	0.7	3.5	1.6
Limestone	Trenton (?)	5440-5450	0.36	3+	ND
Dolostone	Galway	6710-6740	0.11	3.8	2.0

TOC: Total Organic Carbon

\$ TAI: Thermal Alteration Index

* AEVR: Approximate Equivalent Vitrinite Reflectance

8.4 Potential Petroleum Traps

Under this heading, I discuss traps related to surface structures, possible traps in overthrust slices beneath the Taconic allochthon, and possible subtle traps associated with surfaces of unconformity throughout the region.

Possible traps related to surface structures

Geologic structures that are visible at the surface can serve as petroleum traps to the extent that the strata involved contain petroleum; the effects apply within the depth that the structural feature visible at the surface extends into the hidden realm of the subsurface. The fact that geochemical analyses of the organic matter in the strata cut by the Finnegan boring indicate that even near-surface strata have been subjected to a former depth of burial great enough to generate gas implies that all geologic structures within which the dip of the strata reverses offer exploration possibilities that should not be ignored.

A key factor in the origin of a large petroleum deposit is the presence in the subsurface of a long stretch of unbroken strata that dip in the same direction. Such an arrangement provides a large "drainage-area" that is a prerequisite for any large petroleum deposit. An area in which such a large "drainage area" for petroleum might be present is the Saratoga area, which is located at updip end of the strata that dip eastward regionally. The presence of numerous faults in the vicinity of Saratoga Springs, however, suggests that if any long subsurface limb of a structure supplied petroleum for a large trap, then the trap should be sought in areas east of Saratoga.

As discussed in 1990 (Guo, Sanders and G. M. Friedman p. 242, fig3), we are not certain that the large normal fault really exists at west side of the Finnegan boring. If it does, however, and if it formed before the oil in the Galway Formation migrated, then this

fault could have served as a trapping mechanism for the oil residues in the Finnegan boring. If the subsurface relationships show that Sauk strata faulted down on the east against Precambrian basement, then the fault may have prevented further updip migration of oil in the east-dipping strata of the Sauk Sequence.

Possible traps associated with overthrust sheets beneath Taconic allochthon

The fact that in the Finnegan boring, the Sauk-Sequence strata beneath the Taconic allochthon have not experienced time-temperature conditions severe enough to have eliminated any thermogenic natural gas implies that gas possibilities may still exist in the Sauk strata beneath the Taconic overthrust. The Monkton overthrust passes beneath the north end of the Taconic allochthon. According to A. Keith (1933), this means that the Sauk-Sequence carbonates were duplicated by overthrusting prior to the time when the Taconic allochthon was emplaced. The strata on these overthrusts dip eastward; their updip ends have been covered and possibly sealed by the fine-textured strata of the Taconic Sequence. Accordingly, gas may be trapped in the Sauk-Sequence strata beneath the Taconic allochthon.

Possible subtle traps associated surfaces of unconformity

One of the favorite kinds of targets much emphasized by one of America's great petroleum-exploration thinkers, A. I. Levorsen, is a tilted permeable layer that has been truncated and sealed by an unconformably overlying layer. In cross section, the beveled part of the lower layer is shaped like a wedge (Figure 8-5, B). From this shape, Levorsen took his name: "wedge belts of permeability" (Levorsen, 1954). Of them, he wrote:

"Some regional up-dip wedge-outs (sic) of permeability are due to facies changes, some to strand-line phenomena, and some to the unconformable overlap of impermeable rocks on truncated edges

of permeable rocks. The cause of the wedging out is not the significant element; the shape of the permeable formation, with its up-dip edge to obstruct migration of oil and gas, seems to be the important feature. We may say, then, that a permeable formation, with an up-dip wedge edge of permeability from any cause, is a potentially favorable geologic condition, both for the concentration of oil and gas and for the prevention of their escape. The more up-dip wedge-outs (*sic*) of permeable rocks that can be mapped in a prospective province, the better its chances of becoming productive" (Levorsen, 1954, p. 628-629).

As explained in previous paragraphs, the Sauk Sequence (below) and Tippecanoe (above) are separated by the post-Sauk, pre-Tippecanoe surface of unconformity, a feature having regional-, even continent-wide, extent. Other surfaces of unconformity mentioned by Rickard (1973) include: base of Black River, base of Trenton, and within the Trenton (Figure 8-5, c and d).

Even though he did not use the sequence concept, Rickard placed great emphasis on the stratigraphic importance of the post-Sauk, pre-Tippecanoe (or "Knox") unconformity between the Lower Ordovician and older dolomitic carbonates (Sauk Sequence) and the Middle Ordovician and younger limestones and shales (Tippecanoe Sequence) and compiled a paleogeologic map of the rocks beneath the post-Sauk, pre-Tippecanoe ("Knox") surface of unconformity (1973, pl. 9). Rickard stressed the general change of depositional setting that is associated with the post-Sauk, pre-Tippecanoe ("Knox") surface of unconformity: what he termed the older "carbonate shelf (miogeocline)" and the younger Middle Ordovician "miogeosyncline" (1973, p. 3).

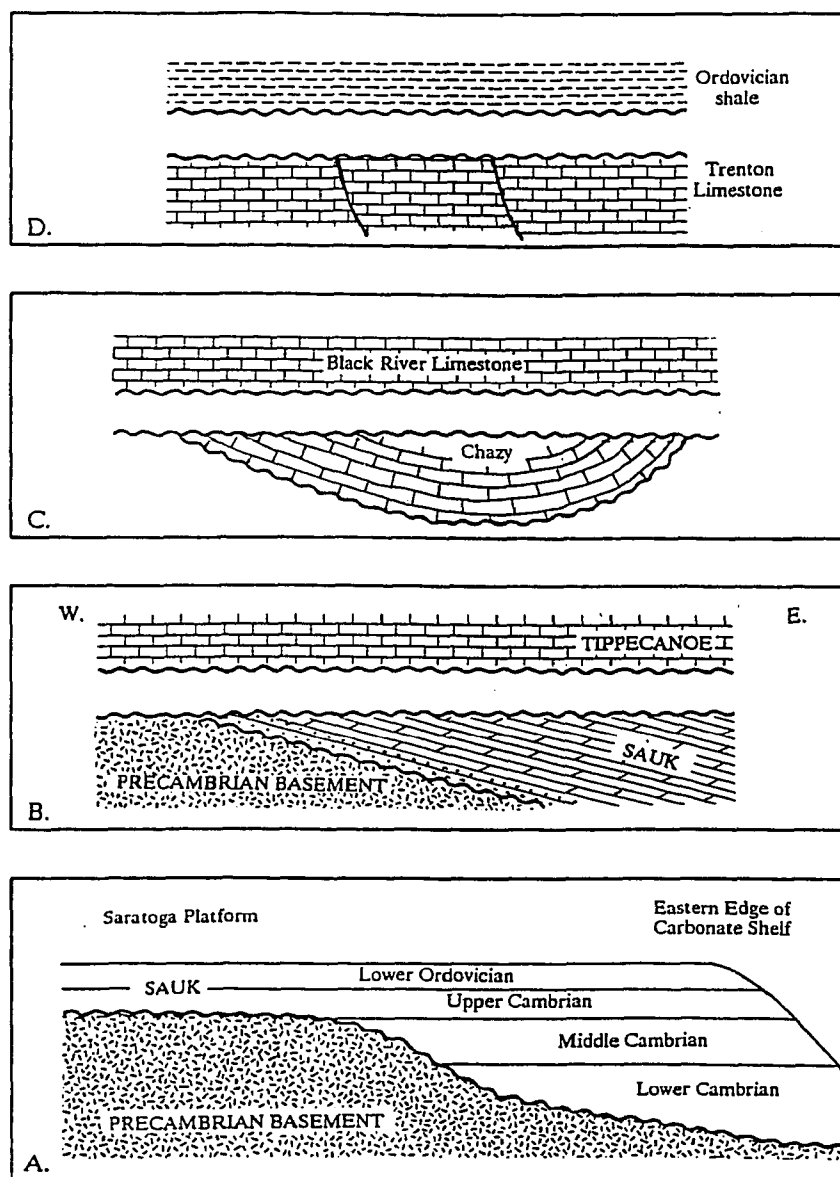


Figure 8-5. Overlapping relationships between sequences and within sequences, northern New York State, shown by schematic E-W restored stratigraphic sections. A. Sauk Sequence (Upper Cambrian in west, Lower Cambrian in east) overlaps Precambrian basement. B. After uplift and erosion, Tippecanoe Sequence overlaps the Sauk Sequence and also rests on Precambrian basement. C. Within the Tippecanoe Sequence, the Black River Limestone overlaps various Chazy Formations. D. Within the Tippecanoe Sequence, the Mid-Trentonian shale overlaps faulted- and eroded Mid-Ordovician carbonates (faults shown schematically by thick curved lines).

Rocks of the Sauk Sequence have trapped hydrocarbons at the post-Sauk, pre-Tippecanoe ("Knox") unconformity in the Mascot-Jefferson City zinc district in eastern Tennessee (Haynes and Kessler, 1989). The Cambrian part of the Sauk Sequence yields oil along the post-Sauk, pre-Tippecanoe ("Knox") surface of unconformity in north-central Ohio (Calvert, 1964a, b, c).

The Sauk Sequence is known to contain gas in southeastern New York (Crom-Wells No. 1 Fee, SW of Middletown, Orange County, Sanders 1983). The gas was encountered in the Halcyon Lake Formation, upper part of the Sauk Sequence. The only indications of gas in the ARCO No. 1 Susi bore hole are associated with the two intervals of vaterite I found in the cuttings from the Halcyon Lake Formation. The vaterite was formed when drilling mud reacted with methane (Friedman *et al.* 1993). Thus, vaterite in the ARCO No. 1 Susi proves that gas exists in the Sauk strata cut by this boring.

In summary, previous drilling has demonstrated that gas-prone rocks exist in New York State from shallow depths downward and that the general geologic requirements for forming subtle traps have been fulfilled. Detailed geologic study of samples from outcrops and from cuttings recovered from bore holes is the only basis for making the necessary paleogeologic maps, one for each surface of unconformity, that are needed in order to define the general sites where appropriate subtle traps for trapping large quantities of gas are likely to be found.

8.5 CONCLUSIONS

Three kinds of positive petroleum indications resulted from the Finnegan boring: (1) a show of gas (even though non-commercial) was found near an unconformity, (2) the oil residues in the pores of some layers within a zone 410 feet thick (depth 6430 to 6840)

in the Galway Formation, and (3) geochemical analyses (by Geochem Labs, Houston) of kerogen samples from the Finnegan boring indicate the organic matter has been heated to but not beyond the mature-super mature stage. That is to say, as a result of previous great depth of burial, the solid kerogen has been heated past the point of generating crude oil to the point where only natural gas can be expected. This finding also implies that in this region, all Lower Paleozoic rocks, even those now exposed at the Earth's surface, are mature enough to contain indigenous petroleum.

The porosity data from the carbonate strata penetrated in the Finnegan boring are consistent with the other indications of former great depth of burial: intergranular porosity of rocks not containing oil residues is only about 2%. The Trenton-Chazy limestones are more porous than all other samples measured. In addition, the level of organic maturity of the Trenton-Chazy limestones is lower than all rocks of the Sauk Sequence. I conclude that the gas potential of this limestone unit is greater than that of the other formations in the Finnegan boring.

In the cuttings from the Sauk Sequence in the Finnegan boring, I found no subsurface counterparts of the kind of vuggy-dolostone facies that is widespread in outcrops. Within the Galway Formation, secondary pores existed before the oil (indicated only by bituminous residues) migrated. Visual estimates of the porosity at time of oil migration are 10% to 15%. This indicates that despite current negligible intergranular porosity in rocks lacking oil residues, porous reservoir rocks previously existed and that their porosity has been preserved by the oil contained within the pores.

The negative economic evaluation of the show of gas in the Finnegan boring does not diminish the overall positive indications for finding commercial petroleum in the Lower Paleozoic rocks of the region nor the geological value of the data. The studies of

material- and data of Finnegan boring when combined with regional geologic analysis strongly suggest that many kinds of petroleum traps may be present within the Lower Paleozoic rocks in eastern New York State and possibly also in adjacent northwestern Vermont. Some may be associated with dip reversals in surface structures or with faults. Others may be found where imbricate slices of the Sauk Sequence have been overridden by the Taconic allocthon. Possibly the largest potential traps may be subtle ones associated with surfaces of unconformity, that is "wedge belts of permeability" (of A. I. Levorsen's usage). The best geologic approach to finding subtle gas traps is to carry out regional studies of the surfaces of unconformity that would enable paleogeologic maps to be prepared for the rocks underlying each of these surfaces (post-Sauk, pre-Tippecanoe or "Knox" surface of unconformity, sub-Trenton surface of unconformity, and so forth).

APPENDIX I: THIN-SECTION LIST

Table 1. Sample list of thin sections studied from Clinton Point Quarry (cores of Dr.sanders' collection)

Briarcliff (from top to bottom)		Pine Plains (from top to bottom)	
Hole No.	Thin section nos.	Hole No.	Thin section nos.
61	CP 284-300	53	CP 161-187 CP 190-196
62	CP 267-283	31	CP 136-159
29	CP 222-257	46	CP 111-125 CP 126-135
		43	CP 1-69
		41	CP 70-110
Total samples			196

Table 2. Sample list of thin sections studied from Winfarm and Halcyon Lake, Dutchess County

Location	Thin sections	Numbers	Formation
Winfarm	W 1 to w 101	101	Halcyon Lake
Halcyon Lake	HiR 1 to 14, 15a,b, 16a,b, 17a,b, 18a,b, 19, 20,	24	Halcyon Lake
Total number		125	

Table 3. Sample list of thin sections (uncovered) studied from Crom-Wells No.1 Fee, Orangy County

Order	Depth (ft.)	Lithology	Formation
1	4690-4702	Limestone	Trenton
2	4702-4705	Xl. Dol.	Trenton
3	4708-4720	Ls.	A. A.
4	4740-4752	Xl. Dol.	A. A.
5	4765-4770.5	Xl. Dol.	A. A.

**Table 4. Sample list of thin sections (calcite stained)
studied from Crom-Wells No.1 Fee, Orangy County**

Number	Depth(ft.)	Lithology (Guo)	Formation (Warthin & Pack 1956)
1	4690-4702	Ls.+ Sh.	Jacksonburg
2	4702-4705	Dls.	
3	4708-4720	Ls. + Sh.	
4	4740-4752	Dls.	
5	4765-4770.5	Dls.+Ls.	
6	4770.5-4773	Ls.+ Dls.	
7	4772-4775	Dls.	
8	4778-4794	Ls.+ Dls	
9	4820-4833	Dls.+ Ls.	
10	4833-4852	Dls. + Dls	
11	4851-4853	Dls.	
12	4856-4860.5	Dls.	
13	4862-4879.5	Dls.	
14	4885-4890	Ls.+ Dls.	
15	4906.5-4914.5	Dls.+ Ls.	Rochdale
16	4914.5-4917	Dls. + Ls.	
17	4926-4940	Ls.+ Sist.+ Sh.	
18	4949-4957	Dls.+ Ls.+ Sist.	
19	4971.5-4974.5	Ls.+ Dls.+Sh.+Sist.	
20	4986-4988	Dls.	
21	4990-4993	Calc.Dls.	
22	5003-5006	Dls.	
23	5045-5075	Dls.	
24	5076-5078	Dls.+Sist.+Chert+Sh.	
25	5107-5114	Dls.	
26	5119-5123	Calc.Dls.	
27	5127-5130	Calc.Dls.+ Ls.	
28	5175-5177	Calc.Dls.+ Dol.Ls.	
29	5181-5182	Calc.Dls.+ Dol.Ls.	
30	5193-5195	Dls.	Halcyon Lake
31	5206-5208	Dls.	
32	5232-5242	Calc.Dls.+Dol.Ls.	
33	5279-5281	Calc.Dls.+Dol.Ls.+Chert	
34	5293-5295	Dls.+Calc.Dls.+Chert	
35	5316-5321	Dls.+SiSt.+ Sh.	
36	5357-5362	Dls.	
37	5373-5374	Dls. with silts	
38	5395-5399	Dls. with silts	
39	5488-5490	Dls.	
40	5522-5524	Dls. with silts	

41	5562-5565	Dls.+Sist.	
42	5566-5568	Ls.+ Calc.Dls.	
43	5601-5604	Dls.	
44	5683-5685	Ls.+ Dls.+ Sh.	
45	5716-5718	Dls.+Silty Dls.+Sist.	Briacliff
46	5777-5781	Ls.+ Dls.+ Sh.+Chert	
47	5816-5818	Dls. mixed Sist.	
48	5874-5877	Dls.+Sh.+Chert+Ls.	Pine
49	5922-5927	Dls.	plains
50	6041-6044	Dls.	
51	6064-6067	Dls.	
52	6082-6087	Dls.+sandy Dls.+Sst.	
53	6114-6119	Dls.+sandy Dls.+Sst.	
54	6149-6153	same above	
55	6179-6201	Dls.	
56	6221-6228	Dls.+Chert	
57	6258-6263	same above	
58	6301-6308	Dls.+ Sist.	
59	6331-6346	Dls.	
60	6434-6438	Dls.+ Chert	
61	6442-6448	Dls.+sandy Dls.+ Sst.	
62	6456-6462	Dls.+ Sst.	
63	6480-6495	Dls.	
64	6520-6525	Dls.+ Sst.	
65	6545-6550	Dls.	
66	6555-6560	Dls.+ Sst.	
67	6570-6575	Dls.+ Sst.	
68	6595-6600	Dls.	
69	6615-6625	Dls.+ Chert+ Sist.	
70	6640-6645	Dls.	
71	6655-6665	Dls.+ Sh.	
72	6685-6690	same above	
73	6710-6715	Dls.	
74	6725-6730	Dls.	
75	6765-6770	Dls.	
76	6785-6790	Dls.	
77	6805-6810	Dls.	
78	6835-6840	Sandy Dls.+ Sst.	

Table 5. Sample list of thin sections (Polished, for CL and Microprobe) studied from Crom-Wells No.1 Fee, Orange County

Order	Depth (ft.)	Description	Formation (Guo)
1.	4555-65	Ls.	Jacksonburg
2.	4851-53	Fine Dls. w. Ca cement	Copake
3.	4866-67.5	Micro Dls, w.l. Ca	Copake
4.	4911-14.5	Dls. w 10% Ls.	Copake
5.	4915-20	Dls & Ls., w. silts	Rochdale
6.	4957-59	a.a.	a.a.
7.	4974.5-80.5	a.a. plus Sh.	a.a.
8.	4996-99	Fine Dls., w. ca	a.a.
9.	5043-45	Crypto Dls., w.l.ca	Halcyon Lake
10.	5075-78	Dls.+Sst+chert,w.l.ca	a.a.
11.	5104-07	Fine Dls. w. ca	a.a.
12.	5129-35	Dls.+ Ls.(dedol.)	a.a.
13.	5161-63	a. a.	a.a.
14.	5172-75	a. a.	a.a.
15.	5182-83	a. a.	a.a.
16.	5204-06	Medium-coarse Dls.	a.a.
17.	5229-32	Dls. + l. Ls. (dedol.)	a.a.
18.	5265-67	a.a.	a.a.
19.	5283-88	a.a.	a.a.
20.	5304-07	a.a.	a.a.
21.	5325-28	Micro Dls.	a.a.
22.	5359-62	Dls.+chert+Sh., w.l.ca	a.a.
23.	5430-31	Fine-medium Dls. w.l.ca	a.a.
24.	5510-13	a.a.	a.a.
25.	5549-52	Fine Dls.	a.a.
26.	HiR 6	Fine Xeno. Dls.	Type section,
27.	HiR 9	Fine Hypidio. Dls.	Contact with
28.	HiR 11a	a.a.	Rochdale, Bethel,
29.	HiR 15a	Medium idio.cherty Dls.	N.Y., Pine
30.	HiR 19	Medium idio. Dls.	Plains Quad.
31.	W 15	MicroXL. idio. Dls.	Winfarm, P.P.
32.	W 21	Micro. Xeno. Dls	Quad.
33.	W 35	Medium. idio. Dls.	a.a.
34.	W 39	Fine. idio. Dls.	a.a.
35.	W 42	Fine. Xeno. Dls.	a.a.
36.	W 48	Medium. idio. Dls.	a.a.
37.	W 52	Calc. Dls.	a.a.
38.	W 59	Calc. Dls.	a.a.
39.	W 66	Poly. Xeno. Dls.	a.a.
40.	W 71	Poly. idio. Dls.	a.a.
41.	W 75	Calc. Dls.	a.a.
42.	W 85	Calc. Dls.	a.a.

Table 6. Sample list of thin sections studied from cuttings of ARCO Susi No. 1 boring

Sample No. requested	Depth (ft.)	Formation	Kind of section
01	3060 to 3070A	Balmville Ls.	@
02	3060 to 3070B	Balmville Ls.	@
03	3770 to 3780	Balmville Ls.	uncovered
04	3790 to 3800	Halcyon Lake Fm. (dol.)	*
05	3820 to 3840	Halcyon Lake Fm. (calcdol.)	@
06	3870 to 3880	Halcyon Lake Fm. (ded. & dol.)	@
07	3880 to 3890	Halcyon Lake Fm. "	*
08	3930 to 3940	Halcyon Lake Fm. (dol.)	@
09	3940 to 3990	Halcyon Lake Fm. (dol.)	*
10	4020 to 4040	Halcyon Lake Fm. (dol.)	@
11	4090 to 4100	Halcyon Lake Fm. (dol.)	*
12	4140 to 4160	Halcyon Lake Fm. (ded. & dol.)	@
13	4300 to 4320	Halcyon Lake Fm. (poss. is Briarcliff)	*
14	4360 to 4370 & 4420 to 4430	Briarcliff Dol. (H.Lake?)	@
15	4570 to 4580	Briarcliff Dol.	+
16	4650 to 4660	Briarcliff Dol. (fine to micr.)	@
17	4820 to 4830	Pine Plains Fm. (dol.)	+
18	4880 to 4890	Pine Plains Fm. "	@
19	5200 to 5240	Pine Plains Fm. "	+
20	5380 to 5390	Pine Plains Fm. "	@
21	5570 to 5580	Pine Plains Fm. (oolitic dol.)	@
22	5900 to 6010	Pine Plains Fm. " "	+
23	6120 to 6130	Pine Plains Fm. " "	@
24	6340 to 6360	Pine Plains Fm. (L.Pt.; lt. (gray micro. dol--Stissing?)	@
25	6480 to 6510	"	@
26	6620 to 6640	L. Pine Plains (gy, micro. dol)	@
27	7001 to 7020	Pine Plains (?) (gy- to dk gy dol)	+

EXPLANATION:

- @ Polished for microprobe
- * Stain for calcite; leave uncovered
- + Stain for dolomite (ferrous iron); leave uncovered

Table 7. Sample list of thin sections studied from Core 73-91, CP Quarry, Pine Plains Formation

Depth (ft.)	Description
25*	Gray, fine dolostone with saddle dolomite
34*	Dark gray dolostone, medium, oolitic
53*	Karst breccia
58*	Gray, medium dolostone, biotubated
64*	Thinly laminated dolostone (tidal bedding?)
78.5	Fine, gray dolostone; thinly laminated
91	Light, v.fine dolostone; stromatolites
100*	Karst breccia
123*	Light gray, v. fine dolostone
137	Light gray, fine- to medium dolostone; massive
148	White, fine dolostone; fracture-vug
174*	Karst breccia
182*	Gray, fine- to medium dolostone; vague laminae
199	Gray, fine dolostone; massive, like 137'
222	Gray, fine- to medium dolostone; bioturbated
229	Fine, gray dolostone; laminated
241*	Gray, medium, oolitic dolostone

* Polished

Table 8. Sample list of thin sections studied from CP Quarry face, Pine Plains Formation

Depth (ft.)	Description
CP1-a*	Dark gray, fine, dolostone with geodes
CP1-b	Same as above
CP2-a*	Karst breccia
CP2-b*	Karst breccia
CP3	Fine-micro, thick-laminated dolostone
CP4*	Light gray, fine vuggy dolostone
CP5-a	Same as above
CP5-b	Same as above
CP6	Dolostone; thickly laminated
CP7*	Gray, fine- to medium dolostone; burrowed

* Polished

Table 9. Sample list of thin sections studied from multiple locations

Sample No.	Description	Locality
1.	Dolomite vein (late, tectonic)*	Newburgh roadcut
2.	Black calcite in dolomite*	Halcyon Lake
		*Microprobe polished
3.	Poughquag Sandstone	Roadcut W of Newburgh
4.	Poughquag Sandstone	Roadcut W of Newburgh
5.	Gneiss, Precambrian on overthrust sheet	Roadcut W of Newburgh
6.	Gneiss, Precambrian on overthrust sheet	Taconic State Pkwy NE of Poughkeepsie
7.	Sandstone block in shale	Kaal Park, Poughkeepsie
8.	Finnegan boring 6150-60*	
9.	6370-80*	
10.	6450-60*	
11.	6480-90*	
12.	6800-10*	
13.	Balmville Ls.*	Balmville
14.	Balmville Ls.*	Balmville

* Polished

APPENDIX II: THE DATA OF THE MICROPROBE ANALYSIS

Table 1. Dolomite (first and second stage) from Crom-Wells No. 1 Fee,
the top of the Wappinger Group

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<---- ppm ---->			<----- % ----->			<----- % ----->			
Crom-Wells, 5075-5078 ft.									
2498	0	0	54.33	44.87	0.48	0	0.26	0	99.94
2129	0	0	55.46	44	0.39	0	0.13	0	99.98
1677	0	0	55.16	43.65	0.31	0	0.73	0.03	99.88
1514	0	0	57.99	41.91	0.09	0	0	0	99.99
1690	0	0	55.67	38.55	0.31	0	4.97	0	99.5
1999	202	0	49.25	40.09	0.4	0.04	8.52	0.03	98.33
1604	178	0	29.76	23.51	0.3	0.03	41.37	0.05	95.02
3413	0	0	35.28	28.04	0.69	0	34.47	0.02	98.5
1577	0	0	23.51	20.36	0.28	0	49.74	0.06	93.95
4001	0	0	55.67	40.84	0.81	0	2.58	0.02	99.92
3205	405	0	57.59	27.69	0.66	0.08	13.8	0	99.82
1236	327	0	53.44	20.5	0.27	0.07	30.19	0.1	104.57
2249	261	0	34.71	24.61	0.4	0.04	31.46	0.08	91.3
4478	291	0	54.65	40.58	0.9	0.05	3.65	0.06	99.89
2354	0	0	37.62	28.19	0.44	0	27.27	0.07	93.59
2238	145	0	51.42	38.53	0.45	0.02	9.23	0.03	99.68
1836	0	0	50.83	38.88	0.36	0	9.56	0.03	99.66
2481	100	0	50.93	38.85	0.5	0.02	8.72	0	99.02
Crom-wells, 5104-5107 ft.									
1187	0	0	55.67	38.47	0.24	0	5.63	0.06	100.07
2618	0	0	27.08	20.82	0.45	0	35.72	0.07	84.14
1743	430	0	53.11	42.64	0.36	0.08	3.45	0	99.64
362	0	0	54.23	44.98	0.07	0	0.66	0.03	99.97
3237	249	0	54.78	43.52	0.64	0.05	0.92	0.03	99.94
2426	313	0	55.03	43.54	0.48	0.06	0.85	0	99.96
11345	0	0	55.03	41.48	2.33	0	1.15	0	99.99
4007	215	0	53.71	43.22	0.76	0.04	1.7	0.31	99.74
742	0	0	61.53	37.83	0.15	0	0.55	0.04	100.1
923	222	0	62.23	36.98	0.18	0.04	0.51	0.05	99.99
511	417	0	54.53	44.96	0.1	0.08	0.31	0	99.98
Crom-Wells, 5043-5045 ft.									
995	225	0	56.23	43.12	0.19	0.04	0.38	0	99.96
349	364	0	54.99	44.61	0.07	0.07	0.23	0.02	99.99
1684	324	0	54.02	43.3	0.32	0.06	2.06	0.03	99.79
96	196	0	53.96	44.62	0.01	0.04	0.14	0	98.77
428	339	0	54.65	44.19	0.08	0.06	0.96	0.02	99.96
1940	344	0	54.69	44.63	0.39	0.07	0.21	0	99.99
1411	0	0	54.95	44.22	0.28	0	0.52	0	99.97
1666	420	0	53.43	44.21	0.33	0.08	1.86	0	99.91
1338	445	0	54.44	43.36	0.27	0.09	0.41	0	98.57

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<---- ppm ---->	<----->	<----->	<----->	<----->	<----->	% ----->	<----->	<----->	<----->
Crom-Wells, 4975-4981 ft.									
3472	182	0	56.32	41.79	0.7	0.03	0.96	0.15	99.95
3086	412	0	55.07	42.37	0.63	0.08	0.31	0.1	98.56
3862	129	0	56.02	42.06	0.78	0.02	1.01	0.06	99.95
4359	163	0	55.87	41.35	0.89	0.03	0.27	0.09	98.5
4501	257	0	53.78	42.86	0.92	0.05	0.84	0.08	98.53
Crom-wells, 5104-5107									
1255	629	0	54	43.92	0.25	0.13	0.41	0.02	98.73
533	0	0	57.56	40.63	0.1	0	0.82	0	99.11
576	425	0	54.34	44.06	0.11	0.08	0.35	0	98.94
0	160	0	54.87	44.02	0	0.03	0.67	0.02	99.61
Crom-Wells 5043-45 ft.									
3710	0	0	54.49	43.56	0.74	0	1.13	0	99.92
3830	357	0	54.57	43.04	0.77	0.07	1.47	0	99.92
1962	0	0	56.3	43.3	0.38	0	0	0.03	100.01
1704	0	0	50.72	41.12	0.33	0	7.4	0.03	99.6
Crom-Wells, 4915-4920 ft.									
2936	209	0	53.64	41.35	0.59	0.04	4.15	0.12	99.89
735	0	0	58.84	37.99	0.14	0	2.62	0.17	99.76
258	328	0	57.24	40.45	0.05	0.06	1.71	0.05	99.56
1600	0	0	59.17	38.87	0.31	0	1.49	0.06	99.9
Crom-Wells 4740-4752									
1531	0	0	40.94	30.16	0.31	0	27.19	0	98.6
206	0	0	58.34	40	0.04	0	1.13	0	99.51
3579	0	0	62.85	37.17	0.74	0	0	0	100.76
0	0	0	63.15	38.53	0	0	0	0.03	101.71
0	0	0	60.07	39.93	0	0	0	0	100
0	0	0	58.3	41.82	0	0	0	0	100.12
1136	0	0	59.05	40.95	0.23	0	0	0	100.23
0	0	0	58.77	41.52	0	0	0	0	100.29
164	0	0	59.05	40.69	0.03	0	0	0.03	99.8
268	0	0	58.53	41.09	0.05	0	0.32	0	99.99
720	0	0	59.2	39.47	0.14	0	1.15	0	99.96
2021	0	0	51.38	37.86	0.39	0	9.95	0	99.58
10557	0	0	58.18	39.56	2.18	0	0	0	99.92
Crom-Wells, 4996-4999 ft.									
14361	0	0	56.74	40.01	2.97	0	0	0	99.72
196	0	0	58.28	40.72	0.04	0	0	0	99.04
0	0	0	58.88	40.02	0	0	1.13	0	100.03
0	0	0	59.14	39.73	0	0	1.14	0	100.01
0	0	0	59.93	40.09	0	0	0	0.02	100.04
0	0	0	58.58	41.47	0	0	0.09	0.02	100.16
0	0	0	58.9	41.11	0	0	0	0	100.01
259	0	0	59.74	39.45	0.05	0	0	0	99.24

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<----- ppm ----->			<----- % ----->						
0	0	0	60.59	39.66	0	0	0	0	100.25
Crom-Wells, 4957-4959 ft.									
1540	0	0	55.69	43.25	0.3	0	0.56	0.08	99.88
3895	0	0	55.49	42.83	0.76	0	0	0.09	99.17
2574	0	0	55.32	43.4	0.48	0	0.51	0.17	99.88
2590	0	0	53.34	41.78	0.49	0	3.92	0.09	99.62
2174	0	0	56.41	42.2	0.42	0	0.82	0.06	99.91
1469	0	0	55.07	44.5	0.28	0	0.08	0.03	99.96
2055	0	0	53.26	40.98	0.4	0	4.97	0.07	99.68
1241	0	0	55.94	42.97	0.24	0	0.03	0.76	99.94
Crom-Wells, 5265-5267 ft.									
937	0	0	54.32	45.49	0.19	0	0	0	100
1360	0	0	54.85	43.93	0.27	0	0.94	0	99.99
0	0	0	63.72	35.71	0	0	0	0	99.43
0	0	0	55.66	41.85	0	0	1.79	0	99.3
0	0	0	66.82	33.6	0	0	0	0	100.42
516	0	0	56.34	43.36	0.1	0	0	0	99.8
0	0	0	62.64	37.71	0	0	0	0.02	100.37
0	0	0	58.76	41.75	0	0	0	0.02	100.53
0	0	0	56.22	43.8	0	0	0	0	100.02
Crom-Wells, 5204-5206 ft.									
619	0	0	54.57	44.97	0.12	0	0.31	0.02	99.99
542	193	0	54.91	44.53	0.1	0.03	0.42	0	99.99
3862	0	0	53.2	43.39	0.77	0	2.5	0.03	99.89
237	127	0	52.7	42.44	0.04	0.02	4.72	0.02	99.94
0	278	0	54.82	44.8	0	0.05	0.31	0	99.98
Crom-Wells, 5104-5107 ft.									
0	0	0	55.35	42.75	0	0	0.58	0.02	98.7
357	0	0	55.42	42.68	0.07	0	0.52	0	98.69
237	0	0	58.51	41.16	0.04	0	0.54	0.03	100.28
217	0	0	56.72	42.27	0.04	0	0.49	0.02	99.54
234	0	0	57.61	43.18	0.04	0	0.54	0.02	101.39
137	350	0	58.76	39.25	0.02	0.07	0.41	0.03	98.54
347	0	0	59.15	39.76	0.07	0	0.51	0.04	99.53

Table 2. Late-stage zoned dolomite (f), Crom-wells, No. 1 Fee, Halcyon Lake Fm.

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<--- ppm --->		<----- % ----->						
5304-5307 ft.								
882.00	98.00	54.62	43.57	0.18	0.02	0.58	0	98.97
1413.00	317.00	54.23	43.47	0.29	0.00	0.42	0	98.41
2082.00	0.00	53.37	40.69	0.40	0.00	0.38	0.05	94.84
12792.00	0.00	55.46	42.31	1.90	0.00	1.22	0.13	100.89
1783.00	0.00	54.27	43.24	0.36	0.00	0.28	0.04	98.15
247.00	194.00	54.91	42.48	0.05	0.03	0.43	0.00	97.90
463.00	183.00	52.65	42.51	0.09	0.03	0.49	0.00	95.77
0.00	253.00	60.31	39.51	0.00	0.05	0.26	0.00	100.13
1431.00	175.00	58.99	36.65	0.28	0.03	0.46	0.02	96.41
1048.00	262.00	54.37	43.43	0.21	0.05	1.14	0.00	99.20
1065.00	197.00	59.25	19.74	0.22	0.04	21.17	0.00	100.42
1004.00	181.00	53.84	42.92	0.20	0.03	0.56	0.10	97.55
603.00	130.00	54.07	43.16	0.12	0.02	0.43	0.03	97.80
12787.00	0.00	57.59	38.88	2.11	0.00	1.27	0.19	99.85
769.00	289.00	54.23	42.24	0.15	0.05	0.37	0.04	97.04
3053.00	0.00	52.36	42.22	0.60	0.00	0.50	0.08	95.68
5402.00	96.00	51.83	41.65	1.06	0.01	0.49	0.08	95.04
2975.00	0.00	53.51	43.78	0.60	0.00	0.31	0.03	98.20
8746.00	96.00	51.42	40.81	1.71	0.01	0.57	0.12	94.52
912.00	249.00	55.16	42.79	0.18	0.05	0.91	0.04	99.09
1229.00	181.00	55.23	43.42	0.24	0.03	0.32	0.04	99.24
667.00	0.00	63.39	34.78	0.13	0.00	0.78	0.00	99.08
Traverse of one crystal, 5304-5307 ft.								
2082.00	0.00	53.37	40.69	0.40	0.00	0.38	0.05	94.84
12792.00	0.00	55.46	42.31	1.90	0.00	1.22	0.13	100.89
1783.00	0.00	54.27	43.24	0.36	0.00	0.28	0.04	98.15
247.00	194.00	54.91	42.48	0.05	0.03	0.43	0.00	97.90
463.00	183.00	52.65	42.51	0.09	0.03	0.49	0.00	95.77
0.00	253.00	60.31	39.51	0.00	0.05	0.26	0.00	100.13
1431.00	175.00	58.99	36.65	0.28	0.03	0.46	0.02	96.41
1048.00	262.00	54.37	43.43	0.21	0.05	1.14	0.00	99.20
1065.00	197.00	59.25	19.74	0.22	0.04	21.17	0.00	100.42
1004.00	181.00	53.84	42.92	0.20	0.03	0.56	0.10	97.55
Zoned dol.(f) Photo 7345-8, ARCO Susi, Halcyon Lake Fm.								
0	0	58.44	41.45	0	0	0.8		100.69
10477	284	52.01	40.02	2.2	0.06	7.02		101.31
0	107	58.02	41.97	0	0.02	0.92		100.93
0	156	56.39	40.49	0	0.03	0.96		97.87
294	0	58.09	40.04	0.06	0	2.14		100.33
98	0	56.88	41.72	0.02	0	2.54		101.16
2386	227	55.96	38.86	0.51	0.04	7.61	0.02	103
384	0	57.71	42.32	0.08	0	0.74		100.85

**Table 3. Dolomite (second stage) in Halcyon Lake Formation from ARCO
No.1 Susi boring and other locations**

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->		<----- % ----->							
Second dolomite w/ dol. (f), ARCO Susi 3820'									
6534	131	57.52	40.02	1.32	0.02	1.43			100.31
3460	202	54.81	43.14	0.71	0.04	1.12			99.82
968	0	60.68	39.25	0.2	0	0.72			100.85
1134	0	58.1	40.24	0.23	0	1.51			100.08
129	0	57.4	41.59	0.02	0	0.56			99.57
192	0	57.82	41.39	0.04	0	0.97			100.22
134	0	60.8	38.11	0.02	0	0.72			99.65
Second dolomite w/black calc. Halcyon Lake Outcrop									
436	465	55.1	45.04	0.09	0.09	0.24			100.56
576	0	54.98	45.14	0.12	0	0.66	0	0	100.9
516	0	55.78	45.34	0.1	0	0.06	0	0	101.28
753	0	55.69	44.35	0.15	0	4.03	0	0	104.22
521	0	54.97	45.24	0.1	0	0.61	0	0	100.92
672	0	54.32	44.69	0.14	0	2.42	0	0	101.57
488	0	55.52	45.2	0.1	0	1.62	0	0	102.44
505	0	54.72	46.09	0.1	0	0.11	0.05	0.02	101.09
473	0	54.93	45.35	0.09	0	0.07		0.02	100.46
504	0	55.13	45.83	0.1	0	0.13	0	0	101.19
509	153	55.56	44.56	0.1	0.03	0.87	0	0	101.12
891	162	55.48	42.75	0.18	0.03	0.4	0	0	98.84
554	91	55.35	44.97	0.11	0.01	0.2	0	0	100.64
438	0	56.66	43.25	0.09	0	0.2	0	0	100.2
521	0	55.39	44.16	0.11	0	2.62	0.02	0	102.3
Second dolomite in ARCO No.1 susi, photo 7541-7									
836	0	56.38	41.97	0.17	0	1.65	0	0	100.17
665	0	55.17	43.42	0.13	0	1.67	0	0	100.39
827	0	55.22	44.38	0.17	0	0.34	0	0	100.11
835	0	55.77	43.74	0.17	0	0.51	0.02	0	100.21
1120	0	53.86	41.79	0.22	0	2.61	0.03	0	98.51
1145	133	54.6	43.75	0.23	0.02	0.95	0	0	99.55
Second dolomite, photo 7553-3, Halcyon Lake Fm.									
110	0	58.03	41.85	0.02	0	1.12	0	0	101.02
Dark core and bright mim, photo 7541-5, ARCO Susi									
1013	185	57.45	41.12	0.21	0.03	1.8	0	0	100.61
16734	356	57.08	38.78	3.48	0.07	0.99			100.4
17977	233	53.51	40.92	3.68	0.04	0.62	0	0	98.77
30107	213	53.48	39	6.21	0.04	0.77	0	0	99.5
18255	157	53.81	41.11	3.76	0.03	0.7	0	0	99.41
219	376	58.62	40.49	0.04	0.07	0.69	0	0	99.91
734	212	59.76	40.28	0.15	0.04	0.46	0.03	0	100.72

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->		<----- % ----->				<----->			
764	156	58.24	40.85	0.15	0.03	1.13	0	0	100.4
1196	0	57.89	41.32	0.25	0	2.46	0.03	0	101.95
5146	256	46.84	32.46	1.08	0.05	21.54	0.04	0	102.01
18594	283	53.75	40.88	3.83	0.05	0.98	0	0	99.49
25208	218	51.81	37.94	5.23	0.04	4.99	0	0	100.01
504	360	58.62	41.4	0.1	0.07	0.23	0	0	100.42
26744	183	51.13	37.81	5.27	0.03	0.83	0.05	0	95.12
47786	157	52.92	36.47	9.87	0.03	0.28	0.02	0	99.59
0	566	59.04	40.95	0	0.11	0.26	0.03	0	100.39

**Table 4. Dolomite (Early and second stage) in Pine Plains Formation
from ARCO No.1 Susi, and CP Quarry**

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->		----- % -----				>			
Early Dol. (a) w/silt, ARCO Susi 6340 ft., photo 7568-17									
20457	271	24.32	32.16	4.82	0.06	50.41	1.93	0	113.7
26447	396	25.88	38.14	6.18	0.09	42.32	0.05	0	112.66
28101	337	24.59	40.02	6.65	0.08	42.68	0.05	0	114.07
31708	307	24.62	44.14	7.65	0.07	39.77	0.11	0	116.36
26417	231	24.85	38.3	6.07	0.05	41.55	0.04	0	110.86
44192	224	22.64	37.89	10.48	0.05	43.18	0.09	0	114.33
Cement between ooids, ARCO Susi 6120 ft., photo 7568-3									
938	202	54.03	46.09	0.19	0.04	0.39	0	0	100.74
0	239	56.33	45	0	0.05	0.45	0	0	101.83
1561	124	54.22	46.06	0.32	0.02	0.35	0	0	100.97
3656	139	52.47	45.6	0.75	0.02	0.35	0	0	99.19
126	360	56.01	44.02	0.02	0.07	0.4	0	0	100.52
0	268	54.41	44.15	0	0.05	0.1	0	0	98.71
0	269	56.41	44.32	0	0.05	0.43	0	0.02	101.23
One ooid traverse, ARCO Susi 6120, photo 7568-4									
3172	142	52.99	45.67	0.65	0.02	0.35	0	0	99.68
1336	180	54.41	45.62	0.27	0.03	0.56	0.02	0	100.91
1644	215	54.48	45.71	0.34	0.04	0.43	0	0	101
3065	215	53.71	45.71	0.64	0.04	0.96	0.02	0	101.08
1028	98	54.29	45.64	0.21	0.02	0.42	0.02	0	100.6
1598	219	53.73	45.97	0.33	0.04	0.38	0	0	100.45

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<--- ppm	---	<-----	----- %			----->			
Two ooids traverse, ARCO Susi 5570 ft.									
1692	278	51.69	44.62	0.35	0.05	3.4	0.07	0	100.18
283	90	54.37	46.52	0.05	0.01	0.56	0	0	101.51
1836	235	53.6	45.91	0.38	0.04	0.79	0.03	0	100.75
890	0	53.57	46.48	0.18	0	0.5	0.04	0	100.77
1054	260	53.51	46.11	0.22	0.05	0.84	0.03	0	100.76
3859	0	46.73	40.39	0.82	0	14.81	0.08	0	102.83
473	0	53.63	46.73	0.09	0	0.62	0	0	101.07
Original ooids cement, CP 73-91, 241', photo 2020-5									
8296	313	50.26	41.67	1.74	0.06	7.43	0.02	0	101.18
5939	0	0.72	0.75	1.3	0	102.7	0.11	0	105.58
2316	0	1.88	0.58	0.5	0	102.52	0.12	0	105.6
5924	0	36.92	29.41	1.27	0	36	0.04	0	103.64
4232	120	40.36	33.2	0.88	0.02	26.32	0.05	0	100.83
One original ooids traverse, CP 73-91, 241', photo 2020-5									
3760	257	53.17	45.58	0.78	0.05	0.5	0.03	0	100.11
3812	250	50.96	43.82	0.79	0.05	5.19	0.03	0	100.84
3459	104	52.85	45.48	0.71	0.02	0.3	0.02	0	99.38
3487	245	52.75	45.61	0.71	0.05	0.36	0	0	99.48
5237	157	52.07	43.65	1.08	0.03	3.11	0.02	0	99.96
6453	126	36.49	30.48	1.35	0.02	32.99	0.05	0	101.38
Early dol. (a), v. fine, CP 73-91, 123'									
4556	137	53.3	44.46	0.94	0.02	1.58	0	0	100.3
7598	207	50.97	41.69	1.58	0.04	6.04	0.03	0	100.35
17391	236	46.76	38.887	3.67	0.05	12.43	0.03	0	101.83
2693	107	53.66	44.57	0.55	0.02	1.26	0.03	0	100.09
3950	256	51.14	42.3	0.83	0.05	7.55	0	0	101.87
Second dol.(b), fine, CP 1-a, loose block									
1460	152	53.95	45.82	0.3	0.03	0.89	0	0	100.99
Fine dol. Newburg, Pine Plains Fm.									
4773	247	54.71	47.74	1.02	0.05	0.44	0	0	103.96
Breccia, CP 73-91, 53', photo 53810-25									
Fe	Mn	CaCO3	MgCO3	FeCO3	MnCO3	SiO2	Na2O	SrCO3	Sum
3044	97	53.41	45.64	0.63	0.02	1.2	0	0	100.9
3545	114	51.96	44.89	0.74	0.02	3.19	0.03	0	100.83
1752	166	53.63	46.73	0.36	0.03	0.64	0	0	101.39
789	257	54.45	46.16	0.16	0.05	0.37	0	0	101.19
2270	0	52.96	46.28	0.47	0	0.48	0	0	100.19
3190	164	53.43	46.21	0.66	0.03	0.79	0.02	0	101.14
6197	116	44.05	37.62	1.3	0.02	18.53	0	0	101.52
7098	107	51.08	42.36	1.48	0.02	5.7	0.03	0	100.67
3118	165	53.72	45.62	0.64	0.03	0.27	0	0	100.28

3255	185	52.61	46.02	0.67	0.03	0.54	0	0	99.87
4003	0	46.13	39.62	0.84	0	15.68	0.02	0	102.29
5250	161	49.47	33.54	1.1	0.03	17.57	0.03	0	101.74

Breccia, CP 2-b, loose block, photo 53810-13

0	133	55.38	45.33	0	0.02	0.2	0	0.02	100.95
2560	135	54.18	44.81	0.53	0.02	1.37	0.02	0	100.93
328	0	54.17	45.86	0.06	0	0.44	0.02	0	100.55
756	95	53.92	45.86	0.15	0.02	0.62	0	0	100.57

Table 5. Late-stage saddle dolomite from Pine Plains Formation

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->		<----- % ----->							
Hydrothermal saddle dol., Newburgh									
11187	476	53.68	43.81	2.31	0.1	0.11			100.01
13001	693	53.11	43.97	2.7	0.15	0.02		0.06	100.01
11892	533	53.6	43.8	2.47	0.11	0.03			100.01
11314	429	53.2	44.25	2.05	0.09	0.04		0.03	99.66
11483	574	52.8	44.65	2.38	0.12	0.08			100.03
12269	679	53.62	43.66	2.54	0.14	0.03		0.02	100.01
12765	680	54.58	42.56	2.64	0.14	0.06		0.02	100
11818	543	53.03	44.35	2.45	0.12	0.04		0.02	100.01
11385	611	53.89	42.4	3.33	0.12	0.27			100.01
11371	598	52.46	44.83	2.35	0.13	0.24			100.01
10800	584	50.99	45.58	2.23	0.11	1.03	0.02		99.96
12124	518	53.83	43.4	2.5	0.11	0.15			99.99
11699	616	54.78	42.63	2.35	0.13	0.07		0.06	100.02
13386	614	53.7	43.31	2.77	0.13	0.1		0.03	100.04
12888	504	53.07	44.09	2.67	0.11	0.03		0.03	100
Saddle dol., CP 73-91, 241', photo 2020-2									
8404	361	52.89	43.82	1.72	0.07	0.42	0	0	98.92
4751	210	53.14	44.49	0.97	0.04	0.41	0	0	99.05
9093	265	53.62	44.16	1.86	0.05	0.28	0	0	99.97
6803	190	53.39	43.17	1.39	0.03	0.78	0	0	98.76
6012	285	53.74	43.57	1.23	0.05	0.4	0	0	98.99
Saddle dol., in vug dolostone, CP 4, photo 2020-18									
9157	222	50.7	43.63	1.83	0.04	0.27	0	0	96.47
8898	217	52.93	45.11	1.84	0.04	0.09	0	0	100.01
5830	222	52.25	45.18	1.19	0.04	0.1	0	0.02	98.78
Saddle dol., dull CL, CP 73-91, 123									
5215	174	52.7	45.45	1.07	0.03	0.36	0	0	99.61
5542	243	53.25	45.29	1.14	0.05	0.12	0	0	99.85
3921	175	52.43	45.99	0.8	0.03	0.16	0	0	99.41

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->		<----- % ----->							
5147	189	52.9	45.44	1.06	0.03	0.42	0	0	99.85
11597	469	53.38	42.75	2.39	0.09	1.07	0	0	99.68
Saddle dol., CP 1-a, Photo 2020-23									
3605	183	55.08	43.59	0.74	0.03	0.23	0	0	99.67
6009	340	53.48	45.07	1.24	0.07	0.25	0.02	0	100.13
3491	110	55.3	44.48	0.72	0.02	0.18	0	0	100.7
3794	134	54.86	44.75	0.79	0.02	0.16	0	0	100.58
Saddle dol., CP 2-b									
4381	208	54.53	43.43	0.9	0.04	0.23	0	0	99.13
4568	301	56.09	42.17	0.94	0.06	0.19	0	0	99.45
4054	243	59.15	40.31	0.84	0.05	0.18	0	0.04	100.57
Saddle dol., non-CL									
15664	531	55.86	40.02	3.23	0.11	0.17	0	0	99.39
17318	593	56.22	39.56	3.57	0.12	0.11	0	0	99.58
17113	593	55.69	39.31	3.5	0.12	0.19	0	0.02	98.83
16119	596	55.87	39.76	3.31	0.12	0.18	0	0	99.24
16557	500	55.72	39.47	3.39	0.1	0.2	0	0	98.88

Table 6. Bright-CL dolomite from Pine Plains Formation

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->		<----- % ----->				>			
Bright zone CP 73-91, 123'									
10615	272	56.16	41.17	2.19	0.05	0.13	0	0	99.7
9166	387	55.36	41.48	1.88	0.08	0.11	0	0	98.91
Bright zone, CP 2-b, photo 53810-9									
302	135	55.26	46.16	0.06	0.02	0.2	0	0	101.7
652	0	54.35	46.31	0.13	0	0.16	0	0	100.95
254	0	54.85	45.5	0.05	0	0.16	0	0	100.56
Bright second dol. CP 73-91, 241', photo 2020-2									
2801	218	53.1	45.66	0.58	0.04	0.55	0.03	0	99.96
4219	218	53.36	44.88	0.87	0.04	0.54	0	0	99.69
2400	191	52.94	45.37	0.49	0.03	0.42	0.03	0	99.28
5799	95	42.23	32.98	1.35	0.02	36.41	0	0	112.99
Red CL in vug dol., CP 4, photo 2020-18									
2773	248	52.78	46.18	0.57	0.05	0.16	0	0	99.74
3745	188	53.11	45.82	0.77	0.03	0	0	0	99.73

**Table 7. Dedolomite from Crom-Wells No. 1 Fee & ARCO No.1 Susi boring,
Halcyon Lake Formation**

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<--- ppm --->			<----- % ----->						
5104-5107 ft.									
102	765	0	95.54	4.42	0.02	0.16	0.58	0.03	100.75
5129-5135 ft.									
353	536	0	92.12	7.48	0.07	0.11	0.64	0.02	100.44
0	626	197	94.95	2.68	0	0.12	0.43	0.02	98.2
216	440	0	94.82	4.28	0.04	0.09	0.31	0.05	99.59
519	169	0	93.11	6.47	0.1	0.03	0.51	0	100.22
268	385	0	75.3	24.98	0.05	0.08	0.52	0.04	100.97
1020	367	0	71.96	19.52	0.21	0.07	8.57	0.04	100.37
1421	258	0	74.95	14.81	0.28	0.05	5.92	0.02	96.03
1940	467	0	89.19	9.22	0.4	0.09	1.13	0.02	100.05
956	0	0	69.95	11.01	0.19	0	17.16	0	98.31
1224	280	0	81.57	15.62	0.24	0.05	0.82	0.04	98.34
107	786	131	95.53	1.13	0.02	0.15	0.34	0	97.17
207	655	0	85.74	9.11	0.04	0.13	2.43	0.03	97.48
0	646	0	95.97	1.33	0	0.13	0.53	0.04	98
0	323	0	89.03	7.25	0	0.06	0.52	0.05	96.91
115	602	0	94.62	1.65	0.02	0.12	0.55	0.08	97.04
5043-5045 ft.									
1027	0	0	82.62	11.39	0.2	0	1.92	0.02	96.15
897	228	0	88.07	6.9	0.17	0.04	1.22	0.03	96.43
3522	407	0	82.53	11.76	0.69	0.08	0.42	0	95.48
798	175	0	92.57	3.47	0.15	0.03	0.29	0	96.51
5104-5107 ft.									
249	956	0	96.13	1.23	0.05	0.19	0.53	0	98.13
0	221	0	90.46	0.97	0	0.04	0.07	0.02	91.56
156	559	0	95.81	3.12	0.03	0.11	0.62	0	99.69
273	340	0	105.42	2.87	0.06	0.07	0.64	0	109.06
4975-4981 ft.									
1669	373	0	81.82	15.23	0.33	0.07	0.16	0.03	97.64
467	598	0	96.15	2.31	0.09	0.12	0.4	0.04	99.11
Dedolomite related calcite vein, Crom-Wells, Halcyon Lk.Fm.									
5104-5107 ft.									
0	1703	0	99.9	0.93	0	0.36	0.57	0	101.76
216	770	0	95.95	1.26	0.04	0.15	0.55	0	97.95
107	670	0	104.31	1.36	0.02	0.15	0.65	0	106.49
0	798	0	97.28	1.34	0	0.16	0.36	0.04	99.18
0	1092	0	97.7	1.17	0	0.22	0.44	0	99.53
210	776	0	96.72	1.26	0.04	0.16	0.58	0.02	98.78
0	1377	254	96.98	1.87	0	0.28	0.46	0	9.59
0	1968	0	98.5	0.87	0	0.22	0.56	0	100.15
0	717	0	96.53	0.87	0	0.14	0.56	0	98.1

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<--- ppm --->	<----- % ----->								
178	692	0	98.77	0.77	0.03	0.14	0.54	0	100.25
119	977	0	93.85	0.81	0.02	0.19	0.55	0.08	95.5
0	444	286	94.85	0.37	0	0.08	0.51	0.04	95.85
0	313	0	96.03	0.52	0	0.06	0.49	0	97.1
5043-5045 ft.									
0	807	366	91.47	1.47	0	0.15	0.11	0	93.2
93	454	395	93.54	1.14	0.01	0.09	0.09	0	94.87
5104-5107 ft.									
265	329	0	71.86	0.87	0.05	0.06	27.21	0.02	100.07
0	591	0	95.71	1.04	0	0.12	0.43	0	97.3
0	163	0	97.11	0.47	0	0.03	0.44	0	98.05

Dedolomite in ARCO No.1 Susi boring 4140 ft., photo 7553-3

Fe	Mn	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	SrCO ₃	Sum
<-- ppm -->	<----- % ----->								
0	308	96.87	1.21	0	0.06	0.58	0	0	98.72
307	145	97.17	0.98	0.06	0.03	0.57	0	0	98.81

ARCO Susi 4140 ft., Photo 7553-8

530	244	79.83	0.75	0.09	0.04	9.25	0.02	0	89.98
839	231	63.33	0.83	0.16	0.04	30.98	0.06	0	95.4

ARCO Susi 4020 ft. photo 7541-7, dark core & yellow rim

0	212	97.3	2.04	0.04	0.04	0.37	0	0	99.79
0	221	97.99	0.37	0	0.04	0.28	0	0.03	98.71
0	234	97.59	1.27	0	0.04	0.27	0	0	99.17
0	284	97.51	1.31	0	0.05	0.25		0	99.12
467	113	75.47	24.2	0.09	0.02	0.95	0	0	100.73

Dedol. cement? CP 73-91, 53', photo 53810-23

100	105	99.85	0.55	0.02	0.02	0.09	0	0.08	100.61
224	295	98.05	1.05	0.04	0.06	1.2	0	0	100.4
0	201	98.22	0.8	0	0.04	0.09	0.05	0	99.2
0	0	99.3	0.39	0	0	0.11	0	0.04	99.84
0	328	98.25	0.89	0	0.06	0.08	0.03	0.01	99.32
0	175	98.74	0.45	0	0.03	0.12	0.04	0	99.38
104	177	98.87	0.46	0.02	0.03	0.1	0.07	0	99.55

Table 8. Calcite

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<---- ppm ---->			<----- % ----->						
Calcite vein in Crom-Wells No. 1 Fee									
5104-5107 ft.									
693	0		95.99	1.47	0.14	0	0.5	0.03	98.13
5283-5288 ft.									
306	0	181	96.85	2.51	0.06	0	0.28	0.05	99.75
0	0	146	96.88	2.02	0	0	0.27	0	99.17
5304-5307 ft.									
159	0		94.89	1.24	0.03	0	0.45	0.07	96.68
394	284		95.22	1.48	0.07	0.05	0.45	0.03	97.3
346	0		93.34	0.53	0.06	0	0.6	0	94.53
199	115	128	96.33	1.13	0.04	0.02	0.35	0	97.87
5304-5307 ft.									
462	369		87.58	4.43	0.09	0.07	6.04		98.21
5104-5107 ft.									
525	0	0	95.96	1.56	0.1	0	0.48	0.04	98.14
509	0	317	97	0.95	0.1	0	0.49	0.04	98.58
5104-5107 ft., the vein cut by dedolomite vein									
1006	248	0	96.36	1.48	0.2	0.05	0.56	0	98.65
475	0	0	96.81	1.17	0.09	0	0.64	0	98.71
0	313	0	96.03	0.52	0	0.06	0.49	0	97.1
720	158	0	94.44	1.16	0.14	0.03	0.51	0.04	96.32
1229	237	0	93.97	1.46	0.24	0.04	0.69	0.05	96.45
977	295	0	95.59	1.19	0.19	0.06	0.51	0	97.54
467	251	285	95.56	1.4	0.09	0.05	0.46	0.03	97.59
4975-4981 ft.									
1746	0	0	93.99	1.25	0.34	0	0.23	0.11	95.92
3288	0	436	93.68	2.02	0.66	0	0.2	0.11	96.67
Precursor calcite in the top of the Wappinger Group									
4915-4920 ft.									
299	0	505	94.25	0.92	0.05	0	0.02	0.05	95.29
1381	442	0	97.08	0.94	0.26	0.08	0.8	0.05	99.21
406	208	359	96.6	1.14	0.08	0.04	0.42	0.06	98.34
578	0	313	94.23	0.92	0.11	0	0.35	0.07	95.68
404	284	0	95.48	1.01	0.08	0.05	0.78	0.06	97.46
4708-4720 ft.									
0	0	0	95.89	0.86	0	0	0	0	96.75
0	0	0	98.88	1.37	0	0	0	0.02	100.27
0	0	0	94.45	2.65	0	0	0.16	0.04	97.3
0	0	0	97.15	0.68	0	0	0	0	97.83
0	0	0	97.03	1.03	0	0	0	0	98.06
0	0	0	97.84	0.77	0	0	0	0	98.61
0	0	0	98.61	1.28	0	0	0	0	99.89
0	0	0	99.55	0.29	0	0	0	0	99.84

Fe	Mn	Sr	CaCO ₃	MgCO ₃	FeCO ₃	MnCO ₃	SiO ₂	Na ₂ O	Sum
<----- ppm ----->	<----- ppm ----->	<----- ppm ----->	<----- % ----->	<----- % ----->	<----- % ----->	<----- % ----->	<----- % ----->	<----- % ----->	<----- % ----->
Relic calcite in dolomite rhombs									
5104-5107 ft.									
0	0	757	92.43	9.52	0	0	0.42	0.0	102.39
89	0	297	85.64	15.94	0.01	0	0.49	0	102.08
5304-5307 ft.									
577	0	0	100.36	1.62	0.12	0	0.44	0	102.54
399	0	0	87.84	13.25	0.08	0	0.48	0	101.65
462	369	0	87.58	4.43	0.09	0.07	0.92	0	93.09
4996-4999 ft.									
0	0	0	97.7	0.73	0	0	0	0	98.43
0	0	0	96.94	0.69	0	0	0	0.03	97.66
259	0	0	95.38	1.04	0.05	0	0	0.03	96.5
0	0	0	96.05	0.72	0	0	0.29	0.02	97.08
470	0	0	95.27	2.74	0.09	0	0	0.02	98.12
0	0	0	94.6	0.57	0	0	3.62	0.08	98.87
0	0	0	95.84	0.57	0	0	1.38	0.03	97.82
0	0	0	97.9	0.6	0	0	0	0.02	98.52
0	0	0	97.98	0.74	0	0	0	0	98.72
0	0	0	96.62	0.67	0	0	0	0	97.29
0	0	0	101.29	0.64	0	0	0	0	101.93
7572	0	0	83.67	5.04	1.46	0	3.39	0	93.56
Late black-calcite vein, Halcyon Lake outcrop									
0	135	0	96.99	0.6	0	0.02	0	0	97.61
156	0	364	98.04	0.52	0.03	0	0.14	0	98.73
143	116	0	97.35	0.46	0.02	0.02	0.05	0	97.9
0	160	0.0	97.26	3.22	0	0.03	0.09	0.08	100.68
0	103	0	85.57	14.05	0	0.02	0.12	0	99.76
204	0	0	72.26	28.99	0.04	0	0.15	0	101.44
142	0	0	97.15	2.13	0.02	0	0.63	0	99.93
506	139	0	87.04	10.72	0.1	0.02	0.71	0	98.59
164	0	0	97.47	1.62	0.03	0	0.26	0	99.38
98	147	0	95.59	3.34	0.02	0.03	0.67	0	99.65

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