Pageoph, Vol. 115 1977), Birkhäuser Verlag, Basel

The Relationship Between *In Situ* Strain Relaxation and Outcrop Fractures in the Potsdam Sandstone, Alexandria Bay, New York[1])

By TERRY ENGELDER[2]) and MARC L. SBAR[3])

Summary – *In situ* strain was measured by overcoring foil-resistance strain gauge rosettes bonded to five outcrops of Potsdam Sandstone near Alexandria Bay, New York. Strain relaxation magnitude and orientation correlated with the area of the intact outcrop outlined by intersecting vertical fractures. The maximum expansion occurred at the outcrop with the largest area between intersecting fractures. Outcrops with more than one set of longer, open fractures or more complicated fracture patterns have lower recoverable strains. Strain relaxation was lowest next to a postglacial pop-up. The orientation of the pop-up indicated relief of an ENE directed compression, the direction also observed as the maximum expansion at the outcrop yielding the largest strain relaxation.

Key words: Stress in situ; Strain relaxation; Intraplate stress field.

1. Introduction

To complement the companion paper discussing the significance of strain relaxation of the Barre Granite we describe the strain relaxation of the Potsdam Sandstone near Alexandria Bay, New York (Fig. 1 of ENGELDER *et al.* [1]). This is a region presumably affected by ENE maximum horizontal compressive stress (SBAR and SYKES [2]). Strain relaxation measurements in the Potsdam Sandstone provide an opportunity to test SBAR and SYKES' observation of uniformly oriented stress in the lithosphere and the extent of transmission of this stress to the surface. In addition we could sample *in situ* strain associated with different fracture patterns within outcroppings of one rock unit in order to further clarify the relationship between *in situ* strain and outcrop fractures. These data also supplement strain relaxation measurements in the Potsdam Sandstone near Plattsburgh, New York (ENGELDER and SBAR [3]; Fig. 1 of ENGELDER *et al.* [1]).

Many *in situ* strain measurements suggest a relationship between the orientations of a dominant fracture set and local strain relaxation (PRESTON [4]; EISBACHER and BIELENSTEIN [5]; BROWN [6]; SWOLFS *et al.* [7]). This relationship exists at all depths from exposed bedding plane surfaces down to 1 km near underground mines. The fact that there seems to be a relationship suggests that caution is necessary when using strain

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relief measurements to detect a regional tectonic stress. In some instances it may be difficult to delineate strain fields whose local orientations are perturbed by fractures. Using solid-inclusion probes, LEE *et al.* [8] demonstrated that conspicuous structures such as fractures and foliation do influence the redistribution of strain around an actively excavated opening.

The relationship of *in situ* strain and locally dominant fracture sets to a regional tectonic stress is further complicated by residual strains. FRIEDMAN and LOGAN [9] demonstrated that residual strains influence the mechanical properties of sandstone so that induced fractures propagate parallel to the maximum compressive residual strain. This implies that fracture orientation may be controlled by a residual stress. Likewise, PRICE [10] presents a model for the downwarp and uplift of a basin in which residual strain and fractures are controlled by the shape of the basin rather than through transmission of more deeply seated stresses.

Methodology

In situ strain was measured by overcoring foil-resistance three component strain gauge rosettes epoxied on a polished horizontal outcrop (FRIEDMAN [11]; BROWN [12]; SWOLFS *et al.* [7]; ENGELDER and SBAR [3]). Strain relaxation accompanied the cutting of a vertical 15.2 cm diameter core using a diamond masonry bit with its axis centered on the strain gauge rosette (overcoring). After four or more days a 7.6 cm diameter core coaxial with the 15.2 cm core was cut to further relax residual strain (SWOLFS *et al.* [13]; NICHOLS [14]). The larger is the initial overcore whereas the smaller is an internal overcore.

Three rosettes were bonded to each outcrop chosen for our experiment. Spacing between rosettes was 1 to 2 m with vertical fractures between each rosette. The gauges were monitored for several days before and after overcoring to establish a base line from which to subtract thermal fluctuations.

2. *Geology of Alexandria Bay vicinity*

Outcrops of lower Paleozoic sediments and Precambrian basement lace the countryside in the vicinity of Alexandria Bay. Many outcrops of the basal Cambrian Potsdam Sandstone are still bare following recent glacial scouring. Generally a quartz arenite but locally a subarkose to arkose, the sandstone was deposited on an erosional surface with less than 100 m of relief (CUSHING *et al.* [15]). Silica overgrowths generally cement the sand, but calcareous cement appears in the uppermost 5 m of the formation (CUSHING *et al.* [15]).

Reactivation of high angle faults in the Precambrian basement followed the deposition of the Potsdam Sandstone. These reactivated faults, whose general strike is N50°E, are expressed as monoclines in the lower Paleozoic sediments. A DAMES and

MOORE Technical Report [16] suggests that the Potsdam sands were unconsolidated at the time of fault motion and that the motion on the reactivated faults was absorbed by soft sediment deformation in the Potsdam sand and by subsequent monoclinal flexing of overlying lithified carbonates. Some NE striking fractures within the Potsdam Sandstone are attributed to stresses associated with minor slip in basement faults following lithification of the sand. This faulting was quite local and did not affect any of the outcrops sampled in our study.

The most recent tectonic features in the Potsdam Sandstone are a number of post-glacial folds commonly called 'pop-ups'. These pop-ups consist of slabs as much as 3–4 m thick which have buckled upward as much as 4 m following the most recent glaciation (Fig. 1). The pop-ups apparently buckled upward in response to a compression until the fold fractured along its crest and flanks, furnishing relief to the bent flanks and permitting them to straighten (CUSHING *et al.* [15]). The orientation of pop-ups has been used to infer the direction of maximum compressive stress in the crust (SBAR and SYKES [2]). The Alexandria Bay pop-ups have a fold axis of NNW which implies that the crustal stress is most compressive in the ENE direction.

The five outcrops selected for our measurements are labelled Baker, Frazier, Kirkey, Nelson and Ostrander (Fig. 2). The Potsdam Sandstone is a quartz arenite at Baker, Frazier, Nelson and Ostrander but a subarkose at Kirkey (Table 1). Kirkey is located near the top of the formation where calcareous cement is abundant. The grain size distribution of this subarkose is bimodal whereas the quartz arenites are unimodal with silica cement.

Figure 1
Postglacial pop-up viewed looking NNW along its axis. The strain relaxation measurements at Nelson were located 30 m ENE from the axis, which is exposed for 100 m.

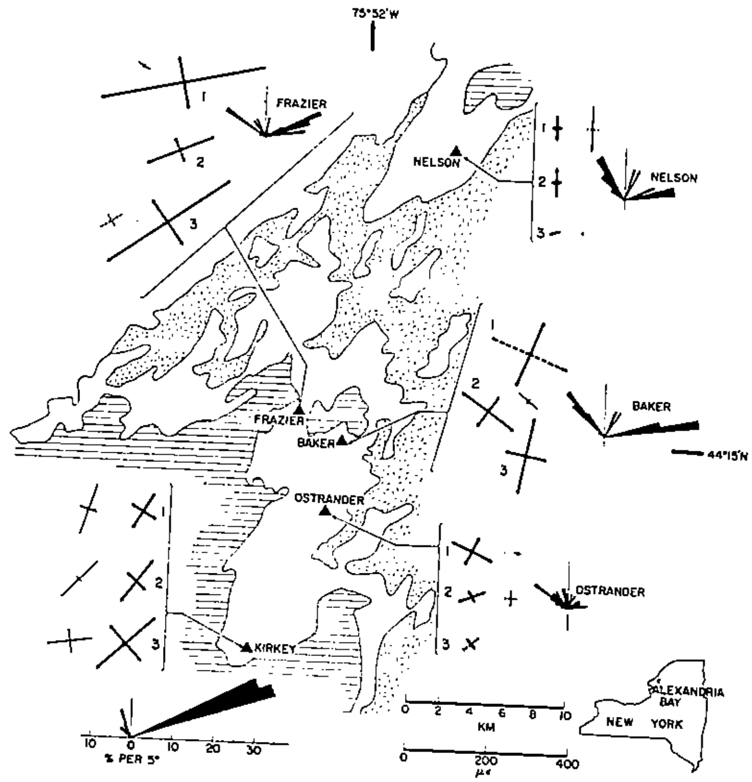

Figure 2
Geology and *in situ* strain in the vicinity of Alexandria Bay, New York. Outcrops of the Precambrian basement are stippled; outcrops of the Potsdam Sandstone are the blank; and outcrops of the lower Paleozoic carbonates are indicated by horizontal lines. The azimuth of the intersection of fractures with outcrop surface are indicated by rose diagrams. This data is divided into 5° intervals and displayed in percent of fractures per 5° interval. Five sample sites are named. The magnitude and orientation of the strain relieved by the initial overcore are indicated by dark arrows. The magnitude and orientation of the strain relieved by an internal overcore are indicated by lighter lines. Solid arrows represent expansion and dashed arrows represent contractions. The magnitude of the relieved strain is represented by a scale in microstrain (με). Four internal overcores cut in the lab four months after initial overcore are: Frazier – 3, Kirkey – 3, Nelson – 3, and Ostrander – 2.

Table 1
Modal analysis of Potsdam Sandstone, Alexandria Bay

	Quartz	Feldspar	Carbonate cement	Silica cement	Rock fragment	Pores	Accessory minerals
1. Baker	86	—	—	13	1	—	—
2. Ostrander	83	—	—	16	1	—	—
3. Nelson	82.3	—	—	6.3	2.3	8.3	0.8
4. Frazier	76	—	—	24	—	—	—
5. Kirkey	66	13.5	15.5	3.5	0.5	0.5	0.5

3. Relation between macrofractures and in situ strain

The orientation of the intersection of fractures with the surface of each outcrop is illustrated by means of rose diagrams (Fig. 2). In the vicinity of Alexandria Bay the most prominent fracture sets strike within 15° of either N65°E or N35°W. Locally a third fracture set appears at N20°E. The majority of fractures at Frazier extend less than 2 m on the outcrop face (Fig. 3), whereas the majority of fractures at Kirkey can be traced up to 50 m (Fig. 4). Fracture lengths are between these extremes at Nelson, Baker and Ostrander. Fracture spacing is between 50 and 70 cm at Baker, 5 and 70 cm at Ostrander, 2 and 100 cm at Nelson, 20 and 100 cm at Frazier, and 50 and 100 cm at Kirkey.

To characterize the state of an outcrop with regard to fractures, some quantitative

Figure 3
View along 0.3 to 2 m long fractures trending ENE at Frazier. The NW trending fracture in the foreground forms one edge of a mechanically continuous portion of the outcrop, which extends back to the vicinity of the geologist. Since the short ENE trending fractures do not outline discrete blocks, they form short discontinuities without interrupting the mechanical continuity of the outcrop.

Figure 4
ENE trending fractures at Kirkey. Many of these fractures are open and thus transmit no normal stress.

combination of fracture length, distance between parallel fractures, orientation of fractures and separation of walls of individual fractures should be considered. In practice it is difficult to combine all four parameters in one function that is meaningful. We feel that it is significant to characterize the outcrops using the area outlined by vertical fractures. This defines the size of mechanically continuous portions of the outcrop. Usually long-intersecting fractures define the boundaries of mechanically continuous portions as illustrated in Fig. 5 where each continuous portion is about 1 m^2. Short but widely spaced fractures form discontinuities without completely interrupting the mechanical continuity of the outcrop (Fig. 3). To be concise we shall refer to the degree of fracturing in each outcrop as fracture density where a higher fracture density is characterized by smaller areas between vertical fractures.

In each outcrop the area outlined by vertical fractures is variable (Fig. 6). Most outcrops of Potsdam Sandstone have areas between 1 and 10 m^2 as is the case at Frazier, Kirkey, and Baker (Figs. 3, 4, and 5). Exceptions occur in the vicinity of postglacial pop-ups such as Nelson (Fig. 2) and on outcrops containing glacial striations. Parts of the outcrop at Nelson were shattered either before or during the formation of the pop-up and, therefore, are plotted in Fig. 6 as very small areas outlined by vertical fractures. Ostrander is a knob of Potsdam Sandstone with 10 m of relief over an area of 2×10^4 m^2. During glaciation many boulders were dragged over the knob forming glacial striations (Fig. 7). Fractures generated during glaciation are responsible for the many orientations of fractures at Ostrander (Fig. 2).

Figure 5
Three fracture sets at Baker. The view is toward the SSW looking along the least dense of the three sets.

The magnitude of the strain relief following the 15.2 cm overcore varies with the fracture density within the Potsdam Sandstone (Figs. 2 and 6). Frazier had the largest strain relaxation and lowest fracture density. Relaxation of intermediate magnitude occurred at Baker and Kirkey each of which has one or more open fracture sets. Small changes occurred at Ostrander, an outcrop characterized by intense fracturing in many orientations, and Nelson, an outcrop undoubtedly affected by a postglacial pop-up.

The relation between orientation of strain relaxation and fractures is not consistent. The maximum expansion at Frazier parallels a major fracture set whereas the maximum expansion of the different gauges trends 15° to 30° from the strike of the same fracture set at Kirkey. At Baker and Ostrander there is no obvious relationship between maximum expansion and fracture orientation primarily because neither fractures nor the strain relief have a single orientation. All three strain measurements at Baker have maximum expansions within a few degrees of the strike of one of the three fracture sets. On the intensely fractured outcrop at Ostrander, two of the maximum expansion directions are within a few degrees of the most preferred orientation for fractures. At Nelson a small amount of strain relief was measured; two rosettes recorded a change on just the north component whereas the third rosette only recorded small changes on the other two components. Here the strain relief was not oriented with respect to outcrop fractures.

Expansion during the internal overcoring of subarkose from Kirkey was more than 100 $\mu\varepsilon$ compared with relaxations of less than 100 $\mu\varepsilon$ for all of the quartz arenites. Internal overcoring of the subarkose yielded strains comparable in magnitude and

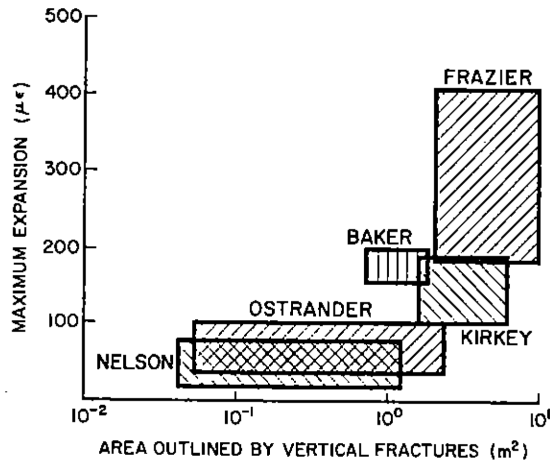

Figure 6
Maximum elongation of strain relaxation following initial overcore plotted as a function of area outlined by vertical fractures (m^2) for five outcrops of Potsdam Sandstone on which *in situ* strain was measured. Hatched areas indicate the extent of variation of both strain relaxation and area outlined by vertical fractures at each outcrop.

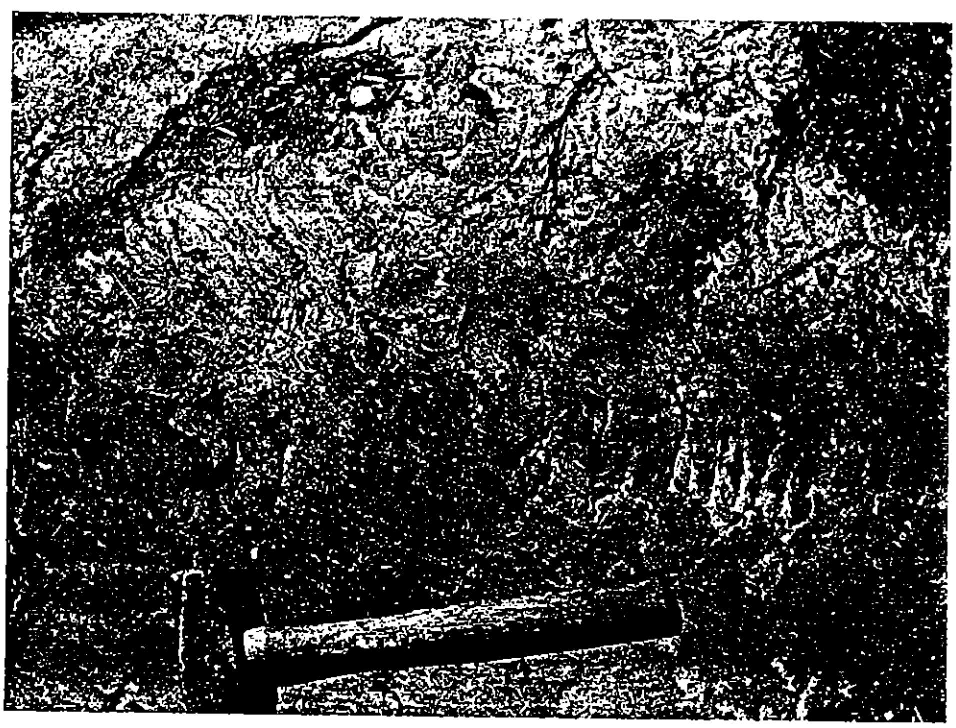

Figure 7
Fractures associated with a glacial wear track at Ostrander. The concave shape of the fractures indicates that the boulder causing this wear track moved from right to left. Other short fractures are seen in the top portion of the photo.

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4. Laboratory analyses

To define the mechanisms of relaxation of the Potsdam Sandstone, we subjected our samples to petrographic analyses and mechanical tests similar to those described in ENGELDER *et al.* [1].

In thin section, observable characteristics which might contribute to mechanical anisotropy or strain relaxation are not present or are subtle. The only sample with any microfracture fabric is the subarkose from Kirkey (Fig. 8). Samples from Frazier and Kirkey have slight long grain axis fabrics which may be attributed to deposition in a fluvial environment (Fig. 9). All of the quartz arenites (Baker, Frazier, Nelson, and Ostrander) have serrated grain boundaries characteristic of pressure solution.

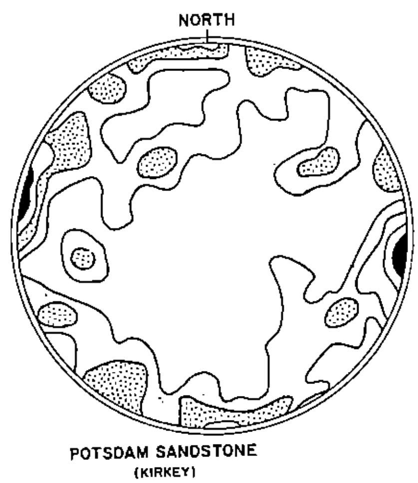

Figure 8
Orientation of poles to microfractures within quartz grains of Potsdam Sandstone at Kirkey. Plane of each diagram is the horizontal surface of the outcrop on which *in situ* strain was measured; data plotted in equal-area, lower hemisphere projection. Microfractures are measured only in a thin section cut parallel with the horizontal plane of the outcrop. Contours are at 6%, 4%, 2%, 1% per 1% area. This diagram is for gauge 3 at Kirkey. Similar microfracture orientations were obtained at Kirkey gauge 2.

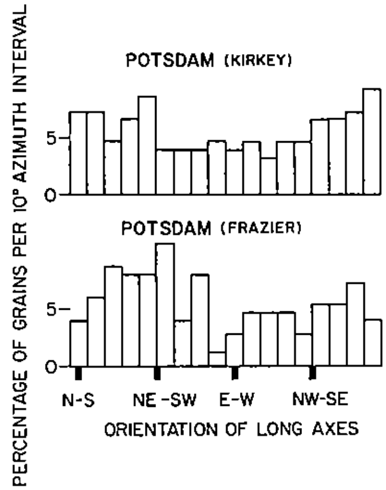

Figure 9
Orientation of long axes of quartz grains in sandstone. Long axes of 150 grains have been measured from each thin section cut parallel to the horizontal plane of the outcrop. Azimuths have been divided into 10° intervals.

The compressional wave velocity and the amount of velocity anisotropy vary from sample to sample (Fig. 10). The highest anisotropy for Potsdam Sandstone occurs in samples from Kirkey which is the only subarkose in which an *in situ* strain measurement was made. Two samples of the subarkose illustrate the variation in velocity between samples. In both cases the anisotropy has the same orientation. The lowest velocity occurred in the Nelson sample which was noticeably more porous than other samples from Alexandria Bay. The fast direction in Nelson is normal to the axis of the postglacial pop-up. One sample from Frazier has a 3% anisotropy whereas another sample has an anistropy of less than 1% (not plotted in Fig. 10).

A core from Frazier with a 3% velocity anisotropy was stressed diametrically in each of six directions to 174 b (Table 2). This load was necessary to achieve radial center strains equivalent to those relieved in the field. From these data compressional wave velocities for each direction in the sample may be estimated using a density of 2.4 gm/cm^2. The sample is elastically anisotropic with the stiffest direction parallel to the direction of maximum expansion upon initial relief. Here the calculated compressional wave velocity anisotropy estimated from static tests is 16% and does not have the same orientation as the measured anisotropy (Fig. 10).

The dynamic tests are probably more indicative of the true anisotropy of Frazier. The static tests are very sensitive to misalignment of the loading anvils and nonlinearity of the rock. Any error in measuring strain (Table 2) is magnified in the calculation of the compressional wave velocity. The orientation of a slight velocity anisotropy of 3% is difficult to find using static tests because of the possibilities for experimental error.

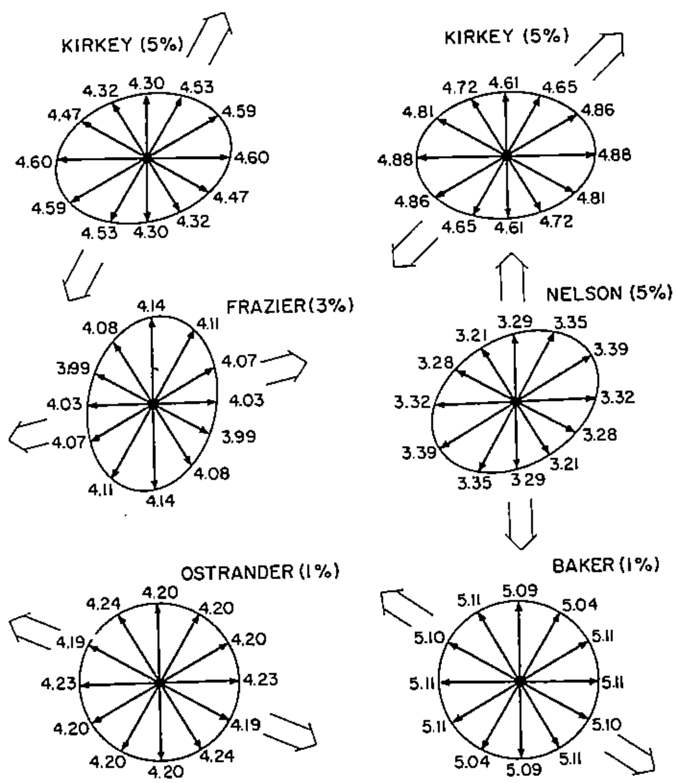

Figure 10

Compressional wave velocities in the horizontal plane of samples of Potsdam Sandstone taken near Alexandria Bay, New York. Units for velocity are km/sec. The orientation of the maximum expansion following initial overcoring is shown with arrows outside each velocity ellipse. Velocity anisotropy is listed next to the name of the sample site. The dimensions and shape of the ellipses are only diagrammatic and do not precisely reflect the velocity anisotropy

Table 2

Potsdam Sandstone (Frazier) (17703 NT)

Direction	N0°E	N30°E	N60°E	N90°E	N60°W	N30°W
$\varepsilon_{r\gamma}$	−248	−215*	−182	−200.2*	−219	−233.5*
$\varepsilon_{\theta\gamma}$	102.5*	104	88.5*	73	87*	101
ν	0.08	0.15	0.15	0.03	0.07	0.10
E	0.41 mb	0.48 mb	0.56 mb	0.50 mb	0.47 mb	0.44 mb
V_p	4.16 km/sec	4.59 km/sec	4.97 km/sec	4.56 km/sec	4.45 km/sec	4.33 km/sec

*) Strains estimated from average of strains at 30° on either side of direction in question.

However, the only fabric of Frazier is a preferred orientation of long grain axes which are more closely aligned with the orientation of the maximum for the static modulus.

5. *Discussion*

Residual strains

As indicated in the companion paper (ENGELDER *et al.* [1]), strain relaxation is influenced by residual strain for some rocks such as the Barre Granite, so care must be exercised in relating strain relaxation to tectonic stresses. The presence of residual strain is indicated by relaxation following internal overcoring. We concluded in the companion paper that residual strains observed during internal overcoring contributed significantly to the relaxation of the initial overcore.

Unlike the Barre Granite, the mechanism associated with the relaxation of residual strain in the Potsdam Sandstone is not obvious. In some cases the strain relieved by the internal overcore is not significantly greater than our experimental error of $\pm 10\ \mu\varepsilon$.

Significant strains were recovered at Kirkey following double overcoring of a subarkose which has an anisotropy (Fig. 10) and a petrographic fabric (Figs. 8 and 9); however, a 60° variation in maximum expansion following internal overcoring and the difference in orientation between the anisotropy and petrographic fabric make it difficult to suggest a unique mechanism for relaxation of residual strain. Opening of microfractures is one possibility but with the preferred strike of about N10°E, the microfractures are not suitably oriented to be the exclusive cause for the relaxation of any of the three internal cores. Another feature unique to the subarkose is a calcite cement which might also contribute to residual strain relaxation in some yet unknown manner.

We observed little, if any, anisotropy which correlates with a relaxation mechanism for residual strain in the quartz arenites (Fig. 10). Evidence for a small anisotropy comes from samples taken at Frazier where quartz grains were deposited with their long axes trending northeast (Fig. 9). The dynamic moduli of samples from Frazier do not reflect this grain shape fabric. However, the static tests indicated that these samples have a high modulus trending N60°E or almost parallel to most preferred orientation of long grain axes (Table 2). Maximum expansion following internal overcoring was normal to the long grain axes or parallel to the low static modulus direction. Yet, because expansion following the initial overcore was parallel to the high modulus direction of the rock, the behavior of cores from Frazier is not comparable to cores taken from the Barre Granite where maximum expansion during both initial and internal overcoring was parallel to the low modulus direction (ENGELDER *et al.* [1]).

One quartz arenite core sampled at Nelson did behave like the Barre Granite relaxing upon internal overcoring with a large component of strain parallel to the maximum expansion during initial overcoring. Although this sample did have a velocity anisotropy its minimum was 30° from the maximum expansion of 'residual' strain, as was the case for Kirkey.

Our conception of the relationship among residual strain, a velocity anisotropy, and a petrographic fabric comes from the behavior of Barre Granite. Basically we found that residual strain occurs in rocks with a strong anisotropy which is the manifestation of a petrographic fabric. This relationship appears to be the same for the Potsdam Sandstone. A subarkose from Kirkey and a quartz arenite from Nelson both have the largest velocity anisotropy and yield significant residual strains which contribute a major component of strain to the initial strain relaxation. We also conclude that residual strain contributed only a small component to the initial strain relaxation of the quartz arenites at Frazier, Baker, and Ostrander.

Outcrop fractures

In the Alexandria Bay region we observed a correlation between magnitude of strain relief and the area of outcrop outlined by vertical fractures (Fig. 6). Outcrops with sets of intersecting open fractures or more complicated fracture patterns have lower recoverable strains. In addition, the relation between maximum expansion and fracture orientation is complicated.

Our hypothesis is that outcrop fractures interrupt tectonic strain transmitted from depth in the lithosphere by reducing the strain magnitude and reorienting the principal axes of this *in situ* strain. These fractures may also partially relieve residual strain, but if residual strain relaxation arises from an interaction with some mechanical element of the rock fabric, as was the case for Barre Granite, a partial relief of residual strain by fracture propagation should not cause its reorientation. Our data support this hypothesis. Although the subarkose at Kirkey was cut by large, open fractures, residual strain as measured after internal overcoring in three different cores had about the same magnitude and orientation. Likewise, large components of residual strain relaxed during initial overcoring; these strains also had about the same magnitude and orientation. The small components of residual strain measured in the quartz arenites from Baker, Frazier, and Ostrander all have maximum expansions in the northwest quadrant. The scatter in magnitude and orientation was about the same regardless of the outcrop fracture length and spacing. The greater intensity of fracturing at Baker or Ostrander did not affect the residual strain relative to that at Frazier.

Considering the magnitude of the relaxation following the initial overcore, there is a direct relationship between the area outlined by vertical fractures and the magnitude at Frazier, Baker, and Ostrander. We interpret this to indicate that more closely spaced and longer fractures interrupt tectonic strain. The spacing of intersecting fractures at Frazier is as much as three meters. This spacing seems to be about the minimum fracture spacing necessary for transmission of a large enough tectonic strain so that strain in blocks separated by vertical fractures is similar in magnitude and orientation. The closer spacing at Baker and Ostrander correlates with an increase in scatter of *in* *situ* strain orientation. This scatter may be caused by open fractures relieving strain normal to the fracture. Outcrops with three or more fracture sets such as Baker, and Ostrander have three or more directions along which tectonic strain could have been relieved near the surface.

Little, if any, tectonic strain was measured at Kirkey. This outcrop contains the longest and most open fractures observed in the vicinity of Alexandria Bay. Although the outcrop contains comparatively large areas outlined by vertical fractures, the fracture sets are apparently long enough, deep enough, or open enough to isolate the outcrop from tectonic strains.

Likewise, the sandstone in the vicinity of the post-glacial pop-up at Nelson contains no component of tectonic strain. Apparently a fairly large volume (10^5 m^3) of sandstone sheared along a bedding plane when the sandstone popped up, thus isolating this volume from tectonic loading. Based on the orientation of the pop-up, the maximum compressive strain prior to its formation was N58°E or parallel to the maximum expansion of the strain relieved at Frazier.

Assuming that the pop-up was an elastic instability, the Euler formula for determining the critical stress for buckling can be used to estimate the ENE directed stress at Nelson (R. PLUMB, personal communication). The thickness of the elastic member which can be measured in the outcrop is 0.5 m (Fig. 1). From laboratory tests we measured a Young's modulus of 0.3 mb. We estimate that the elastic member extends at least 30 m on either side of its axis based on our measurements indicating that the sandstone is detached. Using a length of 60 m and assuming that the member has fixed ends and no side restraints, we calculate a maximum critical buckling stress of 260 bars. The critical stress decreases for longer members. We assume that after buckling the sandstone member collapsed by breaking along vertical fractures.

Regional stress

Our data suggest that tectonic strain at depth in the lithosphere is transmitted to the surface. The strain relief at Frazier appears to be influenced the least by outcrop fractures and residual strain. The ENE trend of the maximum elongation for strain at Frazier is the same as the orientation of the maximum compressive stress as inferred from post-glacial pop-ups and fault plane solutions in New York State (SBAR and SYKES [2]). This maximum compressive stress is believed to be a manifestation of a uniformly oriented regional stress pervading the lithosphere in the northeastern United States.

Strain in the N60°E direction was 200 $\mu\varepsilon$ at Frazier. If Young's Modulus in that direction is on the order of 0.5 mb (Table 2), we have relieved a stress of 100 b at the surface. Many authors have presented graphs showing horizontal stress as a function of depth. In curves such as that shown in HERGET [17] the horizontal stress is about 100 bars at the surface.

Near Alexandria Bay only one outcrop of five sampled appears to contain a significant tectonic strain. Thus we conclude that fractures decouple outcrops from tectonic strain.

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Acknowledgement

This work was supported by contracts with the New York State Energy Research and Development Authority and Nuclear Regulatory Commission plus National Science Foundation Grants EAR-74-07923 and DES-75-03640. John Beavan and Tracy Johnson reviewed the manuscript.

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(Received 11th November 1976)