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A CASE FOR NEOTECTONIC JOINTS ALONG THE NIAGARA ESCARPMENT

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Abstract. In a search for proof that some joints on the Appalachian Plateau are neotectonic, orientation data were collected on more than 1800 fractures in exposures of the Lockport Dolomite in western New York and southern Ontario. Of greatest interest was a late-forming ENE joint set present in the central and western portions of the field area. These joints increase in abundance with proximity to the Niagara Escarpment. The shape of the east-west trending Niagara Escarpment is defined by a series of asymmetric reentrants with a strong ENE linear trend, reflecting the bedrock joint pattern. The joints appear to have formed near the Earth's surface in response to low tensile stresses developed in bedrock adjacent to the retreating escarpment. Since the current shape and position of the escarpment were controlled by glacial activity during the last 3 m.y., it is possible that the ENE joints and reentrants are neotectonic features.

INTRODUCTION

Neotectonic fracture systems are the most recent regional systems to form [Hancock and Engelder, 1989]. These systems generally consist of a set of vertical joints which are presumed to have propagated at shallow depths (< 0.5 km) in response to an effective tensile stress developed during unloading as a result of denudation and lateral relief consequent on uplift. In work on joints in relatively young rocks, stratigraphic evidence is used to date late-formed joints as neotectonic [e.g., Hancock et al., 1984; Bevan and Hancock, 1986; Hancock and Engelder, 1989]. Some regional joints, interpreted as neotectonic, strike parallel to or approximately parallel to the direction of contemporary horizontal maximum stress (S_H) known from in situ stress measurements or fault plane solutions of earthquakes [e.g. Engelder, 1982, 1985; Bevan and Hancock, 1986]. These structures are of potential value for tracking the contemporary stress field in regions where in situ stress measurements and fault plane solutions are not available.

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At present, the northeastern United States is subject to a stress with S_H oriented approximately 060° [Sbar and Sykes, 1973; Zoback and Zoback, 1980, 1989; Plumb and Cox, 1987]. The orientation of S_H was determined through the compilation of in situ stress measurements such as hydraulic fracturing and overcoring experiments in addition to earthquake fault plane solutions and the observation of geologic features such as postglacial pop-ups (Figure 1). A favorite hypothesis is that tectonic stress in the northeastern United States arises as a result of gravitationally induced tractions which develop at the Mid-Atlantic Ridge [Forsyth and Uyeda, 1975; Turcotte and Schubert, 1982]. An ENE regional joint set is present in many localities throughout the northeastern United States, correlates with the orientation of the contemporary tectonic stress field [Engelder, 1982], and maintains a relatively consistent orientation regardless of local structure or tectonic province (Figure 2). One hypothesis is that these fractures form near the Earth's surface as the result of uplift and erosion and are oriented with respect to the neotectonic stress field.

The genetic relationship between late-formed joint sets within Paleozoic rocks of the North American craton and neotectonic stress within the lithosphere of North America is difficult to establish [Hancock and Engelder, 1989]. Outcrop studies in the Appalachian Valley and Ridge of Pennsylvania show that late-formed joints have the geometry and architecture of neotectonic joints and, furthermore, propagated parallel to or approximately parallel (075°-090°) to directions of contemporary horizontal maximum stress (S_H) known from in situ stress measurements or fault plane solutions of earthquakes [Hancock and Engelder, 1989]. Yet, stratigraphic arguments cannot be used to date late-formed joints in the Appalachian Mountains. To support Engelder's [1982] hypothesis that there is a genetic relationship between late-formed joints and the neotectonic stress field, this paper describes young joints and reentrants in the Niagara Escarpment of western New York and southern Ontario.

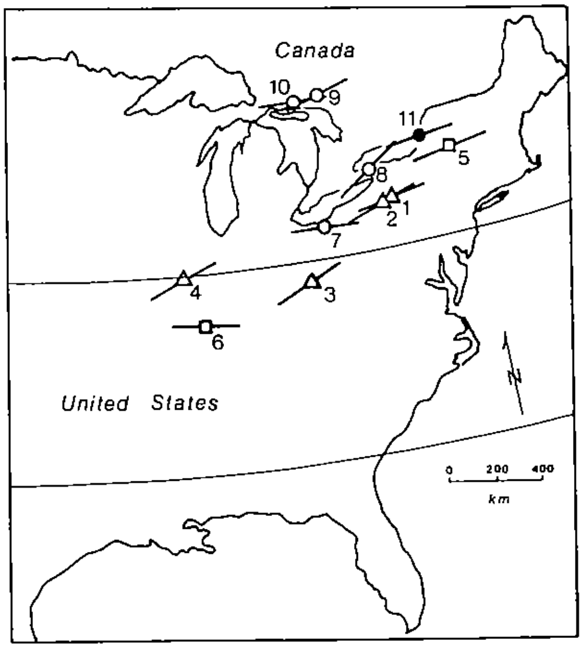

Fig. 1. The status of information on intraplate stress in the eastern United States as of April 1972 based on Sbar and Syke's [1973] compilation. The strike of the horizontal component of maximum compressive stress (S_H) is shown for hydraulic fracture tests (open triangles), fault plane solutions (open squares), overcoring stress measurements (open circles), and post-glacial pop-ups (solid circle). Data sources are 1, 3, and 4, Haimson and Stahl [1969]; 2, Overbey and Rough [1971]; 5, Sbar et al. [1972]; 6, Stauder and Nuttli [1970]; 7, Obert [1962]; 8, Sellers [1969]; 9, Moruzi [1968]; 10, Eisbacher and Bielenstein [1971]; and 11, Engelder and Sbar [1977]. Although Zoback and Zoback [1980, 1989] have added to this data set based on experiments over the past 18 years, the general picture of the orientation of S_H for the neotectonic stress field in eastern North America has not changed.

Fig. 2. The regional ENE joint set in the northeastern United States classified as neotectonic, after Engelder [1982]. The orientation of the joints are shown as solid black lines. Data sources are 1, Parker [1942]; 2, Hancock and Engelder [1989]; 3 and 4, Ver Steeg [1942, 1944]; 5, Powell [1976]; 6, Swenson (Joint patterns in Mississippian and Pennsylvanian rocks in western Kentucky and southern Illinois, submitted to Southeastern Geology, 1989); 7, Holst and Foote [1981]; 8), Bretz [1942]; and 9, this study.

Neotectonic Stress Orientation in Western New York and Southern Ontario

The orientation of S_H in western New York and southern Ontario is well documented [Sbar and Sykes,1973; Lo, 1978; Lee, 1981; and White and Russell, 1982]. Evidence comes from postglacial pop-ups and quarry floor buckles [Saull and Williams, 1974; Lo, 1978; White and Russell, 1982; Williams et al., 1985], in addition to in situ stress measurements [Palmer and Lo, 1976; Haimson and Lee, 1980; Lee, 1981].

Postglacial pop-ups and quarry floor buckles are anticlinal features that form in response to glacial retreat and bedrock excavation, respectively. As confining overburden is removed, top layers of bedrock buckle under the influence of high horizontal stresses, creating a ridge (or fold axis) perpendicular to S_H. Orientations of pop-up and buckle fold axes along with their well-constrained age of formation make these features excellent indicators of the neotectonic stress orientation. The orientation of 67 pop-up and quarry floor buckle axes compiled from southern Ontario [Wallach, 1990] are presented in a rose diagram in Figure 3. The NNW trend of fold axes implies an ENE orientation of maximum horizontal stress.

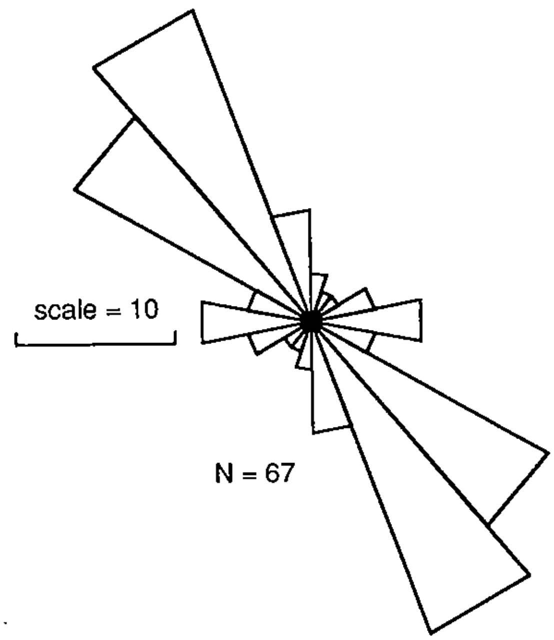

Fig. 3. The orientation of postglacial pop-up and quarry floor buckle axes compiled from southern Ontario in 20° intervals [Wallach, 1990].

The Niagara Escarpment

The contact between the resistant Lockport Dolomite and the underlying less resistant Rochester Shale forms the prominent topographic feature known as the Niagara Escarpment. Gravenor [1975] suggests that the escarpment formed as a result of subaerial erosion prior to the onset of Pleistocene glaciation. Nevertheless, there has been significant glacial erosion of the Niagara Escarpment [Straw, 1968], and it is reasonable to assume that the current shape and position of the escarpment were controlled by scouring and erosion during the glacial advances and retreats of the last 3 m.y. Glacial maps of ice positions show that ice extended a considerable distance south of the Lockport Dolomite outcrop belt in western New York and southern Ontario [Dyke and Prest, 1987]. The Niagara Escarpment is either buried or nonexistent in the eastern section of the study area and emerges as a prominent topographic feature in the vicinity of Gasport, New York, and continues westward through Niagara Falls and Hamilton, Ontario. The purpose of this paper is to investigate the relationship between the Niagara Escarpment and an ENE joint set in the Lockport Dolomite and to test the hypothesis that these joints are neotectonic features.

DATA COLLECTION, REDUCTION, AND RESULTS

Veins and joints were measured in seventeen quarries and one roadcut in the Middle Silurian Lockport Dolomite of western New York and southern Ontario (Figure 4). Virtually all of the systematic veins and joints in the flat-lying Lockport Dolomite are vertical. The fractures show no evidence of shear offset, implying a pure Mode I origin. Orientation data were collected along quarry walls and on quarry pavement surfaces. Because the joints and veins are vertical, these data are presented in two-dimensional rose diagrams consisting of 5° intervals. Figure 5 displays the fracture data in rose diagrams divided into two categories, veins and joints.

In the eastern and central sections of the study area a systematic calcite-filled vein set is present (Figure 5). A detailed discussion of the veins is given by Gross [1989]. In the central and western sections of the study area the most prominent joint sets are a NW-SE set and an ENE set which is approximately parallel to S_H of the contemporary tectonic stress field in the northeastern United States. The appearance of the ENE joint set correlates with the emergence of the Niagara Escarpment.

Scanline Surveys in the Gasport Quarry

The Gasport quarry is located at a point along the Niagara Escarpment where the escarpment changes orientation and therefore provides an excellent opportunity to investigate the relationship between escarpment orientation and bedrock joints as well as joint frequency as a function of proximity to the escarpment. The quarry is approximately 1.75 km long and the escarpment is oriented 105° adjacent to the eastern sector and 060° adjacent to the western sector (Figure 6). A total of nine scanline surveys were conducted along the quarry walls. Strike, dip and distance along the scanline were recorded for all fractures that intersected the tape measure, and stereographic plots showing fracture frequency as a function of orientation were constructed using the computer program developed by Lacazette [1991]. Scanlines 1-5 were conducted in the western sector,, and scanlines 6-9 were measured in the eastern sector. Within the western sector, scanlines 1 and 2 are located along a north-south cut through the 060° trending escarpment, whereas scanlines 3-5 are south of the escarpment edge. In the eastern sector, scanlines 6-8 were measured along the north-south trending eastern wall, and scanline 9 was measured in a pit in the east central portion of the quarry.

At the Gasport quarry the two most prominent joints sets strike approximately 060° and 100° and are here labeled the 060° set and the 100° set. Scanline data from different localities within the Gasport quarry demonstrate that the 060° joint set increases in frequency with proximity to the Niagara Escarpment. The fracture frequency stereographic plots are shown in Figure 7, and peak frequencies for the 060° and 100° sets are listed in Table 1. For the 060° set a comparison of scanlines within the western sector reveals a high frequency of 0.41-0.47 joints per meter in scanlines 1-2 which cut through

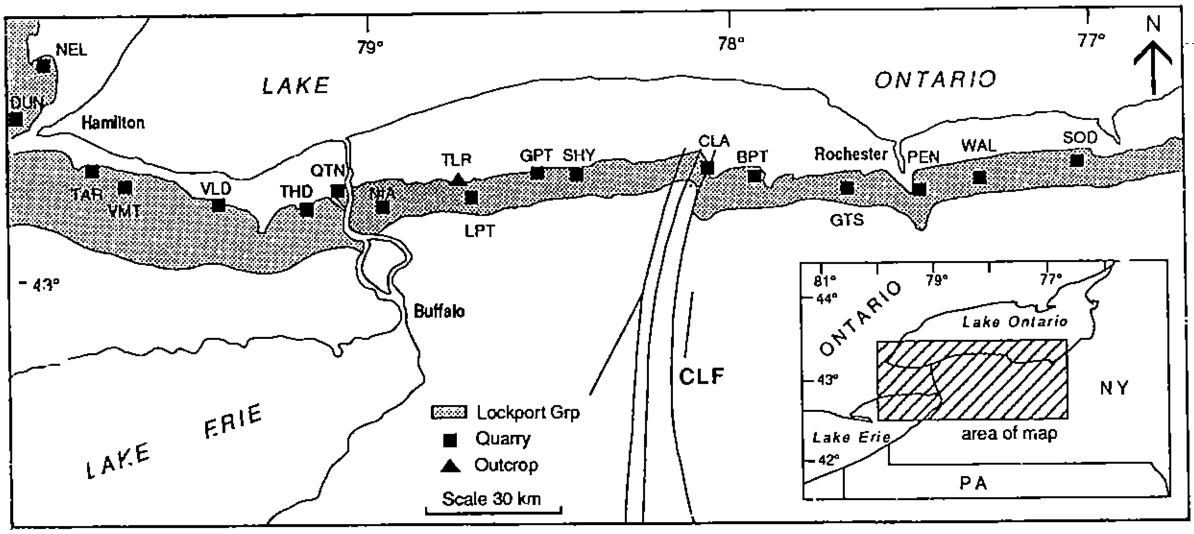

Fig. 4. The outcrop belt of the Lockport Dolomite in the study area. The localities from east to west are SOD = Sodus, N.Y.; WAL = Walworth; PEN = Penfield; GTS = Gates; BPT = Brockport; CLA = Clarendon; SHY = Shelby; GPT = Gasport; LPT = Lockport; TLR = Town Line Road; NIA = Niagara; QTN = Queenston, Ontario; THD = Thorold; VLD = Vineland; VMT = Vinemount; TAR = Taro; NEL = Nelson; DUN = Dundas. CLF = Clarendon-Linden fault.

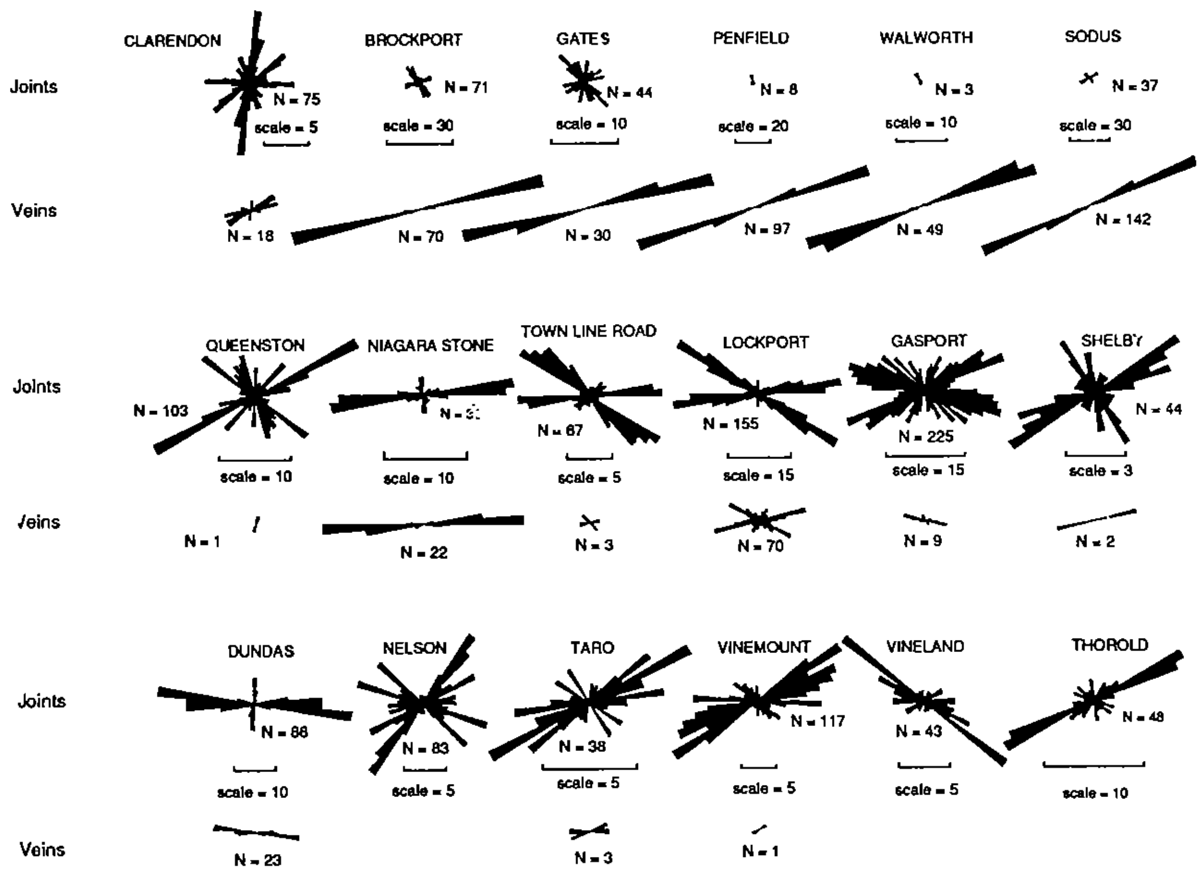

Fig. 5. Rose diagrams of fracture data at each locality separated into veins and joints. There is a common scale for each locality.

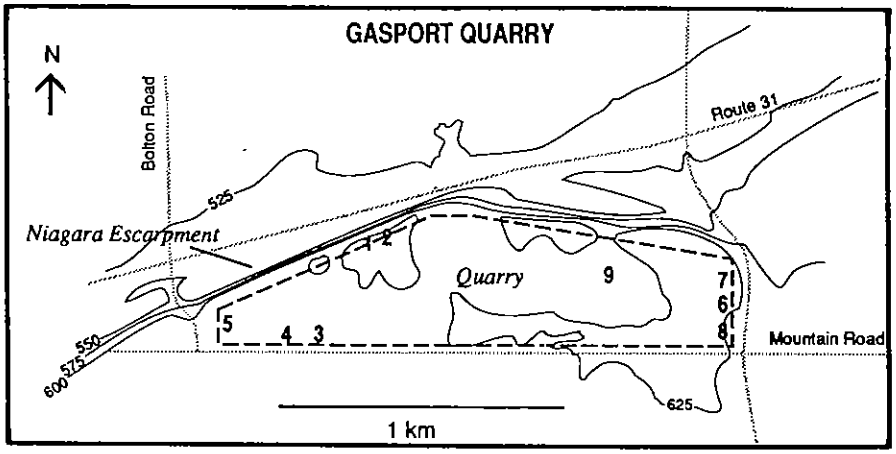

Fig. 6. Map of the Gasport quarry along the Niagara Escarpment. Numbers refer to location of scanline surveys. Contour interval is in feet.

the escarpment versus a lower frequency of 0.25-0.30 joints per meter in scanlines 3-5 measured south of the escarpment. The 060° set displays a higher frequency in the western sector (0.28-0.31) which is adjacent to the ENE trending segment of the escarpment than in the eastern sector (0.10-0.16) which is adjacent to the ESE trending segment. It also may be noted that the 100° set is most abundant in the eastern sector of the quarry. The relatively high frequency of NNE joints in some of the plots results from the small angles these joints form with the north-south scanlines.

Scanline 1 cuts through the 060° trending escarpment in the western sector and provides the unique opportunity to investigate the distribution of the 060° set along a scanline as it approaches the escarpment edge. A plan view of ENE striking joints intersecting scanline 1 is presented in Figure 8. The scanline is 43.3 m in length with two small covered intervals and is oriented 007°. The mean orientation of the fractures was determined and fracture spacing was determined by calculating the perpendicular distance between adjacent fractures. The ENE striking joints along the scanline are divided into two sample populations, a northern section near the edge of the escarpment (38-43.3 m) and a southern section further from the escarpment (0-32 m). The populations were analyzed using the two-sample t test for comparing two population means. Figure 8 shows that the 060° set is not uniformly distributed along the length of the scanline. The mean joint spacing of sample population 1 near the edge of the escarpment is 0.37 m, whereas the mean spacing of sample population 2 further south is 2.53 m. The two-sample t test for comparing two population means describes a greater than 99% confidence that these means are different from each other. Results from scanline surveys in the Gasport quarry suggest a distribution for 060° joints represented by the schematic cross section in Figure 9, where these joints increase in abundance with proximity to the Niagara Escarpment. A similar relationship of more densely spaced joints near the escarpment edge has been observed in the Niagara River Gorge [Lee, 1978].

A total of seven separate abutting relationships between the 060° and 100° joints were observed on the pavement surfaces of the Gasport quarry. In all cases the 060° joint abuts against the 100° joint, implying that the 060° joint set is younger in age. This is consistent with our hypothesis that the 060° joints are neotectonic.

Normalized Factor for Escarpment Height and Proximity

In addition to those at the Gasport quarry, other observations suggest that the ENE striking joints are related to the escarpment. First, they are present only in the portion of the field area where the Niagara Escarpment is a topographic feature. Second, they are most abundant in quarries where the escarpment is most prominent (i.e., highest) such as Queenston, Thorold, Vinemount, and Taro. If these joints are unloading joints which form under near-surface tensile stresses developed at or near the escarpment, then one would expect their development to be directly proportional to the height of the escarpment and inversely proportional to the distance from the escarpment. A normalized factor was created in order to qualitatively assess this expectation. Height in meters and distance to the escarpment in kilometers were measured and normalized values for each site were determined. All of the heights were divided by the highest point along the escarpment (Vinemount quarry), and the distances were divided by the site furthest south of the escarpment (Niagara Stone quarry). A normalized factor was calculated by adding the normalized height to 1 minus the normalized distance (Table 2). This factor is plotted versus the percentage of fractures in the neotectonic orientation in Figure 10. The Niagara Escarpment is not present in the eastern portion of the study area, therefore normalized factors were not calculated for sites between Sodus and Clarendon.

There is a general correlation between the percentage of joints in the ENE orientation and the height and proximity to the Niagara Escarpment as indicated by our normalized factor (Figure 10). When just distance or height versus percentage of joints is plotted separately the correlation is poorer, implying that height and distance are linked. Though it is difficult to quantitatively prove the exact age of the ENE joints, qualitatively they are consistently late-forming and are associated with the development of the Niagara Escarpment. In summary, our normalization-factor analysis leads to the same conclusion as the results from scanline surveys conducted

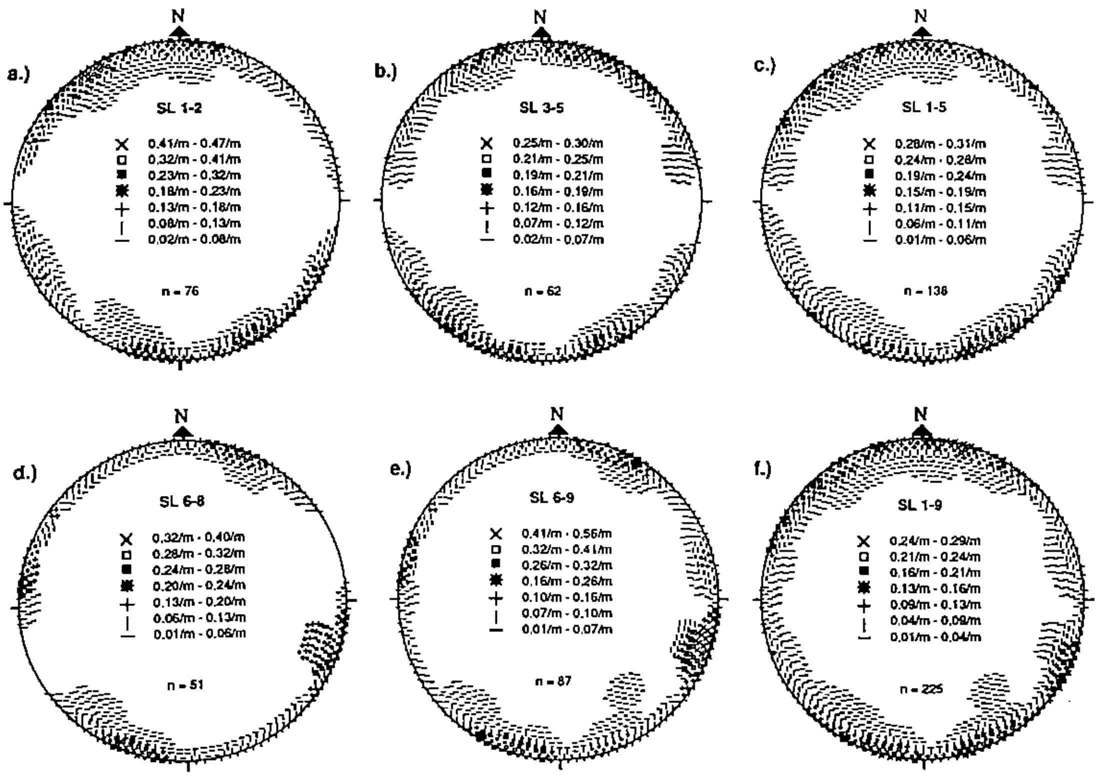

Fig. 7. Joint frequency versus orientation stereoplots for scanlines measured at the Gasport quarry. Refer to text and Figure 6 for description of the scanline surveys.

TABLE 1. Peak Joint Frequencies for the 060° and 100° Joint Sets From Scanline Surveys in the Gasport quarry

Scanline	Number of Data Points	Length, m	Description	Peak Frequency, joints / meter 060° Set	100° Set
1-2	76	60	N-S, western sector, cut through Niagara Escarpment	0.41-0.47	0.18-0.23
3-5	62	79.2	western sector, away from escarpment	0.25-0.30	0.25-0.30
1-5	138	139.1	western sector	0.28-0.31	0.24-0.28
6-8	51	69.8	eastern sector, along eastern wall	0.06-0.13	0.32-0.40
6-9	87	91.2	eastern sector, including Decew pit	0.10-0.16	0.32-0.41
1-9	225	230.3	entire quarry	0.21-0.24	0.24-0.29

TABLE 2. Normalized Values and Percentages of ENE Joints

Outcrop	Distance to Escarpment, km	Normalized Distance	Height of Escarpment, m	Normalized Height	Normalized Factor	% Open Fractures 051°-070°
Gasport	0.22	0.04	24.3	0.29	1.25	17.0
Lockport	2.77	0.46	30.5	0.36	0.9	5.2
Town Line Rd	0	0	21.3	0.25	1.25	4.5
Niagara Stone	5.96	1.00	68.6	0.82	0.82	2.8
Queenston	0.37	0.06	61.0	0.73	1.67	25.2
Thorold	0	0	45.7	0.55	1.55	47.9
Vineland	0.67	0.11	22.9	0.27	1.16	11.6
Vinemount	2.56	0.43	83.8	1.00	1.57	36.8
Taro	1.15	0.19	76.2	0.91	1.72	39.5
Nelson	2.31	0.39	61.0	0.73	1.08	14.5
Dundas	2.82	0.47	45.7	0.55	1.34	0

The Niagara Escarpment is not a prominent topographic feature east of the Gasport quarry (i.e., between Sodus and Shelby).

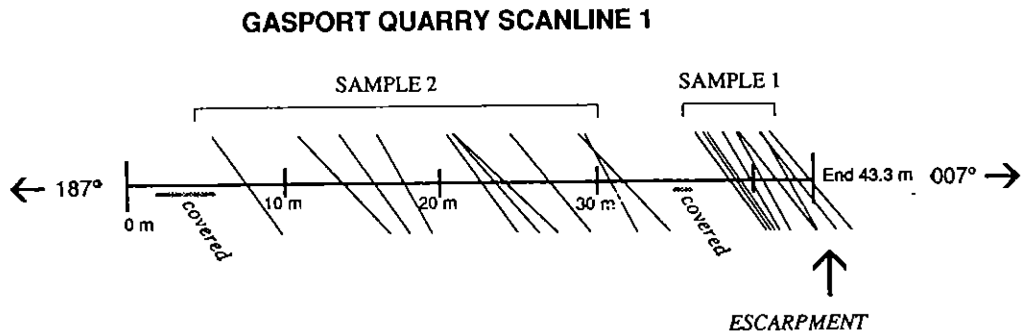

Fig. 8. Map view of scanline 1 in the Gasport quarry, showing intersection of ENE joints.

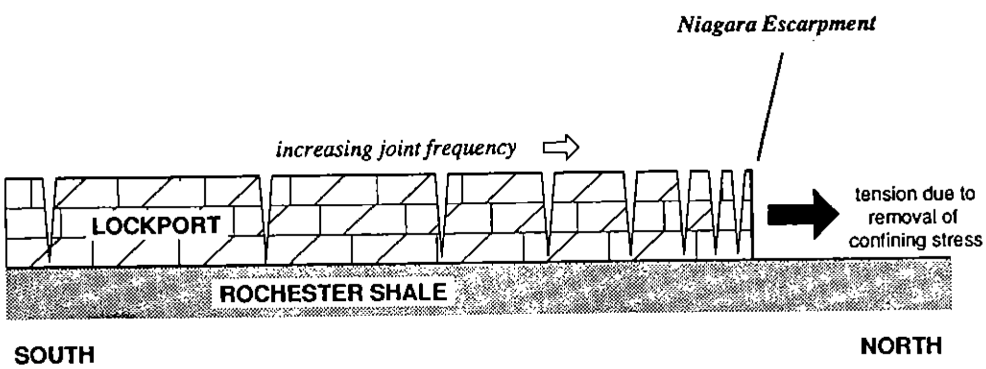

Fig. 9. Schematic cross section through the Niagara Escarpment showing an increase in fracture frequency with proximity to the escarpment face.

at the Gasport quarry, which show that ENE oriented joint development is strongest near to the escarpment.

Reentrants

The general trend of the Niagara Escarpment is east-west, though upon close inspection the escarpment actually consists of a series of angular reentrants which form a "zig-zag" pattern (Figure 11). A reentrant is defined as "a prominent, generally angular indentation in a landform; e.g. an inlet between two promontories along a coastline, or a transverse valley extending into an escarpment" [Bates and Jackson, 1980, p.526]. The distinct linear aspect to the Niagara Escarpment clearly reflects the joint pattern in the bedrock. The reentrants are asymmetric, consisting of a strongly linear ENE oriented face and a less dominant WNW trending face. The ENE faces are oriented approximately 060°. Orientations of 15 ENE reentrant segments were measured from topographic and geologic maps and are plotted versus longitude in Figure 12. The mean ENE reentrant segment orientation is 61.7° with a 99% confidence interval of 3°, calculated according to the von Mises distribution [Cheeney, 1983]. Because the current position and shape of the Niagara Escarpment were established during glacial erosion over the past 3 m.y., it seems reasonable to conclude that the consistent ENE linear reentrant segments of the Niagara Escarpment are indeed neotectonic features.

DISCUSSION

The ENE reentrant segments of the Niagara Escarpment are uninterrupted linear features, in contrast to the WNW segments which have been more extensively dissected (Figure 11).

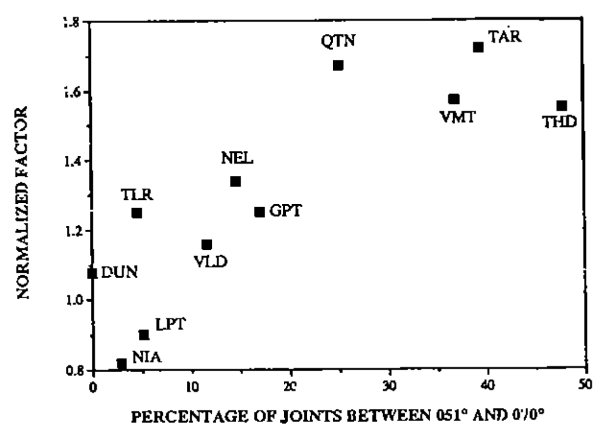

Fig. 10. Plot of the normalized factor (which takes height of the escarpment and distance to the escarpment into account) for each quarry versus the percentage of joints in the neotectonic orientation. Localities as in Figure 4.

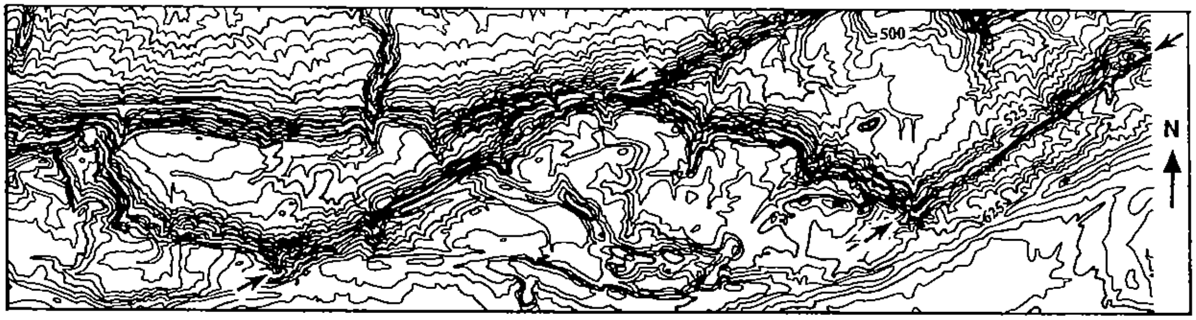

Fig. 11. Map of topographic contour lines along the Niagara Escarpment (Cambria 7.5' Quadrangle, Niagara County, New York). Note the ENE linear reentrants which shape the east-west trending Niagara Escarpment. Contour interval is in feet.

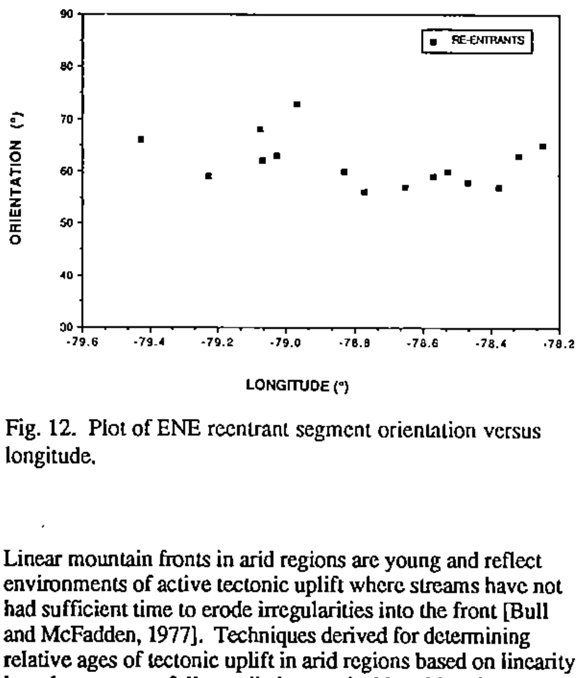

Fig. 12. Plot of ENE reentrant segment orientation versus longitude.

Linear mountain fronts in arid regions are young and reflect environments of active tectonic uplift where streams have not had sufficient time to erode irregularities into the front [Bull and McFadden, 1977]. Techniques derived for determining relative ages of tectonic uplift in arid regions based on linearity have been successfully applied to tropical humid regions [Wells et al., 1988]. By analogy, we suggest that the ENE linear segments of the Niagara Escarpment represent relatively young features due to their lack of erosional irregularities. If so, we suggest that the ENE striking reentrant segments developed within the past 3 m.y. in association with glacial loading, unloading, erosion, and scouring.

Some studies suggest that preexisting fractures act to control the development of glacially derived topography. For example, on the basis of the correlation between a strong topographic grain striking 345° and a well-developed fracture set of about the same orientation, Chapman and Rioux [1958] concluded that the glacially derived topography of Mount Desert Island, Maine, was to some extent controlled by vertical fractures. Other examples of the correlation between well-developed fracture sets and glacially carved topography are recorded in the Adirondack Mountains of New York [Chadwick, 1939; Plumb et al., 1984] and the Finger Lakes of central New York [Engelder and Geiser, 1980]. For all three of these examples the glacially derived topography developed by either plucking on the leeside of topographic rises (e.g., Mount Desert Island) or glacial flow roughly parallel to the preexisting fracture sets (e.g., Seneca and Cayuga Lakes, New York). In contrast, glaciers moved up over the Niagara Escarpment at a high angle to the trend of the ENE reentrants so that glacial flow does not favor plucking during glacial advance. However, spalling along the escarpment may have accompanied glacial unloading. The ENE neotectonic features may have formed as a result of stress release associated with postglacial isostatic uplift and removal of the confining ice load, thereby leading to low tensile stresses normal to the face of the Niagara Escarpment.

Results from scanlines in the Gasport quarry along with the qualitative analysis of our normalized factor from other localities imply that the distribution of ENE joints is directly related to the development of the Niagara Escarpment, as shown schematically in Figure 9. If related to the development of the Niagara Escarpment, they are near-surface unloading joints which propagated during or subsequent to glacial modification of the Niagara Escarpment. This model suggests that a tensile stress must have developed in the Lockport Dolomite near the Niagara Escarpment. Stress measurements in the Niagara River Gorge show S_H parallel to the escarpment and a minimum horizontal stress (S_h), which in many cases is tensile, normal to the escarpment face [Lee, 1978]. The implication here is that tensile stresses are generated upon relaxation of confining pressure during the southward retreat of the escarpment.

A Model for the Formation of the ENE Joints and Reentrants

This paper demonstrates that the ENE joints and reentrants along the Niagara Escarpment are related to each other on the basis of orientation and spatial distribution. The problem then arises as to how these two types of structures developed relative to one another. We attempt to address this issue by discussing three scenarios for the development of the Niagara Escarpment.

The three models are shown in Figure 13. As the glaciers advanced, the escarpment front progressively eroded southward. The first model represents glacial erosion and southward retreat of the escarpment taking place in an isotropic stress field with no preexisting joints (Figure 13a). Due to tensile stress created by the escarpment's topographic relief, joints propagate parallel to the escarpment, decreasing in frequency away from the front. The joints would assume an orientation parallel to the escarpment since the far-field stress is isotropic. This

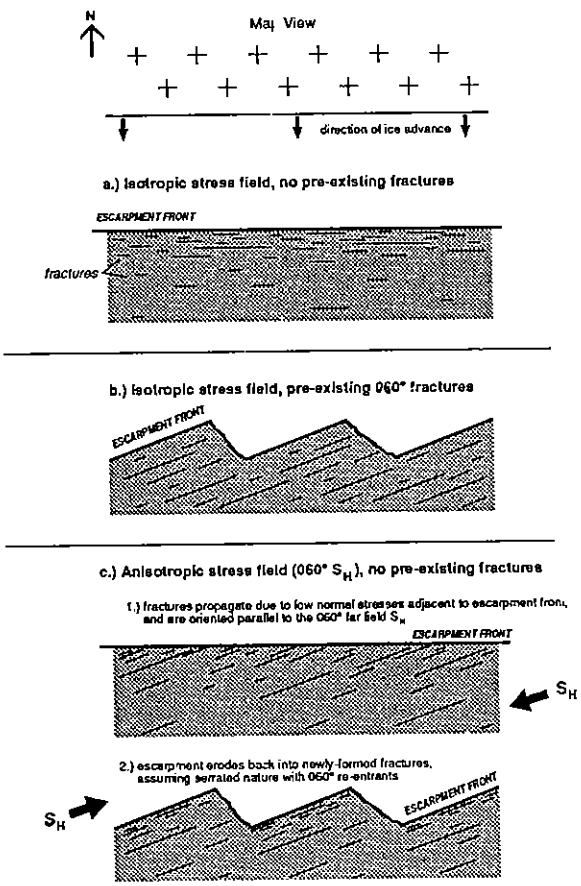

Fig. 13. Three models for the development of joints and reentrants along the Niagara Escarpment. Refer to text for discussion.

model satisfies the observed joint frequency as represented in Figure 9 but does not account for the ENE orientation of joints and reentrants.

The second model consists of ice advancing over a region with preexisting joints oriented 060° (Figure 13b). During the process of erosion bedrock spalls off along the preexisting joints which act as planes of weakness, and the escarpment assumes a strong linear 060° aspect. This model accounts for the preferred 060° orientation of the escarpment but does not explain the observed fracture distribution which is not uniform throughout the Lockport Dolomite.

The third model represents erosion in a region with no preexisting joints and an anisotropic stress field, with S_H oriented 060° (Figure 13c). Initially the horizontal beds of the Lockport Dolomite are compressed. As the escarpment retreats southward there is a general relaxation due to release of confining stress. A component of tensile stress is therefore superimposed on the anisotropic stress field, with the net result that joints propagate with an orientation of 060°. As erosion progresses southward, bedrock spalls off along the newly formed joints, and the escarpment assumes its asymmetric, serrated nature. This scenario explains both the distribution and orientation of joints and reentrants observed along the Niagara Escarpment.

The Role of Tectonic Heredity

Although evidence appears to support a neotectonic origin for the ENE joints, there remains the possibility that their orientation is controlled by a preexisting fabric. This becomes an especially important consideration in light of the presence of an ENE systematic calcite vein set in the eastern and central portions of the study area. These calcite veins probably formed during the late Paleozoic under several kilometers of overburden [Gross, 1989] and therefore may have imparted an ENE fabric in the Lockport Dolomite which later affected the erosion of the Niagara Escarpment. A detailed analysis of vein orientations shows that the veins rotate clockwise from east to west across the study area [Gross, 1989], whereas the reentrants maintain a consistent orientation (Figure 14). Moreover, at the point where the ENE joints and reentrants appear in the Lockport Dolomite the veins have rotated to a significantly different orientation (i.e., 080° to 090°). Since the paleostress orientation inferred from the veins in this portion of the study area is misoriented by 20°-30° from the orientation of the 060° joints and reentrants, it seems most unlikely that the propagation of the late ENE joints is controlled by the vein set.

ENE Reentrants as Indicators of S_H

The ENE orientation of maximum horizontal compressive stress in the northeastern United States has been determined by a number of in situ stress measurements (Table 3). The orientation of S_H derived from ENE asymmetric reentrant segments along the Niagara Escarpment correlate with in situ stress measurements determined from overcoring [Dames and Moore, 1978], hydraulic fracturing [Evans and Engelder, 1986; Plumb and Cox, 1987], borehole breakouts [Plumb and Cox, 1987], and strain relaxation [Engelder, 1984]. Not only can the reentrant segments be utilized as indicators of S_H, but on the basis of their low standard deviation they may in fact provide an excellent constraint for the orientation of S_H in western New York and southern Ontario.

CONCLUSIONS

A series of related ENE joints and reentrants are present in the Lockport Dolomite in western New York and southern

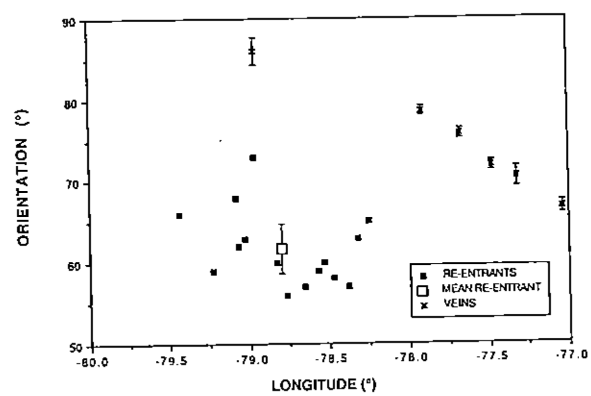

Fig. 14. Plot of orientations of ENE reentrant segments, mean segment value with 99% confidence interval, and systematic vein set versus longitude. Note that in the region where the reentrants are present the systematic veins have rotated to an orientation significantly different from the reentrants.

TABLE 3. The Orientation of S_H in the Northeastern United States and Ontario

Location (Details)	Number of Data Points	Mean S_H (azimuth)	Standard Deviation	Reference
Niagara Escarpment (Linear reentrants - N.Y., Ont)	15	062°	5°	this paper
East Otis, Mass. (Strain relaxation - Algerie Granite)	9	064°	10°	Engelder [1984]
Midcontinent U.S.A. (Hydraulic fracture - Ill., Mich., Wis.)	7	059°	10°	Plumb and Cox [1987]
Appalachian Basin (Hydraulic fracture - ., Penn., Ohio, W.Va.)	10	065°	15°	Plumb and Cox [1987]
Appalachian Basin (Breakouts - N.Y., Penn., Ohio, W.Va.)	13	058°	18°	Plumb and Cox [1987]
South Canisteo, N.Y. (Hydaulic fracture - Appleton Well)	19	078°	23°	Evans et al. [1989]
South Canisteo, N.Y. (Hydraulic fracture - Wilkins Well)	29	066°	24°	Evans et al. [1989]
Nine Mile Point, N.Y. (Overcoring - USBM gauge)	74	076°	28°	Dames and Moore [1978]

Ontario. The ENE joints exhibit the following characteristics:

1. They are consistently oriented at approximately 060° across the study area.
2. They are the last-formed joints in the Lockport Dolomite.
3. They increase in frequency with proximity to the Niagara Escarpment.

The asymmetric reentrants are oriented parallel to the ENE joints and are relatively young in age based on glacial evidence and their strong linearity.

The ENE joints appear to have formed near the Earth's surface in response to the development of tensile stresses during the southward retreat of the Niagara Escarpment. A geologic model which accounts for the observed structural data involves the southward directed erosion of the Niagara Escarpment in a region without preexisting ENE joints and subject to an anisotropic stress field. The anisotropic stress field resulting in the preferred orientation of the ENE joints and reentrants is parallel to the current S_H in the northeastern United States. Therefore we conclude that these features are indeed neotectonic.

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