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A Mechanism for Strain Relaxation of Barre Granite: Opening of Microfractures[1]

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Summary – Strain relaxation in the Barre Granite and surrounding metasediments in Vermont, was measured by overcoring strain gauge rosettes bonded to outcrop surfaces. The average maximum expansion upon relieving 15.2 cm diameter cores trends N55°W, while the average maximum expansion of 7.6 cm diameter cores coaxial with 15.2 cm cores trends N70°W. The maximum strain relief of the internal overcores is normal to the microfracture fabric. Therefore, the mechanism of strain relaxation is attributed to the opening of microfractures either parallel to the rift direction of the Barre Granite or parallel to the foliation of the metasediment. The lack of parallelism between the normal to the rift plane and the maximum expansion of the initial overcore suggests an externally applied strain superimposed on the strain caused by opening of microfractures.

Key words: Stress *in-situ*; Microfracture strain; Strain relaxation; Residual strain.

1. Introduction

The strain relaxation data presented in this paper come from one of nine suites gathered in various areas of the northeastern United States (Fig. 1). In addition to a companion paper (Engelder and Sbar [1]) and Engelder and Sbar [2] other data suites will be published in the near future. In gathering these data we hope to evaluate surface strain relief techniques as a means of measuring stress near the surface of the crust. An initial step in the evaluation of surface strain relief data is to understand the rheological processes occurring during overcoring. Out data from Barre, Vermont, are relevant to this problem.

The relaxation of *in situ* strain which can be observed during overcoring experiments amounts to more than the simple rebound of an isotropic elastic body cut free from its boundary loads. Several relaxation mechanisms contribute either to components of instantaneous or time-dependent recovery of *in situ* strain (Varnes and Lee [3], Nichols and Savage [4]). These mechanisms may be either elastic or inelastic; the latter may occur instantaneously or as a function of time. An important characteristic of *in situ* strain is that it can also be recovered from a rock free of boundary loads. This phenomenon can be attributed to 'residual' stresses locked in a rock during its burial. Voight [5] recognized that rocks as well as metals contain

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significant that an attempt was made to recover a strain inside a freed block rather than at or near the surface of the block. Using the CSIR strain cell which detects surface strains at the bottom of a borehole, GREINER [personal communication, 1976] did not measure a residual strain in Mesozoic limestones north of the Alps.

In this paper, we present further data from the strain relaxation of Barre Granite and surrounding metasediments in the vicinity of Barre, Vermont. HOOKER and JOHNSON [15] used the Bureau of Mines borehole deformation gauge to measure stress in the Barre Granite. Experience with Barre Granite by NICHOLS [11] suggested that we might detect a residual strain at the surface of Barre Granite.

2. *The Barre Granite*

The Barre Granite intrudes a quartzite-phyllite containing Middle Silurian to Lower Devonian fossils. A standard view is that the phyllite is the Gile Mountain Formation after WHITE and JAHNS [16]. This phyllite was subjected to staurolite-zone metamorphism and folded during the Middle Devonian Acadian orogeny. The Barre Granite belongs to the Late Devonian Plutonic Series (PAGE [17]) which includes a group of late post-tectonic plutons, differentiated at depth and emplaced in part by shouldering aside their walls and in part by stoping. In the vicinity of the Barre Granite quarries, the Gile Mountain Formation has a N20°E striking foliation which dips steeply to the west. The Barre Granite's rift direction strikes about N30°E, almost parallel to the foliation of the surrounding metasediments.

The modal composition of Barre Granite is: quartz – 25%; potash feldspar – 20%; plagioclase – 35%; biotite – 9%; muscovite – 9%; and accessories – 2% (CHAYES [18]). The granite has marked mechanical anistropy which parallels the rift plane and correlates with the preferred orientation of microfractures and fluid inclusions [DOUGLAS and VOIGHT [19]). Barre Granite has an orthorhombic symmetry delineated by sonic velocities; the fastest direction is parallel to the rift plane (BUR *et al.* [20]). Residual strains have been observed on the microscopic scale by X-ray techniques (FRIEDMAN [8]) and on a macroscopic scale by overcoring relaxation techniques (NICHOLS [11]). The granite contains large strains relieved during quarry operations with maximum expansion normal to the rift plane (WHITE [21]) and microfracture fabric.

3. *Strain relief of Barre Granite*

Experimental procedure

In situ strain was measured by overcoring three component (60°) foil-resistance strain gauge rosettes bonded to the horizontal rock surface (FRIEDMAN [8], BROWN [22], SWOLFS *et al.* [10], ENGELDER and SBAR [2]). Strain relaxation accompanied the quarry depth (80 m) from the lip of the Smith quarry, whereas the one labelled Wetmore was 20 m from the lip. The outcrop labelled Adam was located 150 meters from the lip of the Adam quarry.

The strain relaxation of Barre Granite

The greatest strain relaxation occurred at Hilltop where the orientation of maximum expansion for three measurements clustered within 5° of N50°W. At Adam, the orientation of maximum expansion varied up to 28° about N68°W. The lowest strain was recovered from Wetmore where the orientation of maximum expansion seemed random. The orientation of maximum expansion was more consistent among measurements at places where larger strains were relieved. In areas of smaller strain relief the magnitude of the relieved strain varied considerably.

At Hilltop the orientations of maximum expansion obtained by the external and internal overcore were within 25° of each other, but the magnitude of the internal strain relief was at least 75% smaller than the initial overcore. With the exception of one measurement from Hilltop, all internal overcores were performed within 3 days of the initial external overcore. At Adam, the orientation of maximum expansion

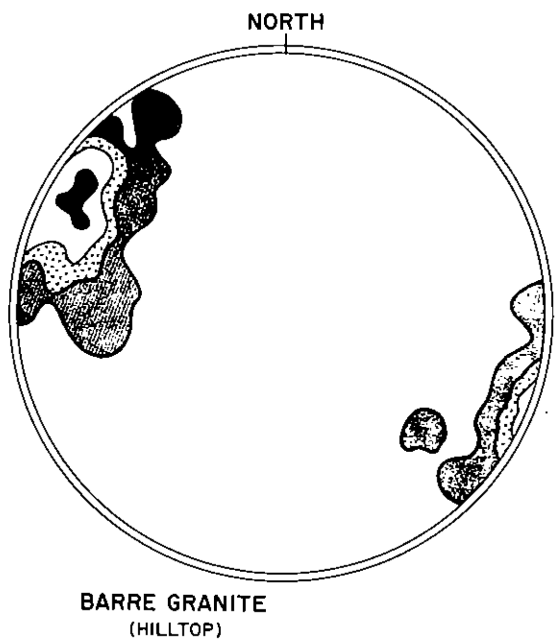

Figure 3
Orientation of 100 poles to microfractures within quartz grains of Barre Granite from Hilltop. Plane of each diagram is the horizontal surface of the outcrop on which *in situ* strain was measured; data plotted in equal-area, lower hemisphere projection. Microfractures are measured only in a thin section cut parallel with the horizontal plane of the outcrop. Contours are at 15%, 10%, 5%, 1% per 1% area.

strain sites is illustrated in Fig. 4. The compressional wave velocity is related to the orientation of the rift plane and preferred orientation of microfractures in Barre Granite. The velocity is fastest parallel to the rift or foliation planes and slowest normal to these planes. The compressional wave velocity anisotropy varies among the *in situ* strain sites. The greatest difference, 53%, occurs in the metasediment and the least, 3%, is found at Adam. Samples taken from approximately the same position in the pluton, Wetmore and Hilltop, have nearly the same compressional wave velocities and velocity variation with direction whereas the sample, Adam, is different. In all instances the maximum expansion upon overcoring was sub-parallel to the direction of the lowest compressional wave velocity.

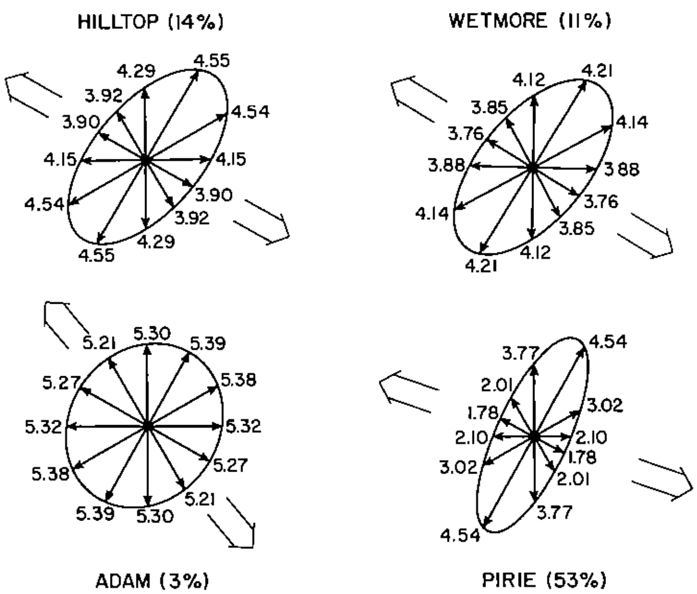

Figure 4

Laboratory measurements of compressional wave velocities in the horizontal plane of samples taken near Barre, Vermont. 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. Samples from Hilltop, Adam, and Wetmore are Barre Granite. Sample from Pirie is a metasediment.

To determine the static moduli, uniaxial compression tests were used. Because the moduli across the diameter of the cores were of greatest interest, the cores were loaded in each of six directions normal to the core's axes. The twelve flats ground on the sides of the cores are also necessary to accommodate the loading anvils. The load was monitored with a calibrated beryllium–copper load cell; shortening across the diameter of the cores was measured with a linear variable differential transformer transducer. Strain gauge rosettes with components at 60° were monitored to measure

For a comparison with the dynamic properties of the rocks the compressional wave velocity (V_p) may be estimated using the relation:

$$V_p^2 = \frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)\zeta}$$

where ζ is the density of the rock.

Three assumptions necessary for the calculation of ν and E are: (1) each component of the strain gauge rosette measures strain at the center of the core, (2) strain in some directions can be computed by measuring strain along other directions, and (3) E and ν are the same for small strains in compression and tension. The first is necessary because the components of a strain gauge rosette are not centered, but all are no more than $\frac{1}{5}$th of a radius away from the axis of the core. In addition, radial strain on the x axis is actually measured rather than tangential strain on the y axis. At the center of the core the two are equal. The second assumption is made because both the radial normal strain (ε_{ry}) and the tangential normal strain ($\varepsilon_{\theta y}$) are necessary in order to calculate Poisson's ratio in a particular direction. With a strain gauge rosette of three components bonded to the end of our cylinder, it is possible to measure just three of six components of both ε_{ry} and $\varepsilon_{\theta y}$. The other three components of each are estimated by averaging the two components at 30° from the unknown component.

Data from diametrical loading of cores at 30° intervals around the axes are listed in Table 1. Cores from Hilltop and Adam were tested. Tests on the metasediment from Pirie failed because of the cores' tendency to split along foliation when loaded

Table 1

Barre granite (Hilltop) (17,703 NT)

Direction	N0°E	N30°E	N60°E	N90°E	N60°W	N30°W
$\varepsilon_{ry} \times 10^{-6}$	−331	−298*)	−249	−373*)	−498	−414*
$\varepsilon_{\theta y} \times 10^{-6}$	+201.5*)	+269	+232.5*)	+196	+165*)	+134
ν	0.26	0.46	0.96	0.18	~0.00	~0.00
E	0.31 mb	0.32 mb	0.36 mb	0.26 mb	0.20 mb	0.25 mb
V_p	3.82 km/sec	ν too high for calculation		3.30 km/sec	2.77 km/sec	3.10 km/sec

Barre granite (Adam) (17,703 NT)

Direction	N0°E	N30°E	N60°E	N90°E	N60°W	N30°W
$\varepsilon_{ry} \times 10^{-6}$	−171	−160*)	−148	−162*)	−175	−173*)
$\varepsilon_{\theta y} \times 10^{-6}$	77.5*)	81	77.5*)	74	74*)	74
ν	0.12	0.17	0.18	0.13	0.09	0.10
E	0.60 mb	0.65 mb	0.69 mb	0.65 mb	0.58 mb	0.60 mb
V_p	4.96 km/sec	5.12 km/sec	5.31 km/sec	5.04 km/sec	4.71 km/sec	4.80 km/sec

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

for the strain relaxation of crystalline rocks near Atlanta, Georgia. Our interpretation is based on the similarity of orientation among the strain relief, the microfractures, dynamic properties and static properties of the Barre Granite.

A load of 17,703 N on our cores is equivalent to a stress of about 100 bars at the center of the core. For the same stress loaded axially on cylinders of Barre Granite, DOUGLAS and VOIGHT [19] found that Young's modulus varied with direction between 0.23 and 0.41 mb. These values are similar to those obtained with our cores from Hilltop. Douglas and Voight conclude that the mechanical anisotropy of Barre Granite is produced by small preferentially oriented cracks parallel to the rift.

The diametrical loading behavior of Barre Granite is compatible with a rock containing a set of microfractures which influence the mechanical properties of the rock. A load normal to the microfractures will close them with comparatively little strain normal to the load, thus giving the granite a very low ν in that direction. Likewise, their closure during loading gives the granite a low E perpendicular to the microfractures because the microfractures have a low stiffness. In contrast a positive load parallel to the plane of the microfractures will tend to open the fractures. This behavior is manifest as an anisotropic ν. E and ν are both relatively higher for loading parallel to the microfractures.

A compelling reason for suggesting that a mechanism for the strain relaxation of the internal overcore in Barre Granite is the opening of cracks is that the orientation of maximum expansion is at right angles to the strike of the predominant orientation of microfractures. Two additional observations support our contention that microfractures relax upon overcoring.

We have identified a relationship between the numbers of open microfractures per unit volume and the magnitude of strain components upon internal overcoring. Thin sections from Adam had fewer open microfractures than observed in thin sections from Hilltop. The magnitude of the strain relieved by the internal overcores at Adam is much smaller than that relieved at Hilltop (Fig. 2). The rock with the larger number of microfractures per unit volume has the larger component of strain relaxation.

Second, the orientation of *in situ* strain relief at Adam is not as consistent as at Hilltop (Fig. 2). In samples from Adam we measured fewer microfractures per unit volume which were more randomly oriented compared to microfractures in Hilltop samples. This is confirmed by laboratory velocity measurements. The larger compressional wave anisotropy at Hilltop is a manifestation of a stronger preferred crack orientation whereas the higher velocities at Adam are manifestations of a smaller number of microfractures per unit volume. If the mechanism for strain relaxation is the opening of microfractures, we would expect the orientation of total strain relaxation to vary from sample to sample at sites which lack a strong preferred orientation of microfractures.

Samples from Wetmore and Hilltop have similar microfracture fabric, and dynamic and static characteristics, yet their *in situ* strain measurements do not correlate.

exposed to weathering this residual stress may be partially relieved by the opening of microfractures.

Upon internal overcoring, Barre Granite at the Hilltop site expanded perpendicular to its microfracture fabric in response to the relaxation of a residual strain. However, there was a lack of parallelism between the normal to the rift plane or microfracture fabric and the maximum expansion direction of the initial overcore. One explanation for this is the presence of an externally applied strain of undefinable magnitude superimposed on the strain relieved by the opening of microfractures, and having principal axes incongruent with the strain relieved by the internal overcore. Alternatively, the residual strain axes may become reorientated after the initial overcoring, making it impossible to separate applied and residual strains.

7. *Conclusion*

The measured direction of maximum expansion at the surface of Barre Granite is normal to the rift plane originating in the preferred orientation of microfractures. These measurements are in agreement with similar measurements made by SWOLFS [29] in the floor of the Wetmore Quarry. The dominant mechanism of strain relaxation at the surface of Barre Granite is the opening of microfractures.

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These data illustrate the inconsistency which may occur between outcrops of rocks which have similar mechanical properties. Unlike data from the other three sites there is no pattern among relaxation of the three 15.2 cm cores or between the 15.2 cm core and the subsequent internal overcore at Wetmore. Because there is no pattern we suspect that the data from Wetmore is of poor quality, although an explanation for this is qualitative. The lip of a 50 m deep quarry was only 20 m from the sample site and quarry operations will have relieved some of the strain prior to our measurement. A major sheeting fracture parallel to the surface or extreme surface weathering could also alter the strain boundary conditions. Finally, there may be a real difference between *in situ* strain or strain relaxation mechanisms from point to point in the Barre Granite as was suggested by NICHOLS [11].

Thin sectioned samples from Hilltop generally contain one open microfracture per mm and can have as many as five open microfractures per mm. In order for the Barre Granite to relax by 400 $\mu\varepsilon$, one microfracture per mm would have to open by 0.4 μm. Cracks opened to 0.4 μm or more are commonly observed in rocks such as a granite (BRACE *et al.* [28]). Thus a strain of 4×10^{-4} could be reasonably accounted for by the opening of microfractures.

X-ray diffraction studies of fresh Barre Granite indicate that quartz crystals in the granite are elastically distorted with their greatest elongation normal to the rift plane (FRIEDMAN [8]). Individual grains removed from the rock (say by overcoring) will therefore have a maximum contraction normal to the rift plane. Total strains produced in this manner will be on the order of 10^{-4}. NICHOLS [11] found the strain relief associated with internal overcoring of an unweathered block of Barre Granite to be compatible with the strain locked into the quartz crystals. The maximum contraction of one of his cores was normal to the rift plane of the block. Since we relieved strains which caused expansion of the core, and since we attribute this expansion to the opening of microfractures, it is quite possible that the internal system of stresses prior to overcoring was altered by weathering, so that prior to overcoring, individual grains were already relieved to some extent.

Weathering may have several effects, among which are the chemical and physical alteration of crack surfaces to decrease their tensile strength[4]) and/or elastic stiffness. The cracks may start to open in response to the residual elastic elongation of the quartz grains and further open when boundary restraints are removed by overcoring. The stiffness of cracks or grains with cracks may be orders of magnitude less than the stiffness of whole grains. This difference in stiffness would result in a net expansion normal to the rift plane counteracting the tendency for unfractured crystals to contract.

Even in the absence of boundary loads internal stresses prior to overcoring are necessary to produce a net strain upon overcoring. By definition these stresses are residual and may be manifest in Barre Granite by elastic distortion. In Barre Granite

[4]) Many cracks in Barre Granite are healed and may have a certain tensile strength.

parallel to the foliation. Each direction was stressed to 174 bars which was necessary to restore the strain released by overcoring.

General comments concerning the static tests are (1) an equivalent load in the N60°W direction on Hilltop, Adam and Pirie cores restored strain nearly equal to that relieved at each of the three sites; (2) when loaded in certain directions cores from Hilltop yielded unreasonable Poisson's ratios (>0.5) and (3) when it is possible to calculate a compressional wave velocity from static data, the calculated velocity varies with direction much like the measured velocity but the calculated velocity is slightly slower than that measured.

5. *Residual strain*

For strain relaxation measurements conducted on Potsdam Sandstone, any strain recovered by an internal overcore into a body without boundary loads is defined as residual strain, regardless of the mechanism of strain relaxation or how the strain was imposed on the rock body (ENGELDER and SBAR [2]). This notion of residual strain in rock is more general than the standard definition as outlined by FRIEDMAN [8] and VOIGHT and ST. PIERRE [6]. A standard notion of residual strain comes from the metals literature where MCCLINTOOK and ARGON [26] define residual strains as recoverable elastic distortions of constituent crystals or grains that satisfy internal equilibrium conditions and that exist in a given volume of rock with no external boundary loads. FRIEDMAN [8] envisions a two component system: (1) elastically distorted crystals, reflecting previous loads, that are locked into the aggregate by (2) other elastically distorted crystals or cement. We suggest that this hypothetical system be modified to include non-elastic distortions and further expanded so that microfractures within crystals or cement be considered as a low modulus component. FRIEDMAN points out [8, page 299] that if one part of the residual strain system consists of low modulus elements, these low modulus elements will yield relatively large strains and dominate the total strain relaxation, even though the internal forces causing the strains in high and low modulus elements are opposite and equal. Furthermore, if the low modulus element has a non-random fabric, such as the microfractures in Barre Granite, then that fabric will control the orientation of strain relaxation.

Residual strains are imposed on a rock when crystals become elastically distorted in response to paleotectonic, paleotopographic, and thermal and chemical histories of the rock (see page 301; FRIEDMAN [8]). Because our measurements, were made at the surface, we cannot exclude the possibility that recoverable strains (residual strains) were generated by physical and chemical processes associated with weathering and may reflect a non-random fabric.

6. *Mechanisms of strain relaxation*

We suggest that the opening of microfractures in the Barre Granite is one major mechanism of strain relaxation. This is the same conclusion reached by NORMAN [27] strain at the center of the core. Although flats were ground parallel to the core axis, we assume as an approximation that we are loading a finite cylindrical core across its diameter.

The stresses and strains inside a cylinder loaded radially may be determined using the Airy stress function expressed in terms of two analytic functions of a complex variable $z = x + iy$ (JAEGER and COOK [24]). In this boundary value problem, the normal and tangential stresses applied to the boundary can be represented by a Fourier series. The solution of the Airy stress function by HONDROS [25] indicates a complicated stress and strain distribution inside the cylinder (Fig. 5). Because of the

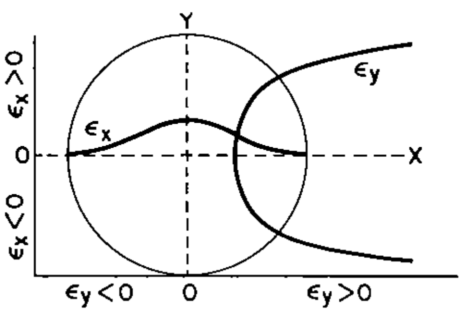

Figure 5
Theoretical strain distribution along the vertical (OY) and horizontal (OX) diameters of a cylinder loaded along the vertical diameter (HONDROS [25]). ε_x and ε_y – radial strain at points on the OX and OY axes.

complicated strain pattern inside the cylinder the ratio of load to diametrical shortening is not an accurate measure of the elastic moduli. However, calculation of the Young's modulus and Poisson's ratio is possible using center strains and the equations derived by HONDROS [25]:

$$\nu = -\left[\frac{\varepsilon_{ry} + 3\varepsilon_{\theta y}}{2(\varepsilon_{ry} - \varepsilon_{\theta y})}\right]$$

and:

$$E = \frac{2P(1 + \nu)(1 - 2\nu)}{\pi D t[\nu\varepsilon_{ry} + (1 - \nu)\varepsilon_{\theta y}]}$$

where ε_{ry} = radial normal strain at a point on OY axis
$\varepsilon_{\theta y}$ = tangential normal strain at a point situated on the OY axis
D = cylinder diameter
P = applied load
ν = Poisson's ratio
E = Young's modulus
t = cylinder length

following the internal overcore differed as much as 41° from that of the initial overcore and the strain was either a small expansion or contraction. The orientation of maximum expansion after the internal overcore at Wetmore was almost normal to the initial maximum expansion and the magnitudes of the axes of the strain ellipse were all less than 25 $\mu\varepsilon$ in either expansion or contraction.

The rift of the Barre Granite strikes N30°E (DOUGLAS and VOIGHT [19]). The average of three initial overcores at Hilltop shows a maximum expansion oriented approximately N50°W, which is 10° more northerly than the normal to the preferred orientation to microfractures (Fig. 3). However, the bisector of the angle of the two most divergent orientations of maximum expansion of the internal overcore, N63°W, is within 3° of the normal to the strike of the rift plane. At Adam, the average of the directions of maximum expansion was about normal to a poorly defined rift plane oriented between N30°E and N39°E. Finally, we observed no relation between the orientation of maximum expansion at Wetmore to the rift plane cited in the literature.

Strain relief of two cores at Pirie in the Gile Mountain Formation consisted of a maximum expansion of 1292 and 1342 $\mu\varepsilon$ with an orientation of N69°W and N73°W (Fig. 2). Relief following one internal overcore was larger (1500 $\mu\varepsilon$) than the initial overcore with axes of the strain ellipse oriented 10° counterclockwise from those of the initial strain relief. The maximum expansion of the internal overcore was approximately normal to the strike of the foliation of this metasediment.

4. *Laboratory analysis*

We subjected our cores to mechanical tests and petrographic analyses to define a mechanical anisotropy in the plane in which strain relaxation was measured. Information on the mechanical anisotropy and data from the internal overcore yield clues concerning the mechanisms contributing to the strain relaxation of the Barre Granite.

Open microfractures and closed microfractures outlined by fluid inclusions are strongly oriented parallel to the rift plane of the Barre Granite (Fig. 3). At Hilltop the maximum concentration of poles to microfractures indicates that most microfractures strike within a few degrees of N30°E. At Hilltop the internal overcore for two samples gave maximum expansions within 2° of the normal to the preferred strike of the microfractures. Microfractures are also strongly oriented at Wetmore and Adam. However, the latter has fewer open microfractures.

To define the mechanical anisotropy across the diameter of our 7.6 cm cores in the laboratory we used both dynamic and static tests. The former consisted of measuring the compressional wave velocity using the pulse matching technique described by MATTABONI and SCHREIBER [23]. In order to mate the barium titanate transducers to the core, we ground twelve flats parallel to the axis, thus allowing us to measure the pulse velocity in six directions at 30° intervals parallel to the plane of strain relief.

The compressional wave velocities for one sample from each of the four *in situ* cutting of a vertical 15.2 cm diameter core to a depth of 20 cm using a diamond masonry bit. A 7.6 cm diameter core coaxial to the 15.2 cm core was cut to further relax residual strain (SWOLFS *et al.* [9], NICHOLS [11]).

Strain relaxation following relief of the rock and thermal effects are primarily responsible for total strain changes recorded over a period of days. Thermal effects can occur because the self compensation of a strain gauge for a temperature change is rarely perfect. However, by using a switching box, a number of strain gauges can be balanced against the same compensation gauge in the second arm of a half bridge. When bonded to a rock, these gauges have approximately the same thermal drift. To further reduce thermal contamination of the strain data, we subtract the thermal strain changes of a compensated, but unovercored, gauge (or the average of several gauges) from the strain changes of each overcored gauge. To obtain enough readings for a reliable correction we monitor the gauges for several days before and after overcoring. In practice this correction for thermal drift is not perfect but minimizes thermal effects so that we can resolve a strain relaxation of $\pm 10\ \mu\varepsilon$ ($1\ \mu\varepsilon$ = a strain of 10^{-6}).

Three outcrops of Barre Granite were selected for strain relief measurements (Fig. 2). The outcrop labelled Hilltop was located at a distance of more than one

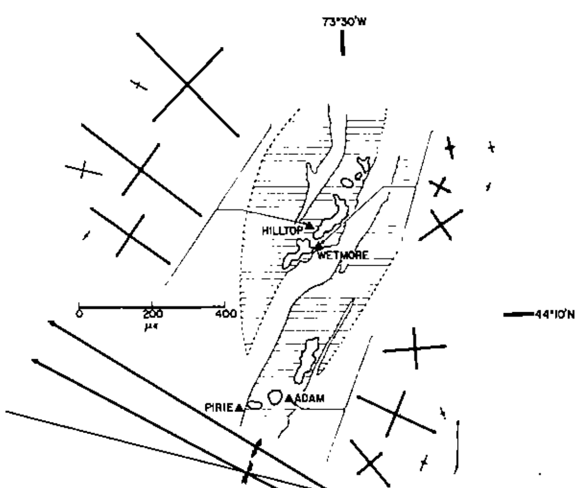

Figure 2

Geology and *in situ* strain in the vicinity of the Barre Granite quarries, Vermont. Outcrops of Barre Granite are indicated by hatch marks. A Paleozoic metasediment surrounds the granite. Four 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 lines represent expansion and dashed lines represent contractions. A scale for the magnitude of the relieved strain is given in microstrain ($\mu\varepsilon$). Quarries are shown within hatch marks.

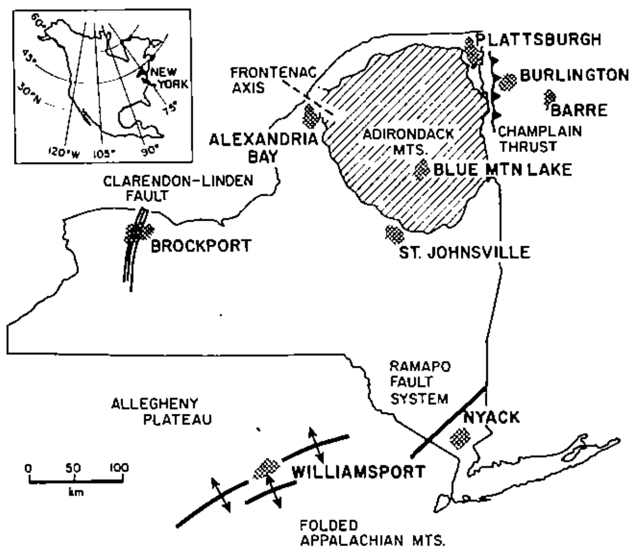

Figure 1
Nine localities, indicated by hatch marks, where *in situ* strain has been measured.

these residual stresses or 'systems of stresses on the inside of a body which are in equilibrium, or approach equilibrium, when neither normal nor shear stresses are transmitted through its exterior surfaces'.

Complications arise from using the strain relaxation of rocks for the purpose of stress measurements because of the difficulty of distinguishing between residual strain and strains caused by tectonic forces which are boundary loads. Moreover, residual strain may mimic elastic strains caused by boundary loads. However, residual strains may contain useful information concerning the tectonic history of the rock (VOIGHT and ST. PIERRE [6]).

Residual strains have been detected using techniques for measuring biaxial strain parallel to free faces of rock (HOSKINS *et al.* [7], FRIEDMAN [8], SWOLFS *et al.* [9], [10], NICHOLS [11], ENGELDER and SBAR [2]). GALLAGHER *et al.*'s [12] photoelastic experiments and SWOLFS *et al.*'s [9], [10] experiments in Cedar City quartz diorite suggest the complex nature of residual strains in rocks and demonstrate that upon cutting a body containing residual strains the largest strain changes occur near the fresh surface. Likewise, NICHOLS' [11] experiments with a block of Barre Granite demonstrate that surficial strains occur on all surfaces during the cutting of fresh surfaces into a rock containing residual strains.

Residual strain is not a universally observed phenomenon in rocks which are free at their boundaries. Using the borehole deformation gauge, HOOKER and DUVALL [13] report an absence of any stress field in a freed slab of porphyritic granite gneiss at Arabia Mountain, Georgia. With the same gauge, MORGAN *et al.* [14] failed to detect any relaxation in a free block of trona from Westvaco, Wyoming. In such cases it is