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Near-Surface in Situ Stress
3. Correlation With Microcrack Fabric Within the New Hampshire Granites

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We studied the correlation between near-surface in situ stress and the preferred orientation of microcracks at two quarries in the Milford granite and one quarry in the Conway granite, New Hampshire. The orientation of in situ stress was determined by overcoring doorstoppers and from the strike of induced borehole fractures produced by a pressurized packer. The preferred orientation of vertical microcracks was determined using ultrasonic measurements to determine P wave velocity V_p on core and in situ and from thin section analyses. In situ V_p anisotropy was determined from interborehole travel time data. At all three sites, directions of maximum compressive stress σ_1 and induced borehole fractures are aligned with the preferred orientation of open microcracks determined from core V_p and thin section data. An analysis of the microcracking sequence within each pluton suggests (1) that the quarry grain resulted from cooling-induced thermal stresses and (2) a method of distinguishing the paleostress axes at the time of cooling from contemporary stress.

INTRODUCTION

New England granites are characterized by a microcrack fabric that allows quarrymen to split the granite in a consistent and predictable manner. Quarrymen refer to the two easiest directions of splitting as rift and grain [*Sedgwick*, 1835; *Tarr*, 1891; *Whittle*, 1900; *Dale*, 1923] (Figure 1). In this paper we discuss the role of rift and grain microcracks in the development of in situ stress at three new England granite quarries.

Our hypothesis is that the orientations of rift and grain record the orientation of paleostress fields. Rift and grain microcracks are mode 1 cracks by virtue of displaying no shear offset. As such, the normal to the crack plane represents the orientation of the least principal stress at the time of crack formation. Since rift and grain cracks are orthogonal, at least two microcracking episodes have occurred, between which the least principal stress must have rotated 90°. This reorientation of the stress field may have accompanied a punctuated cooling of the granite pluton. Our hypothesis stems from the work of *Dale* [1923], who recognized the influence of crustal strain on producing a preferred orientation of fluid inclusions. Dale, however, suggested that after consolidation of the granite, rift and grain cracks propagate along planes of weakness afforded by fluid inclusion sheets. More recent work on the petrology of fluid inclusions suggests that they are healed microcracks [*Tuttle*, 1949; *Wise*, 1964; *Douglas and Voight*, 1969; *Richter and Simmons*, 1977; *Sprunt and Nur*, 1979]. *Sprunt and Nur* [1979] recognized planar domains in quartz crystals aligned with sheets of fluid inclusions. Using cathodoluminescence colors, Sprunt and Nur concluded that some planar domains represented microcracks that healed at a temperature lower than the granite crystallization temperature.

It is difficult to test our hypothesis by any direct method, but the validity of the hypothesis may be inferred from an understanding of three aspects of rift and grain: (1) their regional extent, (2) the degree to which their orientation reflects a paleostress distinct from an independent contemporary stress, and (3) their influence on magnitude and orientation of in situ stress. The significance of rift and grain is that as a rock fabric, it may have a common orientation over a large region [*Wise*, 1964]. Our interpretation of rift and grain is that microcracks with a common orientation grew under the same regional stress field while the host rock was cooling. We postulate a two-component stress field to explain the origin of a single microcrack fabric. The first is a deviatoric regional stress field which controls the orientation of the cracks. The orientation of this stress field is constant during microcracking. The second component is a quasi-isotropic stress caused by cooling of the granite. At the grain scale this cooling set up tensile stresses that induce microfracturing in the quartz normal to the regional least principal stress.

Rift and grain provides the context within which we propose to separate the orientations of the paleostress and contemporary stress fields. If the age of the microcracks constituting rift and grain can be determined, then the orientation of the stress field at a particular time in the history of the cooling granite pluton is known. If the microcracks were sufficiently old (say greater than 10 m.y.), the indicated stress field might

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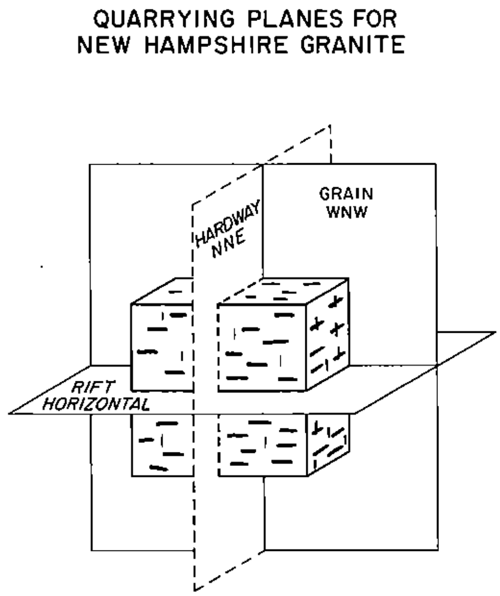


Fig. 1. Diagram of the orthogonal rift, grain, and hardway planes showing their approximate geographic orientation within most New Hampshire granites and their association with orthogonal microcracks (dashes).

be called a paleostress field. General techniques, however, for dating microcracks have yet to be developed beyond the crude inferences from either abutting relationships or from filled microcracks which are older than open microcracks provided both are otherwise identical.

Another aspect of rift and grain concerns the relationship between rift and grain and the relative magnitudes of in situ stress. A study of this relationship is tractable with available technologies and provides the most direct test of our hypothesis. The major purpose of this paper is to describe our strain relaxation experiments in two granite plutons in order to document the relationship between microcrack fabric and in situ stress. The two granites, the Pennsylvania Milford granite and the Jurassic Conway granite, both located in New Hampshire, have well-defined rift and grain.

In situ experiments performed at each of three sites included doorstopper strain relaxation measurements, borehole fracturing tests, and in situ P wave velocity measurements [*Sbar et al.*, 1979; *Plumb*, 1983, *Engelder and Plumb*, 1984]. For purposes of this paper we are concerned with stress orientation in the horizontal plane. Because all measurements were made near the horizontal free surface (depth < 2), one of the principal stresses is assumed to be vertical. The maximum and minimum horizontal strain and stress are denoted by the subscripts 1 and 2, respectively. Borehole fracturing tests respond to stress in a larger volume of rock than that affecting doorstopper gauges. The fracturing tests were done to verify the stress orientation determined by doorstopper gauges.

Laboratory measurements included compressibility and P wave velocity tests on doorstopper cores [*Sbar et al.*, 1979; *Plumb et al.*, this issue]. We determine a pseudolinear compressibility by compressing a core about its circumference [*Sbar et al.*, 1979]. The compressibility measurements allowed us to make a first-order correction for the effect rock anisotropy has on the orientation of stresses. Variations observed in any parameter are due to the inhomogeneity of the granite: the smaller the sample size, the greater the variability.

To check the preferred orientations of microcracks inferred from mechanical tests, thin sections were analyzed with a universal stage microscope. Because we were interested in the variation of stress and mechanical properties in the horizontal plane, all thin sections were cut parallel to the horizontal plane, which in New Hampshire is the rift plane (Figure 1). Microcracks counted included both healed (planes of fluid inclusions) and unhealed cracks [*Tuttle*, 1949; *Wise*, 1964]. We distinguished between cracks in feldspar and quartz and whether the cracks were healed or open, transgranular or intragranular, or aligned with cleavage or twin planes. Poles to all prominent microcracks encountered in traverses of the thin section were plotted on equal-area stereographic projections. The cracks that were plotted on stereonets are intragranular cracks not preferentially aligned with any crystallographic plane of weakness. Transgranular cracks were few by comparison to intragranular cracks and were not well oriented on the scale of a thin section.

We preface our description of the experiments with a summary table showing the correlation between stress directions and fractures found at each site (Table 1).

MILFORD GRANITE: SITE 1

Two of the three sites (sites 1 and 2 in Figure 2) are located near Milford, New Hampshire, in the Milford granite, a light gray massive medium-grained biotite granite of Pennsylvanian age [*Aleinikoff*, 1978; *Aleinikoff et al.*, 1979; *Foland and Faul*, 1977]. Site 1 (called the Kittledge Quarry by *Dale* [1923]) is owned and operated by the Barretto Brothers Granite Company of Milford, New Hampshire. Our drill site was on the quarry floor approximately 30 m below ground level. Conspicuous features of the granite include a well-developed horizontal rift and vertical grain striking N75°W, an aplite dike (N63°W, 30°S), and a mafic dike swarm oriented subparallel with the quarry hardway (Figure 3). Sheet fractures arch with the topography and increase in spacing with depth. The sheets dip gently east-southeast and are at least 3 m thick at the drill site.

In situ experiments at site 1 were made in shallow 7.6-cm (3 inch) diameter boreholes drilled into the quarry floor. The drill site was located to minimize the effects of stress concentrations caused by the pit boundaries (Figure 3*a*). This location was close to a 5-m-wide aplite dike (N65°W, 30°W) which is cut by the early Mesozoic mafic dike (N25°E) [*Aleinikoff*, 1978; *McHone*, 1978]. The aplite was interpreted as a primary igneous structure since the strike is normal to the local flow banding in the quarry [*Balk*, 1937]. It has a biotite flow foliation parallel with the contacts; however, rift and grain in the aplite are identical with the host granite. This is evidence that rift and grain are younger than the aplite dike and are not related to the biotite foliation.

In a thin section cut parallel to the rift plane the preferred orientation of microcracks observed is coincident with the quarry grain reported by *Dale* [1923] (Figure 4*a*). Micro-

TABLE 1. Summary of Results: Correlation Between Fracture Direction and Stress Direction

Site	σ_1	V_{pmax} Core	V_{pmax} In Situ	Fractures Packer-Induced	Fractures Natural
1	N67°W	N75°W	N75°W	N85°W	N75°W
2	N30°E	N43°E	N45°E	N53°E	N47°E
3	N64°E	N54°E	N45°E	N51°E	N45°E

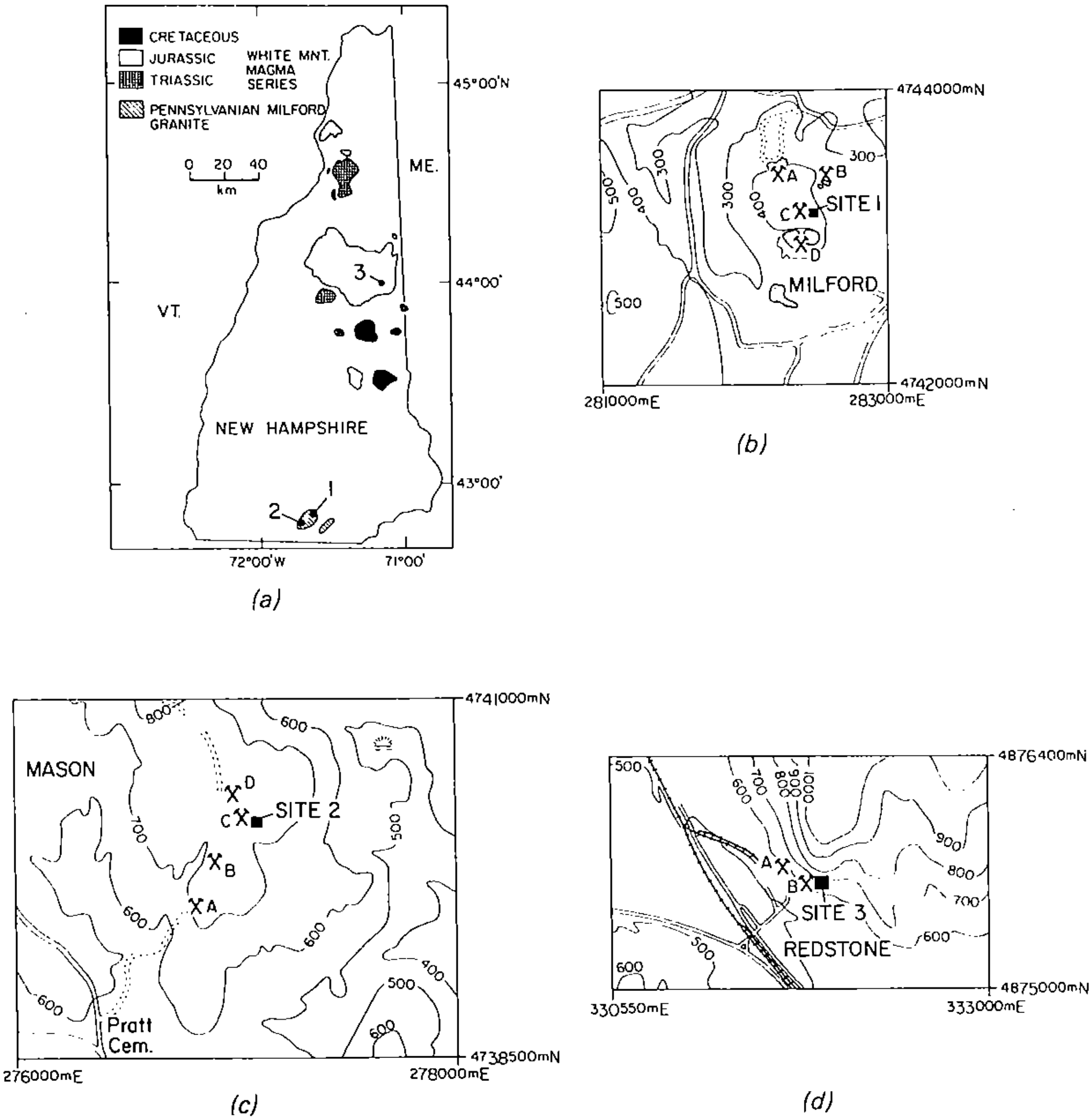


Fig. 2. Location map showing the ages of the granites (Figure 2*a*), and the local topography around each site (Figures 2*b*–2*d*).

cracks observed in two cores (A and C) were similar in preferred orientation, so poles to microcracks have been combined and contoured in the same stereonet. The composite maximum reflects the orientation of both quartz and feldspar cracks. This orientation is parallel with the quarry grain [*Dale*, 1923] but subparallel with healed quartz cracks. An orthogonal crack set is apparent in the composite; this second crack set consititutes the quarry hardway.

Strain relaxation measurements and associated mechanical tests are listed in Table 2. This site in the Milford granite is distinguished by the repeatable nature of all tests. The azimuth of maximum expansion upon strain relaxation is similar for all cores and coincides with the strike of the quarry grain. From pseudolinear compressibility data, estimated in situ stress magnitudes are found to be nearly uniaxial, with σ_1 parallel to the quarry grain. A second calculation of in situ stress was made by measuring the secant moduli in uniaxial compression for the Milford granite [*Yale*, 1980]. Since the axes of elastic symmetry coincide within 5° of our principal axes of strain relaxation, only the normal components of the modulus tensor are used for our stress calculation. As expected, rift and grain cracks give a marked anistropy and produce stress dependent elastic moduli [*Yale*, 1980]. The uniaxial tests indicate that the highest possible elastic symmetry is orthorhombic, with the stiffest axis horizontal and parallel to the intersection of the rift and grain planes. The axis of least stiffness is vertical, coinciding with the intersection of the grain and hardway planes. Table 3 lists stresses computed using secant moduli taken from appropriate stress levels along the unloading curve. The magnitude of σ_1 is about 30% lower than that estimated by applying our pseudolinear compressibility method.

The orientation of anisotropy in the horizontal plane, as indicated by *P* wave velocity and pseudolinear compressibility tests, is that expected from a rock with microcracks aligned with the quarry grain. Figure 5*a* shows a typical example of

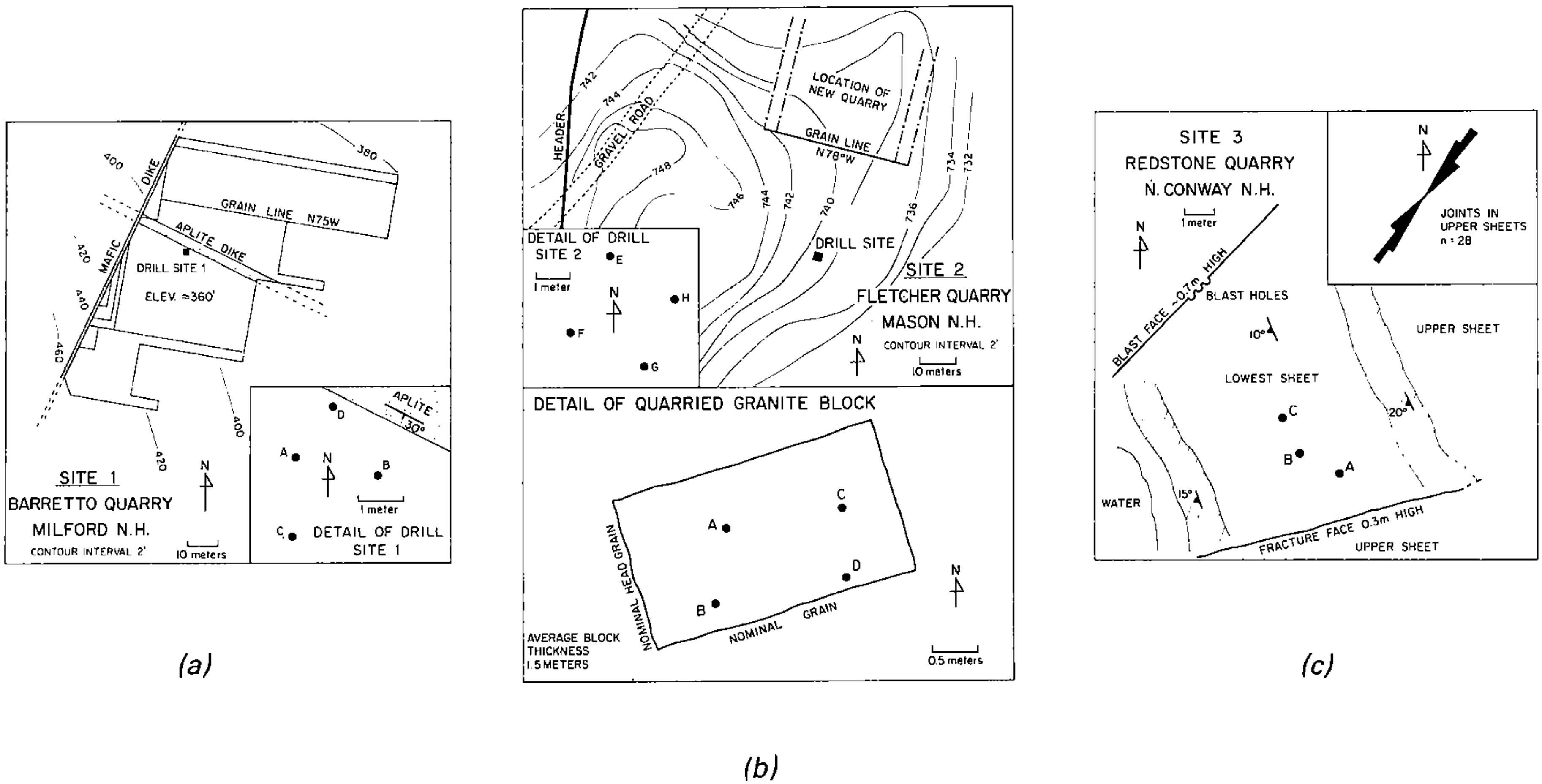
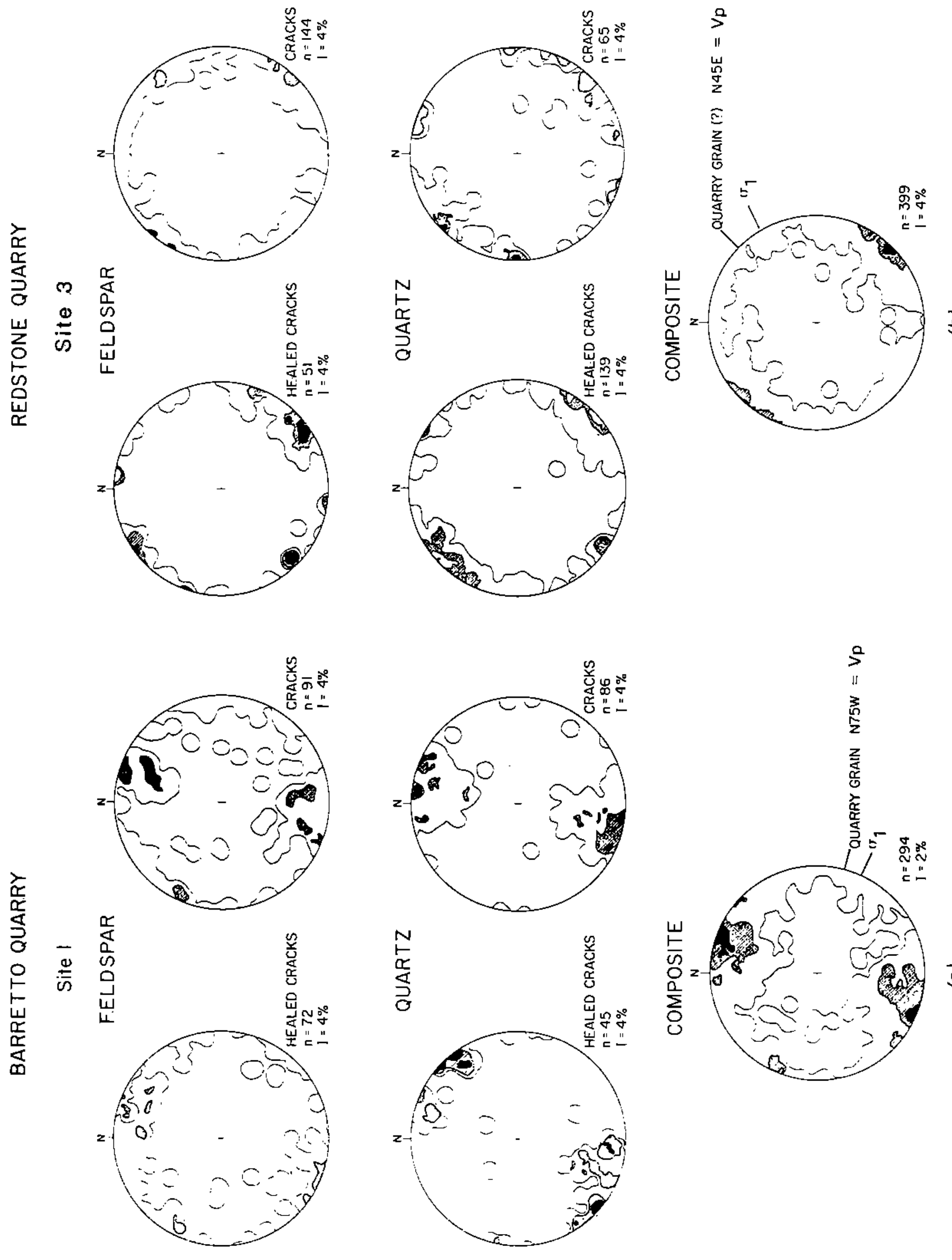


Fig. 3. Detailed site maps showing topography and pertinent rock structure: (*a*) site 1, (*b*) site 2 and (*c*), site 3.


BARRETTO QUARRY
Site 1
FELDSPAR
HEALED CRACKS n = 72 I = 4%
CRACKS n = 91 I = 4%
QUARTZ
HEALED CRACKS n = 45 I = 4%
CRACKS n = 86 I = 4%
COMPOSITE
QUARRY GRAIN N75W = Vp
σ1
n = 294 I = 2%
(a)
REDSTONE QUARRY
Site 3
FELDSPAR
HEALED CRACKS n = 51 I = 4%
CRACKS n = 144 I = 4%
QUARTZ
HEALED CRACKS n = 139 I = 4%
CRACKS n = 65 I = 4%
COMPOSITE
QUARRY GRAIN (?) N45E = Vp
σ1
n = 399 I = 4%
(b)
N

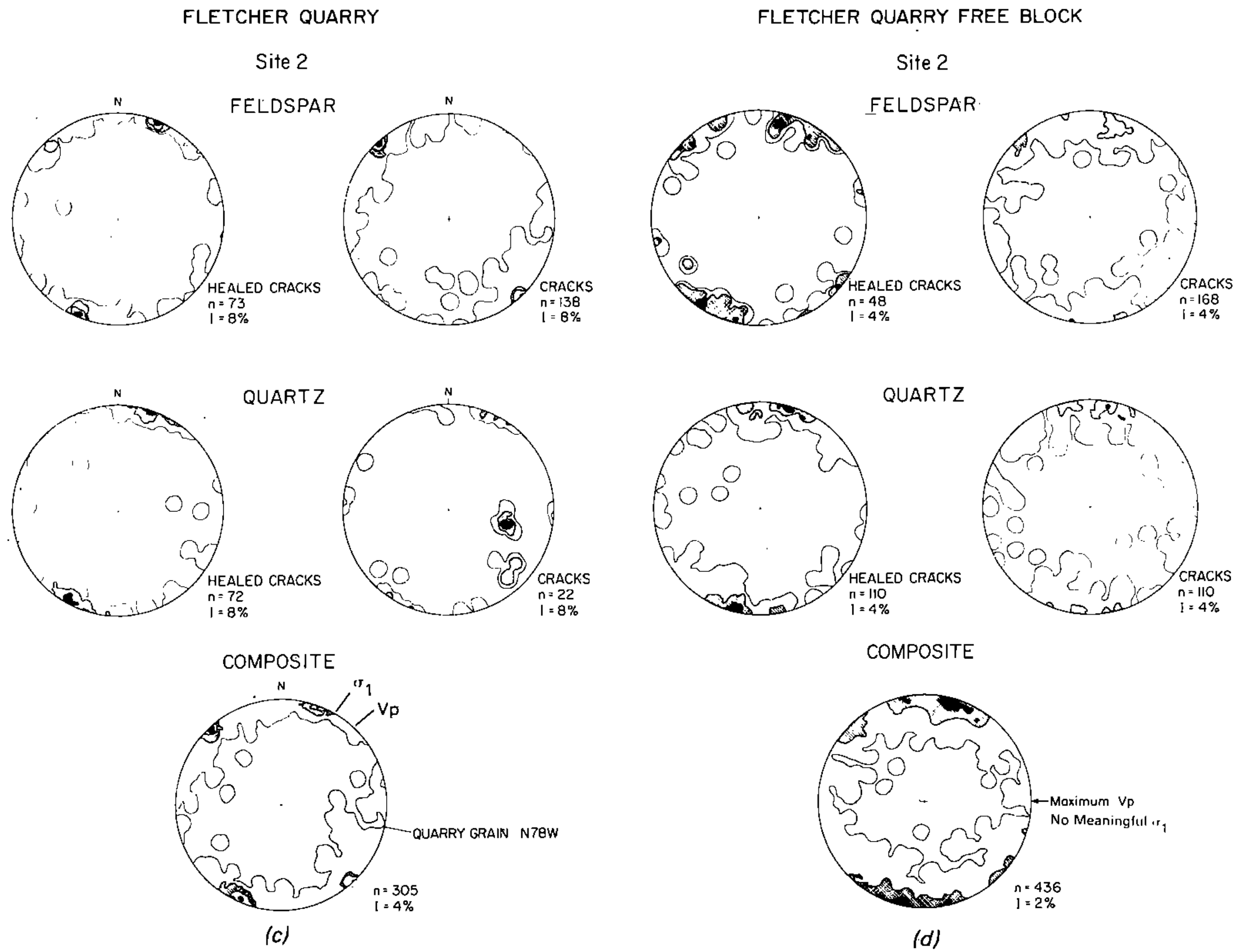


Fig. 4. Stereo diagrams showing the preferred orientation of poles to healed and unhealed intragranular cracks in quartz and feldspar including a composite of the four individual plots, Figures 4*a* and 4*b* (sites 1 and 3) and Figures 4*c* and 4*d* (site 2). The number n of microcracks counted and contour intervals I appear next to each diagram. All thin sections are cut parallel to the rift plane. Orientations of V_{pmax} and σ_1 are shown for reference on the composite diagrams.

TABLE 2. Rock Deformation and Fabric Data

Site	Hole	Depth, cm	Strain Relaxation ε_1, $\times 10^{-6}$	Strain Relaxation ε_2, $\times 10^{-6}$	Strain Relaxation Azimuth of ε_1	Stress σ_1, MPa	Stress σ_2, MPa	Stress Azimuth of σ_1	Pseudolinear Compressibility P, MPa	Pseudolinear Compressibility β_1, $\times 10^{-5}$ MPa^{-1}	Pseudolinear Compressibility β_2, $\times 10^{-5}$ MPa^{-1}	Pseudolinear Compressibility Azimuth of β_1	P Wave Velocity Maximum km/s	P Wave Velocity Minimum km/s	P Wave Velocity Azimuth Maximum
Site 1															
Milford, N. H.	A	33	405	−21	N70°W								4.13	3.55	N75°W
Barretto Quarry	A	74	454	−84	N68°W								4.38	3.85	N75°W
Pennsylvania age	B	25	476	14	N66°W	20.9	−0.5	N66°W	9.0	3.0	2.2	N09°E			
Milford granite	B	53	661	273	N69°W	32.6	9.6	N69°W	10.4	2.7	2.0	N13°E			
	C	33	413	114	N77°W								4.25	3.79	N75°W
Site average			479	62	N69°W	26.7	4.5	N67°W		2.9	2.1	N11°E	4.25	3.73	N75°W
Site 2															
Milford, N. H.	A	56	30	4	+53°*								4.29	4.17	0°*
Fletcher Quarry	A	86	40	−10	+52°*	1.6	−0.1	+53*	1.4	5.3	2.4	+82	4.43	4.21	−15°*
Pennsylvanian age	B	9	15	−6	−3°*										
Milford granite	B	30	−8	−28	−49°*										
	B	42	5	−11	−24°*								4.28	4.02	−30°*
	D	0	121	74	+73°*										
	E	91	302	40	N04°E	7.0	1.4	N09°E	10.4	4.1	3.3	N04°W	4.26	4.01	N50°E
	E	128	339	−17	N01°E								4.11	3.84	N35°E
	E	164	213	77	N43°E	8.6	2.6	N41°E	10.4	2.7	2.3	N69°W	4.22	4.00	N50°E
	F	15	282	89	N20°E	8.3	2.9	N35°E	10.4	4.2	2.3	N07°W	4.14	3.84	N50°E
	F	76	272	−51	N20°E								4.31	3.93	N25°E
	G	51	401	−83	N42°E								4.48	4.24	N45°E
	G	112	443	29	N-S								4.29	4.02	N35°E
	H	8	177	79	N38°E	3.4	2.5	N50°E	10.4	5.1	3.0	N47°W	4.56	3.80	N50°E
Site average			275	49	N18°E	6.5	2.6	N30°E		3.8	2.9	N27°W	4.30	3.96	N43°E
Site 3															
	A	23	145	77	N58°E	6.2	2.6	N55°E	10.4	2.8	2.2	N38°W	5.06	4.46	N65°E
North Conway, N. H.	A	36	157	120	N55°W	9.7	3.5	N73°W	10.4	2.9	1.6	N06°E	4.98	4.61	N80°E
Redstone Quarry	A	53	217	69	N44°E								4.97	4.44	N51°E
Jurassic age	B	23	174	91	N09°E	12.5	6.5	N73°E	10.4	2.5	1.0	N19°W	5.32	4.54	N50°E
Conway granite	B	64	247	20	N49°E	8.0	1.7	N50°E	3.5	3.2	2.0	N40°E	5.14	4.58	N40°E
	B	76	171	50	N49°E								4.91	4.54	N43°E
													5.05		N58°E
	C	47	173	65	N61°E	10.5	0.3	N53°E	10.4	3.7	2.3	N35°W	5.04	4.73	N32°W
Site average			172	82	N47°E	8.6	3.7	N64°E		2.8	2.0	N09°W	5.06	4.56	N54°E

*Angle is positive clockwise from the nominal plane of the free block.

TABLE 3. Stress Calculations Using Stress Dependent Elastic Moduli

Core	$\varepsilon_{x'}$* $\times 10^{-6}$	$\varepsilon_{y'}$ $\times 10^{-6}$	$S_{xx'}$ $\times 10^{-5}$ MPa^{-1}	$S_{xy'}$ $\times 10^{-5}$ MPa^{-1}	$S_{yy'}$ $\times 10^{-5}$ MPa^{-1}	$\sigma_{x'}$ MPa	$\sigma_{y'}$ MPa
A_1	405	−21	3.31	−0.639	12.42	12.3	0.5
A_2	454	−84	3.18	−0.636	12.42	14.3	0.1
B_1	476	14	3.18	−0.635	10.54	15.2	1.1
B_2	661	273	2.84	−0.614	4.81	25.2	8.9
C	413	114	3.31	−0.636	5.97	13.1	3.3

*Azimuths of the x and y axes are N105°E and N15°E, respectively; N105°E is parallel with the quarry grain.

velocity anisotropy measured on cores for site 1. The purpose of this plot is to show the coincidence of maximum P wave velocity parallel with a microcrack fabric. Shown for comparison is a theoretical velocity function proposed by *Crampin et al.* [1980]. This theoretical curve illustrates that the orientation of the observed velocity maximum is compatible with the microcrack distribution. The theoretical function is a model for velocity versus angle of incidence to a dilute concentration of parallel cracks, small compared to a wavelength. For the ultrasonic frequencies used in our measurements the cracks should be smaller than 0.5 cm. In all of our samples, intragranular microcracks and grain sizes are of the order of millimeters. Note that the maximum velocity is parallel with the quarry grain, the microcracks mapped from thin section, and σ_1. By fitting the curve of *Crampin et al.* [1980], we obtain estimates of the crack fabric porosity and a velocity for the rock without a preferred orientation of cracks. We call this velocity the pseudointrinsic velocity because it is usually less than the intrinsic velocity of dry unfractured granite which depending on composition is around 6.2 km/s [*Birch*, 1960]. The lower pseudointrinsic velocity presumably results from a randomly oriented microcrack fabric. Table 4 lists the crack parameters derived from the curve-fitting exercise. These crack parameters are of secondary importance and are just given for completeness. For the purposes of this paper, velocity anistropy was measured to determine the orientation of the crack fabric.

Figure 6 shows the results of in situ P wave velocity tests [*Engelder and Plumb*, 1984]. To make these measurements, we constructed two identical piezoelectric transducers that are hydraulically jacked against the borehole wall in two adjacent boreholes. Both transducers are placed at the same depth ($\approx$ 30–60 cm) below the outcrop surface. The piezoelectric crystals have a resonant frequency of about 0.3 MHz, and travel time is measured to a precision of several microseconds. Distance between holes is measured by tape to the nearest 4 mm (Figure 3*a*). Velocity computed from travel time typically has an error of +0.03 km/s.

The model of *Crampin et al.* [1980] also fits in situ velocity data, assuming that the observed velocity response is due to microcracks aligned with the quarry grain (Figure 6*a*). A comparision between in situ and core velocity anistropy data plotted in Figures 5*a* and 6*a* indicates that stress relaxation did not change the orientation of the microcrack fabric. Instead, core velocities are decreased an equal amount in all azimuths, but the ratio of V_{pmax}/V_{pmin} is similar in both cases (1.14 versus 1.16). Such a change is compatible with an increase of a randomly oriented crack porosity [*Engelder and Plumb*, 1984]. In the model of *Crampin et al.* [1980] this is equivalent to a decrease in the pseudointrinsic velocity. These results show that both rock modulus and in situ stress are anisotropic, that the axes of anistropy and principal stresses are coincident, and that both are aligned with the quarry grain.

MILFORD GRANITE: SITE 2

At site 2 in the Milford granite we compared data from in situ tests with data from tests made in a quarried granite block ("free block"). Site 2 is located on a hilltop about 10 km southwest of site 1 (Figure 2*c*). It is adjacent to a proposed quarry site and 150 m northwest of a currently operating

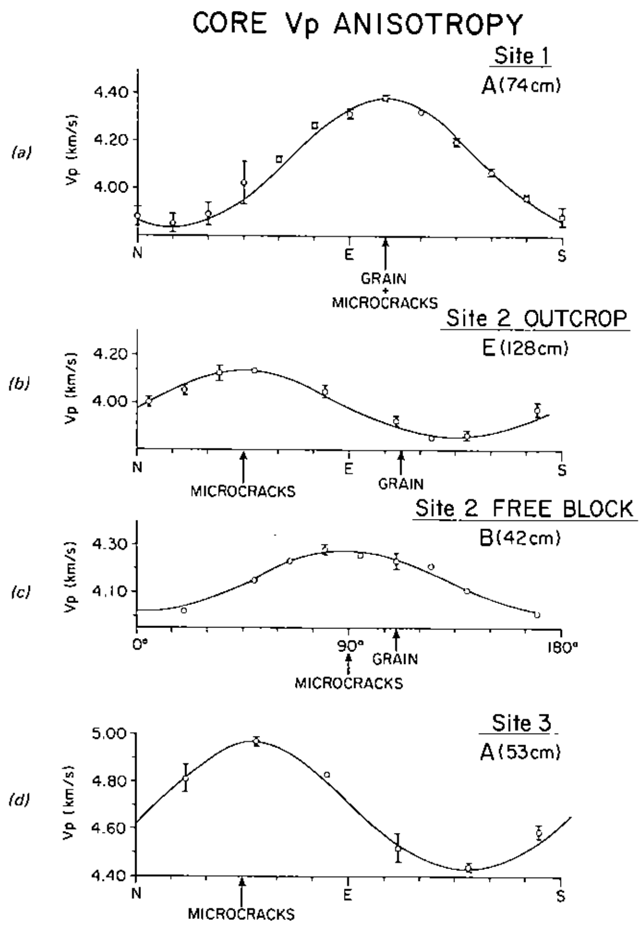


Fig. 5. Examples of typical core velocity measurements for each site showing 1 standard deviation error bars and a theoretical velocity function fit to the data. The theoretical expression gives velocity as a function of azimuth for a material which is anisotropic due to dry cracks [*Crampin et al.*, 1980]. The shape of the curve is constrained by crack orientations observed in thin section (Figure 4), and free variables (crack porosity and intrinsic velocity) used to fit the amplitude are listed in Table 3. Note that all of the core velocity data can be explained by a single preferred orientation of cracks striking parallel with σ_1 (Table 2).

quarry in the Milford granite (Figure 3*b*). These quarries are owned by the H. E. Fletcher Company of Chelmsford, Massachusetts. Our drill site is situated on flat-lying sheeting fracture surfaces approximately 0.5 m thick (Figure 3*b*). These granite sheets have a slightly weathered appearance caused by iron staining from altered biotite grains. Successive sheet surfaces form a terraced morphology near the site. Terraces strike subparallel with topographic contours, the quarry hardway, and decrease in elevation toward the southeast.

A free granite block (dimensions $\approx 2 \times 2 \times 3$ m) was quarried from the main pit several years earlier (Figure 3*b*). Rift and grain planes of the free block were determined by I. Thunberg, the quarry supervisor. In the subsequent discussion, all orientations on the free block will be in terms of angle measured clockwise (plus symbol) from the grain plane. Strain relaxation is measured parallel to the rift plane, as are the in situ measurements.

The preferred orientations of microcracks were measured in core B of the free block and core E of the in situ granite (Figures 4*c* and 4*d*). Both composite figures show two preferred orientations of cracks separated by the same angle (60°) and show that the quarry grain is the more broadly distributed of the two crack sets. The "grain" as defined by cracks in core E is N70°W compared to the nominal quarry grain of N78°W at site 2 and N75°W for the same Milford granite at site 1 [*Dale*, 1923]. The grain plane of both cores is defined by both healed and unhealed quartz and healed feldspar cracks.

The second vertical microcrack fabric strikes N47°E. This set of microcracks is found only in feldspar crystals of both cores B and E. Minor concentrations of healed feldspar cracks have the same strike and dip, but a similar preferred orientation of quartz cracks is absent. Site 2 differs from site 1, where no preferred orientation of feldspar cracks is found. The northeasterly striking feldspar cracks suggest that site 2 has had a more complex stress history than site 1.

In Situ Experiments

In situ strain relaxation measurements were made in several granite sheets located near a new quarry opening. Unlike site 1, the mean azimuth of ε_1 is parallel to the quarry head grain (hardway) and orthogonal to the grain. Within the outcrop the consistent azimuth of ε_1 obtained from different sheets is evidence that sheet fractures do not upset the orientation of the horizontal stress field (Figure 3*b* and Table 2). In situ stress is rotated about 10°–20° east of ε_1 and is subparallel with the preferred orientation of feldspar cracks observed in thin section. Also, core velocity measurements indicate a velocity maximum parallel with the feldspar cracks (Table 2).

TABLE 4. Crack Parameters; Synthetic Data

Site	Crack Porosity	Crack Azimuth	Pseudo-intrinsic *P* Velocity, km/s	Saturation
1 (in situ)	0.060	N75°W	5.68	0
1 (core A)	0.060	N75°W	4.47	0
2 (in situ)	0.250	N45°E	5.23	0.95
2 (core E)	0.029	N45°E	4.17	0
2 (core B)	0.026	0°*	4.32	0
3 (core A)	0.050	N45°E	5.05	0
3 (in situ)	0.060	N45°E	6.01	0

*Angle measured (+) clockwise from the azimuth of maximum V_p (see Figure 4).

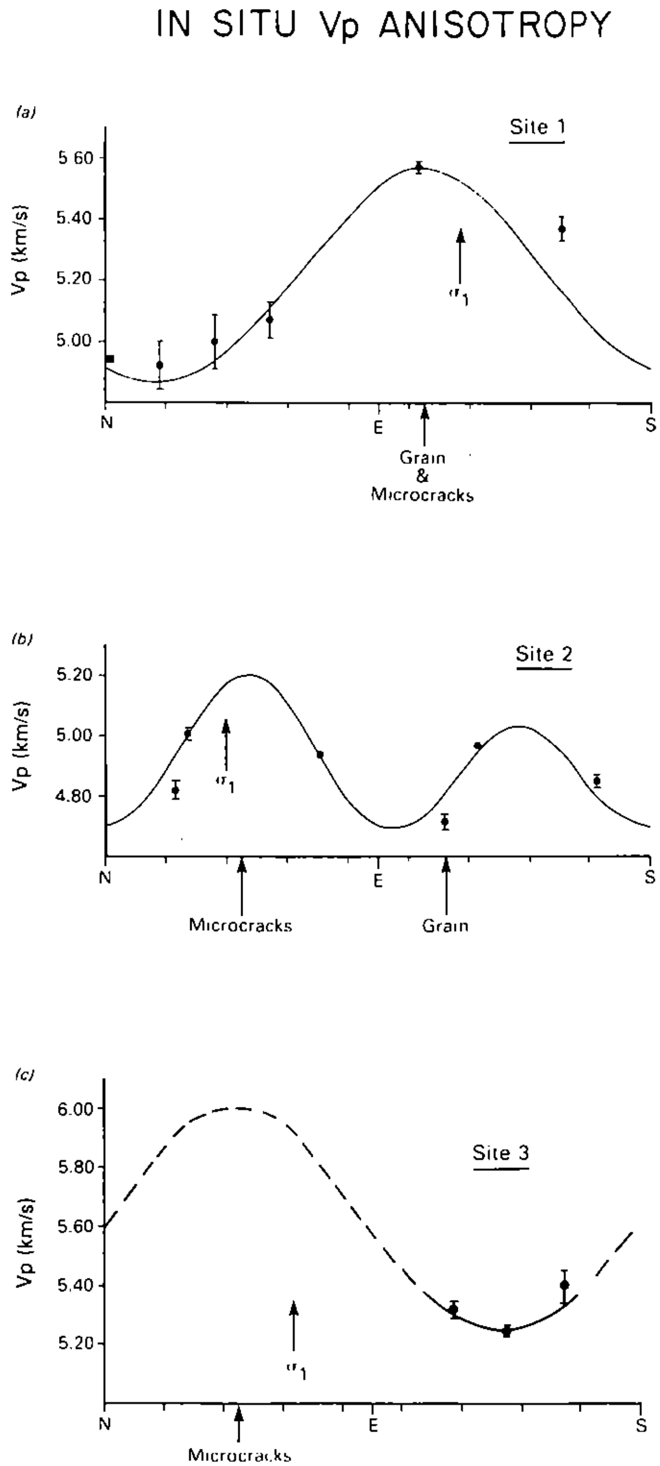


Fig. 6. In situ velocity measurements for sites (*a*)1 and (*b*)2 in the Milford granite showing error bars and a theoretical fit to the data. Constraints on the theoretical curves are described in the text. Unlike site 1, site 2 data cannot be fit by a dry crack model, only a partially saturated crack model was compatible with the observed velocity variations [*Park and Simmons*, 1982]. At site 2 the grain cracks are closed, and only the feldspar cracks cause the anisotropy (Figure 4). At both sites, in situ anisotropy is caused by a single set of cracks aligned with σ_1, and these are the same cracks which control the core velocity anisotropy. Data from site 3 are shown (Figure 6*c*) for reference to a theoretical velocity curve, assuming that anisotropy is caused by cracks shown in Figure 4*b*.

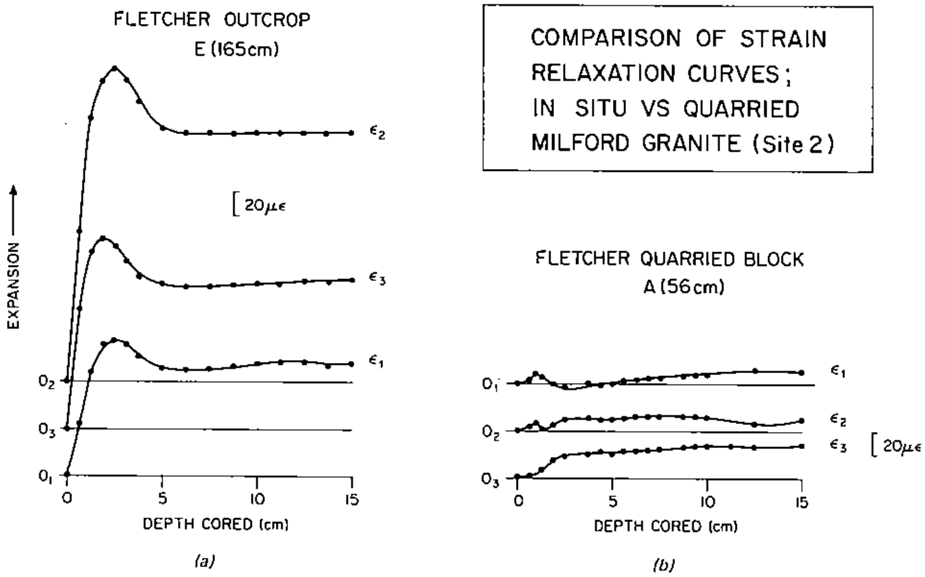


Fig. 7. A comparison of strain relaxation curves obtained from overcoring doorstoppers (*a*) in the outcrop and (*b*) in a quarried granite block at site 2. The shapes of the curves recorded from the outcrop show the characteristic elastic response of a body being stress relieved by overcoring, those recorded from the free block do not. Note that these data are plotted at the same scale.

The shape of core velocity anistropy curves can only be fit by a single preferred orientation of dry cracks with the strike of N45°E (the feldspar cracks) (Figure 5*b*). Using *Crampin et al.*'s [1980] analysis, we find that the grain cracks do not noticably contribute to the core velocity anisotropy. Thus the velocity data complement the thin section observations, implying that the grain cracks have fewer stress-free surfaces than the feldspar cracks (i.e., they behave like healed cracks) [*Crampin et al.*, 1980].

The crack model of *Crampin et al.* [1980] cannot fit the in situ velocity data. We obtain a good fit using a model which permits partially water-saturated cracks [*Park and Simmons*, 1982]. Using the Park and Simmons model, we found that only partially saturated feldspar cracks could fit the observed velocity maxima and minima. In situ velocity anisotropy data cannot be fit by dry feldspar cracks, dry grain cracks, or a combination of dry grain and dry feldspar cracks (Figure 6). The problem with fitting the data results from the minimum velocity observed at an azimuth of 112° (the quarry grain) and the higher velocities at 71° and 123°. Input for our trial models consisted of crack porosity, percent saturation, and the observed preferred orientations of cracks. Saturated crack porosity was varied until a fit to the data was obtained. Combining partially saturated grain and feldspar cracks results in a minimum V_p shifted northerly of the observed minimum. Partially saturated grain cracks places a maximum where the observed velocity is minimum. Model parameters used are given in Table 4. A better fit to the observed velocity gradients might be obtained by varying the intrinsic velocity and the degree of saturation. In addition, the crack porosity predicted by this model seems unrealistic. However, the constraints obtained by this simple iteration using existing data are sufficient to support our contention that grain cracks are closed in situ and that in situ stress is aligned with the feldspar crack fabric.

Free Block Experiments

Strain relaxation measurements on the free block detected only low-level residual stresses. Estimated σ_1 stress magnitudes are less than 25% of σ_1 values for the in situ granite (Table 2). Unlike the other New Hampshire sites, there is no simple correlation between the azimuth of ε_1 and a preferred orientation of microcracks. There was also a factor of 3 increase in the standard deviation of ε_1 azimuths recorded in the free block compared to that of in situ data.

Velocity anisotropy recorded on core B is compatible with only one of the two microcrack sets shown in Figure 4*d*. V_{pmax} is in the direction of microcracks observed in a sample of the free block. In geographic coordinates these cracks are found to coincide with the grain cracks. Unlike outcrop cores, velocity anisotropy is caused by the grain cracks and not the feldspar crack fabric. Also, note that the azimuth of maximum compressibility (β_1) is normal to the grain cracks (Table 2). These results show that granite which has been stress relieved for some time has open microcracks aligned with the grain plane.

Conway Granite: Site 3

Site 3 owned by the H. E. Fletcher Company is located on a hillside at the abandoned Redstone (pink) Quarry near North Conway, New Hampshire (Figure 2). This rock is the massive coarse-grained pink biotite granite member of the Conway granite [*Dale*, 1923]. This granite has a fresh appearance with no marked signs of weathering. Our drill site is located on the lowest sheet surface in the oldest workings of the Redstone Quarry (Figures 2*d* and 3*c*). In the sheet above the one we drilled into are conspicuous vertical joints striking between N30°E-N50°E at about 1-m spacing and 1–2 m in length.

At site 3 the preferred orientations of microcracks are parallel to the local quarry workings (Figures 3*c* and 4*b*). A common, strong preferred orientation of healed and unhealed cracks is found for both quartz and feldspar. This set is vertical and strikes N45°E parallel to joints in the overlying granite sheets and the blast face produced by early quarrying operations (Figure 3) but does not agree with the regional grain trend reported by *Dale* [1923]. However, we will call these microcracks the grain, meaning the local grain for this site.

TABLE 5. Volume Changes of Quartz and Feldspar Due to Changes of Boundary Conditions

Boundary Conditions	Volume Change*		Preferentially Fractured Mineral
	Feldspar	Quartz	
Cool 100°C†	-15×10^{-4}	-52×10^{-4}	quartz
α-β phase transition	0	-1.3×10^{-2}	quartz
Uplift 1 km‡	6.2×10^{-4}	7.0×10^{-2}	feldspar
Cool 650°–25°C and uplift 12 km	-2.1×10^{-3}	-2.5×10^{-2}	quartz

*$dV_i/V_i = \alpha_i dT + \beta_i dP$; $i = 1$ (Quartz), $i = 2$ (Feldspar); $\alpha_1 = 51.5 \times 10^{-6}$ °C^{-1}, $\alpha_2 = 14.5 \times 10^{-6}$ °C^{-1}; $\beta_1 = -2.6 \times 10^{-5}$ MPa^{-1}, $\beta_2 = -2.3 \times 10^{-5}$ MPa^{-1}.

†Assumed geothermal gradient: 25°C/km.

‡Assumed lithostatic load: 26.5 MPa/km.

Results of strain relaxation and laboratory tests are listed in Table 2. The majority of ε_1, σ_1, and maximum V_p orientations are parallel with the grain. The azimuths of β_1 indicate locally complex microfabrics which are not clearly reflected in the velocity anisotropy data. Regardless, the azimuths of ε_1, σ_1, and maximum V_p show the same simple relationship to a preferred orientation of microcracks observed at the other two sites.

Core velocity anisotropy curves are best fit by a preferred orientation of dry cracks with the same strike as those observed in thin section (Figure 5*d*). In situ velocity anisotropy data are insufficient to constrain the orientation of open cracks (Figure 6*c*). In situ V_p has a local minimum at an azimuth of N45°W and increases for azimuths to the north and south [*Engelder and Plumb*, 1984]. These data are at least compatible with the set of dry microcracks striking N45°E.

DISCUSSION

Mechanism of Strain Relaxation

In the Milford granite at site 1, strain relaxation produced an equal *P* wave velocity decrease in all directions. Although this site was dominated by grain cracks, it seems clear that opening of the grain cracks did not play a dominant role during the strain relaxation. If only the grain cracks had opened during strain relaxation, there would have been a large reduction in velocity normal to the cracks and little reduction parallel to the cracks. One plausible mechanism for the uniform velocity decrease independent of azimuth is the opening of a uniformly distributed but randomly oriented set of dry or saturated cracks [*Thill et al.*, 1973; *O'Connell and Budiansky*, 1974; *Engelder and Plumb*, 1984]. The effect of opening saturated cracks is that the cracks become undersaturated. The granite was above the water table, however, so we think it unlikely that the granite was saturated. The effect of further drying an undersaturated core is difficult to assess. If undersaturation or drying is ruled out, the results imply that randomly oriented cracks opened upon overcoring and caused a drop the *P* wave velocity.

In contrast to the strain relaxation at site 1 the mean azimuth of ε_1 is normal to the grain cracks in the Milford granite at site 2. This simple geometry suggests that ε_1 may have been controlled by the opening of the grain cracks [*Engelder et al.*, 1977]. However, the laboratory and in situ velocity anisotropy data do not support this conclusion. In thin section a set of feldspar cracks appears parallel to the known direction of maximum in situ stress. Likewise, the maximum *P* wave velocity is also parallel to this set of cracks rather than the grain cracks. Furthermore, the grain cracks appear to be healed and hence should not have contributed to the strain relaxation at site 2. Other factors which may have contributed to differences between relaxation behavior at sites 1 and 2 include (1) the positions of the two quarries relative to the surrounding topography and (2) the position of the drill sites relative to sheet fracturing.

The strain relaxation curves for in situ and free block measurements at site 2 differ. The in situ curves are like the theoretical elastic response of the center of a cylinder as it is stress relieved [*Wong and Walsh*, 1979]. The strain recorded in a stress-free block should only be due to drill bit pressure. Measured strains caused by bit pressure should be large as the bit starts cutting but then decrease to zero as the bit cuts to depth equal to a core diameter [*Wong and Walsh*, 1979]. This was not the observed response when we drilled into the stress-free block at site 2. Note that the final strain changes are low but none are zero (Figure 7). These differences suggest that strain recorded in the free block was not simply the elastic relaxation of uniform applied tractions at the core boundary. Instead, the recorded strains may reflect the reequilibration of nonuniform residual stresses [*Varnes and Lee*, 1972]. Whether the differences between in situ versus free block strain relaxation curves are diagnostic of residual stress fields or just the response of this granite to low-level stress is uncertain.

Preferential Microcracking in Quartz or Feldspar

We have shown that the in situ stress (σ_1) at three widely spaced locations is parallel with a microcrack fabric. At sites 1 and 3 the fabric consists of both open and healed microcracks. At site 2 only open microcracks are found to parallel σ_1; healed cracks have other orientations. Thus at sites 1 and 3 the orientation of in situ stress is correlated with a preexisting stress defined by the orientation of healed microcracks. A microcracking sequence may be inferred by assuming that the healed microcracks formed before open microcracks. By assuming that these are mode 1 cracks, we may also infer the general stress orientation at the time of cracking. We use this information to infer the development of the quarry grain and the stress history of granite plutons.

Any models for the origin of rift and grain must account for *Dale*'s [1923] observation that ubiquitous sheets of fluid inclusions form in quartz crystals. Fluid inclusions are found in all of the granites that we studied and are most conspicuous at site 3. Although less abundant than in quartz, the fluid inclusion sheets are also present in feldspars (Figure 4).

The preferential fracturing of certain crystals can be traced to differential stresses that develop between crystals of a polycrystalline material upon cooling or decompression. Intergranular stresses have been known by metallurgists for nearly a century [*Heyn*, 1914]. In geological materials, large thermal expansivity and compressibility contrasts exist between quartz and most other rock-forming minerals [*Rosenfeld and Chase*, 1961; *Devore*, 1969; *Nur and Simmons*, 1970; *Voight and St. Pierre*, 1974; *Savage*, 1978]. Volume changes that would normally result from pressure or temperature changes in a pure mineral are inhibited by the interlocking of minerals within polycrystalline rocks, thus leading to intragranular stresses [*Greenwood*, 1921; *Ellis*, 1921]. Nonuniform cooling or pressurization of monomineralic aggregates can also lead to intergranular stresses [*Greenwood*, 1921; *Alman and Black*, 1963]. The magnitude of stress differences between minerals depends on the contrast in physical properties and the heating-pressurization (PT) history of the aggregate. Because of the spatial distribution of quartz and feldspar in granite it is useful to consider quartz as a spherical inclusion welded inside a spherical feldspar shell (a bisphere) [*Hashin*, 1962; *Nur and Simmons*, 1970; *Savage*, 1978]. The effect of cooling this bisphere is to induce tensile stress in the quartz and compressive stresses in the feldspar. The effect of depressurization on the bisphere is to induce tensile tangential stress in the feldspar and compressive stress in the quartz. Isobaric cooling favors cracking in quartz because $(-\Delta V/V)_q > (-\Delta V/V)_f$. Isothermal depressurization favors cracking in feldspar because $(\Delta V/V)_q > (\Delta V/V)_f$.

Phase transitions provide another mechanism for generating grain scale stress. Phase transitions in metal lead to stresses exceeding their yield strengths [*Greenwood*, 1921; *Marburger and Koistinen*, 1959]. The α-β phase transition in quartz results in about a 1.3% decrease in volume [*Kirby*, 1968]. The bisphere response to this volume change is analogous to cooling.

Aleinikoff [1978] determined that the Milford granite crystallized at temperatures between 650° and 700°C at a minimum depth of 11 km. Using this information and the physical properties given by *Savage* [1978], we calculated volume changes for quartz and feldspar resulting from several changes in PT conditions (Table 5). So long as the volume changes in quartz and feldspar are not equal, stresses will be induced in both minerals. If grain scale stresses caused by cooling and depressurization are superposed, then the likelihood of preferential fracturing of host or inclusion is diminished. Note that the volume change associated with depressurization of the quartz is small compared to that associated with cooling. Uplift along a normal geothermal gradient favors cracking in quartz, whereas isothermal uplift may favor cracking in feldspar. Although, the systematic cracking of quartz is more likely, feldspar may crack under certain stress-temperature histories. The observation that certain minerals have preferentially been fractured argues against simultaneous cooling and depressurization.

Results of this study and others cited above show that cracks form preferentially in quartz and that they often have a preferred orientation (Figure 4). Most of the intragranular cracking occurs because of the material property contrasts between quartz and feldspar, while the preferred orientation of cracks results from external differential stresses on the granite [*Wise*, 1964; *Voight and St. Pierre*, 1974].

Microcracking of the Milford Granite

The orientation of the grain (vertical microcracks) in the Milford granite is west-northwest (Figure 3). At site 1 the grain consists of healed and open cracks in both quartz and feldspar (Figure 4). The grain at site 2 is well developed as healed and open quartz cracks and healed feldspar cracks (Figure 4). Both quarries show evidence of cracking, healing, and recracking in the grain direction with no apparent change in the orientation of least compressive stress (σ_3). Since similar preferred orientations are found in both quartz and feldspar, neither cooling ($T_0 < 550°C$) nor depressurization alone can explain this distribution of cracks. Instead, a sequence of rapid isothermal uplift followed by cooling may have been necessary to produce the cracking and recracking.

The occurrence of cracks nonaligned with the grain is evidence for a more complex stress history at site 2. This second microcrack orientation indicates that σ_3 rotated almost 90° from its orientation during the formation of the grain cracks. Since this fabric is only found at site 2, it must have formed in response to more localized stress conditions. Site 2 is located at the top of a hill in an area of higher topographic relief than site 1 (Figure 2*c*). Hence recent lateral stress relief is more likely at site 2 because the quarry is above the adjacent valley floor.

Some but not total strain relief at site 2 has occurred by lateral expansion of the granite toward directions of least confinement (I. Thunberg, personal communication, 1981). Thunberg, the quarry supervisor, reports that when a granite contains "pressure," it will creep along "bedding" (sheet fractures) in the direction of least resistance. In the case of site 2 the direction is downhill (SE) toward local valleys. The mechanism of stress relaxation as described by Thunberg is the same as that proposed by *Chapman* [1958]. By this mechanism, feldspar cracking relieves the downslope component of stress, while a component of stress remains normal to the direction of downslope creep. At site 2, ε_1 and σ_1 are subparallel with topographic contours and the strike of vertical faces between sheets, confirming Thunberg's observations (Figure 3*b*).

Microcracking of the Conway Granite

In situ stress and rock fabric data collected at site 3 provide evidence supporting the *Hoskins and Russell* [1981] model for the origin of residual strain in crystalline rock. Hoskins and Russell proposed a microcracking mechanism to explain the orientation and deviatoric character of residual strain in isolated blocks of crystalline rock. The essence of their model is that upon cracking, rocks containing microresidual stress (e.g., thermally induced intragranular stresses) will have the "minimum contained residual stress" normal to the cracks and the "maximum contained residual stress" parallel to the cracks.

A modification of the Hoskins and Russell model can explain the alignment of an in situ stress and microcracks at site 3 if we assume that (1) sheet fractures caused the quarry outcrop to behave like an isolated block and (2) an elastic anisotropy and planes of weakness in the form of a healed microcrack fabric were present prior to the cracking episode specified in their model. The elastic anistropy has the effect of orienting the resulting stress field during further thermal cooling without relying on highly deviatoric far-field stresses. In this case, σ_1 generated upon recracking is aligned with the once healed microcrack fabric. Another way of looking at this result is that the contemporary stress is apparently aligned with a paleostress direction recorded by the orientation of the healed microcracks. The microcrack fabric at site 3 is composed of healed and open cracks in both quartz and feldspar. However, in thin section, healed quartz cracks are most conspicuous (Figure 4*d*). In situ stress (σ_1), joints in the overlying granite sheet, and the azimuth of $V_{p\max}$ measured on core are all aligned with this fabric.

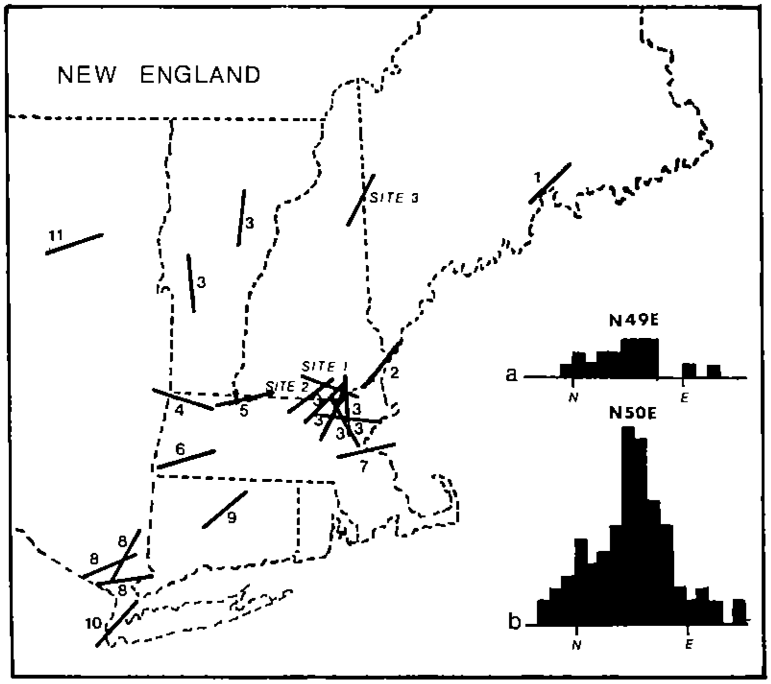


Fig. 8. Map of near-surface maximum compressive stress for New England and eastern New York. All data come from overcoring measurements. Inset histograms: (*a*) site average data and (*b*) all measurement regardless of site locations. The statistical orientation of near-surface stress is N50° E. Data sources are 1, *Lee et al.* [1979]; 2, *Lindner and Halpern* [1978]; 3, *Hooker and Johnson* [1969]; 4, *Foundation Sciences, Inc.* [1971]; 5, *Northeast Nuclear Energy Co.* [1974]; 6, *Engelder* [1984]; 7, R. Plumb (unpublished data, 1979); 8, *Dames and Moore* [1977]; 9, *Nataraja* [1977]; and 10, *Ciancia et al.* [1979].

Application of the Hoskins and Russell model at site 3 requires recracking where the recracking provides the mechanism for the orientation of σ_1. Here the effects produced by topography or joints were absent. Unlike site 2, neither the crack fabric nor σ_1 are aligned with topography. Site 3 is far enough away from the blast face not to have been stress relieved by the free surface (Figure 3*c*), and the only nearby joints are in an overlying granite sheet. These joints are parallel to σ_1 and the microcrack fabric in the underlying granite and perhaps reflect a more evolved stress relaxation of the overlying granite sheet.

Regional Picture

It is currently unclear whether New England is subjected to a single regional stress field or if it is divided into several stress provinces [*Sbar and Sykes*, 1973; *Zoback and Zoback*, 1980; *Yang and Aggarwal*, 1981]. The only evidence for deep-seated contemporary stress orientation comes from fault plane studies of infrequent local earthquakes. Taken at face value, the fault plane data are inconclusive [*Yang and Aggarwal, 1981; Pulli and Tokzos*, 1981]. To date, only shallow-near-surface stress measurements have been made in New England, and these have been made where the influence of joints and topography cannot be ignored. Here and in other locations, effects of topography and joints complicate the interpretation of near-surface stress data [*Plumb et al.*, this issue].

Sbar et al. [this issue] have shown that near-surface stress orientations near the San Andreas fault can be attributed to regional tectonics. The success of the San Andreas experiment was due to the greater depth of samples, the larger number of measurements, and the tectonic setting. Because of the low stress magnitudes measured near the surface in the Mojave, effects of thermal stresses were recognized. This problem was overcome by making measurements below the thermally stressed zone [*Sbar et al.*, this issue]. Thermal stress effects were not a problem in the northeast because near-surface stress magnitudes are about an order of magnitude larger than the estimated diurnal and annual thermal stresses.

Figure 8 is a map of New England showing the average stress orientation at 19 overcoring sites. Two histograms are also shown of the azimuthal frequency distribution of stress orientation: Figure 8*a* represents site average data and Figure 8*b* represents all measurements combined without regard for site location. The shape of the distributions reflect the influence on the measurements by such variables as topography, rock fabric, and residual stress. Note that both distributions are unimodal.

To improve the statistical significance of any conclusion, we might make, we tested the null hypothesis that the data set "a" is just a sampling of a parent population represented by data set "b." A chi-square test confirmed that each population is normally distributed. The "*F*" and "*t*" tests show that the populations are indistinguishable at the 95% confidence level. Therefore we have no basis to claim that population "a" and "b" are statistically different. Population "b" has a clear but broad peak with mean orientation of N50°E and a standard deviation of 33°. The clear peak in the population "b" suggest that the near-surface measurements are indicative of a regional stress field. We believe that the broad distribution is due to effects of topography, joints, and residual stress on the stress measurements.

Presently, there is insufficient evidence to indicate if this regional stress direction is just a near-surface stress or a tectonic stress. We note, however, that this near-surface stress field is (1) compatible with most of the *P* axes of local earthquakes in the depth range of 0–2 km (A. Kafka, personal communication, 1981) and (2) only slightly different from the direction of maximum horizontal stress documented farther to the west [*Sbar and Sykes*, 1973; *Zoback and Zoback*, 1980; *Yang and Aggarwal*, 1981]. Although these data are not conclusive, it appears that much of New England may be part of the Mid-Continent stress province.

CONCLUSIONS

The direction of σ_1 is aligned with a microcrack fabric at each of three New Hampshire granite quarries. At all sites the cracks parallel to σ_1 controlled the orientation of maximum V_p on cores and the orientation of maximum V_p in situ.

The microcracking at sites 1 and 3 was parallel with healed microcracks in quartz. A recracking mechanism is proposed to explain the alignment of σ_1 with a healed microcrack fabric at site 3. By this mechanism a healed microcrack fabric constitutes an elastic anistropy, which upon recracking results in σ_1 coaxial with the healed and recently opened microcracks. A microcracking sequence for site 2 was based on an analysis of preferential cracking of quartz and feldspar. Preferential fracturing of quartz is possible if granite is cooled isobarically; preferential fracturing of feldspar is possible if depressurization of the granite occurs isothermally.

A generalization of the recracking mechanism can explain the stress orientation data collected in the New Hampshire granites. The generalized mechanism predicts the maximum principal stress to be aligned with a planar fabric constituting a tensile strength anisotropy. This fabric may be a healed microcrack fabric such as found at sites 1 and 3, where the contemporary regional stress orientation parallels the fabric trend and a paleostress direction. The fabric may also be newly created where the contemporary stress orientation is controlled by the anisotropy in the boundary conditions but not tectonic stress as, for example, at site 2. Accordingly, a body of crystalline rock undergoing uplift (cooling and depressurization) could acquire a deviatoric state of stress as a result of preferential cracking in the direction of a fabric or in the direction normal to the least principal stress of the contemporary tectonic stress field. Therefore in crystalline rock only a large areal sampling can help distinguish local stress fields from regional, geophysically important stress fields.

A statistical analysis was made of existing stress measurements from New England. The conclusions are that the mean near-surface stress orientation is N50°E with a standard deviation of 33°. The existing data provide no evidence for multiple near-surface stress provinces within New England but suggest that New England may be part of the Mid-Continent stress province.

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