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**SUBSURFACE BRINE DISPOSAL IN THE SAUK SEQUENCE OF
CENTRAL AND WESTERN NEW YORK: IMPLICATIONS FOR
NEW SALT-CAVERN GAS-STORAGE RESERVOIRS**

by

MOSSBAH M. KOLKAS

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

1998

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

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ABSTRACT

SUBSURFACE BRINE DISPOSAL IN THE SAUK SEQUENCE OF CENTRAL AND WESTERN NEW YORK: IMPLICATIONS FOR NEW SALT-CAVERN GAS-STORAGE RESERVOIRS

by

Mossbah M. Kolkas

Advisor: Professor Gerald M. Friedman

Based on the regulations provided by the Department of Environmental Conservation (DEC) and the United States Federal Injecting Control (UIC), a satisfactory method of brine disposal is required for salt-cavern natural gas storage operations. In this research, selected wells from the Sauk Sequence of central and western New York have been chosen to be tested for brine-disposal sites. The study includes facies analysis, diagenesis, and petrophysical characteristics (porosity, permeability, recovery efficiency, and fluid saturation) of selected rock samples from the Sauk intervals.

The Cambro-Ordovician Sauk Sequence of central and western New York consists of a basal sandstone sheet (Potsdam Formation) overlain by a carbonate sequence (Theresa Formation). This group is subdivided into lithofacies and microlithofacies based on the lithologic heterogeneities, microstructures, and fossil contents. These lithofacies and microlithofacies were deposited within a shallow marine setting.

The diagenetic sequence of the Beekmantown Group lithologies is established based on the fabrics and the textural analysis using the petrographic microscope, the luminescope, and the electron microprobe. This sequence records: early dolomitization, silicification, chemical compaction,

dedolomitization, and finally late dolomitization. These diagenetic modifications affected the reservoir qualities (porosity, permeability, recovery efficiency, and fluid saturation) within this group.

Petrophysical analysis, using the mercury-injection technique, concluded that the petrophysical parameters, porosity, permeability, recovery efficiency, pore diameters, and fluid saturation vary among the lithofacies and microlithofacies. Supported by capillary pressure tests, the Potsdam Sandstone and some intervals within the Theresa Formation demonstrate high reservoir quality and acceptable thickness that make them excellent sites for brine disposal.

TO THE LOVING MEMORY OF MY PARENTS

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This work is dedicated to the memory of my parents for their love, encouragement and sacrifice.

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PART I

INTRODUCTION, RESEARCH OBJECTIVES, PALEOGEOGRAPHY, PREVIOUS STUDIES, AND RESEARCH METHODS

CHAPTER I: INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

An enormous amount of brine is generated during the leaching process in salt caverns designed for gas storage. Injection of brine into deep-subsurface, porous, and permeable formations may be the most environmentally acceptable method of disposal. Thus, subsurface brine disposal has become an unavoidable and expensive part of salt-cavern storage development. Careful investigation of possible disposal formations and sites is, therefore, a prerequisite for salt-cavern development.

Brine disposal in a porous subsurface formation is not a new concept. Oil-field brines have been disposed in the subsurface since the beginning of the oil industry. In New York State, oil-and gas-field operators, for example, Lenape, Envirogas, and Weaver used this method of disposal in the Medina and Queenston Sandstone (NYDEC, Data). Some salt companies in New York also use old underground salt mines to dispose their recycled waste water (DEC, 1988). Subsurface disposal of brines will have greater relevance in New York State because salt cavern gas-storage fields are being developed or proposed. Thus, identification of suitable geologic formations for brine disposal will heighten interest in New York as a location for high deliverability salt-cavern storage or even low-deliverability gas storage.

This study includes stratigraphy, facies distribution, and diagenesis of the Cambro-Ordovician Beekmantown Group to gain a better understanding of its petrophysical properties and its ability as a brine disposal site. Two cores from Niagara and Steuben Counties plus three sections of well cuttings from Steuben, Wyoming, and Cayuga Counties have been selected for this study (Fig. 1-1).

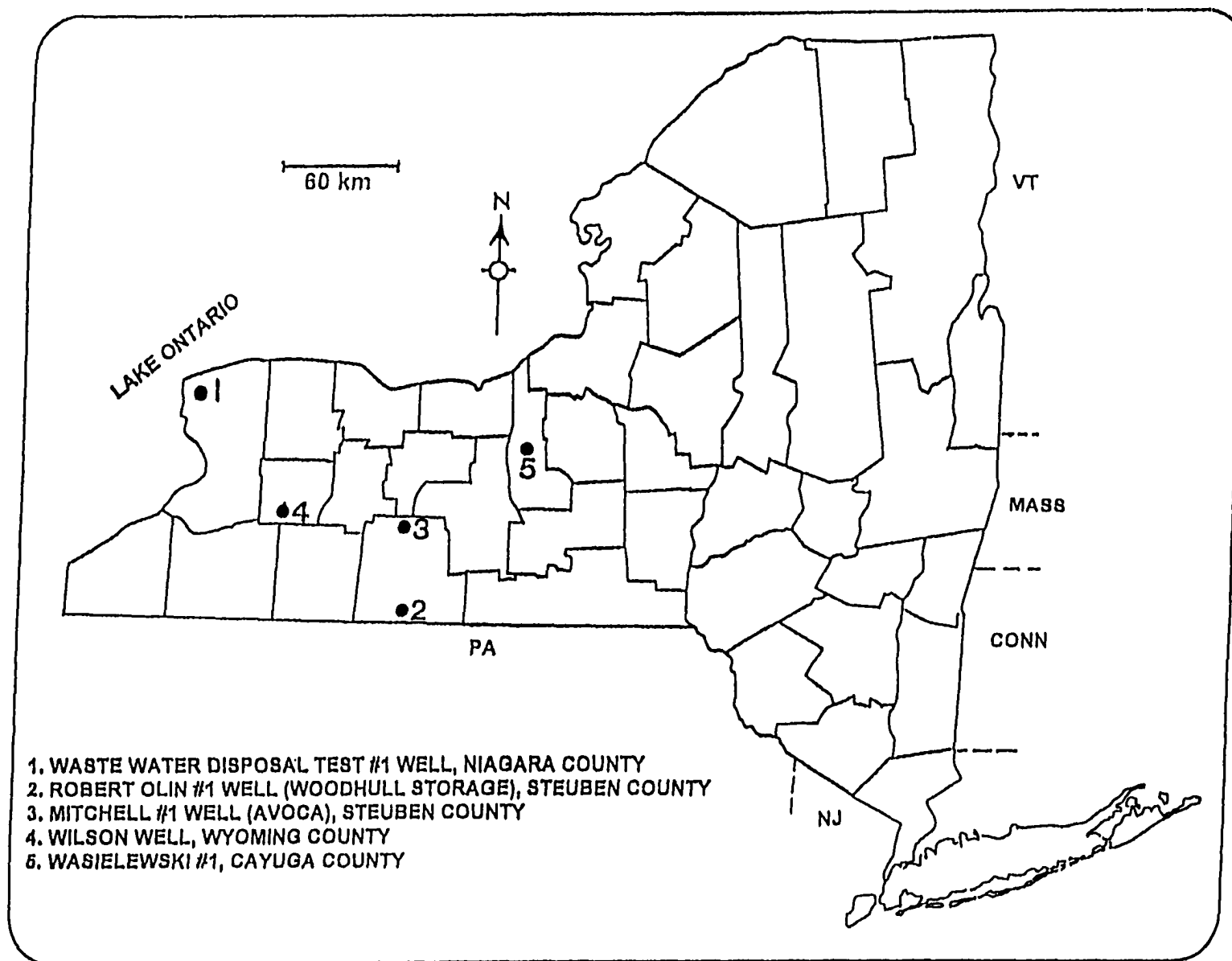


Figure 1-1: General location of the selected wells in central and western New York State.

1.2 Research Objectives

The main objective of this research project is to find zones within the subsurface Cambro-Ordovician Sauk Sequence rocks of central and western New York that could be used as brine disposal sites. The rocks of the Sauk Sequence have been chosen for brine disposal by the JMC Avoca salt cavern gas-storage project of Steuben County and were recommended for chemical waste-water disposal in Erie County (DePetro, 1968). Due to regional and inter-regional petrographic and diagenetic heterogeneity of the Sauk rocks, intensive facies analysis and petrographic studies are performed to evaluate their petrophysical characteristics (porosity, permeability, recovery efficiency, and fluid saturation).

This research provides petrographic and petrophysical information on the subsurface Sauk rocks of central and western New York. The study focuses on facies distribution, stratigraphy and diagenetic modifications that controlled the petrophysical properties of the Sauk rocks within the study area. Results of this research may be used to locate suitable reservoirs within the Sauk Sequence for gas storage or brine disposal.

CHAPTER 2: PALEOGEOGRAPHY AND REGIONAL STRATIGRAPHY

2.1 Paleogeography and Geologic Setting

During the Cambro-Ordovician period, the North American region was covered by an epeiric sea (Rodgers, 1968; Fisher, 1977; Friedman and Radke, 1979). Shallow-water carbonates were deposited in latitudes ranging from 20° N to 20° S (Fig. 2-1). Figure 2-2 shows the paleogeography of the North American Continent during the Early Ordovician time. However, the deposition of carbonates ceased in the late Early Ordovician when the Proto-Atlantic (Iapetus) ocean started to close (Fig. 2-3). This movement created a subduction zone along the eastern margin of North America (Rodgers, 1968). Because of this subduction, sea level dropped and the continental shelf was uplifted and exposed, as recorded by the inter-regional post-Sauk, pre-Tippecanoe (Knox) unconformity surface. Following this orogenic activity, the Taconic orogeny that occurred in the Middle of Late Ordovician, intensely deformed the surrounding area (Levin, 1996).

2.2 Regional Stratigraphy of the Sauk Sequence of New York

Generally, the Cambro-Ordovician strata in New York state are represented by the Sauk and Tippecanoe Sequences (Sloss, 1963). In the central and western sections of New York, the Sauk Sequence consists of the Beekmantown Group (Fig. 2-4) rests unconformably on the Precambrian basement complex and is separated from the overlying Tippecanoe Sequence by the post-Sauk, pre-Tippecanoe Unconformity. In eastern New York, the Beekmantown Group is thick and consists of the Potsdam, Theresa (Galway), Little Falls, Hoyt, and Tribes Hill Formations (Fig. 2-4). The Beekmantown Group in the west is thinner and is represented by the Potsdam and Theresa Formations (Fig. 2-4). The Little Falls Formation and other overlying Cambro-Ordovician strata were either removed by later erosion or not deposited in this area. In this research, the Potsdam and

Theresa Formations of the Beekmantown Group have been studied in detail to learn about their facies distributions, diagenesis, and petrophysical characteristics. The thicknesses of these formations are varied in the studied wells (Fig. 2-5).

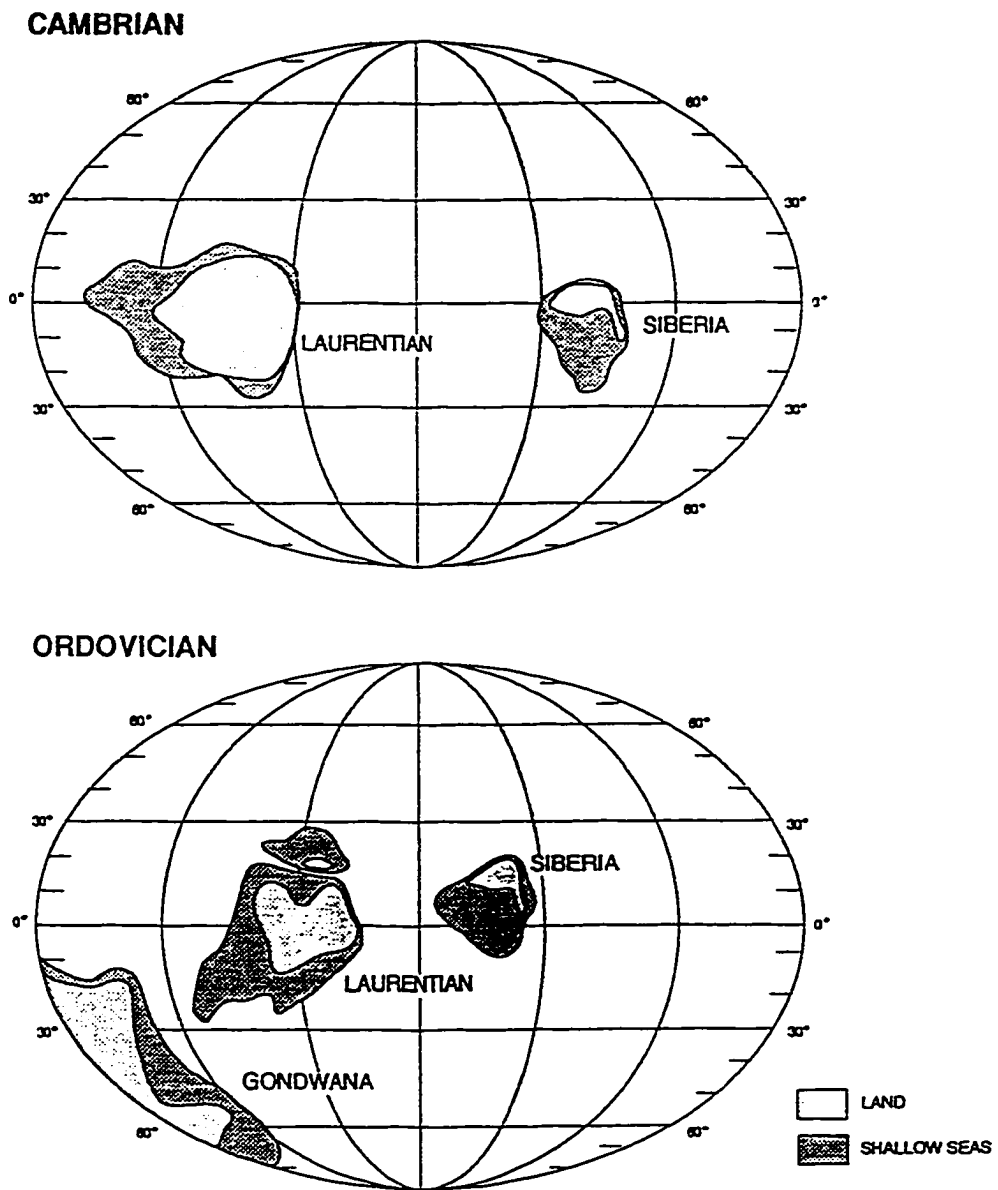


Figure 2-1: Cambrian and Ordovician paleogeographic maps showing where carbonate deposits formed in the latitudinal belts between 20° N and 20° S latitude (Scotese et al., 1979).

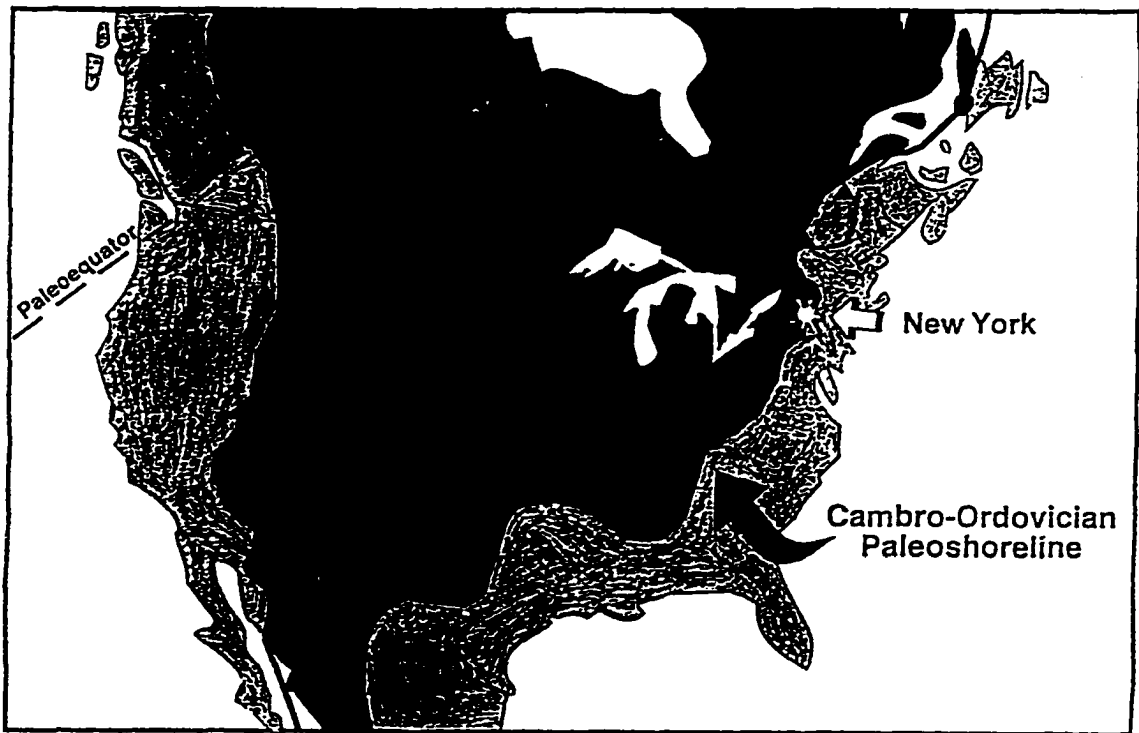


Figure 2-2 : Paleogeography of North America in the Cambro-Ordovician time showing the position of the paleoequator, the paleoshoreline, and the position of New York (modified from Dykstra and Longman, 1996).

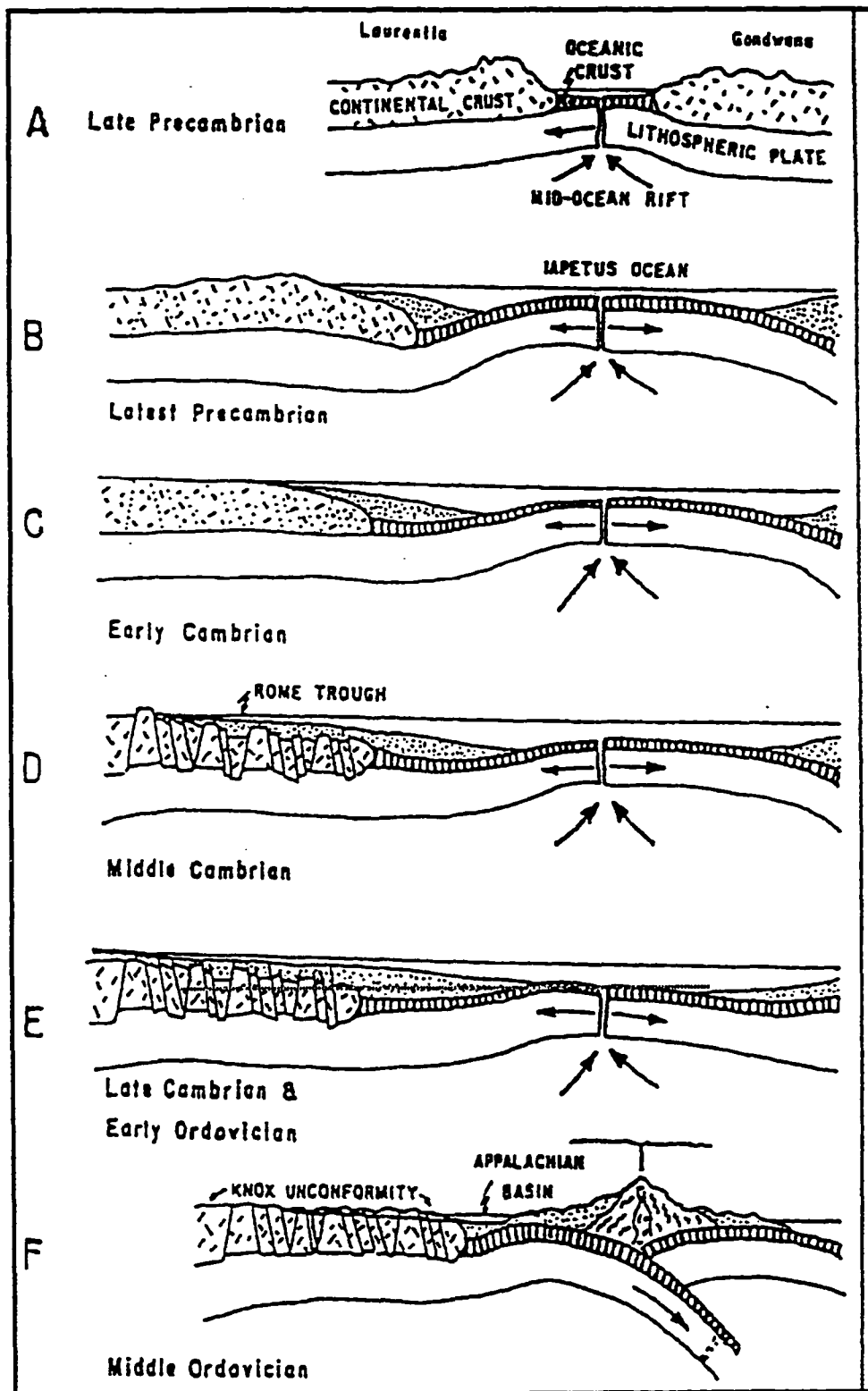


Figure 2 -3. Plate tectonic model of the study area from Late Precambrian to Middle Ordovician (Riley et al, 1993).

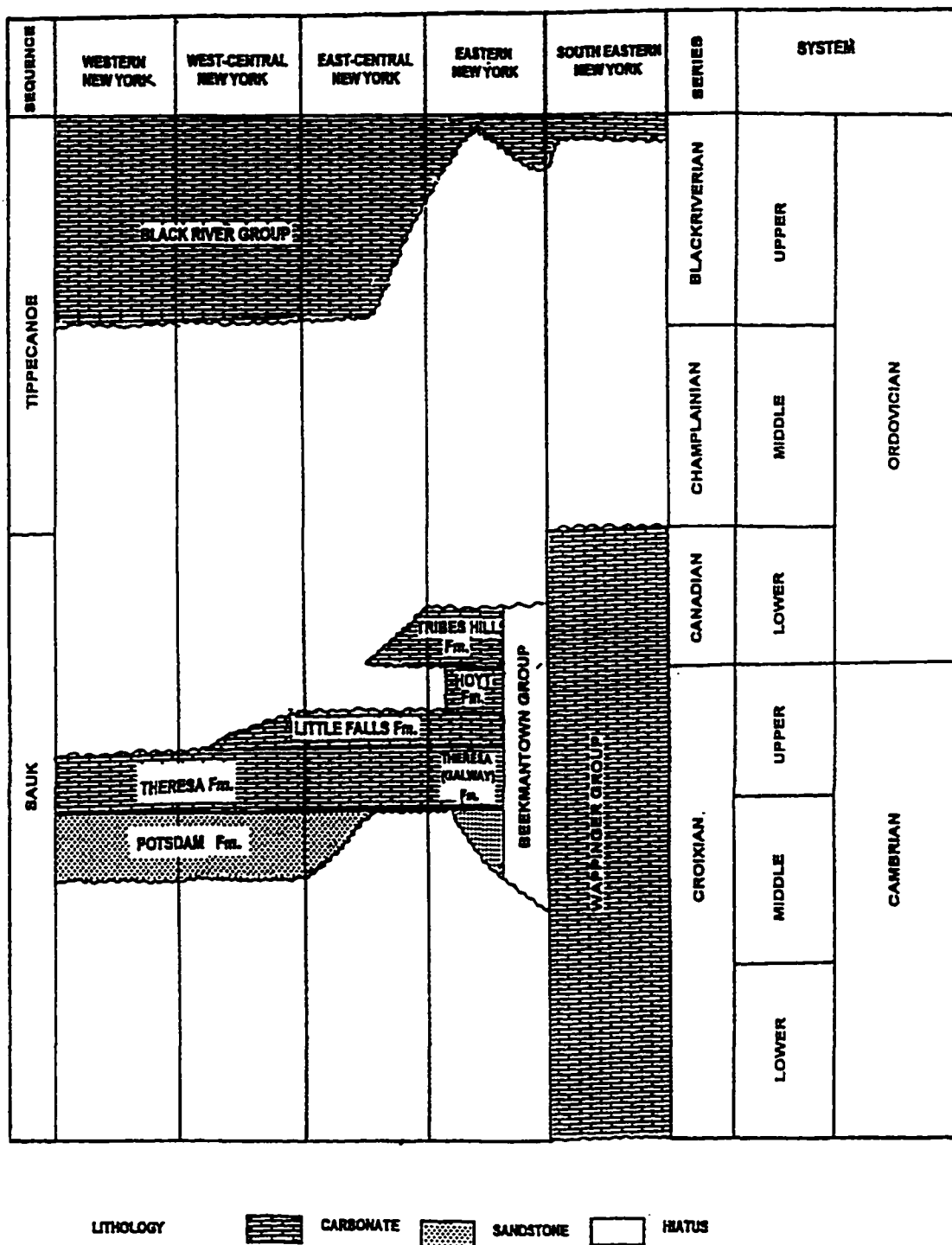


Figure 2-4. Regional stratigraphy of the Cambro-Ordovician strata of New York State (Modified from Patchen et al, 1984).

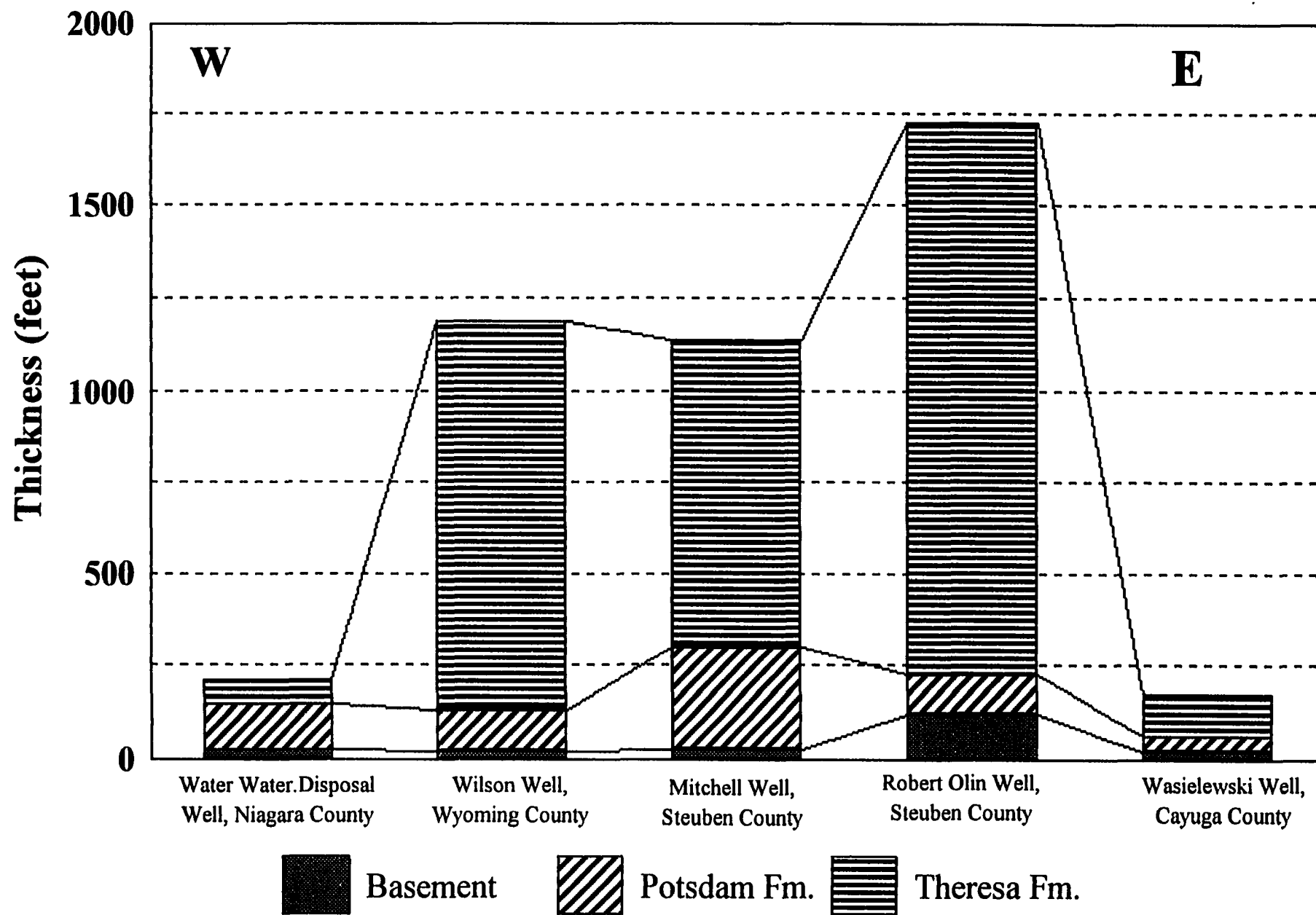


Figure 2-5. A thickness-correlation chart of the Potsdam and Theresa formations (Beekmantown Group) in the selected wells of western and central New York.

CHAPTER 3: PREVIOUS STUDIES

3.1 Facies Analysis and Diagenesis

Since the 1950's, many studies have been carried out on the Sauk intervals in New York State. These include studies of their diagenetic history, depositional environments, lithofacies distribution, and petroleum-bearing potential.

Braun and Friedman (1969) divided the Tribes Hill Formation of the Beekmantown Group of the Mohawk Valley into ten lithofacies, representing three depositional environments: subtidal, intertidal, and supratidal. Buyce and Friedman (1975) suggested that the detrital cores of authigenic feldspar in the Tribes Hill Formation came from windblown tephra from the Taconic island-arc terrane beyond the shelf margin. Fisher (1977) published a detailed correlation chart for the Beekmantown and other Cambro-Ordovician strata of New York. Rubin and Friedman (1977) described evidence of peritidal deposition in the Tribes Hill Formation. Friedman and Radke (1979) compared the Beekmantown carbonates of New York to the Lower Ordovician carbonates of the Nimaroo Formation of Queensland, Australia, and inferred remarkably similar depositional conditions. Harris and Friedman (1982) interpreted the Lower Ordovician Ogdensburg Formation of the St. Lawrence Valley to be a shallow-water peritidal deposit. Curl et al. (1984) subdivided the subsurface Tribes Hill Formation (Lower Ordovician) of the Mohawk Valley, New York, into eleven lithofacies representing different depositional environments. Guo et al. (1990, 1991, 1992) published studies on microlithofacies, petrophysical characteristics, and petroleum prospects in lower Paleozoic platform strata beneath the Taconic Allochthon in Washington County, Eastern New York. They concluded that porosity and oil migration are controlled by depth of burial of the Paleozoic strata and stated that the general geologic requirements for forming subtle hydrocarbon traps have

been fulfilled. Chuanmao et al (1992) studied the rocks of the Wappinger Group of the Sauk sequence in Dutchess County, New York. They reported that the dolostone facies was characterized, for the most part, by low porosities (1% for example), but some brecciated samples showed porosities of up to 6%. Friedman (1994a) subdivided a core section from the Dunham Formation (Cambro-Ordovician) of Vermont into a set of three parasequences. Each parasequence shows a coarsening upward that was followed by an abrupt change into finer grain sizes. He suggested that the abrupt change in grain size across the non-depositional or erosional surface coincides with a marine flooding surface. Friedman (1994b) reported that the stacking patterns of the cyclic parasequences in Cambro-Ordovician carbonates of eastern New York and western Vermont could be due to rapid sea-level changes and anomalous storm periods. Friedman (1995) concluded that the Cambro-Lower Ordovician (Sauk) carbonate cyclic stacking patterns of the Appalachian passive (Gondwana) margin consist of fifth-order epeiric platform cycles (~1 to 5m thick, 50 -100 ky duration). He suggested that these Sauk fifth-order epeiric platform cycles may have resulted of extraterrestrial forcing or tectonic events that involved rapid changes in relative sea-level. Friedman et al. (1996) reported the results of a two-year research project to determine the suitability of different geologic formations for gas storage in New York state. They recognized two types of gas-storage reservoirs: 1) low-deliverability depleted gas fields and 2) high-deliverability salt caverns. They recommended that additional field investigation and full analysis of each geologic formation could provide valuable petrophysical data on the detailed internal heterogeneities of the targeted formations.

3.2 Previous Petrophysical Studies

Petrophysical characteristics (porosity, permeability, recovery efficiency, and fluid saturation) of oil and gas-producing carbonate facies throughout the geologic column have been studied by many geologists. Washburn (1921) was the first to suggest using mercury injection as a laboratory technique to determine the pore size distribution in porous rocks. He formulated an equation for this purpose which can be expressed as:

$P_c = -2\gamma \cos \theta / r$ where P_c = capillary pressure (dynes/cm²), γ = surface tension of Hg (480 dynes/cm), θ = contact angle of mercury in air (140°), and r = radius of pore aperture for cylindrical pore. Wardlaw (1976) described the general geometry of pores and pore connections or throats in selected samples of dolostones. He concluded that as dolomite crystals grow and porosity is reduced, polyhedral pores are transformed to tetrahedral pores and finally to interboundary-sheet pores. As a result, pore structure becomes geometrically simpler and more regular and pore-size to throat-size ratios increase. Wardlaw and Taylor (1976) interpreted the pore structure and capillary behavior in reservoir rocks based on the mercury capillary pressure curves. Wardlaw and Cassan (1978) estimated the recovery efficiencies in various reservoir rocks by visual observation of pore systems. They summarized that samples of high porosity with pores and throats of relatively uniform size and low pore-to-throat size ratio have high recovery efficiencies. Also, they stated that the addition of large pore-to-throat size ratios decrease recovery efficiencies. Wardlaw, McKellar, and Yu (1988) used mercury porosimetry to examine pores and throat-size distributions of various carbonate samples from different locations. By comparing the results with those obtained from direct observation of pore spaces at high magnification, they concluded that porosimetry indicates volume and size of pore-throats, but high magnifications may provide information about geometrical patterns

of pore shapes. Ghosh and Friedman (1989) studied the petrophysics of a dolostone reservoir in the San Andres Formation (Permian) of west Texas. They classified the San Andres carbonates into five groups based on their petrophysical properties. Friedman, Ghosh, and Urschel (1990) studied the petrophysical characteristics related to depositional environments and diagenetic overprint of the San Andres Formation, Mabee field, west Texas. They concluded that the porosity in the ooid grainstone facies is generally well developed, at approximately 15%. However, this porosity has been reduced or occluded by late diagenetic anhydrite cement. Also, they noticed three types of porosity: moldic, interparticle, and intercrystalline. Kopaska-Merkel and Friedman (1989) subdivided the partially dolomitized Hunton Group of Oklahoma and Texas (Lower Paleozoic) into five petrofacies and four subpetrofacies based on their recovery efficiencies, effective porosities, median pore throat sizes, and shape of capillary-pressure curves. Also, they reported that these petrofacies and subpetrofacies can be used to predict the distribution of oil and gas reservoirs, seal units, and to pinpoint potential stratigraphic traps. Melas and Friedman (1992) classified the Smackover carbonates (Jurassic) in the Conecuh embayment, Alabama and Florida into reservoir and non-reservoir petrofacies based on capillary-pressure curves.

Amthor, Mountjoy and Machel (1994) studied the regional-scale porosity and permeability variations in Leduc Buildups (Upper Devonian) of the Rimbey-Meadowbrook reef, central Alberta, Canada. They stated that the dolomitization during shallow burial (600-120m) has changed the petrophysical properties of Leduc Formation carbonates. These changes include a decrease in porosity and a minor increase in permeability.

Lucia (1995) used the relationship between carbonate rock-fabrics and petrophysical properties to establish a general classification of pore spaces in carbonate reservoirs. He recognized

two types of pores: interparticle porosity and vuggy porosity (separate vugs and touching vugs).

Luo and Machel (1995) examined pore sizes and pore-throat types in a heterogeneous dolostone reservoir of the Devonian Grosmont Formation, western Canada. Based on their observations, they classified the pore types into four sizes: microporosity (pore diameters $< 1\text{ }\mu\text{m}$), mesoporosity (pore diameters $1 - 1000\text{ }\mu\text{m}$), macroporosity (pore diameters $1 - 256\text{ mm}$), and megaporosity (pore diameters $> 256\text{ mm}$).

Woody, Gregg, and Koederitz (1996) concluded that the petrophysical properties of the dolomite petroleum reservoirs and aquifers vary depending on the petrographic texture of the dolomite crystals. Also, they reported that diagenetic modifications can be used as a predictor of petrophysical properties of dolomite reservoirs.

CHAPTER 4: MATERIALS AND RESEARCH METHODS

4.1 Availability of Materials and Data

The New York State Geological Survey (NYSGS) well data-base indicates that approximately 200 wells have been drilled through the Cambro-Ordovician Sauk Sequence of New York State. Approximately, 150 geophysical well logs are available from these drilled wells. Also, the NYSGS data base indicates the availability of 20 sections of well cuttings and three cores in western New York. Two of these cores, one from the Waste Water Disposal Test Well #1 of Niagara County and the other from Robert Olin #1 of Steuben County, plus three sections of well-cuttings from Steuben, Wyoming, and Cayuga Counties (Fig. 1-1) have been borrowed from the NYSGS. The available materials were studied at the Northeastern Science Foundation (NeSF), Rensselaer Polytechnic Institute, Troy, New York, and Brooklyn College of the City University of New York.

4.2 Methods and Laboratory Procedures

Petrographic studies were performed on a total of 189 thin sections (including cores and well-cutting samples) from selected wells of central and western New York State (Fig. 1-1). The examination was performed by using a hand lens, Spencer binocular microscope (15 X) and Projection Macroscope. Staining methods were applied to distinguish carbonate minerals (Friedman, 1959; Dickson, 1965). A Leitz Wetzlar Ortholux Microscope equipped with a Leitz Orthomat automatic camera system for high resolution photography was used to determine the mineral composition, textures, microstructures, and diagenetic relationships of the selected thin sections. A total of 88 thin sections were uncovered and polished for petrographic study using the Nuclide luminescope at the Northeastern Science Foundation in Troy, New York. Following the luminescence study, these thin sections were carbon coated and analyzed using a fully automated

Jeol 733 electron microprobe at the Rensselaer Polytechnic Institute in Troy, New York. Based on the color contrast and appearance of different petrographic textures under the luminoscope, a probe traverse was selected on each one of these thin sections. Each point on this traverse represents a distinctive chemical composition of various amount of trace-element concentrations (see Appendix B for complete probe analysis).

Micrometrics Pore Sizer 9305 was used to determine the petrophysical properties of selected well cutting and core plugs at Northeastern Science Foundation, Troy, New York.

Detailed explanation of the applied methods and techniques that used in this research are as follows:

4.2.1 Carbonate staining method (Friedman, 1959; and Dickson, 1965)

Each Step should be performed in the given order until a definite identification is made.

1. Etch the uncovered thin section with 1.5% HCL for 10 to 15 seconds. Both calcite and ferroan calcite show considerable etch. Dolomite and ferroan dolomite show negligible etch.
2. Stain with 0.2g Alizarin red S dissolved in 100 cc of 1.5% HCl (ARS) + 2.0 g potassium ferricyanide dissolved in 100 cc 1.5 HCl acid (PF), mixed in the ration ARS : PF = 3:2, for 30 to 45 seconds. Calcite will show a very pale pink to red. The calcite surface parallel to the c-axis is more deeply stained than a basal section. This feature assists petrofabric analysis. Basal sections will stain in pale pink color. Ferroan calcite show very pale pinkish red to dark blue. The two superimposed produce mauve-purple to royal blue. Dolomite takes no stains. Ferroan dolomite becomes deep turquoise, depending on the ferrous iron content.
3. Stain with ARS solution (prepared as in step 2) for 10 to 15 seconds. Calcite and Ferroan calcite become very pale pink. Dolomite and Ferroan dolomite take on no color.

Distilled water must be used in making up all solutions and for washing surplus stains from the thin sections. Step 1 removes all grinding dusts. The etch section is then immersed in an acidified mixture of two stains (Step 2). Each stain works independently and there is no mutual interference. If the partly stained section is immersed in an acidified solution of Alizerine red S for a few seconds, the color differentiation of the carbonate will be increased, but it is important not to exceed 15 seconds of staining (Step 3). Then rapidly and carefully clean with distilled water and dry quickly because the stain is water soluble. The stained surface should not be touched because it is easily rubbed off. To protect the surface, a layer of diluted durofix is painted on with a camel hairbrush.

4.2.2 Cathodoluminescence technique in carbonate rocks

Of the total thin sections, 88 were uncovered and polished for petrographic study using the Nuclide Luminoscope, Model ELM-2 at Northeastern Science Foundation, Troy, New York. This method provides a qualitative analysis of the mineral composition and crystal-to-crystal relationship within the thin section. In this study, the purpose of using the Cathodoluminescence technique is to determine the diagenetic sequence including cement stratigraphy, compositional zonation due to various mineral concentration in carbonate crystals, feldspar, and quartz particles.

Theory:

Generally, the cathodoluminescence properties of carbonate minerals are governed by physical phenomena that are common to all oxygen-dominated crystalline substances. These minerals display luminescence when excited with an electron beam. This beam has a maximum energy of 25 kV and a maximum current of 1 mA. An electron beam of this energy can generate x-rays from the targeted area. The excitation and luminescence processes involve electronic transitions between energy levels of atoms or ions (Machel et al, 1991). This transitional movement of

electrons resulted in a visible radiation that produced by certain materials under electron bombardment (Fig. 4-1). The generated-cathodoluminescence colors of carbonate minerals are controlled by trace-element (impurities) distribution and concentration within their crystals' lattice. These trace elements can be divided into three groups: 1) Activators; 2) Sensitizers; and 3) Quenchers.

1) Activators:

Mn^{+2} is the most important activator in calcite and dolomite minerals. The Mn^{+2} content in carbonate minerals is positively correlated to observed or measured luminescence intensities (Machel, 1991). Luminescence from transition elements, such as Mn^{+2} or Cr^{+2} , is due to energy transitions of electrons that occupy orbitals in the outer, partially filled 3d shell. Under the electron beam, Mn^{+2} is orange red or orange yellow in color and its emission spectrum shows a characteristic broad band centered at approximately 570 - 600 nm in case of calcite-emission spectrum (Fig. 4-2) and 600 - 650 nm in case of dolomite-emission spectrum (Fig. 4-3).

2) Sensitizers:

Sensitizer elements act as a catalyst in chemical reactions. Some activator elements may be excited in the presence of the sensitizer if it absorbs incident radiation. Pb^{+2} , Ti^{+3} , and Ce^{+3} are common sensitizer elements of Mn^{+2} -activated cathodoluminescence. However, carbonate minerals have enough impurities of Mn^{+2} , as a result, the presence of the sensitizers are not necessary.

3) Quenchers:

Quenchers are those element that trap a part of the energy originally absorbed by activators. This process leads to decrease the extinction of the luminescence intensity. Fe^{+2} is the most important quencher element in carbonate minerals. The higher the Fe^{+2} content the darker the

Figure 4-1. The process of excitation (absorption) and emission (luminescence) in a hypothetical substance having the electronic energy levels shown (energy increasing from E-0 to E-4, not to scale). At low temperature and in the absence of any exciting mechanism, only level E-0 is occupied. Excitation lifts an electron from E-0 to E-1, or to E-2, or to E-3, or to E-4, depending on excitation energy. The excited electron cascades from E-4, E-3, or E-2 to E-1 non-radiatively. The band gap between E-1 and E-0 is larger than the “critical” level, and the electron drops to the ground state via emission of a photon (luminescence). AB shows the absorption spectrum, EM shows the emission spectrum (not to scale). Only the spin-allowed transition has a high absorption energy (E-0 - E-1).

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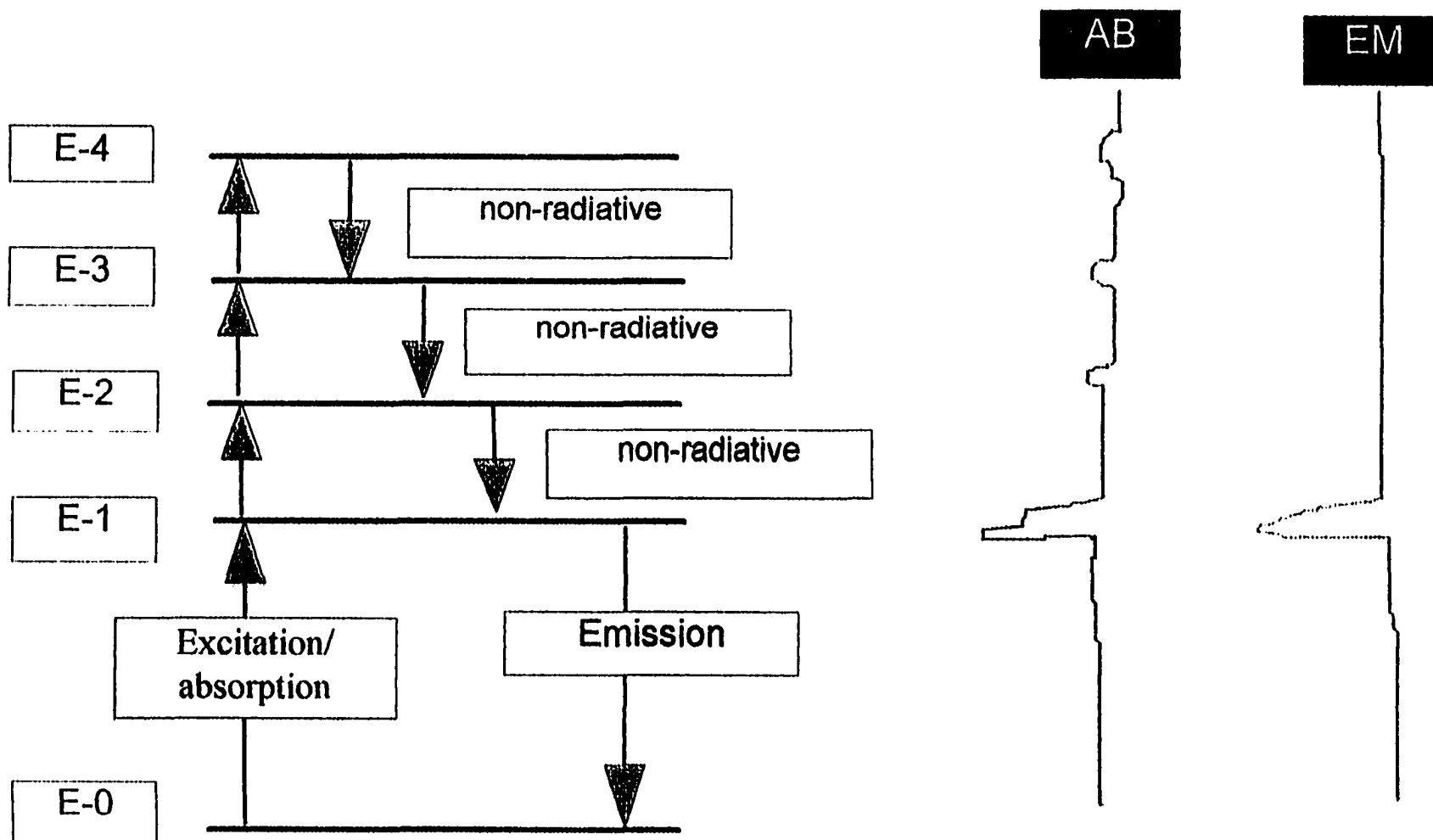


Figure 4-1. A diagram showing emission and absorption of lights due to the transitional movement of electrons within the energy levels (modified from Machel, 1991).

Fig. 4-2. Calcite-Emission Spectrum

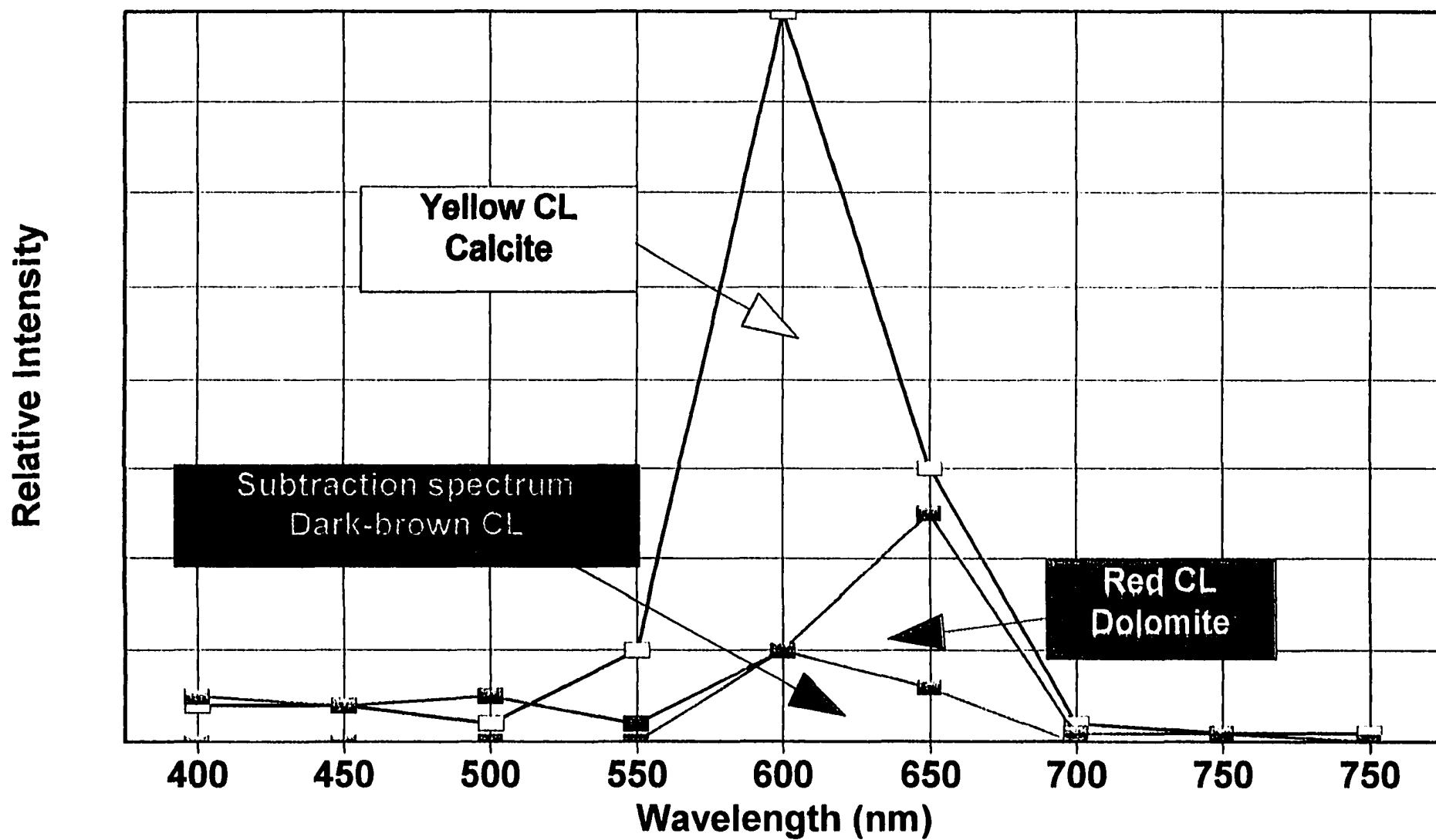
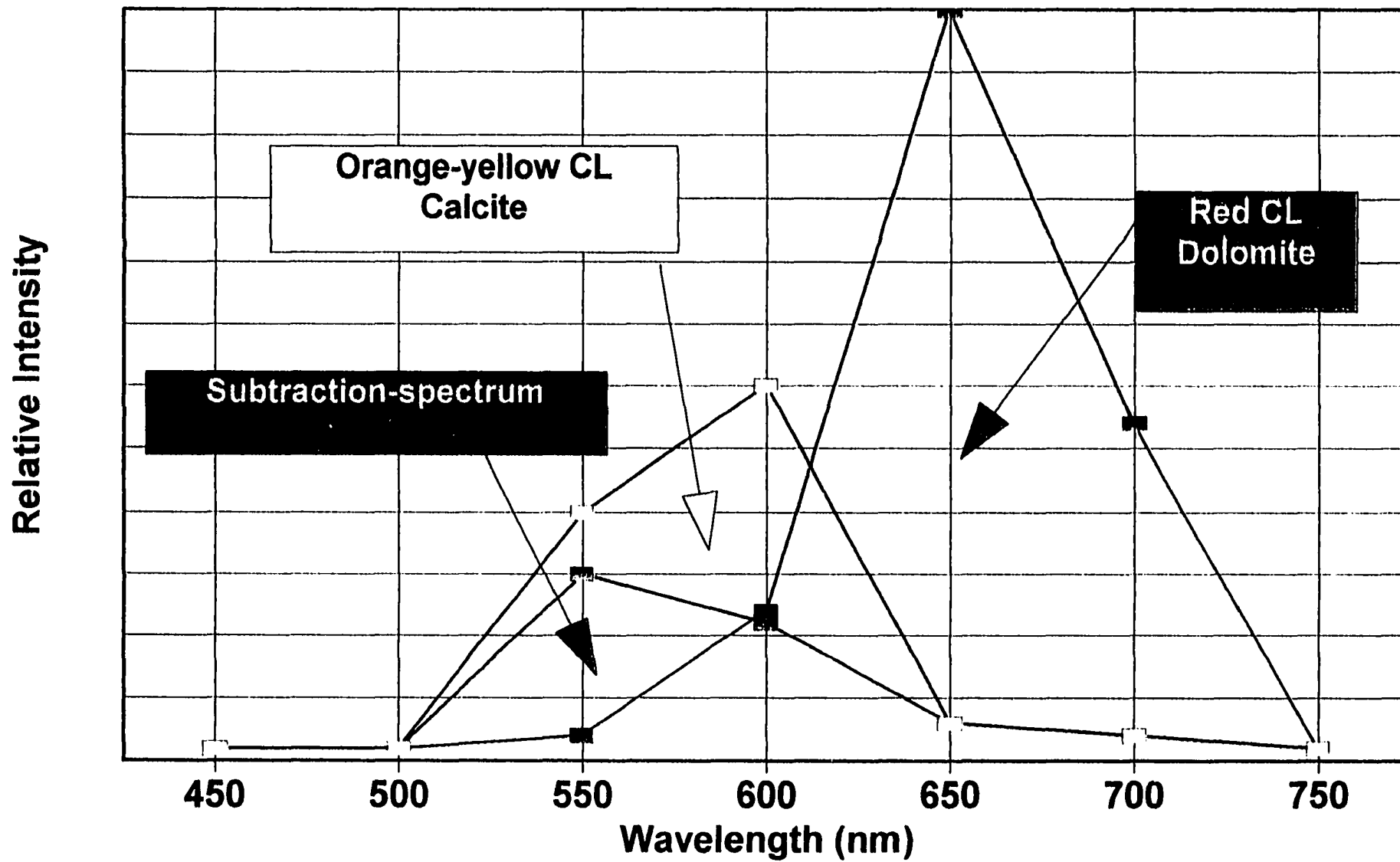


Fig. 4-3. Dolomite-Emission Spectrum



luminescence color. Based on these observations, we can distinguish the Fe^{+2} -rich and Mn^{+2} -rich layers in zoned calcite or dolomite. Table 1 shows the luminescence of the important minerals in carbonate rocks.

Table 4-1. Luminescence of the important minerals in carbonate rocks

MINERAL	LUMINESCENCE
Dolomite	Red
Ferroan Dolomite	Dull red to almost non-luminescent
Calcite	Yellow to orange
Ferroan Calcite	Dull orange
Detrital Feldspar	Bright blue
Authigenic Feldspar	Non-luminescent
Detrital Quartz	Very dull blue to non-luminescent *
Authigenic Quartz	Non-luminescent
Zircon	Very bright Yellow

* Dull-blue luminescence occurred only under a very intense beam.

4.2.3 Scanning Electron Microscope and Electron Microprobe Analyses

Following the luminescence study, same thin section were carbon coated and qualitatively analyzed using a fully automated Jeol-JSM-840 scanning electron microscope and Joel 733 electron microprobe at the Rensselaer Polytechnic Institute located in Troy, New York. The operating condition of these to machines was as follows: 15 Kv accelerating voltage, 15 na beam current, 10 microns beam diameter, and X-ray maximum counting times of 60 seconds.

Theory:

The operating theory of the scanning electron microscope and the electron microprobe are very similar. The scanning electron microscope is designed primarily for imaging and the electron microprobe is constructed to perform a chemical analysis on small selected areas or points of solid samples such as rock-thin sections. The operating theory of these equipments is based on excitation of the X-rays by a focussed electron beam. The generated X-rays spectrum contains lines which are characteristic of the elements present in the analyzed sample. Consequently, a qualitative analysis is easy to obtain by identifying the lines from their wavelengths (Photon energies). By comparing the intensities of these lines with those emitted from standards (pure elements or compounds of known composition) it is also possible to determine the concentrations of the elements in form of quantitative analysis (Reed, 1996). The scanning electron microscope is a useful tool to provide images of three-dimensional objects because it records the secondary electrons that released from the sample by electron beam impinging. Therefore, the scanning electron microscope is capable of a wide range of magnifications that overlaps the range of the light microscope or hand lens at low magnification and the transmission electron microscope at high magnification. On one hand, The light microscope has a maximum resolution between 2,000 - 3,000 angstroms. This magnification can not separate two close points within the thin section. The maximum effective magnification of the light microscope is about 1, 000 diameters. On the other hand, The best transmission electron microscopes have a resolution between 2 - 5 angstroms that gives a magnification exceeds a million diameters. Fortunately, the scanning electron microscope is useful over a magnification range from 15 - 100,000 diameters. When the primary electron beam interacts with the specimen, electrons and other radiations are produced which can be used to form images and to analyze chemically the

microstructure elements.

4.2.4 Mercury Porosimetry and Petrophysical Analysis

Petrophysical analysis of selected core plugs and well cuttings were performed using a Micrometrics Pore Sizer. The purpose of this analysis is to calculate and evaluate the petrophysical parameters (porosity, permeability, recovery efficiency, and fluid saturation). The results of this analysis help in distinguishing the best candidate-geologic intervals that are suitable for gas storage or brine disposal within the Cambro-Ordovician Beekmantown Group in central and western New York. In order to insure the accuracy of this test, two sets of ninety two standard cylindrical core plugs of 12 mm in diameter and approximately 10 mm in height were made from the two-core sections of the Waste Water Disposal #1 Well, Niagara County (39 samples) and Robert Olin #1 Well, Steuben County (53 samples). Also, two sets of sixty two assemblies of well-cutting chips were selected from Mitchell #1 Well (Avoca), Steuben County (29 samples), Wilson Well, Wyoming County (19 samples), and Wasielewski #1 Well, Cayuga County (14 samples). The core plugs and the well-cutting chips were soaked in a 50/50 solution of toluene and acetone for 48 hours, followed by 24 hours in pure acetone to ensure that they were clean. These samples were dried out using a 60°C oven. The core plugs were analyzed for capillary-pressure test by using the Mercury Micrometrics Pore Sizer 9305, equipped with two low-pressure ports and a high-pressure one. Using this pore sizer, a pore throat up to 0.003 microns can be measured. In this experiment, Mercury is used as a testing capillary-pressure fluid because the cohesive forces between the mercury molecules are stronger than the adhesive forces between them and the solid sample (i. e. mercury is non-wetting liquid). Samples were sealed into a penetrometer, evacuated, filled with mercury, then pressure was increased incrementally, and finally the pore throat diameters were

measured at each increment by using this equation $D = - (1/p) 4\gamma \cos \theta$. where D is the diameter, p is the applied pressure, γ is the surface tension (480 dynes/cm for mercury) and θ is the contact angel (130° for mercury).

Theory:

Mercury porosimetry is based on the capillary law governing liquid penetration into small pores. This law, in the case of a non-wetting liquid like mercury and cylindrical pores, is expressed by:

$$D = - (1/P) 4\gamma \cos \theta \quad (1)$$

where D is the pore diameter, P is the applied pressure, γ is the surface tension, and θ is the contact angle (all in consistent units). The volume of mercury (V) penetrating the pores is measure directly as a function of applied pressure. This diameter minus volume information (D - V) serves as a unique characterization of pore structures. Actually, pores are rarely cylindrical, hence equation 1 constitutes a special model. Such a model may not be the best to represent pores in actual rock samples. However, using of this equation is generally accepted as the practical means for pore diameter calculation, otherwise, finding an equation for irregular pore diameter would be the most complex problem to be experienced. The surface tension of mercury varies with purity. The accepted value is 484 dynes/cm. The contact angle between mercury and the solid containing the pores varies with respect to the solid composition. A value of 130 degrees is recommended in the absence of specific information to the contrary. Mercury extruding from pores upon reduction of pressure is in general accord with equation 1, but indicated pore diameters are always offset toward larger diameters. This results from equivalent volumes of mercury extruding at pressures lower than those at which the pores were intruded. It is also commonly observed that actual pores always trap

mercury. The first phenomenon is usually attributed to receding contact angles being less than advancing ones. The second is likely due to pore irregularities giving rise to enlarged chambers and “ink-well” structures. The results give rise to hysteresis phenomena , i. e. distinct intrusion and extrusion pressure - volume (P - V) curves. The pore surface area is calculated from the PV (pressure-volume) work that expended in forcing mercury into the pores. The work dW required to immerse an area dA of pore wall is expressed by:

$$dw = \gamma \cos \theta dA = - PdV \quad (2)$$

The total pore area is then

$$A = \frac{-1}{\gamma \cos \theta} \int_{V \min}^{V \max} p dV \quad (3)$$

where Vmax. and Vmin. correspond, respectively, to the volume of mercury when pores of maximum size were first penetrated and pores of minimum size were filled.

PART II

FACIES ANALYSIS

CHAPTER 5: FACIES DISTRIBUTION AND DEPOSITIONAL ENVIRONMENTS OF THE BEEKMANTOWN GROUP (SAUK SEQUENCE) OF CENTRAL AND WESTERN NEW YORK

5.1 Facies Analysis and Depositional Environment

Sedimentary-facies analysis is used to differentiate parts of the historical geologic record. It refers to the combined products of past conditions, processes, and events as recorded over the earth's surface to represent some fraction of geological history (Moore, 1957). The facies patterns of different geologic formations exhibit a diversity of compositional and textural variations that aid in deciphering the paleo-depositional environments and the related diagenetic history.

The Cambro-Ordovician Beekmantown Group (Sauk Sequence) of central and western New York is divided into lithofacies and microlithofacies. These lithofacies and microlithofacies consist of a basal sand sheet covered by a carbonate sequence that was deposited within a tidally influenced shallow-marine environment (epeiric sea). The lithologies of this carbonate sequence are dominated by dolostone and sandy dolostone. In places, this sequence of lithologies is interrupted by deposits of detrital quartz particles that derived from the nearby clastic source of the highly-elevated Canadian Shield.

Petrographic analyses of two cores collected from the Waste Water Disposal #1 Well, Niagara County, and the Robert Olin #1 Well, Steuben County plus three sections of well cuttings from the Mitchell #1 Well of Steuben County, the Wilson Well of Wyoming County, and the Wasielewski #1 Well of Cayuga County, New York, indicate that the Beekmantown Group (Sauk Sequence) in this region consists of a basal Potsdam and the overlying Theresa Formations. The Potsdam Formation consists of a coarse-grained, poorly-sorted quartzose sandstone at the bottom

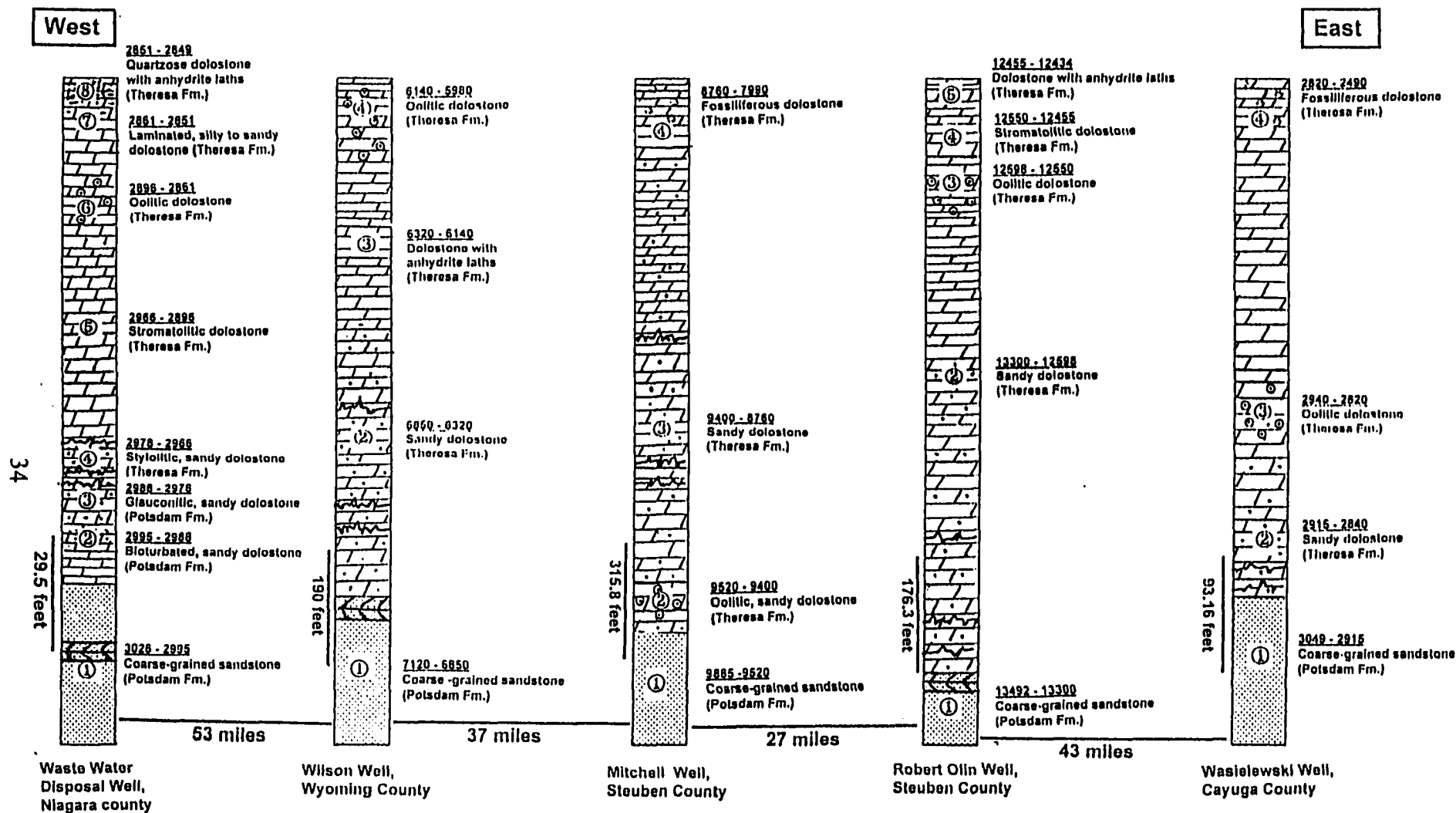
and a medium to fine-grained calcitic, quartzose sandstone at the top. The Theresa Formation is represented by sandy dolostone that grades upward into a medium to fine-grained dolostone.

In well-cutting sections, the micro-sedimentary structures and contact relationships between different rock types are usually missing. Therefore, information derived from cores is more complete than that derived from well cuttings. In this study, the lithologic information obtained from core sections has been defined as “Lithofacies” and the lithologic information derived from well cuttings has been defined as “Microlithofacies” (Guo, Sanders, and Friedman, 1990; Kolkas and Friedman, 1993).

Figure 5-1 shows that the two core sections of the Beekmantown Group (Cambro-Ordovician) in Waste Disposal #1 Well and Robert Olin Well have been divided into eight and five lithofacies respectively, whereas the well-cutting sections of the same group in Wilson #1 Well, Wasielewski #1 Well, and Mitchell #1 Well have each been divided into four microlithofacies.

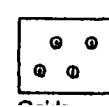
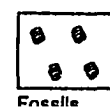
Petrographic investigation indicates that the core section of the Waste Water Disposal #1 Well of Niagara County, New York has the most varieties of lithofacies (Fig. 5-1). As a result, to avoid repetition of information and interpretation, the lithofacies of this core section have been described and interpreted in detail and are used as a model for the other wells. However, the “fossiliferous dolostone” microlithofacies appears in only two wells, Wasielewski #1 of Cayuga County and Mitchell #1 of Steuben County (Fig. 5-1), thus it will be described and interpreted separately.

Figure 5-1: A vertical sequence of the different lithofacies and microlithofacies of the Beekmantown Group (Cambro-Ordovician) in selected wells of western and central New York. Note, the lithologies of a core section in the Waste Water Disposal Well of Niagara County have been divided into eight lithofacies. The lithologies of well-cutting sections in Wilson Well of Wyoming County, Mitchell Well of Steuben County, and Wasielewski Well of Cayuga County have each been divided into four microlithofacies. The lithologies of a core section in Robert Olin Well of Steuben County have been divided into five lithofacies.



LITHOLOGY

STRUCTURES/PARTICLES



5.2 Lithofacies of the Beekmantown Group in Waste Water Disposal #1 Well, Niagara County, New York

5.2.1 Lithofacies 1: Coarse-grained sandstone (Potsdam Formation)

Description: This lithofacies occurs at the base of the Beekmantown Group. It consists of 90% - 95%, gray to yellowish gray, coarse to medium-grained, rounded to subrounded, poorly sorted (bimodal texture) quartz grains (Fig. 5-2). The other 5% - 8% is comprised of feldspar particles. There are calcite cements throughout this lithofacies. The lower section of the core has sets of micro-cross laminae, 2 to 4 inches thick. These cross-laminae sets are separated by horizontally laminated silty sandstone. The upper part of this lithofacies consists of well-sorted, medium-grained quartz sand with sutured-boundary contacts between the quartz grains (Fig. 5-3).

Interpretation: The abundant amount of the bimodal, detrital quartz particles strongly suggests this lithofacies was deposited in a nearby clastic source area. The cross-laminae and the variability of the grain sizes represent a rapid deposition during high-energy events. The presence of horizontally-laminated silty sandstone between the cross-stratified sandstone suggests this lithofacies was deposited by an unidirectional and/or oscillatory current in the transitional flow to upper flow regimes (Allen, 1970). The lack of the cross-laminae and uniformity of the sand sizes, in the upper section of this lithofacies mean the current's energy has decreased and low-energy conditions prevailed. The sutured-boundary contacts between the quartz particles could be indicative that they were derived from a metamorphic source (Friedman et al, 1992). The presence of the cross-stratified sandstone strongly suggest that lithofacies was deposited within the high energy intertidal setting.

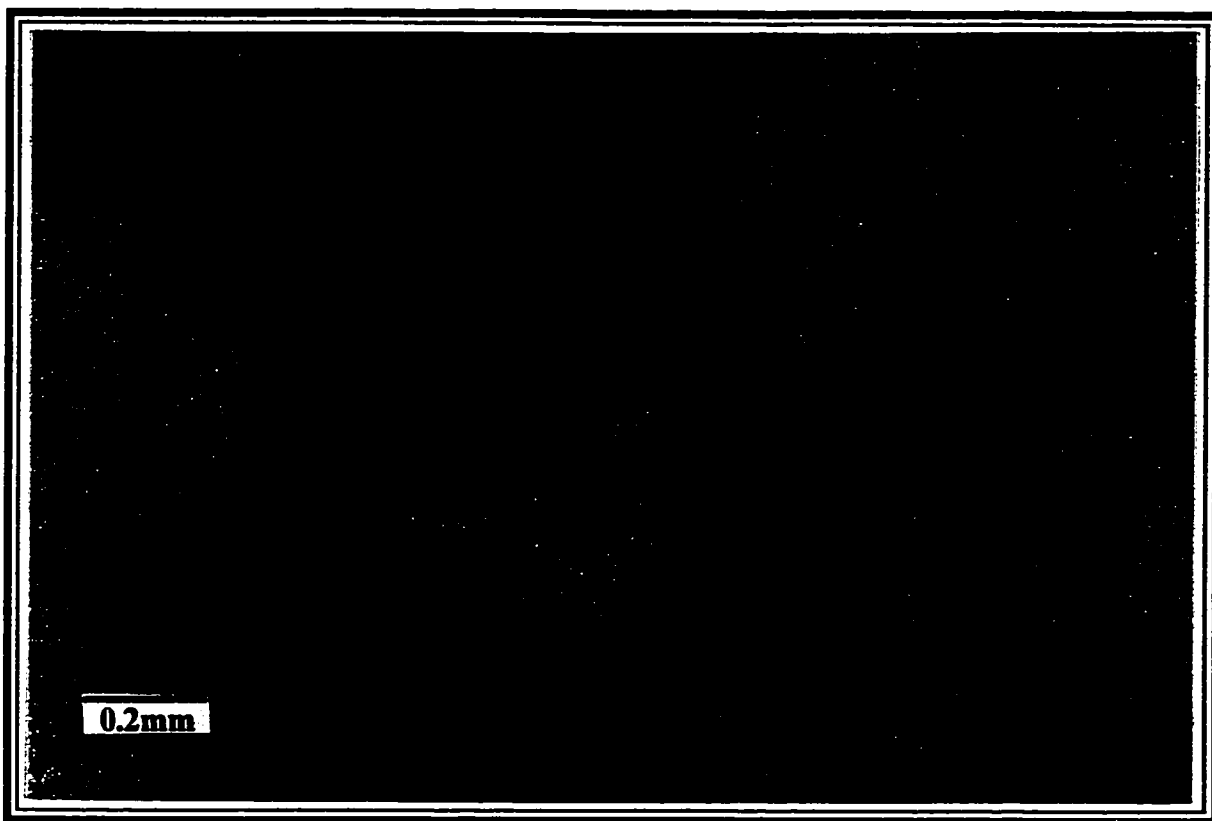


Figure 5-2. Lithofacies 1-Coarse-grained sandstone. Photomicrograph of a thin section under crossed nicols, showing rounded to subrounded, bimodal quartz grains. Note the sutured-boundary contacts between the quartz grains (arrow).

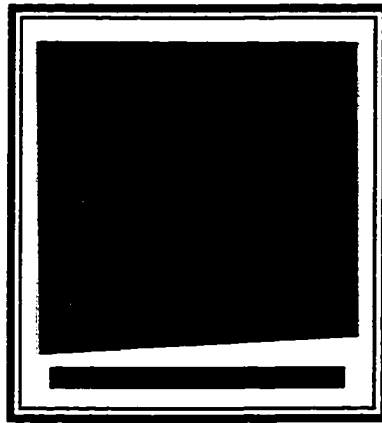


Figure 5-3. Lithofacies 1-Coarse-grained sandstone. Photograph of a core section showing two sets of cross-laminae that are separated by horizontally laminated silty sandstone. Bar scale equals 2".

5.2.2 Lithofacies 2: Bioturbated, sandy dolostone (Potsdam Formation)

Description: This lithofacies consists of a light colored, fine to medium-textured, hypidiotopic to xenotopic dolomite (crystal span 50 microns to 150 microns in diameter), about 20% quartz sand, and 6% feldspar grains. Many vertical and horizontal burrows are filled with quartz and dolomite crystals (Fig. 5-4). Calcite cement is common in this lithofacies.

Interpretation: The filled burrows are a sign of stirring and churning of sediments done by organisms (Friedman, et al. 1992). In this process, the organisms burrow into the sediments searching for food or shelter leaving behind different kinds of vertical and horizontal holes. Consequently, these holes may be filled by late diagenetic minerals that could be preserved in the rock record. This highly bioturbated lithofacies indicates decrease in the current energy. The numerous burrows, are good indicators of burrowing organisms that were abundant in this environment. Probably, the lower rates of sand supply and the calm condition allowed colonization by infaunal burrowing organisms within the sediments (Shinn, 1968; Selleck, 1978). This evidence strongly suggests that this lithofacies was deposited in the low energy of a subtidal-shallow marine setting.

5.2.3 Lithofacies 3: Glauconitic, sandy dolostone (Potsdam Formation)

Description: This lithofacies is composed of light to dark gray, euhedral to subhedral, fine to medium-textured dolomite (30 microns -180 microns in diameter). Saddle dolomite occurs as cavities-filling cements throughout this unit. Detrital quartz (20%), feldspar (8%), and some pyrite particles are scattered in this lithofacies. Glauconite pellets are very common (Fig. 5-5).



Figure 5-4. Lithofacies 2-Bioturbated, sandy dolostone. Photomicrograph of a thin section under plane-polarized light, showing horizontal and vertical burrows (arrow) that are filled by late diagenetic quartz and dolomite crystals.

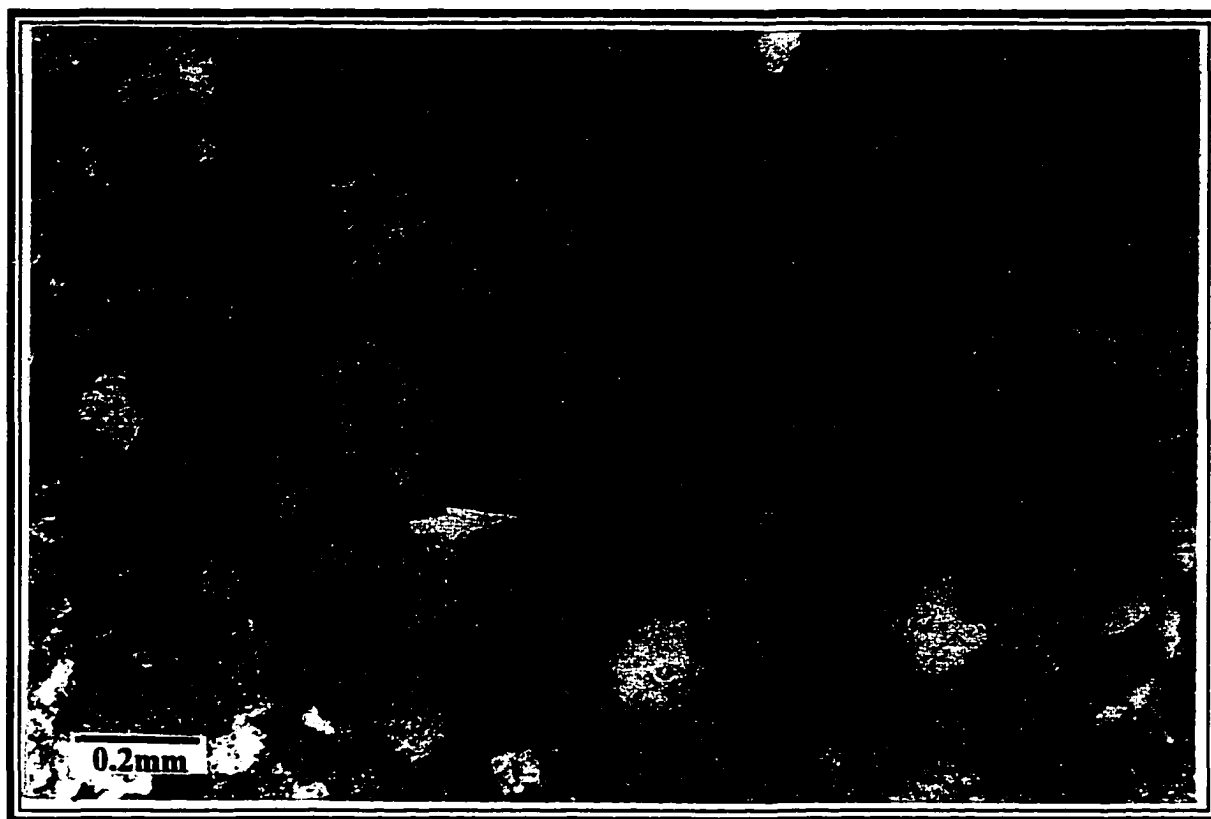


Figure 5-5. Lithofacies 3- Glauconitic, sandy dolostone, Photomicrograph of a thin section under plane-polarized light, showing glauconite pellets (arrow). Note pyrite particles (dark) and detrital quartz grains (light).

Interpretation: Glauconite is an intrabasinal mineral that grows biochemically in the water of a depositional basin (Friedman et al., 1992). The presence of glauconite pellets strongly suggests that this lithofacies was deposited in an agitated shallow-marine setting of low sedimentation rate with temporary subaerial exposure (Heim, 1934; Fisher, 1954). The glauconite-bearing strata are located at the base of transgressive/regressive cycles (Vail et al., 1984, 1991; Posamentier, 1988). The glauconite forms in a normal marine salinity or slightly alkaline solution (pH 7 - 8) , warm water, slightly reducing condition, and in the presence of phosphorites, volcanic ash, iron sulphide and decaying organic matter (Fisher, 1954; McCrae, 1972; Larsen, 1980; Logvinenko, 1982; Haq, 1991). Initially, glauconite forms as an authigenic sediment in the marine environment by replacement of preexisting particles. Commonly, K-poor glauconitic smectites are the first to form as a clay mineral that progressively alters to K-rich glauconitic mica (Odin and Fullagar, 1988). This glauconitic mica begins to fill pores and fractures within the particles and then replaces the pre-existing materials (Logvinenko, 1982; Van Houten and Purucker, 1985). The presence of the pyrite particles along with the glauconitic pellets in this lithofacies strongly suggests reducing conditions. This lithofacies probably formed in a shoal or in an intertidal to subtidal reducing environment. This lithofacies may have been exposed to uplifting conditions after deposition as indicated by the presence of the cavities-filling saddle dolomite.

5.2.4 Lithofacies 4: Stylolitic, sandy dolostone (Theresa Formation)

Description: This lithofacies consists of dark to light gray colored, medium-textured, hypidiotopic to xenotopic dolomite (100 microns to 120 microns in diameter). Horizontal stylolitic seams are abundant in this lithofacies. Light gray, subrounded, detrital quartz and feldspar grains are common (Fig. 5-6). Glauconite particles similar to those of the previous lithofacies are common. Calcite

cement is present. Some pyrite particles and disseminated organic materials are scattered throughout this lithofacies.

Interpretation: Riecke's principle of thermodynamics states that dissolution of a mineral tends to occur most readily at points where external pressure is greatest, and that crystallization occurs most readily at points where external pressure is least. This principle leads to stylolitization (pressure dissolution) in form of sutured surfaces along which nonsoluble material has accumulated to build a residue (Friedman et al., 1992). The abundance of the horizontal stylolitic seams in this lithofacies strongly suggests dissolution and chemical compaction that probably took place during the diagenetic processes of the preexisting carbonates and evaporitic minerals. This stylolitization may developed in karst areas that resulted from the post-Sauk, pre-Tippecanoe unconformity surface. The stylolite seams act as impermeable barriers to prevent the movement of fluids perpendicular to the plane of the stylolites, but serve as channels to permit the fluid movement along the stylolite seams. Detrital quartz grains were driven by wind or/and water currents. The glauconite particles of this lithofacies are similar to those of the previous one. This lithofacies probably was deposited in an intertidal to subtidal setting.

5.2.5 Lithofacies 5: Stromatolitic dolostone (Theresa Formation)

Description: This lithofacies is composed of dark clayey, irregular laminae. The thickness of the laminae ranges from 0.3 to 1.0 mm. Some laminae are filled with microcrystalline dolomite (Fig. 5-7). There are some rounded to subrounded intraclasts and completely micritized peloids. Also, some detrital quartz and feldspar particles are present in this lithofacies.

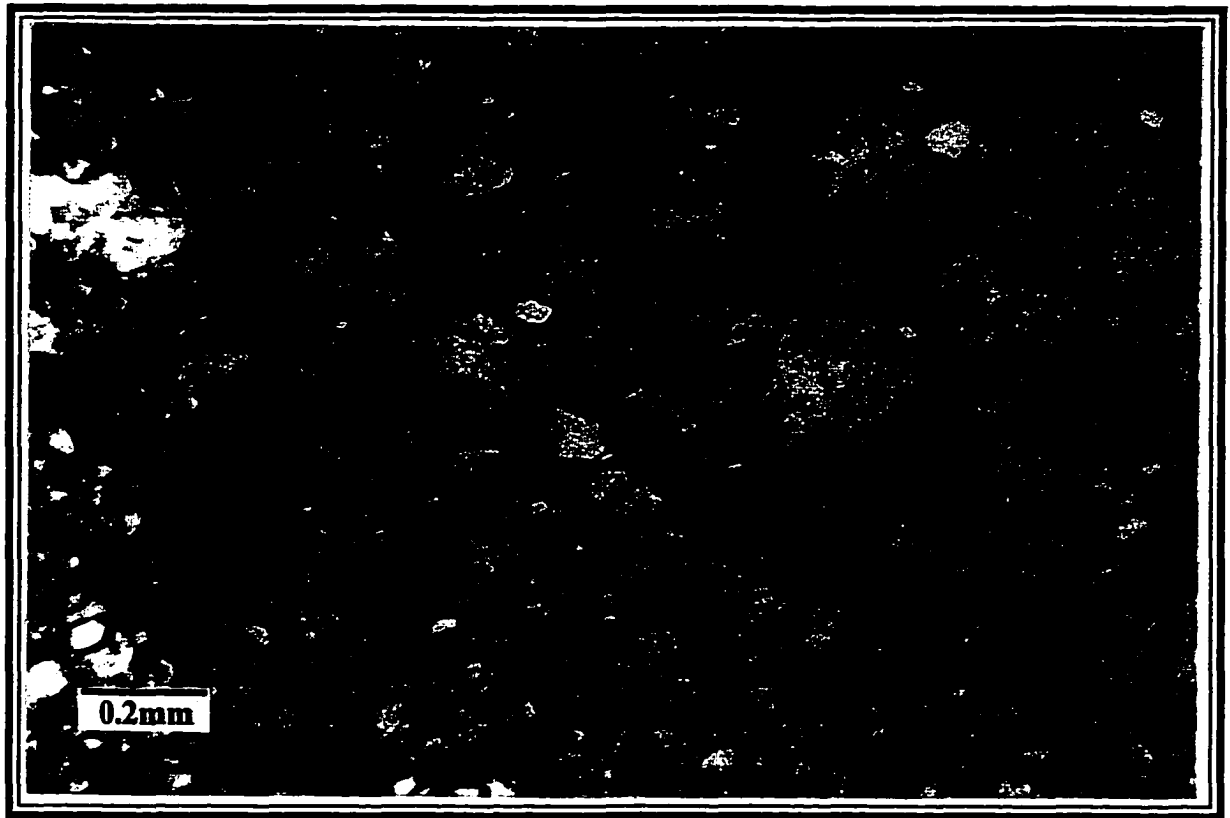


Figure 5-6. Lithofacies 4-Stylolitic, sandy dolostone. Photomicrograph of a thin section under plane-polarized light, showing framework of horizontal stylolitic seams (dark) in hypidiotopic to xenotopic dolomite matrix.

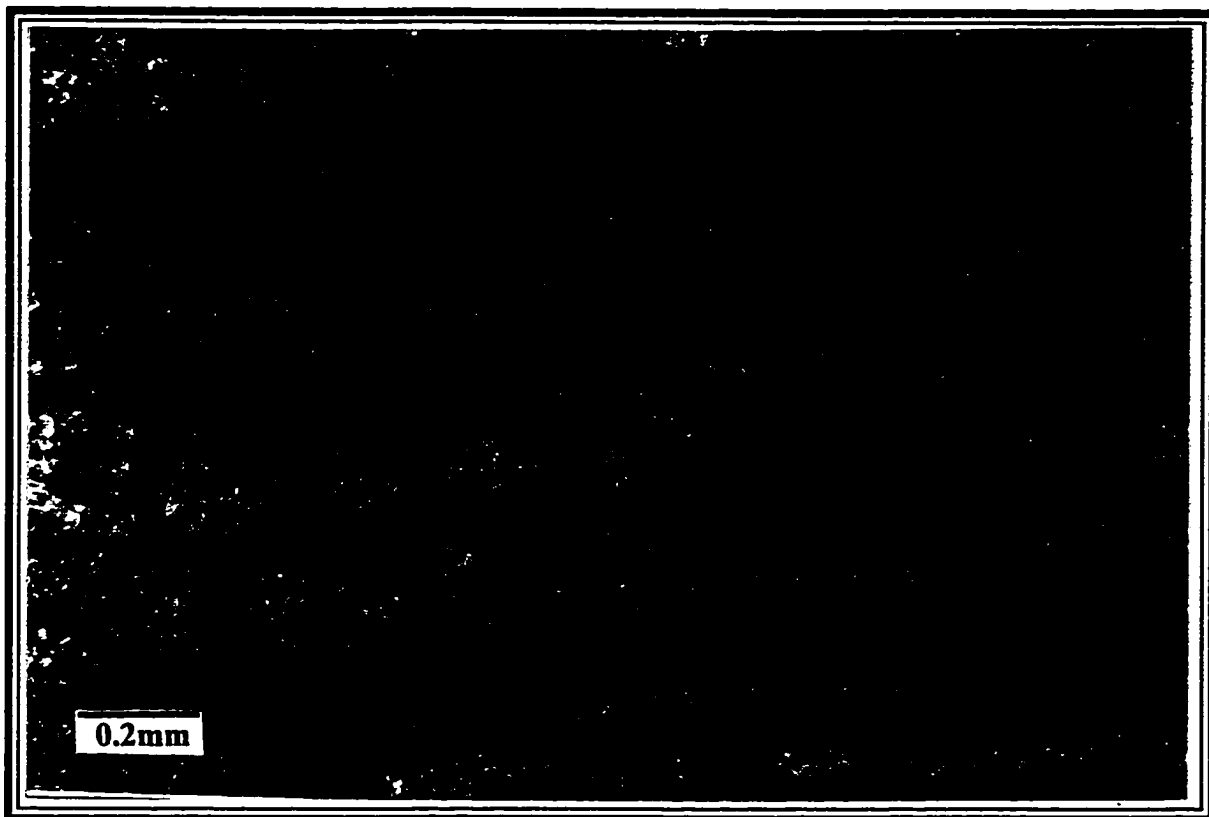


Figure 5-7. Lithofacies 5-Stromatolitic dolostone. Photomicrograph of a thin section under plane-polarized light, showing irregular stromatolitic laminae that filled with microcrystalline dolomite.

Interpretation: These irregular laminae are preserved stromatolites and are the product of the interaction of the microbial organisms and the sedimentary processes (Walter, 1977). Stromatolites were formed by aggrading and binding thin mud layers with smooth cyanobacterial mats. Usually, the transported fine muds are trapped and bound by the mats to form the laminated structures. These stromatolites are formed in a tropical to subtropical shallow marine setting . Hypersaline conditions are the most favorable for their preservation. The presence of these stromatolites along with the fine to medium-sized dolomite crystals indicate shallow warm, marine water. Apparently, this stromatolitic lithofacies was deposited within the intertidal to supratidal, evaporitic, sabkha environment.

5.2.6 Lithofacies 6: Oolitic dolostone (Theresa Formation)

Description: This lithofacies is composed of fine to medium hypidiotopic to idiotopic dolomite crystals (100 micron - 250 micron). Colors range from brownish gray to dark gray. Some intraclasts are also present in this lithofacies. Abundant amounts of concentric ooids (Fig. 5 -8) are the most significant feature of this lithofacies. The diameters of ooids range from 0.2 mm. to 0.4 mm. Some of these ooids have a drusy quartz center. Half-moon ooids are also present (Fig. 5-9). Well preserved silicified micritic envelopes of former peloidal particles have been recognized (Fig. 5-10).

Interpretation: The abundance of oolitic grainstones in this lithofacies strongly indicates high-energy environment within an agitated shallow water of tidally-controlled marine setting (Friedman, 1970; and Bathurst, 1975). Usually, these ooids are formed by the precipitation of aragonitic layers around a nucleus. The symmetrical pattern of the ooid-coating layers are created by the constant rocking motion of the agitated water, allowing an even coating of calcium carbonate to form (Conway and Friedman, 1984).

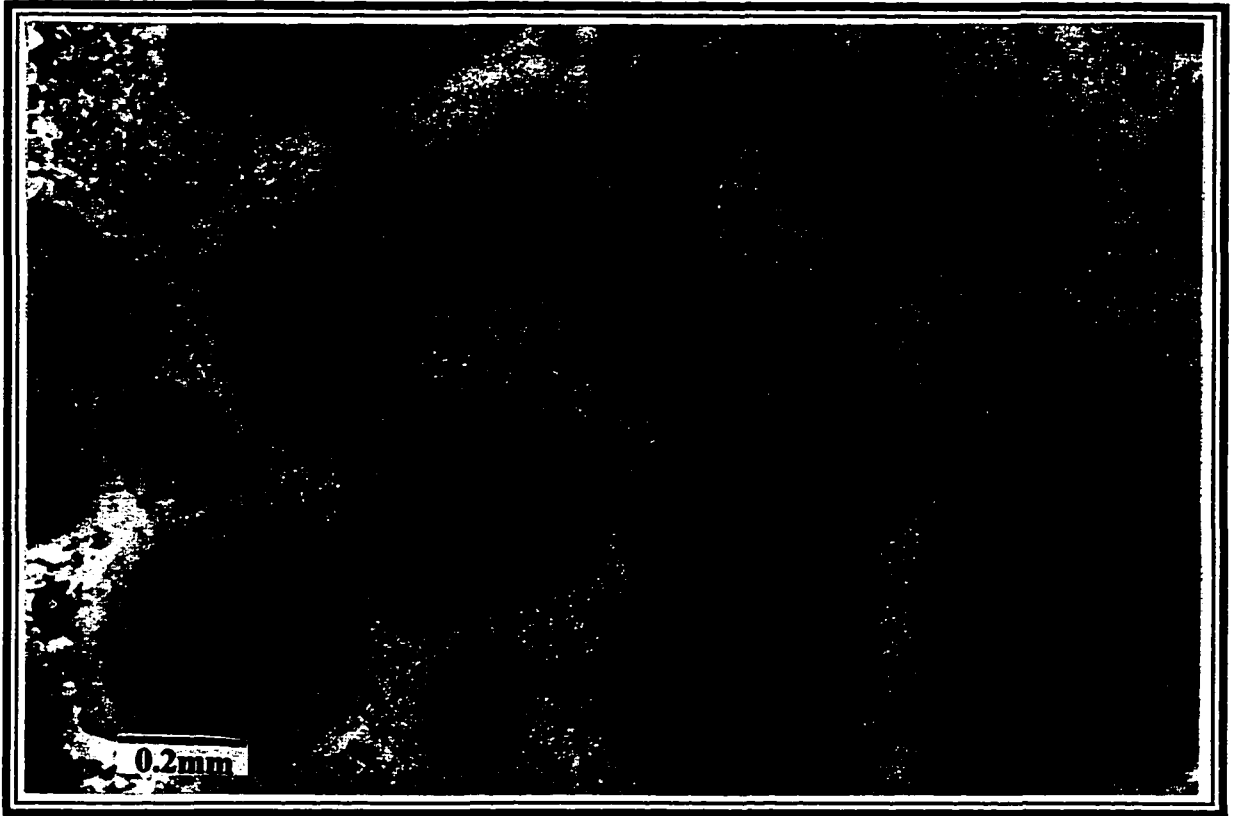


Figure 5-8. Lithofacies 6- Oolitic dolostone. Photomicrograph of a thin section under plane-polarized light, showing concentric ooids in dolomitic matrix.



Figure 5-9. Lithofacies 6- Oolitic dolostone. Photomicrograph of a thin section under plane-polarized light, showing half-moon ooids in a fine dolomitic matrix.

The half-moon ooids are environmentally significant because they usually form when the cores collapse and settle against their outer rims. Carozzi (1963) associated the nucleus collapse to dissolution processes of sulfate minerals (anhydrite and gypsum) that incorporated within the inner structure of the ooids. Friedman and Radke (1979) and Curl, Zagorski, and Friedman (1984) reported that the half-moon ooids have been recognized in the Cambro-Ordovician coeval Nimaroo Formation of Queensland, Australia and Tribes Hill Formation of the Mohawk Valley of New York. This lithofacies is a good indicator of vanished evaporites of an arid environment.

5.2.7 Lithofacies 7: Laminated, silty to sandy dolostone (Theresa Formation)

Description: This lithofacies consists of alternating dark gray to light gray laminae (Fig. 5-11). The thickness of these laminae ranges from 1 mm to 2 mm. The dark gray laminae exhibit subhedral to anhedral dolomite crystals (20 micron to 30 micron in diameter). The light laminae mainly consist of anhedral dolomite crystals (10 micron to 20 micron in diameter). Detrital quartz grains are scattered throughout this unit.

Interpretation: Commonly, the microcrystalline laminated dolostone forms as a syngenetic-dolomite type on the modern supratidal and upper intertidal flats (Friedman and Sanders, 1967). This reflects alternations of sediment input and microbial activity where, in elevated salinities, the cyanobacteria and algae trap and bind fine material to generate laminated sediments known as cryptalgal laminite (Reading, 1996; Friedman et al. 1992). Also, lack of fossils suggests hypersaline conditions. This lithofacies probably formed in an upper intertidal to supratidal setting.

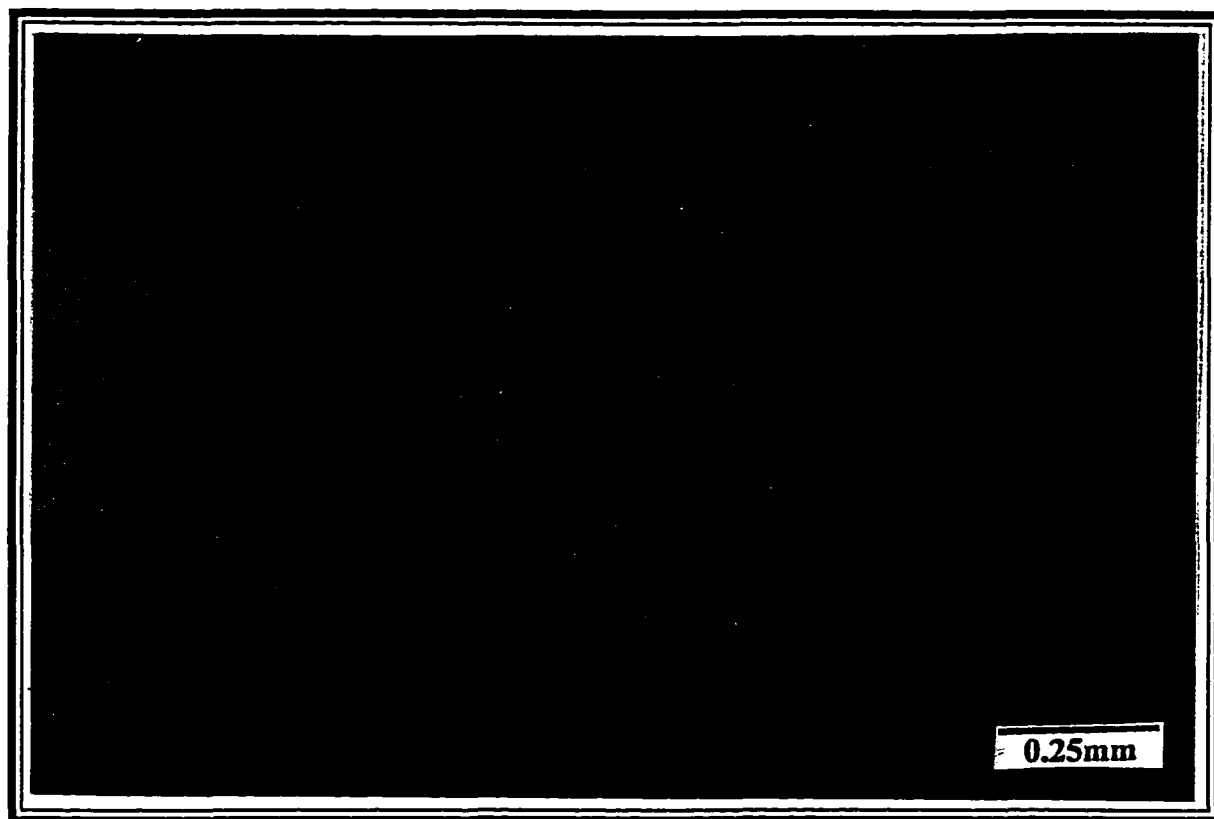


Figure 5-10. Lithofacies 6- Oolitic dolostone. Photomicrograph of a thin section under plane-polarized light, showing well-preserved micrite envelope of a former peloidal particle in a sandy dolomitic matrix. Note the core of this envelope is completely silicified.

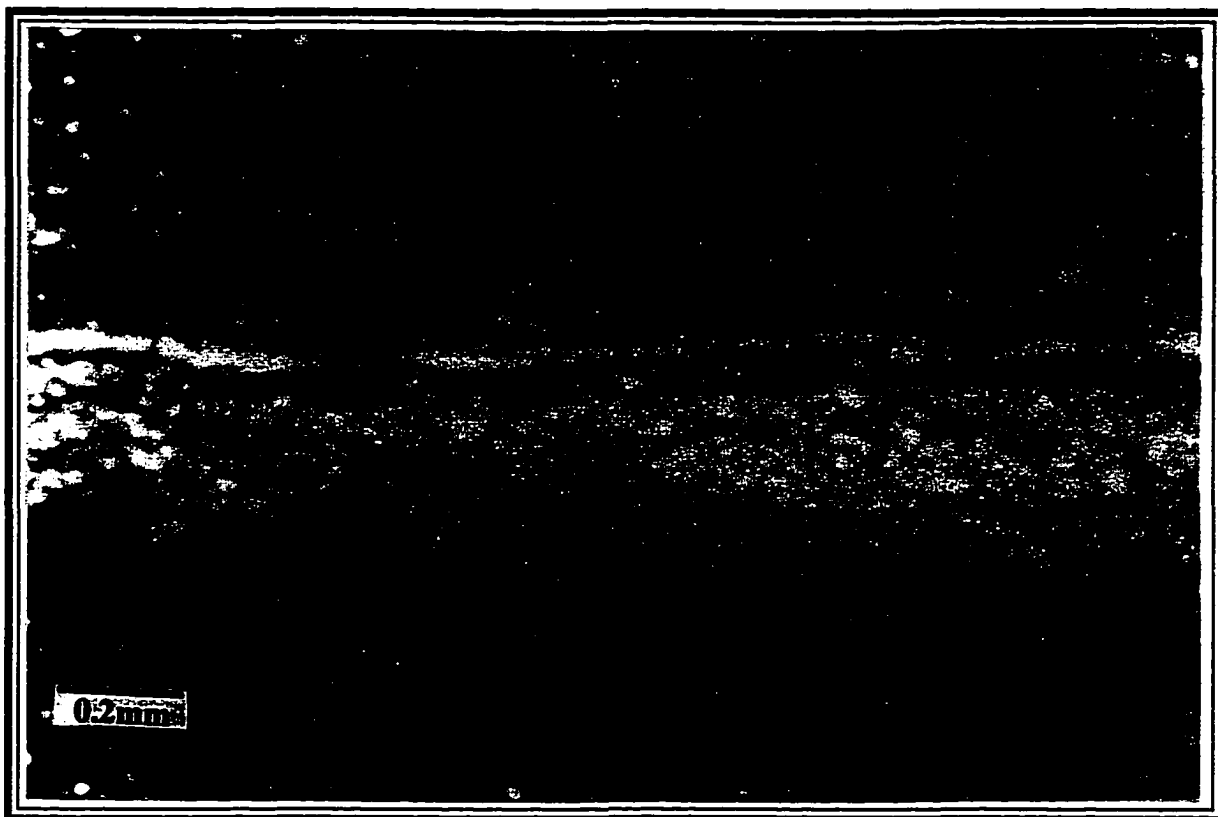


Figure 5-11. Lithofacies 7- Laminated, silty to sandy dolostone. Photomicrograph of a thin section under plane-polarized light, showing alternate dark and light laminated silty to sandy dolostone.

5.2.8 Lithofacies 8: Quartzose dolostone with anhydrite laths (Theresa Formation)

Description: This lithofacies consists of gray to dark gray, fine to medium, subhedral to euhedral dolomite crystals (20 -80 micron in diameter). Well-rounded to sub-rounded, light gray detrital quartz grains represent 8-10% of this lithofacies (Fig. 5-12). Some anhydrite laths are scattered throughout the thin section (Fig. 5-13). Also, a former anhydrite nodule is filled by megaquartz particles (Fig. 5-14). A few of these megaquartz particles have anhydrite inclusions. Well-developed euhedral authigenic feldspar crystals are present (Fig. 5-15). Also, some pyrite particles have been recognized.

Interpretation: The presence of fine-textured dolomite along with the anhydrite laths indicates supratidal setting under an arid shelf condition of sabkha environment (Curtis, et al, 1963; Kinsman, 1969; Friedman, et al. 1992). Also, the presence of the authigenic feldspar crystals may be a good indicator of a hypersaline setting. These authigenic feldspar crystals may have replaced wind-transported tephra that accumulated among microbial mats on the hypersaline supratidal setting. The scattered pyrite in this lithofacies probably formed in a reducing condition that prevailed in the hypersaline environment (Friedman, 1966; Friedman and Sanders, 1967; Braun and Friedman, 1969; Friedman and Radke, 1979). This lithofacies is interpreted to have been deposited in a supratidal environment under arid and hypersaline conditions similar to those of modern sabkha environments.



Figure 5-12. Lithofacies 8- Quartzose dolostone with anhydrite laths. Photomicrograph of a thin section under crossed nicols, showing detrital quartz grains embedded in a fine dolomitic matrix. Note the indentation of the quartz grain (arrow) that may have resulted from leaching processes.



Figure 5-13. Lithofacies 8- Quartzose dolostone with anhydrite laths. Photomicrograph of a thin section under crossed nicols, showing anhydrite laths (arrow) that display bright second-order interference colors. Note the fine textured dolomite matrix.

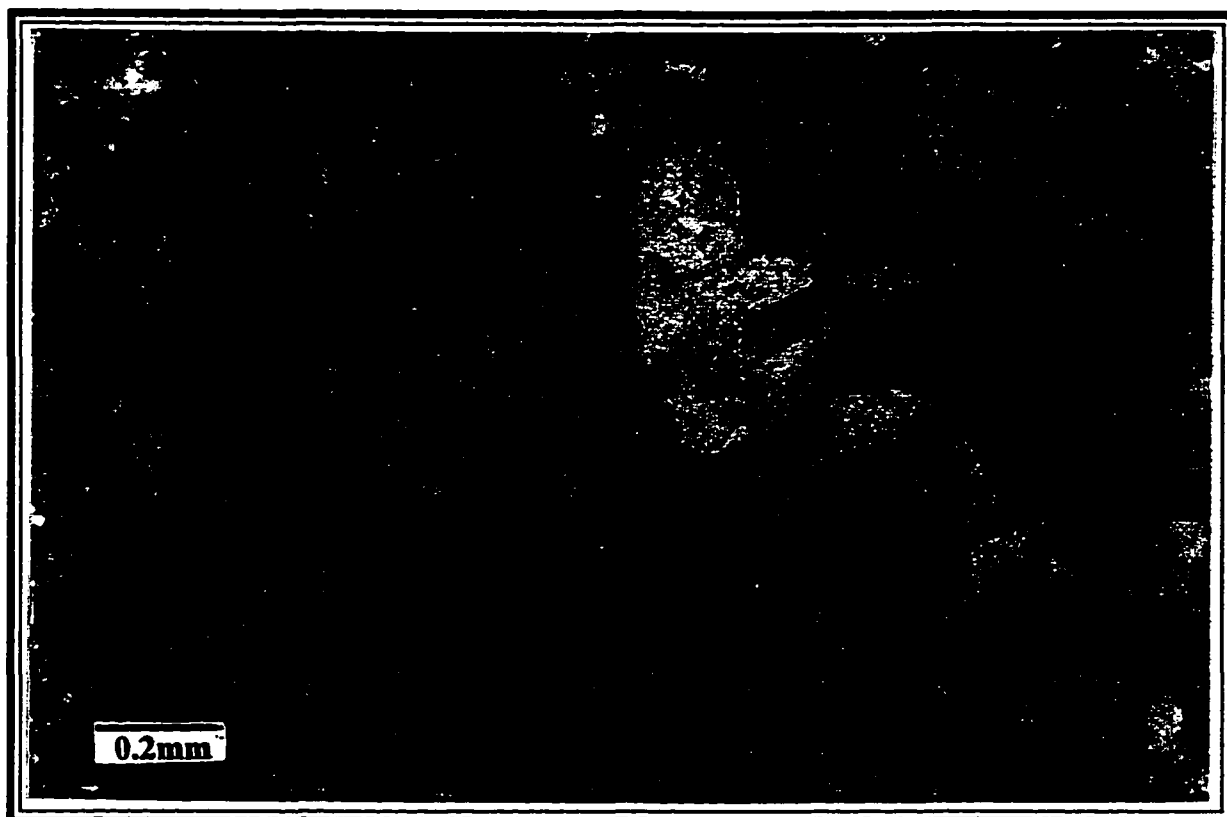


Figure 5-14. Lithofacies 8- Quartzose dolostone with anhydrite laths. Photomicrograph of a thin section under plane-polarized light, showing a former anhydrite nodule filled by megaquartz particles (arrow).



Figure 5-15. Lithofacies 8- Quartzose dolostone with anhydrite laths. Photomicrograph of a thin section under crossed nicols, showing well-developed euhedral authigenic feldspar crystal (arrow).

5.2.9 Microlithofacies 4: Fossiliferous dolostone (Theresa Formation) in Mitchell Well of Steuben County and Wasielewski Well of Cayuga County (Fig. 5 -1).

Description: This microlithofacies consists of euhedral to anhedral, gray to light gray, fine to medium-textured dolomite crystals (120 - 160 micron in diameter). Fossil fragments of trilobites (Fig. 5-16), ostracods (Fig. 5-17), crinoid stems (Fig. 5-18), bryozoa (Fig. 5-19), and brachiopods (Fig. 5-20) are present in abundance in this microlithofacies. Most of these fossil fragments have been partially or completely dolomitized. Also, some dolomitized ooids and peloidal particles have been recognized in this microlithofacies. Most of the fossil remains have been pervasively dolomitized.

Interpretation: Many bryozoan and ostracods species thrived in normal marine salinities during late Cambrian and early Ordovician (Levin, 1996). They are most abundant and diverse on the continental shelf from 20 to 80 meters deep (Ryland, 1970; Dodd et al, 1981). Also, the brachiopods appear to have been most common in shallow subtidal tropical seas (Rudwick, 1970). Initially, the fossil constituents of this lithofacies flourished in calm conditions of a subtidal shelf setting. However, the abundance of the fossil fragments reflects storm-generated settings within a peritidal environment.

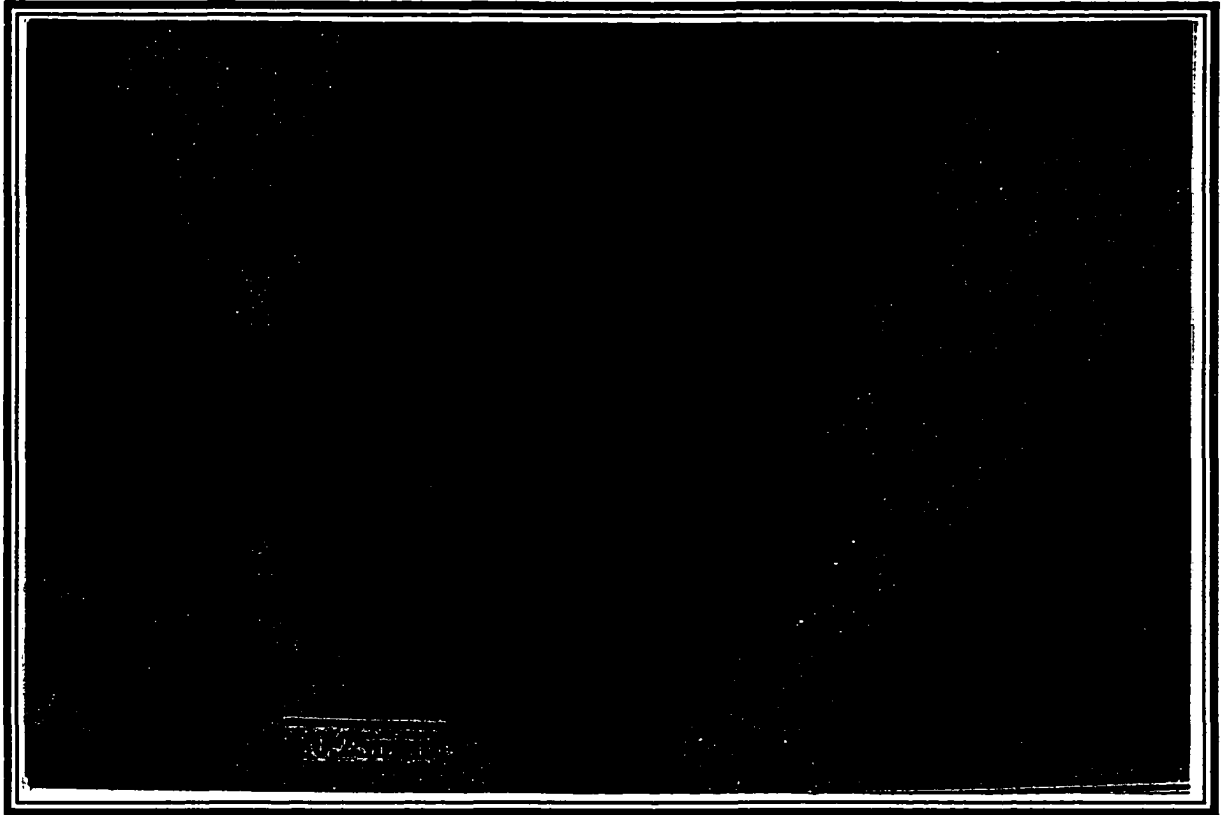


Figure 5-16. Microlithofacies 4 (well cuttings)- Fossiliferous dolostone. Photomicrograph of a thin section under plane-polarized light, showing fragments of trilobites.

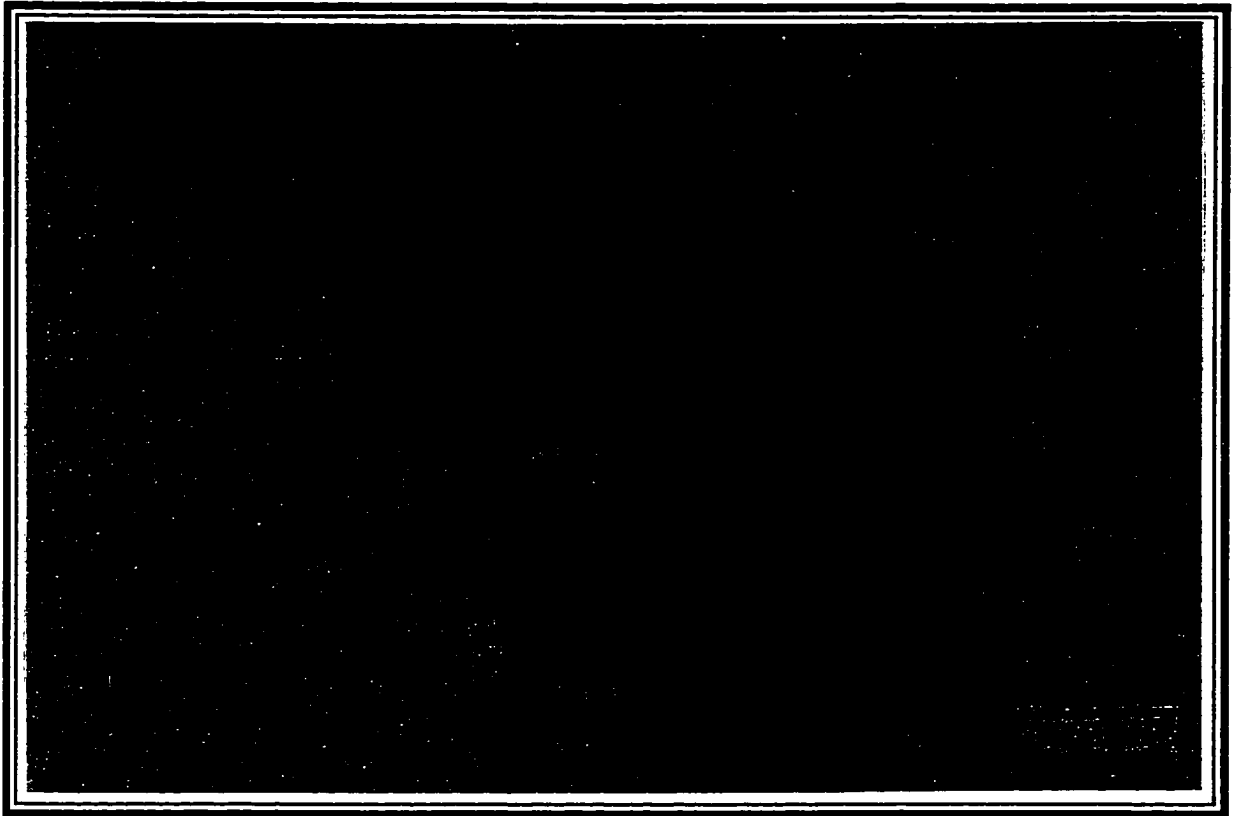


Figure 5-17. Microlithofacies 4 (well cuttings)- Fossiliferous dolostone. Photomicrograph of a thin section under plane-polarized light, showing a fragment of ostracode (arrow).

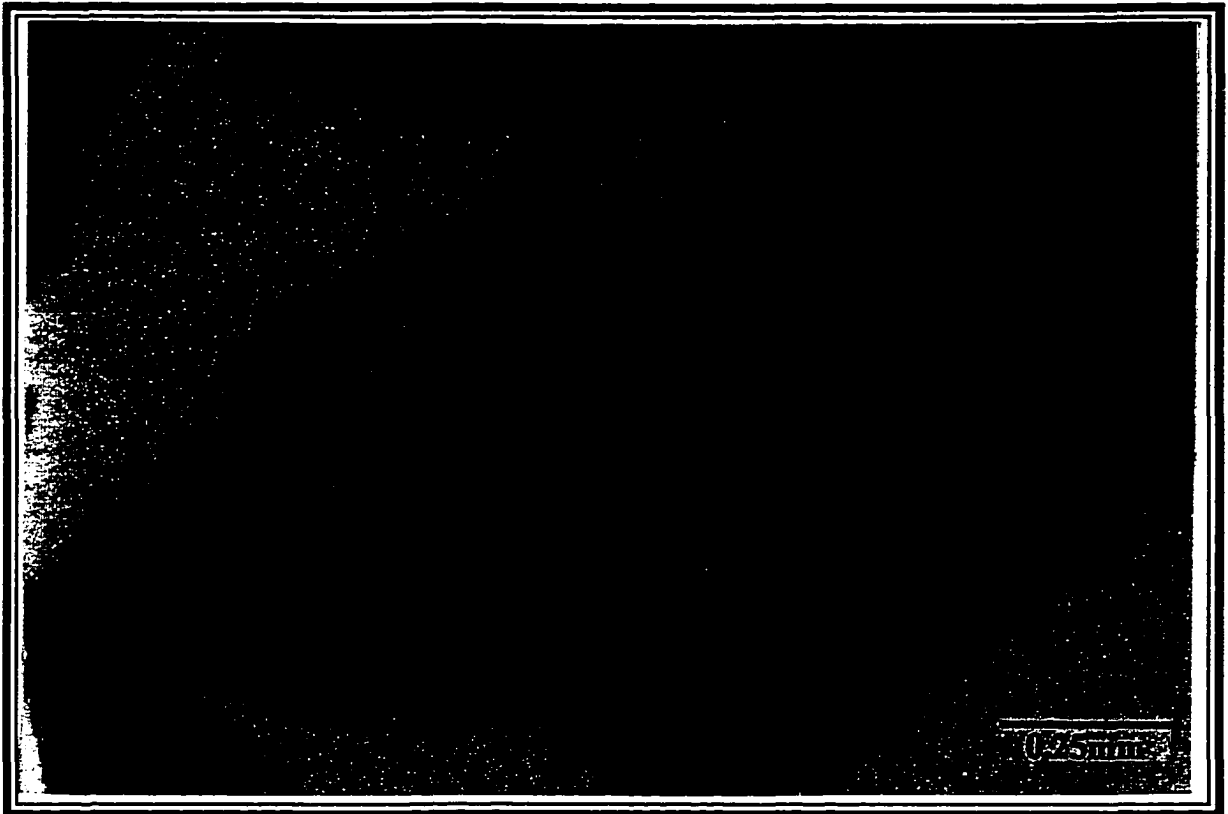


Figure 5-18. Microlithofacies 4 (well cuttings)- Fossiliferous dolostone. Photomicrograph of a thin section under plane-polarized light, showing a crinoidal fragment in a dolomitic matrix.

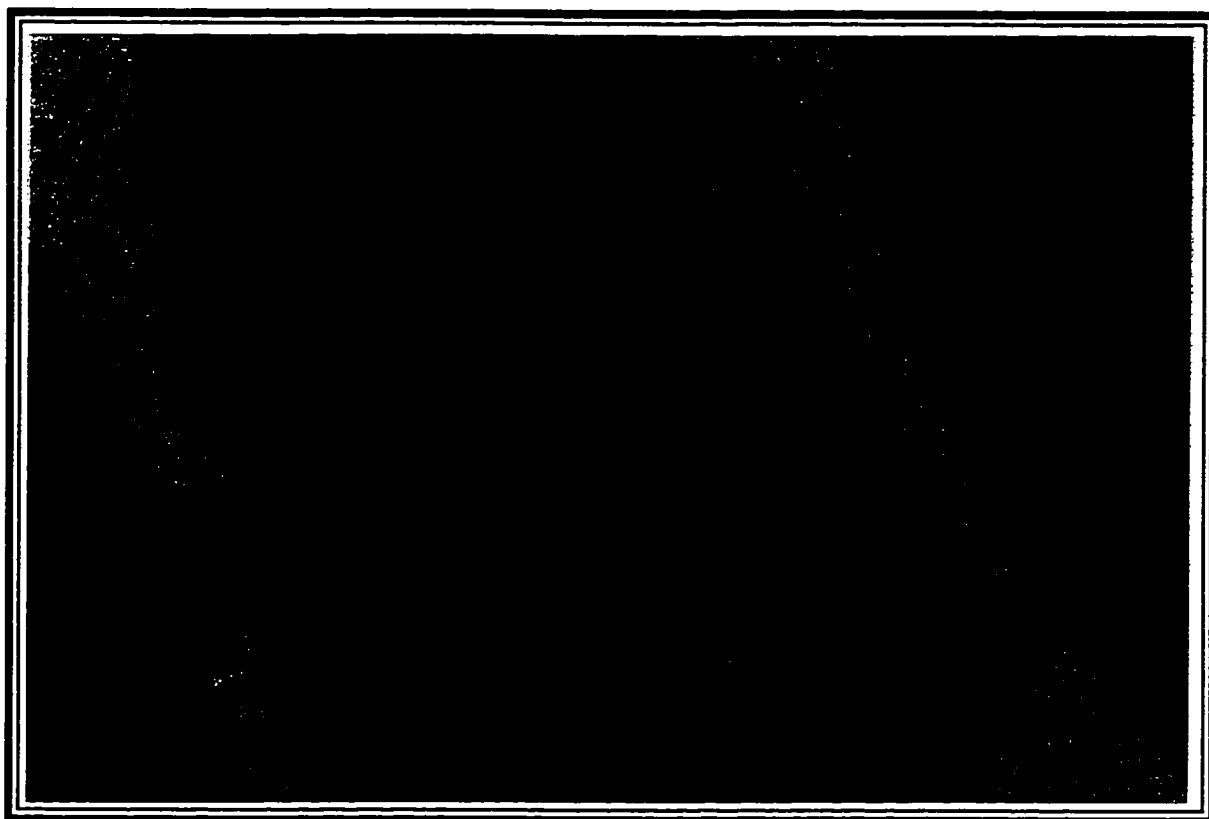


Figure 5-19. Microlithofacies 4 (well cuttings)- Fossiliferous dolostone. Photomicrograph of a thin section under plane-polarized light, showing bryozoan fragment in a dolomitic matrix.

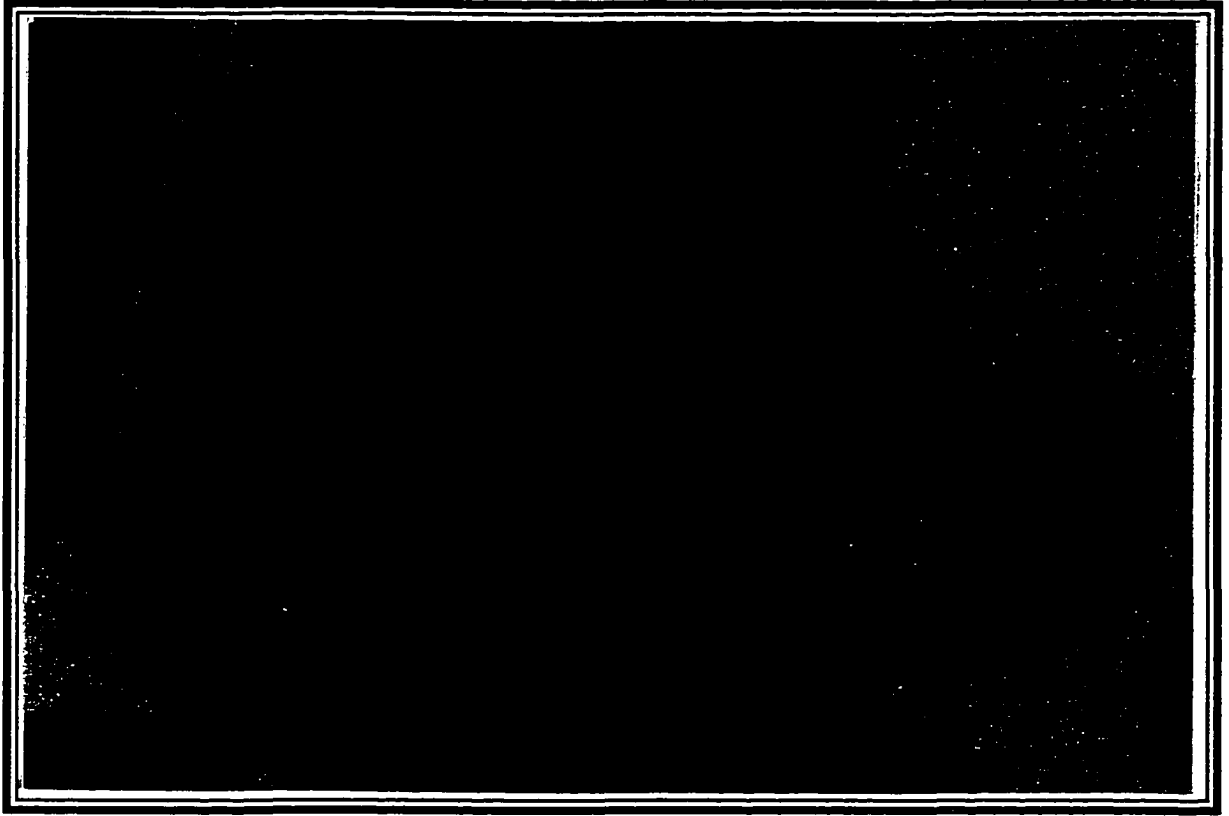


Figure 5-20. Microlithofacies 4 (well cuttings)- Fossiliferous dolostone. Photomicrograph of a thin section under plane-polarized light, showing a dolomitized fragment of brachiopod.

5.3 Proposed Model of the Depositional Environment

Detailed-facies analyses of core sections and well cuttings indicates that the Cambro-Ordovician Beekmantown Group of central and western New York was deposited in the craton-wide epeiric sea within the peritidal environment. The lithofacies and microlithofacies of the studied wells consist of a basal sandstone overlain by a carbonate grainstone, oolitic dolostone, fossiliferous dolostone, stromatolitic dolostone, laminated dolostone, and quartzose dolostone with anhydrite laths. A shoaling upward cycle is apparent. The proposed model of the paleoenvironmental settings of these lithofacies and microlithofacies is shown in figure 5-21.

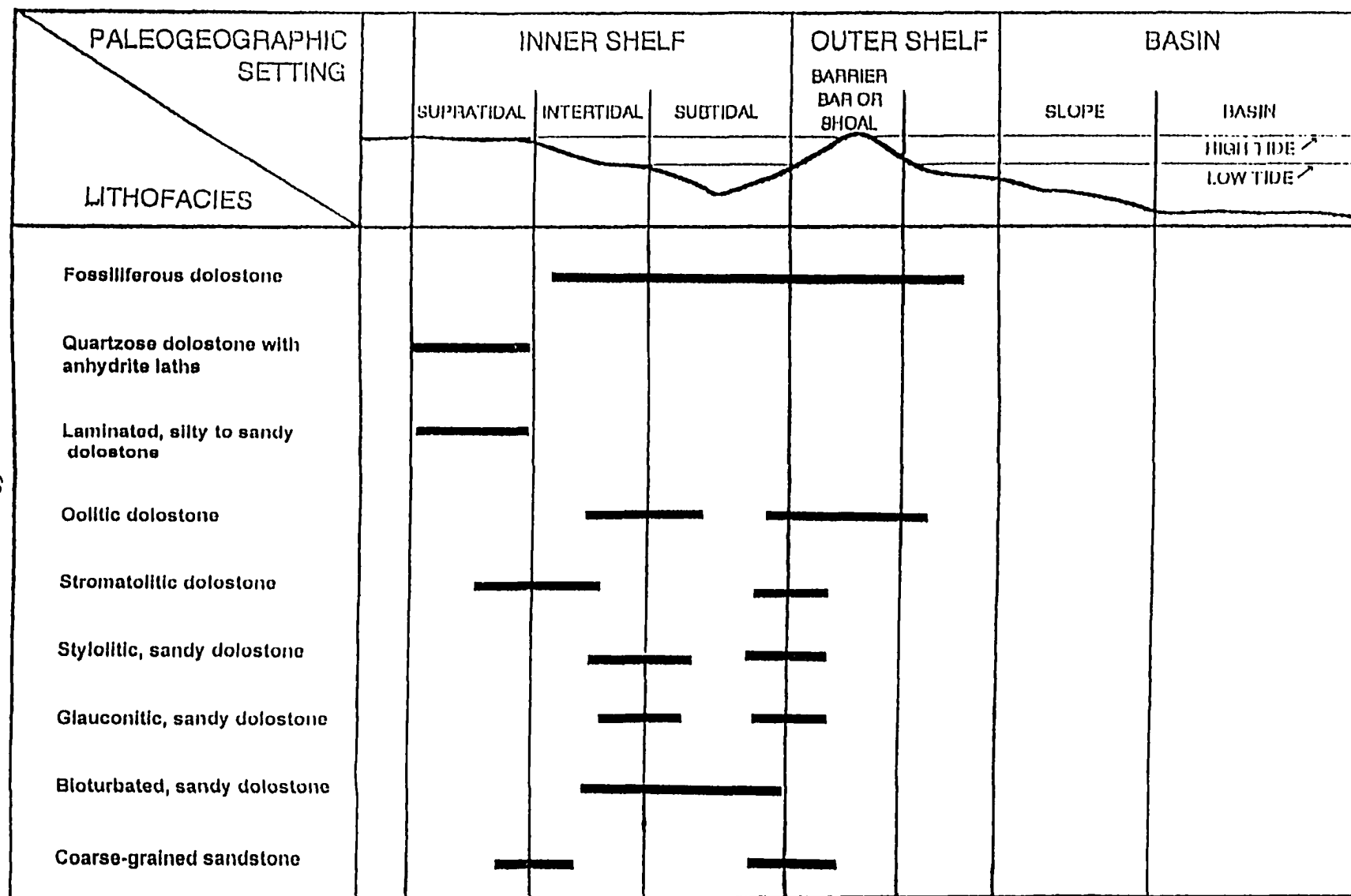


Figure 5-21: Proposed paleoenvironmental setting of the Beckmantown Group of central and western New York.

PART III

DIAGENESIS AND GEOCHEMISTRY

CHAPTER 6: DIAGENETIC HISTORY OF THE BEEKMANTOWN GROUP (SAUK SEQUENCE) OF CENTRAL AND WESTERN NEW YORK

6.1 General Statement

The term “diagenesis” was introduced to the geologic literature by Von Guembel in 1868 (McLlreath, et. al., 1990). Diagenesis can be defined as the changes in the character and composition of sediments, beginning from the moment of deposition, and lasting until the resulting materials (rocks) are moved into the realm of metamorphism (Larsen and Chilingar, 1979). Diagenetic modification includes processes such as compaction, cementation, recrystallization, replacement, coalification, and generation of hydrocarbons due to degradation of the organic materials. The boundary between diagenesis and metamorphism varies based on the degrees of mineralogic stabilities that characterize different rock types. However, in general, the diagenetic processes usually occur at a pressure of 0.1MPa to 10 Mpa (1.0 bar to 1 kilobar) and at a temperature ranging from 0° to 300°C. These conditions are correspondent to a maximum depth of about 10 to 15 kilometers (Bates and Jackson, 1987).

Petrophysical properties (porosity, permeability, fluid saturation, and recovery efficiency) of rock samples are controlled by the intensity of the diagenetic modifications. On the one hand, pores can be occluded by precipitation, replacement, and recrystallization of the diagenetic minerals. On the other hand, porosity may increase by leaching, dissolution, and biogenic activities over the preexisting rocks.

Petrographic investigation using a cathodoluminescent microscope and an electron microprobe for selected dolomite samples from the Beekmantown Group records a timing sequence

of diagenesis as follows: 1) deposition of the original sediments; 2) dolomitization; 3) silicification; 4) chemical compaction (stylolitization); 5) dedolomitization; and 6) precipitation of saddle dolomite (pore-filling dolomite).

6.2 Dolomitization and Dolomite Textures: Petrography and Geochemistry

Dolostone is a large constituent of the Cambrian and Ordovician rocks in the North American Continent. Dolomitization is more abundant in the ancient and modern tidal flats than in any other environment. The high-evaporation rate in the tidal flats assists in the formation of evaporitic minerals such as gypsum and anhydrite. Precipitation of these evaporitic minerals increase the Mg/Ca ratio of the residual brine. Movement of these brine throughout the lime mud increases the Mg content that leads to dolomitization (Friedman and Sanders, 1967).

The term “texture” can be defined as the general physical appearance or character of rock, including the geometric aspects of, and the mutual relations among, its component particles or crystals; e.g. the size, shape, and arrangement of the constituents of a sedimentary rock. The term is applied to the microscopic features as seen on a smooth surface of a homogeneous rock or mineral aggregate (Bates and Jackson, 1987). In this study, Friedman’s terminology (1965) of crystallization textures and fabrics in sedimentary rocks as well as the classification provided by Sibley and Gregg of dolomite rock textures (1987) were followed to determine different types of dolomites.

The mineral dolomite is not only varied in Mg:Ca ratios and the degree of order (stoichiometry) but it also varies in trace element contents such as iron (Fe), Manganese (Mn), Strontium (Sr), and silicon (Si). These elemental variations and their concentration values strongly indicate that dolomite forms under various conditions within different environmental settings. Basically, dissolution and precipitation of trace elements such as Fe, Mn, Sr, and Si in carbonate

rocks are controlled by an important factor known as the “Kinetic effect”. Rate of dissolution and precipitation can be expressed as:

$$dc/dt = k_m (C_s - C)^m \quad (C \leq C_s) \quad (\text{Lerman, 1979})$$

where k_m is the reaction-rate parameter of dimensions $(g\text{ cm}^{-3})^{1-m} \text{ sec}^{-1}$, when the rate of change dc/dt is in units of $g\text{ cm}^{-3} \text{ sec}^{-1}$, and C_s ($g\text{ cm}^{-3}$) is an equilibrium or steady-state concentration value to which the solution tends with time. The power exponent m is called the order of the reaction. For dissolution, the value of the right-hand side of the equation must be positive and concentration (C) increases with time. As a result, $dc/dt > 0$. For precipitation, concentration (C) decreases with time and $dc/dt < 0$. The precipitation requires that the term on the right-hand side of the equation has a negative value and can be written as $-k_m (C - C_s)^m$, with the condition of $C > C_s$.

Furthermore, the concentration of these major and trace elements in the dolomite samples is governed by the distribution coefficient “D” of each element and its abundance in the parent fluid.

This can be expressed as: $[m_{Me}/m_{Ca}]_{(solid)} = D [m_{Me} / m_{Ca}]_{(water)}$, where m indicates the molar concentration of a given element, Me represents the trace element in metal form, D is the distribution coefficient. This clearly explains the concentration of a trace element in a mineral composition is directly proportional to its concentration in the original water (Veizer, 1983; Allen and Wiggins, 1993). Trace elements may replace major elements in solid solution based on Goldschmidt’s rules of substitution. These rules are: 1) The ions of one element can extensively replace those of another in ionic crystals if their radii differ by less than about 15%; 2) Ions whose charges differ by one unit substitute readily for one another provided electrical neutrality of the crystal is maintained. If the charges of the ions differ by more than one unit, substitution is generally slight; 3) When two different ions can occupy a particular position in a crystal lattice, the ion with the higher ionic

potential forms a stronger bond with the anions surrounding the site; and 4) Substitution may be limited, even when the size and charge criteria are satisfied, when the competing ions have different electronegativities and form bonds of different ionic character (Faure, 1991). Based on these rules, there are three ways in which the ions of trace elements are partitioned between the solid and liquid phases. These are camouflage, capture, and admission (Faure, 1991). Camouflage occurs when the trace element has the same charge and a similar ionic radius as the major element it is replacing. Capture takes place when a trace element enters a crystal preferentially because it has a higher ionic potential than the ions of the major element. Admission involves the entry of a foreign ion that has a lower ionic potential than the major ion either because it has a lower charge or a larger radius, or both. Admission of ions is very important in carbonate rocks because it is very common especially in replacement of Ca^{+2} (1.08 Å) by Sr^{+2} (1.21 Å) in calcite and dolomite. Evidently, admission of foreign ions into the crystal of a major element is ultimately controlled by the size criterion expressed in Goldschmidt's first rule. Also, the Mg^{+2} (0.66 Å) can be replaced by Fe^{+2} (0.71 Å) and Mn^{+2} (0.75 Å) and all these three elements may replace the Ca^{+2} in the dolomite mineral.

Based on the petrographic study of the selected thin sections from different lithofacies and microlithofacies, six dolomite textures have been recognized. These dolomite textures have been classified based on crystal sizes, shapes, uniformity and trace-element distribution. These textures are as follows: 1) unimodal, very finely crystalline, planar-e (euhedral) dolomite, 2) unimodal, very finely crystalline, planar-s (subhedral) dolomite, 3) medium to coarsely crystalline, planar-e (euhedral) dolomite, 4) coarsely crystalline, non-planar dolomite (non saddle dolomite), 5) very coarsely crystalline, non-planar dolomite (saddle dolomite), and 6) polymodal dolomite.

6.2.1 Texture 1: Unimodal, very finely crystalline, planar-e (euhedral) dolomite

This dolomite consists of euhedral crystals whose sizes are less than 50 microns. All of the dolomite crystals within this texture are homogeneous in their optical properties (Fig. 6-1) . This texture is common in Lithofacies 7 and 8 of Waste Water Disposal #1 Well of Niagara County, Lithofacies 3 of Wilson Well, Wyoming County, and Lithofacies 5 of Robert Olin Well, Steuben County. Under the luminoscope, this dolomite displays a bright red color (Fig. 6-1). Also, scattered detrital feldspar and quartz particles are present (Fig. 6-1). There is no evidence to confirm that this type of dolomite has replaced a precursor calcite or skeletal fragments.

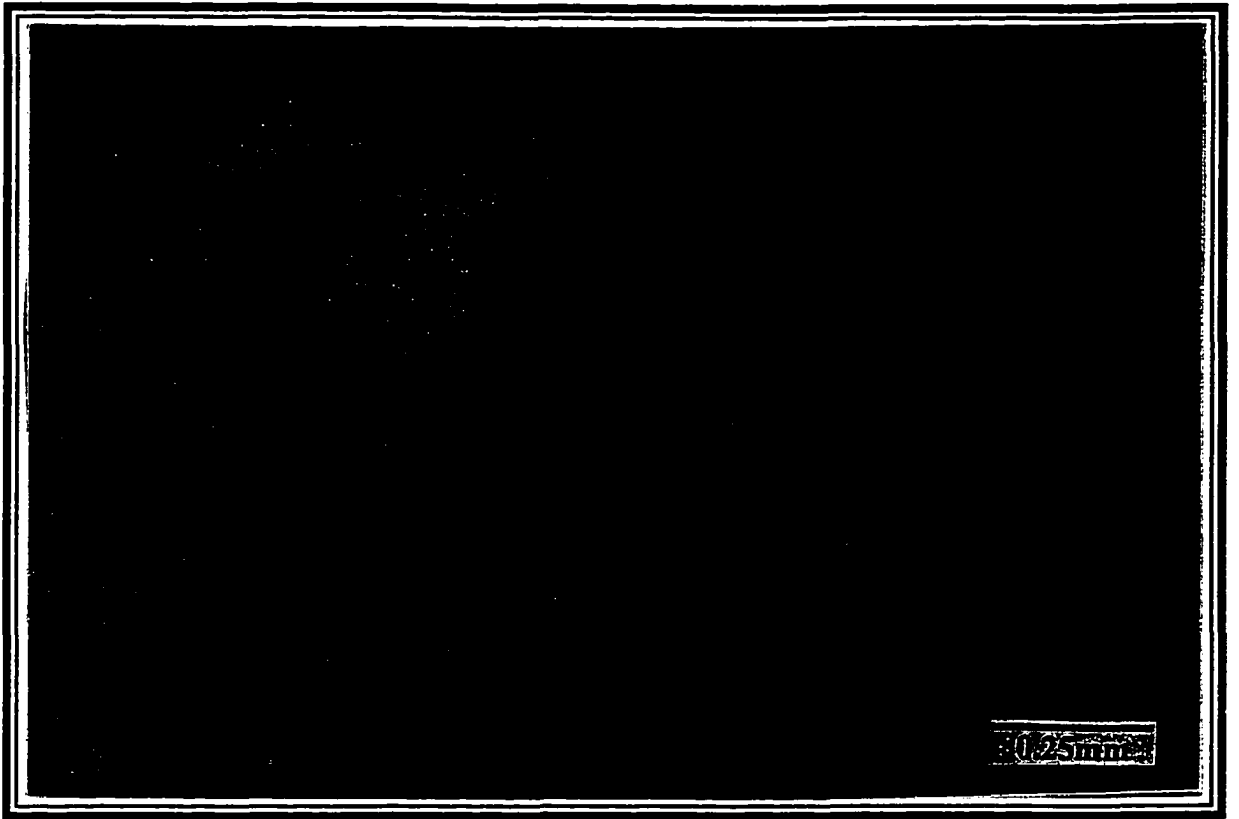
These typical euhedral-dolomite crystals were described by Friedman and Sanders (1978), and Sibley (1982). They reported that these types of euhedral, unimodal crystals are syngenetic or formed *in situ* due to a homogeneous distribution of the nucleation-growth rate. Probably the Mg^{2+} cations were absorbed in large quantities onto the growing calcite lattice which resulted in precipitation of high-magnesian calcite to reach equilibrium phase with the sea water causing stability surface. The dolomite crystals of this texture are nonstoichiometric (the average $CaCO_3 : Mg CO_3 = 59 : 41$). The average trace-element distribution of this kind of dolomite is: Fe = 746 ppm, Mn = 244 ppm, Sr = 791 ppm, and Si = 166 ppm (Fig. 6 -1C). These early-formed dolomite crystals (penecontemporaneous) are rich in strontium compared to late (diagenetic) dolomite crystals (Land, 1985; and Shukla, 1988). The luminescence-red color of this dolomite texture is due to its enrichment of the manganese content (Fig. 6 -1B).

Figure 6-1. Texture 1: Unimodal, very fine crystalline, planar-e (euhedral) dolomite.

(Robert Olin #1 Well, Steuben County, depth: 12444 feet)

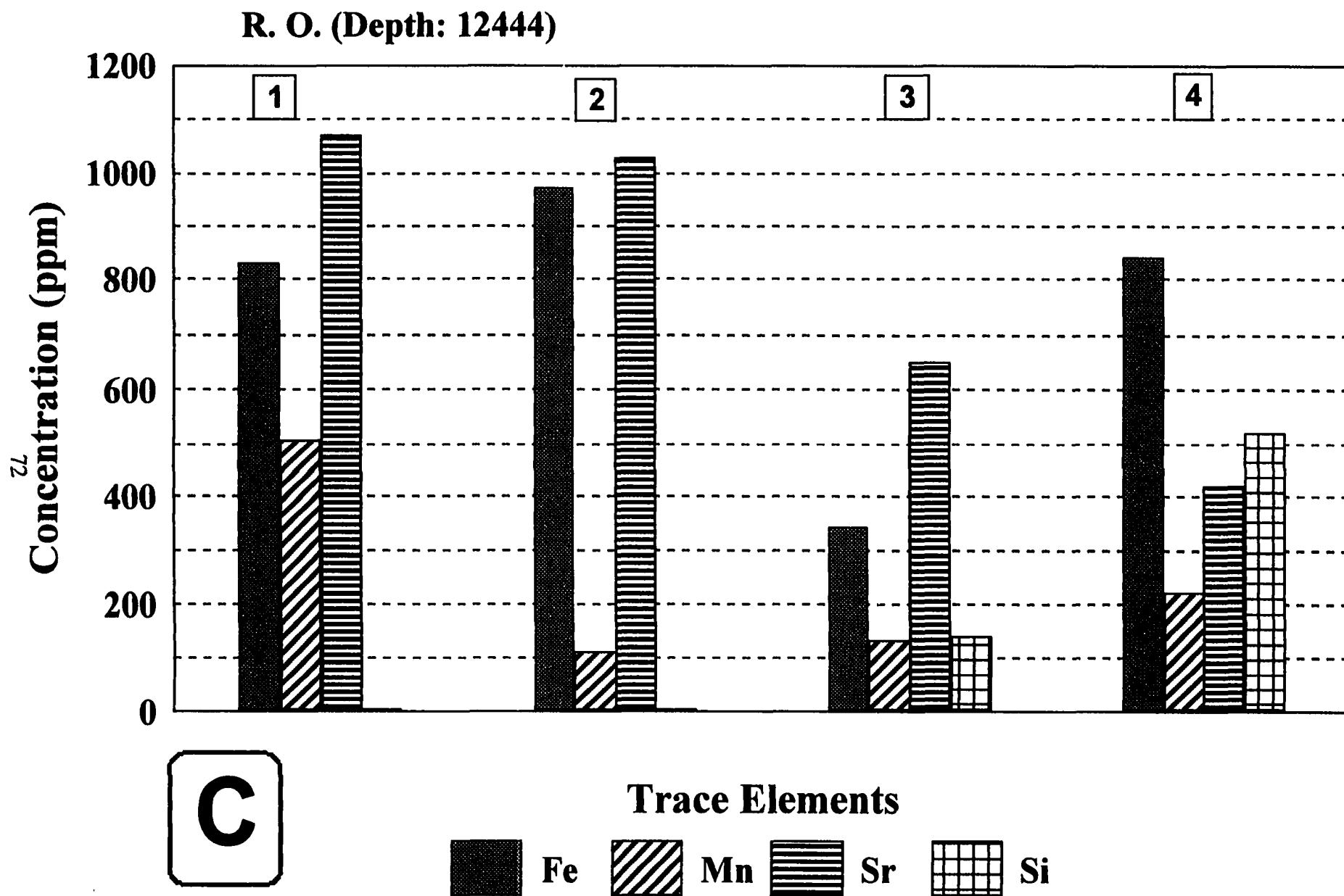
- A) Photomicrograph of a thin section in plane-polarized light, showing very fine, uniform dolomite crystals and scattered detrital quartz and feldspar particles.
- B) Same view under luminescope; note the dolomite crystals are homogeneous and red in color, quartz grains are dull, detrital-feldspar particles are light blue, and a few zircon grains appear bright yellow. Also, note that the continuous red color of the dolomite crystals indicate that this type of dolomite has not replaced a precursor calcite or skeletal fragments.
- C) Trace-element concentrations along a probe traverse as shown in (B). Note, points 1 and 2 are relatively high in Sr^{2+} and Fe^{2+} content compared to points 3 and 4.

A



B





6.2.2 Texture 2: Unimodal, very finely crystalline, planar-s (subhedral) dolomite

The crystal size of this type of dolomite is less than 30 microns (Fig. 6-2). This texture is common in Microlithofacies 4 of both Mitchell #1 Well of Steuben County and Wasielewski #1 Well of Cayuga County and Microlithofacies 3 of Wilson Well, Wyoming County. The cathodoluminescence color of this dolomite is red (Figs. 6-2, 6-3). It is apparent that this dolomite has replaced the original skeletal debris of bryozoa (Fig. 6-2) and the precursor lime mud (Fig. 6-3). The luminescence study and microprobe analysis strongly supported this observation by the presence of yellow-calcite patches within the red-dolomite crystals (Fig. 6-2) and the appearance of the yellow- calcite zones that rimmed some of the replacive, red-dolomite crystals (Fig. 6-3). The probe analysis reveals that this type of replacive dolomite is rich in calcium and low in magnesium (the average of $\text{CaCO}_3:\text{MgCO}_3 = 64:36$). Also, manganese concentration is slightly high (average = 966 ppm). Other trace elements are present in low concentration (Fig. 6-3C).

6.2.3 Texture 3: Medium to coarsely crystalline, planar-e (euhedral) dolomite

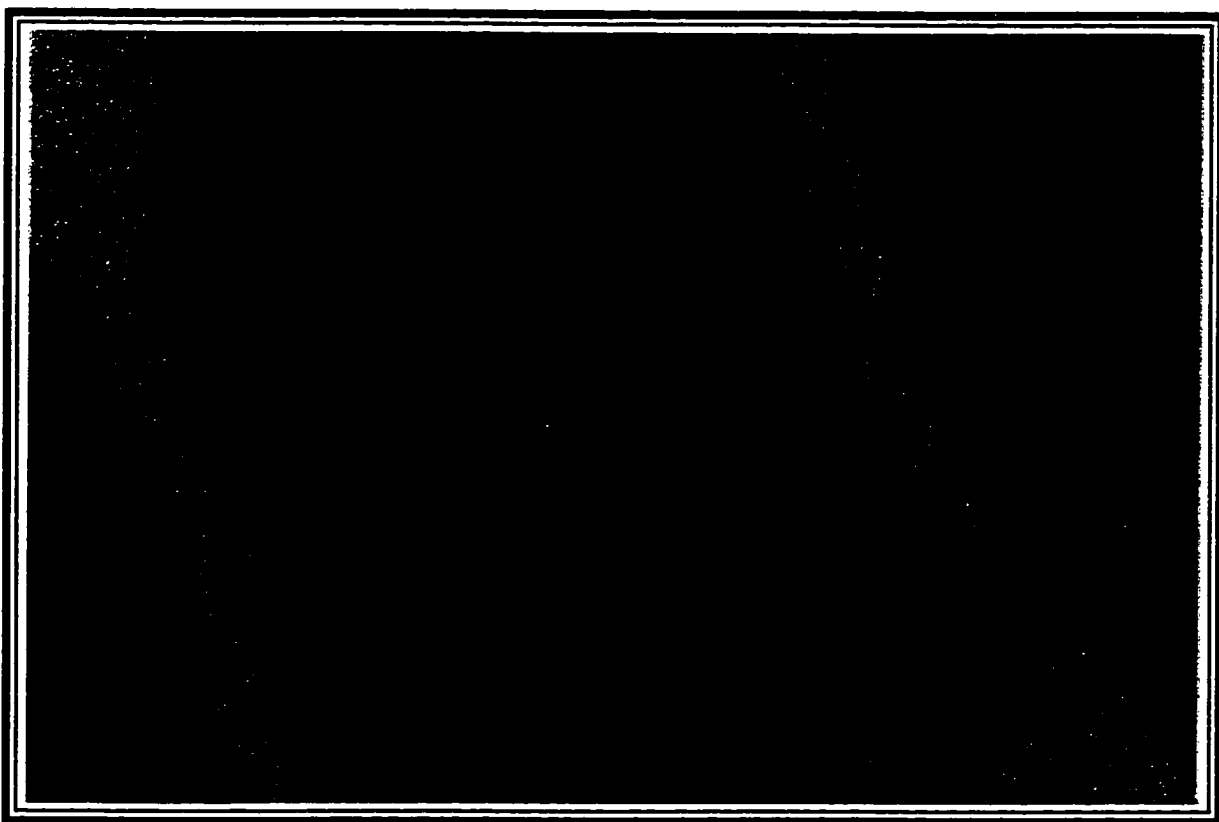
The crystals of this texture display perfect euhedral shapes. The size of these crystals ranges from 100 - 180 microns in diameter (Fig. 6-4). This type of dolomite is common in both Microlithofacies 4 of Mitchell Well, Steuben County and Wasielewski Well, Cayuga County. The crystals of this texture are zoned. Upon excitation with the electron beam, they show dark cores and alternate dull and red zonation (Fig. 6-4). Petrographic investigation shows no evidence of any replacement textures.

Figure 6-2. Texture 2: Unimodal, very fine crystalline, planar-s (subhedral) dolomite.

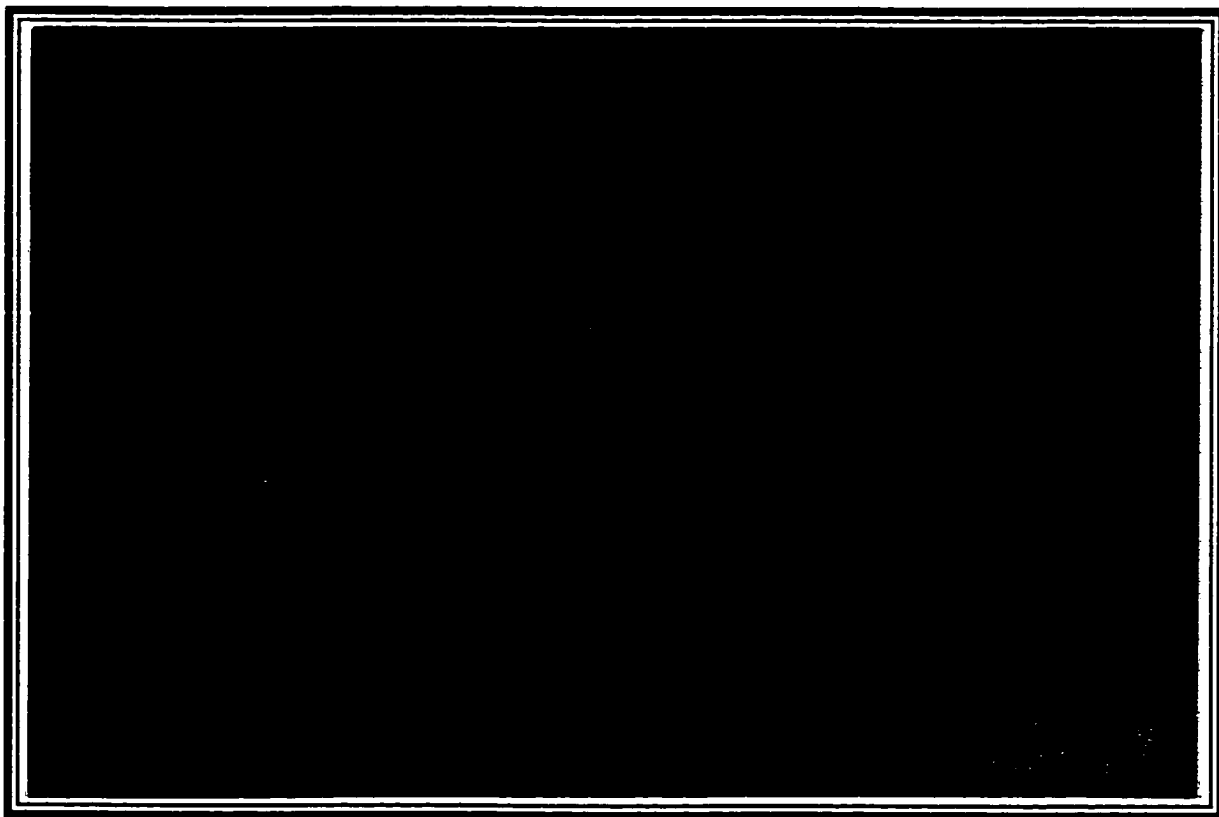
(Well cuttings from Wasielewski #1 Well, Cayuga County, depth: 2560' -2580')

- A) Photomicrograph of a thin section in plane-polarized light showing subhedral, fine crystalline dolomite that replaced a bryozoan fragment.
- B) Same view under luminoscope; note the bryozoan fragment has been dolomitized (red).
- C) Trace-element concentration along the probe traverse as shown in B. Note this texture is rich in Mn^{2+} in points 2 and 3. Si^{2+} is only found in point 3.

A



B



Wasielewski Well (Depth: 2560' - 2580')

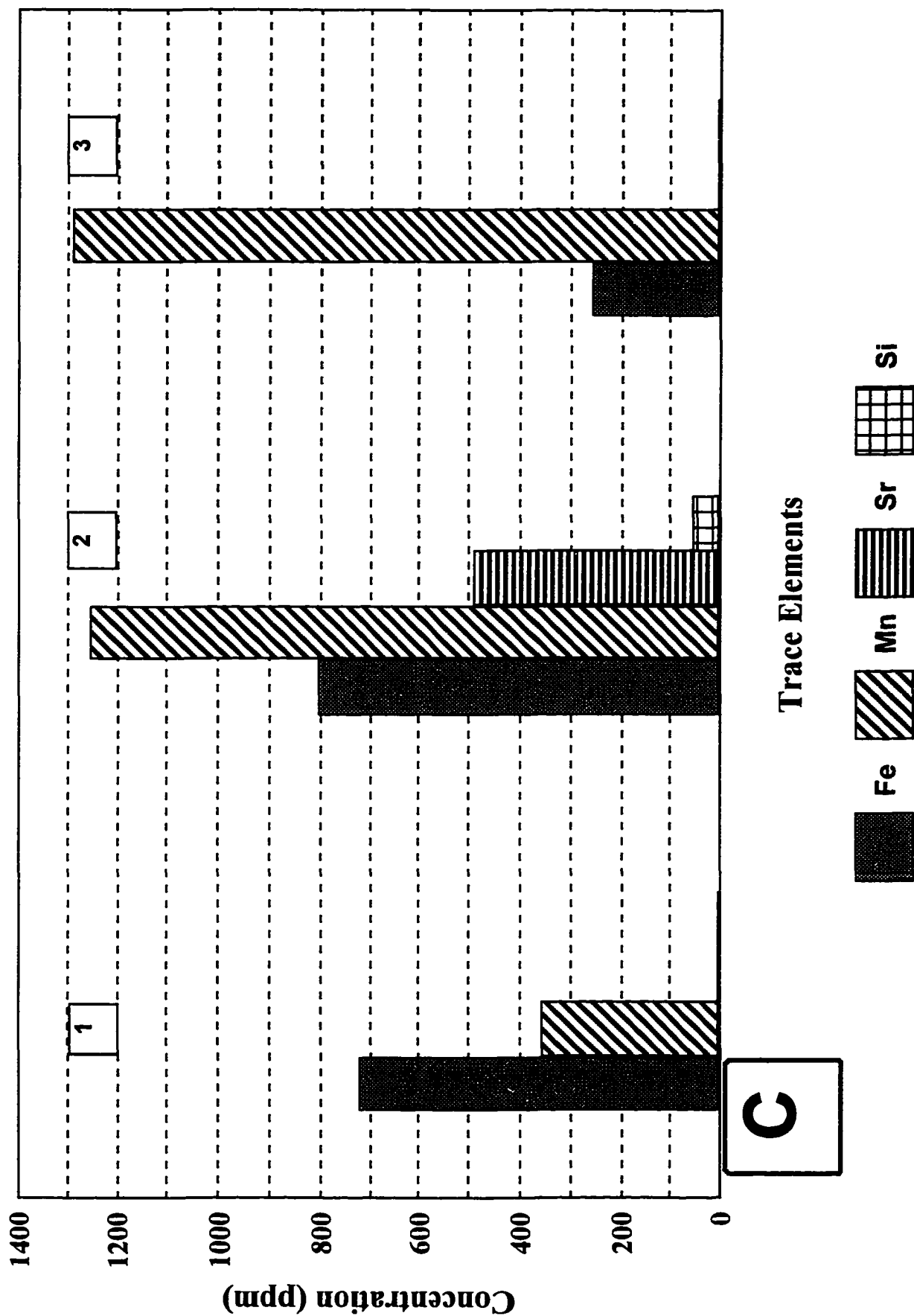
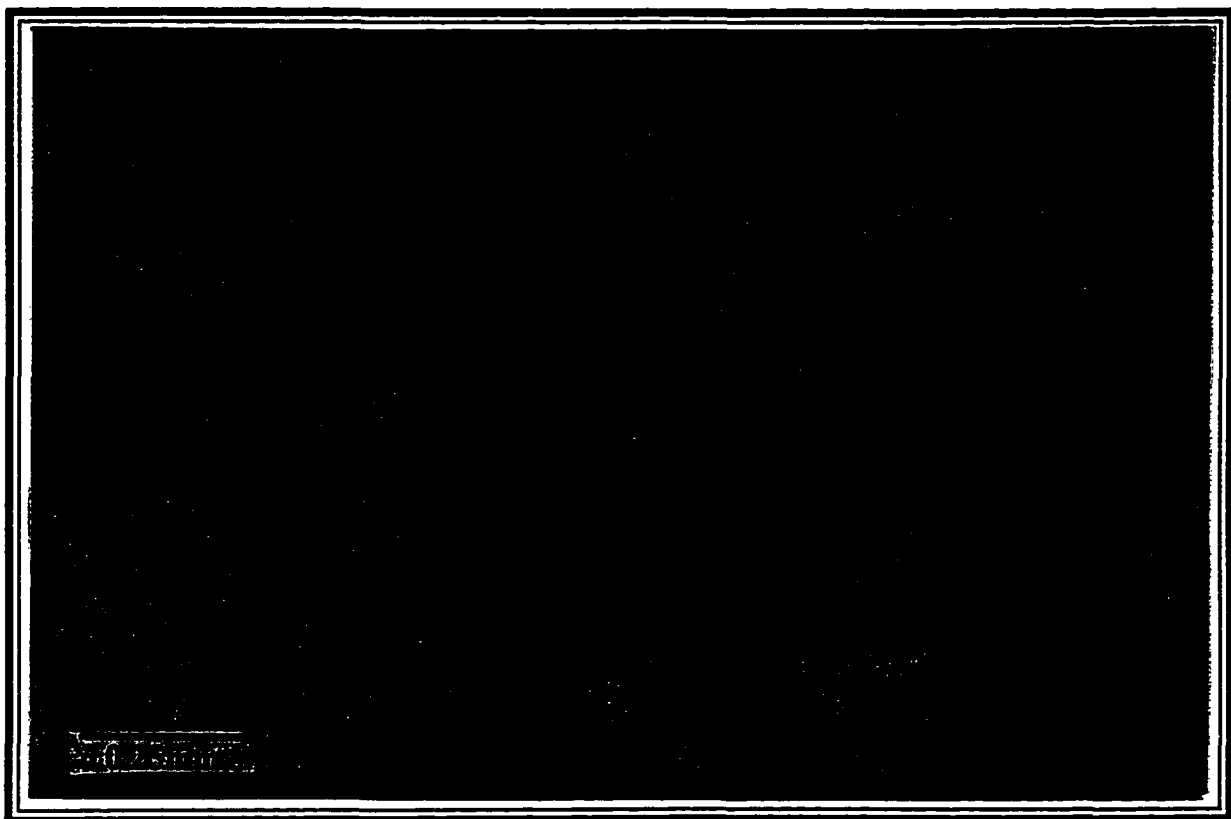


Figure 6-3. Texture 2: Unimodal, very fine crystalline, planar-s (subhedral) dolomite.

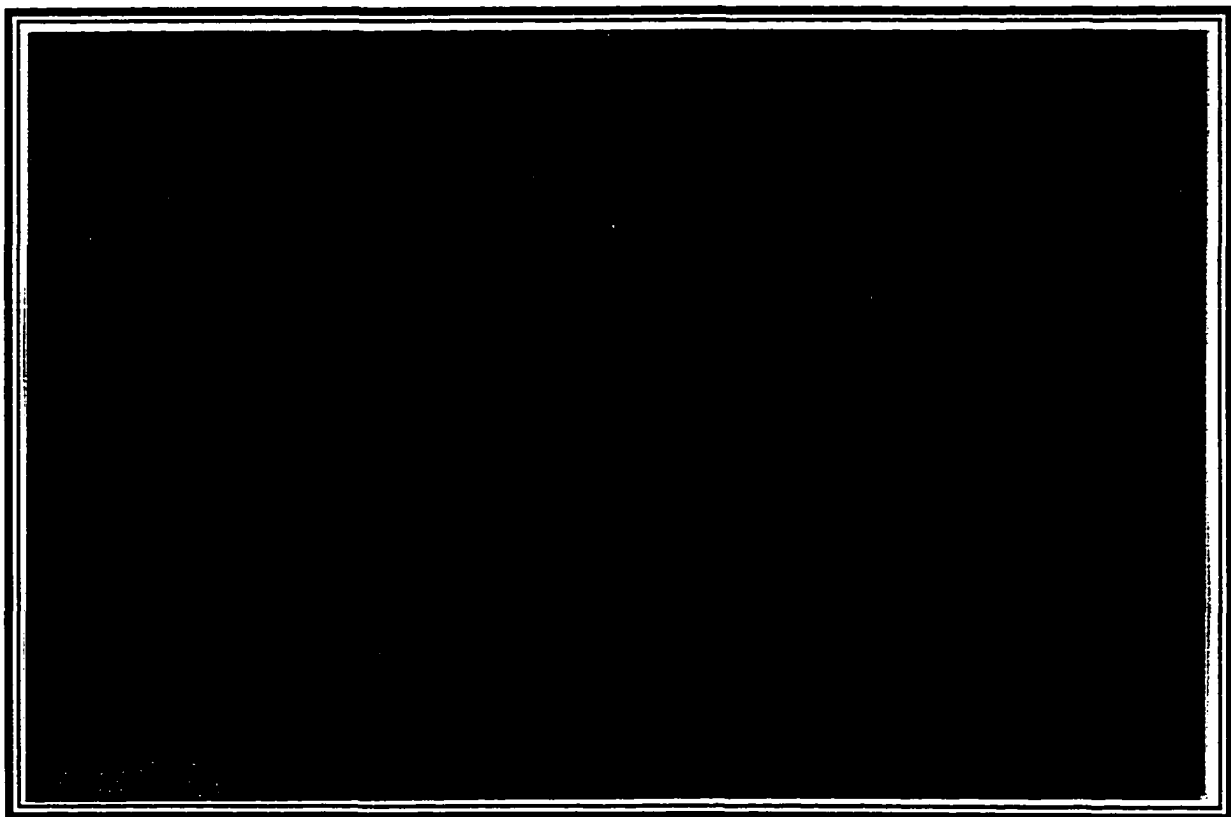
(Well cuttings from Wilson #1 Well, Wyoming County, depth: 6140' -6150')

- A) Photomicrograph of a thin section in plane-polarized light, showing that sample consists mainly of very fine, subhedral dolomite crystals.
- B) Same view under luminescope, note that the relics of calcite (yellow) within the dolomite crystals (red) indicate that this dolomite has replaced precursor lime mud.
- C) Trace-element concentrations along the probe traverse as indicated in B. This texture is rich in Mn^{2+} and Fe^{2+} . Sr^{2+} is only found in point 1 with low concentration. Si^{2+} is detected in points 2 and 3.

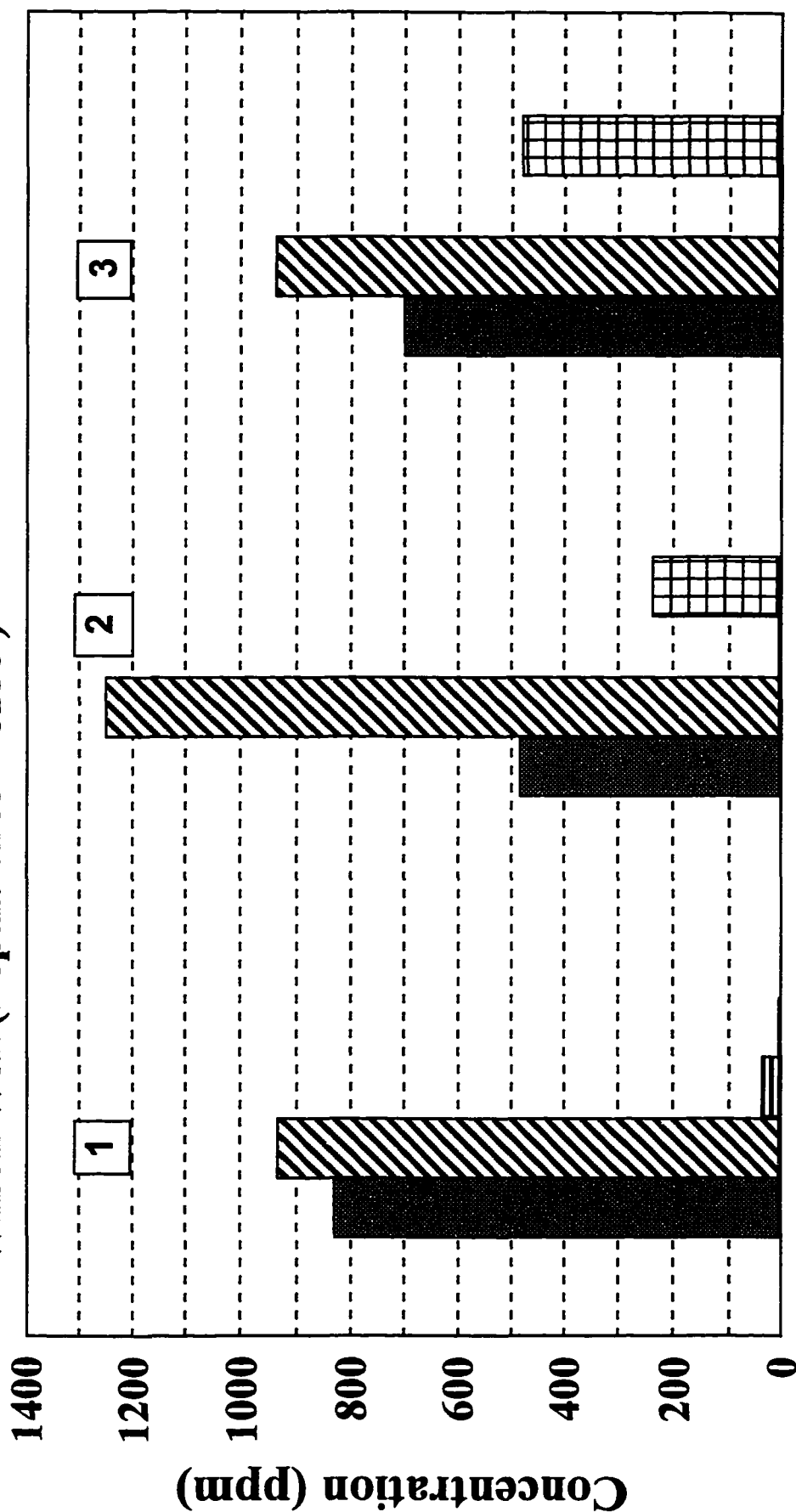
A



B



Wilson Well (Depth: 6140' - 6150')



C

Trace Elements

Fe Mn Sr Si

The detected values of the major elemental composition support that this type of dolomite is nonstoichiometric (the average of the $\text{CaCO}_3 : \text{MgCO}_3 = 60 : 40$). The dolomite crystals are zoned and show a high concentration of iron (average = 2100 ppm) and strontium is also present in high concentration (1774 ppm). The average concentration of the manganese in this texture equals 672 ppm (Fig. 6-4C). Silicon concentration is not recorded and could be below the detection limit.

6.2.4 Texture 4: Coarsely crystalline, non-planar dolomite (non-saddle dolomite)

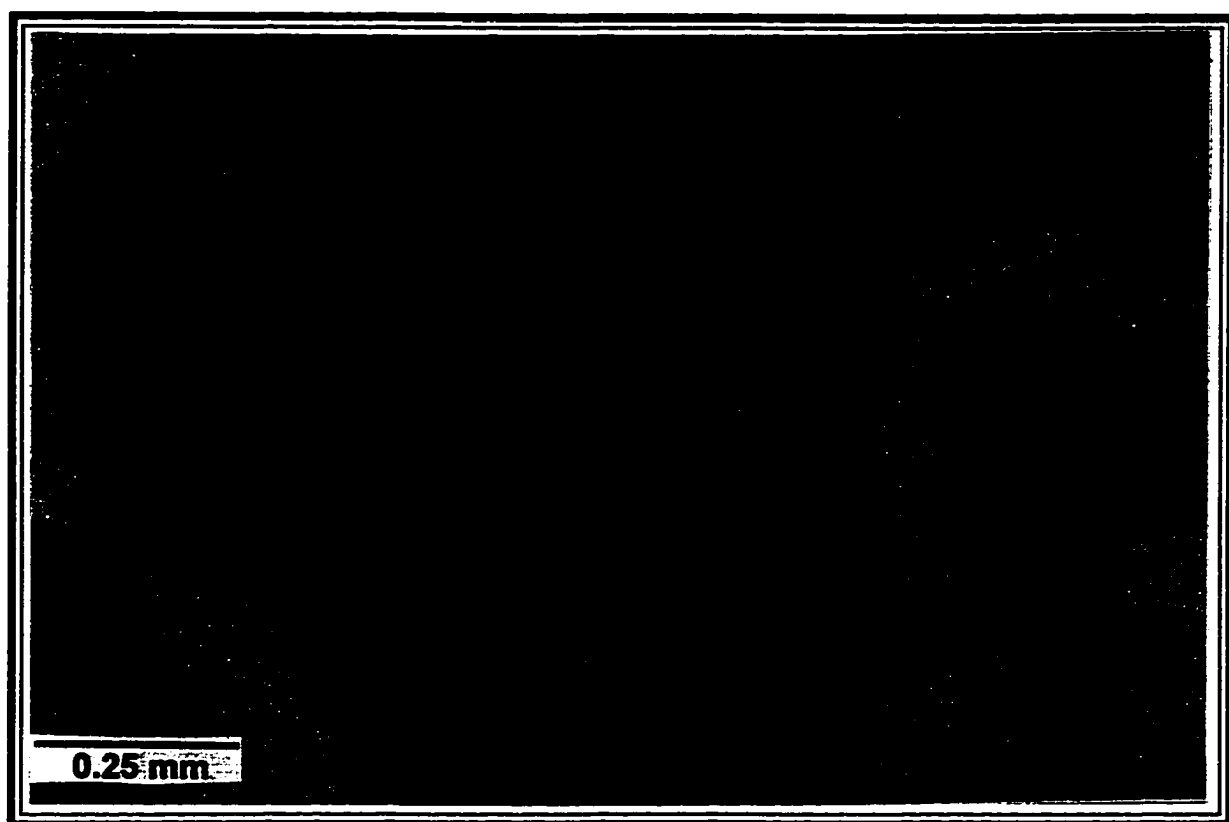
This dolomite texture consists of anhedral, closely packed dolomite crystals. The crystal sizes of this type of dolomite range from 250 to 600 microns in diameter. The crystal boundaries have curved, lobate, and serrated outlines (Fig. 6-5). This texture developed locally in patches as a void cement in both Lithofacies 5 of the Waste Water Disposal Well of Niagara County, Lithofacies 4 of the Robert Olin Well of Steuben County, and in both Microlithofacies 4 of the Wasielewski Well of Cayuga County and the Mitchell Well of Steuben County. This type of dolomite is usually associated with other types of dolomite such as the unimodal, very finely crystalline, planar-e dolomite and/or the unimodal, very finely crystalline, planar-s dolomite (Fig. 6-5). The cathodoluminescence study reveals that this type of dolomite displays dull to very dark red color. However, it grades into zoned crystals with planar outlines in form of dog-tooth structures at the void's rim (Fig. 6-5 A, B). Truncation and amputation of the crystals are common feature of this type of void-filling dolomite (Fig. 6-5). The probe detection of the major and trace elements indicates that this type of dolomite cement is nonstoichiometric (the average of the $\text{CaCO}_3 : \text{MgCO}_3 = 64 : 36$). High concentration of iron (2038 ppm), manganese (270 ppm), and low concentration of strontium (698 ppm) and silicon (1298 ppm) (Fig. 6-5C) were detected by the probe.

Figure 6-4. Texture 3: Medium to coarse crystalline, planar-e (euhedral) dolomite.

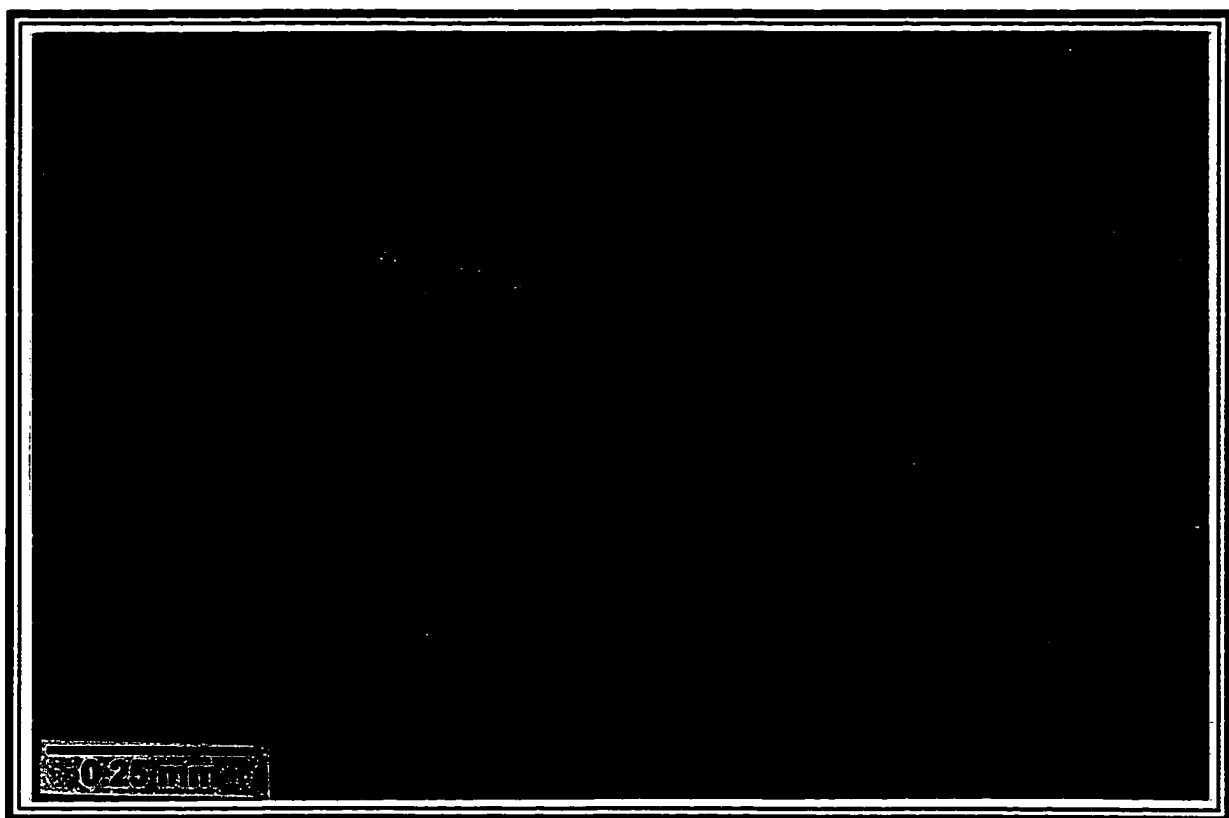
(Well cutting from Mitchell #1 Well, Steuben County, depth: 8360' - 8370')

- A) Photomicrograph of a thin section in plane-polarized light, showing large euhedral dolomite crystals
- B) Same view under luminoscope showing concentric zones (dull and red). The dark zones are Fe^{+2} rich and the red ones are Mn^{+2} rich.
- C) Trace-element concentration along the probe traverse that is shown in B. This texture is rich in Fe^{2+} content that make it dark to dull in color. Also, Sr^{2+} is recorded by high concentration (over 500 ppm) in this texture. No Si^{2+} was found in this texture.

A



B



Mitchell Well (Depth: 8360' - 8370')

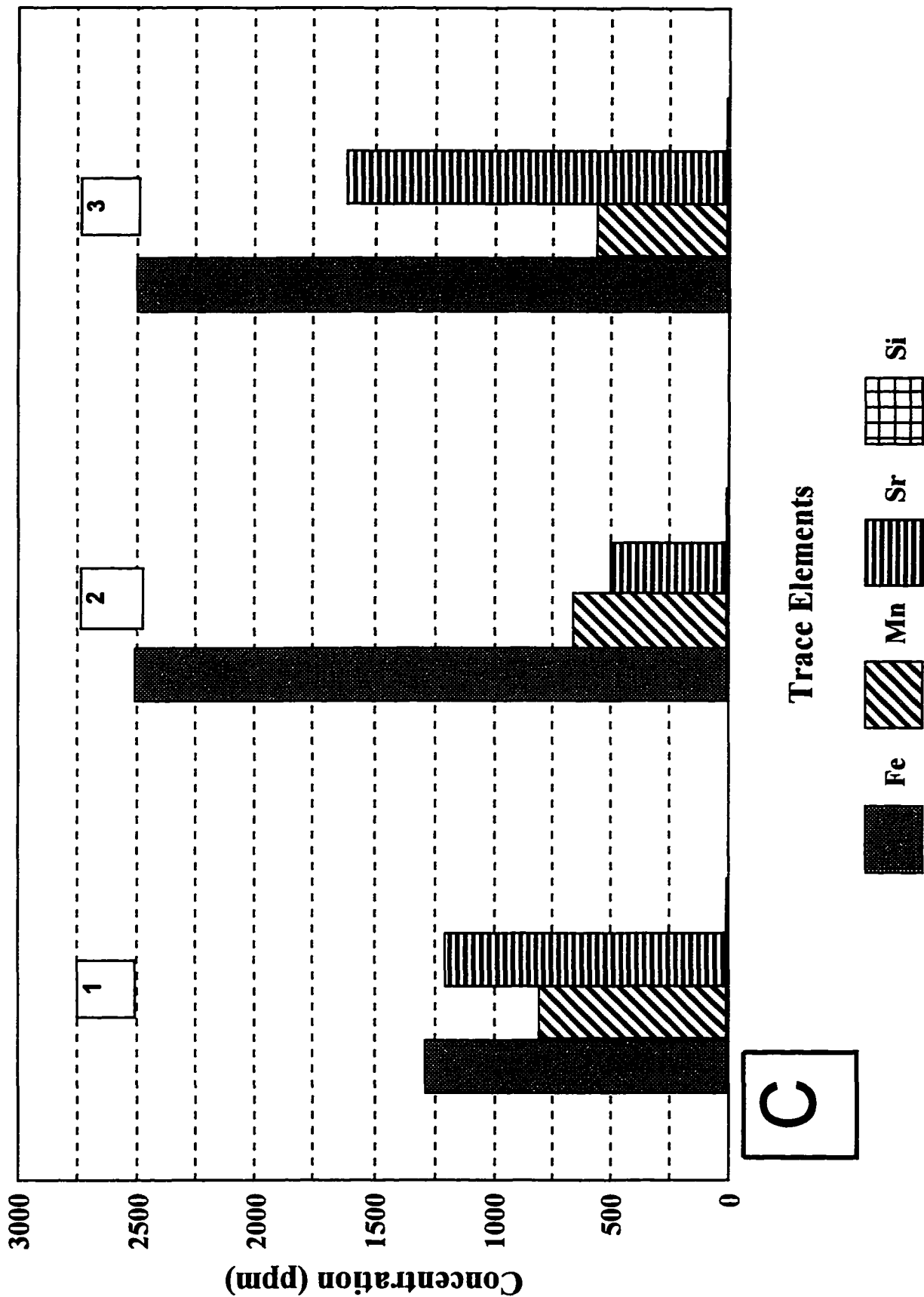
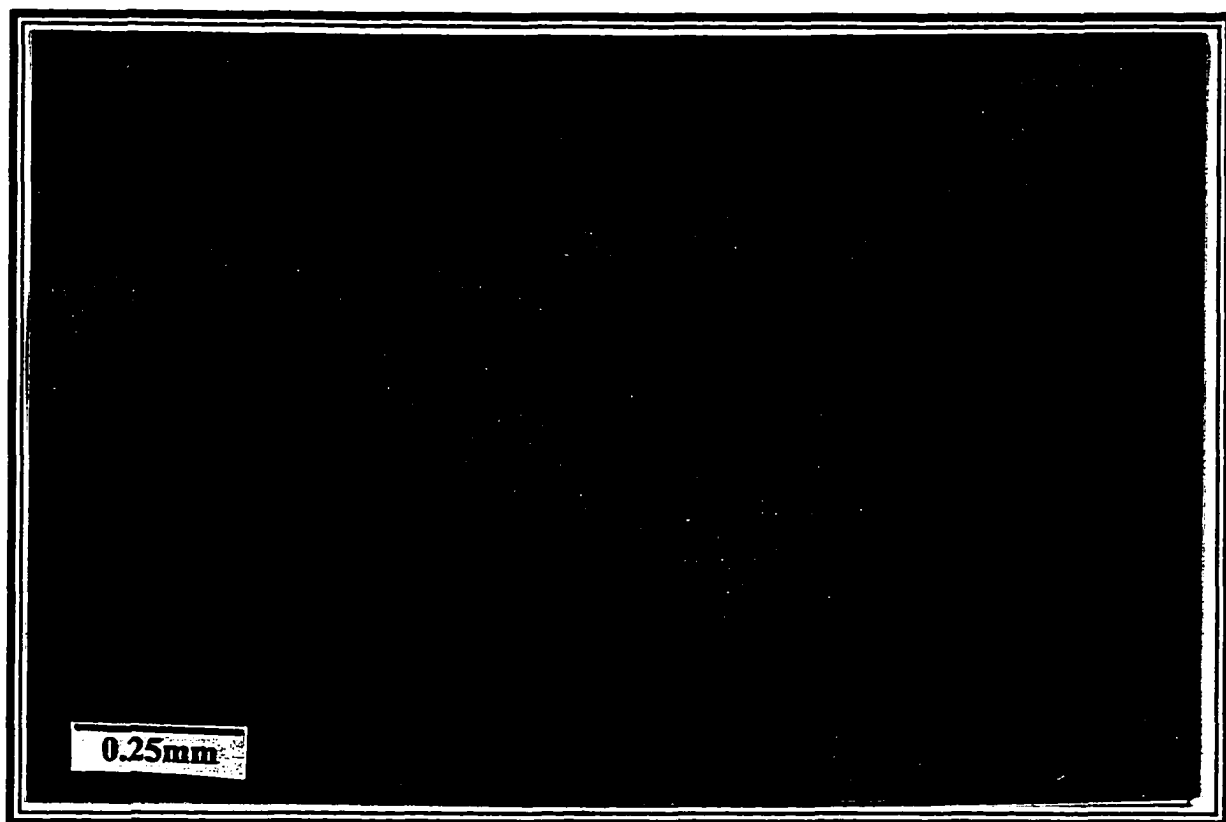


Figure 6-5. Texture 4: Coarsely crystalline, non planar dolomite (non saddle dolomite).

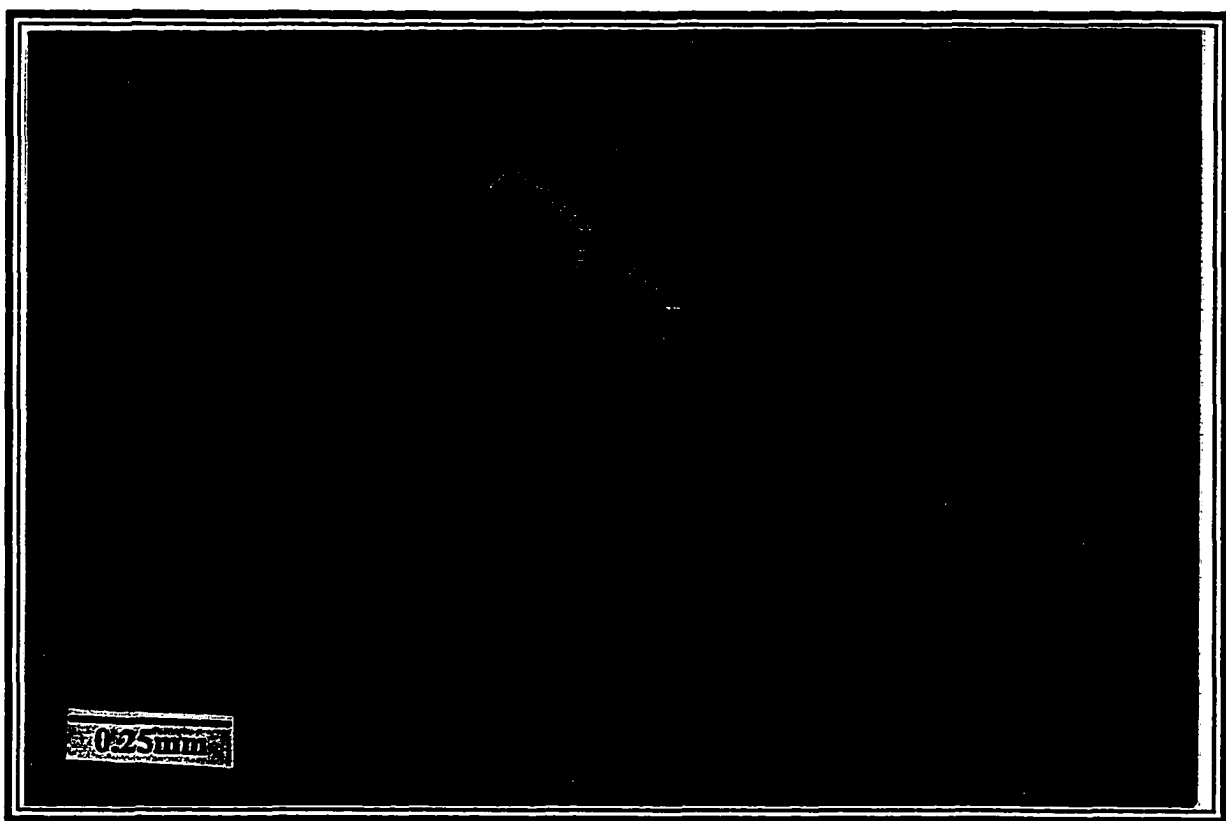
(Robert Olin #1 Well, Steuben County, depth: 12538')

- A) Photomicrograph of a thin section in plane-polarized light, showing coarse, closely packed dolomite crystals that filling a former void. Note the crystal boundaries have curved outlines.
- B) Same view under luminoscope showing that texture displays dull to very dark red color in the center of the void. However, it grades to zoned crystals with a planar outline in form of dog-tooth structures at the void's rim.
- C) Trace-element concentrations along the probe traverse as shown in B. Note the high concentration of Fe^{2+} in point 3 (at the void's center) compared to the other points. Sr^{2+} concentration is high in this texture.

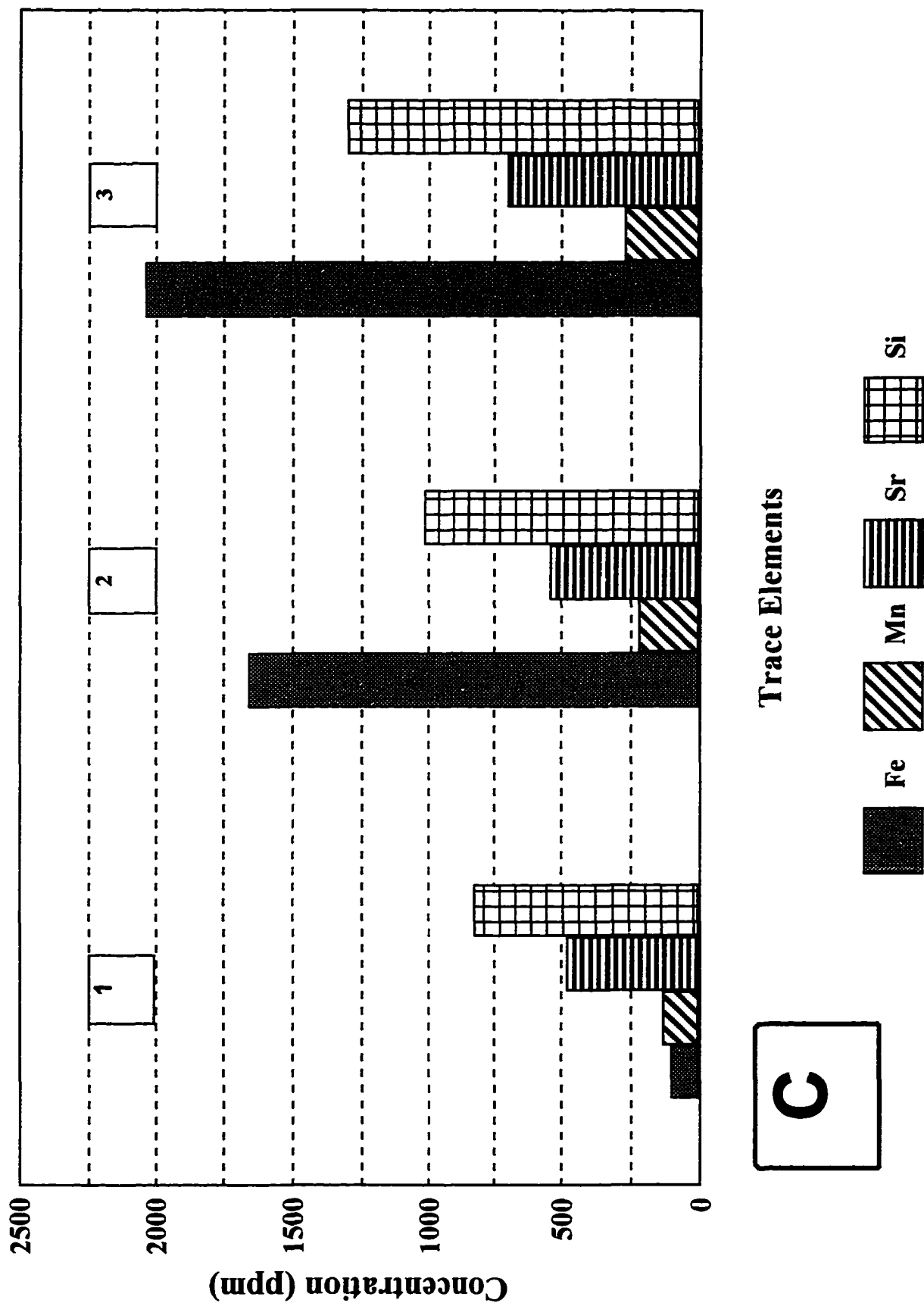
A



B



Robert Olin (Depth: 12538)



6.2.5 Texture 5: Very coarsely crystalline, non-planar dolomite (saddle dolomite)

This type of texture consists of large crystals (700 - 1200 microns in diameter) that are closely packed, saddle-shaped faces, and milky white in color under plane-polarized light (Fig. 6-6). These dolomite crystals are characterized having a sweeping extinction under the crossed nicols that makes them distinguishable from the other dolomite types. Distribution of saddle dolomite among different lithofacies and microlithofacies is varied. However, the concentration of this dolomite texture has been observed in Lithofacies 4, 5, and 7 of the Waste Water Disposal Well of Niagara County, Lithofacies 4 of the Robert Olin Well of Steuben County, and in places in Microlithofacies 3 and 4 of the Wilson Well of Wyoming County, Microlithofacies 3 of the Wasielewski Well of Cayuga County, and Microlithofacies 2 of the Mitchell Well of Steuben County. The dolomite occurs as void, vugs, and fracture filling (cement) throughout the lithofacies and microlithofacies. As a result, this type of dolomite occludes pore spaces and has a negative effect on the reservoir quality. The saddle dolomite is rich in calcium and has a lower concentration of iron as compared to the other dolomite cement (Texture 4). The dolomite cement is nonluminescence under the electron beam which may related to its optical orientation (Fig. 6-6).

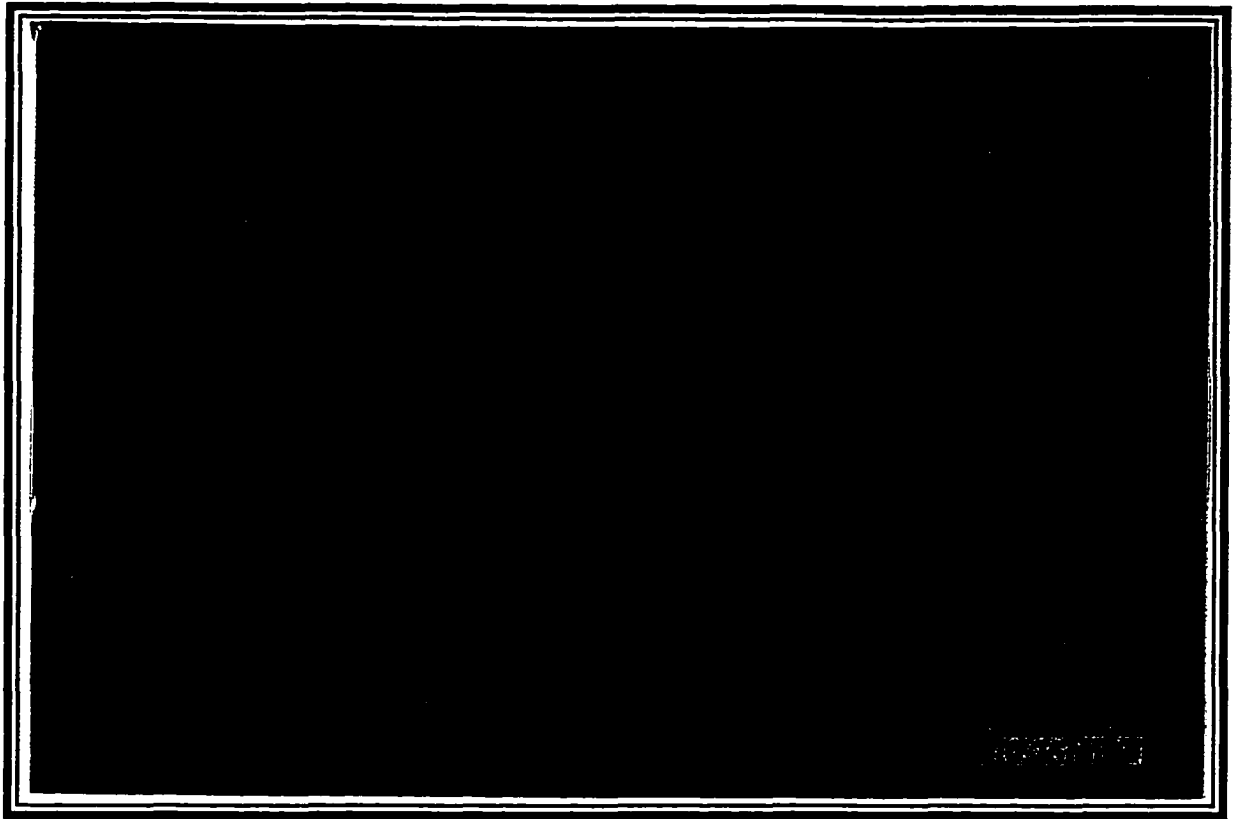
Saddle dolomite, as noted by probe analysis is nonstoichiometric (the average of the CaCO_3 : $\text{MgCO}_3 = 67 : 33$). It has a high manganese (1004 ppm) and iron (520 ppm) content. Also, this dolomite cement has a measurable amount of Si (4017 ppm) and Sr (502 ppm) (Fig. 6-6C-point 3).

Figure 6-6. Texture 5: Very coarsely crystalline, non-planar dolomite (saddle dolomite).

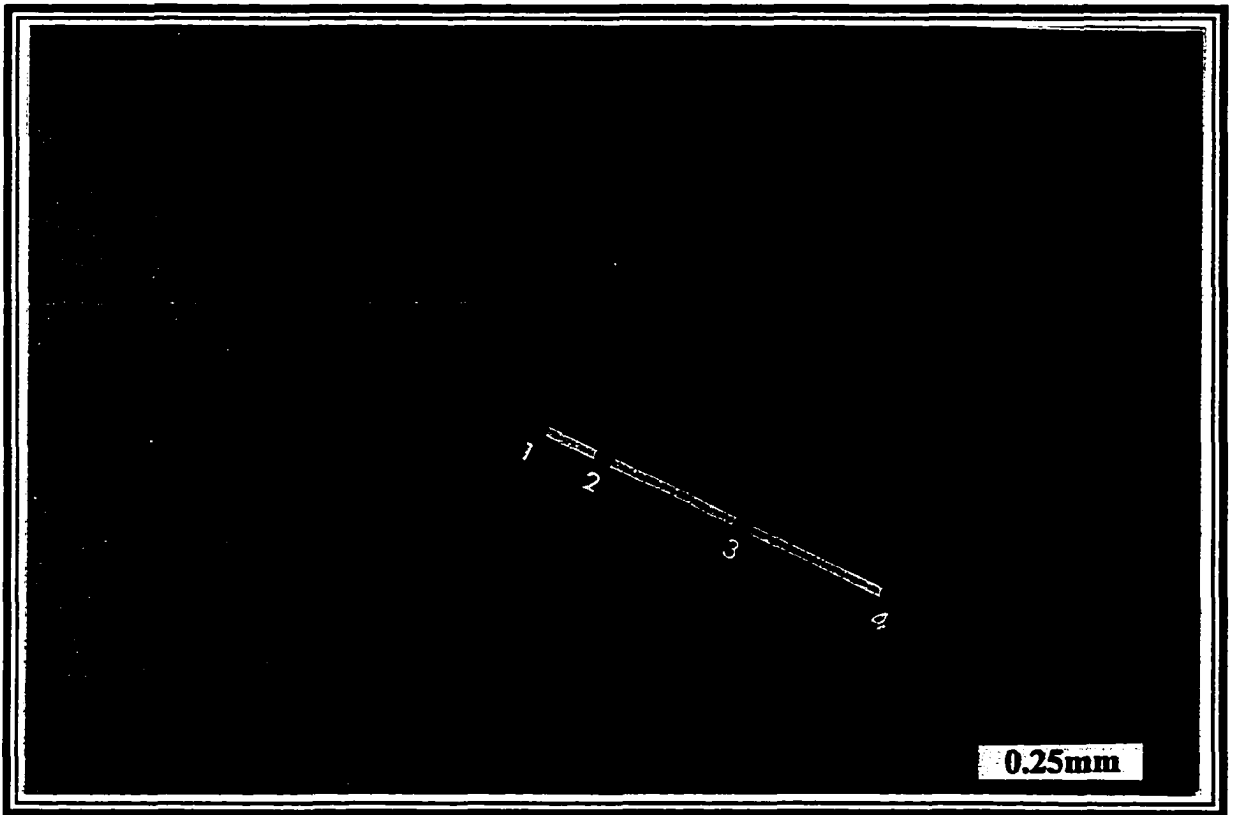
(Waste Water Disposal #1 Well, Niagara County, depth: 2896')

- A) Photomicrograph of a thin section in plane-polarized light, showing closely packed, saddle-shaped dolomite crystals.
- B) Same view under luminescope showing dull to non-luminescence saddle-dolomite crystals (point 3) that filled a large void within zoned red dolomite (point 1). Note the replacive origin of this saddle dolomite which has an inclusion of a zoned dolomite rhomb (point 3).
- C) Trace-element concentrations along a probe traverse as indicated in B. Note the probe detection indicates high Si^{2+} content compared to other elements (point 3). Also, Mn^{2+} is higher than Fe^{2+} in this texture (point 3).

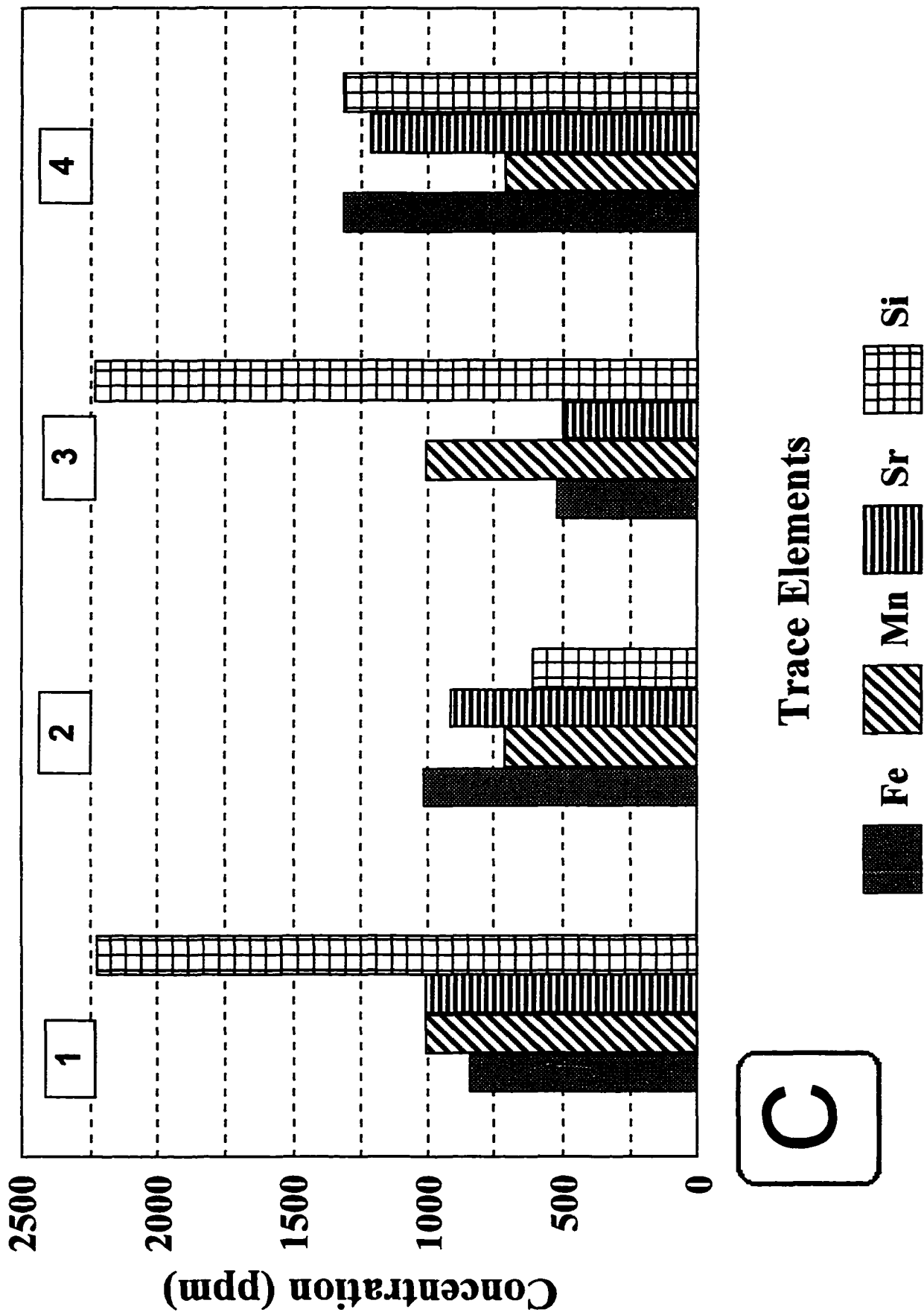
A



B



W.W.D Well (Depth: 2896')



6.2.6 Texture 6: Polymodal dolomite

Like its name, this dolomite consists of a combination of more than two types of dolomite.

Figure 6-7 shows microfractures and a continuous-dissolution seam which intersect a crinoidal fragment (?). Based on cross-cutting relationships under the luminoscope, at least 4 generations of dolomite have existed in this particular texture. The skeletal fragment (Fig. 6-7) has been replaced by two types of dolomite. A dark zoned, planar-e dolomite at the core of this skeletal fragment, which is similar to the matrix of the entire thin section, and a cryptocrystalline-red dolomite at the outer edges. Medium-sized, zoned-dolomite crystals grew as scattered rhombs within the matrix at the microfractures and the stylolitic horizons (Fig. 6-7). Later, these zoned dolomite crystals have been intersected by late-generation cryptocrystalline red dolomite (Fig. 6-7). This type of polymodal dolomite texture occurs in Lithofacies 7 of Waste Water Disposal Well, Niagara County, Lithofacies 5 of Robert Olin, Steuben County, Microlithofacies 3 of Wasielewski Well, Cayuga County.

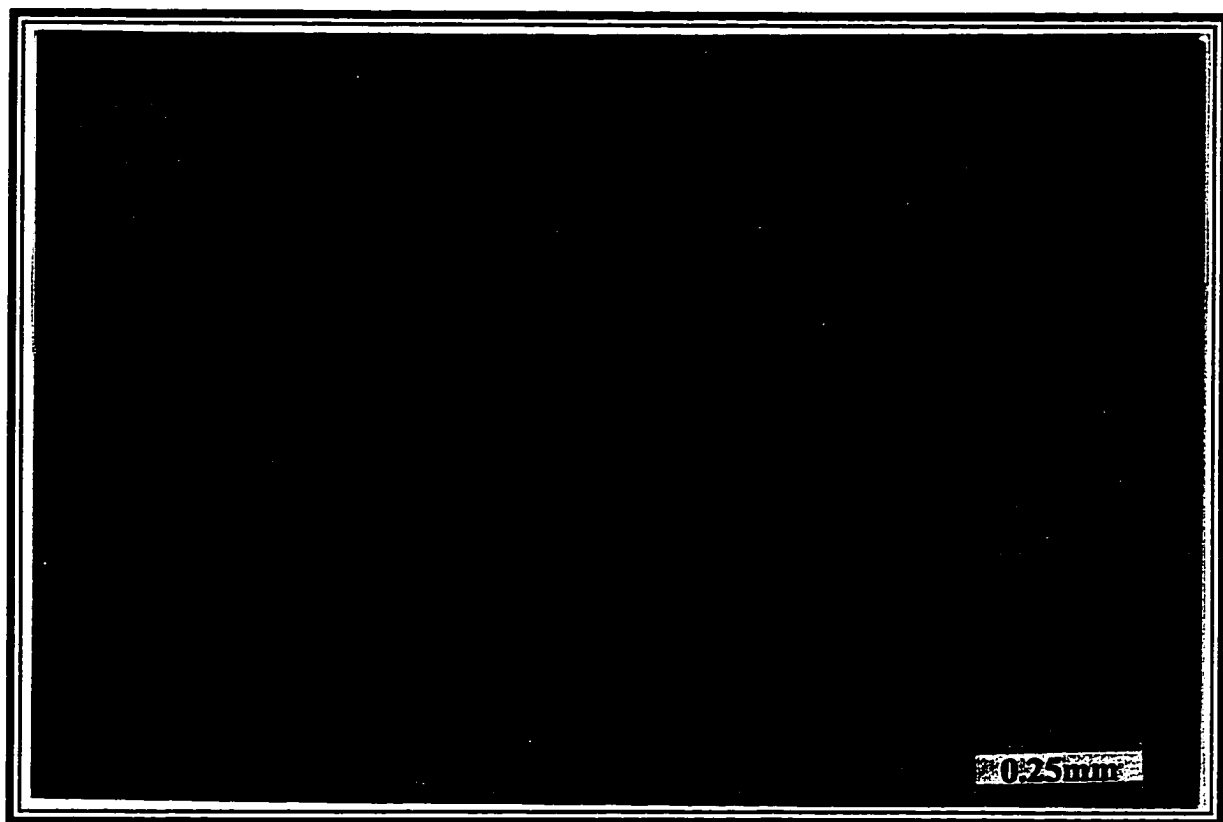
The probe detection of the major and trace-elements distribution of this polymodal dolomite shows a wide variation in the concentration values of the selected points along the probe traverse (Fig. 6-7C).

Figure 6-7. Texture 6: Polymodal dolomite.

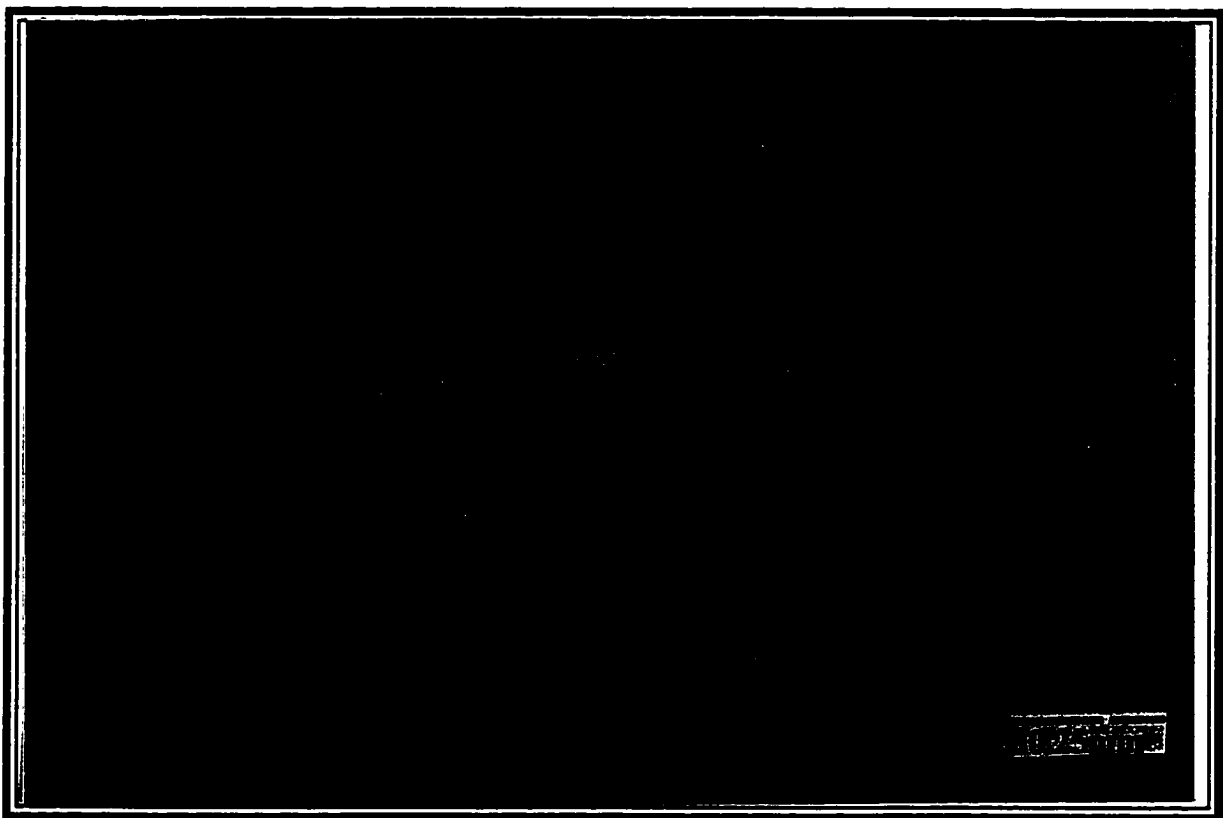
(Waste Water Disposal #1 Well, Niagara County, depth: 2854')

- A) Photomicrograph of a thin section in plane-polarized light showing microfractures and a continuous dissolution seam which intersected a crinoidal fragment.
- B) Same view under luminoscope; at least four generation of dolomite are recognized. Note the replacement of skeletal fragment by two types of dolomite crystals. Dark zoned, planar-e dolomite at the core of this skeletal fragment and cryptocrystalline-red dolomite at the outer edges. Also note the medium-sized, zoned dolomite crystals grew as scattered rhombs within the matrix in the microfractures and stylolite horizons. These zoned-dolomite rhombs are intersected by late-generation cryptocrystalline, dolomite crystals.
- C) Trace-element concentration along the probe traverse as shown in B. Note, the analyzed points show different levels of trace-element concentrations.

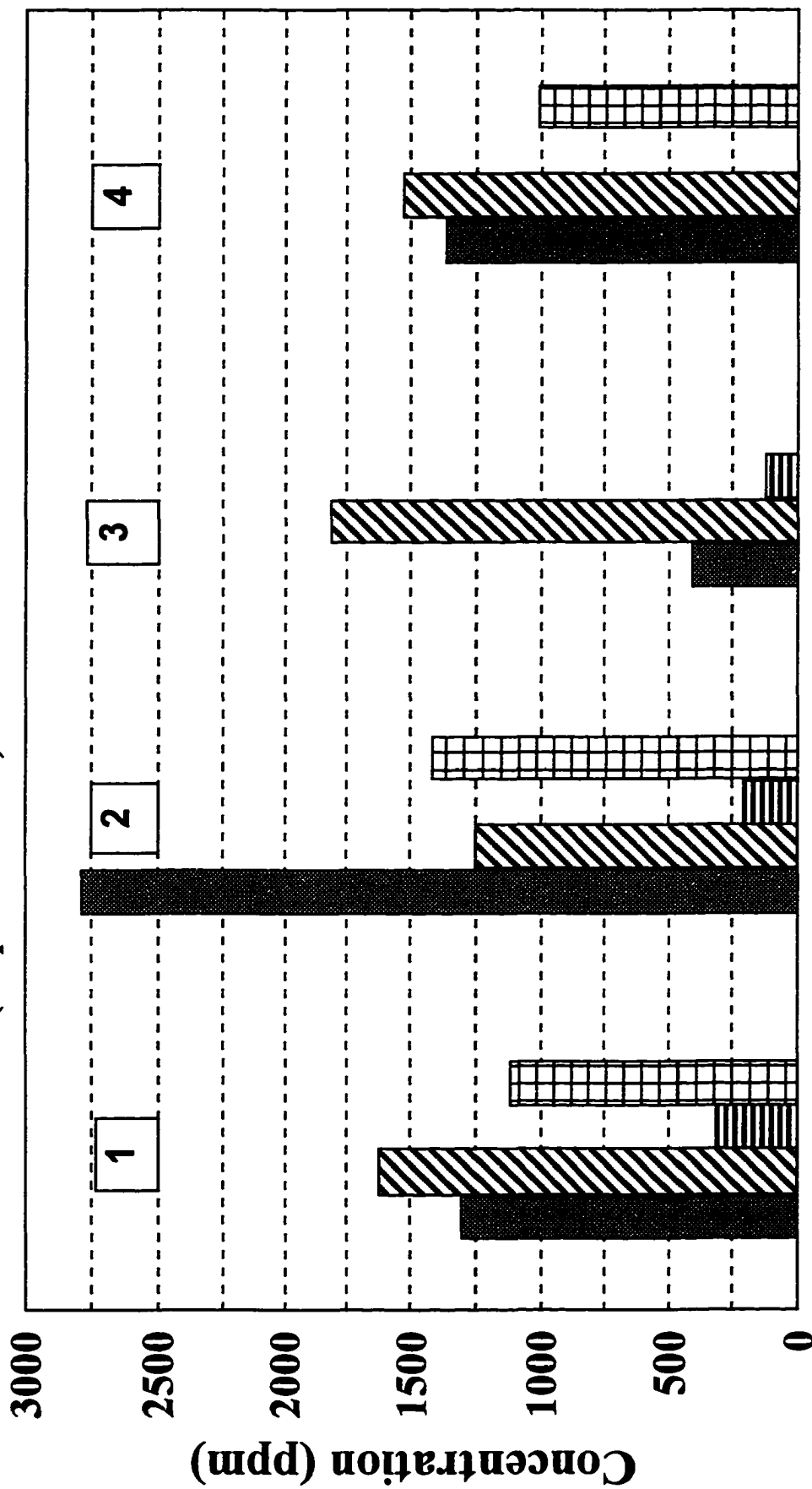
A



B



W.W.D. Well (Depth: 2854')



C

Trace Elements



6.2.7 Dolomite Replacement and Cementation

Replacement Dolomite: Comprehensive dolomitization has occurred in both the Potsdam and Theresa Formations of the Beekmantown Group (Sauk Sequence) of studied wells. These replacive dolomite crystals are coarsely crystalline and their shapes range from anhedral (xenotopic texture) to euhedral (idiotopic texture). Zoned ferroan dolomite is abundant and is considered to be the major element of the replacive-dolomite type (Figs. 6-4 and 6-5). The origin of this replacement dolomite may have resulted from the invasion of the former limestone by magnesium-rich water. The invasion could have happened through mega- and microfractures, joints, faults, and pore spaces. The source of this magnesium-rich solution responsible for these dolomitization processes is obscure.

Void-filling Dolomite (Dolomite Cement): This type of dolomite is very common in the Theresa Formation (Beekmantown Group) and is represented by coarsely crystalline dolomites that precipitated as cement in the available void spaces. In the Beekmantown Group, Textures 4 (non-saddle dolomite) and 5 (saddle dolomite) are the constituents of this void-filling dolomite (Figs. 6-5 and 6-6). The crystals range from 200 to 1200 microns in diameter. These crystals are non-luminescent because they are rich in iron. The dolomite cement shows crystal growth on the margins of the pre-existing voids. Petrographic observation of some selected thin sections from the Waste Water Disposal #1 Well of Niagara County shows inclusions of zoned-ferroan dolomite within the saddle dolomite (Fig. 6-6). It is evident, the saddle dolomite originated during the late-stage diagenesis.

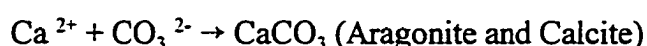
6.2.8 Origin of the Beekmantown Group Dolomites

The origin of dolomites throughout the geologic time is still an unsolved mystery. However, many attempts have been made to understand this problem. In 1823, Van Bush proposed a theory

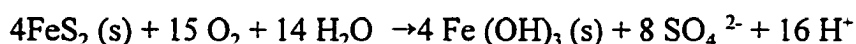
called “The Plutonist-Neptunist theory for dolomite formation”. He ascribed the formation of mineral dolomite to volcanic vapors of deep-seated origin. This theory was attacked by Virlet in 1835 (Gohau, 1991). In 1836, Eli de Beaumont related the origin of dolomite to circulation of magnesium biocarbonate-rich solution through limestone beds. Also, he stated that the molecular replacement of limestone by dolomite should be accompanied by a decrease in volume of the original rock to the extent of about 12.1 percent. This theory was conformed by Morlot in 1838 upon his experiment of testing the actual porosity in dolomite samples. In 1900, Suess proposed the sedimentary origin of most dolomites which was widely accepted (Gohau, 1991).

In his discussion about the origin of dolomite, Fairbridge (1957) formulated what is known as the “dolomite question”. This discussion is mainly concerned with the origin of dolomites throughout the geologic record. This proposed question was the seed of many studies in order to understand this problem by trying to reach a logical solution. Various studies reported that dolomite forms from different-chemical fluids under different environmental settings (Graf and Goldsmith, 1956; Friedman and Sanders, 1967; Zenger, 1972; Carpenter, 1980; Land, 1980,1985; and Sibley et al., 1987). Despite the environmental conditions and the chemistry of the dolomitization fluids being different, the mechanism that allowed dolomites to form should have been the same throughout the geologic record. This mechanism is most likely to be controlled by the climate (Tucker and Wright, 1990), global sea level fluctuation (Sibley, 1991), and evolution of the world ocean and atmosphere. These conditions may have resulted in changes including the pressure of CO₂ which in return influenced the saturation of the carbonate minerals in the oceans and seas (Sandberg, 1983; Tucker, 1992). Also another school of thinking believes that formation of dolomite is controlled partially or totally by the presence of the organic matters and reducing bacteria. As

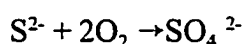
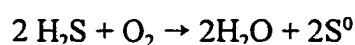
suggested by McKenzie (1981) and Baltzer et al. (1994) in their discussion about the origin of dolomites in sabkha settings, they concluded that bacterial reduction of sulphates lead in increasing alkalinity and oxidation of microbial mats. These processes are associated with distribution of the dolomite in the sabkha of Abu Dhabi. Also, Oren (1989) reported that high Mg^{2+} , Ca^{2+} , Cl^- , and Na^+ are associated with the photosynthetic and heterotrophic benthic bacterial communities of the hypersaline sulfur spring of the shore of the Dead Sea (Hamei Mazar). Lazar et al. (1989) concluded that gradual precipitation of bases such as calcite, aragonite, magnesite, pyrite, and sedrite reduce the total alkalinity according to the following reaction:



Pyrite oxidation also may involve dissolution. In this case the total alkalinity may drop as indicated by the following equation:



Following that step is the oxidation of dissolved sulfide that may occur nonbiologically or biologically to form sulfate as follows:



Generally, the hypersaline settings are rich in dissolved organic matter that is associated with microbial mats. The hypersaline brine that is rich within the microbial mats environment may react with the pore water. Consequently, the total alkalinity increases causing elevation of the Mg/Ca ratio in the sea water. As a result, the Mg^{2+} replaces the Ca^{2+} in the preexisting limestone and eventually leads to dolomitization. Generally, the regulatory mechanism between the microbial mats and dolomitization processes is not fully understood.

Dolomitization is more abundant in the ancient and modern tidal flats than in any other environment. This is because of the high evaporation rate that may have resulted in the formation of evaporitic minerals such as gypsum and anhydrite. Precipitation of these evaporitic minerals increases the Mg/Ca ratio of the residual brine. Movement of these brines throughout the lime mud elevates the Mg content that leads to dolomitization (Friedman, 1967).

Petrographic and geochemical studies indicate three possible origins of the Beekmantown Group dolomites. These origins are: replacement dolomite, primary dolomite (penecontemporaneous), and void-filling dolomite.

Replacement Dolomite:- Comprehensive dolomitization has occurred in both the Potsdam and Theresa formations of the Beekmantown Group (Sauk Sequence) of the studied wells. These replacive dolomite crystals are coarsely crystalline and their shapes range from anhedral (xenotopic texture) to euhedral (idiotopic texture). Zoned ferroan dolomites are abundant and considered to be the major element of the replacive-dolomite type (Figs. 6-4 and 6-5). The origin of this replacement dolomite may have resulted from the invasion of the former limestone by magnesium-rich water. The invasion could have happened through mega-and micro-fractures, joints, faults, and pore spaces. The source of this magnesium-rich solution that is responsible for this vast-dolomitization processes is obscure.

Primary (Penecontemporaneous) Dolomite:- Primary dolomite is represented by the presence of the finely crystalline or micritic dolomite (Fig. 6-1, 6-2). It is common in the upper part of the Beekmantown Group (Theresa Formation). The origin of primary dolomite could be from direct nucleation of the crystals in the water column from the sufficient of Mg^{+2}/Ca^{+2} ratio that permits crystallization of dolomite rhombs (Textoris, 1969; Zenger, 1972; Land, 1985). Friedman and

Sanders (1967, 1978) referred to this finely crystalline dolomite as resulted from “capillary concentration” of hypersaline brines through porous sea-marginal sediments.

Void-filling Dolomite :- Void-filling dolomite is very common in the Theresa formation (Beekmantown Group) and is represented by coarsely crystalline dolomites that precipitated as cement in the available void spaces. In the Beekmantown Group, Textures 4 (non saddle dolomite) and 5 (saddle dolomite) are the constituents of this void-filling dolomite (Figs. 6-5 and 6-6). The crystals range from 200 to 1200 microns in diameter. These crystals are non-luminescent and the probe analysis indicates that their contents are rich in iron. This dolomite cement shows crystal growth on the margins of the pre-existing voids. Petrographic observation of some selected thin sections in the Waste Water Disposal #1 Well of Niagara County shows inclusions of zoned-ferroan dolomite within the saddle dolomite (Fig. 6-6). This clearly indicates that the saddle dolomite has a late-stage diagenetic origin.

6.2.9 Model of Dolomitization

Petrographic analysis of the available core sections and well cuttings from the Beekmantown Group of central and western New York support the evaporitic origin of their dolomites. During the Cambro-Ordovician time, a relative sea level dropped resulted in subaerial exposure of the Beekmantown strata. Consequently, the evaporation rate was high at the tidal flat environment. In such settings, a supratidal evaporative and reflux dolomitization by marine water may have taken place. The evaporating origin of the Beekmantown dolomite is supported by the presence of the abundant evaporitic minerals. Figure 6-8 shows halite crystals within a fine dolomitic matrix. Two models of dolomitization can be applied to explain the mechanism of these dolomitizations. These models are: 1) Seepage Refluxion, and 2) Capillary Concentration.

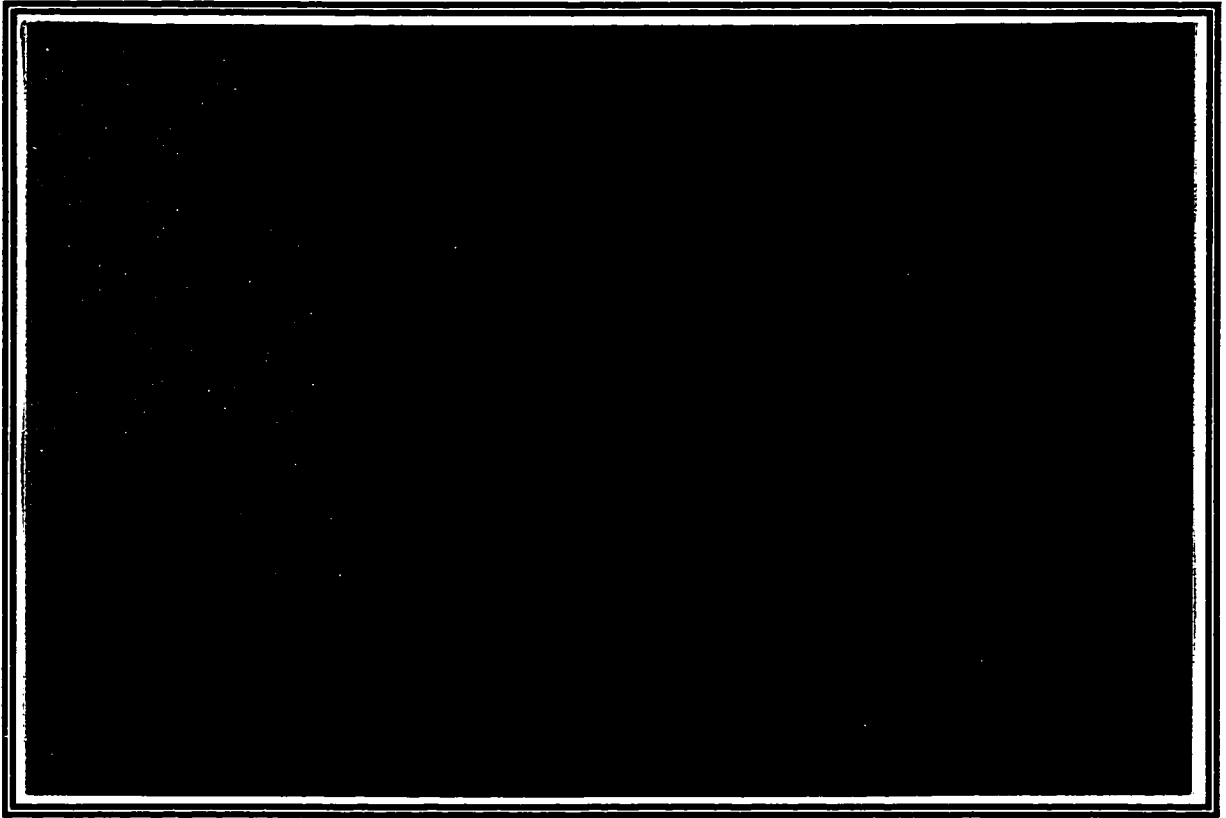


Figure 6-8. Scanning-electron micrograph showing halite crystals (high relief) embedded in a fine dolomitic matrix. Bar scale = $1\mu\text{m}$.

Seepage Refluxion: This model was proposed by Adams and Rhodes (1960). They concluded that dolomitization is a result of high evaporation in coastal lagoons where sea water is concentrated beyond the point of gypsum saturation and which removed calcium ions from the sea water. Consequently, the remaining Mg-enriched brines settled on the sea floor. As a result, this magnesium-rich fluid filled the pore spaces in the sediments beneath the lagoon and seeped downward. Eventually, a large volume of Mg-rich water passed through the carbonate sediments causing dolomitization (Fig. 6-9).

Capillary Concentration: This model was proposed by Friedman and Sanders (1967). They found that dolomitization is common in the tidal-flat environments of the arid setting more than any other environment. The high evaporation rate in this arid setting creates a capillary force that generates upward movement of sea water through the carbonate sediments (Fig. 6-10). In such environment, evaporite minerals such as Gypsum and anhydrite are the first to form. Formation of these minerals increases the Mg/Ca ratio leading to dolomitization (Shinn and Ginsburg, 1964, Friedman and Sanders, 1967).

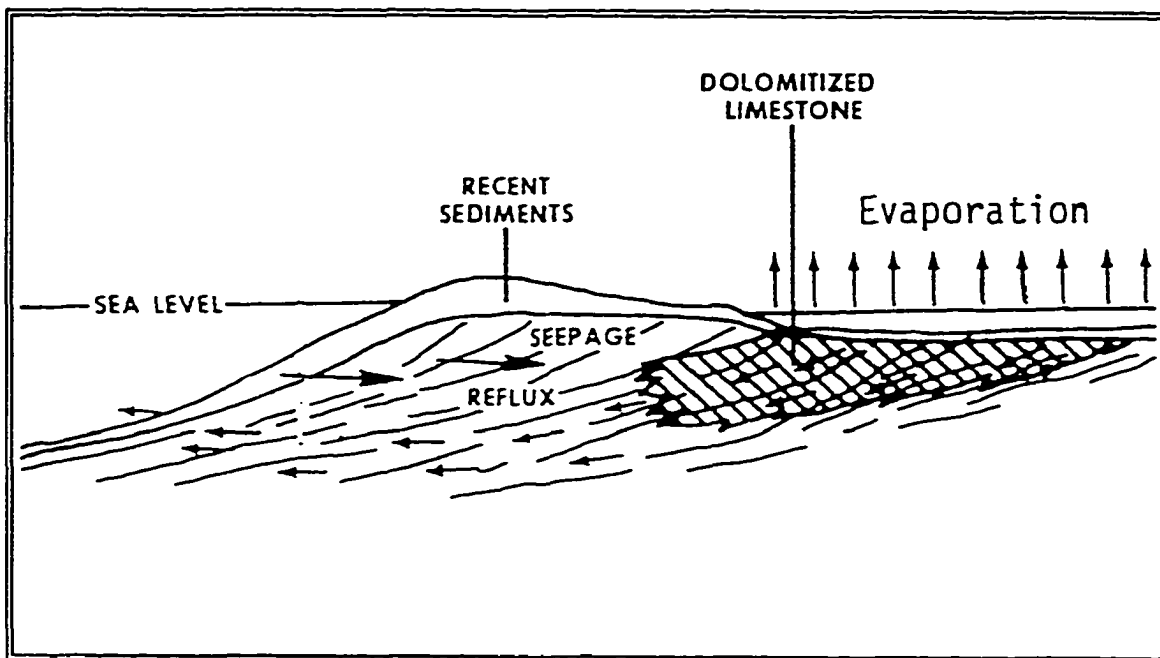


Figure 6-9. Diagram of model for dolomitization by seepage reflux (modified from Zenger, 1972).

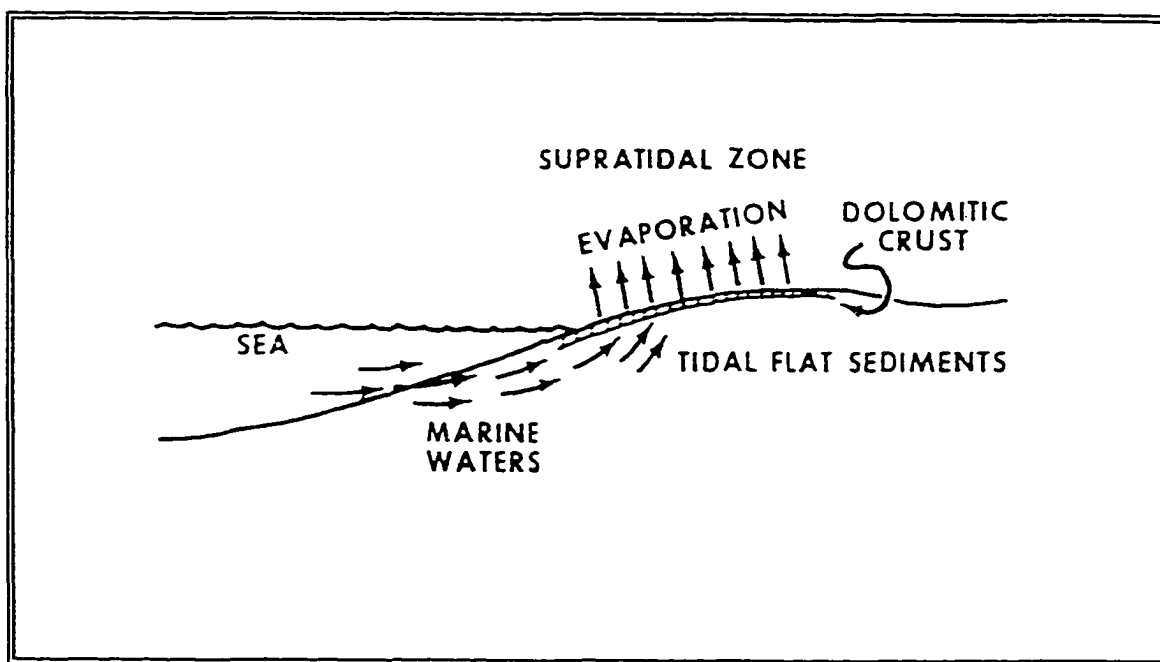


Figure 6-10. Diagram of model for dolomitization by capillary concentration (modified from Zenger, 1972).

6.3 Silicification

The Precambrian shield of the North American Continent is composed of igneous and metamorphic rocks. Feldspar and quartz minerals form the majority of these rocks (Calvert, 1964). The detrital materials including feldspar and quartz particles that were transported to the Cambrian and Early Ordovician (Sauk sequence) seas from the nearby Canadian Shield that was subaerially exposed (Friedman et al., 1992). In 1975, Buyce and Friedman performed a chemical analysis on 1,328 carbonate core samples, ranging in age from Cambrian to Devonian, from 45 quarries in New York State. They found that the insoluble portions of the Cambrian and Lower Ordovician strata of New York State contain more K-feldspar than the younger rock analyzed. Also an abundance of authigenic K-feldspar in the Cambro-Ordovician Sauk sequence was reported in New York State (Braun and Friedman, 1969; Friedman, 1993). Precipitation of authigenic-silicate minerals, including quartz and feldspar crystals, occurred as replacement of the pre-existing minerals or pore-filling cement. It was once believed that the authigenic K-feldspar precipitation resulted from a large-scale brine migration that was related to the late Paleozoic Alleghenian-Ouachita orogeny (Bethke and Marshak, 1990; Schedl et al., 1992). However, this authigenic feldspar originated from volcanic glass that altered to zeolite and finally to feldspar as a stable end product (Buyce and Friedman, 1975; Friedman, 1990). These authigenic-feldspar crystals in the Cambro-Ordovician rocks may have replaced wind-transported tephra on the arid shelf (Friedman, 1990). The isotopic dating using $^{40}\text{Ar}/^{39}\text{Ar}$ spectrum analysis reveals that these authigenic-feldspar crystals are dated Pennsylvanian in age, whereas the original detrital feldspar particles originated during Cambro-Ordovician time (Friedman, 1993). The presence of authigenic-silica aggregates is interpreted as indirect evidence of evaporitic, sabkha-type settings in the Cambro-Ordovician strata of North America and Australia

(Friedman and Radke, 1979; Friedman, 1980; Friedman and Shukla, 1980; Curl et al, 1984).

Through petrographic investigation and cross-cutting relationships, I propose that silicification postdated dolomitization in the Beekmantown Group dolomites. Some dolomitized ooids and peloidal particles have been completely or partially silicified (Fig. 6-11). Generally, the nucleation rate plays an important role in the formation and accumulation of silicate crystals from silica-bearing fluids. Also, available pore spaces control the precipitation and distribution of the authigenic silica throughout the different lithofacies and microlithofacies. Initially, cavities were blocked with microquartz particles that represented a fast nucleation rate of silica formation (Folk and Pittman, 1971). By the late Early Ordovician, the dolomitization process was followed by merging of the carbonate platform which later became subaerially exposed. As a result, erosion occurred that later was recorded by an unconformity surface known as the post-Sauk, pre-Tippecanoe Unconformity. Winds probably transported vast amounts of the detrital quartz and feldspar particles to their depositional settings. Then, siliceous particles were dissolved by meteoric waters making the interstitial water supersaturated with silicate ions that started to precipitate in the available pore spaces and voids causing silicification.

6.4 Stylolitization (Chemical Compaction)

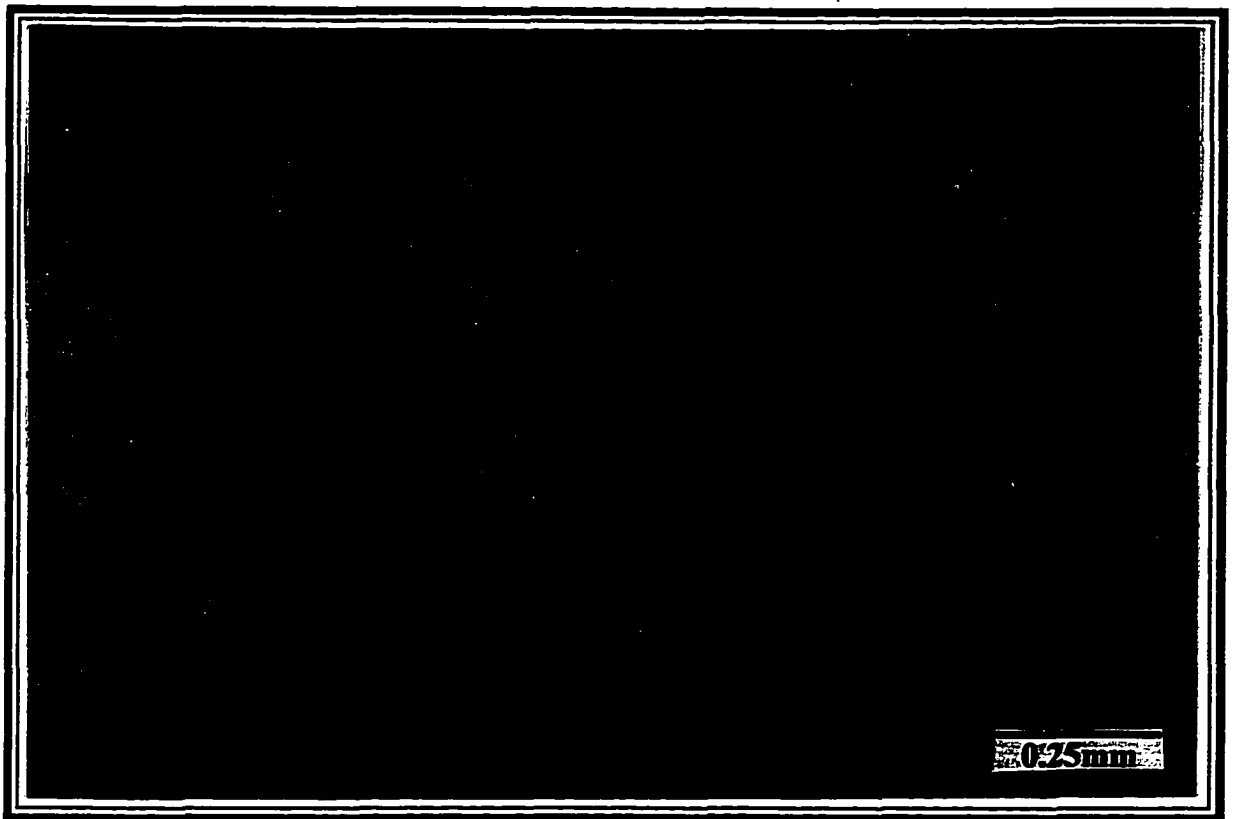
A stylolite is a serrated interface between two masses of rock that has a sutured appearance in sections normal to the plane of the stylolite (Buxton and Sibley, 1981; Bathurst, 1987; Friedman et al, 1992). A dissolution seam is a type of stylolite with an undulatory, non-serrated pressure-dissolution surface (Railsback, 1993). High-pressured fluids penetrate weak areas, then chemically reacting with the surrounding carbonate, thus creating stylolites (Friedman et. al., 1993).

Figure 6-11. Silicification.

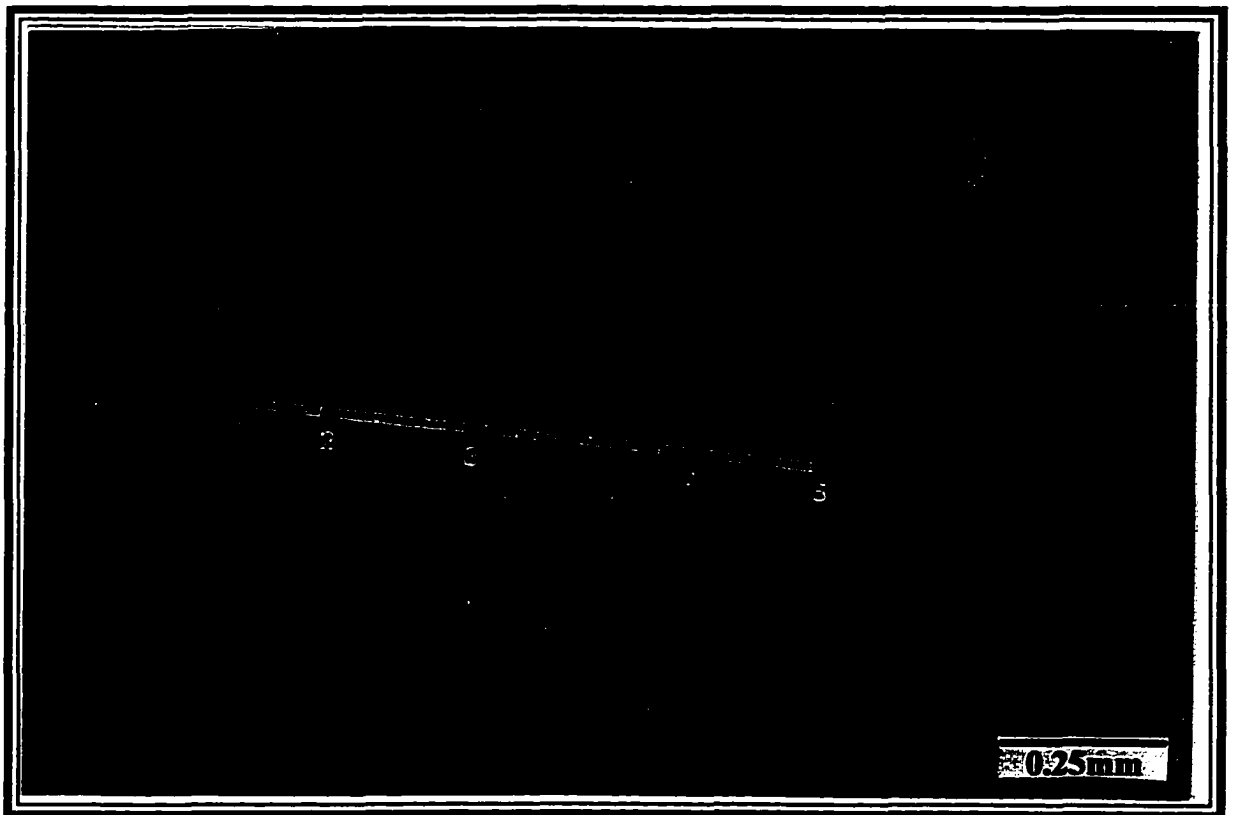
(Waste Water Disposal #1 Well, Niagara County, depth: 2882')

- A) Photomicrograph of a thin section in plane-polarized light showing well preserved micrite envelope of former peloidal particles in a sandy matrix .
- B) Same view under luminescope; note the core of this micrite envelope is filled with quartz (dark to dark blue), ferroan dolomite (dark), and feldspar particles (bright blue).
- C) Trace-elements concentration along the probe traverse as shown in B. Note the concentration of Si^{2+} is very high at point 4 compared to the other points.

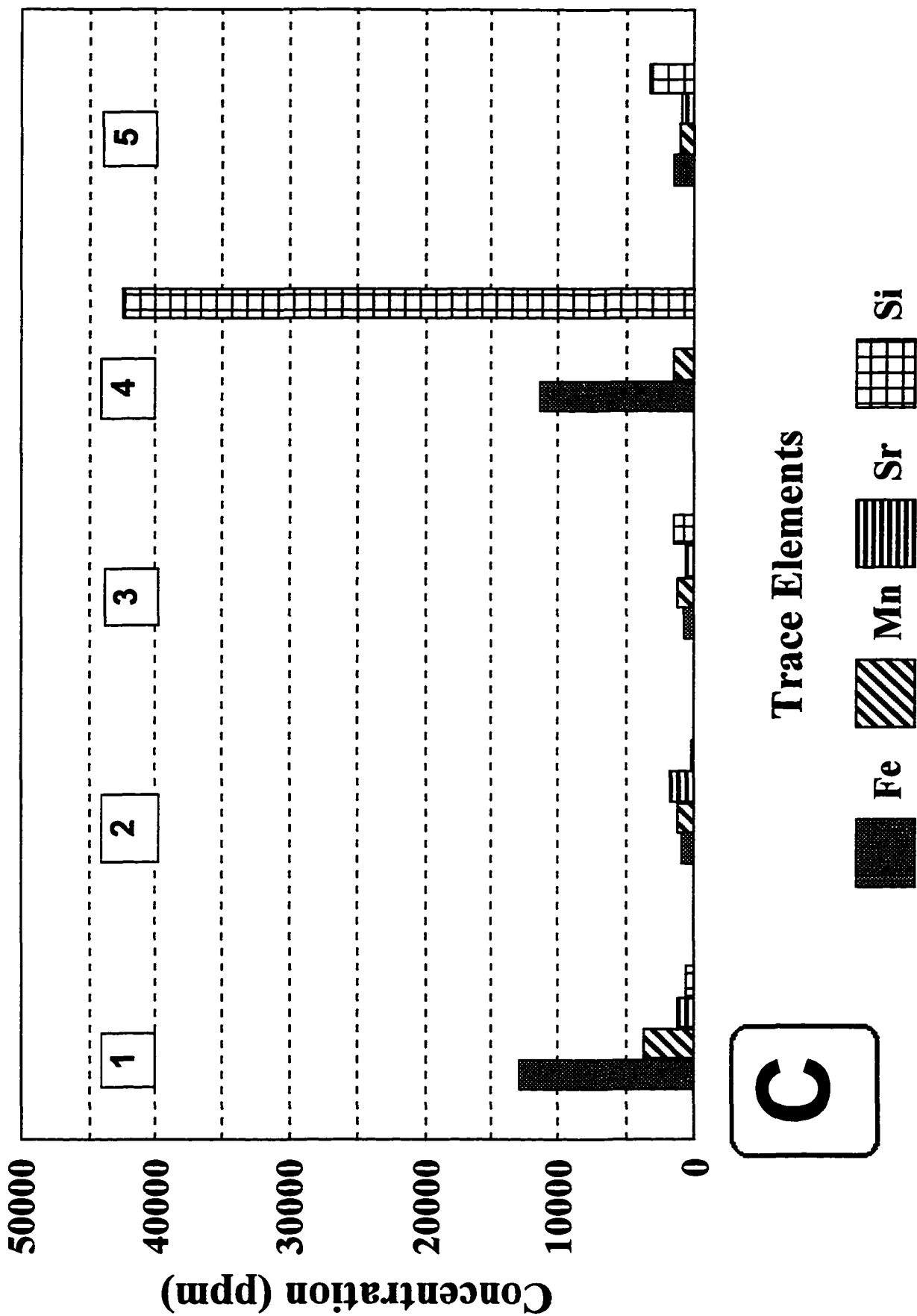
A



B



W.W. D. Well (Depth: 2882')



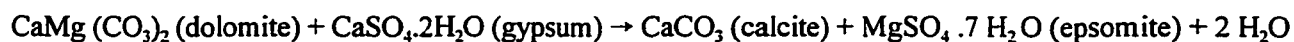
Stylolites and dissolution seams play an important petrophysical role in oil and gas reservoirs. On the one hand, stylolites and dissolution contribute to the destruction of porosity by supplying cement that fills pore spaces (Finkel and Wilkinson, 1990). On the other hand, they serve as seal units for oil and gas traps which are effective microstructures in preserving and possibly enhancing reservoir quality.

Stylolite patterns vary depending on the lithologies and grain-size distribution throughout the studied samples. Stylolites and dissolution seams are abundant in the fine-crystalline dolomites (50 to 100 microns) as compared to the coarse-crystalline ones. Some stylolites terminate at large vugs or microfractures. Insoluble clayey materials as well as detrital-quartz and feldspar particles accumulate along the stylolite boundaries (Fig. 6-12). However, the intensity of the pressure solution helps in the dissolution of soluble minerals within the stylolites that form secondary cement. The relative timing of stylolitization occurred after dolomitization and silicification (Fig. 6-12).

6.5 Dedolomitization (Calcitization)

Dedolomitization describes the replacement of dolomite by calcite proposed by Van Morlot in 1848 (Goldberg, 1967). As a prerequisite for dedolomitization (calcitization) to occur, the $\text{Ca}^{+2}/\text{Mg}^{+2}$ ratio should be high enough in the reacting solution to form calcium carbonate (Evamy, 1967). The Ca^{+2} ions are rich in the evaporitic setting where gypsum and anhydrite are abundant.

Formation of calcite in the evaporitic setting can be expressed by the following equation:



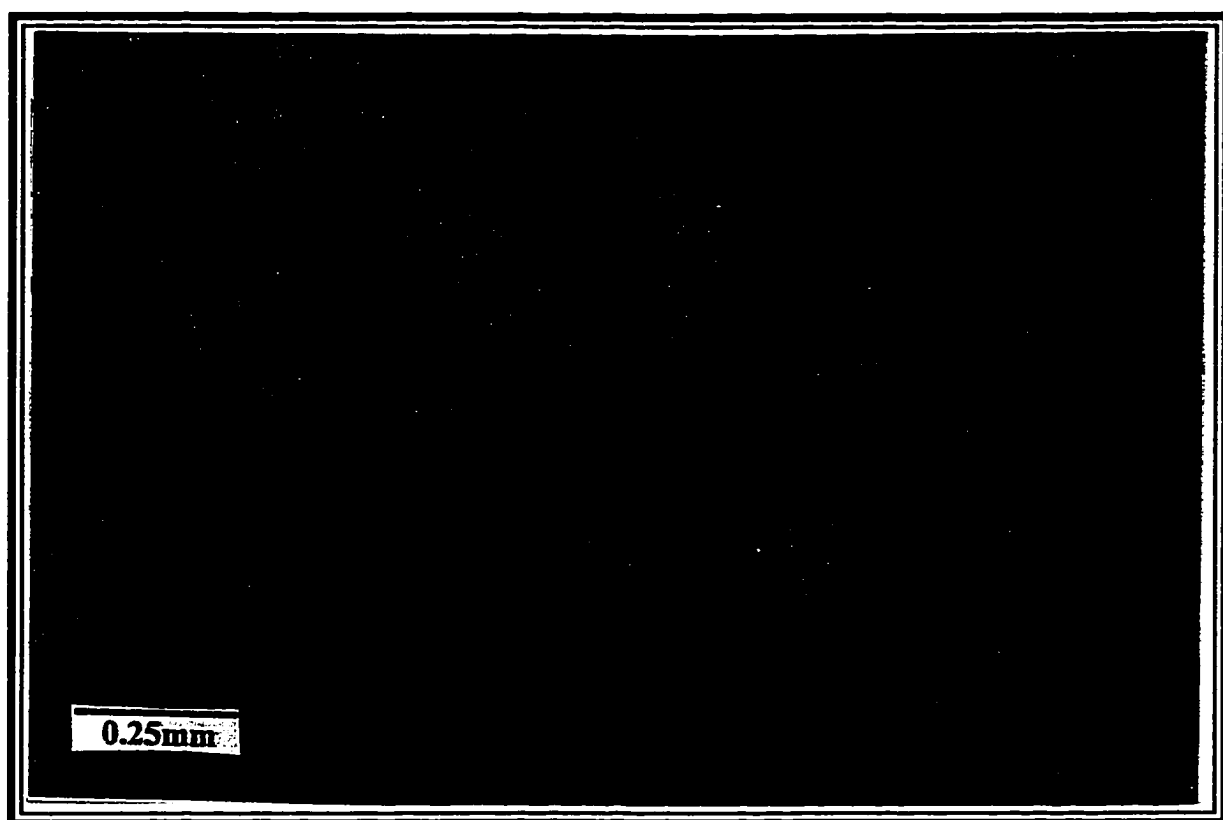
The solubility of dolomite minerals in an aqueous solution is controlled by the partial pressure of CO_2 and the presence of gypsum. Gypsum is an active dedolomitization agent when partial pressures of CO_2 are low (Chilingar, 1965). DeGroot (1967) concluded that dedolomitization

Figure 6-12. Stylolitization.

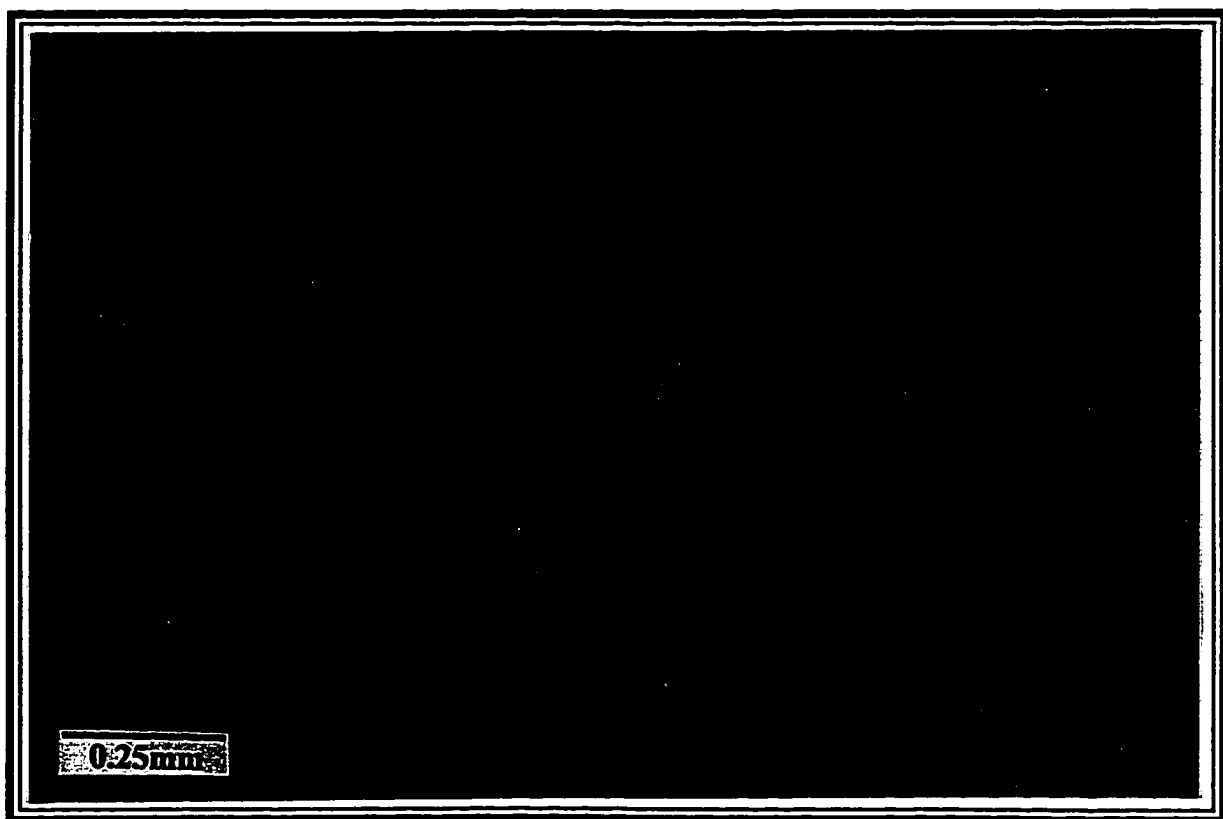
(Robert Olin #1 Well, Steuben County, depth: 12465')

- A) Photomicrograph of a thin section in plane-polarized light showing stylolite in sandy dolomitic matrix.**
- B) Same view under luminoscope; note the red color of the dolomite crystals, the bright blue color of the detrital feldspar particles, and the dull to non-luminescence color of the quartz particles. Also note that the silicate minerals within the stylolite have cemented former pore spaces.**

A



B



becomes ineffective at temperatures higher than 50°C. This supports the idea that dedolomitization can only occur at or near surface conditions where the temperature and CO₂ pressure are relatively low (Schmidt, 1965; Braun and Friedman, 1970; Friedman and Radke, 1979; Curl, Zagorski, and Friedman, 1984). In contrast, other studies prove that dedolomitization is not only restricted as a near-surface process, but it may also occur in deep or shallow zones (Holail et al., 1988; Budai et al., 1984). Guo, Sanders, and Friedman (1992) found that dedolomitization, in eastern New York, may have resulted from subaerial erosion during the post-Sauk, pre-Tippecanoe exposure.

In this study, the textural evidence of the dedolomitized samples are recognized by the presence of dolomite rims surrounding newly-formed calcite crystals (Fig. 6-13), the sharp margins between dolomite and calcite crystals (Fig. 6-14), and parts of the early-formed dolomite crystals floating in the newly-developed calcite crystals (Fig. 6-14). Also, petrographic observation shows abundance of calcite veins in the studied samples. These calcite veins may have developed in the same time as dedolomitization process. Initially, these veins were completely dolomitized and then gradually were replaced by calcite. Figure 6-15 shows calcite vein intersect a dolomitic matrix. This calcite vein contains some inclusions of dolomite crystals which strongly indicate that the calcitization event was post dolomitization.

The microprobe analysis proves that the major composition of the dedolomitized areas are mainly CaCO₃ (90% - 96%). Magnesium is recorded in low concentration (0.1% - 0.5%). Trace element detection proves that the manganese is higher than the iron in the dedolomitized points (Figs. 6-13C, 6-14C, 6-15C). The luminescope study shows that all the dedolomitized samples are fully luminescence (bright yellow) with no zonation (Figs. 6-13B, 6-14B, 6-15B). Silicon and strontium concentration are very low within the dedolomitized areas (Figs. 6-13C, 6-14C, 6-15C).

The lack of strontium in the dedolomitized samples supports the fact that dedolomitization developed near surface and very close to recharge areas of the fresh-water paleoaquifer. This paleoaquifer may have generated within the area of the Paleokarst that modified from the post Sauk, Pre-Tippecanoe unconformity surface that had happened in the Middle Ordovician time.

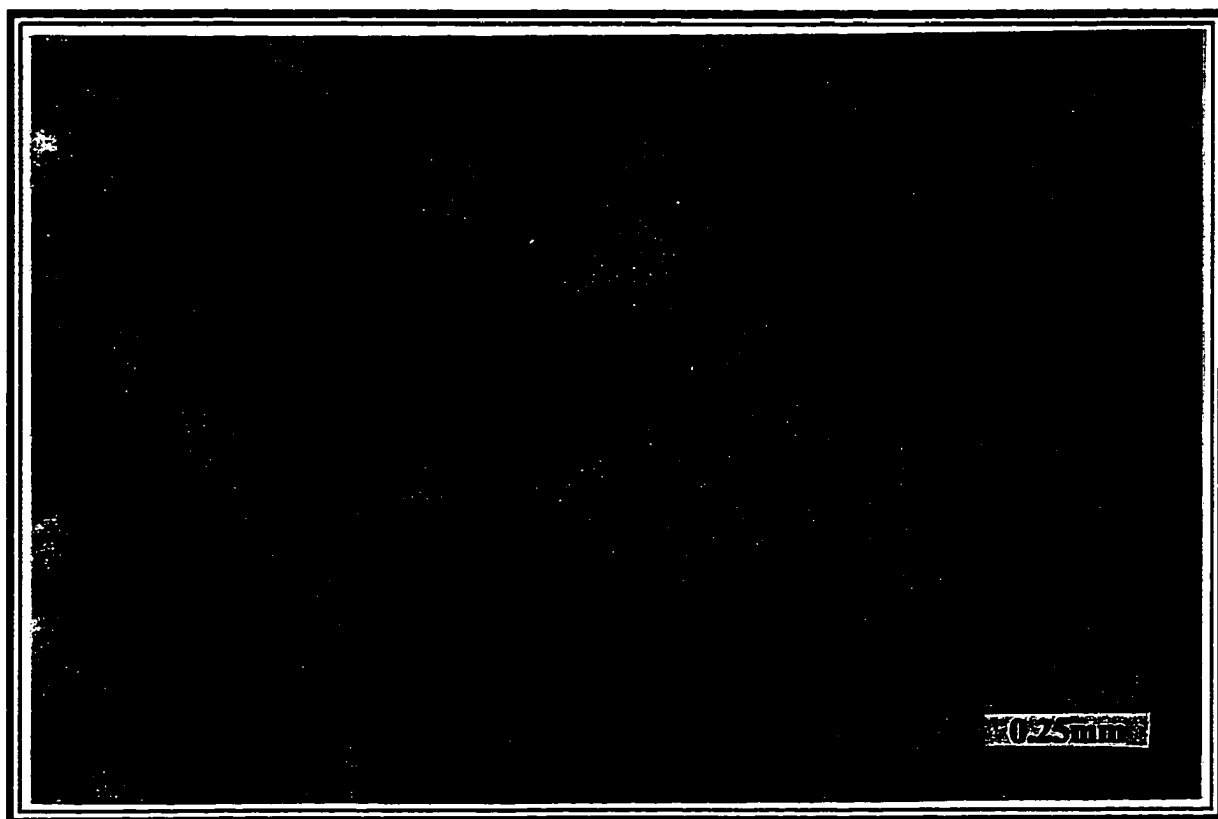
Dedolomitization process is recorded in Lithofacies 5 (stromatolitic dolostone), Lithofacies 2 (Bioturbated, sandy dolostone), and Lithofacies 3 (Glaucous, sandy dolostone) of the Waste Water Disposal Well of Niagara County, Microlithofacies 3 (oolitic dolostone) of the Wasielewski Well of Cayuga County, and Microlithofacies 4 (oolitic dolostone) of the Wilson Well of Wyoming County.

Figure 6-13. Dedolomitization (calcitization).

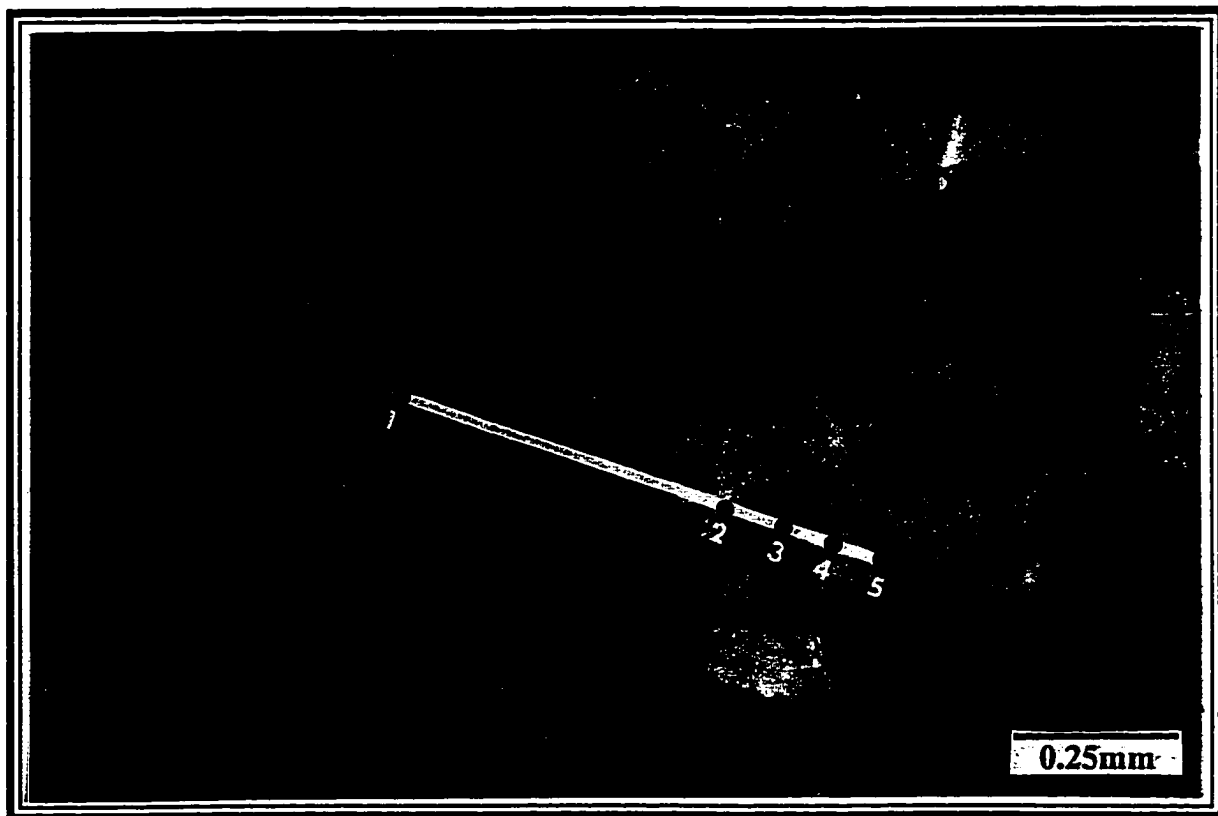
(Waste Water Disposal #1 Well, Niagara County, depth: 2978')

- A) Photomicrograph of a thin section in plane-polarized light showing glauconite pellets, quartz, and feldspar particles in a dolomite and calcite matrix.
- B) Same view under luminescope; note the sharp contrast between the dolomite crystals (red) and the calcite crystals (yellow). The thin dolomite rims completely encompasses the newly-formed calcite crystals. There are also some dolomite relics within the replaceive calcite crystals. This is the onset of early dedolomitization.
- C) Trace-element concentrations along a probe traverse as shown in figure 6-13B indicate that at points 1, 3, and 5 where dolomitization occurs the Fe^{2+} concentration is high as compare to points 2 and 4 where calcite replaces dolomite (dedolomitization). Also note that at points 2 and 4 the Sr^{2+} concentration is not detected. The lack of Sr^{2+} at these points shows that dedolomitization resulted from a meteoric water invasion.

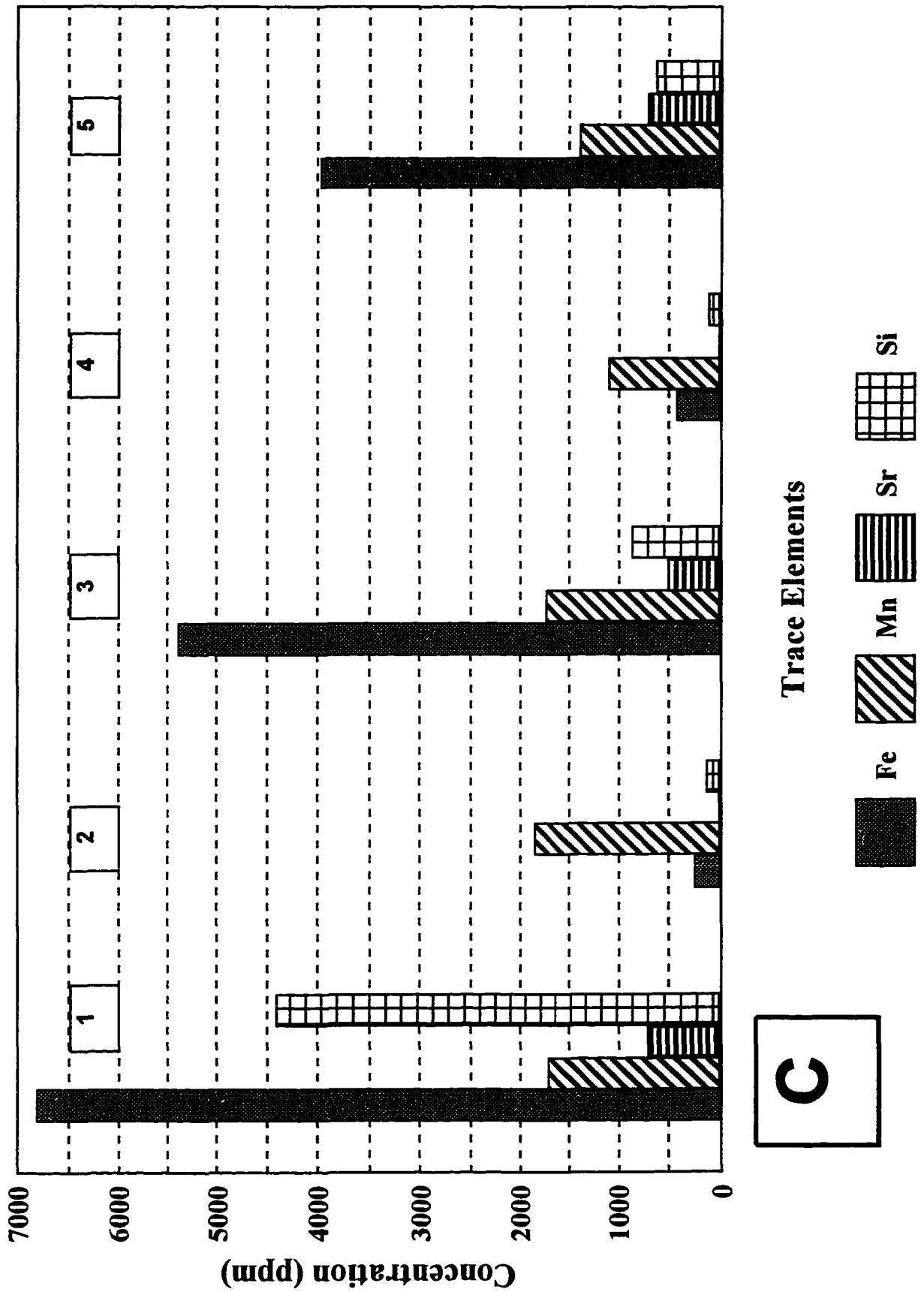
A



B



W.W.D. Well (Depth: 2978')



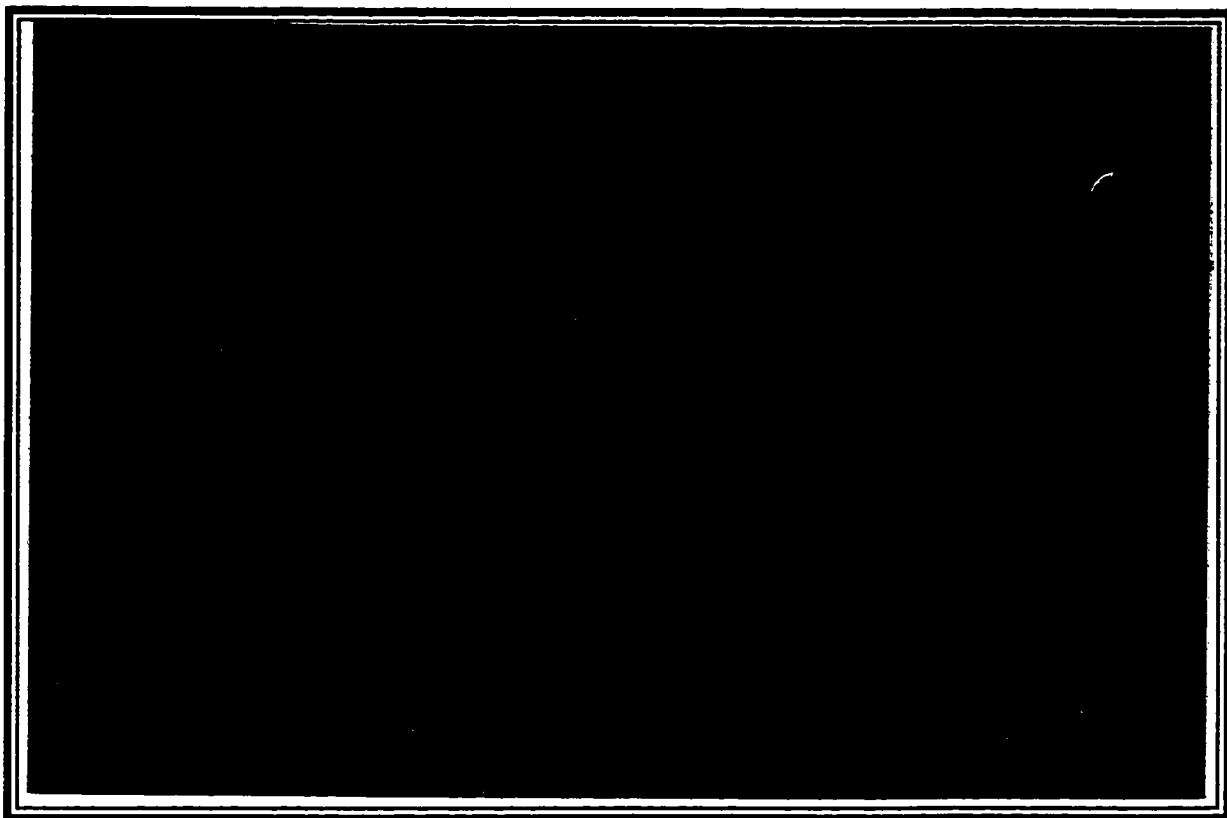
C

Figure 6-14. Dedolomitization (calcitization).

(Waste Water Disposal #1 Well, Niagara County, depth: 2987')

- A)** Photomicrograph of a thin section in plane-polarized light showing coarse to medium, euhedral to subhedral dolomite and calcite crystals.
- B)** Same view under luminescope; showing calcite (yellow) is replacing dolomite (red). Note the sharp margins between the dolomite crystals (red) and the calcite crystals (yellow) and the dolomite rhomb that floating in the calcitic matrix.
- C)** Trace-element concentrations along a probe traverse as shown in figure 6-14B indicate that at points 1, 3, and 5 where dolomitization occurs the Fe^{2+} concentration is high as compare to points 2 and 4 where calcite replaces dolomite (dedolomitization).

A



B



W.W.D. Well (Depth: 2987')

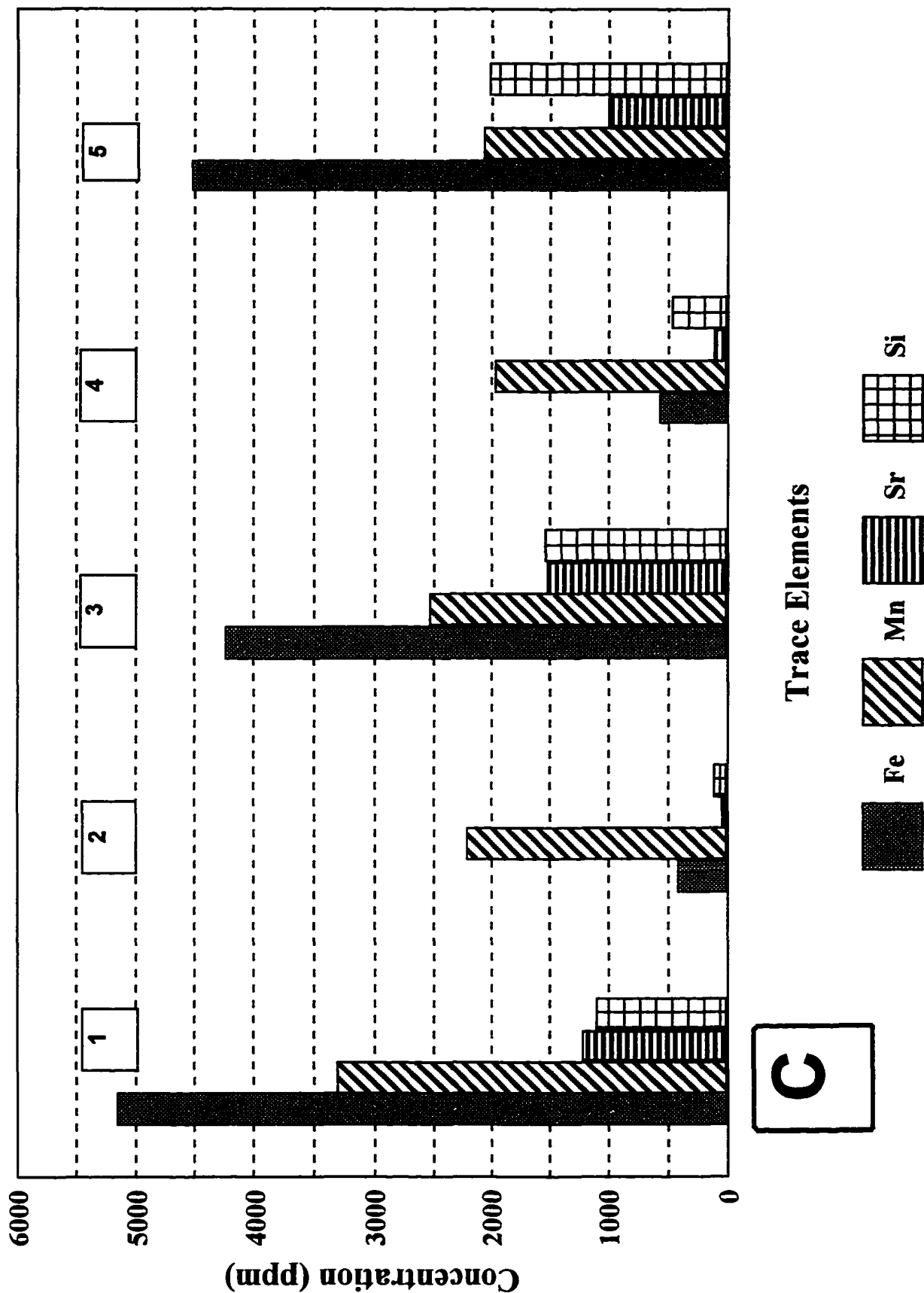
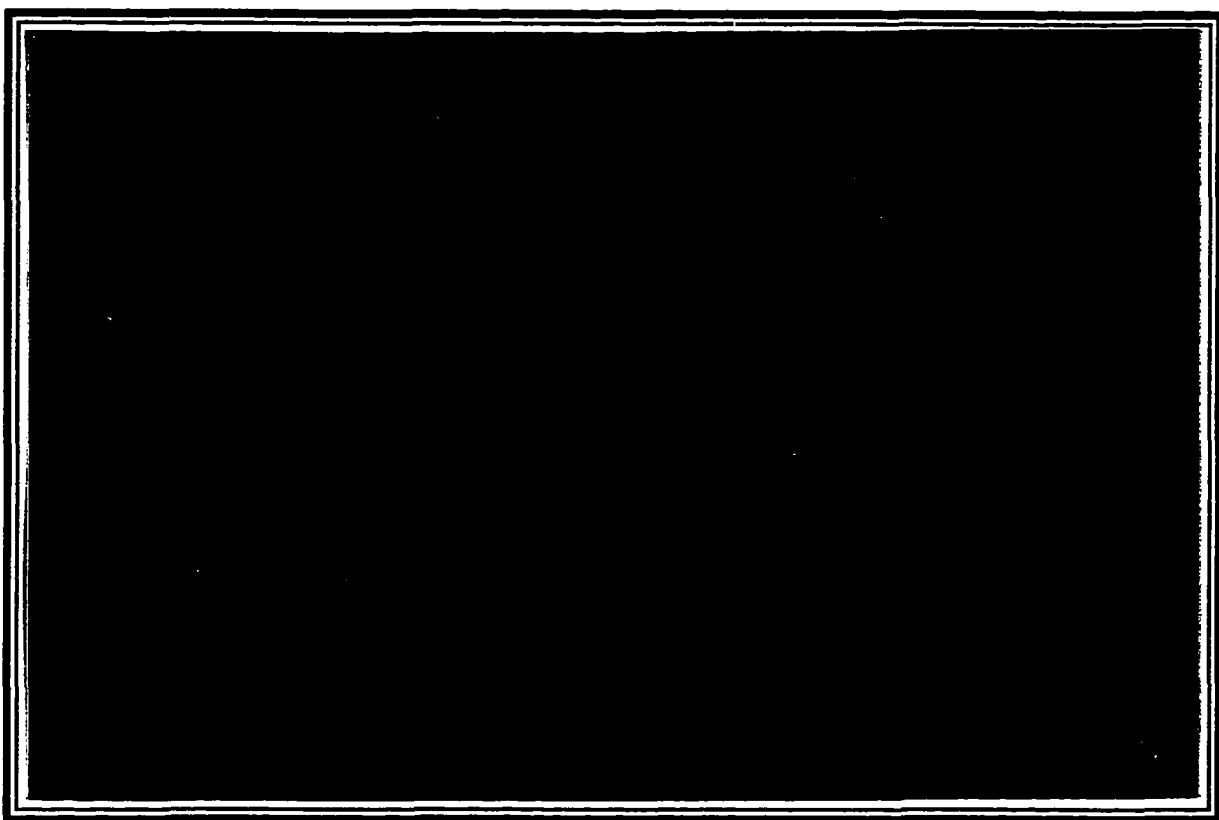


Figure 6-15. Dedolomitization (calcite vein).

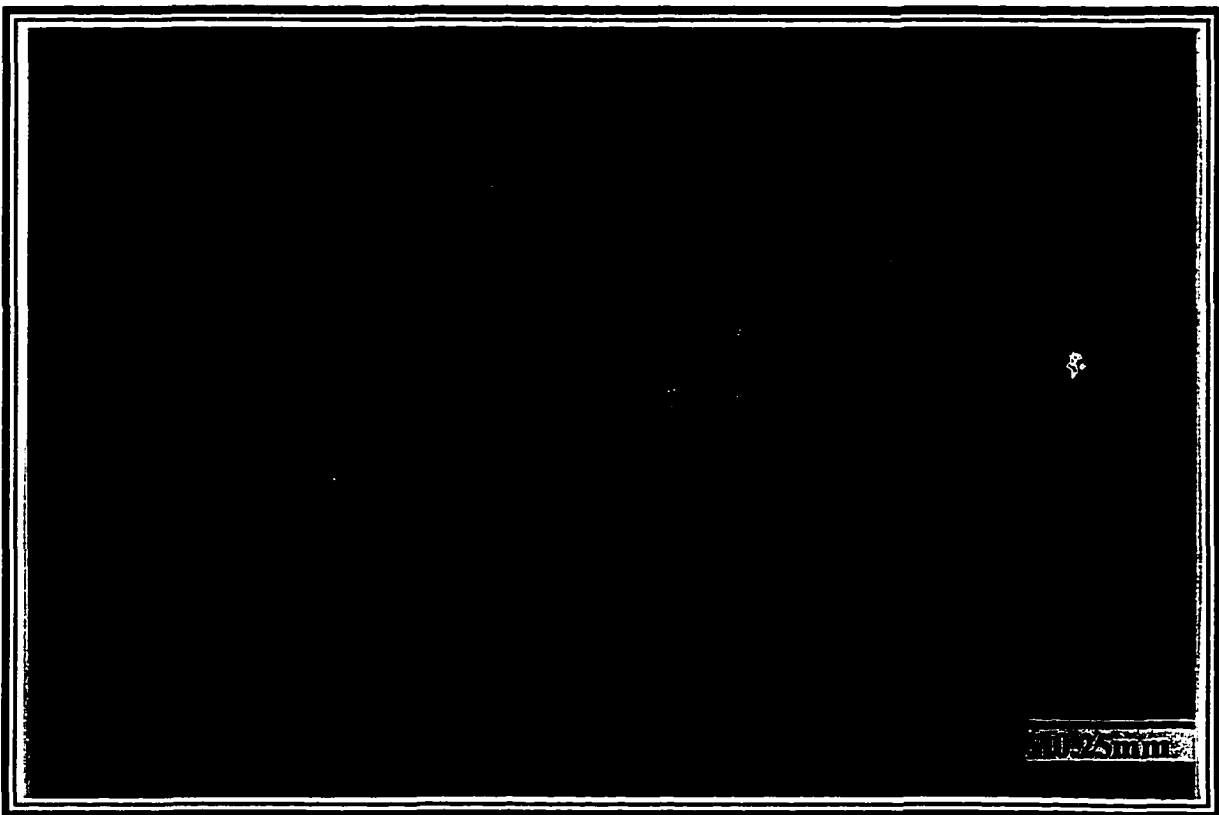
(Waste Water Disposal #1 Well, Niagara County, depth: 2897')

- A) Photomicrograph of a thin section in plane-polarized light showing a calcite vein in a hypidiotopic to xenotopic dolomitic matrix.
- B) Same view under luminescope; note the orange color of the calcite vein due to the iron enrichment.
- C) Trace-element concentrations along a probe traverse as shown in figure 6-13B. Note that the dolomitic matrix at point 1 and 3 is rich in the Fe^{2+} and Sr^{2+} compared to point 2 where calcite replaces dolomite (dedolomitization).

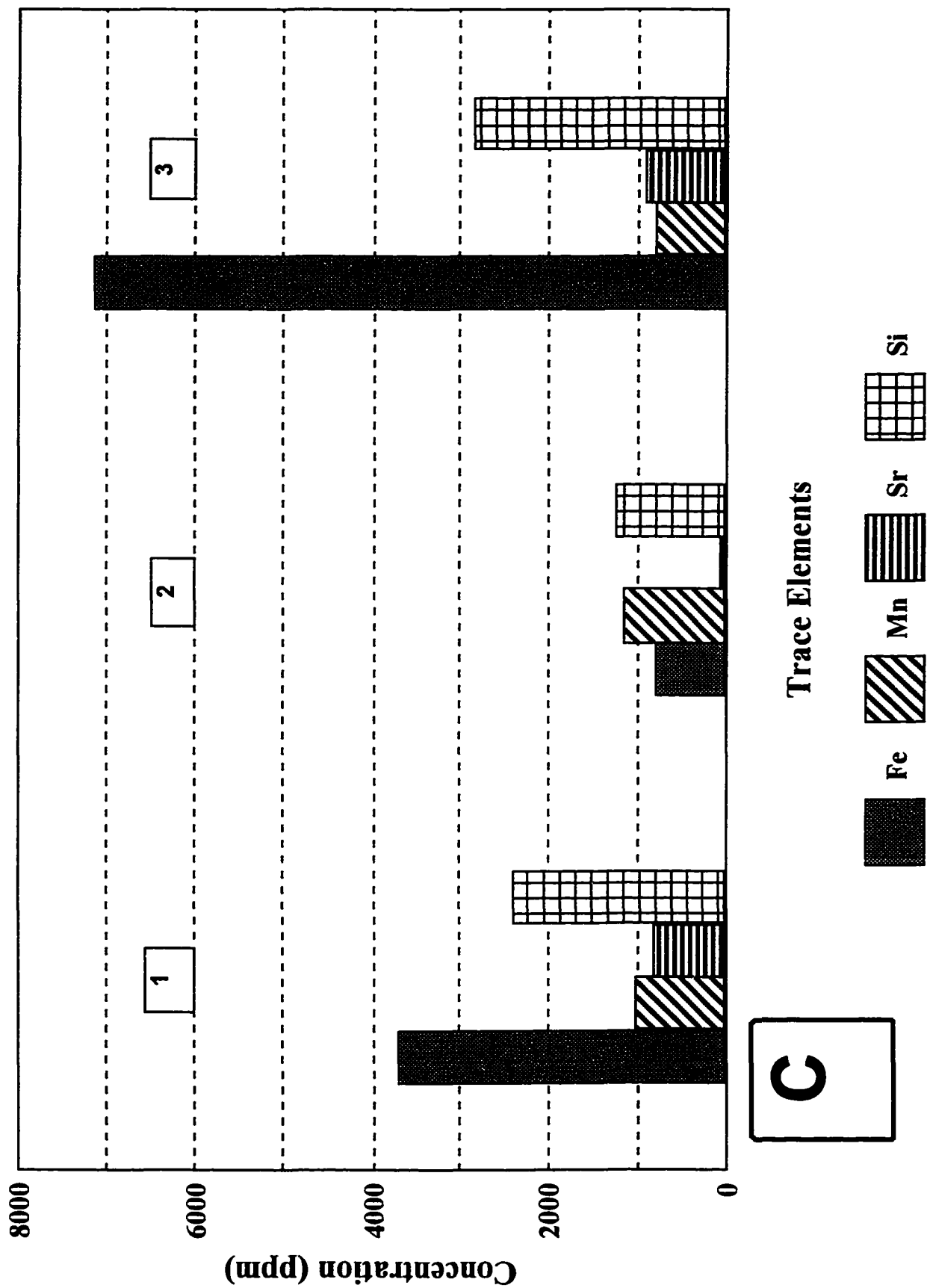
A



B



W.W.D. Well (Depth: 2897')



6.6 General Paragenetic Sequence

Recognition of the paragenetic sequence of the Beekmantown Group (Sauk Sequence) of central and western New York is recognized based on: 1) cross-cutting relationships, 2) grain and crystal arrangements within the dolomite texture, and 3) inclusion of former minerals and ghosts of the original fabrics within the textures.

Petrographic investigation using a cathodoluminescence microscope and an electron microprobe of selected dolomite samples from the Beekmantown Group (Cambro-Ordovician) of central and western New York State revealed a timing sequence of diagenesis. This sequence is as follows: 1) deposition of the original sediments; 2) dolomitization; 3) silicification; 4) chemical compaction (stylolitization); 5) dedolomitization; and 6) precipitation of saddle dolomite (pore-filling dolomite).

The paragenetic sequence began with the precipitation of the original lime mud in the bottom of the Cambro-Ordovician shallow sea. Later, these muds crystallized to form unstable aragonite that eventually stabilized to calcite. As time elapsed, the well-developed calcite crust was dolomitized by magnesium-rich fluid resulting from the dissolution of anhydrite and gypsum in a hypersaline setting. Followed by silicification, most of the remaining interparticle and intercrystalline pore spaces were occluded by the precipitation of a silicate cement which was formed from dissolution of feldspar and quartz particles under ordinary weathering conditions. Next, generations of solution channels and stylolites resulted from chemical compaction of fluids in weak areas and the dissolution of silicate minerals. These well-developed stylolites and solution channels served as pathways for calcium-rich fluids to flow freely within the Beekmantown dolomite. Increased Ca/Mg ratios led to the calcitization (dedolomitization) of the pre-existing dolomite. Finally, late fractures and cavities, resulting from uplifting conditions, were filled by the coarsely

crystalline saddle and non-saddle dolomite. Figure 6-21 shows the proposed paragenetic sequence of the Cambro-Ordovician Beekmantown Group (Sauk Sequence) of central and western New York.

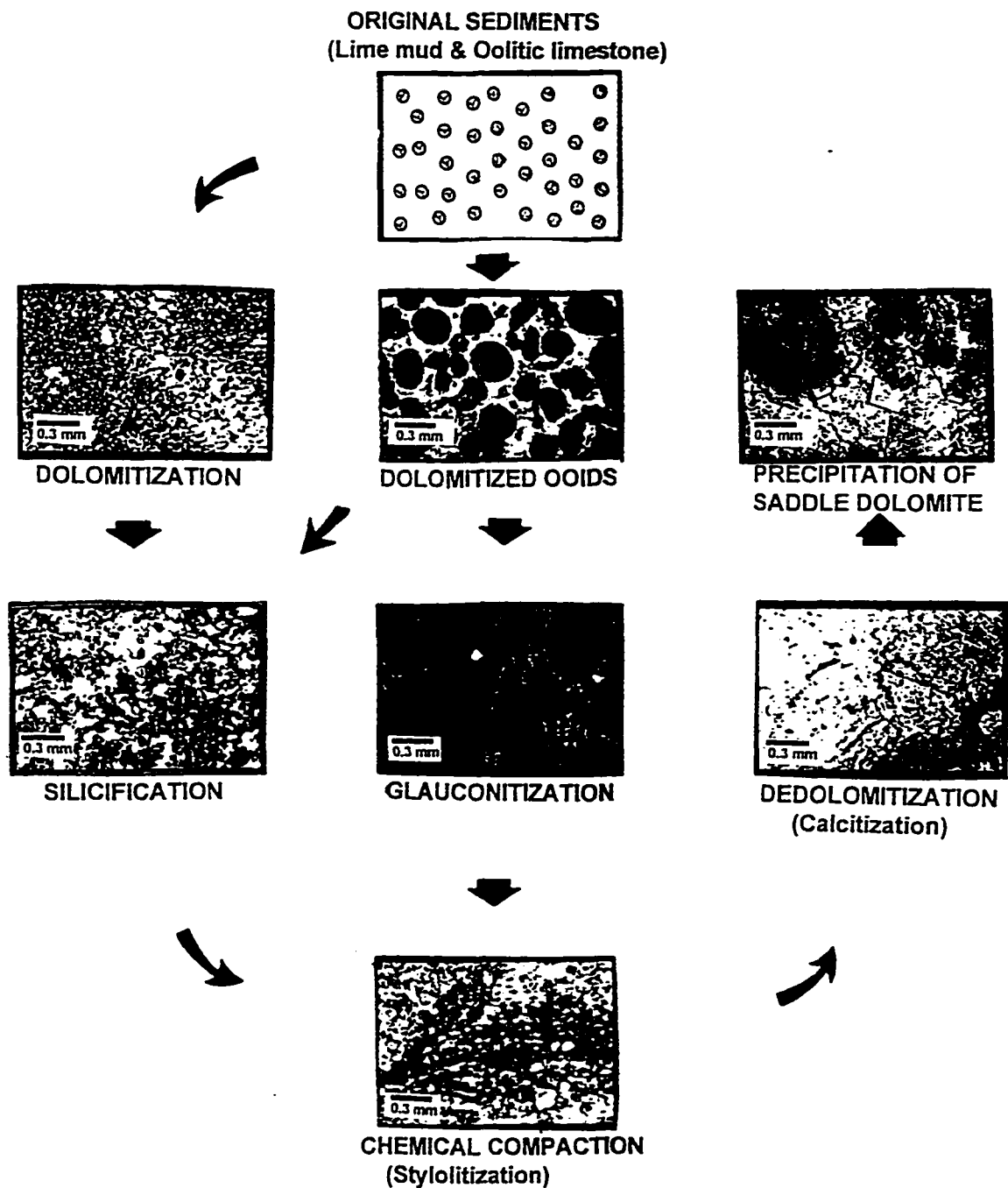


Figure 6-21. Proposed general scheme of the paragenetic sequence of the Beekmantown Group in central and western New York.

PART IV

PETROPHYSICAL ANALYSIS AND RESERVOIR CHARACTERISTICS

CHAPTER 7: PETROPHYSICAL PARAMETERS AND RESERVOIR CHARACTERISTICS

7.1 General Statement

As pointed out by Morrill (1996) in his publication of Avoca, New York Salt Cavern Gas Storage Facility, five factors are required to have a successful salt-cavern natural gas-storage facility. These factors are: 1) a sufficient salt thickness to prevent possible collapse, 2) reasonable salt depth to ensure storage of a large amount of gas (the greater the depth the greater the amount of the storage gas within the salt formation), 3) an appropriate location that must be close to the interstate pipelines, 4) availability of a leaching-water source (water wells) to create the cavern space, and 5) a satisfactory method of brine disposal. Based on the environmental regulations, the last factor is the most critical one in site selection. The lack of this factor will make the site unsuitable for gas storage even if the other factors look promising.

Several geologic factors must be considered in order to properly assess the suitability of a particular rock formation for gas storage or brine-disposal development. These factors are known as petrophysical properties that include porosity, permeability, recovery efficiency, fluid saturation, applied pressure, gas-displacement mechanism, and capacity of the gas storage reservoir. Usually, these petrophysical properties of the geologic formations vary widely depending on the nature of these formations. For example, pure carbonates may demonstrate 10% to 20% porosity. Mixing of carbonate with evaporite rocks may show practically zero porosity. Well-consolidated sandstones display about 10% to 15% porosity, and unconsolidated sands show up to 30% or more porosity. Though shales and clays may contain over 40% liquid by volume, they are extremely fine-grained plus their voids are not interconnected making them practically impermeable so the fluid-flow porosity is low. Thus petrophysical studies of the gas-storage reservoirs or brine disposal facilities

are required in the understanding and the evaluating of petrophysical heterogeneity in a deposystem.

This research provides information about the petrophysical properties of the subsurface Beekmantown Group of the selected wells (Fig. 1-1) in central and western New York. Petrographic and porosimetric analysis indicate that the carbonate rocks of this group display megascopic and microscopic heterogeneities. These variations began at the time of the sedimentation within the depositional environment and continued during the different stages of diagenesis. Accordingly, the petrophysical properties of the studied formations vary based on the severity of the diagenetic modification.

7.2 Development of the Salt-Cavern Gas-Storage Sites in New York

New York State has a long history of leadership in developing underground gas- storage sites. The first gas-storage site in the United States was established in 1916 when the Zoar gas field in Erie County was converted into a storage reservoir. By 1961, another fourteen storage fields were developed, and seven more were added between 1970 to 1991 (Friedman et al., 1995). All twenty-two operating storage reservoirs in New York were converted from depleted gas fields with low deliverability. Nineteen of those are in sandstone reservoirs of the Lower Silurian Medina Group and the Lower Oriskany Formation. The other three fields are in limestone reservoirs of the Middle Devonian Onondaga and Tully formations. All the storage reservoirs are located in the gas producing areas of southwestern New York and are linked to the major interstate transmission lines. Recent developments in underground gas storage in New York State are mainly from the carbonate-reef storage sites that are located in the Onondaga pinnacle-reef trend (Friedman et al., 1995).

In 1994 the Northeastern Science Foundation started preliminary investigation into the salt cavern and brine disposal of New York State. The purpose of this pioneering investigation was to

gather information and to obtain research guidelines to salt-cavern development that may help in locating new sites for gas storage within New York State. They studied cores and well cuttings from the Beekmantown Group (Sauk Sequence) which were collected from strategic locations in eastern, central and western New York to test their abilities as gas- storage or brine- disposal sites. The research team of the Northeastern Science Foundation concluded that the upper Silurian bedded salt (halite) deposits of subsurface New York State are a part of a much larger salt basin covering central and southwestern New York, western Pennsylvania, northern West Virginia, eastern Ohio and much of Michigan. The salt in New York occurs in the Syracuse and Vernon formations of the Salina Group (Fig. 7-1), and is interbedded with shale, anhydrite, and dolostones (Fig. 7-2). The salt-bearing horizons of these formations are often correlatable across states and have been designed as Vernon B, and Syracuse D, E, and F, and the Syracuse F is often subdivided into five different units (Fig. 7-3). The net aggregate thickness of the salt units in the Salina Group is up to 800 feet, but individual salt beds probably do not exceed a thickness of 30 feet anywhere in New York State. The Salina Salt occurs at a depth of 500 to 4000 feet. Salt mining in New York State began in the late 1880's and as a result left many cavities in the subsurface. Using of these cavities for gas storage remains a strong possibility. However, these cavities may be improperly plugged and are prone to flooding.

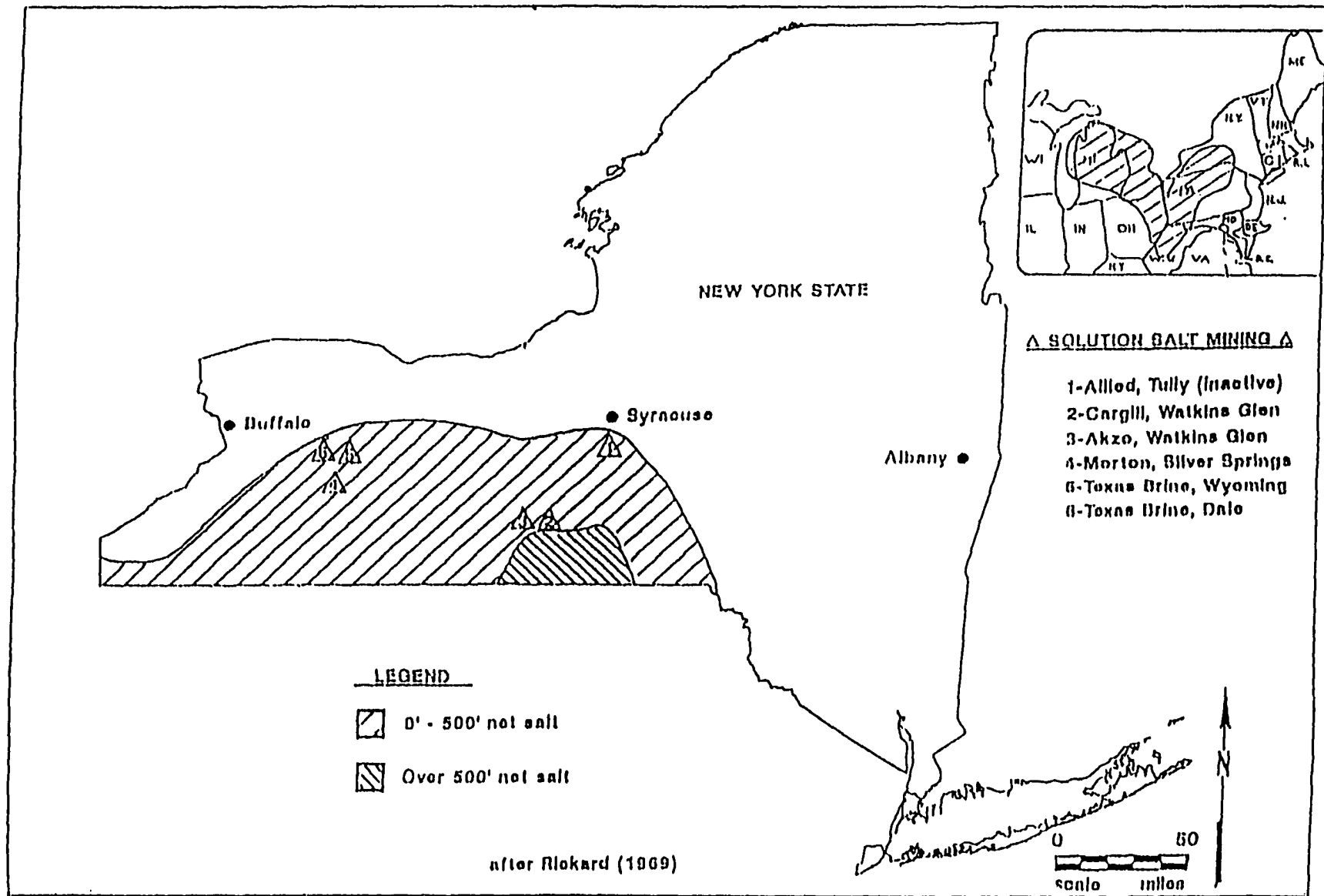


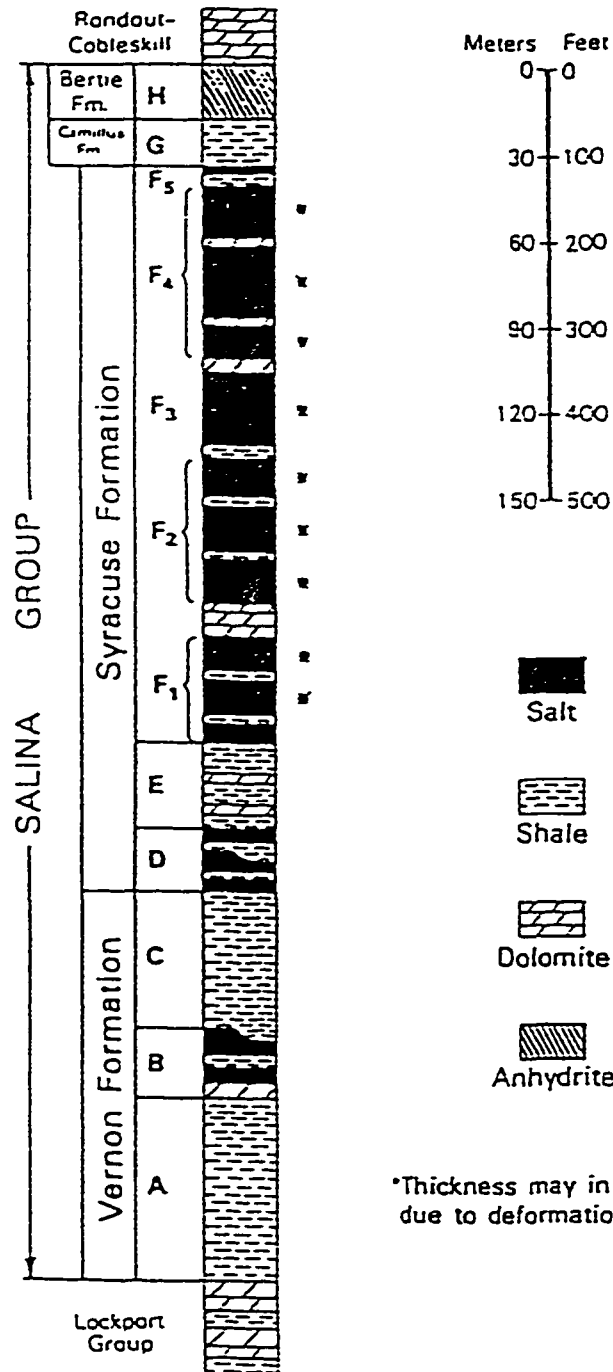
Figure 7-1: Map showing subsurface occurrence of the Salina Group (upper Silurian) salt deposits in New York State and the region in eastern USA (inset) underlain by salt of the same age. The names and locations of the five active and one inactive solution salt mines of New York State are also shown (from Sanford and Briggs, 1994).

STRATIGRAPHIC SECTION CENTRAL NEW YORK

PERIOD	GROUP	UNIT	LITHOLOGY	EXPLANATION
DEVONIAN	UPPER	GENESEE	WEST RIVER ITHACA RENNICK SHERBURNE PENNYAN GENESEO	SHALE WITH MINOR SILTSTONE AND LIMESTONE
		?		
		?	TULLY	LIMESTONE WITH MINOR SILTSTONE AND SANDSTONE
	MIDDLE	HAMILTON	MOSCOW LUDLOWVILLE SKANEATELES MARCELLUS	SHALE WITH MINOR SANDSTONE AND CONGLOMERATE
			ONONDAGA	FOSSILIFEROUS LIMESTONE & REEFS
		TRISTATES	ORISKANY	QUARTZITIC SANDSTONE
	LOWER	HELDERBERG	MANLIUS RONCOUT	LIMESTONE AND DOLOSTONE
SILURIAN	UPPER		AKRON- COBLESKILL	DOLOSTONE AND LIMESTONE
		SALINA	BERTIE CAMILLUS SYRACUSE VERNON	SHALE, DOLOSTONE, ANHYDRITE AND HALITE
			LOCKPORT (Schenectady Mem.)	LIMESTONE AND DOLOSTONE STROMATOLITE MOUNDS
			ROCHESTER SHERBURN RONDEQUOIT	SHALE SANDSTONE (Harrison) LIMESTONE REEFS
	LOWER	CLINTON	WILLOWVALE SAVOUQT WOLCOTT SODUS BEAR CREEK FURNACEVILLE KODAK	SHALE SANDSTONE AND SHALE LIMESTONE SHALE (Onondaga Conglomerate and Sandstone) HEMATITE or IRON ORE SANDSTONE
		MEDINA	GRIMSBY	SANDSTONE AND SHALE
ORDOVICIAN	UPPER		QUEENSTON OSWEGO LORRAINE UTICA	SANDSTONE AND SHALE SHALEY SANDSTONE SHALE WITH SANDSTONE AND SILTSTONE
		TRENTON - BLACK RIVER	TRENTON BLACK RIVER	FOSSILIFEROUS LIMESTONE AND MINOR DOLOSTONE
		BEEKMAN - TOWN		LIMESTONE
	LOWER			
CAMBRIAN	UPPER		LITTLE FALLS THERESA POTSDAM	DOLOSTONE, SANDSTONE AND SANDY DOLOSTONE QUARTZITIC SANDSTONE
PRECAMBRIAN			MARBLE, QUARTZITE, etc...	METAMORPHIC AND IGNEOUS ROCKS

Figure 7-2: Stratigraphic column for central New York. The Salina Group is highlighted (from Swensen and Potashnik, 1994).

SOUTH-CENTRAL NEW YORK



*Thickness may in part be due to deformation.

Figure 7-3: Generalized columnar section of the Salina Group in south-central New York showing the different salt horizons (from Swensen and Potashnik, 1994).

7.3 Underground Injection Wells

Underground injection of liquid wastes has been widely performed in the United States for many years (Wentz, 1989). These liquid disposal wells are placed in confined geological formations deep below the surface. However, the most important issue in this operation is to avoid any impact to human population and the environment. The primary environmental consideration in approving an injection-well permit is to protect underground water resources. The injecting wells prevent the movements of the injected fluids into or between potential drinking water resources (Matsumoto et al., 1992). Based on the regulations provided by the Department of Environmental Conservation (DEC) and the United State Federal Injection Control (UIC), injection wells for brine disposal must be constructed into deep formations below any underground drinking water and at least 2000 feet beneath the surface. To ensure successful results, the injection operation should be performed within porous and impermeable formations to prevent fluid migration.

7.4 Relationships between Diagenetic Modification and Petrophysical Parameters

Based on petrographic analysis of selected thin sections, the Beekmantown Group (Sauk Sequence) of central and western New York, has been divided into various lithofacies and microlithofacies. These lithofacies and microlithofacies depict lithologic heterogeneities that are recorded by changes in textural components. These changes resulted from variations in sediment supply, sea-level fluctuation, and local tectonics (Reeckmann and Friedman, 1982). These lithofacies, as explained earlier in chapter five, were formed and modified within a peritidal setting. Moreover, they show a wide range of diagenetic modifications that have developed since time of deposition. On a microscopic scale, diagenetic modifications were revealed by textural variations, microstructures, replacements, mineralization, cements, and dissolution. These diagenetic changes

have created pore patterns within the rock formation. Microscopic observation of the pore system revealed a variety of porosity types including interparticle porosity that may have developed as a result of the dissolution process of the cement between the carbonate particles (Fig. 7-4), intercrystal porosity that have been modified within the crystal as a result of dissolution of the original crystal's fabrics (Fig. 7-5), moldic porosity that created by dissolution and selective removal of former dolomite rhombs (Fig. 7-6), micro-channel porosity that serves as continuous pathways of the fluids throughout the rock samples (Fig. 7-7), and vugs that were created by dissolution and solution enlargement of the pre-existing pores (Fig. 7-8).

7.5 Mercury Injection and Capillary-Pressure Curve Models

In this study, pore-system analysis in the selected core plugs and well-cutting assemblies were performed using the Micrometrics Pore Sizer 9305 at the Northeastern Science Foundation, Troy, New York. Complete sets of data from the selected five wells are shown in Appendix B. Mercury porosimetry is an effective method for quantitative analysis of pore-throat diameters which control the movement of the fluids into and out of the oil and gas reservoirs. These pore throats govern the movement of the fluids into and out of the reservoir rocks via pulging and blind pores (Fig.7-9). The bulging pores are a free pathway for the fluid migration. They are chamber-like structures that connected to one another or to the adjacent blind pore through several pore throats (Fig. 7-9). The blind pores are connected to the bulging pore only via one pore throat (Fig. 7-9). In this experiment, the applied pressure ranges from 14 psia to 20,000 psia that measured pore-throats sizes ranging from 190 to 0.0003 microns. Such high pressure assists in understanding the pore system in deeply-buried reservoirs. Pressure of 15,000 to 20, 000 psia (Hg-air) is most likely to be similar to reasonable oil-column heights in real reservoirs (Kopaska-Merkel and Amthor, 1988).

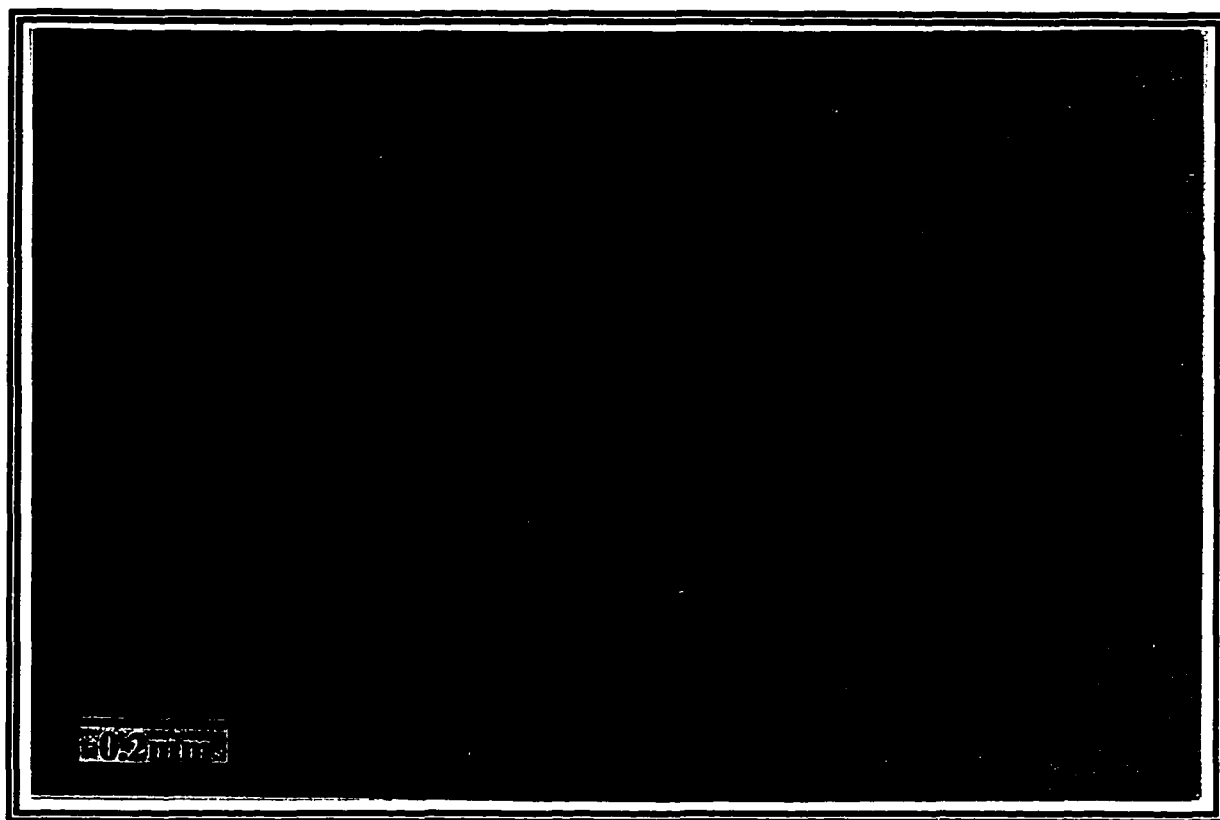


Figure 7-4. Photomicrograph of a thin section under plane-polarized light from the Waste Water Disposal #1 Well , Niagra County at depth of 3012', showing interparticle porosity (blue in color).

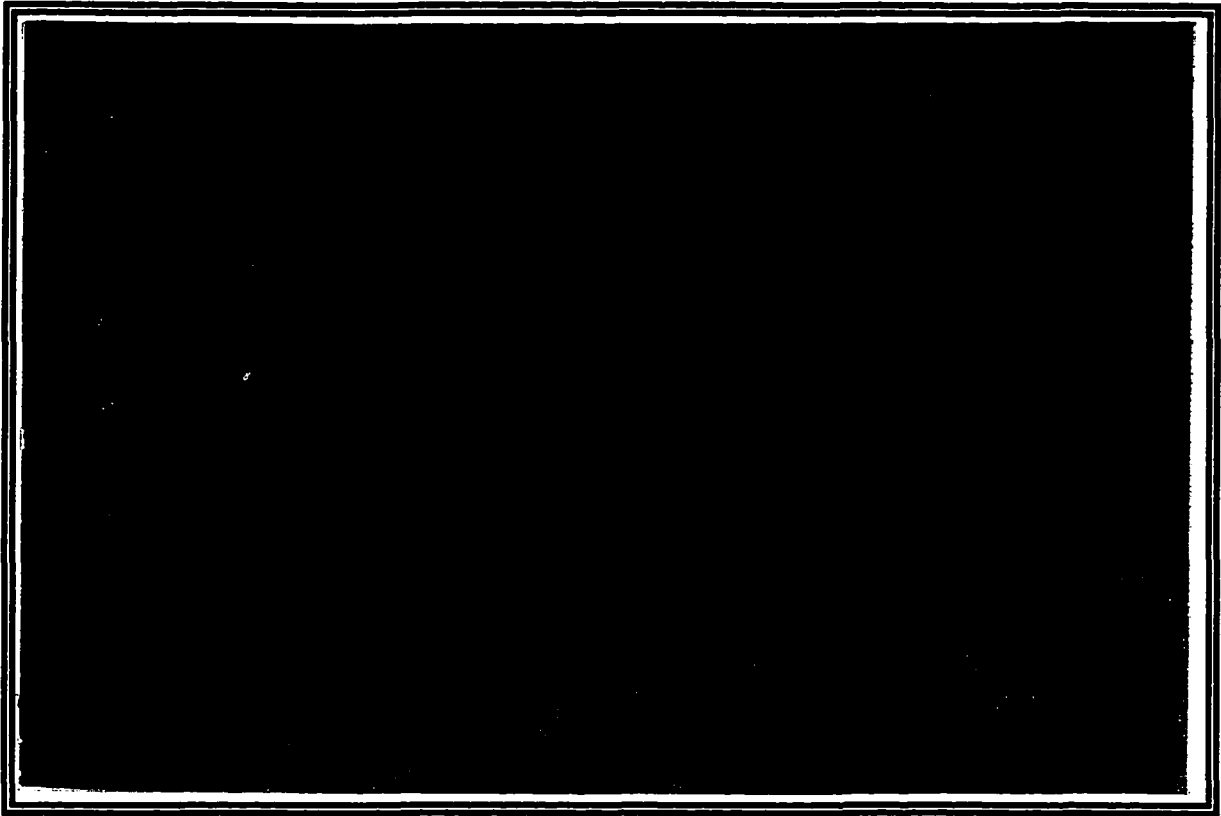


Figure 7-5. Scanning-electron micrograph of a thin section from the Waste Water Disposal #1 Well, Niagara County at depth of 3005', showing intercrystal porosity in the form of well-developed pore space within the dolomite crystal. Bar scale = 10 μm .

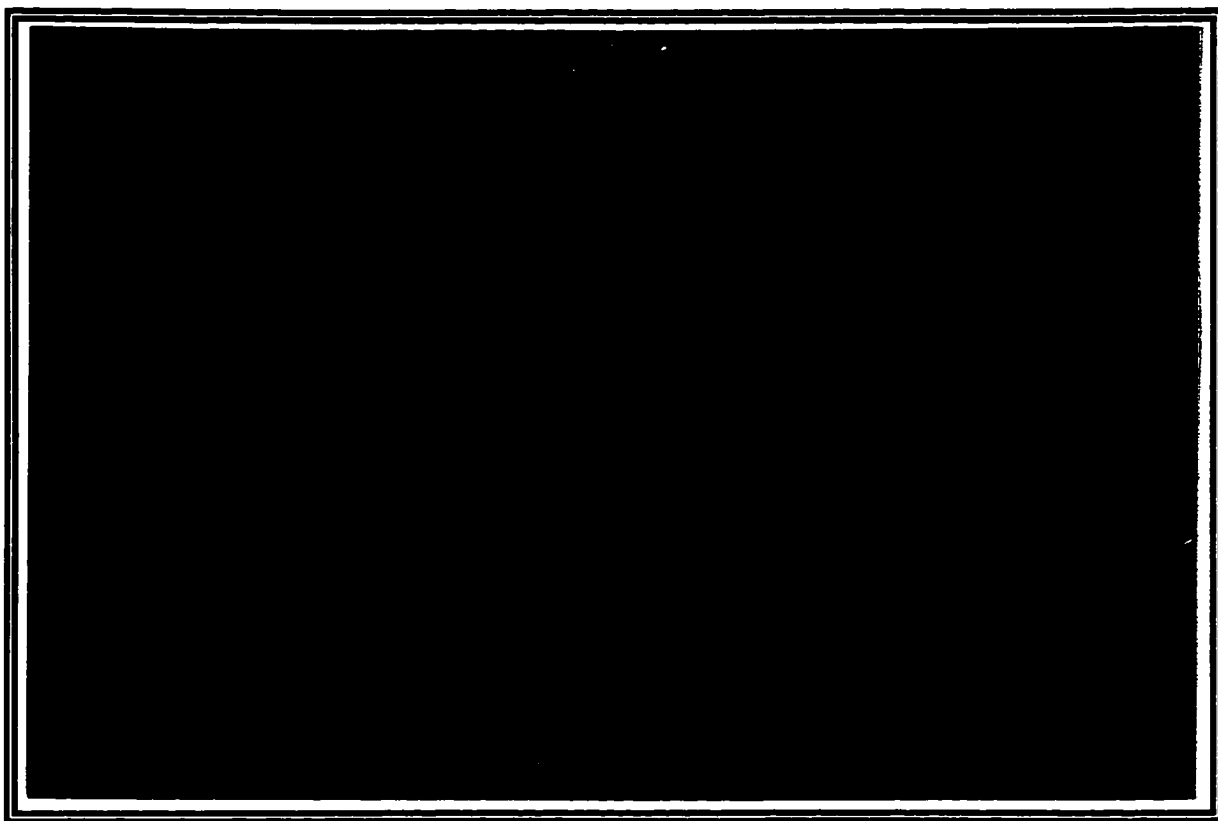


Figure 7-6. Scanning-electron micrograph of a thin section from the Waste Water Disposal #1 Well, Niagara County at depth of 2968', showing moldic porosity that was created by dissolution and selective removal of former dolomite rhombs (arrows). Bar scale = 10 μm .

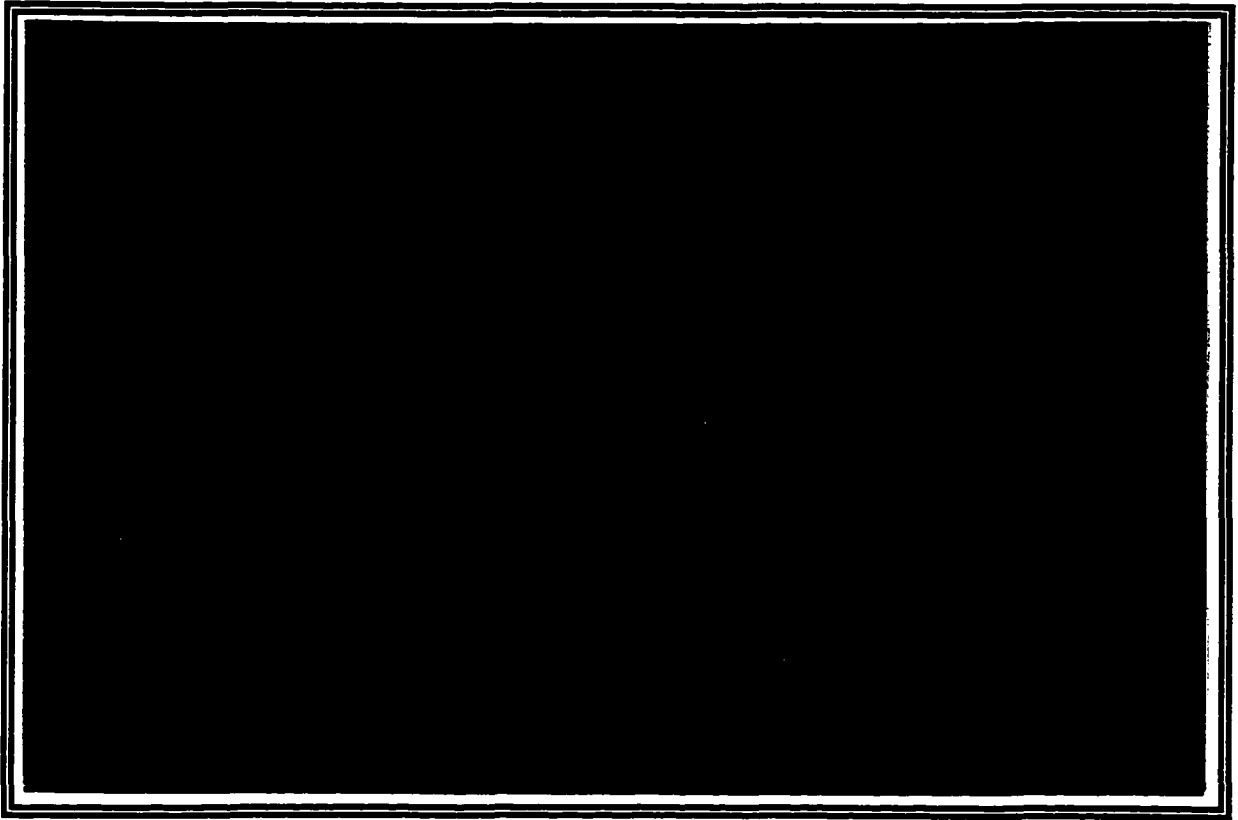


Figure 7-7. Scanning-electron micrograph of a thin section from the Robert Olin #1 Well, Steuben County at depth of 12598', showing micro-channel porosity that serves as continuous pathways of the fluids throughout the rock samples. Bar scale = 10 μm .

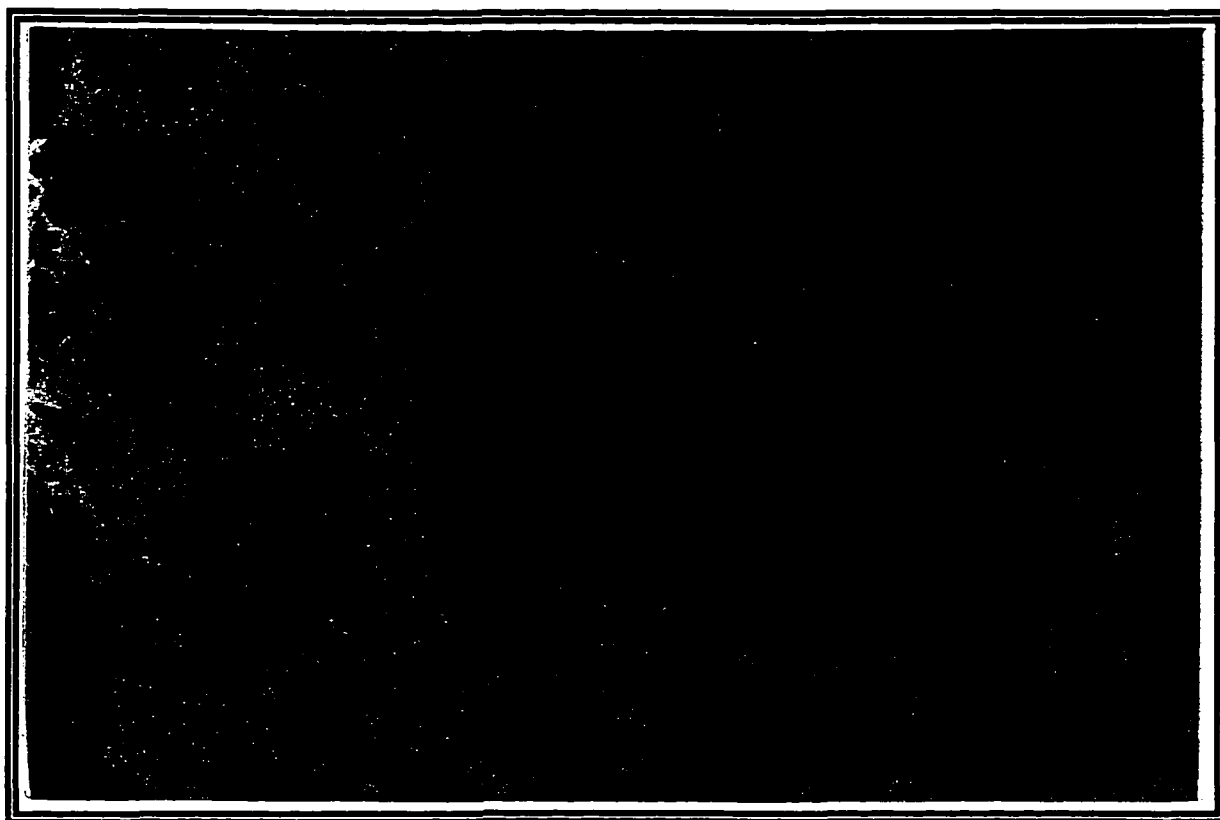


Figure 7-8. Scanning-electron micrograph of a thin section from the Robert Olin #1 Well, Steuben County at depth of 12435', showing vuggy porosity that was created by dissolution and solution enlargement of the pre-existing pores. Bar scale = 10 μm .

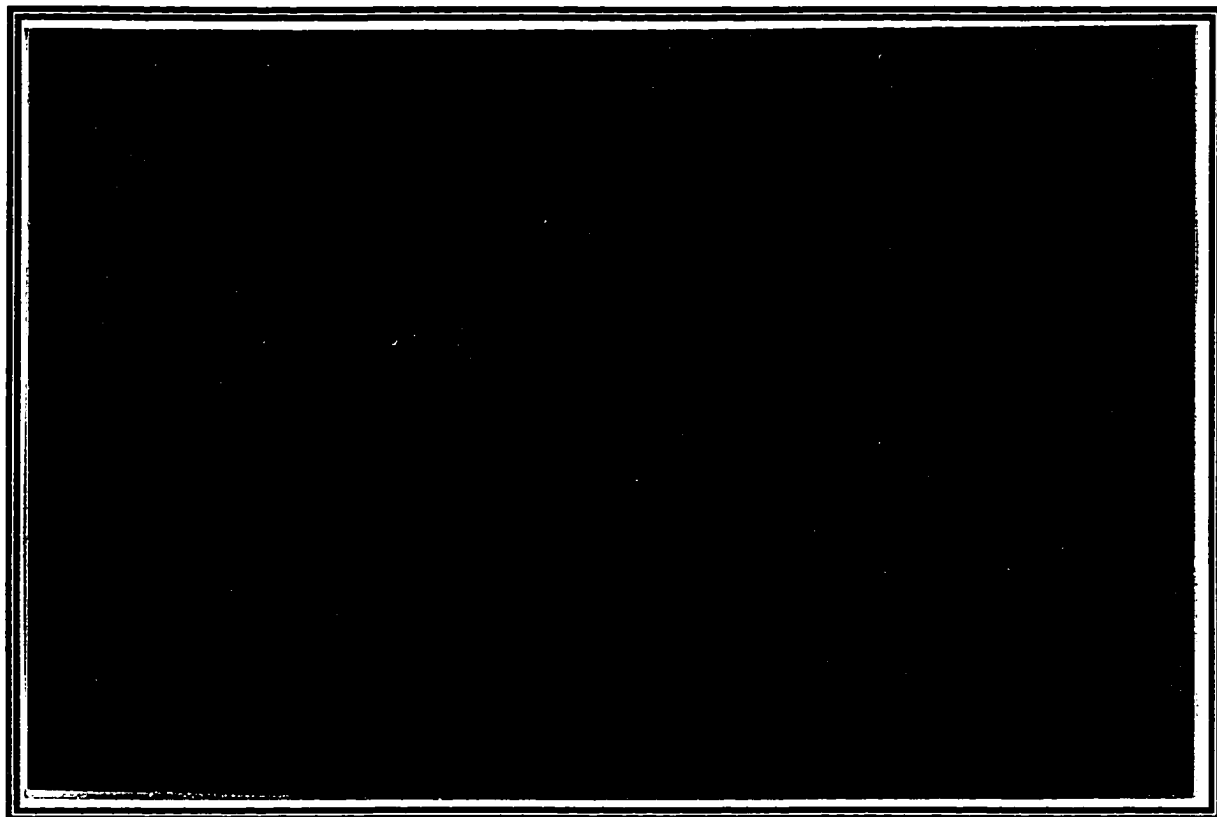


Figure 7-9. Scanning-electron micrograph of a thin section from the Waste Water Disposal #1 Well, Niagara County, showing a system comprised of pores (P) And throats (T) of variable sizes. Bar scale = 10 μm .

Basically, the applied pressure values are plotted versus the volume of mercury injected into the pore spaces. The volume of the intruded mercury is a function of pore diameters in the measured samples. The resulting curve of plotting this information is known as the Capillary-pressure curve. The obtained curve serves as a fast method to identify the petrophysical properties including pore-throat diameters and fluid behavior of a given sample. Generally, injection of mercury into a given samples occurs in three steps that can be recognized in the capillary-pressure curve (Fig. 7-10). The first step is represented by a steep-slope segment, at the beginning of the experiment, where the large-pore throats are filled with mercury at low pressure (Fig. 7-10). The second segment is represented by a flat part of the capillary curve known as the plateau that indicate a narrow range of mercury-injection values and pore-throat sizes (Fig. 7-10). The third part of the capillary curve represents the high pressure stage at which almost all the small pore spaces are filled with mercury (Fig. 7-10). This stage also is defined by the irreducible minimum wetting-phase saturation of the rock pore system at the maximum capillary pressure attained (Wordlaw, 1976; Melas and Friedman, 1992).

7.5.1 Capillary-pressure curve models and their petrophysical interpretations

Volume and size distribution of pore-throats, textural heterogeneity of the pore system, connectivity, and intrusion rate are factors controlling the form of the capillary-pressure curves (Wardlaw and Taylor, 1967; Amthor, Kopaska-Merkel and Friedman, 1988). Based on analysis of ninety-two samples of core plugs and well cuttings, four types of capillary-pressure curves have been recognized. Each of these curves has its unique petrophysical properties including porosity, recovery efficiency, pore-throat sizes, and fluid saturation. These four types of capillary-pressure curves are as follows:

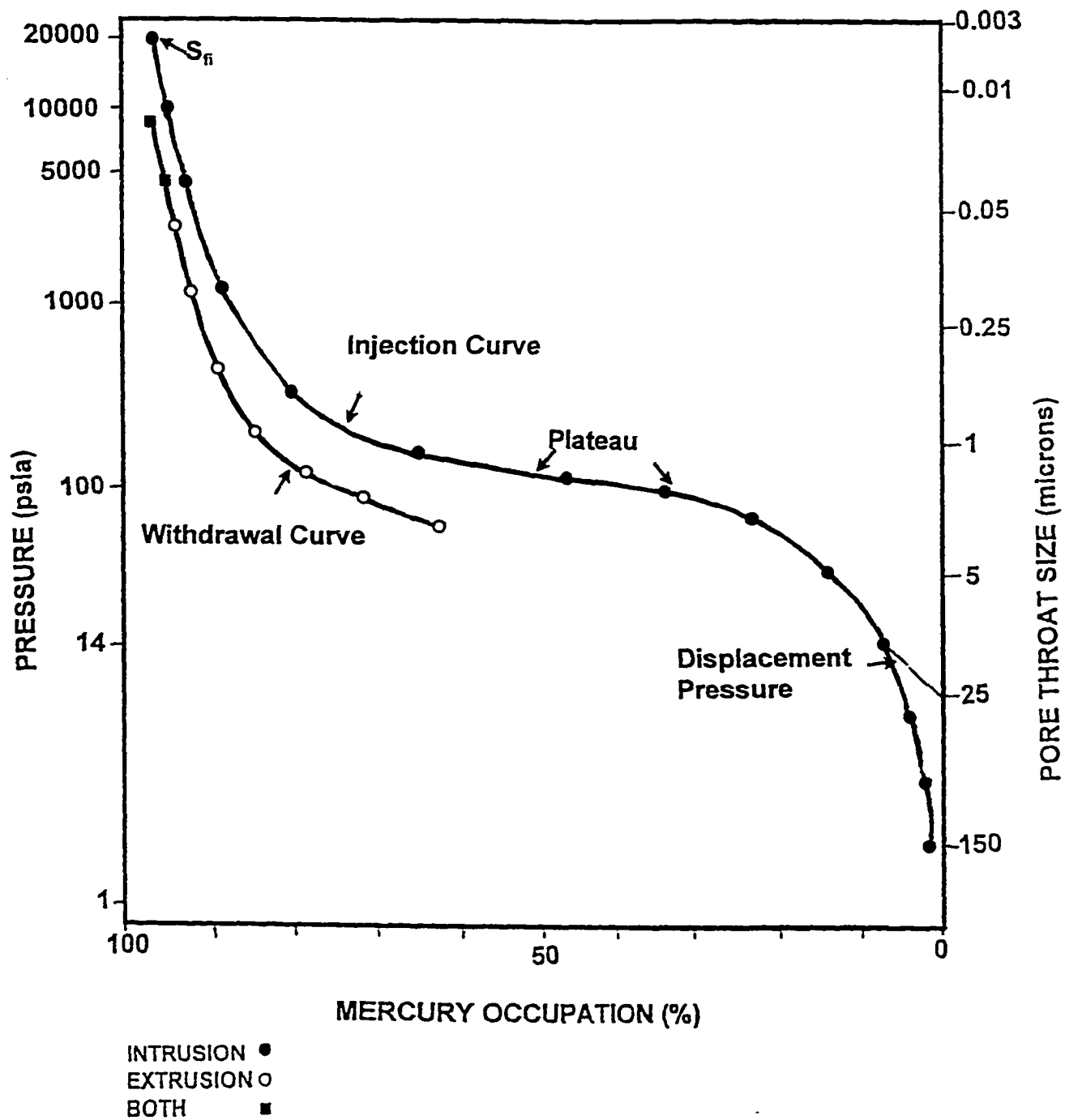


Figure 7-10. A typical mercury capillary-pressure injection curve plotted on semilog scale. S_{ri} = irreducible fluid saturation.

1. Convex capillary-pressure curve (Fig. 7-11): this type of curve represents reservoir rocks of low porosity ($\leq 2\%$) and high recovery efficiency ($\geq 70\%$). Most of the mercury intrusions have occurred at high pressure more than 4000 psia. All the tested samples in this group characterized by small pore throats. Consequently the production or fluid injection will be economical only under high pressure. The high values of the recovery efficiency because the applied pressure during the intrusion are much greater than the released pressure during the extrusion process. Also, permeability is very low due to small throat sizes (≤ 0.1 md).

2. Concave capillary-pressure curve (Fig. 7-12): this curve signifies core samples and well cuttings that characterized by high porosity ($\geq 6\%$) and low recovery efficiency ($\leq 20\%$). All the analyzed samples of this group have large median pore-throat sizes. The mercury intrusion occurred at relatively low pressure (14 psia). The recovery efficiency of this group is low because the applied pressure in case of mercury intrusion is much less than the released pressure during the extrusion. In many cases during pressure reduction, when low pressure is achieved (14 psia), the remaining mercury (non-wetting fluid) inside the pore throat would be isolated from the sample surface and therefore can not be withdrawal.

3. Gently sloping-capillary pressure curve (Fig. 7-13): this curve represents core samples and well cuttings that have intermediate porosity ($\approx 4\%$) and intermediate recovery efficiency ($\approx 35\%$). The analyzed samples of this group have intermediate pore-throat sizes (5 to 0.01 microns). The mercury occupation started at 100 psia and reached to its maximum at 800 psia. The recovery-efficiency values are vary depending in the distribution of pore-throat sizes and the total amount of mercury withdrawal upon releasing pressure.

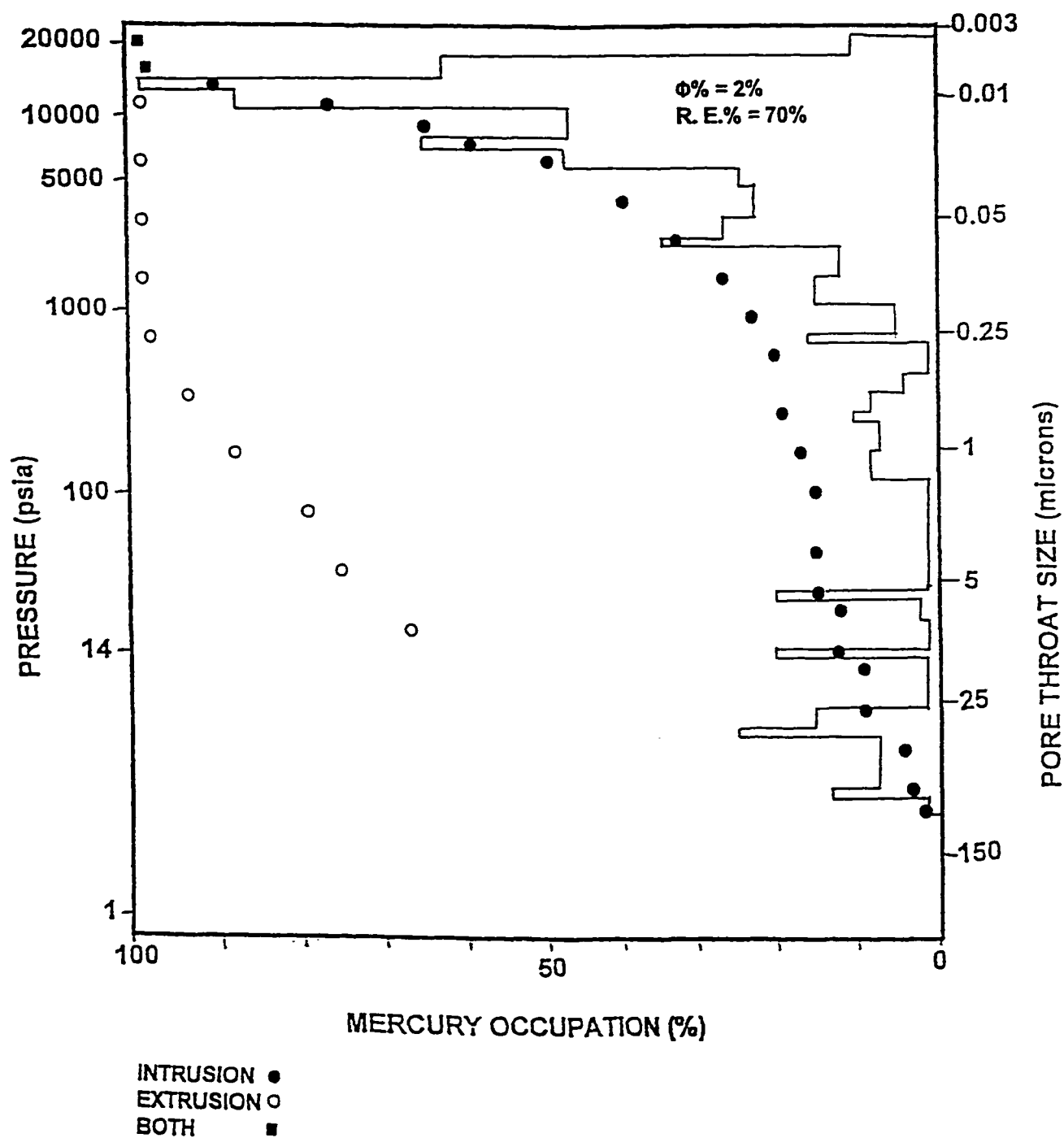


Figure 7-11. Convex capillary-pressure curve- This curve represents petrofacies with low porosity and high recovery efficiency (Porosity = 2%; Recovery efficiency = 70%).

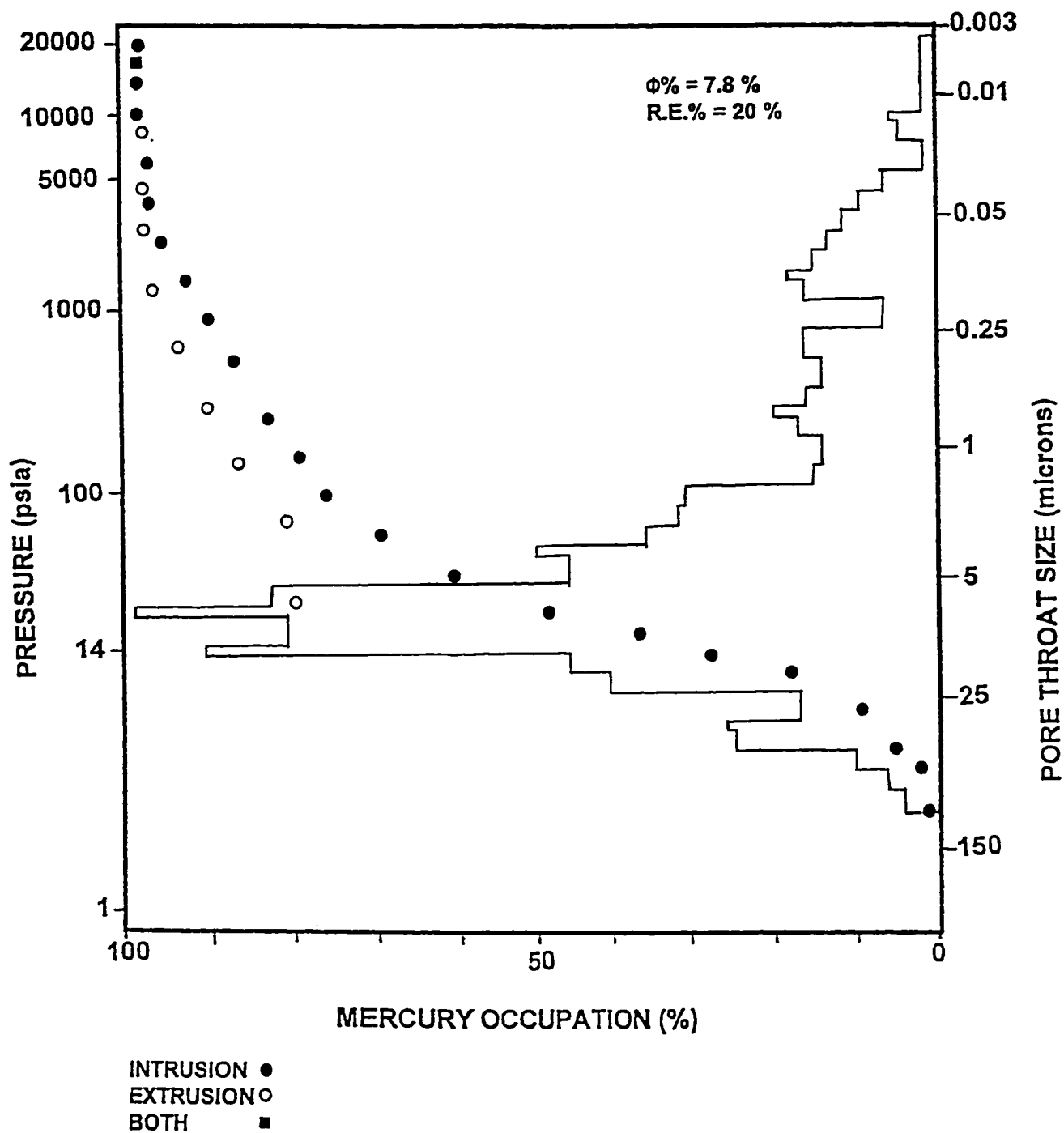


Figure 7-12. Concave capillary-pressure curve- This curve represents petrofacies with high porosity and low recovery efficiency (porosity = 7.8%; Recovery efficiency = 20%).

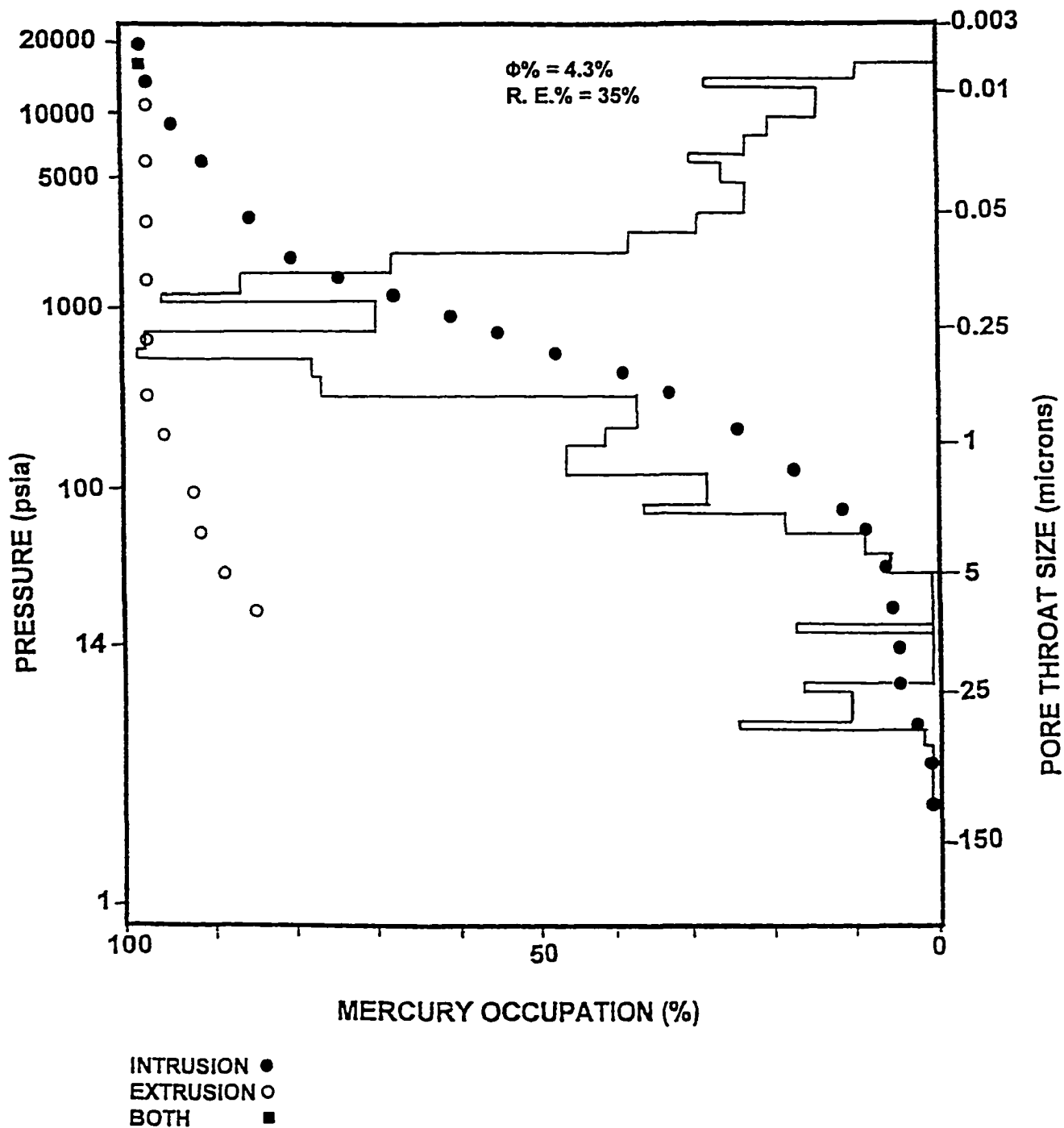


Figure 7-13. Gently sloping apillary- pressure curve- This curve represents petrofacies with an intermediate porosity and intermediate recovery efficiency (porosity = 4.3%; Recovery efficiency = 35%).

4. Polymodal capillary-pressure curve (Fig. 7-14) : This curve represents core samples and well cuttings that have low porosity and low recovery efficiency. The porosity values range from 1 % to 3%. The median throat sizes are widely varied (100 - 0.003 microns). However, the majority of pore-throat-sizes of this group are considerably large (100 to 1 microns). Because of these large pore sizes, the recovery efficiency values are low. The mercury occupation started at 14 psia and reached to its maximum at 8000 psia.

7.6 Petrofacies Analysis

The intensity of the diagenetic modifications varied throughout the lithofacies and microlithofacies of the Beekmantown Group. These diagenetic modifications produced a set of petrofacies. These petrofacies reflect strong relationships between the lithologies and petrophysical parameters including porosity, permeability, recovery efficiency, pore diameters, and fluid saturation. Detailed quantitative analysis were performed using mercury porosimetry (see Appendices B & C).

7.6.1 Waste Water Disposal #1 Well, Niagara County

Table 7-1 represents a set of petrophysical data obtained from the porosimetric analysis of this well. High to moderate porosity values were recorded in the coarse-grained sandstone (Potsdam Formation), the stromatolitic dolostone (Theresa Formation), and the laminated, silty to sandy dolostone (Theresa Formation). The highest porosity value was recorded in coarse-grained sandstone petrofacies of the Potsdam Formation (Fig. 7-15) with an average of 4.7%. The highest recovery efficiency values were recorded in the bioturbated, sandy dolostone of the Potsdam Formation (Fig. 7-16) with an average of 65 %. However, the entire well possesses low permeability values that range from <0.001 to 0.015 millidarcy (Fig. 7-17). The Glauconitic sandy dolostone petrofacies (Potsdam Formation) has the largest pore diameter values (Fig. 7-18) with an average of 0.76 microns. Based

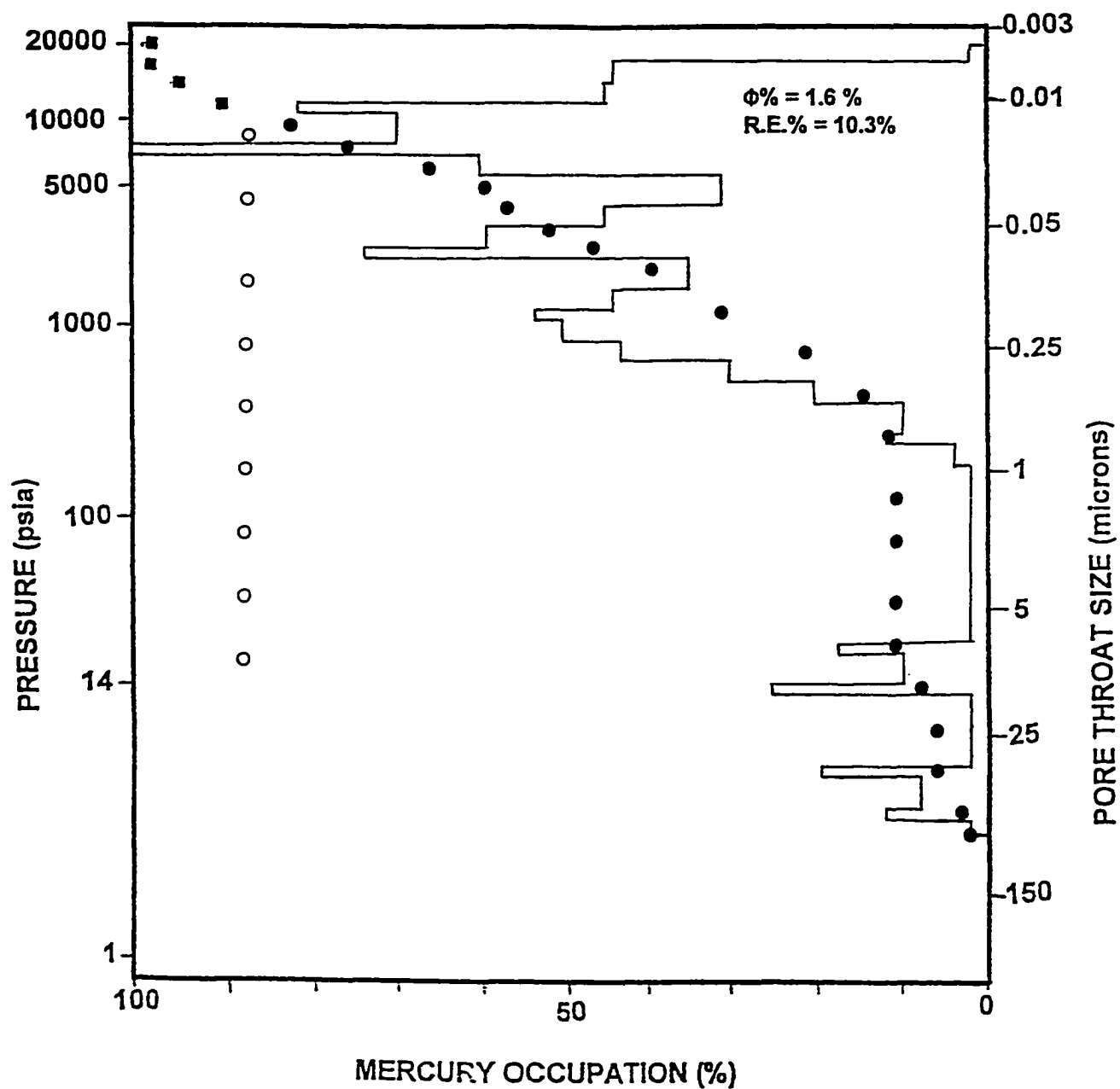


Figure 7-14. Polymodal capillary-pressure curve - This curve represents petrofacies with low porosity and low recovery efficiency (porosity = 1.6 %; Recovery efficiency = 10.3%).

Fig. 7-15. Porosity distribution in the Waste Water Disposal #1 Well, Niagara County, NY.

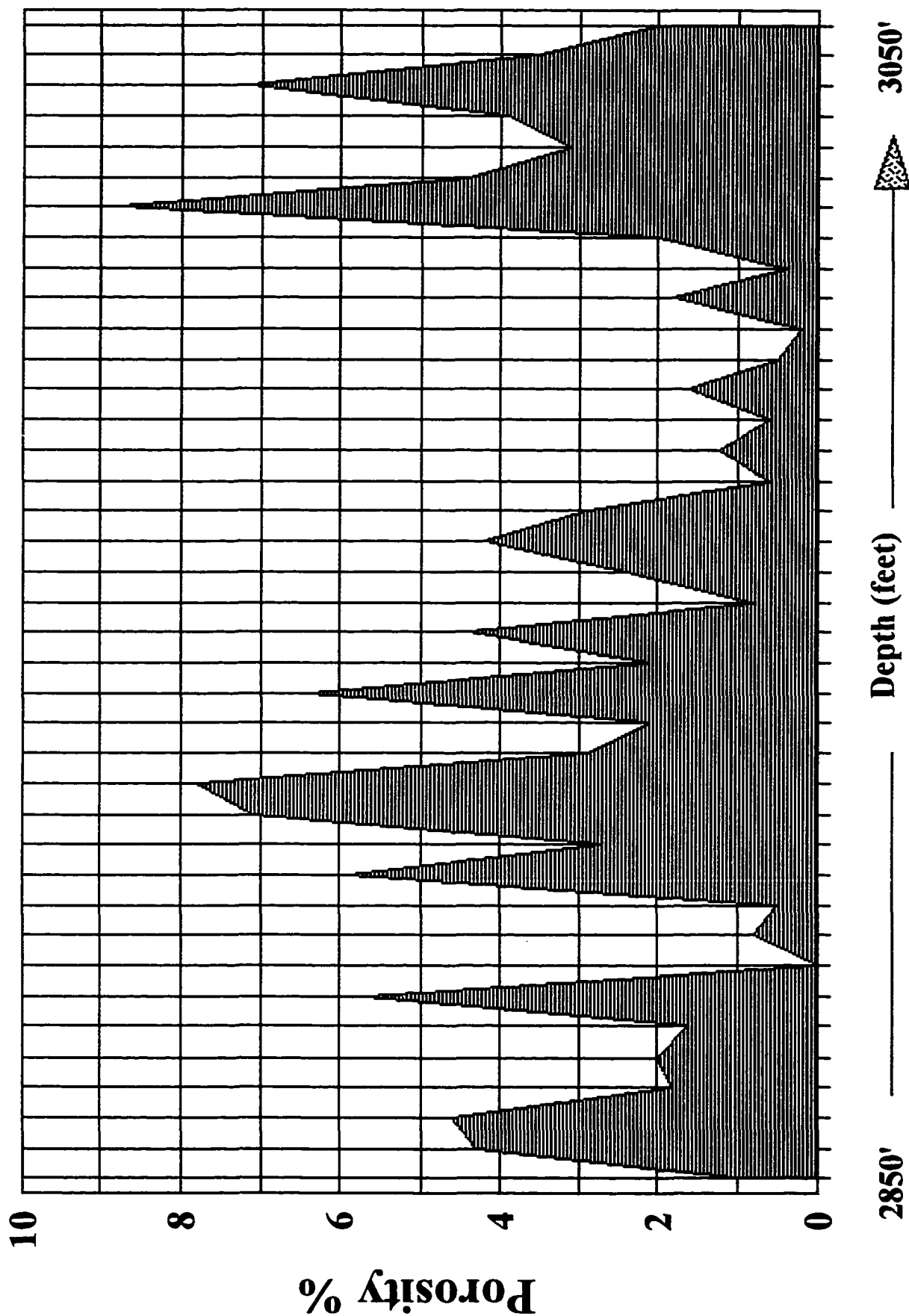


Fig. 7-16. Recovery-efficiency values in the Waste Water Disposal #1 Well, Niagara County, NY.

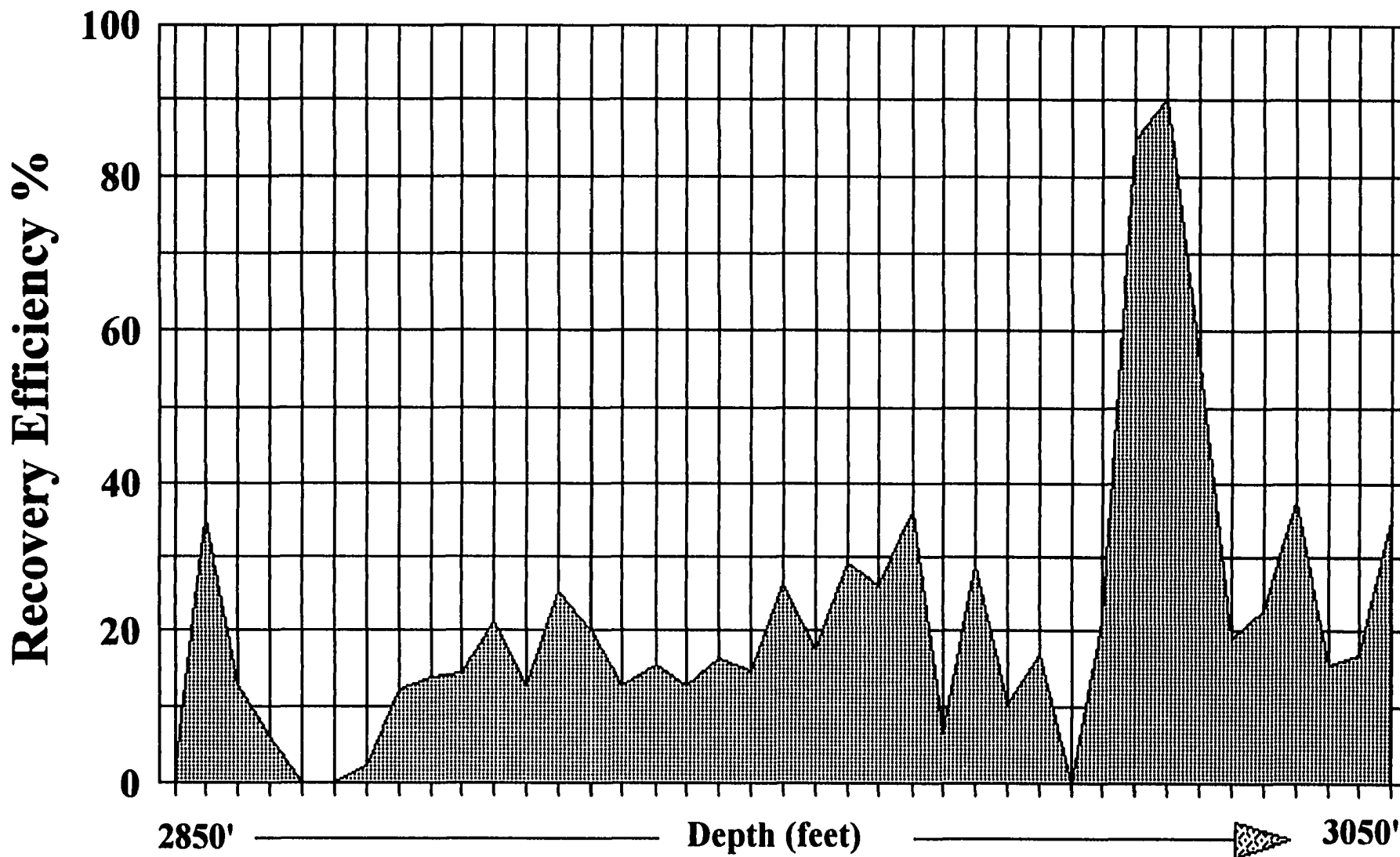


Fig. 7-17. Permeability values in the Waste Water Disposal Well, Niagara County, NY.

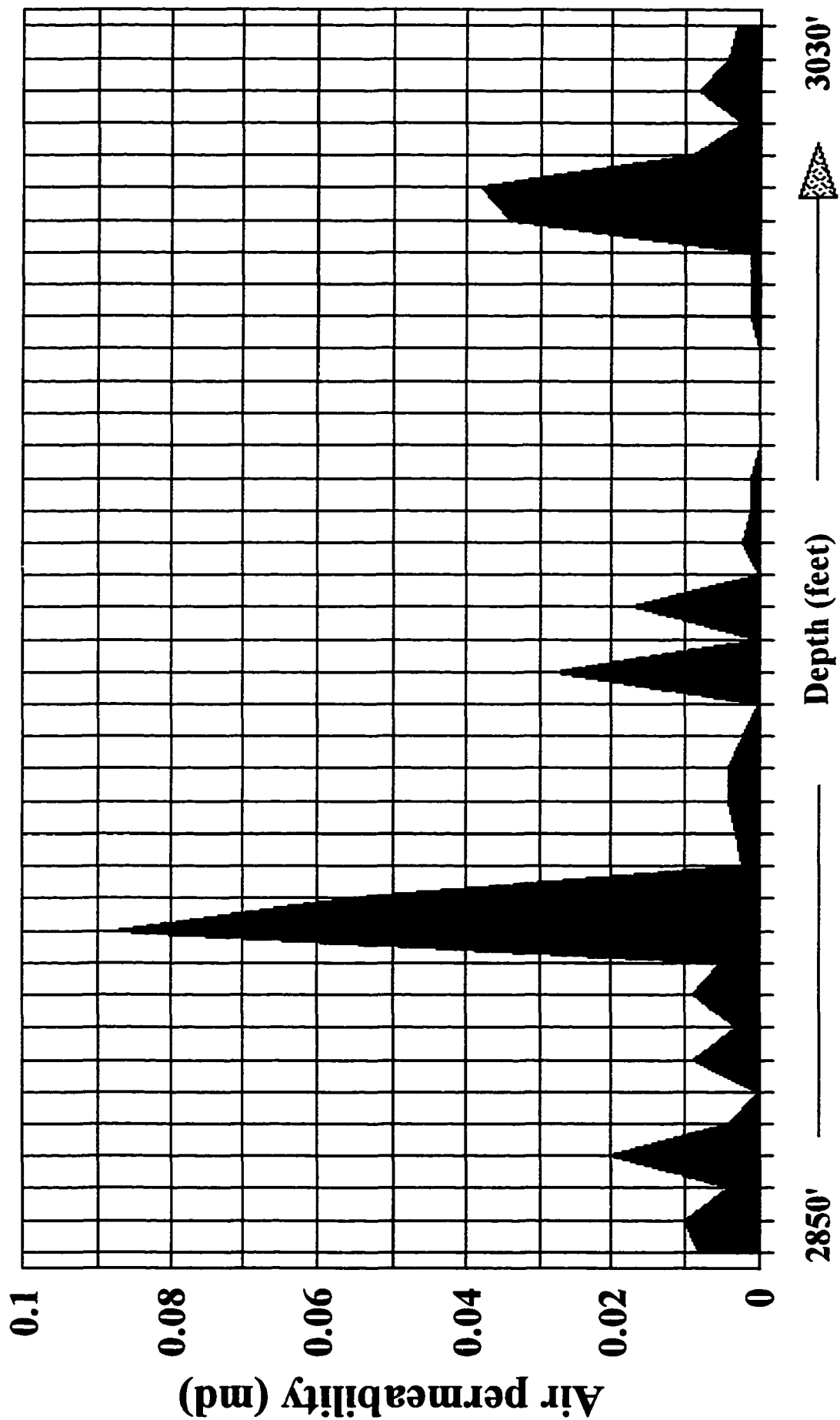
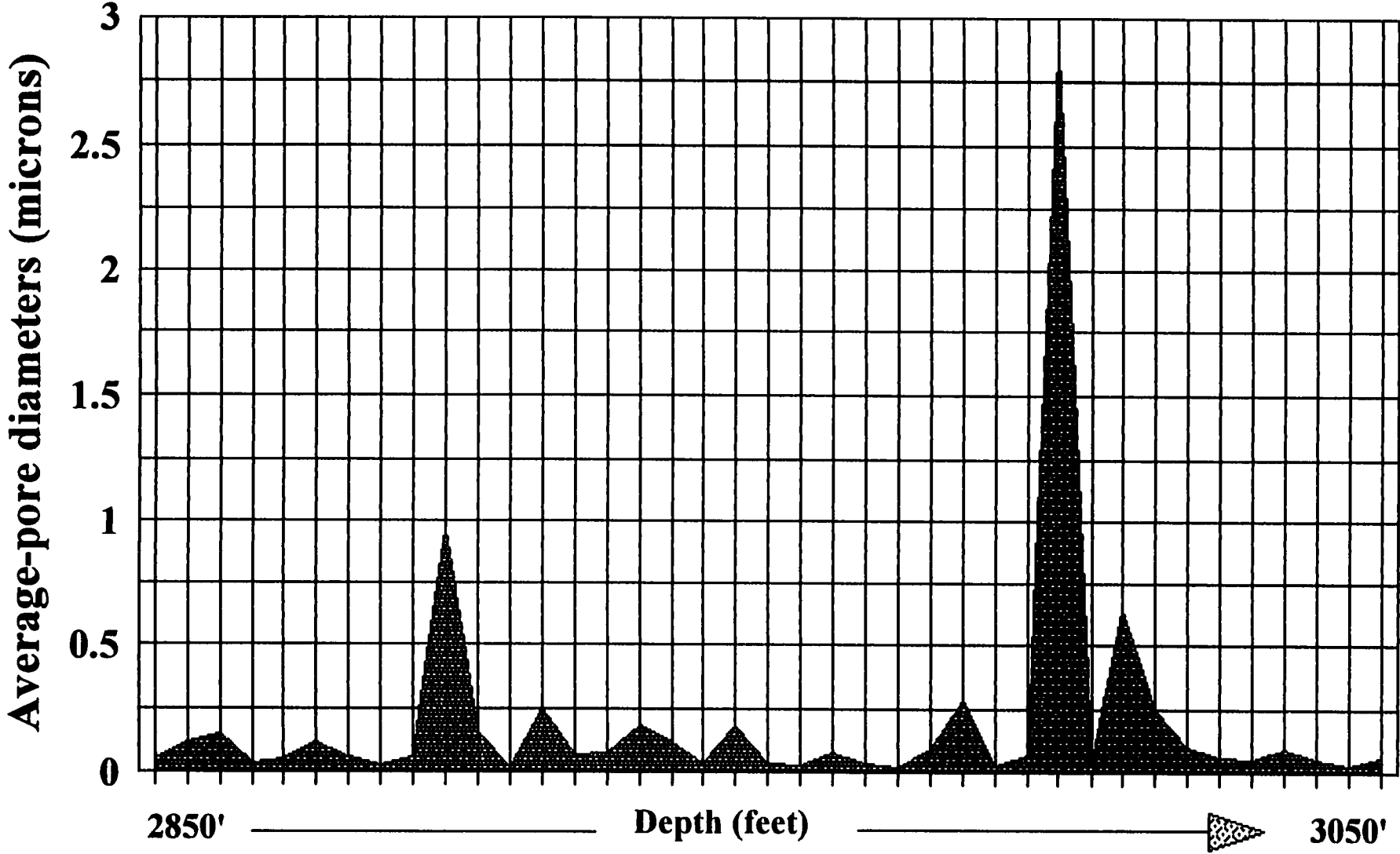


Fig. 7-18. Distribution of average-pore diameters in the Waste Water Disposal # 1 Well, Niagara County, NY.



on the capillary pressure test, the Coarse-grained sandstone (Potsdam Formation), the Stromatolitic dolostone (Theresa Formation), and the Laminated, silty to sandy dolostone (Theresa Formation) petrofacies were occupied by mercury at low pressure (800 - 1800 psia). As a result, these petrofacies are the best candidates for brine-disposal intervals.

Table 7-1: Petrophysical data of a core section from the Waste Water Disposal Test Well #1 (W.W.D. Well), Niagara County, New York.						
Petrofacies	Depth Interval (ft)	Average Porosity Percent ($\phi\%$)	Air Permeability (mD)	Recovery Efficiency Percent (R.E. %)	Median Pore Diameter (μm)	Average Pore Diameter (μm)
Quartzose dolomite with anhydrite laths	2851-2849	2.7	0.009	18.7	0.47	0.09
Laminated, silty to sandy dolostone	2861-2851	3.2	0.003	9.5	0.41	0.10
Oolitic dolostone	2996-2861	2.3	0.004	3.6	2.37	0.07
Stromatolitic dolostone	2966-2896	3.5	0.015	18.5	4.54	0.15
Stylolitic, sandy dolostone	2978-2966	0.6	0.001	32.4	22.14	0.15
Glauconitic, sandy dolostone	2988-2978	0.8	<.001	12.1	7.33	0.76
Bioturbated, sandy dolostone	2995-2988	1.4	0.001	65.5	5.13	0.32
Coarse-grained sandstone	3026-2995	4.7	0.014	28.9	0.22	0.06

7.6.2 Robert Olin #1 Well (Woodhull Storage), Steuben County

The petrophysical parameters of this well vary among the lithofacies (Table 7-2). Locally, porosity is relatively high within the coarse-grained sandstone of the Potsdam Formation, the sandy dolostone of the Theresa Formation, and the dolostone with anhydrite laths of the Theresa Formation compared to the other petrofacies (Fig. 7-19). Recovery efficiency percent shows high values at the boundary between the Potsdam and Theresa Formations (Fig. 7-20). The average pore diameters within the oolitic dolostone petrofacies of the Theresa Formation are high (Fig. 7-21).

Fig. 7-19. Porosity distribution in the Robert Olin #1 Well, Steuben County, NY.

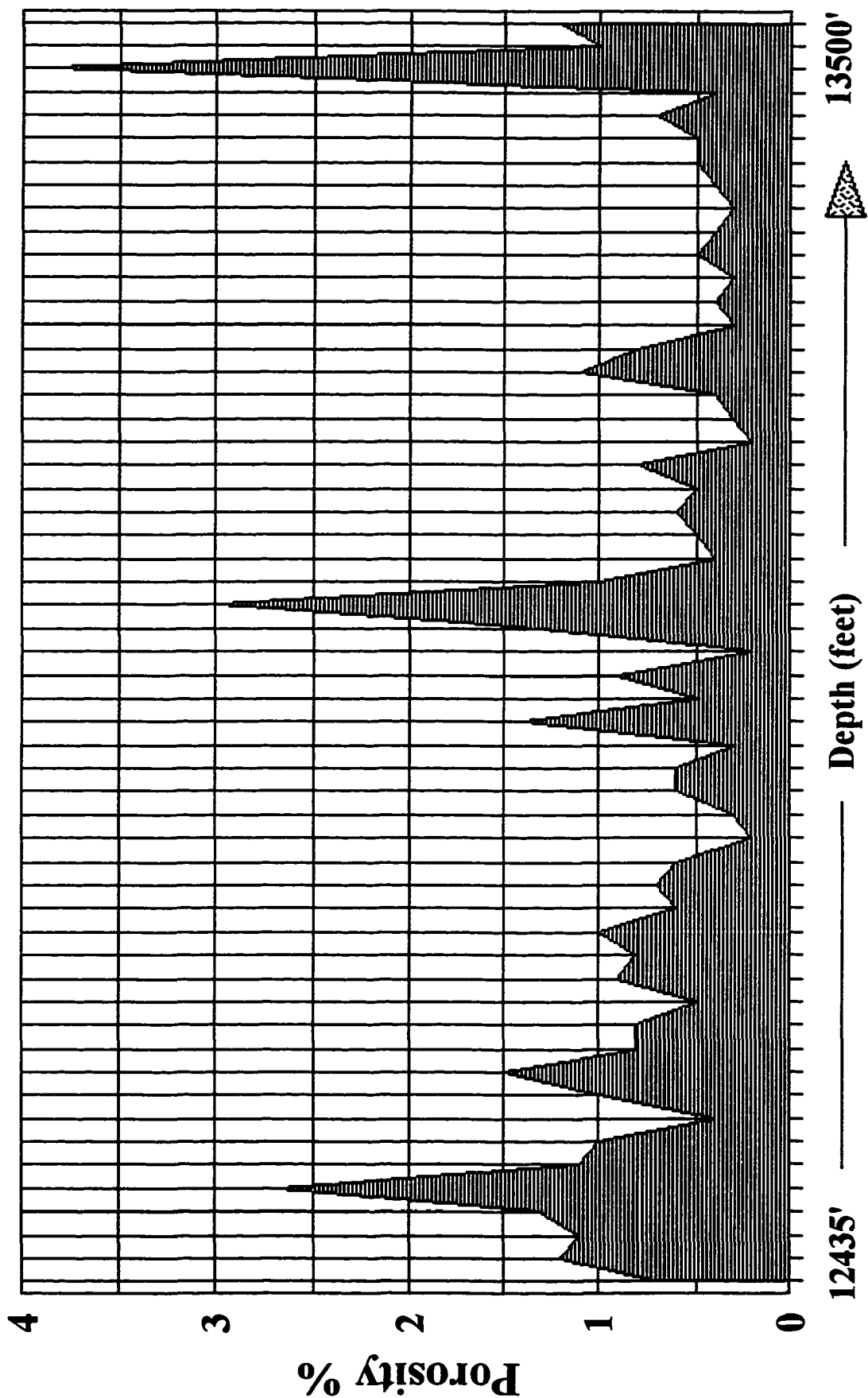


Fig. 7-20. Recovery-efficiency values in the Robert Olin #1 Well, Steuben County, NY.

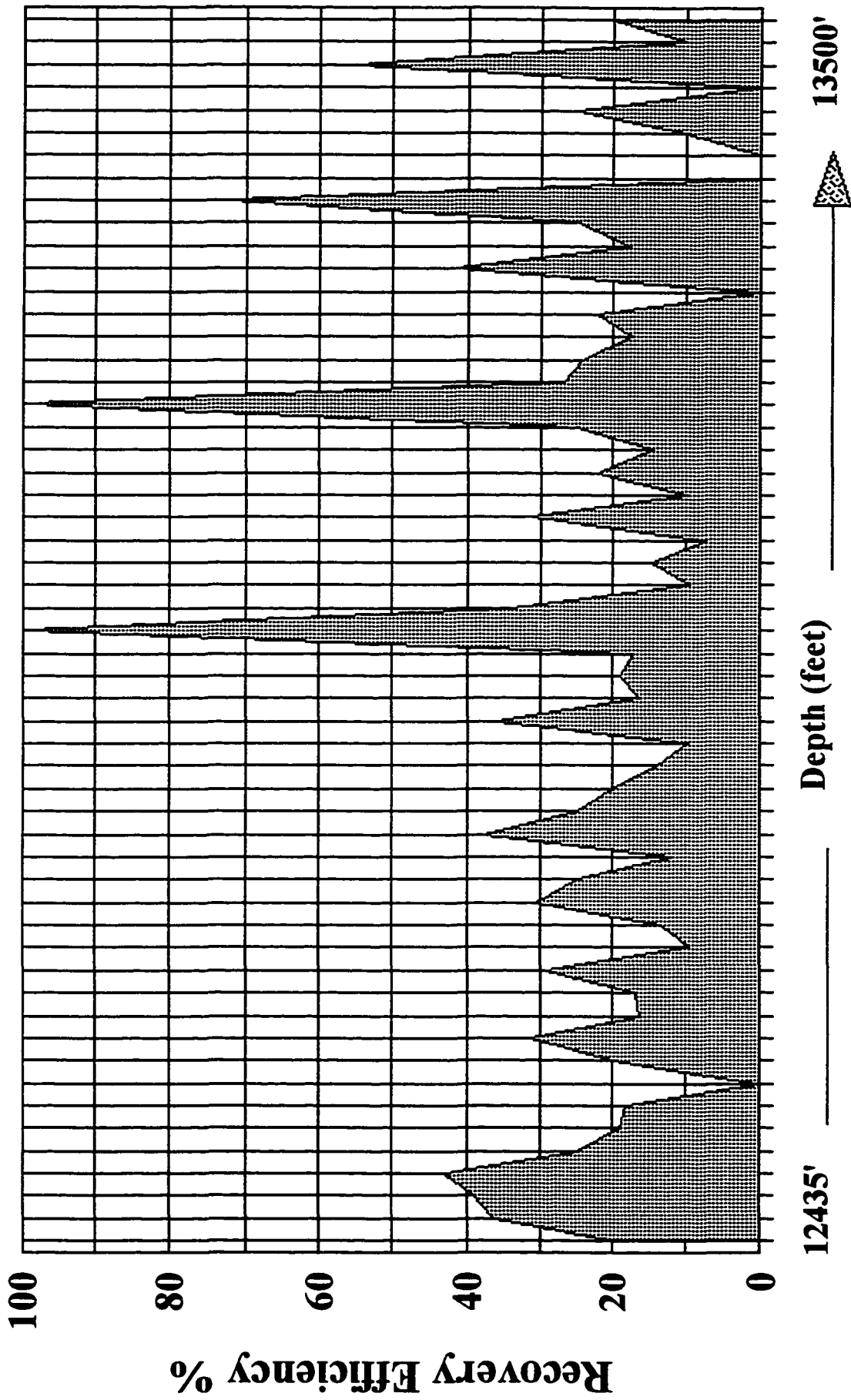
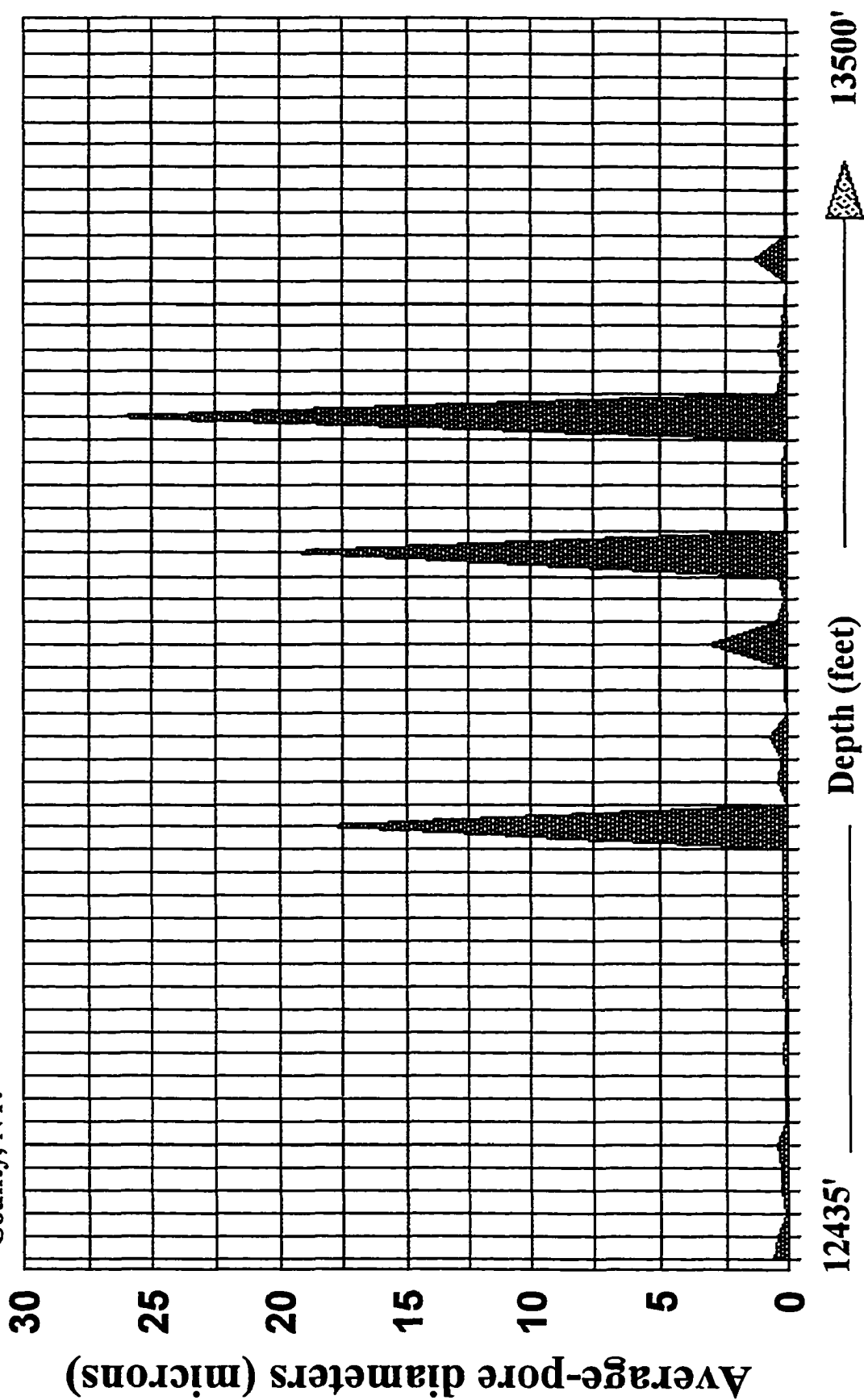


Fig. 7-21. Distribution of average-pore diameters in the Robert Olin #1 Well, Steuben County, NY.

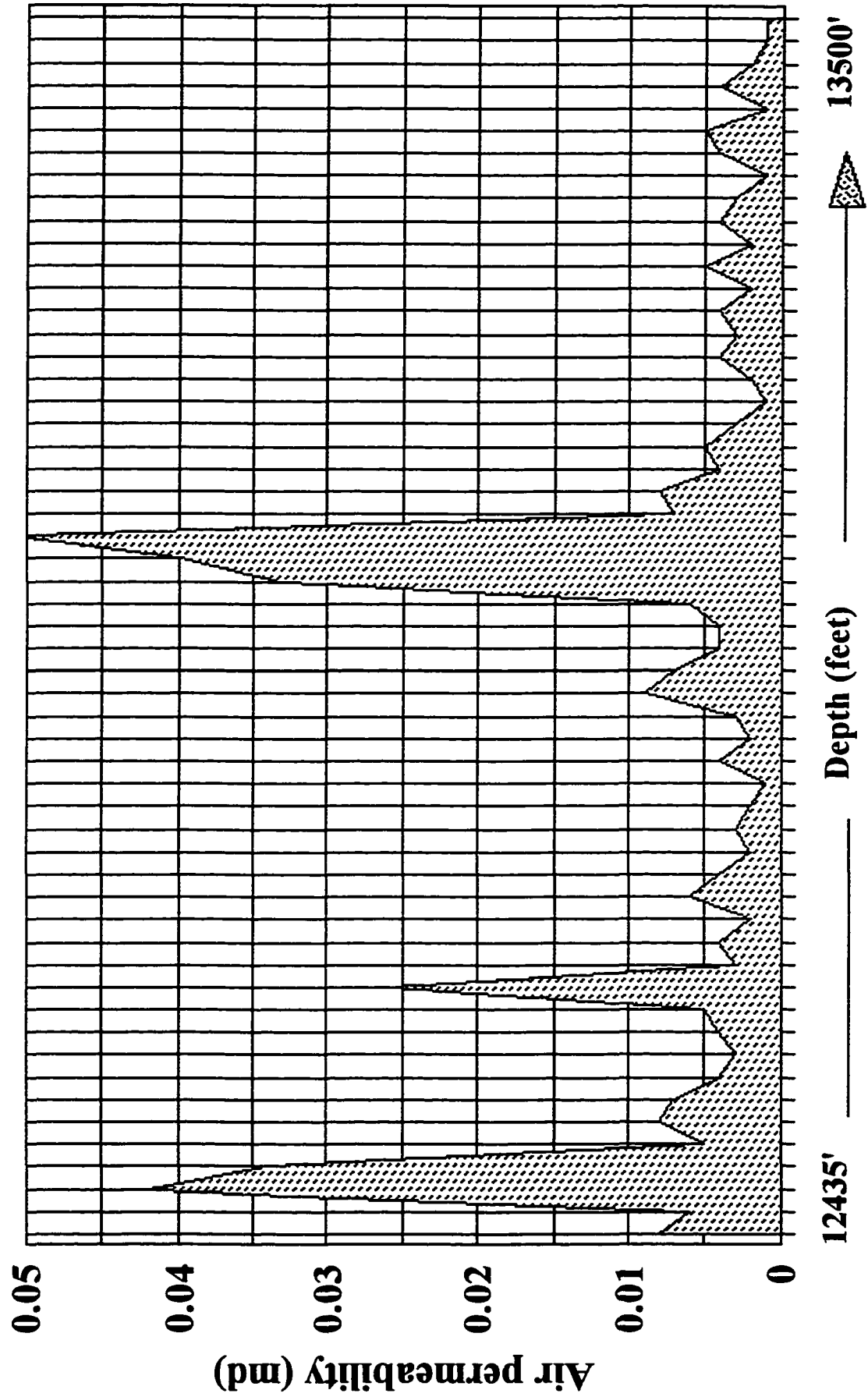


These high values (28 microns) resulted from the presence of voids, vugs, and microfractures within certain sections. The permeability values are very low and ranging from 0 to 0.05 millidarcy (Fig. 7-22). The average porosity values throughout this well are very low. Most of the pore spaces have been occluded by cementation during the diagenetic processes. The average pore diameters range from 0.06 to 0.3 microns within this well. However, a few samples have large pore diameters which indicate the presence of local vugs and microfractures. Petrographic evidence supports this conclusion (Fig. 7-8). Normally, these vugs and microfractures filled with mercury at very low pressure (100 - 800 psia) and their recovery efficiencies percent are very low (close to zero). In conclusion, this well does not have a good reservoir quality for gas storage or brine disposal.

Table 7-2: Petrophysical data of a core section from the Robert Olin #1 Well, Steuben County, New York.

Petrofacies	Depth Interval (ft)	Average Porosity Percent ($\phi\%$)	Air Permeability (mD)	Recovery Efficiency Percent (R.E. %)	Median Pore Diameter (μm)	Average Pore Diameter (μm)
Dolostone with anhydrite laths	12455-12434	1.1	0.011	22.4	4.16	0.22
Stromatolitic dolostone	12550-12455	0.7	0.009	29.1	10.12	2.17
Oolitic dolostone	12598-12550	0.5	0.003	29.0	17.93	2.50
Sandy dolostone	13300-12598	0.5	0.005	5.0	6.05	0.09
Coarse-grained sandstone	13492-13300	1.4	0.003	22.6	1.83	0.11

Fig. 7-22. Air-permeability values in the Robert Olin #1 Well, Steuben County, NY.



7.6.3 Mitchell #1 Well (Avoca), Steuben County

Generally, the average porosity values within this well is ranging from 2.4 % to 5.5 % (Table 7-3). The highest value of porosity is recorded in the sandy dolostone petrofacies of the Theresa Formation that located between 8760 and 9400 feet deep (Fig. 7-23). Within this part of the Theresa formation, the porosity values range from 2.8 to 7.4 percent (Fig. 7-23) with an average of 5.5%. The lowest porosity values is detected at the fossiliferous dolostone petrofacies (Table 3) with an average of 2.4%. Recovery efficiency percent is relatively high (40%) in the sandy dolostone petrofacies (Fig. 7-24). The average pore diameters range from 0.06 to 1.0 microns (7-25). According to the mercury-capillary pressure values, brine disposal in this well should be injected at high pressure (5000 - 8000 psia). As a result, the Potsdam sandstone and the sandy dolostone petrofacies of the Theresa formation could be good sites for brine disposal.

Table 7-3: Petrophysical data of well-cuttings from the Mitchell (Avoca) Well, Steuben County, New York.					
Petrofacies	Depth Interval (ft)	Average Porosity (ϕ %)	Average Recovery Efficiency (R.E. %)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
Fossiliferous dolostone	8760-7990	2.4	20.3	7.47	0.08
Sandy dolostone	9400-8760	5.5	26.5	12.11	0.30
Oolitic, sandy dolostone	9520-9400	4.2	7.9	6.79	0.08
Coarse-grained sandstone	9885-9520	4.9	30.00	8.76	0.06

7.6.4 Wilson Well, Wyoming County

Table 7- 4 depicts the petrophysical data obtained from the porosimetric analysis of the Wilson #1 Well of Wyoming County. The petrophysical parameters (porosity, recovery efficiency, and the average pore diameters) varied among the four petrofacies. The coarse-grained sandstone

Fig. 7-23. Porosity distribution in the Mitchell # 1 Well, Steuben County, NY.

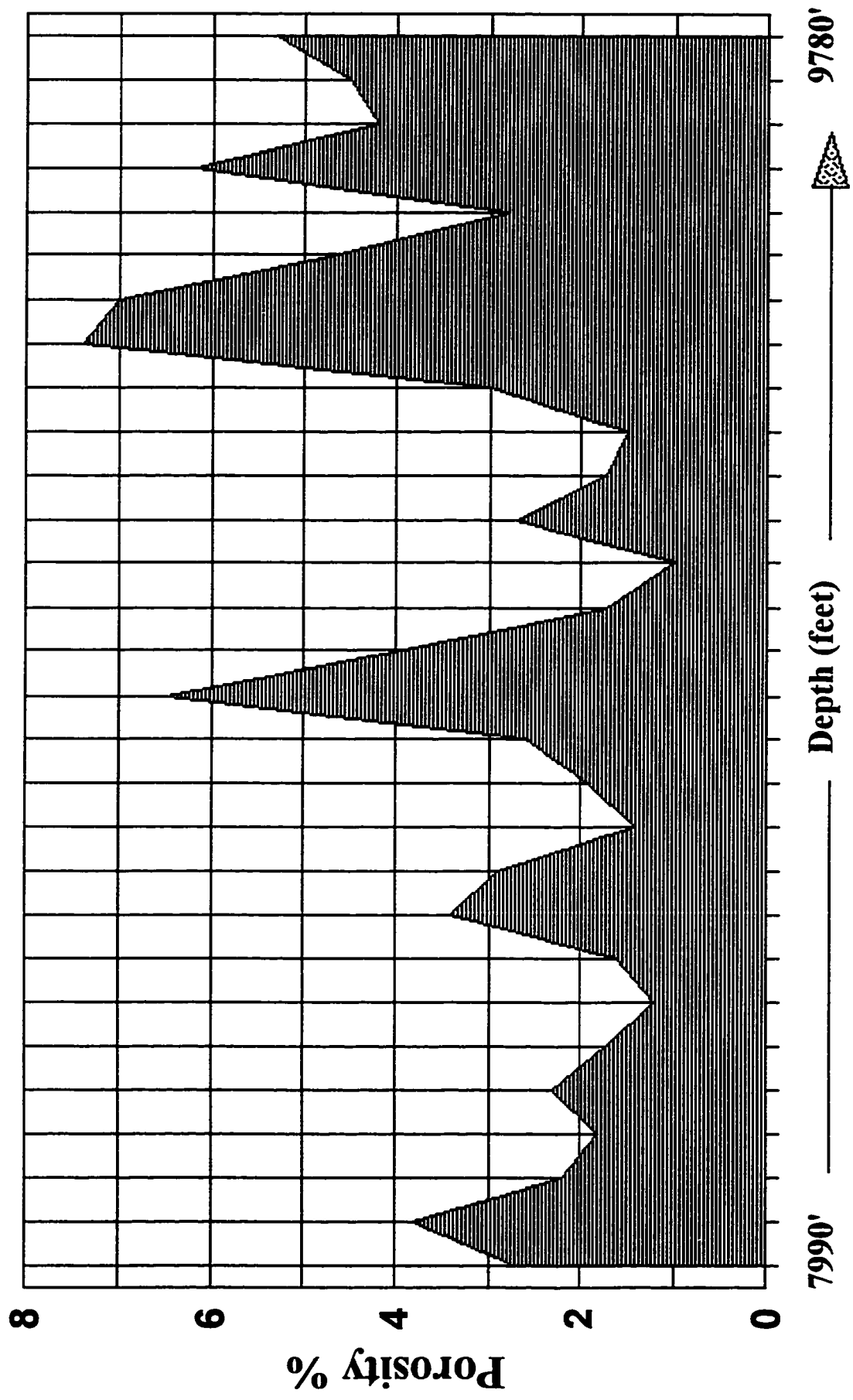


Fig.7-24. Recovery-efficiency values in the Mitchell # 1 Well, Steuben County, NY.

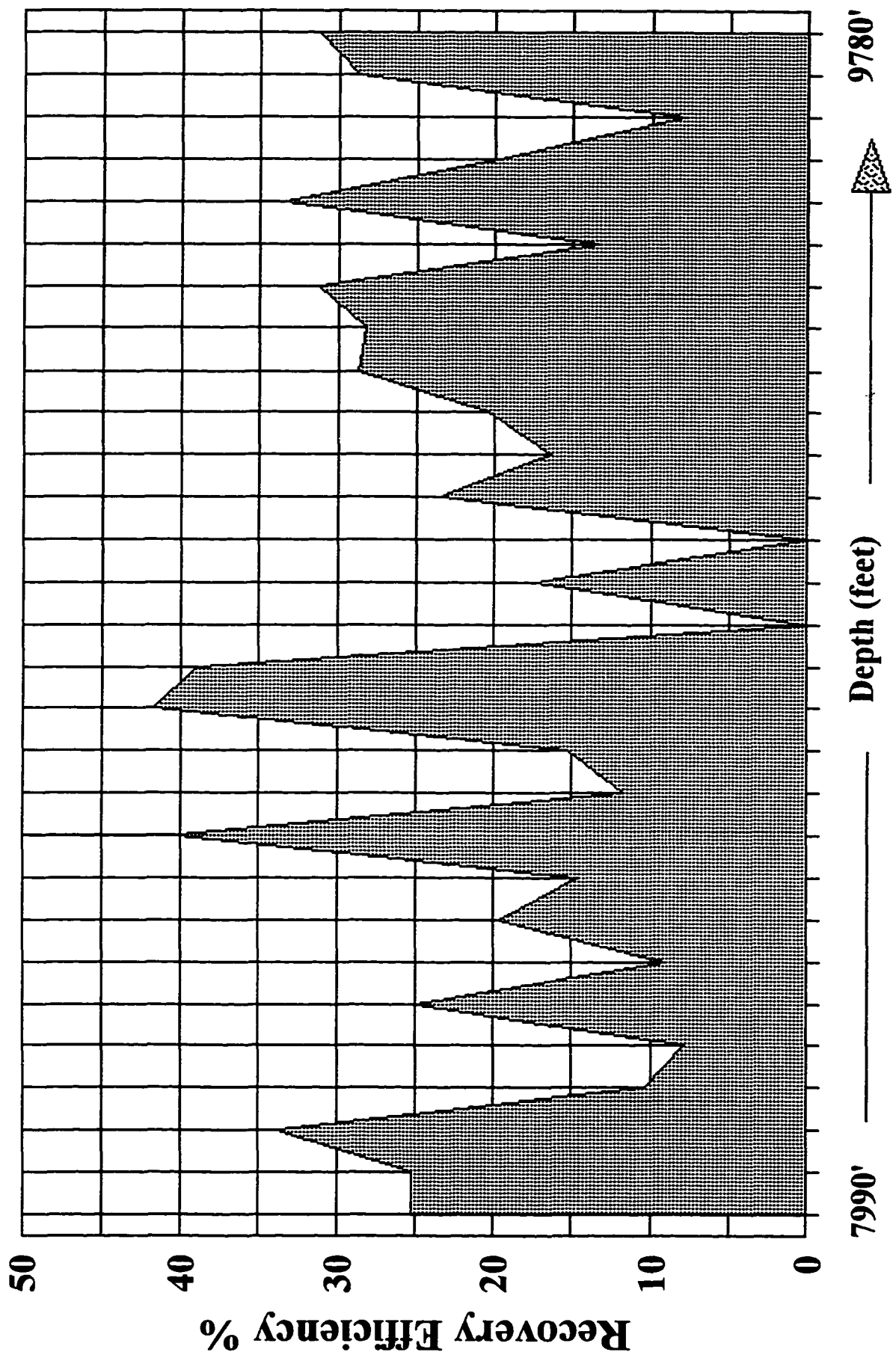
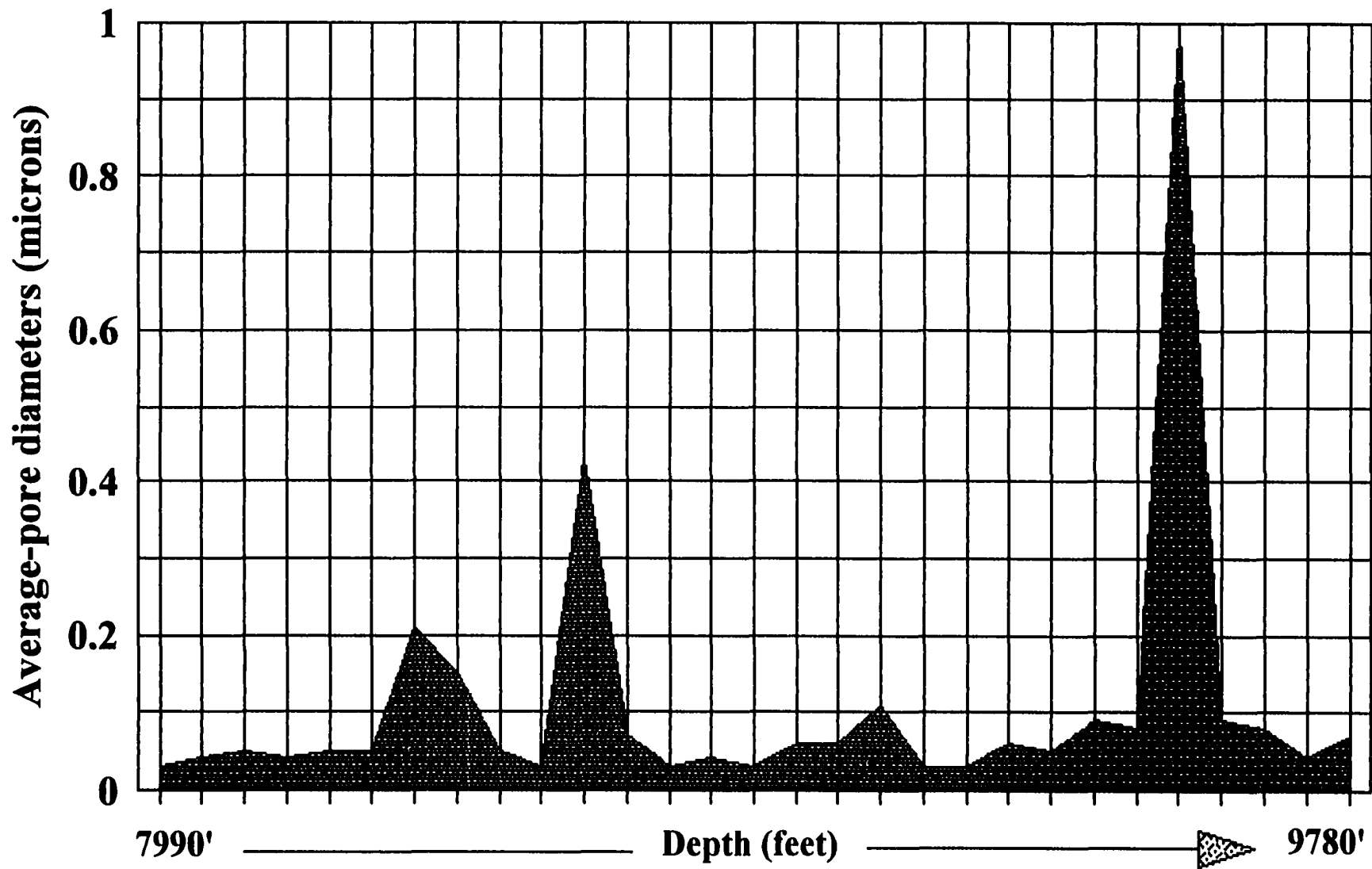


Fig. 7-25. Distribution of average-pore diameters in the Mitchell # 1 Well, Steuben County, NY.



of the Potsdam Formation possesses the highest porosity (Fig. 7-26) with an average of 9.2%. The average pore diameter of this coarse-grained sandstone petrofacies is 1.46 microns (Fig. 7-27). Pore-diameter values represent relatively large pore spaces. As a result, the recovery efficiency percent in the coarse-grained sandstone is very low with an average of 25% (Fig. 7-28). The porosity value of the sandy dolostone petrofacies (Theresa Formation) ranges from 2.1 to 10.5 % with an average of 5.2 %. The average pore diameter of this petrofacies is 0.11 microns (Table 7-4). The porosimetric analysis indicates that injection of liquid into such pore diameter of the coarse-grained sandstone and the sandy dolostone petrofacies occurs at relatively low pressure (900 to 1500 psia) that make them good candidate for brine-disposal intervals. These two petrofacies are overlain by the dolostone with anhydrite laths and the oolitic dolostone petrofacies that possesses low porosity, moderate recovery efficiency, and small-pore diameters. Consequently, the dolostone with anhydrite laths and the oolitic dolostone petrofacies act as a cap rocks that prevent gas and fluid migration from the underlie sandy dolostone and the coarse-grained sandstone petrofacies.

**Table 7-4: Petrophysical data of well-cuttings from the Wilson Well,
Wyoming County, New York.**

Petrofacies	Depth Interval (ft)	Average Porosity Percent (ϕ %)	Recovery Efficiency (R.E. %)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
Oolitic dolostone	7120-6850	2.4	32.6	4.12	0.04
Dolostone with anhydrite laths	6850-6320	2.1	32.9	2.23	0.05
Sandy dolostone	6320-6140	5.2	31.8	8.53	0.11
Coarse-grained sandstone	6140-5980	9.2	12.1	11.25	0.60

Fig. 7-26. Porosity distribution in the Wilson #1 Well, Wyoming County, NY.

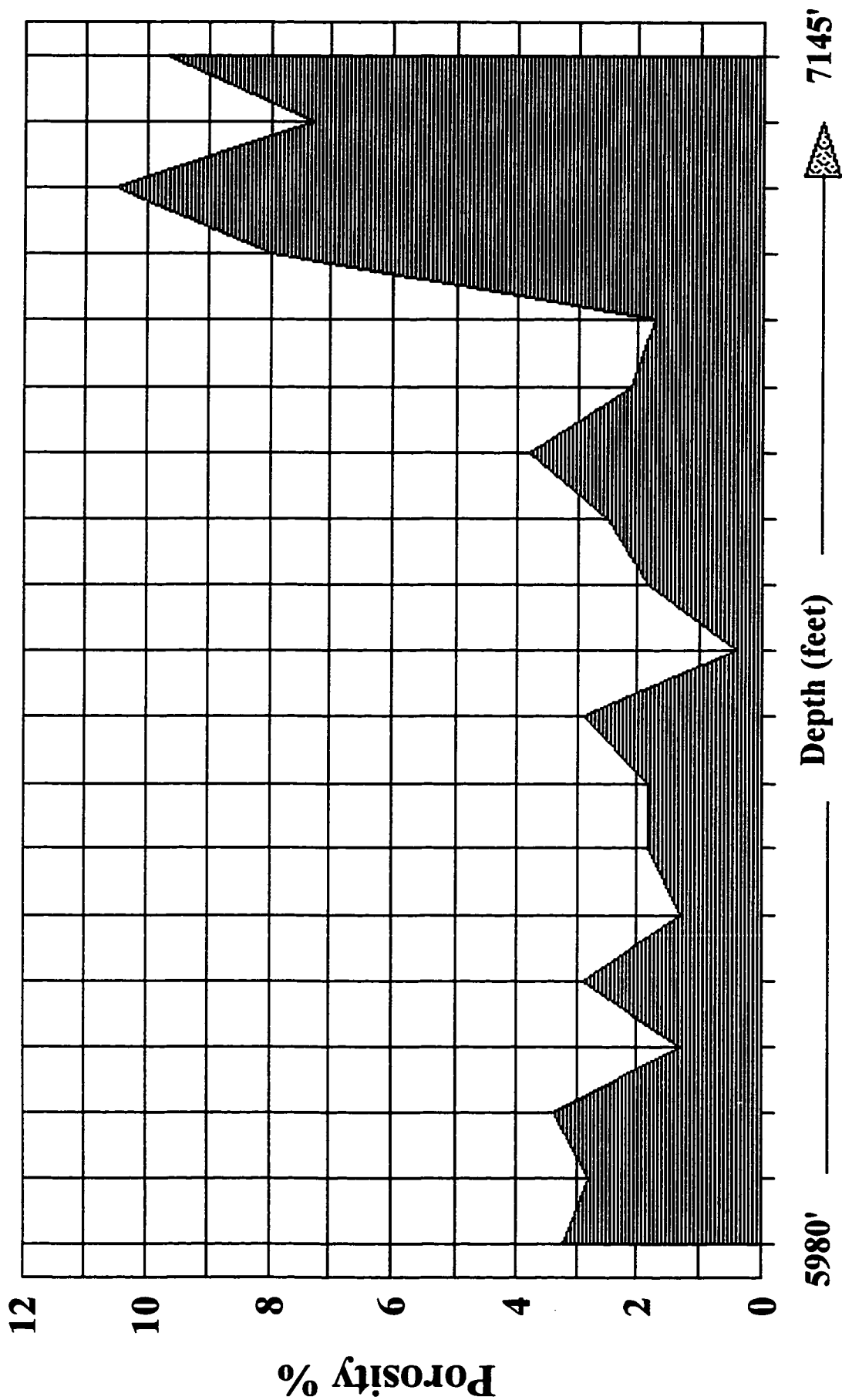


Fig. 7-27. Distribution of average-pore diameters in the Wilson #1 Well, Wyoming County, NY.

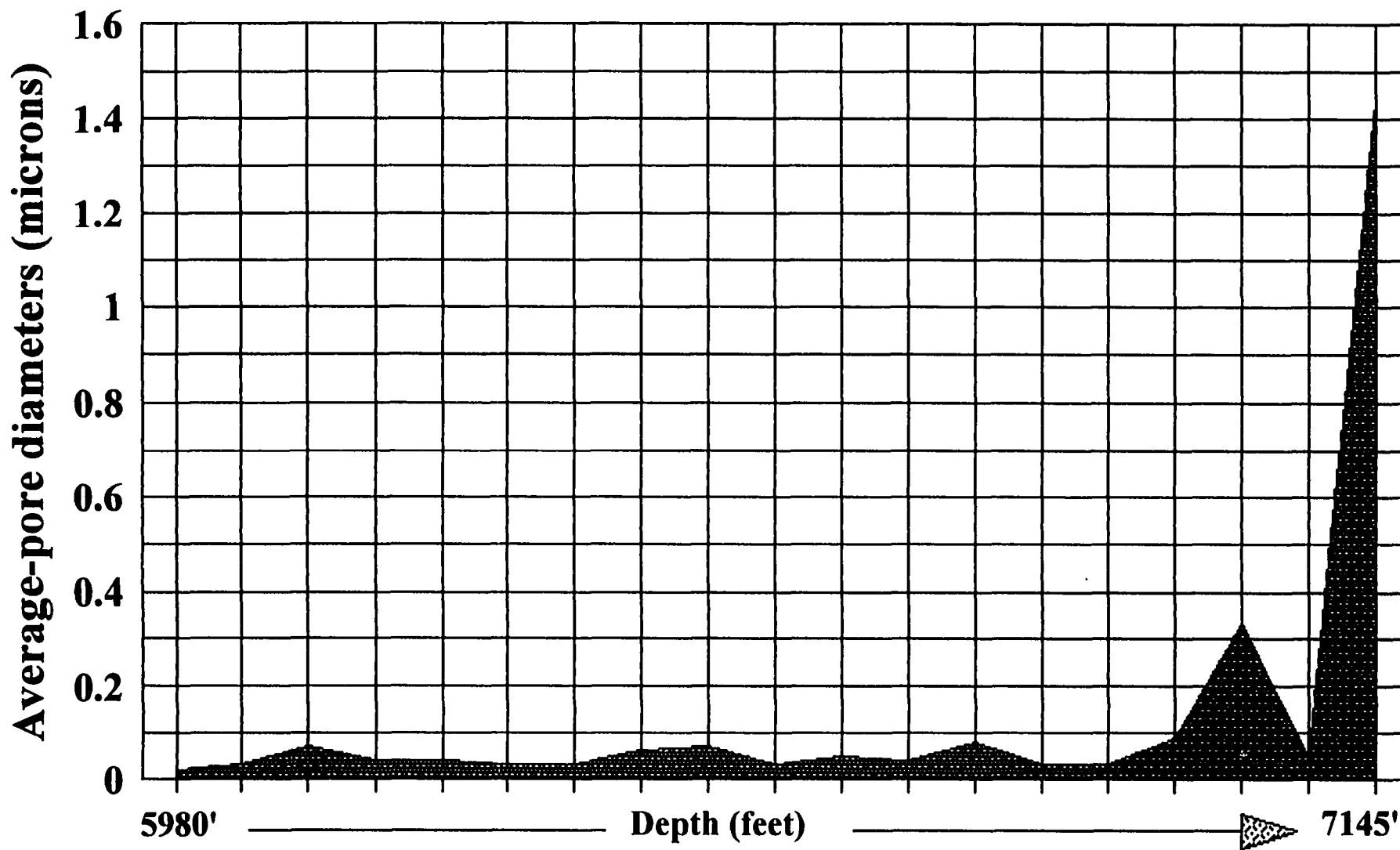
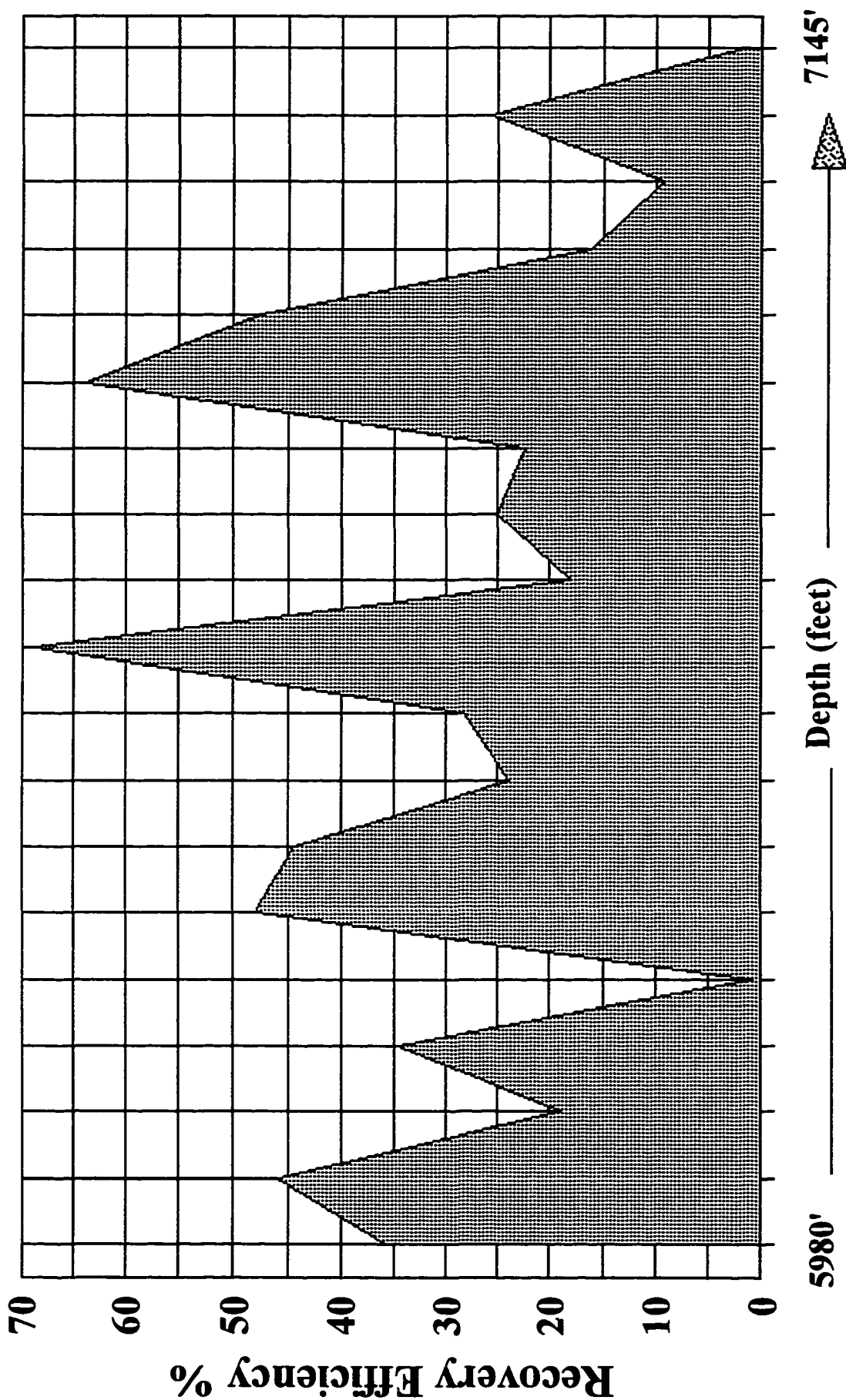


Fig. 7-28. Recovery-efficiency values in the Wilson #1 well, Wyoming County, NY.



7.6.5 Wasielewski #1 Well, Cayuga County

Petrophysical analysis of selected samples from different petrofacies is shown in Table 7-5.

The fossiliferous dolostone petrofacies that located between 2490 - 2820 feet has the highest porosity value within this well (Fig. 7-29). However, the pore diameter of this petrofacies is relatively small (Fig. 7-30) within the range of 0.03 to 0.09 microns. Mercury occupation of these small pore spaces started at 5000 psi. Also, the highest-average recovery efficiency percent is 23.7% in this well (Fig. 7-31). The rest of the petrofacies shows an average porosity that ranges from 2.1 to 3.2 %. Based on data obtained from the porosimetric analysis, this well may be considered a brine-disposal site because of its shallow depth, reasonable porosity, and intermediate recovery efficiency.

**Table 7-5: Petrophysical data of well-cuttings from Wasielewski #1 Well,
Cayuga County, New York.**

Petrofacies	Depth Interval (ft)	Average Porosity Percent (ϕ %)	Recovery Efficiency Percent (R.E. %)	Median Pore Diameter (μm)	Average Pore Diameter (μm)
Fossiliferous dolostone	2820-2490	3.5	23.7	2.07	0.05
Oolitic dolostone	2940-2820	2.5	29.8	0.11	0.03
Sandy dolostone	2915-2840	3.2	27.6	3.74	0.04
Coarse-grained sandstone	3049-2915	2.1	29.2	7.16	0.04

Fig. 7-29. Porosity distribution in the Wasielewski #1 Well, Cayuga County, NY.

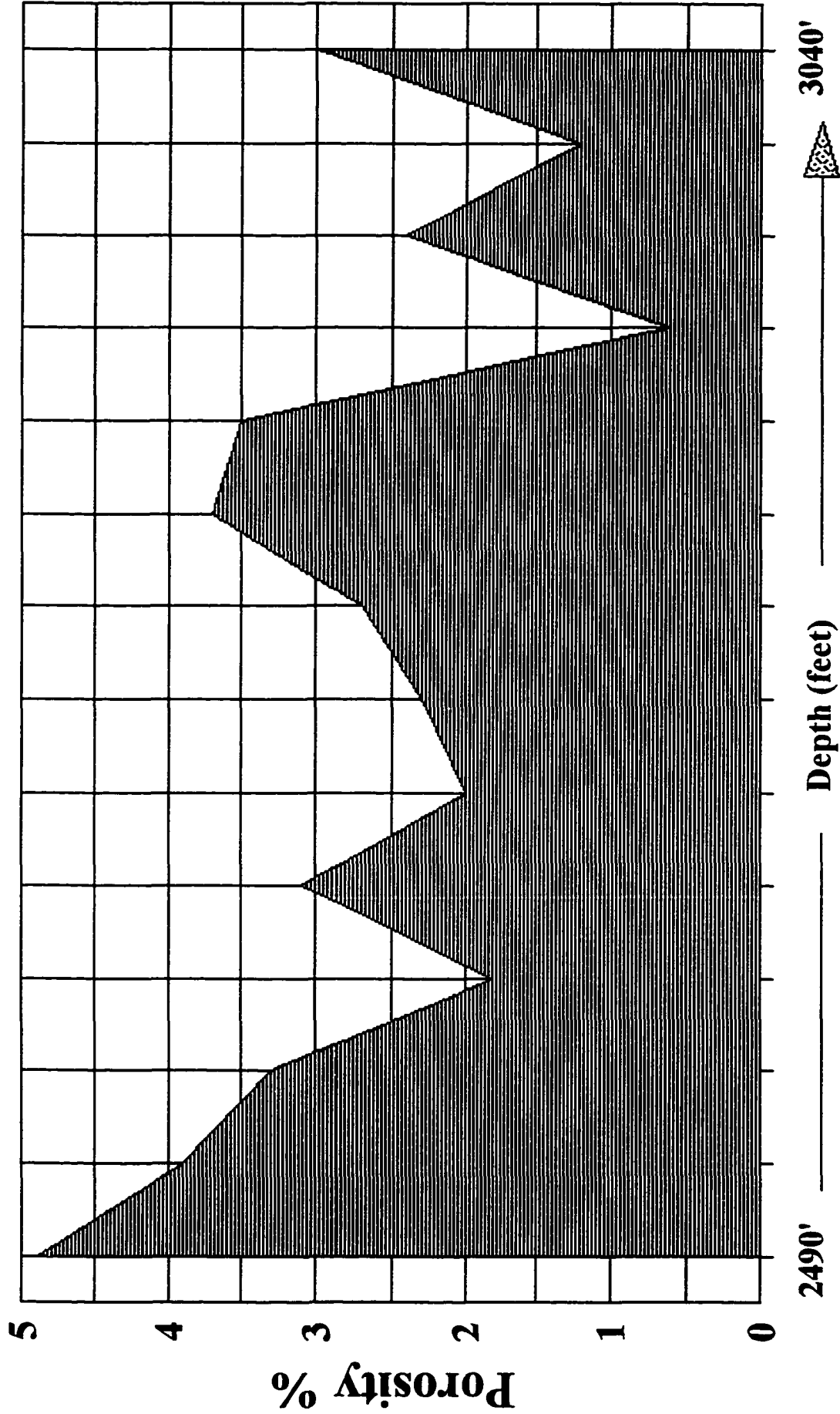


Fig. 7-30. Distribution of average-pore diameters in the Wasielewski # 1 Well, Cayuga County, NY.

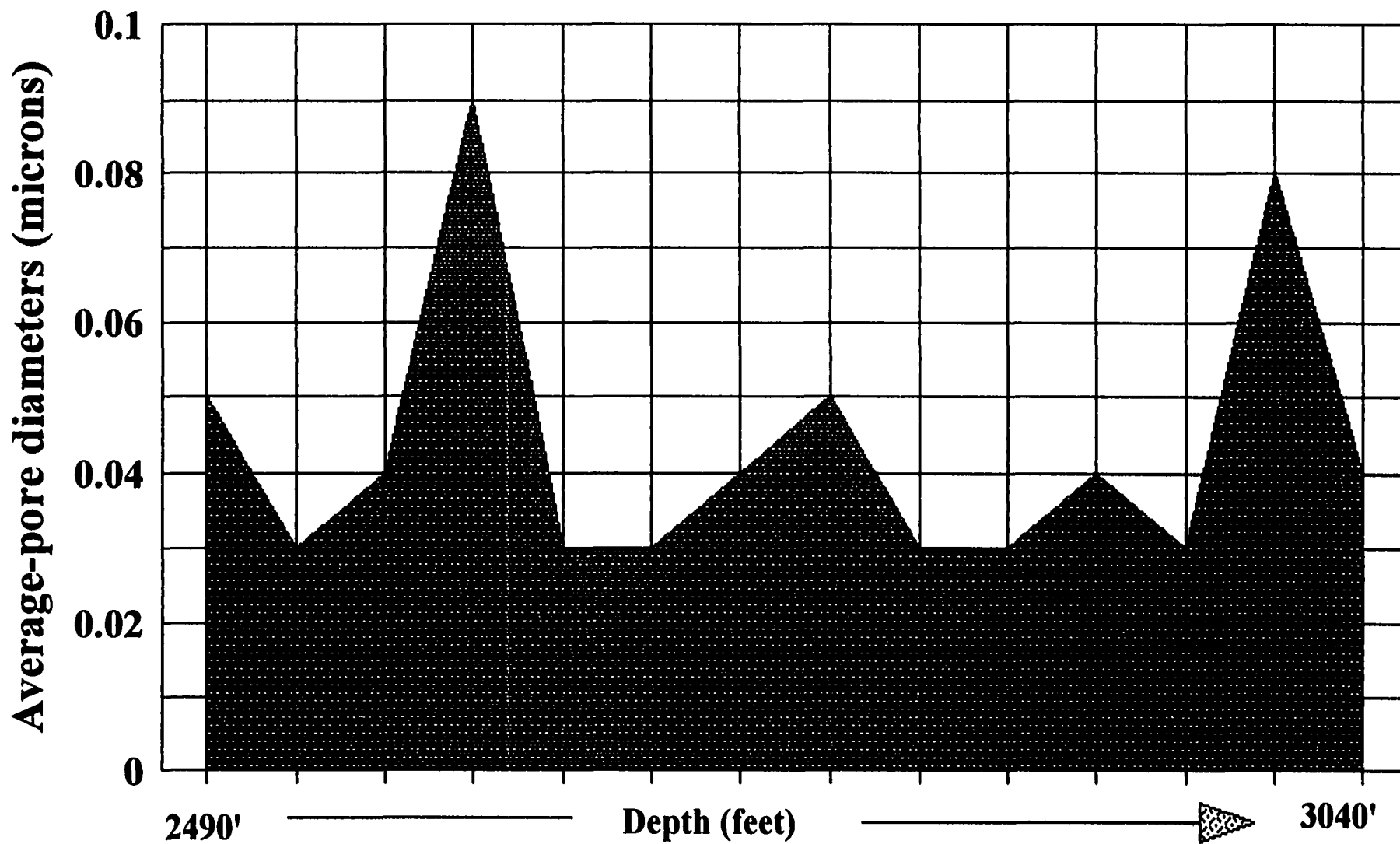
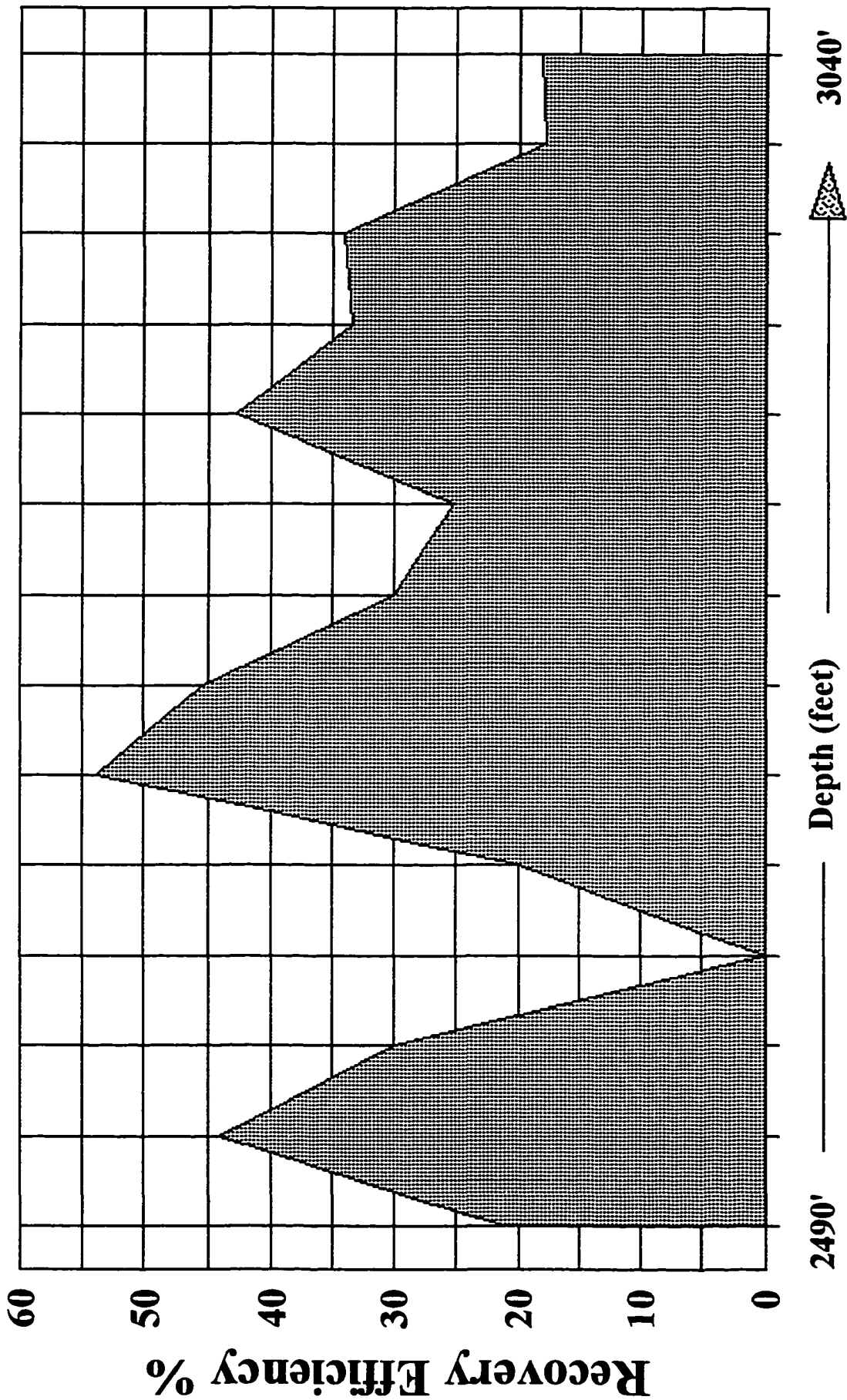


Fig. 7-31. Recovery-efficiency values in the Wasielewski #1 Well, Cayuga County, NY.



CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Results from the petrographic, chemical and petrophysical analyses from the Cambro-Ordovician Beekmantown Group are as follows:

- ◆ The thickness of the Potsdam Formation ranges from 60 to 365 feet, whereas the Theresa Formation ranges from 129 to 1530 feet within the studied wells.
- ◆ Dissolution, mineralization, recrystallization, and precipitation processes affected the textural properties, including porosity, permeability and fluid saturation of varying degrees throughout the Cambro-Ordovician Beekmantown Group.
- ◆ The highest porosity value, 10.5% was determined in the Potsdam Formation of the Wilson #1 Well, Wyoming County at intervals 6760-6830 feet (Fig. 8-1).
- ◆ The highest recovery efficiency percentage, 90% was recorded in the Potsdam Formation of the Waste Water Disposal #1 Well, Niagara County at depths of 2997 feet (Fig. 8-2).
- ◆ The largest pore diameter, 27.14 microns was recorded in the Theresa Formation in the Robert Olin #1 Well, Steuben County at depths of 12572 feet (Fig. 8-3).
- ◆ The lowest porosity value of 0.2% was measured in the lower section of the Theresa Formation of the Robert Olin #1 Well, Steuben County at depths of 12463 feet.
- ◆ The lowest average recovery efficiency value is 5.0% was detected in the Robert Olin #1 Well, Steuben County at depth intervals of 12598-13300 feet.
- ◆ The smallest average pore diameter (0.4 microns) was found in the Wilson #1 Well, Wyoming County at interval of 6850-7120 feet.

Fig. 8-1. Correlation chart of the porosity values in the selected wells of the Beekmantown Group in central and western New York.

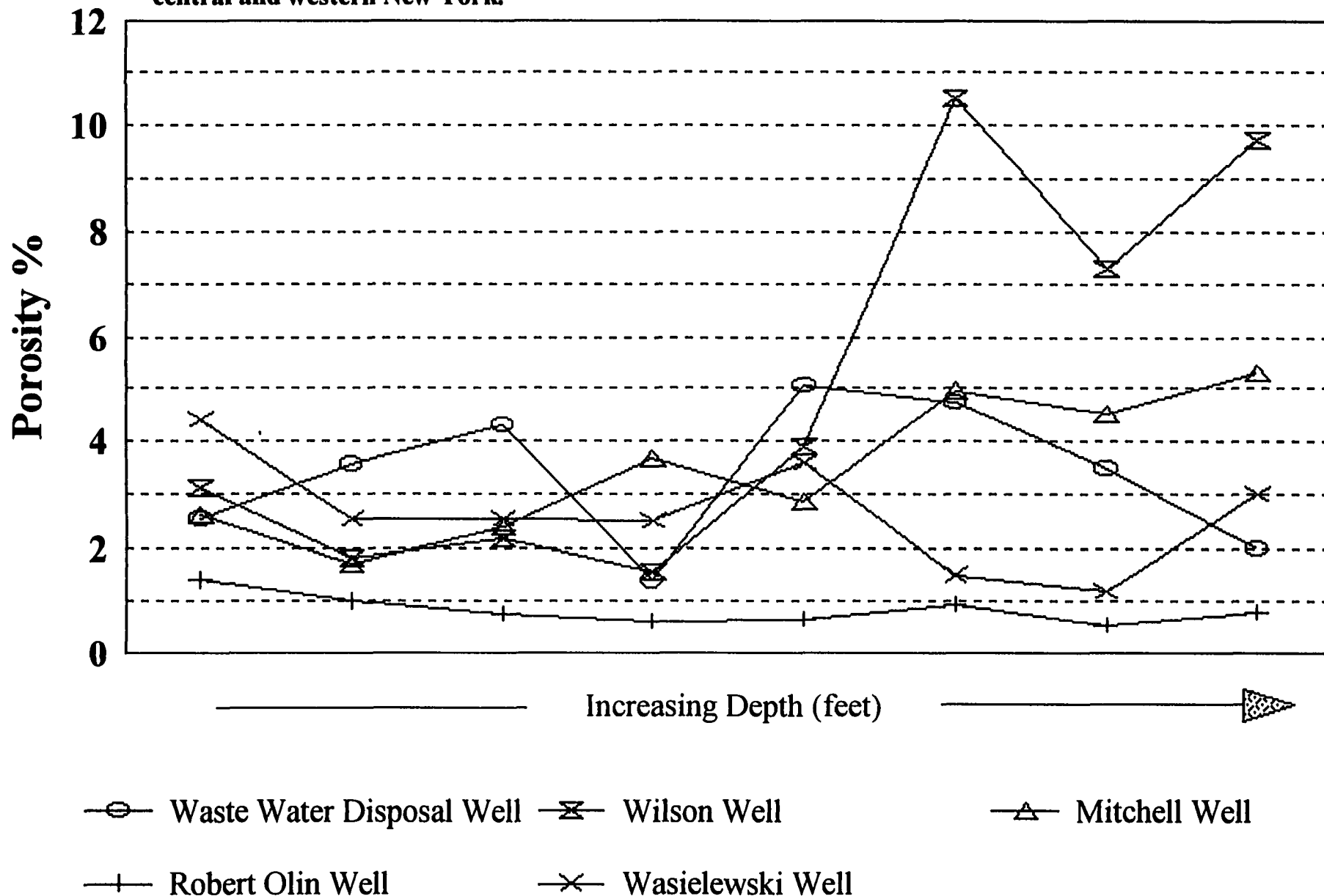


Fig. 8-2. Correlation chart of the recovery-efficiency values in the selected wells of the Beekmantown Group in central and western New York.

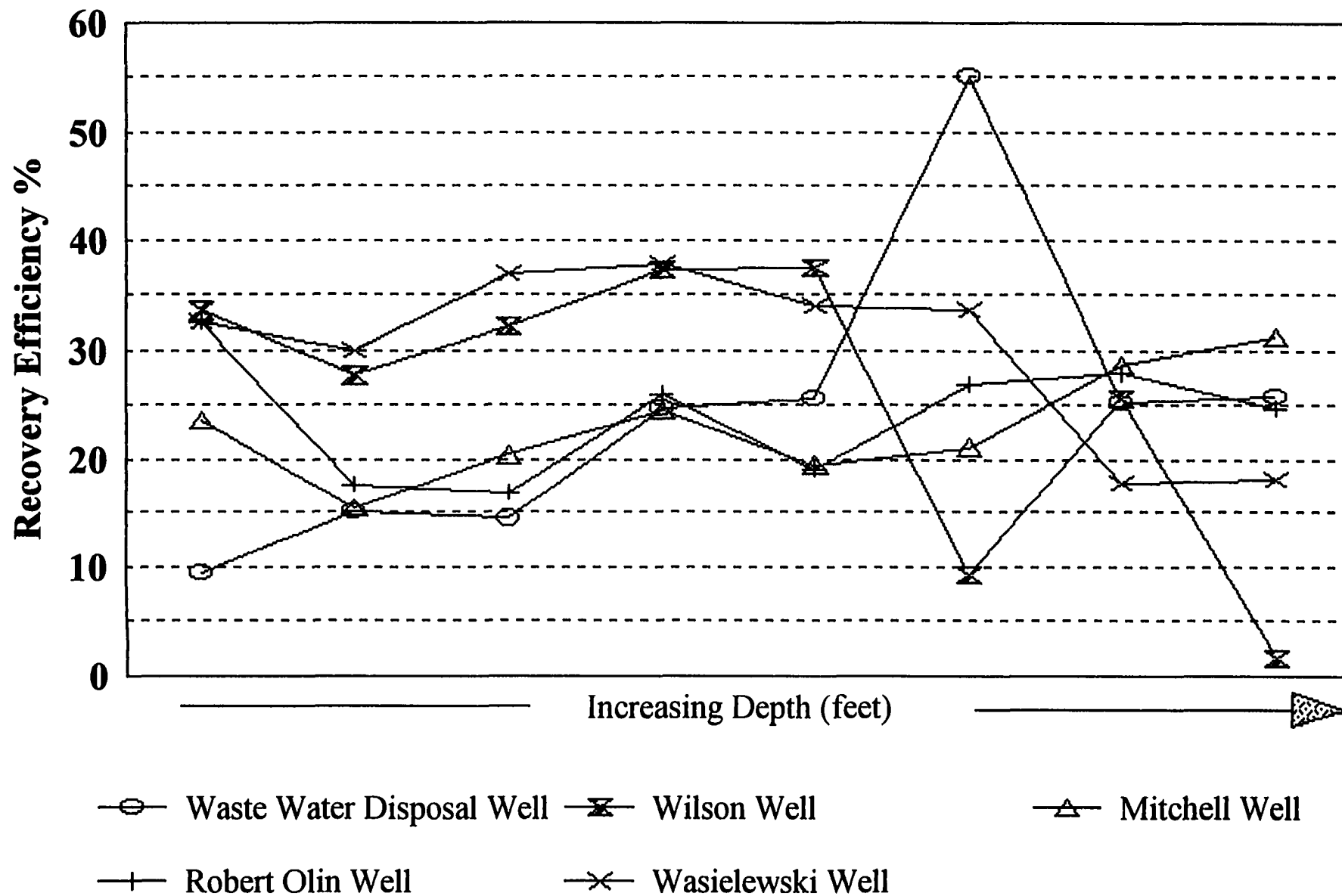
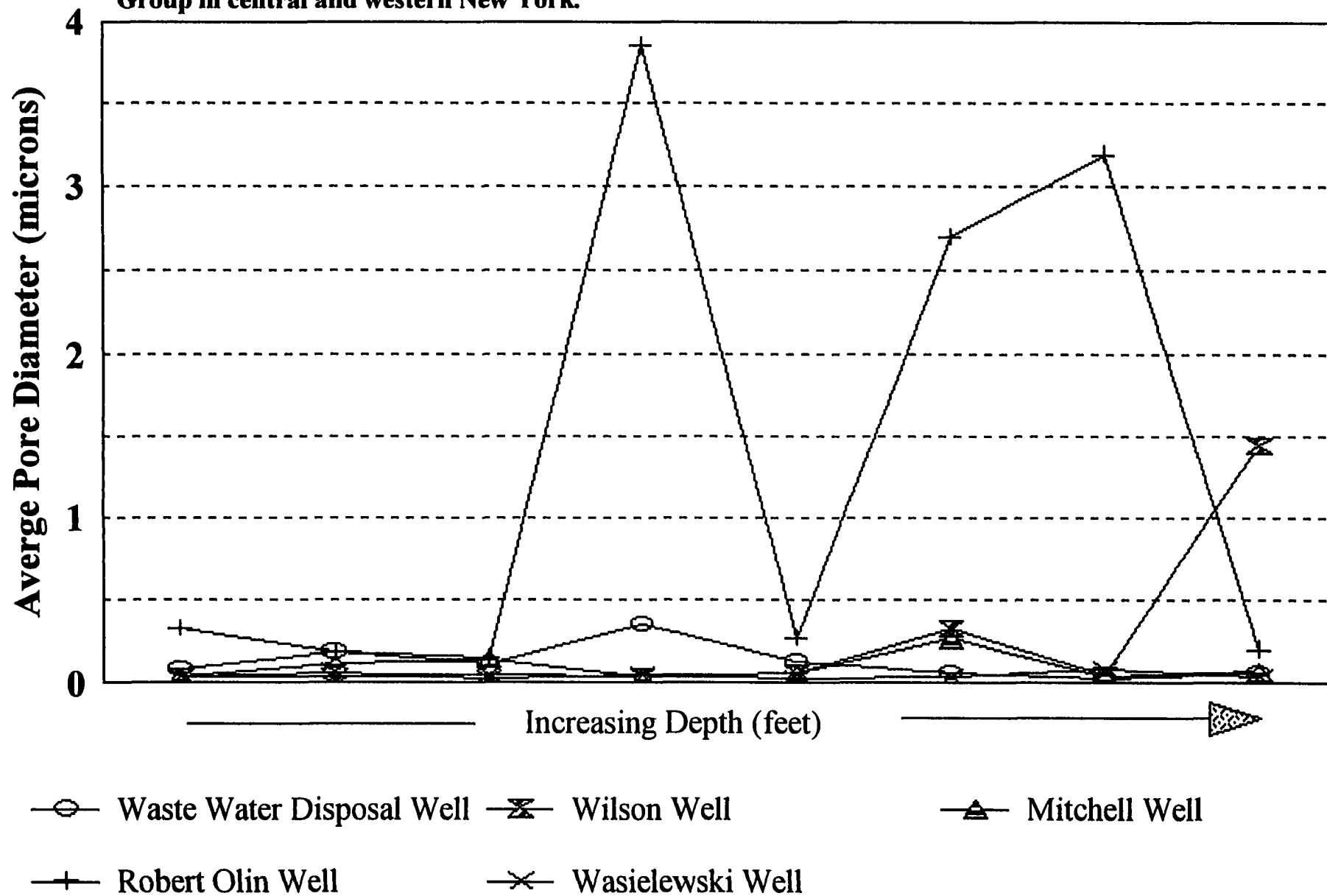


Fig. 8-3. Correlation chart of the average-pore diameters in the selected wells of the Beekmantown Group in central and western New York.



In conclusion the Potsdam Formation (sandstone) is characterized by higher porosity, permeability, and recovery efficiency compared to the overlying Theresa Formation (sandy dolostone and dolostone). The sandy dolostone and dolostone of the Theresa Formation were subjected to severe diagenetic modification resulting in alternating impermeable to porous intervals. These impermeable intervals may serve as a seal units to prevent lateral and vertical migration of gas and fluid from the Potsdam Sandstone and the porous zones of the Theresa Formation. Based on the data obtained from this study, the prerequisite for good brine-disposal sites is satisfied within the Sauk intervals of central and western New York.

8.2 Recommendations

This study shows that the Cambro-Ordovician Beekmantown Group of central and western New York fulfills the requirement for brine disposal site. However, its very important to take into account the following recommendations to ensure the best result of the brine-disposal operations:

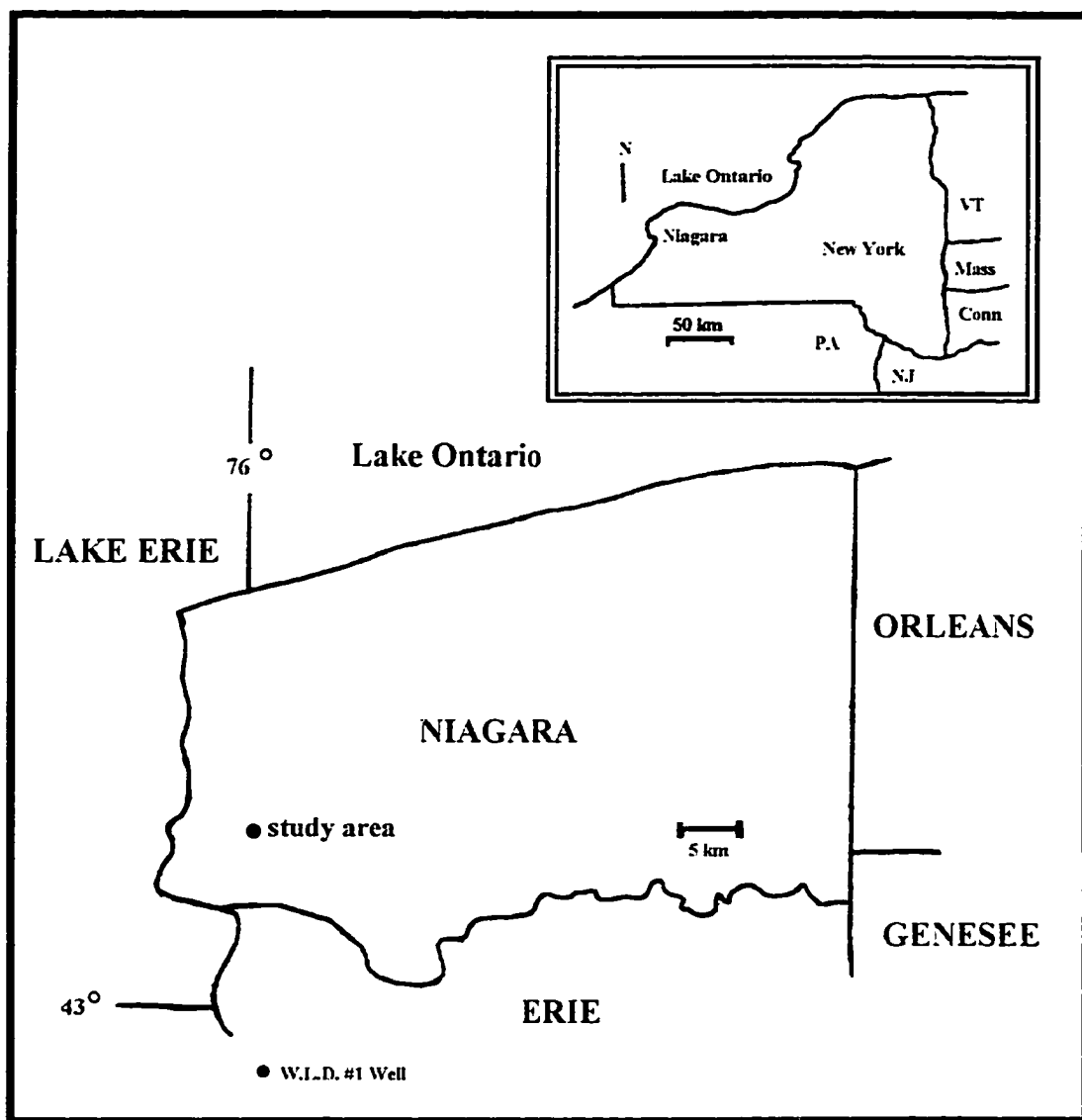
- ◆ The measured-permeability values are low in the studied well. Consequently, artificial fracturing is required to interconnect the naturally occurring fractures and fissures in the rock surrounding the wellbore that will led to increase reservoir permeability and increase reservoir injection rates. Hydraulic fracturing can be applied as effective methods to increase the permeability of the reservoirs. For more information about well fracturing, Middlebrook (1995) provides a detailed discussion.
- ◆ A regional and local fresh-water flow system must be understood. The deepest fresh-water zone must be identified, and a water-quality baseline survey of surrounding fresh water supplies should be made. Also, a detailed water table map of the brine-disposal area is required based on the instruction of the New York State Department of Environmental

Conservation that stated that no reinjection of well fluids will be allowed in, above, or below any primary groundwater aquifer.

- ◆ A detailed structural geology of this area will aid in understanding the relationship between the large scale features such as faults, folds, joints, and fractures that affect the brine injecting technique.
- ◆ Based on our study, the laboratory experiment using mercury injection into the selected samples from the studied wells shows that the Cambro-Ordovician Sauk rock could retain an injecting pressure up to 20,000 psi. However, during the actual field experiment this pressure may vary. So, step-rate injectivity tests should be performed to determine the fracture pressure. Initially, this can be done by injecting fluid in a series of constant-rate operation then gradually increasing the injecting rate from low to high values. This injecting pressure should be monitored by pressure recording device. If the injecting fluids pressure rates should abruptly change, fracturing has probably occurred.
- ◆ Access to major gas transmission pipelines is an important factor to reduce the cost of transportation.

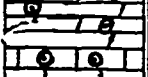
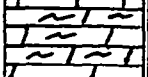
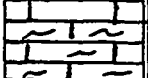
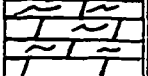
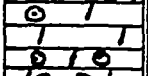
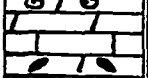
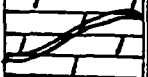
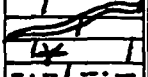
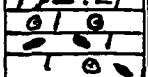
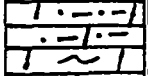
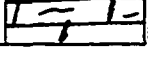
Appendices

APPENDIX A: Core descriptions



General location of the Waste Water Disposal #1 Well in Niagara County, New York.

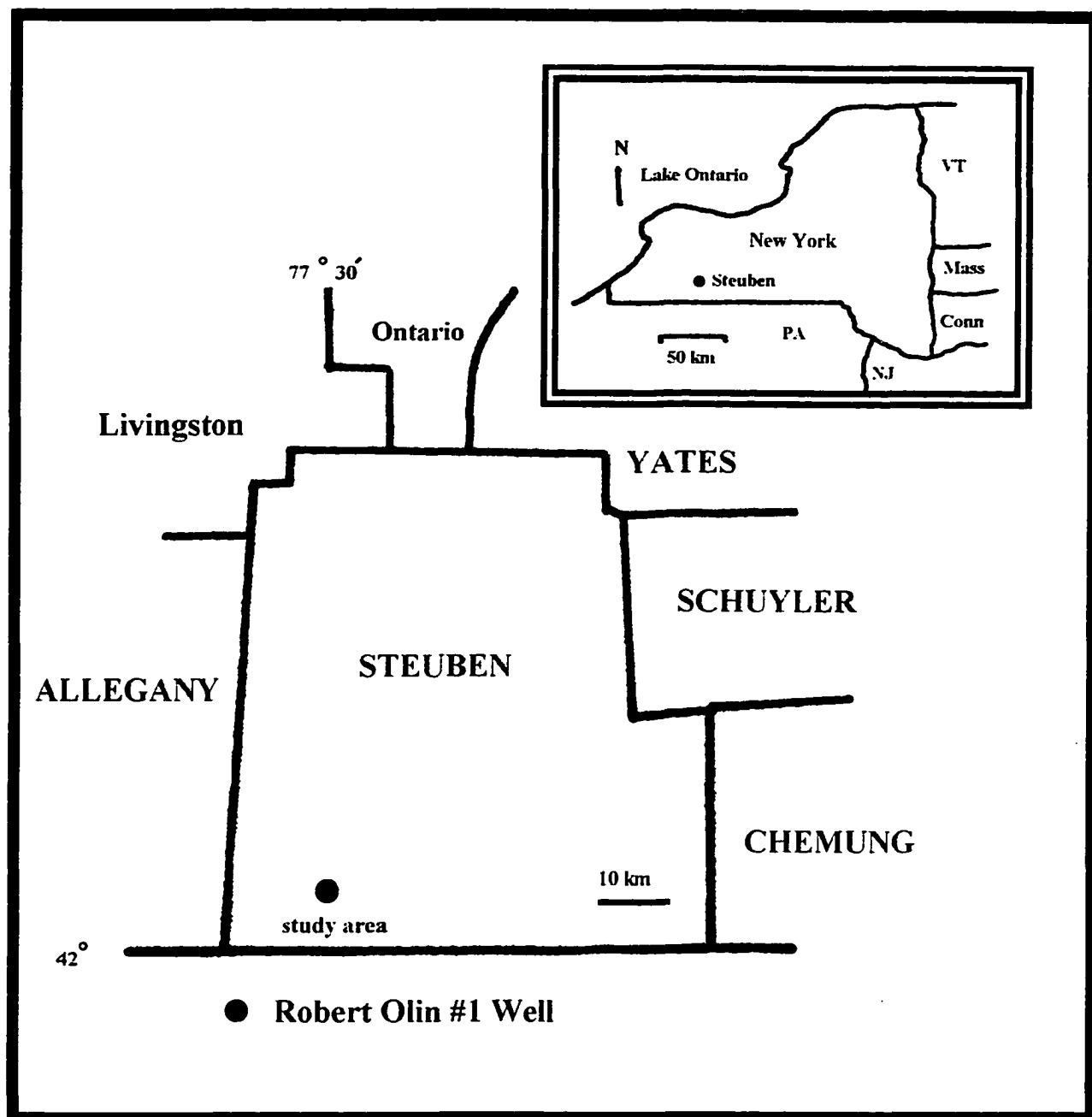
Description of core section from 2849 to 3041 feet depth of the Beekmantown Group in Waste Water Disposal #1 Well, Niagara County, New York. Continued on the next page.

Depth (feet)	Description	Lithology
2849	Coarse-textured, poorly sorted (fanglomeratic) detrital quartz in fine to medium-textured dolomitic matrix, grapestone, feldspar, calcite cement, laminated silty to sandy dolomite, quartz veins, scattered ooids, anhydrite laths.	
2857	Medium to fine-textured calcitic quartz sand, some scattered glauconitic pellets, coarse grained detrital quartz, some oolitic dolomite, scattered pyrite, calcite cement in places.	
2868	Medium to fine-textured calcite quartz sand, laminated silty calcareous dolomite, calcite cement.	
2882	Oolitic dolostone, scattered pyrite, calcite veins, micrite envelopes, some glauconite pellets, feldspar, saddle dolomite, anhydrite laths.	
2898	Medium-textured detrital calcitic quartz sand, grapestones calcite veins, calcite cement, stylolites, intraclasts.	
2905	Laminated stromatolitic dolomite, sandy dolomite and calcite veins.	
2906	Alternate layers of fine laminated dolomite and sandy dolomite, calcite cement, saddle dolomite.	
2910	Oolitic sandy calcitic dolomite, saddle dolomite, calcite cement, stylolites, pyrite.	
2939	Alternate layers of fine to medium-textured sandy and calcite dolomite, glauconite pellets, calcite cement, saddle dolomite.	
2949	Medium-textured quartz sand embedded in fine dolomitic matrix, glauconite pellets, stylolites, pyrite.	
2958	Interbedded medium to fine-textured dolomite and medium-textured silty sandy dolomite, feldspar, stylolites.	
2960	Medium-textured quartz sand with calcite cement, feldspar.	
2969	Medium-textured sandy dolomite, pyrite, organic debris (bioturbation). Feldspar, laminated sandy to silty dolomite, stylolites, calcite cement.	
2978	Glauconitic silty to sandy calcareous dolomite, organic debris, feldspar.	
2983	Interbedded silty shale and fine-textured dolomite, oolitic dolomite, scattered glauconitic pellets.	
2985	Alternate lamination of medium and fine-textured dolomite, laminated stromatolitic dolomite.	

Depth (feet)	Description	Lithology
2987	Alternate layers of silty to sandy shale and fine-textured dolomite. laminated stromatolitic dolomite, stylolites.	
2988	Highly bioturbated skeletal dolomite.	
2991	Alternate layers of silty shale with fine to medium-textured calcitic dolomite, detrital quartz feldspar, stylolites.	
2995	Coarse to medium-textured quartz sand (sutured boundary contact), calcite cement, calcite veins, feldspar.	
3000	Coarse to medium-textured sandy dolomite, stylolites, calcite cement, scattered pyrite, feldspar.	
3003	Coarse to medium-textured quartz sand with calcite cement, feldspar.	
3009	Coarse-textured quartz sand in medium textured dolomitic matrix, feldspar.	
3010	Coarse-textured quartz sand with calcite cement, feldspar.	
3014	Coarse-textured, poorly sorted (fanglomeratic) quartz sand, calcite cement, feldspar particles.	
3026	Coarse to medium -textured, well compacted. sutured boundaries, quartz crystals, fanglomeratic quartz sand, feldspar.	
3030	Coarse- textured sandy dolomite, cross bedding, quartzite fragments.	
3041	Basement and fragments of crystalline metamorphic rocks.	

Symbols

Lithology		Structure/Particles	
	Crystalline Rock		Cross bedding
	Sandstone		Pyrite
	Dolostone		Glaucinite
	Silt		Laminae
	Limestone		Ooids
			Stylolites



General location of Robert Olin #1 Well in Steuben County, western New York.

Description of core section from 12434 to 13500 feet depth of the Beekmantown Group in Robert Olin #1, Steuben County, New York. Continued on the next page.

Depth (feet)	Description	Lithology
12434	Medium to fine (100-150 μm in diameter), dark to light gray, xenotopic to hypidiotopic dolomite crystals. Porosity is low in this thin section. Also, rounded to subrounded, coarse to medium grained detrital quartz particles are abundant throughout the thin section (10 - 15%). Some of the quartz particles enhance intergranular porosity. Anhydrite crystals and laths are scattered throughout the thin section. No fossils have been recognized.	1 . 1 1 1 . 1 . . .
12435	Medium-textured, light gray quartz sand (70%) is cemented by xenotopic, microcrystalline dolomite. The sutured boundary contact between the quartz grains is obvious. Particles that have peloidal structure and fossil fragments, that filled with anhydrite laths in part, are present. Porosity is about 2-4% in this thin section in form of intragranular and intergranular.	. 7 . 1 . 1 . .
12437	Medium, light gray subhedral dolomite types. Subrounded, detrital quartz sand (10-15%). Anhydrite laths also found.	. . 7 1 .
12441	Medium textured (100-140 μm in diameter), subhedral dolomite. Anhydrite detrital quartz (<5%) are present.	1 . 1 .
12444	Coarse textured (200-300 μm in diameter), subhedral dolomite, anhydrite, and some detrital quartz are found. Porosity is low.	1 . .
12445	Medium to fine textured dolomite (50-100 μm in diameter) , grain-supported texture, detrital quartz grains are scattered throughout the thin section (8%). Porosity is low.	1 7 .
12447	Idiotopic to xenotopic, medium textured (80-160 μm in diameter) dolomite. Anhydrite laths and detrital quartz (<5%) are present. Porosity is low.	1 . .
12452	Coarse-textured (200-500 μm in diameter), light, saddle dolomite (shows undulose extinction). Evidence of leaching in place. Anhydrite laths and detrital quartz (<5%) are present.	1 . .
12453	Medium to fine textured dolomite (100-150 μm in diameter), saddle dolomite is filling cavities and veins. Some scattered detrital quartz.	1 .
12454	Subhedral to anhedral, medium to fine textured dolomite (100-180 μm in diameter). Anhydrite id filling voids and replacing dolomite in places. Subrounded to sub angular detrital quartz, stylolites, dolomite crystals replaced by anhydrite(anhydrite cleavage still well preserved) are present.	1 .
12455	Coarse to medium, subhedral to anhedral, dolomite textured, some dolomite crystals replaced anhydrite. Subrounded to subangular detrital quartz particles are scattered throughout the thin section.	1 . 7 1 .

Depth (feet)	Description	Lithology
12459	Medium-textured dolomite (100-160 in diameter), detrital quartz. Stylolites are present.	
12463	Subhedral to euhedral, medium to fine dolomite crystals are filling former voids.	
12471	Medium to fine textured dolomite, saddle dolomite crystals are filling former voids.	
12516	Coarse to medium grained, subrounded to subangular, quartzose sandstone comprises 50% of thin section. Subhedral, laminated, stromatolitic dolomite textured.	
12518	Alternative layers of light and dark, subhedral to anhedral dolomitic texture (stromatolitic), the dark lamina consist of argillaceous materials and the light laminae consist of detrital quartz.	
12521	Subrounded to subangular, coarse to medium, detrital quartz grains (20%). Subhedral to anhedral, medium to fine dolomitic texture. Some anhydrite laths are present.	
12534	Subrounded, coarse to medium detrital quartz grains (25%), subhedral dolomitic texture, saddle dolomite cavities.	
12584	Oolitic dolostone, euhedral to subhedral dolomite, subangular to subrounded quartz grains, saddle dolomite is present.	
12590	Oolitic, euhedral to subhedral dolomite, rounded to subrounded, detrital quartz grains are present.	
12596	Large anhydrite crystals, fine to medium dolomitic texture, saddle dolomite filling former cavities.	
12598	Fine-texture dolomite (50-100 µm in diameter). Detrital quartz, feldspar and stylolites are present.	
13482	Coarse to medium-textured particles. Some anhedral to subhedral dolomite are present.	
13492	White to pink quartzite particles. Some anhedral to subhedral dolomite are present.	

Symbols

Lithology



Anhydrite



Sandstone



Dolomite

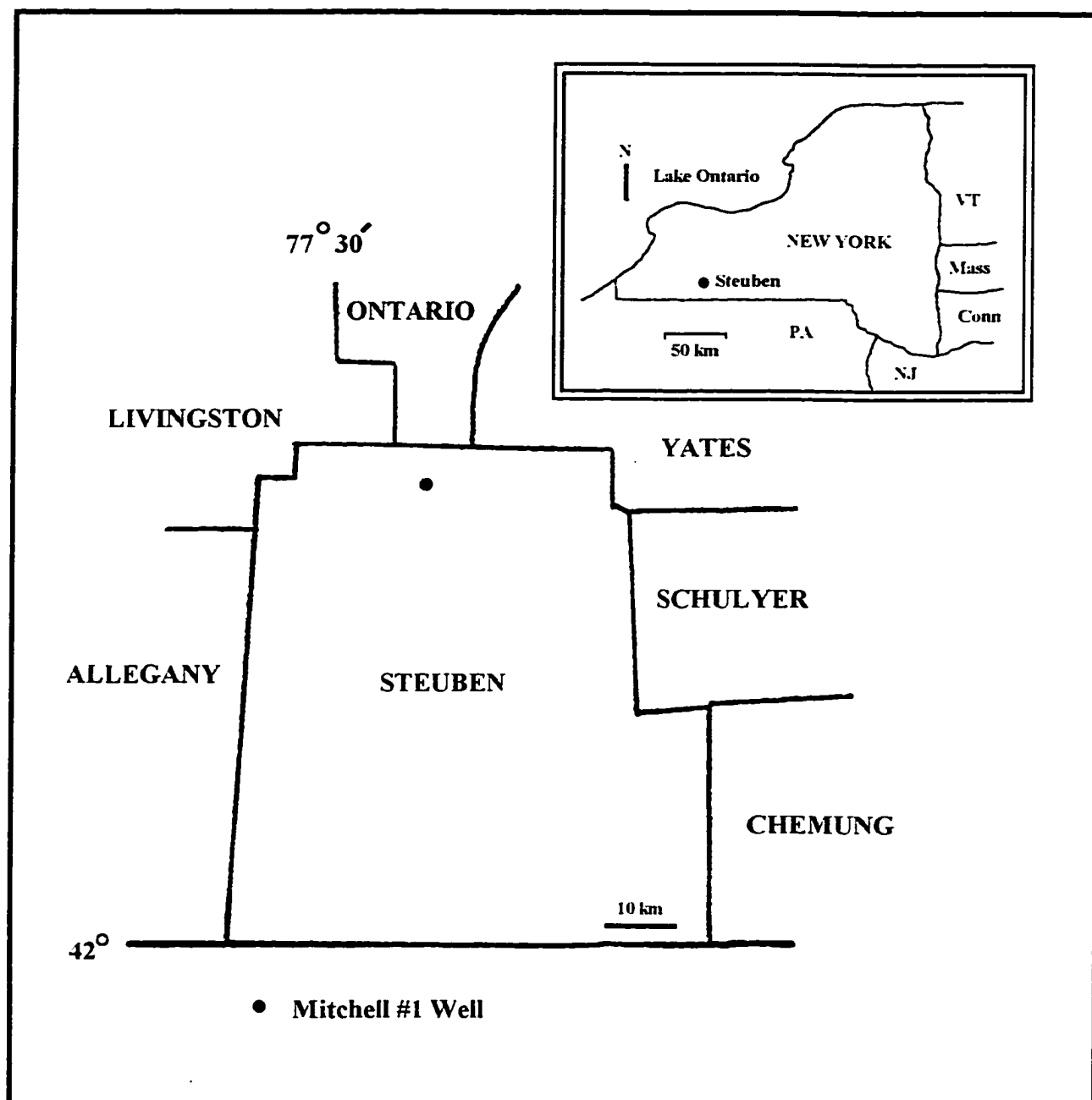
Structure/Particles



Ooids

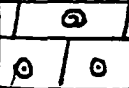
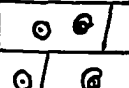
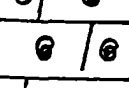
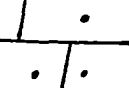
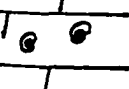
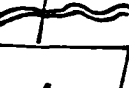
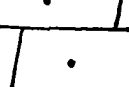
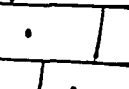
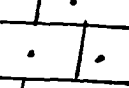
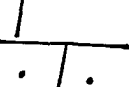
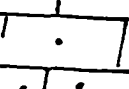
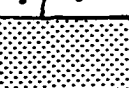
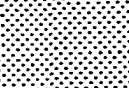
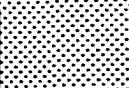
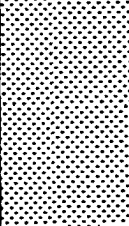


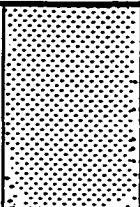
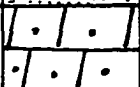
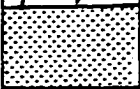
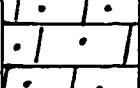
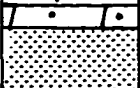
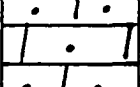
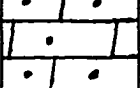
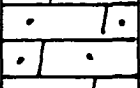
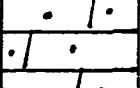
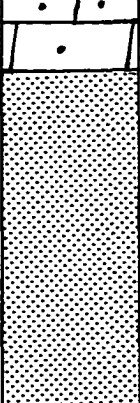
Stylolites

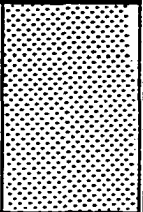


General location of Mitchell #1 Well, Steuben County, New York

Description of well-cuttings section from 7990 to 9885 feet depth of the Beekmantown Group in Mitchell #1 Well (Avoca), Steuben County, New York. Continued on next page.

Depth (feet)	Description	Lithology
7990	Medium to fine (90-120 μm in diameter), dark gray, hypidiotopic to xenotopic dolomite crystals, peloidal particles are present.	
8030	Medium to fine (100-150 μm in diameter), dark gray, xenotopic dolomite crystals, oolitic, fossiliferous dolostone.	
8300	Subhedral to anhedral, medium to fine textured dolomite (100-150 μm in diameter), some fossil fragments are present.	
8360	Coarse to medium (180-300 μm in diameter), subhedral to anhedral, dolomite textured, fossil fragments embedded in dolomitic matrix.	
8390	Coarse to medium (190-340 μm in diameter), subhedral to anhedral, fossiliferous dolomite textured, subrounded to subangular detrital quartz grains are present (3%).	
8410	Coarse to medium (250-350 μm in diameter), subhedral to anhedral dolomite crystals. Some stylolites are present.	
8550	Medium to fine (180-90 μm in diameter) dolomite crystals. Subangular to subrounded quartz grains are present (3%).	
8570	Fine to medium (80-170 μm in diameter) dolomite crystals, abundant of subrounded to subangular detrital quartz (25%).	
8620	Medium to coarse (230-390 μm in diameter) dolomite crystals, subangular to subrounded detrital quartz grains are common (40%).	
8680	Coarse, subhedral to anhedral dolomite crystals, detrital quartz and feldspar particles are common (35%).	
8710	Medium to coarse (210-380 μm in diameter) dolomite crystals, abundant of subrounded detrital quartz grains (50%), some shale particles are also present.	
8760	Light gray, fine- to medium-textured sandstone (85%), subhedral to anhedral, fine to medium dolomite crystals (50-150 μm in diameter), some feldspar particles are present.	
8810	Light to dark gray, medium-textured sandstone (75%), stylolites, feldspar particles, some dark gray, subhedral to anhedral dolomite crystals are common (10%).	
8860	Light gray, coarse-textured sandstone (85%), some feldspar and dolomite particles are present.	
8900	Subrounded to subangular, medium, light gray detrital quartz grains (90 %), calcite cement, feldspar particles.	

Depth (feet)	Description	Lithology
8930	Coarse-textured, light gray sandstone (90%), the quartz particles show sutured boundary contacts, some subhedral to anhedral dolomite crystals are present.	
8970	Subrounded to subangular, medium, light gray, detrital quartz grains (90%), some dolomite crystals are present.	
9000	Light gray, hypidiotopic to xenotopic dolomite texture, subrounded, detrital quartz particles are common (40%).	
9050	Subrounded to subangular, medium to light gray, detrital quartz (85%), feldspar particles and some dolomite crystals are present.	
9090	Coarse to medium grained, subrounded to subangular, quartzose sandstone(40%), medium-textured dolomite (100-160 µm in diameter).	
9140	Medium to fine textured dolomite (100-180 µm in diameter), subrounded to subangular detrital quartz particles are present (35%).	
9190	Idiotopic to xenotopic, medium-textured dolomite (80-160 µm in diameter), detrital quartz particles (10%) are present.	
9230	Coarse to medium-textured quartz sand (180-360 µm in diameter), in medium textured dolomitic matrix (90-170 µm in diameter).	
9270	Subhedral to anhedral, medium-textured dolomite (130-190 µm in diameter), subrounded, medium, light gray detrital quartz particles are present (40%).	
9340	Light gray, fine to medium (80-180 µm in diameter), xenotopic dolomite crystals, subrounded detrital quartz and feldspar particles are present.	
9400	Subhedral to anhedral, light to dark gray, dolomite crystals, detrital quartz particles are common.	
9470	Subhedral, light gray, medium-textured dolomite (140-210 µm in diameter), detrital quartz, feldspar particles, and some ooids are present.	
9520	Medium-textured (120-210 µm in diameter), sandstone with sutured boundary contacts.	
9600	Light gray, coarse-textured sandstone, calcite cement, feldspar particles are present (3%).	
9630	Light to dark gray, medium-textured sandstone, feldspar particles and some calcite cement.	
9700	Subrounded to subangular. light gray. medium-textured sandstone.	
9750	Coarse to medium-textured, well compacted, sutured boundaries, quartz particles are present.	
9800		

Depth (feet)	Description	Lithology
9800	Coarse-textured quartz sand with calcite cement, some feldspar particles are present.	
9840	Light to dark brown, well compacted, coarse sand particles.	
9885	Coarse-textured sandstone, poorly sorted quartz sand, some feldspar particles are present	

Symbols

Lithology



Dolostone



Sandstone

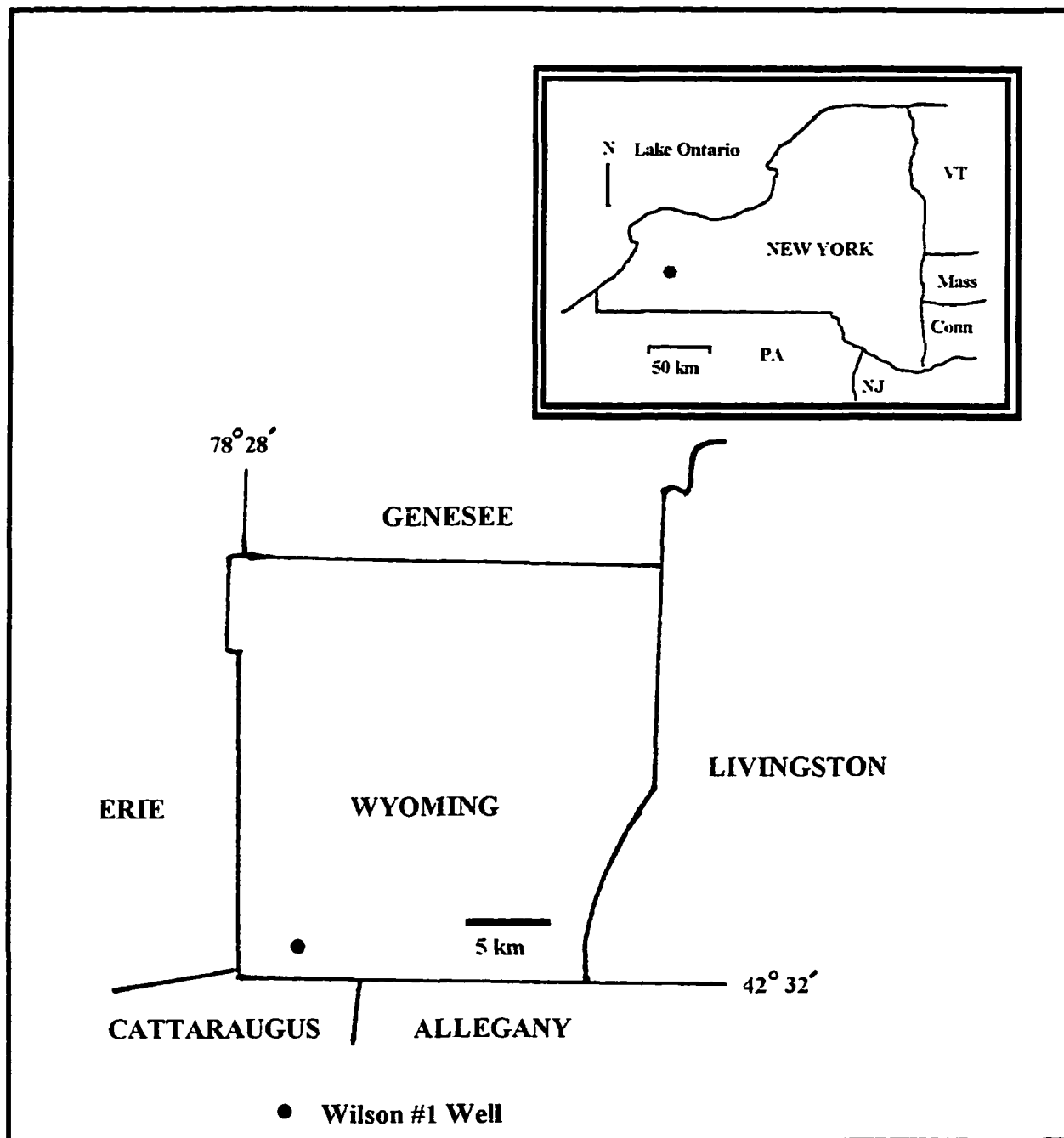
Particles



Ooids

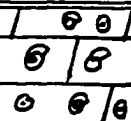
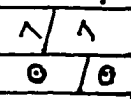
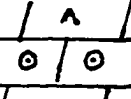
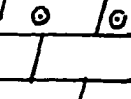
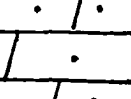
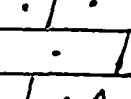
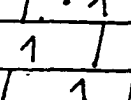
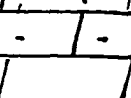
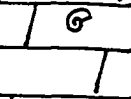
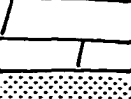
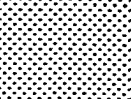
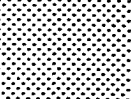
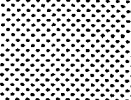


Fossil
fragment



General location of Wilson #1 Well, Wyoming County, New York.

Description of well-cuttings section from 5980 to 7144 feet depth of the Beekmantown Group in Wilson Well, Wyoming County, New York. Continued on next two pages.

Depth (feet)	Description	Lithology
5980	Subhedral to anhedral, microcrystalline, gray dolomite crystals, fossil fragments, dolomitized ooids.	
6020	Fine-textured (30-70 µm in diameter), gray to dark gray, subhedral to anhedral dolomite crystals, fossil fragments.	
6070	Fine-textured (50-80 µm in diameter), light gray calcareous dolomite, concentric ooids, peloids, some anhydrite laths.	
6120	Medium-textured (100-140 µm in diameter), subhedral to anhedral dolomite, peloid, concentric and radial ooids.	
6140	Medium-textured (120-180 µm in diameter), subhedral dolomite crystals, subrounded to subangular, medium detrital quartz grains (15%).	
6190	Medium-textured (140-180 µm in diameter), subhedral to anhedral dolomite crystals, subrounded to subangular, medium detrital quartz grains (10%).	
6220	Coarse to medium, subhedral to anhedral dolomite crystals.	
6230	Euhedral to subhedral, dark gray dolomite crystals, dolomite crystals replaced anhydrite (anhydrite cleavage still well preserved).	
6250	Medium-textured, subhedral to anhedral dolomite crystals.	
6260	Medium-textured, subhedral to anhedral dolomite crystals, some anhydrite laths.	
6280	Medium-textured (120-170 µm in diameter), gray to dark gray, subhedral to anhedral crystals, fossil fragments.	
6310	Rounded to subrounded, coarse to medium detrital quartz grains (25%), medium, subhedral dolomite crystals.	
6320	Subrounded to subangular, medium, light gray detrital quartz grains, calcite cement.	
6340	Subrounded to subangular, medium, light gray detrital quartz grains (95%). Some subhedral dolomite crystals.	
6350	Subrounded to subangular, medium, light gray detrital quartz grains (95%). Some subhedral to anhedral dolomite crystals.	
6370	Subrounded to subangular, medium, light gray detrital quartz grains (90%), calcite cement.	

Depth (feet)	Description	Lithology
6440	Subrounded to subangular, medium light gray detrital quartz grains (95%), calcite cement.	
6500	Angular to subangular detrital quartz grains (90%). Some subhedral to anhedral dolomite crystals.	
6510	Euhedral to subhedral, medium to fine textured dolomite (100-180 μ m in diameter), detrital quartz grains are scattered throughout the thin section (25%).	
6530	Subhedral to anhedral, medium textured dolomite (140-190 μ m in diameter). Subrounded to subangular quartz grains are common.	
6570	Subhedral to subangular, medium. light gray detrital quartz grains (95%), calcite cement.	
6590	Subhedral to anhedral, medium textured dolomite (120-170 μ m in diameter). Subrounded to subrounded quartz grains are common (25%).	
6670	Light gray, hypidiotopic to xenotopic dolomite textures.	
6720	Light gray, hypidiotopic to xenotopic dolomite textures.	
6760	Euhedral to subhedral, medium to fine textured dolomite (120-180 μ m in diameter), calcareous fossil fragments are present.	
6780	Subhedral to subangular to subangular, medium, light gray detrital quartz grains (90%), calcite cement.	
6830	Light gray, hypidiotopic to xenotopic dolomite textures. Subrounded to subangular quartz grains are common (25%).	
6850	Subrounded to subangular, medium, light gray detrital quartz grains (90%), calcite cement.	
6920	Subrounded to subangular, medium, light gray detrital quartz grains (95%), calcite cement.	
6930	Dark brown, fine-grained argillaceous materials, subrounded to subangular, medium, light gray detrital quartz grains (90%).	
7000	Subrounded to subangular, medium, light gray detrital quartz grains (95%).	
7030	Subrounded to subangular, medium, light gray detrital quartz grains (95%).	
7100	Subrounded to subangular, medium, light gray detrital quartz grains (95%). Subhedral to anhedral, medium to fine textured dolomite (50-150 μ m in diameter) (30%).	
7120	Medium -textured, light gray quartz grains, the sutured boundary contacts between the quartz grains are obvious.	

Symbols

Lithology



Dolostone



Sandstone



Anhydrite

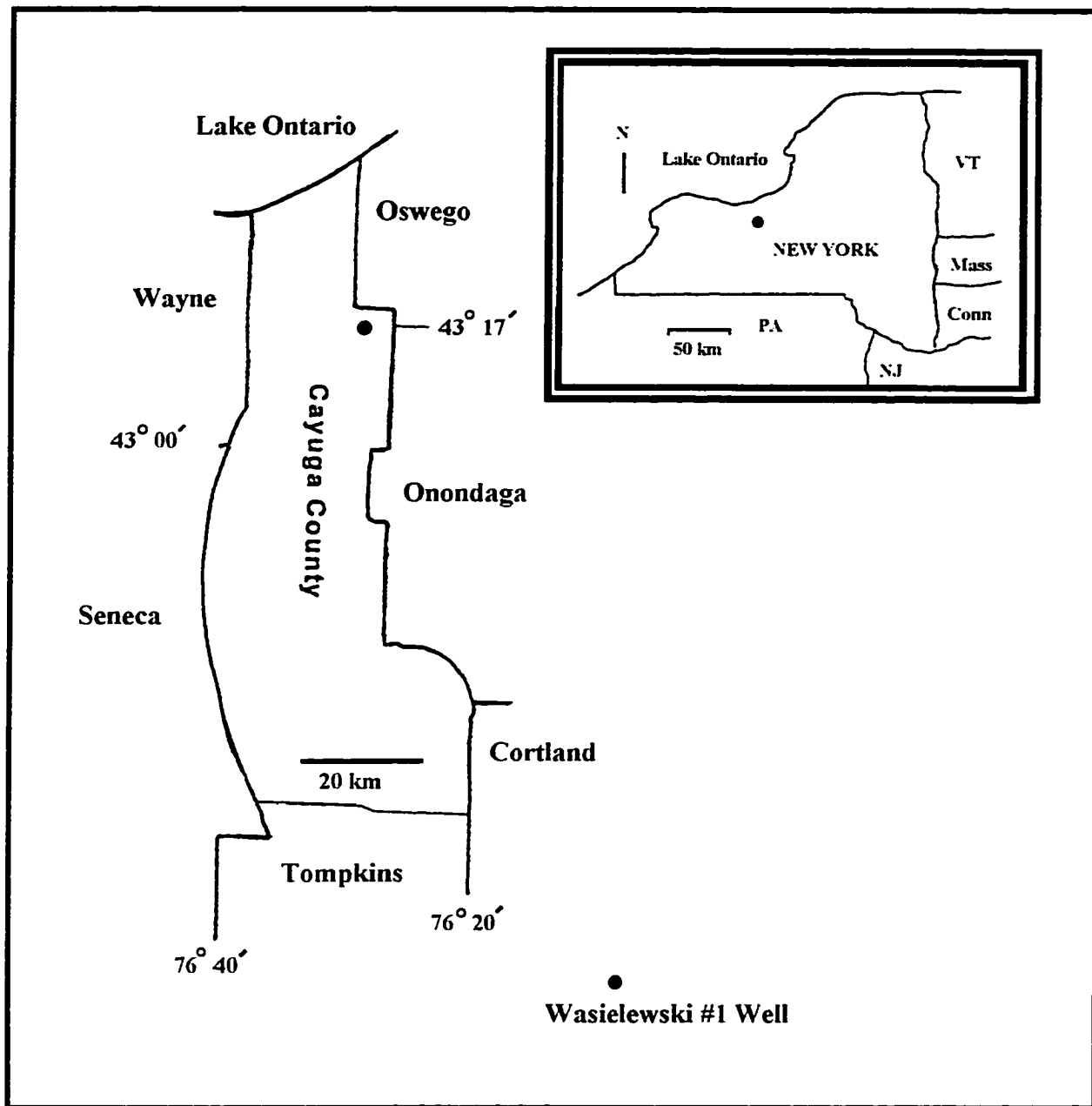
Particles



Ooids



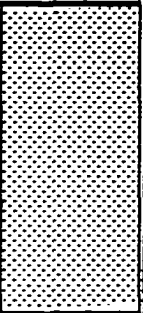
Fossil
fragments



General location of Wasielewski #1 Well, Cayuga County, New York.

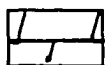
Description of well-cuttings section from 2490-3049 feet depth of the Beekmantown Group in Wasielewski #1 Well, Cayuga County, New York . Continued on the next page.

Depth (feet)	Description	Lithology
2490	Subhedral to anhedral, microcrystalline (60-90 μ m in diameter), gray to dark gray dolomite crystals, fossil fragments are common.	
2500	Gray to dark gray, medium dolomite crystals (90-150 μ m in diameter), some fossil fragments are present.	
2550	Subhedral, gray to light gray, fine to medium (90-160 μ m in diameter), fossiliferous dolomite.	
2600	Hypidiotopic to xenotopic, gray to light gray, fine to medium (70-150 μ m in diameter) dolomite crystals, highly fossiliferous calcitic dolostone.	
2680	Light to dark gray, medium-textured dolostone (120-180 μ m in diameter), peloidal particles are common.	
270	Subhedral to anhedral, gray to dark gray, microcrystalline (80-100 μ m in diameter) dolomite crystals, fossil fragments are present.	
2740	Dark gray, microcrystalline (60-90 μ m in diameter) dolomite crystals, some peloidal particles and ooids are present.	
2760	Fine to medium (80-180 μ m in diameter), gray to light gray, subhedral to anhedral, fossiliferous dolomite textured, some quartz particles are present (2%).	
2790	Subhedral to anhedral, dark gray, fine-textured dolomite (50-90 μ m in diameter).	
2820	Fine-textured dolomite (50-100 μ m in diameter), subangular to subrounded detrital quartz particles are common (10%).	
2840	Light gray, medium-textured quartz sand (80%), some anhedral to subhedral dolomite crystals are present.	
2860	Fine-textured dolomite (60-90 μ m in diameter), subangular to subrounded quartz grains are common, very few ooids are scattered throughout the thin section.	
2890	Light gray, medium-textured quartz sand (75%) embedded in light gray subhedral, fine dolomitic matrix.	
2900	Subhedral to anhedral, fine-textured dolomite (80-100 μ m in diameter), a few fossil fragments are present.	
2910	Fine to medium-textured dolomite (90-180 μ m in diameter), subrounded to subangular detrital quartz particles are present (10%).	

Depth (feet)	Description	Lithology
2930	Subrounded to subangular, medium light gray, detrital quartz grains.	
2950	Light gray, subangular medium-textured quartz sand.	
3000	Gray to light gray, subrounded to subangular, fine to medium-textured quartzose sandstone, some stylolites are present.	
3049	Medium to coarse-textured, light gray, subrounded to subangular quartzose sandstone, feldspar particles are present (5%).	

Symbols

Lithology



Dolostone



Sandstone

Particles



Ooids



Fossil
fragments

Appendix B: Microprobe Analysis.

Analysis of major and trace-element concentrations (ppm) along probe traverses of selected-dolomite samples in the Waste Water Disposal #1 Well, Niagara County, NY.

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
2849	1	224198	129420	1028	1131	1028	308
	2	214359	131763	2983	1131	617	3909
	3	216612	120135	22737	922	1639	0
	4	206965	121738	13889	2946	631	3788
	5	222985	129775	3687	1024	1229	0
	6	219844	125494	15015	1826	1826	0
	7	215332	122989	18243	3690	717	0
	8	225472	132033	1320	609	1422	0
	9	223364	130049	5190	1221	1119	0
2851	1	218568	12971	7762	1736	1123	715
	2	219699	128874	8285	1330	1534	0
	3	220223	129872	6256	1820	18401	0
	4	202297	126240	8325	1810	411	2673
	5	213752	125333	1180	2212	174	715
	6	190905	105322	2562	2614	0	30449
	7	182334	104102	1764	1901	0	20694
	8	194424	102130	2031	3034	0	23070
	9	215066	126472	1080	1312	1324	1222
2854	1	206568	112526	1300	1622	320	1121
	2	196022	104021	2780	1253	212	1412
	3	211845	123553	410	1812	124	0
	4	195012	110124	1361	1524	0	1006
2861	1	228269	132394	704	1408	1509	0
	2	223827	120136	20156	3610	1304	0
	3	224655	130576	4359	9120	1521	0
2867	1	220724	129068	5069	913	913	3650
	2	322234	10591	578	1692	0	342
	3	218477	125497	5767	1193	0	11933
	4	226310	131552	3125	1310	1210	0
	5	224325	134112	2920	1108	1007	0
	6	226642	131289	2024	1113	1012	0
2868	1	221580	133049	1420	710	710	2332
	2	218848	118433	20346	6073	506	1316
	3	229680	128960	3745	3745	1113	708
	4	223030	128772	4037	4037	303	4036
	5	220567	133952	1530	1530	1632	0
	6	228298	129909	1712	1712	1108	1208
	7	221060	129740	10460	1408	1006	1006
2870	1	214320	129234	1321	1032	811	0
	2	212228	124425	2532	1283	122	0
	3	219124	129254	1604	1226	102	812

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
2882	1	221321	124848	12870	3648	1216	608
	2	227497	131741	1008	1210	1814	202
	3	224453	118759	744	1168	637	1484
	4	188050	105384	11309	1501	0	42534
	5	221076	129889	1430	1123	919	3268
2896	1	227429	128055	844	1010	1010	2225
	2	225898	132524	1012	708	910	607
	3	333863	99875	520	1004	50	235
	4	225953	131182	1315	708	1214	1315
2897	1	221517	127082	3701	1028	823	2365
	2	314578	99821	789	1156	68	1231
	3	223672	128903	7128	803	903	2823
2903	1	221743	129616	4120	487	0	2543
	2	219547	127905	1002	228	0	789
	3	221401	125878	8523	353	503	1225
	4	221960	124194	2107	216	0	446
2921	1	221486	132290	1420	229	858	2224
	2	216438	134567	1150	455	1041	1501
	3	212225	131252	963	3252	802	1121
2939	1	224987	128999	5180	1320	1219	0
	2	220810	126831	8035	1221	305	3051
	3	221357	129740	4202	1230	1230	512
	4	215600	120783	5747	1277	1383	1916
	5	220499	125090	6572	1027	1438	2876
2948	1	359078	1576	985	985	0	1209
	2	304794	2691	2392	1096	0	715
	3	324527	5364	15589	810	0	1324
2960	1	213521	129412	1110	355	182	0
	2	215225	130214	1820	323	154	1212
	3	214032	129532	1624	425	178	1401
2969	1	215632	132708	1235	224	545	1257
	2	214065	126012	2512	353	825	1596
	3	211024	131032	4545	221	756	1415
	4	218545	128525	2321	322	322	1212
2978	1	216064	126538	6805	1700	700	4401
	2	286547	98541	256	1850	0	145
	3	231280	123863	5390	1726	508	854
	4	367008	4033	427	1082	20	120
	5	222974	86691	3959	1371	707	633

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
2987	1	221021	131104	5152	3301	1215	1102
	2	314512	95841	412	2205	52	122
	3	220432	130414	4245	2521	1513	1534
	4	298556	105861	564	1960	120	468
	5	219552	128562	4512	2056	1001	2012
3007	1	214585	123523	1202	5223	1005	2212
	2	212234	128965	8212	4450	801	1510
3019	1	223523	132542	6421	1425	821	0
	2	219014	128841	5922	1472	545	1212
	3	224056	124814	4312	2524	732	1045
	4	218123	126623	1080	3512	641	1413
3032	1	215631	114930	26253	7816	1102	0
	2	223039	124489	7455	1328	1328	2145

Major and trace-element concentrations (ppm) along probe traverses of selected- dolomite samples in the Robert Olin # 1 Well, Steuben County, NY.

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
12434	1	222130	129634	2243	110	511	0
	2	221943	131005	1053	230	0	532
	3	225081	130534	1212	280	476	0
12435	1	211908	130821	543	327	287	0
	2	223650	129067	1087	265	834	567
	3	221340	127987	1231	128	106	0
12439	1	218690	129560	1060	157	1098	212
	2	219658	131875	754	183	545	511
	3	218560	128864	622	128	1023	410
12441	1	222143	131443	3586	98	0	1156
	2	228575	130806	921	459	910	0
	3	228337	125207	996	0	0	335
12442	1	222450	125897	832	107	0	512
	2	219567	125065	1243	154	534	106
12444	1	222041	136133	829	506	1070	0
	2	223000	136013	972	114	1025	0
	3	229231	135159	341	132	650	142
	4	224216	135320	840	222	420	520
12445	1	217870	134287	745	110	0	0
	2	209234	129898	1081	358	234	103
	3	214043	132254	565	154	198	59
12447	1	226409	133158	2200	190	624	86
	2	221985	134678	1907	469	0	85
12452	1	216053	130557	2268	457	0	9666
	2	215426	139014	640	436	1503	0
	3	223068	134002	355	0	844	1631
	4	274249	96002	827	303	1146	615
	5	221078	145882	1029	149	1115	276
	6	211531	129898	16681	1476	1165	144
12453	1	213289	131032	2554	270	0	0
	2	215076	128989	1287	186	1250	152
12454	1	218452	132752	2938	165	0	2040
	2	215461	127775	12954	2045	0	163
	3	220216	134736	1075	616	0	0
12455	1	221540	134521	1298	152	0	0
	2	221961	134219	758	195	0	741
	3	224442	132810	920	487	564	164

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
12459	1	240552	128060	510	0	250	358
	2	221256	136414	3416	0	0	160
	3	230097	129304	5819	184	573	0
12465	1	229737	130413	1286	451	371	674
	2	214141	136225	7432	2177	0	328
	3	231900	128688	2298	692	0	432
12468	1	217217	138005	767	0	0	0
	2	215889	140912	1270	697	0	876
	3	215463	139375	897	54	0	423
	4	226086	131049	780	231	0	106
12471	1	213310	137239	1215	174	1059	299
	2	207999	133600	3630	508	571	914
	3	212690	142568	2980	462	1003	656
12516	1	204054	126654	1476	560	110	841
	2	211098	131254	1723	225	843	454
12518	1	226082	132236	432	404	0	408
	2	223921	135102	1442	198	163	213
	3	228162	132842	1515	212	0	0
12521	1	223921	129754	1156	543	0	0
	2	228162	131276	823	159	443	854
	3	221000	131290	411	88	576	722
12530	1	194013	135053	3194	571	0	19512
	2	203919	139893	1708	0	936	153
	3	226294	136377	415	135	856	364
12532	1	218047	131180	140	421	543	0
	2	221050	129956	120	387	498	265
	3	218508	130821	112	455	634	0
	4	218023	130432	130	401	276	387
12538	1	213252	129834	107	135	476	823
	2	223241	124408	1650	220	534	1012
	3	221352	126854	2038	270	698	1298
12584	1	204220	135043	1210	523	0	1075
	2	198589	130198	4230	380	0	578
	3	207598	126543	2822	225	0	808
12587	1	195234	136023	2576	155	0	1035
	2	199001	140821	1056	250	632	535
	3	218034	143076	2287	289	443	887
12588	1	216098	130498	1043	325	0	0
	2	214056	132295	1845	285	567	634
	3	219008	129823	1512	226	398	987

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
12589	1	196089	129912	754	258	0	0
	2	214087	130532	1023	320	554	0
	3	213832	132290	1043	304	1290	587
	4	214423	130056	898	295	845	334
12596	1	195621	130565	2212	226	234	0
	2	198067	128987	2576	207	398	632
	3	204555	129043	1032	320	893	587
12598	1	213823	128034	1098	263	0	0
	2	214043	130809	845	223	534	809
	3	212298	129670	1298	352	387	935

Major and trace-element concentrations (ppm) along probe traverses of selected- dolomite samples in the Mitchell #1 Well, Steuben County, NY.

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
7990 - 8000	1	221610	116956	852	365	28	0
	2	215228	112442	451	256	25	225
	3	217349	114504	1265	182	0	1210
8030 - 8040	1	225340	117510	809	218	0	1600
	2	212554	120183	145	183	19	851
				1543	190	57	113
8120 - 8130	1	214565	123036	123	242	6	0
	2	213476	122265	536	258	19	432
	3	217458	113298	142	453	38	510
8250 - 8260	1	198856	125673	827	360	0	0
	2	215487	124518	526	343	0	0
	3	216690	123486	902	436	7	0
	4	214556	124734	454	569	22	1416
8360 - 8370	1	198134	125863	1291	802	1210	0
	2	192534	124532	2509	657	2500	0
	3	189265	125690	2501	556	1612	0
8390 - 8400	1	214587	127834	4576	665	0	210
	2	213598	114573	2154	532	82	860
	3	219776	117520	3506	451	63	1228
8410 - 8420	1	215045	114565	5687	253	46	17920
	2	195576	124509	4247	327	23	0
8550 - 8560	1	213598	128841	1004	351	27	130
	2	216509	124762	2683	349	13	96
	3	218590	120240	2423	341	0	52
8570 - 8580	1	219878	124304	1254	650	717	822
	2	216245	124507	1412	454	925	126
	3	219059	118949	2621	389	1152	0
9050 - 9060	1	222729	124793	2140	293	0	156
	2	219099	119576	2443	258	26	1209
9090 - 9100	1	218636	124730	353	224	30	143
	2	214556	113295	683	249	83	1521
	3	214787	114530	501	273	53	107
9490 - 9500	1	210834	114705	1663	356	75	0
	2	211576	125929	1265	348	53	130
	3	210943	124574	3245	260	186	1587
	4	210382	114329	1223	245	0	0

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
9770 - 9780	1	214530	114730	476	569	0	122
	2	217820	130239	5434	524	0	0
9810 - 9820	1	216283	102228	1712	369	250	225
	2	226576	112396	2432	343	121	128
	3	214349	124039	1232	541	0	185

Major and trace-element concentrations (ppm) along probe traverses of selected-dolomite samples in the Wasielewski #1 Well, Cayuga County, NY.

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
2490 - 2500	1	224680	112018	1211	222	68	108
	2	229095	123629	848	254	120	94
2500 - 2560	1	332540	95252	1893	350	84	0
	2	330226	102328	1259	221	78	66
	3	281482	96018	1612	193	42	128
2560 - 2580	1	222351	101218	721	358	0	0
	2	219830	98979	802	1254	49	55
	3	219092	89629	257	1287	0	0
2580 - 2600	1	225032	128073	518	242	0	159
	2	223567	124019	1458	225	107	175
2600 - 2640	1	225505	122683	1803	150	123	229
	2	214539	122378	1573	241	89	328
	3	222394	127102	1293	322	56	121
2640 - 2680	1	217023	128023	1493	174	62	253
	2	218094	124798	1893	228	41	144
	3	213658	124541	2293	192	128	105
2680 - 2710	1	305032	100221	1025	196	93	86
	2	300229	98887	1587	256	110	98
2710 - 2740	1	212038	135021	1632	354	33	73
	2	225382	128076	1484	324	0	124
	3	224571	127442	0	290	0	142
2800 - 2820	1	214319	113008	1795	268	88	236
	2	109403	124034	1574	192	55	150
2890 - 2900	1	221479	128565	2185	240	128	128
	2	219026	124532	2582	343	84	214
2900 - 2910	1	213504	123518	1063	348	92	98
	2	216638	126439	1112	325	59	0
	3	220383	127890	895	198	85	0
2940 - 2950	1	217817	112073	1436	428	39	210
	2	216428	111456	1229	355	64	145

Major and trace-element concentrations (ppm) along probe traverses of selected-dolomite samples in the Wilson #1 Well, Wyoming County, NY.

Depth (feet)	Points	Ca	Mg	Fe	Mn	Sr	Si
5980-5990	1	221402	126542	1421	832	129	0
	2	213330	117250	2265	229	107	121
	3	212823	115340	1020	204	59	483
6140-6150	1	227340	10029	828	931	35	0
	2	228345	98211	484	1250	0	254
	3	219780	74544	702	935	0	479
6190-6200	1	226945	124162	1274	245	0	0
	2	214439	128670	493	220	103	479
	3	212010	134210	1516	1232	86	812
	4	212567	115322	1413	240	115	0
6230-6240	1	217930	126480	1205	318	167	45
	2	208963	125640	1491	228	126	886
	3	214239	113290	1784	246	0	724
6250-6260	1	215569	133420	2180	627	109	1120
	2	227294	84410	1521	224	87	205
6260-6270	1	224732	105620	1484	513	116	0
	2	212320	99410	1293	223	89	0
	3	215421	115420	830	255	45	579
	4	310539	85432	1105	274	0	0
6310-6320	1	212439	125973	801	228	105	1201
	2	214885	128546	593	176	126	102
	3	215444	123427	1206	1901	121	856
6340-6350	1	105421	129620	1422	324	82	578
	2	226598	126439	2218	289	56	0
	3	218547	125820	1003	248	48	0
	4	213483	115733	1528	237	0	0
6510-6520	1	217523	99587	2595	256	20	131
	2	213565	124095	1449	228	125	148
	3	214439	116023	2127	191	0	104
6830-6850	1	225378	102054	1183	210	77	106
	2	224139	114510	820	256	35	37
6930-6950	1	224876	124460	905	187	0	584
	2	212349	128774	1422	269	0	0

Appendix C: Petrophysical Analysis.

Petrophysical data from core samples of the Cambro-Ordovician Sauk Sequence in Hooker Chemical's Waste Disposal Test Well #1, Niagara County, New York.

Depth (ft)	Lithology	Porosity % (Φ %)	Air Permeability (mD)	Recovery Efficiency % (R.E. %)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
2849	Sdy. Dol.	1.0	0.008	2.3	0.37	0.05
2850	Sdy. Dol.	4.3	0.010	35.0	0.57	0.12
2852	Sdy. Dol.	4.6	0.004	12.7	0.75	0.15
2861	Sdy. Dol.	1.8	0.002	6.2	0.06	0.04
2870	Sdy. Dol.	2.0	0.004	0.0	0.19	0.05
2871	Dol.	1.6	<0.001	0.0	0.18	0.12
2882	Dol.	5.7	0.009	2.3	0.07	0.06
2896	Dol.	0.0	0.003	12.1	9.04	0.03
2902	Dol.	0.8	0.009	13.8	0.07	0.06
2903	Dol.	0.5	0.005	14.3	40.4	0.97
2905	Dol.	5.9	0.088	21.2	1.64	0.16
2906	Dol.	2.7	0.055	12.8	0.02	0.02
2910	Dol.	7.1	0.002	25.2	7.55	0.25
2911	Dol.	7.8	0.003	20.0	0.1	0.07
2914	Dol.	2.9	0.004	12.8	0.11	0.08
2921	Dol.	2.1	0.004	15.5	16.68	0.18
2922	Sdy. Dol.	6.4	0.002	12.6	0.46	0.12
2939	Sdy. Dol.	2.1	<0.001	16.1	0.41	0.04
2940	Sdy. Dol.	4.4	0.028	14.5	0.27	0.18
2950	Dol.	0.8	<0.001	26.4	0.13	0.04
2953	Dol.	2.4	0.017	17.5	0.03	0.03
2956	Dol.	4.2	<0.001	29.1	0.12	0.08
2966	Dol.	2.9	0.002	25.9	0.04	0.04
2969	Sdy. Dol.	0.6	0.001	36.0	0.03	0.02
2978	Sdy. Dol.	0.6	<0.001	28.8	44.26	0.28

Depth (ft)	Lithology	Porosity % ($\Phi\%$)	Air Permeability (mD)	Recovery Efficiency % (R.E. %)	Median Pore Diameter (μm)	Average Pore Diameter (μm)
2979	Sdy. Dol.	1.6	<0.001	10.3	0.13	0.03
2980	Sdy. Dol.	0.5	<0.001	16.7	7.64	0.07
2987	Sdy. Dol.	0.2	<0.001	0.0	21.44	2.88
2988	Sdy. Dol.	1.8	0.001	21.4	0.09	0.04
2990	Sdy. Dol.	0.4	0.001	85.0	14.41	0.64
2997	S.S.	2.0	0.001	90.0	0.89	0.25
3000	S.S.	8.8	0.034	56.0	0.32	0.1
3004	S.S.	4.4	0.038	19.0	0.09	0.06
3010	S.S.	3.1	0.009	22.8	0.15	0.05
3011	S.S.	3.9	0.002	37.6	0.22	0.09
3012	S.S.	7.2	0.008	15.3	0.09	0.05
3016	S.S.	3.5	0.004	16.7	0.05	0.03
3026	S.S.	2.0	0.003	35.0	0.6	0.06

Dol. = Dolostone

Sdy. Dol. = Sandy dolostone

S.S. = Sandstone

Petrophysical data from core samples of the Cambro-Ordovician Sauk Sequence in Robert Olin Well #1, Steuben County, New York.

Depth (ft)	Lithology	Porosity % (Φ %)	Air Permeability (mD)	Recovery Efficiency% (R.E. %)	Median Pore Diameter (μm)	Average Pore Diameter (μm)
12434	Sdy. Dol.	0.7	0.008	20.0	10.9	0.6
12435	Sdy. Dol.	1.2	0.006	36.5	0.9	0.4
12437	Sdy. Dol.	1.1	0.042	39.0	0.5	0.09
12439	Sdy. Dol.	1.3	0.034	42.9	0.9	0.3
12441	Sdy. Dol.	2.7	0.005	25.0	22.9	0.26
12442	Sdy. Dol.	1.1	0.008	18.9	0.80	0.41
12444	Sdy. Dol.	1.0	0.007	18.0	12.5	0.12
12445	Dol.	0.4	0.004	0.0	0.36	0.08
12447	Dol.	1.0	0.003	20.0	0.20	0.13
12448	Dol.	1.5	0.004	31.5	0.38	0.2
12449	Sdy. Dol.	0.8	0.005	16.1	0.14	0.07
12450	Sdy. Dol.	0.8	0.026	16.6	0.18	0.11
12452	Sdy. Dol.	0.5	0.003	29.4	0.64	0.21
12453	Dol.	0.9	0.004	9.4	0.11	0.06
12454	Dol.	0.8	0.002	13.3	11.04	0.3
12455	Sdy. Dol.	1.0	0.006	30.6	0.30	0.15
12456	Sdy. Dol.	0.6	0.004	25.0	0.18	0.21
12458	Sdy. Dol.	0.7	0.002	11.5	0.27	0.2
12459	Dol.	0.6	0.003	38.1	0.90	0.17
12463	Dol.	0.2	0.002	25.0	29.8	18.52
12464	Dol.	0.3	0.001	20.0	12.58	0.05
12465	Dol.	0.6	0.004	13.6	3.78	0.34
12468	Sdy. Dol.	0.6	0.002	9.5	4.39	0.24
12469	Sdy. Dol.	0.3	0.003	36.4	40.3	0.71
12471	Dol.	1.4	0.009	16.3	0.08	0.04

Depth (ft)	Lithology	Porosity % (Φ %)	Air Permeability (mD)	Recovery Efficiency% (R.E. %)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
12472	Dol.	0.5	0.007	18.8	0.18	0.11
12518	Dol.	0.2	0.004	100.0	7.19	3.11
12521	Sdy. Dol.	1.3	0.006	34.0	1.07	0.46
12524	S.S.	3.0	0.033	9.3	0.29	0.08
12528	S.S.	1.0	0.040	14.6	0.68	0.37
12530	Sdy. Dol.	0.4	0.050	7.1	36.4	19.92
12531	Dol.	0.5	0.007	31.3	0.08	0.09
12532	Dol.	0.6	0.008	9.5	12.10	0.13
12534	Sdy. Dol.	0.5	0.004	22.2	21.54	0.19
12536	Dol.	0.8	0.005	14.2	0.27	0.21
12538	Dol.	0.2	0.003	25.0	0.35	0.03
12572	Sdy. Dol.	0.3	<0.001	100.0	39.86	27.14
12584	Sdy. Dol.	0.4	0.002	26.7	11.7	0.39
12586	Sdy. Dol.	1.1	0.004	24.4	9.96	0.16
12587	Sdy. Dol.	0.8	0.003	17.2	10.62	0.37
12588	Dol.	0.3	0.004	22.2	6.84	0.15
12589	Dol.	0.4	0.002	0.0	39.32	0.13
12590	Sdy. Dol.	0.3	0.005	41.7	7.89	0.05
12593	Sdy. Dol.	0.5	0.002	17.6	40.43	1.30
12594	Dol.	0.4	0.004	25.0	0.17	0.08
12596	Dol.	0.3	0.003	72.7	35.63	0.06
12597	Sdy. Dol.	0.4	0.001	0.0	1.08	0.06
12598	Dol.	0.5	0.004	0.0	11.74	0.09
13482	S.S.	0.5	0.005	10.0	0.35	0.09
13484	S.S.	0.7	0.001	25.0	0.16	0.08
13492	S.S.	0.4	0.004	0.0	6.67	0.13
13499	S.S.	3.9	0.002	55.3	0.15	0.12

Dol. = Dolostone

Sdy. Dol. = Sandy dolostone

S.S. = Sandstone

Petrophysical data from well-cuttings of the Cambro-Ordovician Sauk Sequence in Mitchell (Avoca) Well, Steuben County, New York.

Depth Interval (ft)	Lithology	Porosity% (Φ %)	Recovery Efficiency% (R.E.%)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
7990-8000	Dol.	2.7	25.2	0.09	0.03
8000-8010	Dol.	3.8	25.2	0.38	0.04
8020-8030	Dol.	2.2	33.7	11.18	0.05
8040-8050	Dol.	1.8	10.4	11.91	0.04
8050-8060	Dol.	2.3	7.9	30.41	0.05
8080-8090	Dol.	1.7	25.0	1.02	0.05
8100-8110	Dol.	1.2	9.1	19.80	0.21
8130-8140	Dol.	1.6	19.7	34.90	0.15
8160-8170	Dol.	3.4	14.6	10.64	0.05
8190-8200	Dol.	2.9	40.2	0.15	0.03
8220-8230	Dol.	1.4	11.8	15.2	0.43
8240-8250	Dol.	1.9	15.3	7.3	0.07
8250-8260	Dol.	2.6	41.7	0.03	0.03
8310-8320	Dol.	6.5	39.0	0.07	0.04
8390-8400	Dol.	3.9	0.0	0.07	0.03
8410-8420	Dol.	1.7	17.4	0.26	0.06
8420-8430	Dol.	1.0	0.0	0.61	0.06
8440-8450	Dol.	2.7	23.5	4.17	0.11
8480-8490	Dol.	1.7	16.4	0.02	0.03
8560-8570	Dol.	1.5	20.4	0.09	0.03
8610-8620	Dol.	3.0	28.7	4.10	0.06
9030-9040	Dol.	7.4	28.3	8.21	0.05
9040-9050	Sdy. Dol.	7.0	31.2	14.90	0.09
9090-9100	Sdy. Dol.	4.6	13.3	10.74	0.08

Depth Interval (ft)	Lithology	Porosity% (Φ %)	Recovery Efficiency% (R.E.%)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
9240-9250	Sdy. Dol.	2.8	33.3	14.57	0.99
9500-9510	Sdy. Dol.	4.2	7.9	6.79	0.08
9670-9680	S.S.	4.5	28.7	10.4	0.04
9770-9780	S.S.	5.3	31.2	7.12	0.07

Dol. = Dolostone

Sdy. Dol. = Sandy dolostone

S.S. = Sandstone

Petrophysical data from well-cuttings of the Cambro-Ordovician Sauk Sequence in Wilson Well, Wyoming County, New York.

Depth Interval (ft)	Lithology	Porosity % (Φ%)	Recovery Efficiency% (R.E.%)	Median Pore Diameter (μm)	Average Pore Diameter (μm)
5980-6010	Dol.	3.2	35.8	0.02	0.02
6010-6020	Dol.	2.8	45.9	0.04	0.03
6020-6040	Dol.	3.4	18.9	19.11	0.07
6050-6070	Dol.	1.3	34.6	8.36	0.04
6070-6100	Dol.	2.9	0.8	1.16	0.04
6100-6120	Dol.	1.3	47.9	0.13	0.03
6120-6150	Dol.	1.8	44.3	0.04	0.03
6150-6190	Dol.	1.8	23.9	9.45	0.06
6210-6230	Dol.	2.9	28.3	1.04	0.07
6230-6250	Dol.	0.4	68.8	0.02	0.03
6250-6290	Dol.	1.8	17.9	0.25	0.05
6290-6300	Dol.	2.5	25.0	0.18	0.04
6300-6360	Sdy. Dol.	3.8	22.3	4.67	0.08
6360-6400	Sdy. Dol.	2.1	63.75	0.04	0.03
6400-6440	Sdy. Dol.	1.7	47.6	0.08	0.03
6440-6760	Sdy. Dol.	8.0	16.0	26.12	0.09
6760-6830	S.S.	10.5	9.2	11.74	0.33
6830-6970	S.S.	7.3	25.6	4.25	0.05
6970-7144	S.S.	9.7	1.6	17.77	1.44

Dol. = Dolostone Sdy. Dol. = Sandy dolostone S.S. = Sandstone

Petrophysical data from well-cuttings of the Cambro-Ordovician Sauk Sequence in Wasielewski #1 Well, Cayuga County, NY.

Depth Interval (ft)	Lithology	Porosity % (Φ %)	Recovery Efficiency% (R.E.%)	Median Pore Diameter (μ m)	Average Pore Diameter (μ m)
2490-2500	Dol.	4.9	21.0	1.12	0.05
2500-2550	Dol.	3.9	44.1	0.07	0.03
2550-2600	Dol.	3.3	29.9	0.08	0.04
2600-2660	Dol.	1.8	0.0	19.04	0.09
2660-2710	Dol.	3.1	20.0	0.20	0.03
2710-2720	Dol.	2.0	53.8	0.04	0.03
2720-2750	Dol.	2.3	45.5	0.09	0.04
2800-2820	Sdy. Dol.	2.7	29.9	0.63	0.05
2880-2890	Sdy. Dol.	3.7	25.2	6.85	0.03
2910-2930	Sdy. Dol.	3.5	42.9	0.05	0.03
2930-2932	S.S.	0.6	33.3	0.90	0.04
2932-2934	S.S.	2.4	34.0	0.07	0.03
2934-2937	S.S.	1.2	17.8	34.50	0.08
3026-3038	S.S.	3.0	18.1	0.30	0.04

Dol. = Dolostone

Sdy. Dol. = Sandy dolostone

S.S. = Sandstone

Appendix D: Glossery of Petrophysical Terms.

Mercury porosimetry technique was used in this study to evaluate the petrophysical properties of the Beekmantown Group of central and western New York. Provided is an explanation and calculation of the petrophysical parameters from the this analysis:

Apparent (skeletal) Density is the density of the sample as calculated for the bulk density and adjusted for the pore volume measured at the maximum pressure attained during the run (20,000 psi in this experiment).

Average Pore Diameter ($4V/A$) is obtained by assuming that all pores are right cylinders. Thus, when the pore volume ($V = \pi d^2 \ell \div 4$) is divided by the pore area ($A = \pi d \ell$), the pore diameter (d) is equal to $4V/A$. Therefore, the volume increment of cylindrical capillaries which includes a distribution of pore sizes will yield a pore diameter value that is the average diameter for this group of capillaries.

Bulk Density = sample weight $\div$ sample volume.

It can be calculated from the sample weight (g) and the sample volume (cc) at the initial mercury filling pressure.

Capillary % provides the percentage of the available intrusion volume used in the penetrometer. This number should preferably range between 25% and 90% of a given stem volume.

Density (ρ) is the mass or quantity of a substance per unit volume. Units are kilogram per cubic

meter or grams per cubic centimeter.

Effective Porosity is the volume of the void spaces through which gas, water, or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment. The porosimetric analysis shows variation of the porosity values among the lithofacies and microlithofacies. These variation are based on the lithology and the intensity of the diagenetic modification.

Fluid Saturation ratio is the volume of contained liquid in a given rock to the volume of the voids of the same rock sample.

$$\text{Fluid Saturation ratio (\%)} = V_L + V_V \times 100$$

V_L = volume of contained liquid in a rock V_V = volume of the voids of the rock sample

Median Pore Diameter (or Radius) is the 50% (percentile) value obtained from both area and volume distribution curves. Frequently, these values will differ because the smaller pores contribute more to the total pore surface area than the larger pores for a given increment of mercury intrusion volume. Therefore, the area distributions will have a tendency to shift to the smaller pore sizes when compared to pore volume distribution.

$$d = \frac{-4\gamma \cos \theta}{p} \quad \text{or} \quad r = \frac{-2\gamma \cos \theta}{p}$$

d = pore diameter p = applied pressure r = pore radius

θ = contact angle γ = surface tension

Permeability (K) is a measure of the ability of the reservoir rock to conduct gas or fluid through it. It is generally measured in the laboratory in plugs taken from reservoir core samples. A good storage reservoir may have both good porosity and permeability. Sandstones and carbonates (both limestones and dolostones) generally provide the best porosity-permeability combinations. However, pressure and reservoir capacity also play significant roles in gas storage reservoir.

Permeability (**md**) is the ability of rock to allow fluid movements through its mass without any change in its structure or fabrics. It is a property of the porous medium and is independent of the nature of the liquid or the potential field. Permeability depends on factors of size, shapes, degree of connection among pore spaces, and on the viscosity of the fluid and pressure driving it.

Permeability is expressed mathematically as:

$$Q = \frac{K \mu A (P_2 - P_1)}{L}$$

Q = quantity of fluid transmitted in a unit time (cm³/s)

K = coefficient of permeability (related to sizes, shapes, and interconnection of pores)
measured in millidarcies (md)

μ = viscosity of fluid (centipoises), a factor influenced by temperature

A = cross-sectional area of connected pores at right angles to the direction of flow (cm²)

L = length along which the differential pressure is measured (cm)

P₂ - P₁ = pressure difference (atmospheres) between two points separated by distance L

Porosity is the ratio, in percent, of the volume of void spaces to the total volume of a solid. The porosity of the reservoir rock formation indicates how much pore space is available within the reservoir to be occupied by gas or other fluids. Porosity is expressed mathematically as:

$$\text{Porosity (\%)} = \frac{\text{total volume} - \text{volume of solid}}{\text{total volume}} \times 100$$

Porosity can be calculated from porosimetric analysis by using the following equation:

$$\text{Porosity } (\phi\%) = \text{Total intrusion volume} \times \text{Bulk density} \times 100$$

Recovery Efficiency Percent (R.E.%) represents the percentage volume of a liquid (mercury in case of mercury porosimeter) that will be recovered upon ejection test by decreasing the pressure from 20,000 to 14 psi and it is dependent on the permeability of the sample and expressed mathematically as:

$$\text{R.E. \%} = \frac{\text{Total intrusion volume} - \text{Minimum intrusion volume}}{\text{Total intrusion volume}} \times 100$$

Note: the total intrusion volume at the highest applied pressure and the minimum intrusion volume at the lowest applied pressure.

Sample Volume is equal to the penetrometer volume minus the volume of mercury in the penetrometer with the sample.

Total Intrusion Volume is the maximum volume of mercury intruded into the pores at the maximum pressure attained (20,000 psi in this experiment).

Total Pore Area is the area of the pores based on the assumption of cylindrical geometry of the pore spaces, and summed up over the pressure range of mercury intrusion into the pores.

Volume of mercury = weight of mercury $\div$ density of mercury (13.53 g/cc).

Weight of Mercury = weight of penetrometer with sample and mercury minus the weight of penetrometer with the sample.

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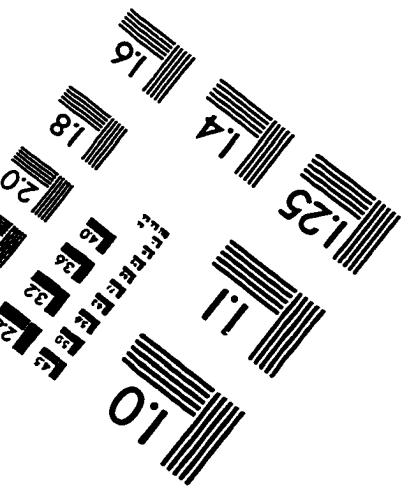
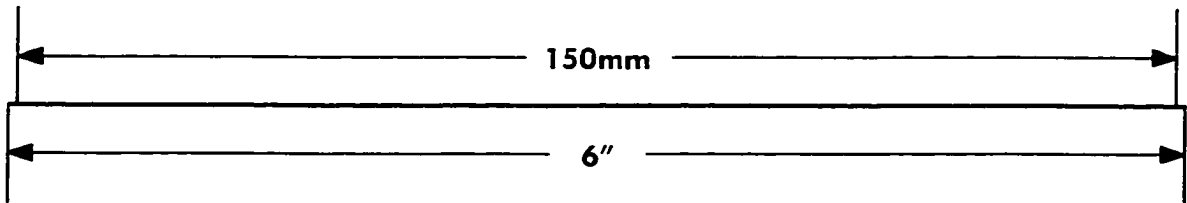
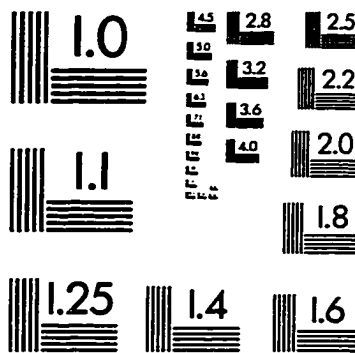
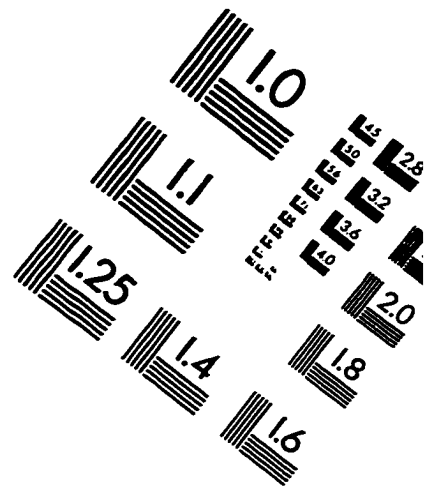
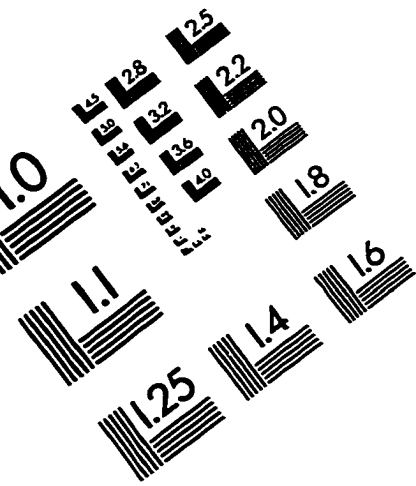
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IMAGE EVALUATION TEST TARGET (QA-3)



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