STRATIGRAPHY, STRUCTURAL GEOLOGY, AND HYDROGEOLOGY OF THE LOCKPORT GROUP: NIAGARA FALLS AREA, NEW YORK

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INTRODUCTION

The Niagara Falls area is known for its classic geology. An internationally recognized stratigraphic sequence of uppermost Ordovician and Silurian rocks is exposed along the walls of the Niagara Gorge. Summaries of the geology of this area are provided in Tesmer (1981) and Brett and Calkin (1987).

The purpose of this field trip is to provide an overview of some current research on the stratigraphy, structural geology, and hydrogeology of the Upper Silurian[1/] Lockport Group, which caps the section exposed in the Niagara Gorge. There has been much recent interest in the Lockport Group, particularly in the Niagara Falls area, where ground water within it has been contaminated by hazardous waste. In 1987 the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), began a 4-year study of the hydrogeology of the Niagara region. The primary objective of this study is to define the regional ground-water flow system so that a three-dimensional ground-water flow model can be constructed that can provide a regional hydrogeologic framework for future site-specific research efforts. An important supporting objective of this study is

[1/] The U.S. Geological Survey recognizes "Lower," "Middle" and "Upper" Silurian and designates the Lockport Group as Middle Silurian. However, in a New York State Geological Survey publication by Rickard (1975), the use of "Middle" Silurian was abandoned in New York and was replaced with the terms "Lower" and "Upper" Silurian to be consistent with European usage. The Lockport Group is designated as Upper Silurian by Rickard (1975) and will be referred to as such in this paper.

to identify the major water-bearing zones and to determine their regional extent, which has required detailed study of the stratigraphy and structural geology of the Lockport Group.

High-resolution stratigraphy has been used to aid in identification and correlation of horizontal regional water-bearing zones. Brett and others (written commun. 1990)[2/] have divided previously recognized stratigraphic units into new regionally extensive formations, members, beds, and informal units and have extended some units into the study area from adjacent areas where they were previously defined and(or) made changes in the placement of their lower or upper contacts. These revisions, which are the result of research conducted at the Department of Geological Sciences at the University of Rochester, in cooperation with the USGS, have been based on observations of outcrops and of cores obtained through the USGS/USEPA project. The revised nomenclature discussed herein is provisional and is formally proposed within a larger study of the Niagaran Series (C. E. Brett and others written commun. 1990) and comply with the requirements of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 1983). A summary of this work for the Lockport Group is presented in the "Stratigraphy" section.

Ground water in the Lockport Group flows primarily through extensive, nearly horizontal bedding planes that are connected to a limited extent by high-angle fractures. Because these fractures significantly affect ground-water flow rates and directions, it is important to determine the regional and local fracture framework. A study of fractures in the Lockport Group of western New York and southern Ontario was completed by Gross (1989); results of that work are summarized in the "Structural Geology" section.

The three stops on this field trip (Fig. 1) are described in detail in the following sections. Stratigraphy and structural geology will be discussed at the first two stops and hydrogeology will be discussed at the last stop. The first stop will be at the Frontier Stone Quarry in the Town of Gasport, where we will examine the stratigraphy of the Gasport Limestone, the lowermost formation in the Lockport Group. This quarry is located along a reentrant on the Niagara Escarpment so we will also examine changes in joint orientations along this feature. The second stop will be at the Niagara Stone Quarry in the Town of Niagara, where we will examine the Lockport Group stratigraphy from the base of the Gasport Limestone to the upper part of the Eramosa Dolomite (previously termed the "Oak Orchard Dolomite"). We will also discuss fractures and large-scale "pop-ups" on the quarry floor. The final stop (also in the Town of Niagara) will be at a site where the USGS has conducted detailed electromagnetic surveys and hydraulic tests as part of the USGS/USEPA regional hydrogeologic study. This stop will include a demonstration of electromagnetic techniques, including terrain conductivity and VLF (very low frequency), and a discussion of downhole instrumentation and the cross-hole hydraulic testing program that has been conducted at the site.

STRATIGRAPHY

by William M. Goodman and Dorothy H. Tepper

The stratigraphy of the Niagara area is well known; some of the pioneering paleontologic and stratigraphic studies in the region were conducted by the renowned geologist James Hall, beginning in 1838. These early studies resulted in the establishment of the Niagara region as the type locality for the Niagaran Series (Lower and Upper Silurian[1]) of eastern North America. The Niagara area is underlain by approximately 60 m (meters) of relatively undeformed dolomites and limestones of the Upper Silurian Lockport Group of the Niagaran Series. The rocks in the Niagara area were deposited in shallow epeiric seas in the northern Appalachian Foreland Basin. These units are widespread; their lateral equivalents outcrop to the northwest of the study area and eventually extend into the Michigan Basin. Cyclic vertical facies changes and erosional surfaces in the Lockport Group are related to relative sea-level oscillations and to emergence of the Algonquin Arch concurrent with lateral migration of the Appalachian Basin axis (Brett and others 1989).

Basis for Stratigraphic Revisions

One purpose of this field trip is to present revised stratigraphic nomenclature (Fig. 2) for the

[2/] (C. E. Brett, University of Rochester; W. M. Goodman, University of Rochester; S. T. LoDuca, University of Rochester; D. H. Tepper, U.S. Geological Survey; W. L. Duke, Pennsylvania State University; and B. Y. Lin, written commun. 1990) will be cited hereafter as (C. E. Brett and others, written commun. 1990).

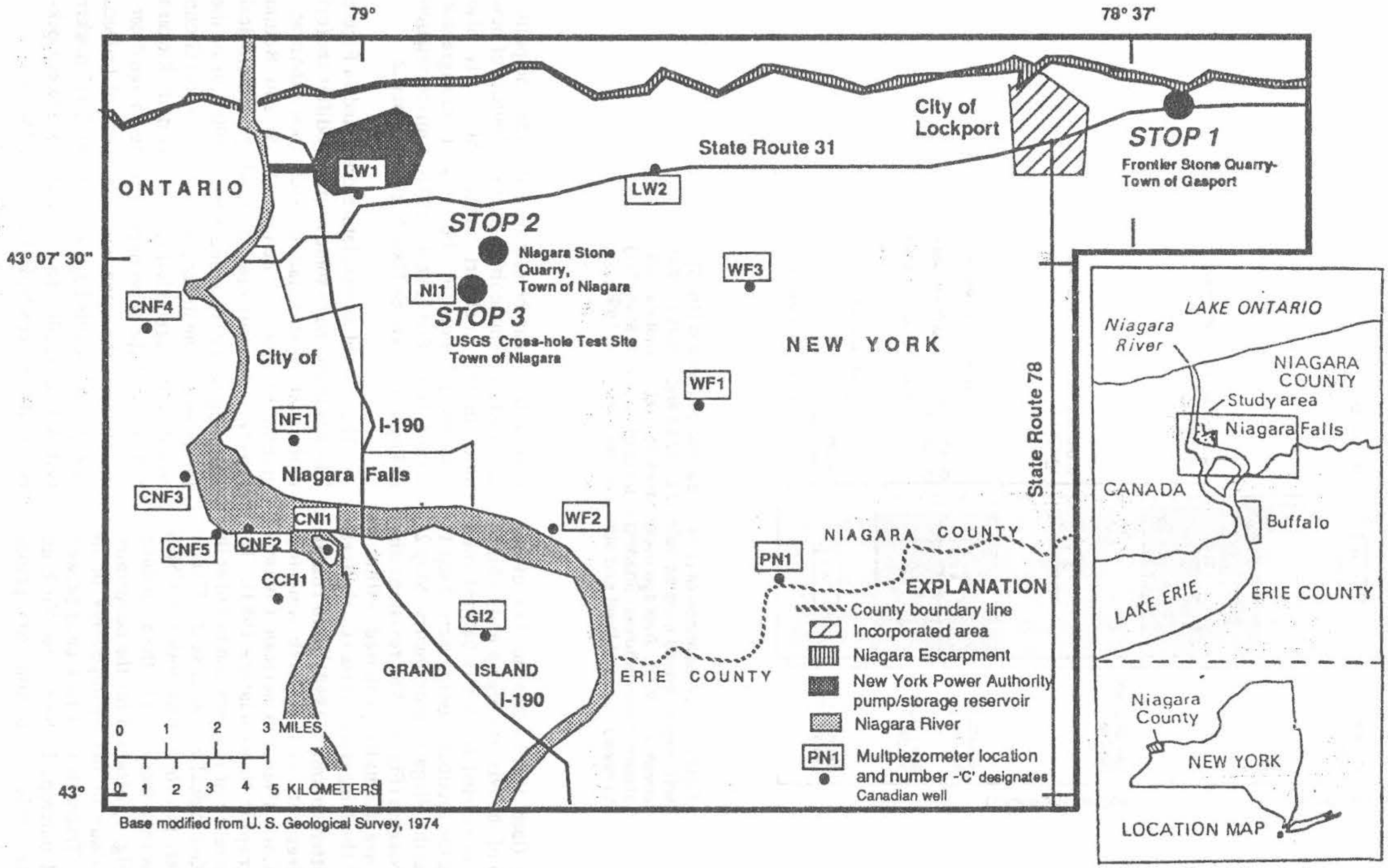


Figure 1. -- Location of field-trip stops and multipiezometer installations where core was collected.

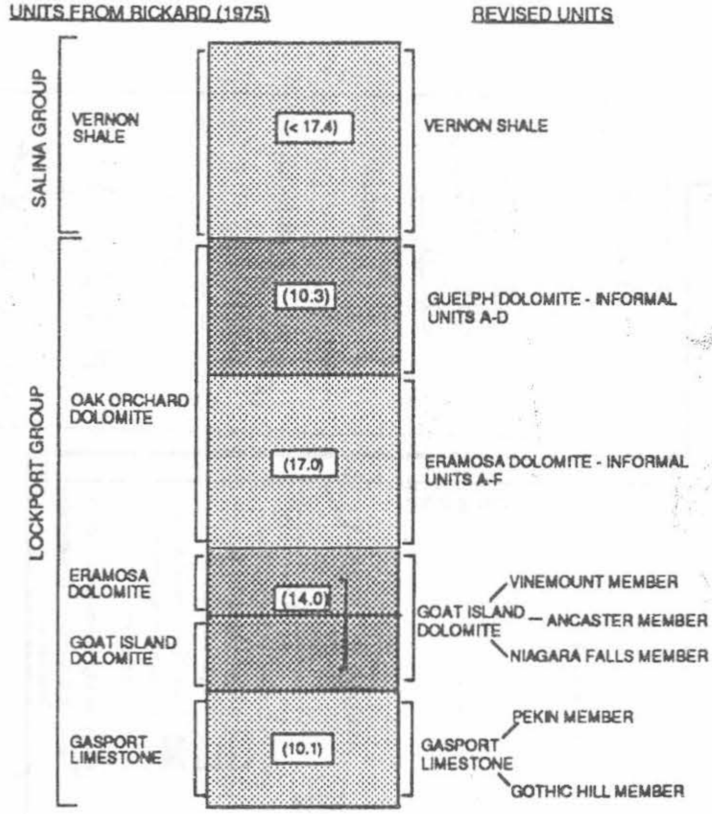


Figure 2. - Comparison of units as defined by Rickard (1975) with newly revised units as defined by Brett and others (written commun. 1990). Average thicknesses of units (in meters) are shown in parentheses. Shading of units in column is according to revised units of Brett and others (written commun. 1990).

Upper Silurian (late Wenlockian to Ludlovian) Lockport Group of the Niagara region and to highlight the details of revised and newly defined units as they appear at the Frontier Stone Quarry (Stop 1) at Gasport, and at the Niagara Stone Quarry (Stop 2) in the Town of Niagara (Fig. 1). **The revisions discussed herein are formally proposed within a larger study of the Niagaran Series (C. E. Brett and others, written commun. 1990)[2/] and comply with the requirements of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 1983).** The revisions are the result of research conducted at the Department of Geological Sciences at the University of Rochester, in cooperation with the USGS. This research has been facilitated by the availability of nine cores (Fig. 1) obtained for the cooperative USGS/USEPA study of the hydrogeology of the Niagara region. Traceability of rock units between these cores and outcrops in both New York and Ontario indicates that a uniform stratigraphic nomenclature can be established across the political boundary. In addition to the definition of new units in the Lockport Group, this study also resolves conflicts in the present stratigraphic nomenclature that have arisen from miscorrelation of key units between New York and Ontario.

The revised nomenclature presented in Figure 2 builds upon and to some degree modifies and(or) replaces the nomenclature based upon lithostratigraphic analyses of Zenger (1965) and Bolton (1957). Furthermore, detailed paleontological sampling by LoDuca and Brett (1990 a,b) of the formations in the lower part of the Lockport Group modifies the age relations presented in Rickard (1975). In addition to improvements in age determinations at the stage level, the work of LoDuca (1990) has provided a useful faunal/floral marker bed that has facilitated correlation of lower Lockport units between widely spaced sections.

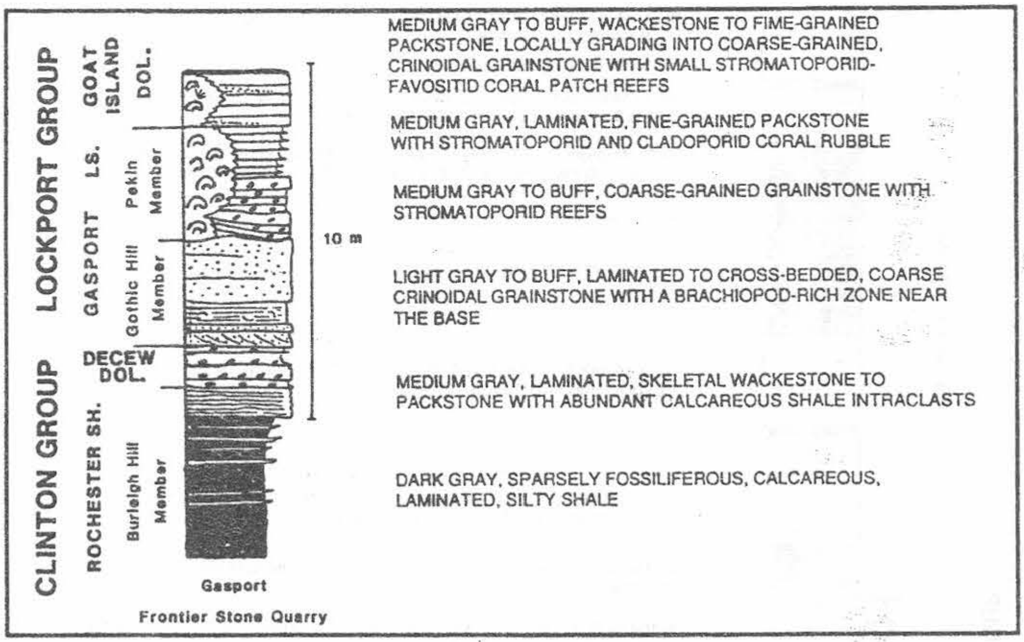


Figure 3.-- Stratigraphic section from the Frontier Stone Quarry in Gasport (Stop 1, Fig. 1).

At the two quarry stops on this trip, we will see three of the four formations that constitute the lower 37 m of the entire 50 to 60 m of medium-bedded to massive, argillaceous limestones and dolomites and thin shales that form the Lockport Group. The following discussion includes a general description of the newly revised stratigraphic units, in ascending order. The contact of the Lockport Group with the underlying Clinton Group is placed at the disconformable contact between the DeCew Dolomite and the Gasport Limestone and can be seen at the Frontier Stone Quarry at Gasport (Stop 1). Details of the stratigraphy at this quarry are shown in Figure 3. A composite stratigraphic column based on the exposures at the Niagara Stone Quarry in the Town of Niagara (Stop 2) and on core from the USGS Niagara (NI-1) test hole (Stop 3) is shown in Figure 4. The contact between the Lockport Group and the overlying Salina Group is not exposed in outcrop but can be seen in the USGS Grand Island (GI-2) core (Fig. 5). The gradational boundary of the Guelph Dolomite and the overlying Vernon Shale is arbitrarily placed by Brett and others (written commun. 1990) at the first black shale bed that is greater than 2.5 cm (centimeters) thick.

Revised Stratigraphy of the Lockport Group

As defined by Brett and others (written commun. 1990), the Upper Silurian Lockport Group of the Niagara region consists of the following four formations, in ascending order: the Gasport Limestone; the Goat Island Dolomite; the Eramosa Dolomite; and the Guelph Dolomite. Decisions on the names of the revised formation- and member-scale units have been based on the quality of the type sections, established stratigraphic boundaries, and historical precedence. Although three of the four formations retain traditional names based on New York sections, the contacts between units with Canadian type sections have been shifted considerably for consistency with Canadian usage. The revised stratigraphic units are outlined below.

Gasport Limestone. The type section for the Gasport Limestone is in the Frontier Stone Quarry at Gasport, in Niagara County (Stop 1). The Gasport Limestone as defined by Brett and others (written commun. 1990) consists of the Gothic Hill Grainstone Member (lower member) and the Pekin Member (upper member) (Fig. 4). The Gothic Hill Grainstone Member is a light pinkish gray to buff,

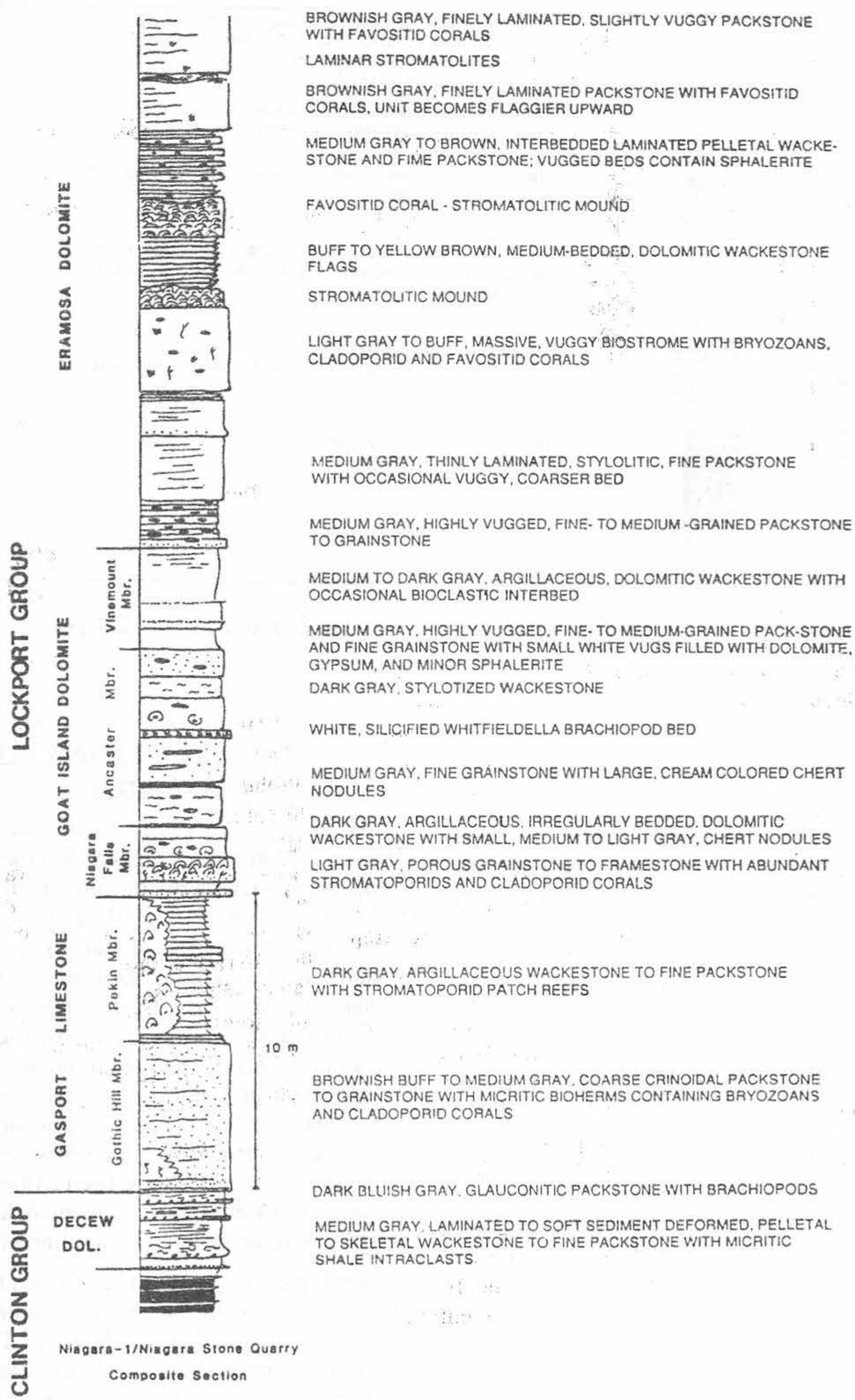


Figure 4.--Composite stratigraphic section based on exposures at the Niagara Stone Quarry in the Town of Niagara (Stop 2) and on the U.S. Geological Survey Niagara (NI-1) core (Stop 3).

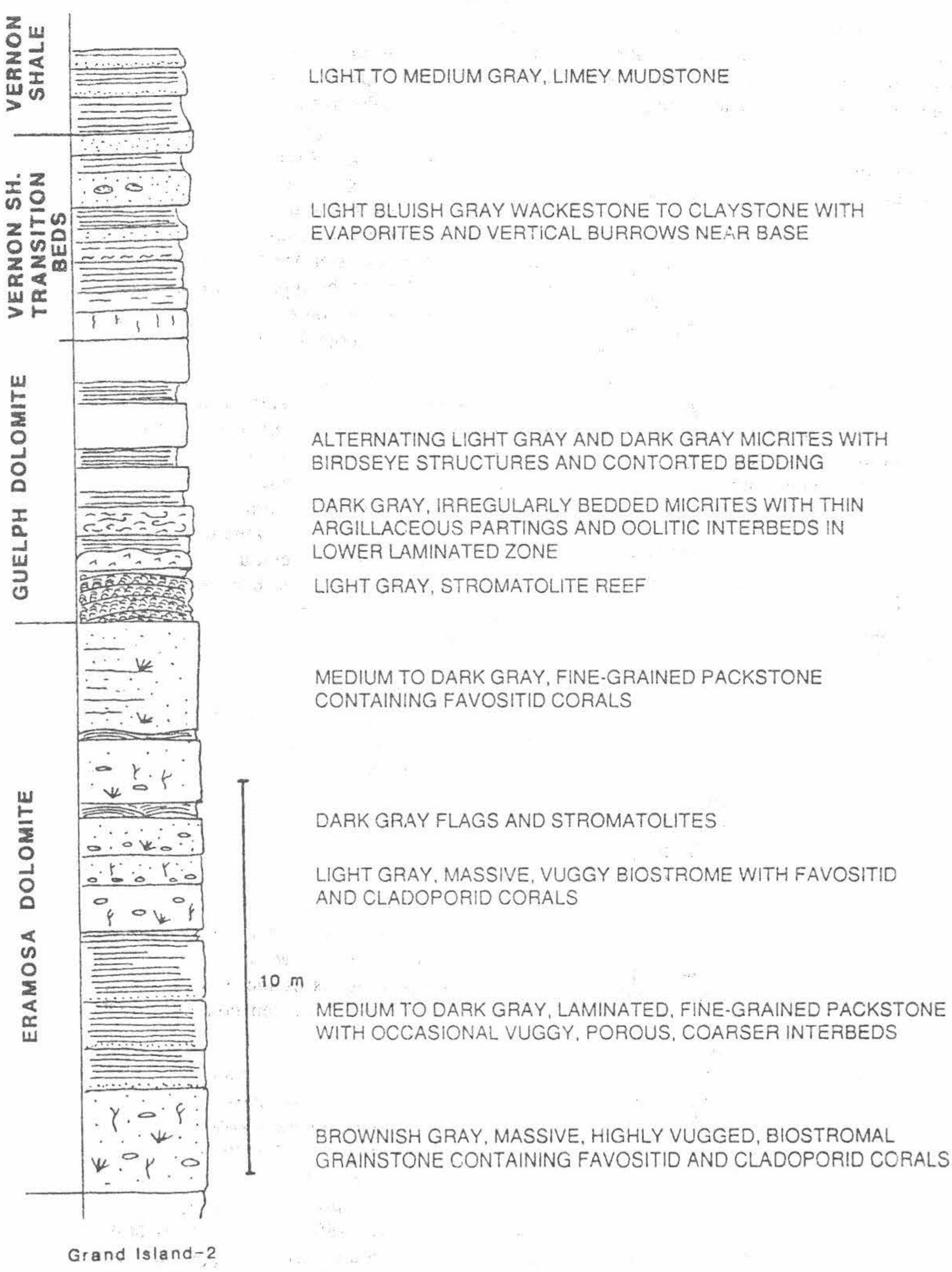


Figure 5.--Stratigraphic section from the U.S. Geological Survey Grand Island (GI-2) core (location shown on Fig. 1).

coarse crinoidal packstone to grainstone containing micritic, bryozoan-rich patch reefs. The Pekin Member is a dark olive gray, argillaceous wackestone to fine-grained packstone that commonly contains stromatoporoid, favositid, and cladoporid coral patch reefs.

The basal contact of the Gothic Hill Grainstone Member with the underlying DeCew Dolomite of the upper part of the Clinton Group is a sharp erosional unconformity in the Niagara region. The upper contact of the Gothic Hill Grainstone Member with the overlying Pekin Member is sharp but conformable over 0.3 to 0.6 m of condensed biostromal to biohermal beds. The upper contact of the Pekin Member with the overlying Niagara Falls Member of the Goat Island Dolomite ranges from gradational to sharp, depending upon local variations in the grain size of the basal beds of the Niagara Falls Member of the Goat Island Dolomite.

In the USGS cores, the thickness of the Gasport Limestone ranges from 5.9 to 11.3 m and averages 10.3 m. Both its members are highly variable in thickness in the Niagara region; the Gothic Hill Grainstone Member ranges from 0.9 to 6.4 m thick, whereas the Pekin Member ranges from near pinchout to as much as 8.2 m thick.

Goat Island Dolomite. The type section for the Goat Island Dolomite is on the north side of Goat Island, at the brink of Niagara Falls (Howell and Sanford 1947). The Goat Island Dolomite as redefined by Brett and others (written commun. 1990) has been divided into three members: the Niagara Falls Member; the Ancaster Member; and the Vinemount Member (Fig. 2).

The Niagara Falls Member is the basal member of the Goat Island Dolomite. In the Niagara region, it is similar to the Gothic Hill Grainstone Member of the Gasport Limestone in that it locally consists of very coarse, pinkish gray, crinoidal grainstones with bioherms containing stromatoporoids, and favositid and cladoporid corals. The coarse grainstones typically flank the small patch reefs and commonly grade laterally into finer grained, medium-bedded wackestones or into fine packstones over broad areas where reefs are absent. In these extensive non-reef areas, the contact between the Niagara Falls Member and the underlying Pekin Member is obscure. The thickness of this unit is variable, ranging from less than 0.9 m at the north end of Niagara Gorge to over 4.6 m at the Frontier Stone Quarry in Lockport.

The Niagara Falls Member is sharply but conformably overlain by the Ancaster Member, which consists of medium gray, medium-bedded, cherty wackestones to fine packstones. Chert nodules are commonly cream colored but may be dark gray and contain well-preserved rugose corals, brachiopods, gastropods, and, rarely, trilobites. The Ancaster Member, like the Niagara Falls Member below it, is variable in thickness and the two units appear to have a compensatory thickening/thinning relation. Thickness of the Ancaster Member ranges from a maximum of 7.6 m at the type locality to a minimum of 0.6 m at the south end of the Niagara Gorge and averages about 3.7 m.

The Ancaster Member is overlain by the Vinemount Member of the Goat Island Dolomite. The contact between the two members is relatively sharp but conformable. "Vinemount" is a Canadian term that will, in accordance with revisions in Brett and others (written commun. 1990), be used in New York consistent with Canadian usage. In the Niagara region, the Vinemount Member is a medium gray, thin- to medium-bedded, dolomitic, argillaceous wackestone to fine packstone with numerous thin, calcareous shale partings. The Vinemount Member is sparsely fossiliferous; the most common fossils are diminutive rugose corals and brachiopods. Beds are commonly bioturbated and take on a "vermicular" appearance. The thickness of the Vinemount Member in the Niagara region is relatively uniform, ranging from 3.0 to 6.1 m.

The contact between the Vinemount Member of the Goat Island Dolomite and the overlying Eramosa Dolomite is placed at the sharp contact between the thin-bedded, argillaceous carbonates and shales of the Vinemount Member and the massive dolomitic packstones of the now-abandoned (C. E. Brett and others, written commun. 1990) Oak Orchard Dolomite.

Eramosa Dolomite. Use of the name "Eramosa" has become confused in the past century. As revised by Brett and others (written commun. 1990), to be consistent with Canadian usage, the Eramosa Dolomite immediately overlies beds in western New York previously designated as Eramosa by Zenger (1965), which are regarded herein as the Vinemount Member (upper member) of the Goat Island Dolomite. As redefined by Brett and others (written commun. 1990), the Eramosa Dolomite is a tripartite massive-flaggy-massive unit that contains several distinctive marker beds.

The lower and upper members are characterized by massive-bedded to biostromal, fine grainstones containing variably abundant favositid and cladoporid corals. The basal bed of the Eramosa Dolomite is a distinctive, highly vugged 0.9- to 1.5-m-thick unit that is traceable over broad areas of western New York. The upper fine grainstone contains a medial stromatolite marker bed that is widely traceable although it is typically only 0.3 m or less thick. The middle member of the Eramosa Dolomite is flaggy and contains large, loaf-shaped stromatolitic, thrombolitic, and favositid coral mounds. The Eramosa Dolomite ranges from approximately 13.7 to 16.8 m in thickness. The contact between the Eramosa Dolomite and the overlying Guelph Dolomite is placed at the sharp boundary between the upper grainstone unit and an overlying distinctive, regionally widespread stromatolite reef horizon.

Guelph Dolomite. The name "Guelph Dolomite" has been extended into the Niagara region by Brett and others (written commun. 1990) and constitutes what has previously been termed the upper part of the Oak Orchard Dolomite. Outcrops of these strata are scarce. However, the USGS Grand Island (GI-2) core includes the entire Guelph Dolomite (Fig. 5). The basal Guelph consists of a lower 1.2- to 1.5-m-thick stromatolitic to thrombolitic reefy zone. The algal structures are overlain by argillaceous micrite with distinctive contorted bedding and oolitic layers. This enterolithic unit passes upward into thin- to medium-bedded peritidal micrites that contain vertical burrows and evaporites. The upper 4.6 m of these micrites have been labelled "Vernon transition" beds; they record the gradual change from carbonate to fine- grained clastic depositional environments in the Niagara region.

STRUCTURAL GEOLOGY

by Michael R. Gross

The sediments within the Niagara area strike approximately east-west and dip to the south at about 5.3 m/km (meters per kilometer), in a homoclinal structure. The most prominent structural feature in the Lockport Group is the Clarendon-Linden Fault (Fig. 6A), which has been interpreted as a series of north-south-trending, basement-related normal faults that intersect the Lockport Group outcrop belt in the vicinity of Clarendon (Fakundiny and others 1978). The two main systematic fracture sets within the Lockport Group are an east-northeast calcite vein set and an east-northeast joint set. Rose diagrams of fracture orientations for vertical veins and joints are shown in Figure 6B; these fractures were mapped in 17 quarries and one roadcut along the 250-km-long outcrop belt of the Lockport Group in western New York (Fig. 6A) and southern Ontario. Most of the fractures in these quarries are vertical.

The veins and joints may be distinguished as distinctly separate systematic fracture sets on the basis of their geographic distribution, orientation, and the depth and mechanism of their propagation. In terms of geographic distribution, the veins are absent between the Clarendon-Linden Fault and the Niagara Stone Quarry, whereas the joints are most common in those areas where the Niagara Escarpment is a prominent topographic feature. The veins display a significant clockwise rotation in orientation from east to west, whereas the joints and topographic reentrants are consistently oriented across the outcrop belt. The veins also differ from the joints in their depth and mechanism of propagation; the veins appear to have propagated under considerable overburden, possibly as a result of high fluid pressures driven by a topographic high to the east, whereas the joints appear to have propagated later and closer to the surface, possibly during uplift and erosion.

Asymmetric Reentrants in the Niagara Escarpment: A Case for Neotectonic Joints

The northeastern United States is currently in a state of compression, with the maximum horizontal stress oriented approximately 060° (Sbar and Sykes 1973; Zoback and Zoback 1980). An east-northeast regional fracture set is present in many localities throughout the Northeast that correlates with this orientation (Engelder 1982). According to Hancock and Engelder (1989), these neotectonic joint systems are the most recent to form within a region subject to uplift and erosion, and they generally form within the upper 0.5 km (kilometer) of the crust in response to an effective tensile stress developed during unloading. These late-formed or neotectonic joints in some terrains are likely to reflect the orientation of the neotectonic or contemporary tectonic stress field.

The general trend of the Niagara Escarpment is east-west, although it actually consists of a series of angular reentrants that form a zig-zag pattern (Fig. 7). The distinct linear aspect of the Niagara Escarp-

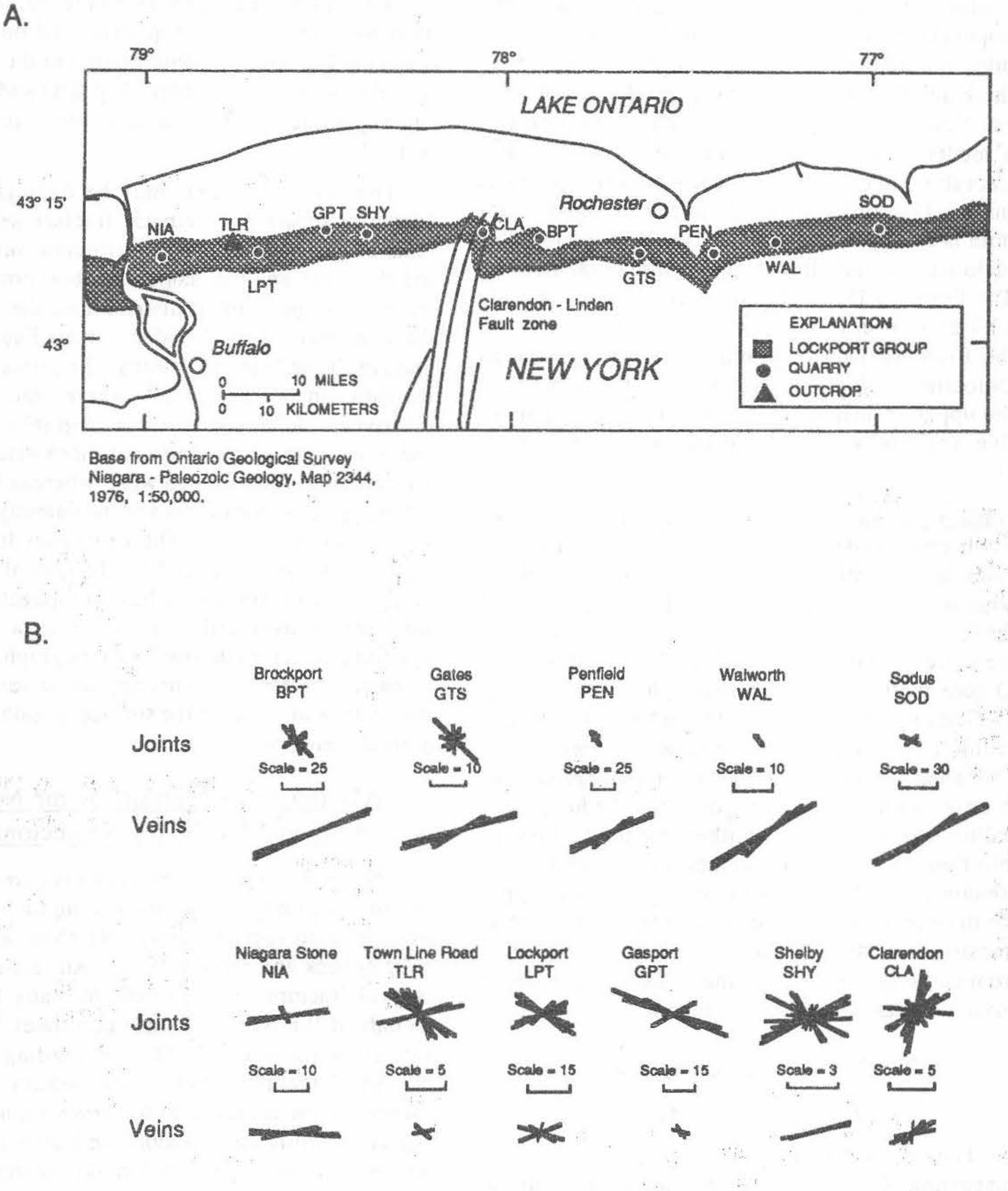
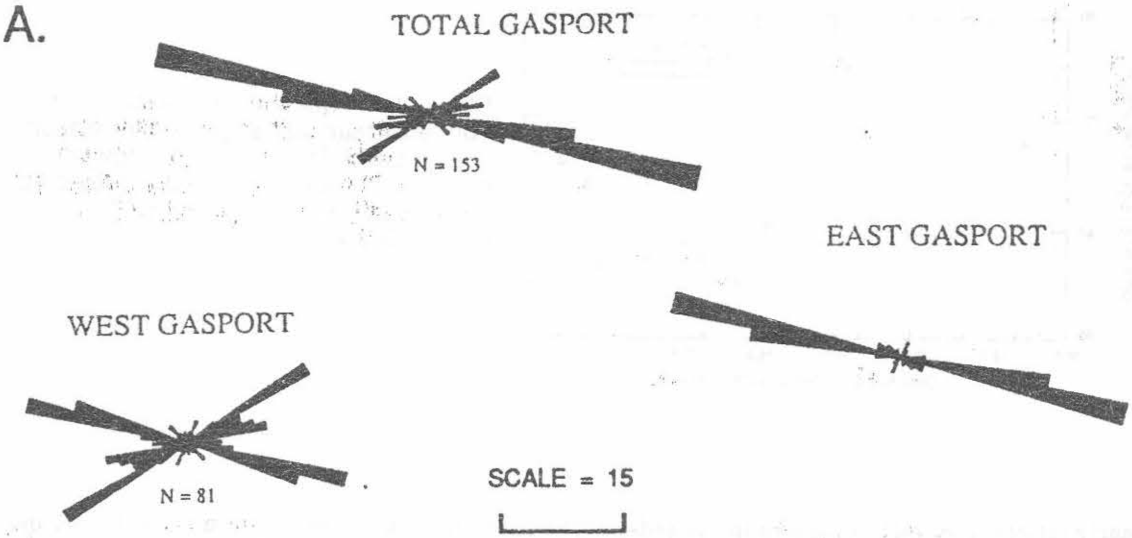


Figure 6. -- A. Locations of quarries and outcrops referenced in 6B. (Modified from Gross 1989). B. Rose diagrams of fracture data from 11 sites between Sodus and Niagara Falls, New York. The data are divided into two categories: joints and veins. Rose diagrams are in 5° intervals, and the scales differ from site to site. (Modified from Gross 1989).

A.



B.

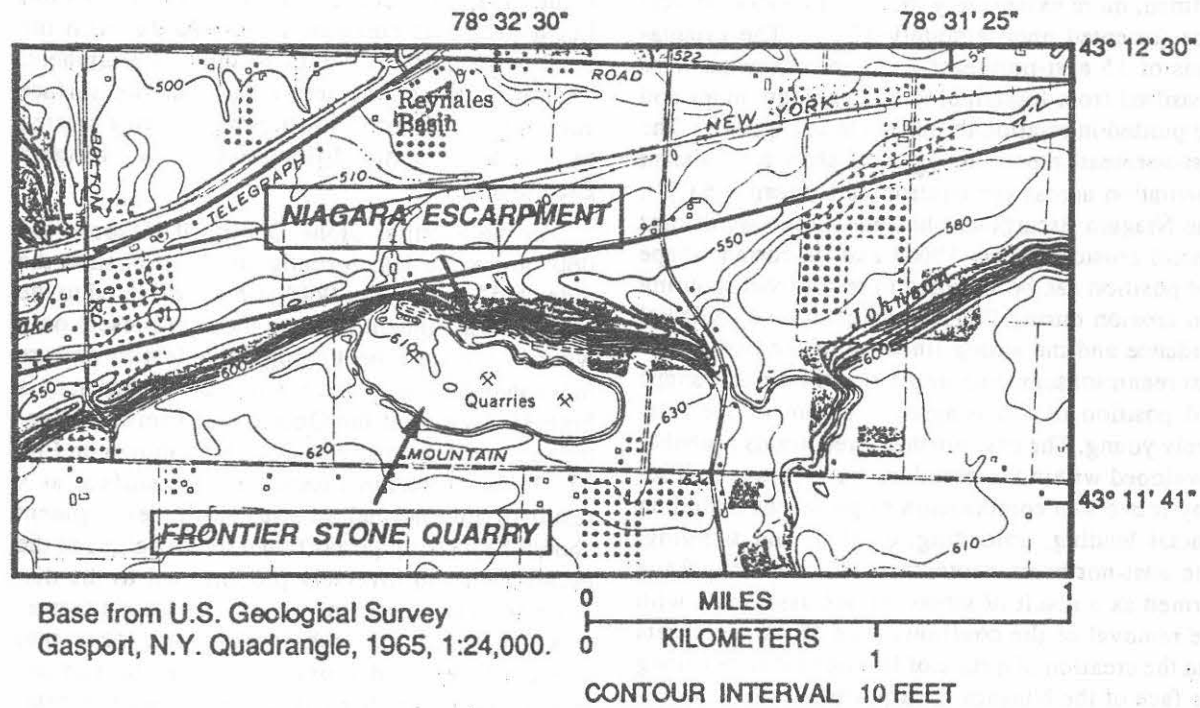


Figure 7. -- A. Rose diagrams of fractures from the eastern and western sectors of the Frontier Stone Quarry in Gasport (stop 1). (Modified from Gross 1989). B. The quarry is located at a major change in joint orientation along the Niagara Escarpment.

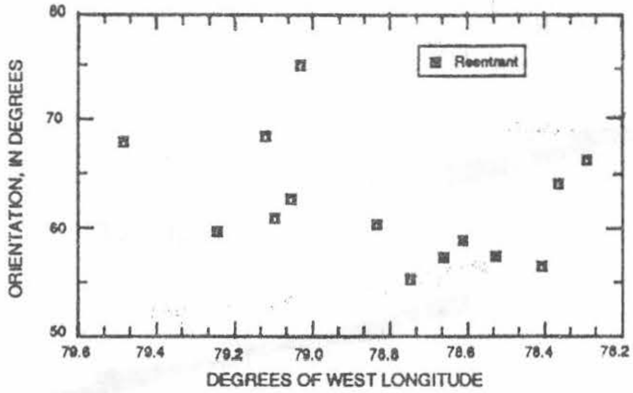


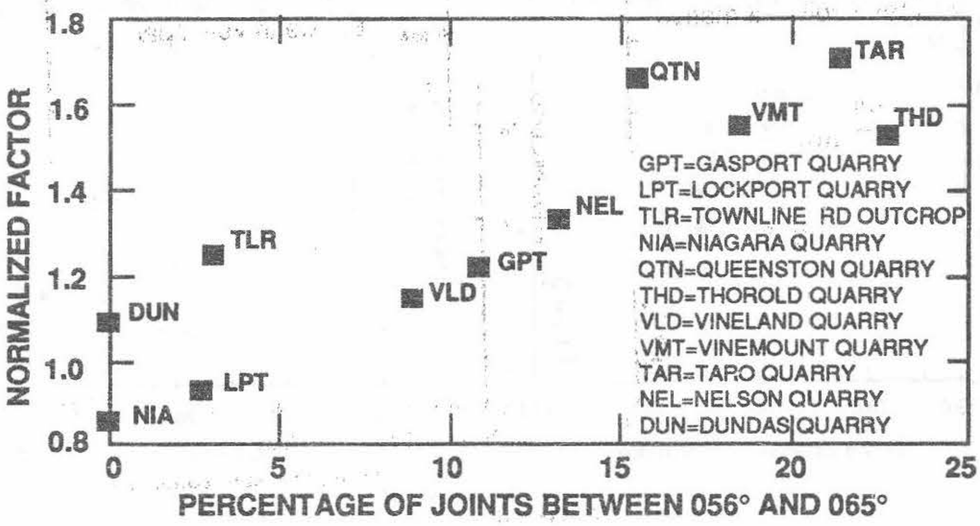
Figure 8. - - Orientation of east-northeast reentrant segments in relation to longitude. The reentrants show a consistent orientation across the outcrop belt (mean = 61.7°). (Modified from Gross 1989).

ment clearly reflects the fracture pattern in the bedrock. The reentrants are asymmetric and typically consist of a strongly linear east-northeast face (oriented approximately 060°), which is parallel to the contemporary tectonic stress field, and a less well-defined, more extensively dissected west-northwest face (oriented approximately 105°). The orientations of 15 east-northeast reentrant segments were measured from topographic and geologic maps and are plotted in relation to longitude in Figure 8. The east-northeast reentrant segments show a consistent orientation across the outcrop belt (mean = 61.7°). The Niagara Escarpment has undergone significant glacial erosion (Straw 1968) and its current shape and position can be assumed to result from scouring and erosion during Pleistocene glaciation. Glacial evidence and the strong linearity of the east-northeast reentrant segments imply that the current shape and position of the Niagara Escarpment are relatively young. The east-northeast reentrants probably developed within the past 3 million years and, if so, may relate to a combination of processes including glacial loading, unloading, erosion, and scouring. The east-northeast neotectonic features may have formed as a result of stress release associated with the removal of the confining load of the ice sheets and the creation of a state of low normal stress along the face of the Niagara Escarpment.

The Frontier Stone Quarry in Gasport (Stop 1) is located at a major change in joint orientation along the escarpment and thus permits study of the effect of topography on fracturing; that is, the relation between escarpment orientation and bedrock fractures. The escarpment is oriented approximately 105° adjacent to the eastern sector of the quarry and about 060° adjacent to the western sector (Fig. 7). The quarry is approximately 1.5 km across. The rose diagram of the eastern sector shows the dominant fracture set at 105°, parallel to the adjacent escarpment wall. The 105° joint set is present in the western sector along with a joint set oriented 060°, which is parallel to the adjacent 060° segment. The 060° set is absent in the eastern sector. Local joint sets correlate in orientation with the local orientation of the Niagara Escarpment. Therefore, these fractures form near the surface and may be related to low normal stresses created by the topographic differential of the Niagara Escarpment.

In the Frontier Stone Quarry at Gasport, the 060° joints are late forming and abut against the older 105° joints. The 060° joints are related to the Niagara Escarpment because they are present only where it is a prominent topographic feature and are most abundant in quarries where the escarpment is highest, such as at the Queenston, Thorold, Vinemount, and Taro quarries (locations shown on Fig. 9). If these fractures form near the surface as a result of low normal stresses, their development should be directly proportional to the height of the escarpment and inversely proportional to the distance from the escarpment. A "normalized factor" was developed for each locality that takes into account height and proximity to the escarpment, and this factor has been plotted in Figure 9 in relation to the percentage of joints within a 10-degree interval of the neotectonic orientation of 060°. Although it is difficult to prove quantitatively that these fractures are neotectonic, qualitatively they are consistently late forming and appear to correlate with the prominence of the Niagara Escarpment. The distinction, if any, between joints and the east-northeast reentrant segments is not clear because both are linear features related to the

A.



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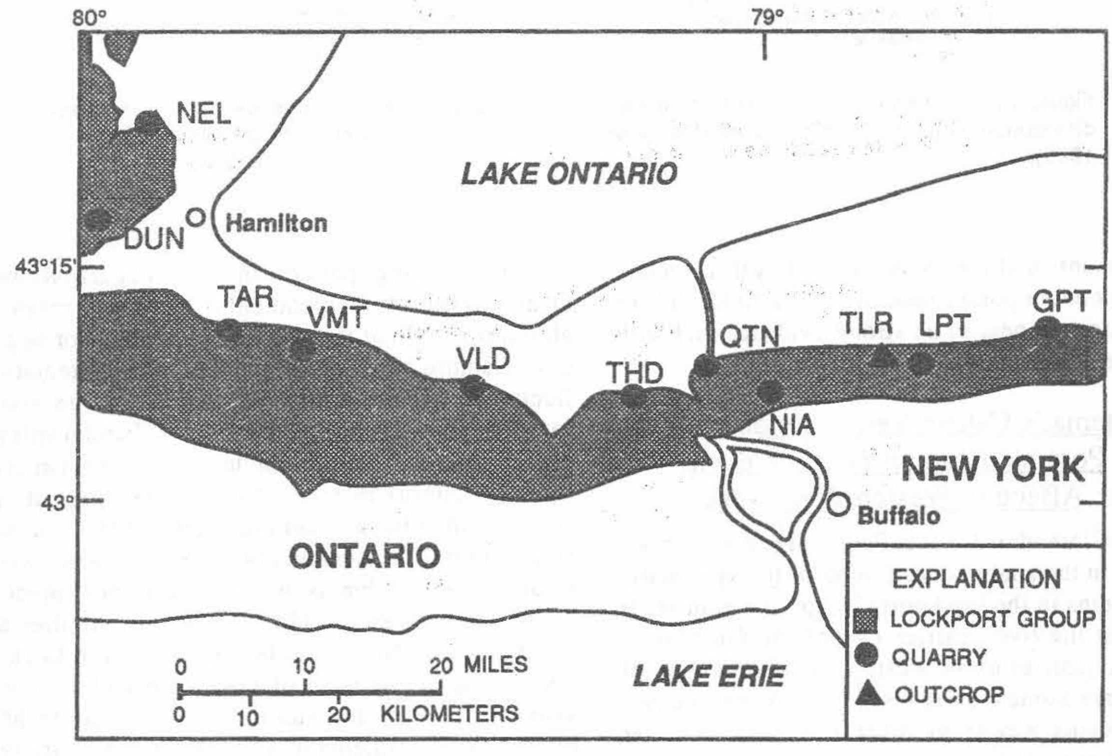


Base from Ontario Geological Survey
Niagara - Paleozoic Geology,
Map 2344, 1976, 1:50,000

Figure 9.-- A. Normalized factor for selected quarries and outcrops in relation to the percentage of joints in the 10° interval surrounding the neotectonic orientation of 060°. (Modified from Gross 1989). B. Locations of quarries and outcrops referenced in 8A. (Modified from Gross 1989).

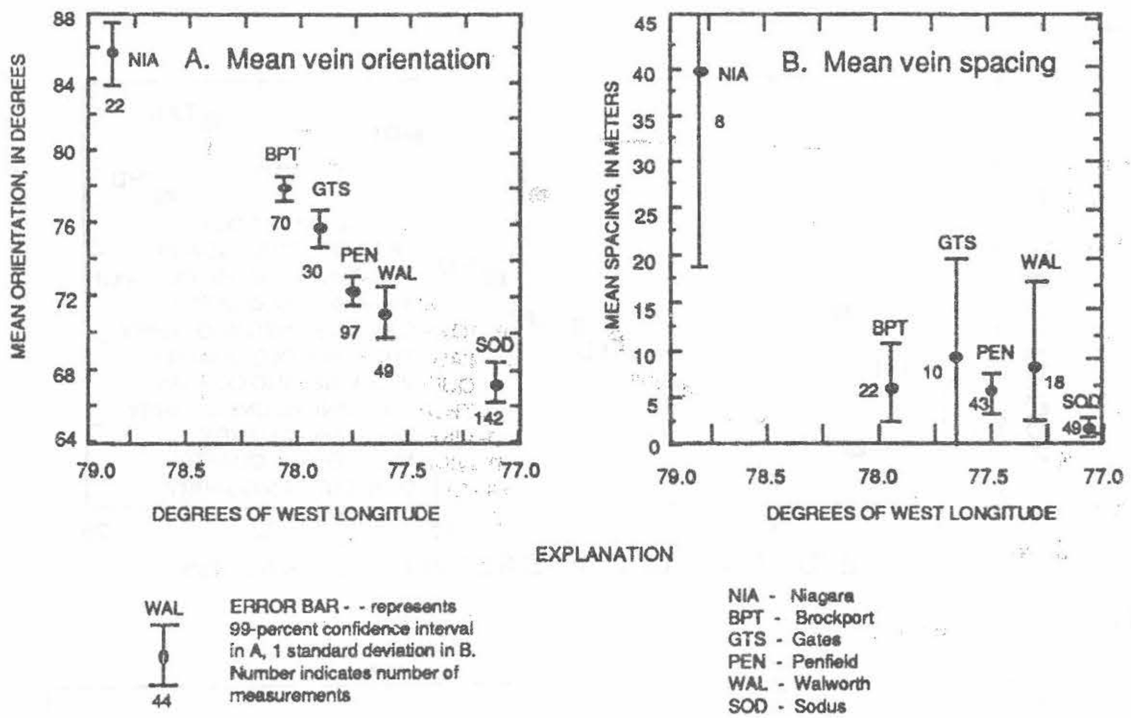


Figure 10. - - Mean vein orientation and mean vein spacing in relation to longitude. The von Mises distribution (Cheeney 1983) was used to determine mean vein orientation. (Modified from Gross 1989).

development of the escarpment and both correlate with the contemporary tectonic stress field. These observations appear to be strong evidence that both are neotectonic.

Systematic Calcite Veins: Evidence for a Possible Acadian Tectonic Event Affecting Western New York

The Clarendon-Linden Fault (Fig. 6A) plays a key role in the spatial distribution of the systematic calcite veins in the Lockport Group: the vein set is present in the five quarries east of the fault but is absent in quarries to the west, with the exception of the Niagara Stone Quarry (Fig. 6B). A few nonsystematic veins appear in other quarries. Another characteristic of the systematic vein set is that the mean vein orientation rotates clockwise from 067° in the east to 086° in the west (Fig. 10A). The veins are extremely consistent in orientation at each outcrop, as indicated by a 99% confidence interval of less than 2°. The veins do not appear to propagate into the DeCew Dolomite (immediately below the base of the Lockport Group), and vein spacing generally increases from east to west (Fig. 10B).

The blasting pattern in the Niagara Stone Quarry results in perpendicular faces and creates an impression that the bedrock consists of orthogonal fracture sets; however, only one systematic fracture set is present--the east-west calcite vein set. The veins are oriented 086° ± 1.7° and display a mean spacing of approximately 37 m. Vein apertures are approximately 2.23 cm. Although it is rare to find suitable fluid inclusions in the calcite vein material, homogenization temperatures were measured in five inclusions. The mean homogenization temperature of 115° C (Celsius) implies a minimum of 3 km of overburden above the Lockport Group at the time of vein propagation. The veins in the Niagara Stone Quarry appear to be related to the systematic vein set in the quarries east of the Clarendon-Linden Fault. Their orientation is east-northeast (consistent with the clockwise rotation) and they are remarkably consistent in orientation within the quarry. The veins are planar, vertically and horizontally extensive, and consist of the same fill material.

A model of the geologic conditions that would result in the propagation of the systematic vein set

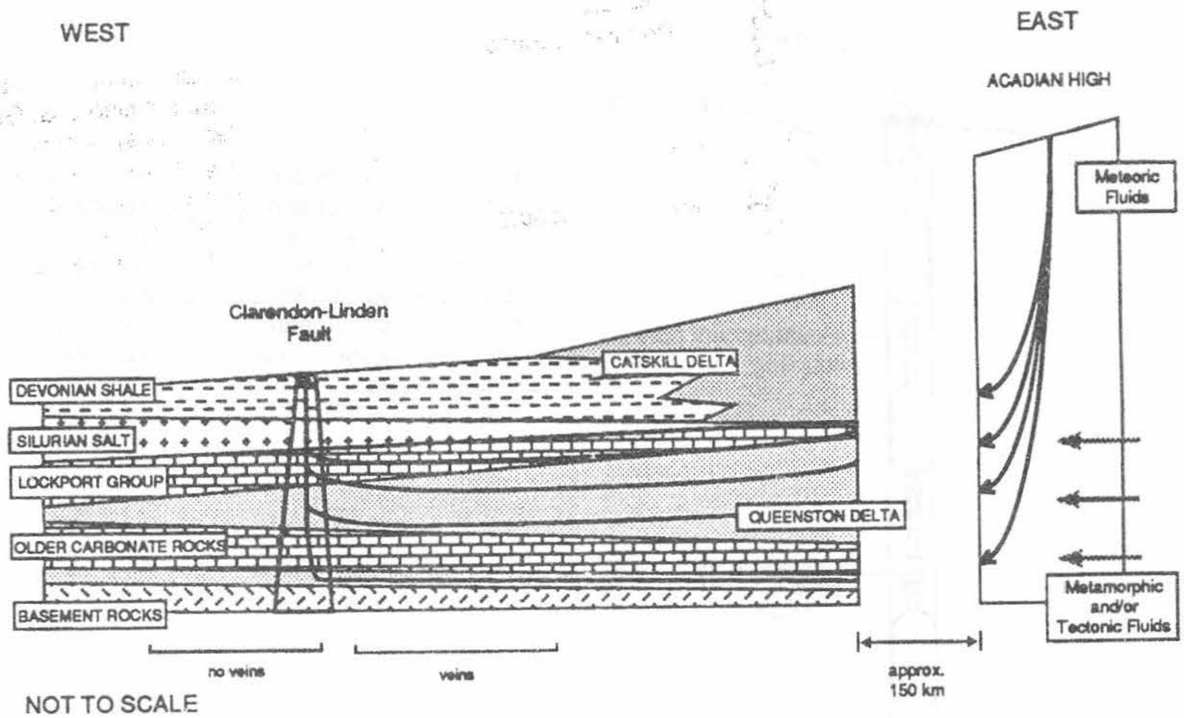


Figure 11. -- Conceptual pattern of fluid circulation during the late Paleozoic that may have resulted in propagation of the systematic veins. (Modified from Gross 1989).

in the Lockport Group must take into account the following observations: (1) the presence of veins east of the Clarendon-Linden Fault and their absence west of it; (2) the clockwise swing in vein orientation from east to west; (3) homogenization temperatures of vein fill which imply a circulation of fluids in excess of 115° C at the time of fracture propagation; and (4) a general increase in vein spacing from east to west. All of the above individual pieces of evidence point toward a highland to the east that provided the topographic head required to circulate fluid westward and to propagate veins in the Lockport Group.

Stress trajectories at the time of crack propagation can be inferred from the strike of a regional joint or vein set. S_H (maximum horizontal stress) trendlines for cross-fold joints in forelands may converge toward a major depocenter that emerges from the core of a fold-thrust belt. The eastward convergence of S_H trendlines drawn parallel to the strike of the veins is incompatible with S_H inferred from Alleghenian structures of the Appalachian Plateau and with other post-Paleozoic structures. However, east-west trendlines are compatible with tectonic features dated as Acadian.

A possible scenario of fluid circulation during the Acadian Orogeny is shown in Figure 11. As a result of the topographic high created during the Acadian Orogeny, fluid flow was downward into the Lockport Group from the east, and the fluids were then trapped beneath the overlying impermeable Salina Group salt units, which pinch out near Syracuse. The salt prevents fluids from circulating upward; therefore, high fluid pressures built up in the Lockport Group that resulted in vein propagation. As the fluids continued to circulate westward, they intersected the Clarendon-Linden Fault zone and were drained to the surface, which lowered fluid pressures immediately to the west of the fault. At Clarendon, the systematic veins disappear and remain absent until their reappearance at Niagara Falls. Vein spacing generally increases westward; the closest spacing is in Sodus and the widest is in Niagara Falls. This westward increase in vein spacing may reflect a westward decrease in fluid pressure.

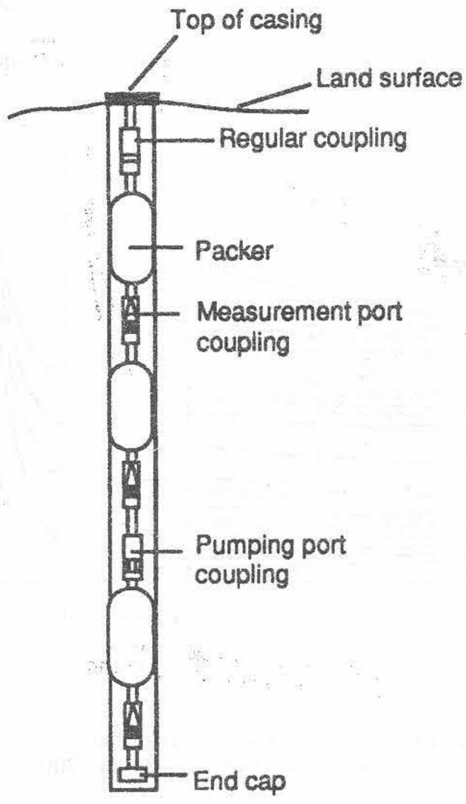


Figure 12. -- Multipiezometer system that was used to instrument the nine U.S. Geological Survey test holes. The system consists of down-hole casing, packers, regular couplings, and specialized couplings designed to function as measurement ports or pumping ports. The packers are arranged to isolate zones of interest.

The dominant fracture peak at the Clarendon Quarry (Fig. 6B) is oriented north-south, which corresponds to the north-south-trending Clarendon-Linden Fault zone. The overlying sedimentary cover may have been draped over the upthrown basement blocks, resulting in extension and the observed fracture distribution. Such pervasive fracturing would have provided a high permeability conduit through which fluids from the east could have drained.

HYDROGEOLOGY

by Dorothy H. Tepper, Richard M. Yager, and William M. Kappel

Although the Lockport Group is the principal aquifer in the Niagara area, it is not heavily pumped because the Niagara River provides the major public-water supply. Well yields in areas not affected by induced infiltration from the Niagara River typically range from 0.0006 m^3/s (cubic meters per second) to 0.0062 m^3/s but yields as high as 0.0601 m^3/s have been recorded. Some industrial wells near the Niagara River produce more than 0.1263 m^3/s as a result of induced infiltration from the river (Johnston 1964). Ground water in the Niagara Falls region generally flows southwestward from recharge areas near the escarpment toward the Niagara River, the primary discharge zone. However, the direction of flow has been altered by manmade structures such as the Falls Street Sewage Tunnel and the buried conduits system that transports water from the Niagara River to the reservoir at the Robert Moses Power Plant. A detailed study of the effects of the power plant on ground-water flow in the upper part of the Lockport Group is presented in Miller and Kappel (1987).

As part of the cooperative USGS/USEPA study of the hydrogeology of the Niagara Falls area, nine test holes (Fig. 1) were drilled to provide information on stratigraphy, fracture distribution, hydraulic head and other hydraulic characteristics, and ground-water geochemistry. Four of the holes were drilled to the Queenston Shale (top of the Ordovician System) and five were drilled to the Neagha Shale (Clinton Group of the Silurian System). A triple-tube wireline-coring technique was used to obtain continuous core from each test hole.

Multipiezometer Casing and Pressure Profiles

A multipiezometer system designed by Westbay Instruments Ltd.[3/] was used to instrument each of the nine test holes. This system, which will be discussed in detail at Stop 3, consists of downhole casing, packers, regular couplings, and specialized couplings designed to function as measurement ports or as pumping ports (Fig. 12). The packers on the casing string are used to isolate zones of interest. Each isolated zone contains a measurement port and may contain a pumping port. Specialized downhole tools are lowered into the central access pipe to activate these ports. Hydraulic head measurements and samples for water-quality analyses can be obtained through the measurement ports. The pumping ports are used to perform hydraulic tests.

At each site, an initial set of pressure measurements was taken soon after the packers were inflated to check for packer-seal integrity and to determine the initial pressure conditions in each isolated zone. Pressure distribution with depth was then measured bimonthly until equilibrium conditions were reached.

Profiles of dynamic pressure in relation to depth at the USGS Wheatfield (WF-1) test hole (Fig. 1) are shown in Figure 13A. "Zero" dynamic pressure represents hydrostatic pressure with depth. Any zone that plots to the left of the zero line is underpressured with respect to hydrostatic conditions, and any zone that plots to the right of the zero line is overpressured. As can be seen from the plot for November 1987, most zones below an altitude of 130 m were initially overpressured; this is attributed to the low permeability of the rock and to "packer squeeze" effects, which created temporarily high initial pressure readings. Recent downhole pressure conditions, which were stable from October 1988 to October 1989, are indicated on the October 1989 plot.

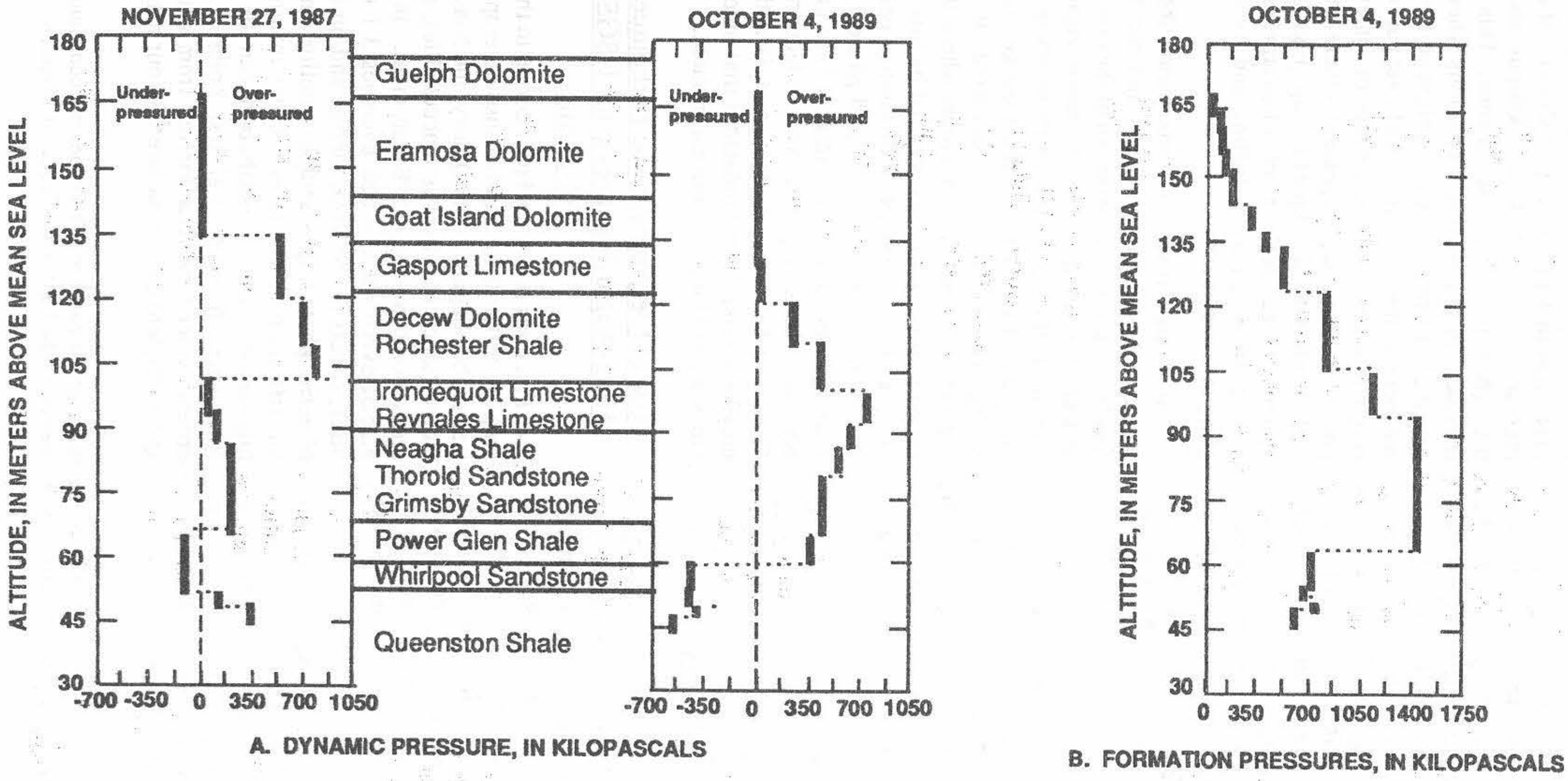
The relation between pressure and depth shown for the USGS Wheatfield (WF-1) test hole in Figure 13 is typical for the Niagara region. It shows an overpressured zone extending from the Rochester Shale down into the Power Glen Shale. An underpressured zone occurs below this, near the contact between the Queenston Shale and the Whirlpool Sandstone. The formation pressure profile in Figure 13B presents the same data as pore pressures in relation to depth. This plot shows that a constant pressure of about 1,520 kilopascals extends throughout the overpressured zone. This condition is typical in gas-bearing formations where the gas density is so small that the weight of the gas does not increase the pressure in the lower part of the reservoir. In contrast, the density of water is much greater, so that pressure generally increases linearly with depth in the Lockport Group (Fig. 13B). The presence of gas in the zones of overpressuring has been confirmed during drilling and by later sampling in these intervals.

An underpressured zone near the contact between the Queenston Shale and the Whirlpool Sandstone is observed in seven of the nine test holes instrumented with multipiezometer casing in the Niagara Falls area. Four of these seven test holes are within 3 km of the Niagara Gorge. Underpressuring is commonly encountered in partially depleted gas-bearing formations where the resaturation of pore spaces is restricted by low formation permeability and reduction of relative permeability due to the presence of two fluid phases. The gas-bearing formations in the Niagara Falls area probably have been depleted by production in both Canada and the United States and, in addition, gas may be leaking from formations that outcrop along the Niagara Gorge and the escarpment.

Use of Electromagnetic Techniques to Map High-Angle Fractures at the USGS Niagara (NI-1) Site

Fractures in the Lockport Group in the Niagara area are difficult to map because outcrops are limited to the Niagara Stone Quarry, the Niagara River Gorge (much of which is inaccessible), and a few areas along the Niagara Escarpment. In addition, glacial overburden, which averages 3.1 to 18.3 m thick, covers the bedrock surface and limits the use of aerial photographs and(or) satellite imagery for identification of fractures. Little information on high-angle fracture distribution can be obtained from cores from vertical test holes. However, ground-water flow data derived from aquifer tests and well-yield data, structure-contour maps of var-

3/ Use of brand and(or) firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey, the University of Rochester, or the Pennsylvania State University.



EXPLANATION

- DYNAMIC PRESSURE - -Vertical lines represent packed-off intervals. Dotted lines connect adjacent zones.
- LINE OF ZERO DYNAMIC PRESSURE (hydrostatic conditions).

EXPLANATION

- FORMATION PRESSURE - -Vertical lines represent packed-off intervals. Dotted lines connect adjacent zones.

Figure 13. - - Profiles of dynamic pressure and formation pressure in relation to depth at the U. S. Geological Survey Wheatfield (WF-1) test hole. (Location shown in Fig. 1).

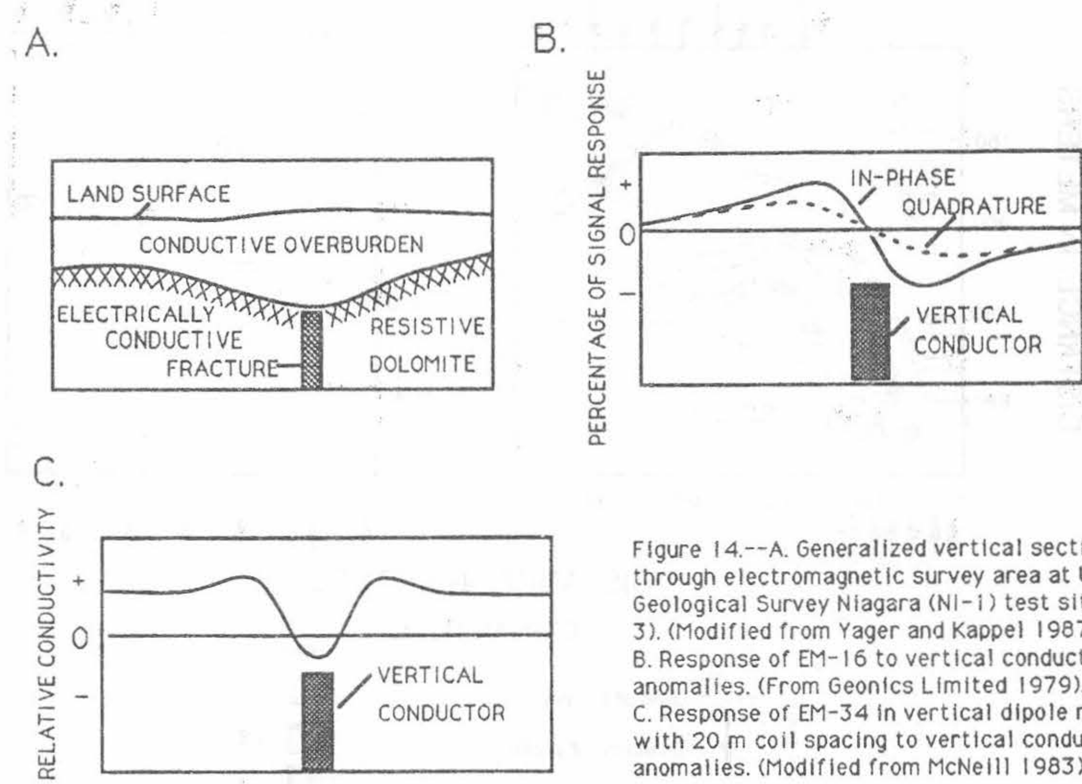


Figure 14.--A. Generalized vertical section through electromagnetic survey area at U.S. Geological Survey Niagara (NI-1) test site (stop 3). (Modified from Yager and Kappel 1987). B. Response of EM-16 to vertical conductive anomalies. (From Geonics Limited 1979). C. Response of EM-34 in vertical dipole mode with 20 m coil spacing to vertical conductive anomalies. (Modified from McNeill 1983).

ious stratigraphic horizons, and electromagnetic techniques can be used to delineate fracture trends and zones of intense fracturing.

The USGS Niagara (NI-1) site (Fig. 1) is unusual among the nine USGS test hole sites because the horizontal water-bearing zones appear to be well connected by high-angle fractures. As a result of these connections and a strong downward hydraulic gradient, freshwater (total dissolved solids < 3,000 mg/L (milligrams per liter)) is found deeper (34 m) at this site than at the others studied. Evidence for high-angle fractures in the Lockport Group at this site was first obtained through electromagnetic surveys using VLF (EM-16) and terrain conductivity (EM-34) equipment manufactured by Geonics Ltd. Reconnaissance surveys were performed rapidly with the EM-16, and areas of interest were then mapped in greater detail with the EM-34, which provides finer resolution. A detailed discussion of these techniques and the results of these surveys are presented in Yager and Kappel (1987).

Mapping electrically conductive high-angle fractures in the resistive dolomite (Fig. 14A) with these instruments is similar to mapping buried ore deposits or pipelines. The instruments will record a distinctive response (or anomaly) when crossing over a buried conductor (Fig. 14B,C). The extent and orientation of the vertical fractures can be mapped if measurements are taken along several parallel profiles.

Johnston (1964) hypothesized that a band of high transmissivity extends across the Lockport Group and is probably caused by an abundance of vertical joints or enlargement of the horizontal bedding planes. Additional evidence for the presence of this high-transmissivity zone is presented in Yager and Kappel (1987). The NI-1 site was chosen for study with electromagnetic techniques because it lies along this trend. The frequency of conductive anomalies was much higher at the NI-1 site than at another site 4.8 km east of this trend (Fig. 15).

Cross-Hole Hydraulic Testing Program

Cross-hole hydraulic tests were conducted at the NI-1 site to confirm the fracture trends identi-

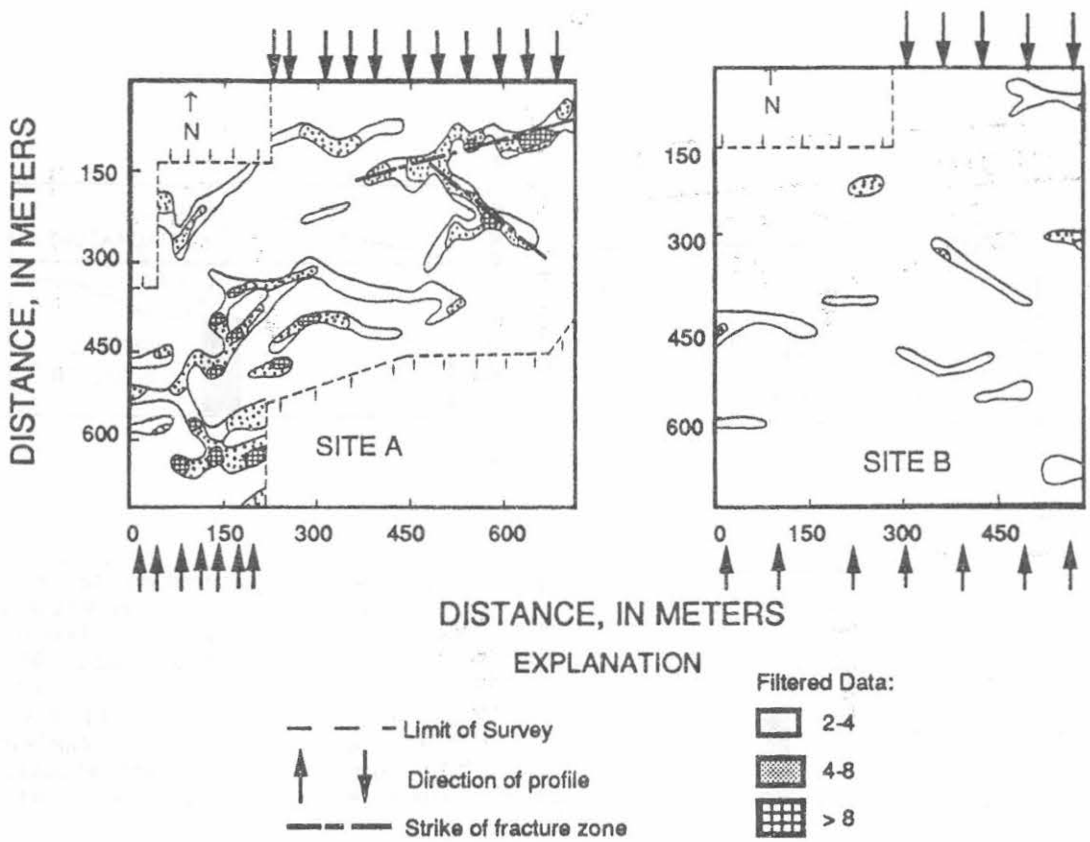


Figure 15.--Electromagnetic anomalies interpreted as generalized fracture zones at site A (NI-1 site) (Stop 3, Fig. 1) and at site B, 4.8 km east of site A. Interpreted from in-phase data measured by EM-16, filtered by method of Fraser (1969). (Modified from Yager and Kappel 1987).

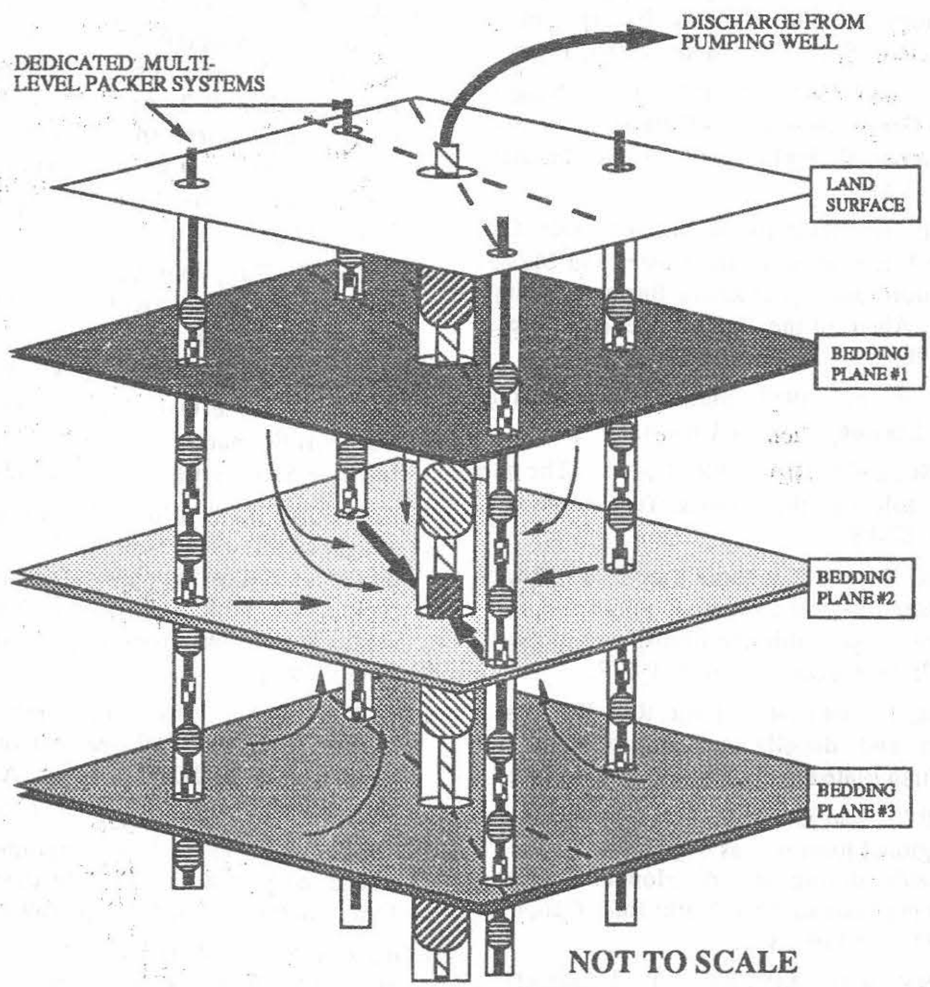
fied with the electromagnetic equipment and to measure the vertical conductance between the horizontal fracture zones (Fig. 16A). Four additional test holes were sited to complete a 5-spot pattern (Fig. 16B) along or away from fractures mapped by the electromagnetic techniques. These test holes were cored and multipiezometer casing was then installed. Core obtained from the center hole contained a high-angle fracture, and information provided by an acoustic televiewer log revealed the strike of this fracture to correspond with a trend identified from the electromagnetic surveys. After coring was completed, the center hole was reamed to a 15.2-cm diameter and was left open to serve as a pumped hole. Drawdowns induced by pumping were measured in the pumped fracture zone and in two or three adjacent zones that were hydraulically isolated from each other by a removable packer string. "Mini-packer" strings allowed simultaneous measurement of four fracture zones in each test hole. As many as 20 isolated intervals were monitored in each test. Drawdowns were measured with vibrating-wire transducers manufactured by Geokon Inc, and were then recorded by a CR10 data logger built by Campbell Scientific Instruments.

Results of the cross-hole tests confirm the presence of vertical connections between horizontal fracture zones; however, these connections do not appear to extend to the weathered bedrock surface. The distribution of drawdown within some of the horizontal fracture zones is isotropic, as in a homogeneous porous medium. In other zones, the drawdown distributions display a high degree of heterogeneity, indicating pathways of high transmissivity within the fracture plane, perhaps as a result of increased dissolution at the intersections of horizontal and high-angle fractures. The directions of highest transmissivity correspond to orientations of high-angle fractures interpreted from the electromagnetic surveys.

ACKNOWLEDGMENTS

The authors would like to thank the owners of the Frontier Stone Quarry in Gasport and the Niagara Stone Quarry in Niagara for providing access to their respective quarries.

A.



B.

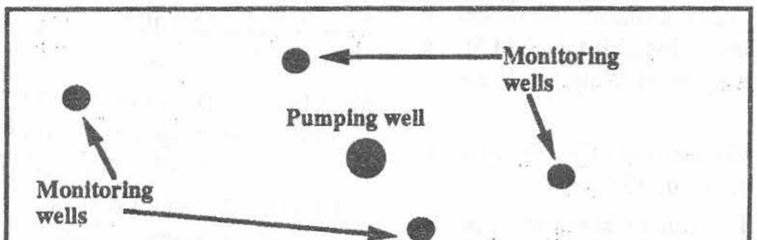


Figure 16. -- A. Isolation of bedding planes for cross-hole hydraulic testing with the multipiezometer system in each of the four monitoring wells. The pumping well is shown in the center. B. Plan view of the U. S. Geological Survey Niagara (NI-1) cross-hole hydraulic test site (Stop 3, Fig. 1).

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ROAD LOG FOR LOCKPORT GROUP FIELD TRIP

CUMULATIVE MILEAGE	MILES FROM LAST POINT	ROUTE DESCRIPTION
		From Fredonia State College, proceed north on I-90 toward Buffalo. Follow I-90 east from Buffalo and get off at Exit 49 for Depew, Rt. 78
0.0		At traffic light at toll booth, turn left (north) onto Rt. 78 and follow into Lockport. Enter City of Lockport at 14.1 miles.
15.3	15.3	At intersection of Rt. 78, Rt. 93, and Rt. 31, turn right (east) onto Rt. 31. At the time this road log was compiled (March 1990), there was construction (including detours) on Route 31 in Lockport. Follow Rt. 31 through Lockport and continue eastward toward Gasport.
18.1	2.8	At junction of Rt. 77, veer left and **continue to follow Rt. 31 east.**
20.7	2.6	Enter Town of Gasport. Stay on Route 31 east, which is called Rochester Street in town.
23.4	2.7	Pass under conveyor belt that crosses Rt. 31 and turn left immediately after the conveyor belt into the Frontier Stone parking lot. Wait in driveway for further instructions. **THIS IS STOP #1.**
		Return to vehicles and follow Rt. 31 west back into Lockport.
29.8	6.4	Enter City of Lockport.
31.6	1.8	At intersection of Rt. 31 and Rt. 78, turn left (south) onto Rt. 78. **THIS IS THE LUNCH STOP.** There are a number of restaurants and fast-food chains on this road. Reconvene at the specified time at the parking lot of the Niagara County Office Building at 59 Park Avenue. To get there, return to the intersection of Rt. 78 and Rt. 31 and turn left (west) onto Route 31. Go 0.1 miles on Route 31, and turn right onto Hawley St. just after passing a small park. Go 1 block on Hawley St. to the stop sign, then turn right onto Park Avenue and immediately turn left into the parking lot of the Niagara County Office Building.
31.7	0.1	Turn left out of the parking lot of the Niagara County Office Building. Turn right at the yield sign onto Route 31 west (around 300 feet from the parking lot).
33.3	1.6	Route 93 goes off to the right but stay on Route 31, which is now called Saunders Settlement Road.
35.1	1.8	Enter Town of Cambria.
41.4	6.3	Pass entrance to Niagara County Community College on the right.

41.8	0.4	Enter Town of Lewiston.
43.5	1.7	Pass Niagara-Wheatfield Middle School and senior high school on the left.
44.2	0.7	Turn left onto Walmore Road.
45.8	1.6	At stop sign, turn right onto Lockport Road.
46.3	0.5	Pass entrance to Niagara Falls Air Force Base on left.
47.3	1.0	At fork in road, continue straight (right side of fork), staying on Lockport Road.
48.1	0.8	Turn right onto Miller Road; after 0.1 miles, turn right onto Quarry Road. Follow Quarry Road through the gate, then turn left and park at Niagara Stone Division parking parking lot. **THIS IS STOP #2.**
		Return to vehicles and proceed to end of Quarry Road.
49.0	0.9	At end of Quarry Road, turn left onto Miller Road.
49.1	0.1	Turn left at stop sign onto Lockport Road.
49.8	0.7	Turn left at intersection of Lockport Road and Packard Road.
50.3	0.5	Turn right (first right) onto Tuscarora Road.
50.6	0.3	Turn right onto dirt road at fence line and follow lead vehicle to **STOP #3.** ***Beware of broken glass and pipes sticking up in the road!***

END OF FIELD TRIP