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Strain Relaxation Measurements in the Vicinity of New York State Using Surface Overcoring Techniques

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STRAIN RELAXATION MEASUREMENTS IN THE VICINITY OF NEW YORK STATE USING SURFACE OVERCORING TECHNIQUES

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EXECUTIVE SUMMARY

STRAIN RELAXATION MEASUREMENTS IN THE VICINITY OF NEW YORK STATE USING SURFACE OVERCORING TECHNIQUE

The New York State Energy Research and Development Authority is concerned with many aspects of energy from exploration to marketing. One aspect concerns the siting of power plants and nuclear plants in particular. The siting problems include locating areas where the probability of large earthquakes is low. There are several approaches to assessing the seismic risk in an area the size of New York State. Locating all seismic areas using seismographs is useful in this regard. However, the record of historic earthquakes spans such a short period of time that it is uncertain whether the record is representative of earthquake potential.

Another technique for studying earthquake potential is to measure earth stress because higher stressed areas are more likely to have earthquake The following report prepared by Lamont-Doherty Geological Observatory of Columbia University addresses itself to the problem of measuring stress in New York State and adjacent areas. Information contained within this report will be useful for those concerned with the measurement and interpretation of stress in New York State.

ABSTRACT

The purpose of this project is to contribute to the understanding of the state of stress within the crust of northeastern United States. Specific objectives include an evaluation of the *in situ* strain relief technique for determining the state of stress at a specific site and to provide data on the state of stress in New York State and adjacent areas. Specific descriptions of 1976 *in situ* tests are given.

Strain relaxation measurements from the central Adirondack Mountains, New York, northwestern Vermont, and central Pennsylvania are described. In the central Adirondack Mountains, the average strain relaxation is N60°W. This direction corresponds to the elastically stiff direction for most samples. We infer that a maximum expansion in the stiff direction represents the recovery of an external load. The initial strain realxation of samples from central Pennsylvania was low, suggesting the absence of high crustal stresses in that area. Residual strains in central Pennsylvania are also low. From data on the mechanical properties of rocks from central Pennsylvania, we believe that P-T conditions removed residual tectonic strain by annealing. In northwestern Vermont the maximum expansion upon overcoring was WNW-ESE and is atrributed to the opening of microcracks which parallel the foliation.

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I. INTRODUCTION

The magnitude and orientation of stress in the crust is a subject of debate in solid earth geophysics. Within continental plates the stress field appears to have the same orientation over areas of as much as 10^6 km^2 (Sbar and Sykes, 1973). On the scale of continents, the stress field does vary in orientation (Street, Herrmann and Nuttli, 1974; Sbar and Sykes, 1977). These ideas concerning magnitude and orientation of the stress field come from fault-plane solutions of earthquakes, hydrofracture measurements, in situ strain relief measurements, and observations of Quaternary and historic crustal deformation. Part of the debate concerning crustal stress stems from the lack of understanding of just what each of these techniques is measuring.

We have conducted a program of strain relaxation measurements on carefully selected surface outcrops for the purpose of trying to understand strain relaxation as a possible indicator of the crustal stress field. The development of this strain relaxation technique is important because it is an inexpensive stress-measuring technique compared with those which require deep boreholes. Because the technique can be applied at the surface or shallow depths, many measurements can be made over short periods of time. However, the surface strain relaxation measurements are still poorly understood because the orientation of the strain relaxation is influenced by the fabric of the rock, residual strain, and weathering.

To date our strain relaxation measurements in the northeastern United States have been influenced by tectonic stress, microcrack fabric, and a residual strain. Near Alexandria Bay, New York, tectonic stress was measured in Cambrian sandstone (Engelder and Sbar, 1977). Near Barre, Vermont, the relaxation of microcracks clearly controlled the orientation of strain relaxation, thus masking the relief of crustal stresses (Engelder, Sbar, and Kranz, 1977). Strain relaxation in western New York included a component of residual strain which we attribute to a NNW compression which occurred during the folding of the Appalachian Mountains (Engelder and Sbar, 1976).

We have focused our strain relaxation measurements in the northeastern United States where information on the crustal stress field comes primarily from the orientation of earthquake fault-plane solutions (Sbar and Sykes, 1977). In brief, areas of Ohio, New York and southeastern Canada have fault-plane solutions showing a ENE-trending maximum compressive stress (Figure 1). This trend for the orientation of fault-plane solutions does not extend to New England, southern New York, New Jersey or Delaware.

In this study we made further measurements in the Adirondack Mountain area of northern New York where the presence of a ENE maximum compressive stress has been indicated by fault-plane solutions and surface strain relaxation measurements. Specifically we focused on the Blue Mountain Lake - Racquette Lake area where many earthquake swarms have been detected since 1970 (Sbar, Armbruster, and Aggarwal, 1972). In previous work on strain relaxation of Paleozoic sedimentary rocks surrounding the Adirondack Mountains, we have detected a maximum expansion trending between N45°E and N90°E (Engelder and Sbar, 1976a; Engelder and Sbar, 1976b; Engelder and Sbar, 1977). We wished to check for this ENE trend by making strain relaxation measurements in the foliated metamorphic rocks of the Blue Mountain Lake area.

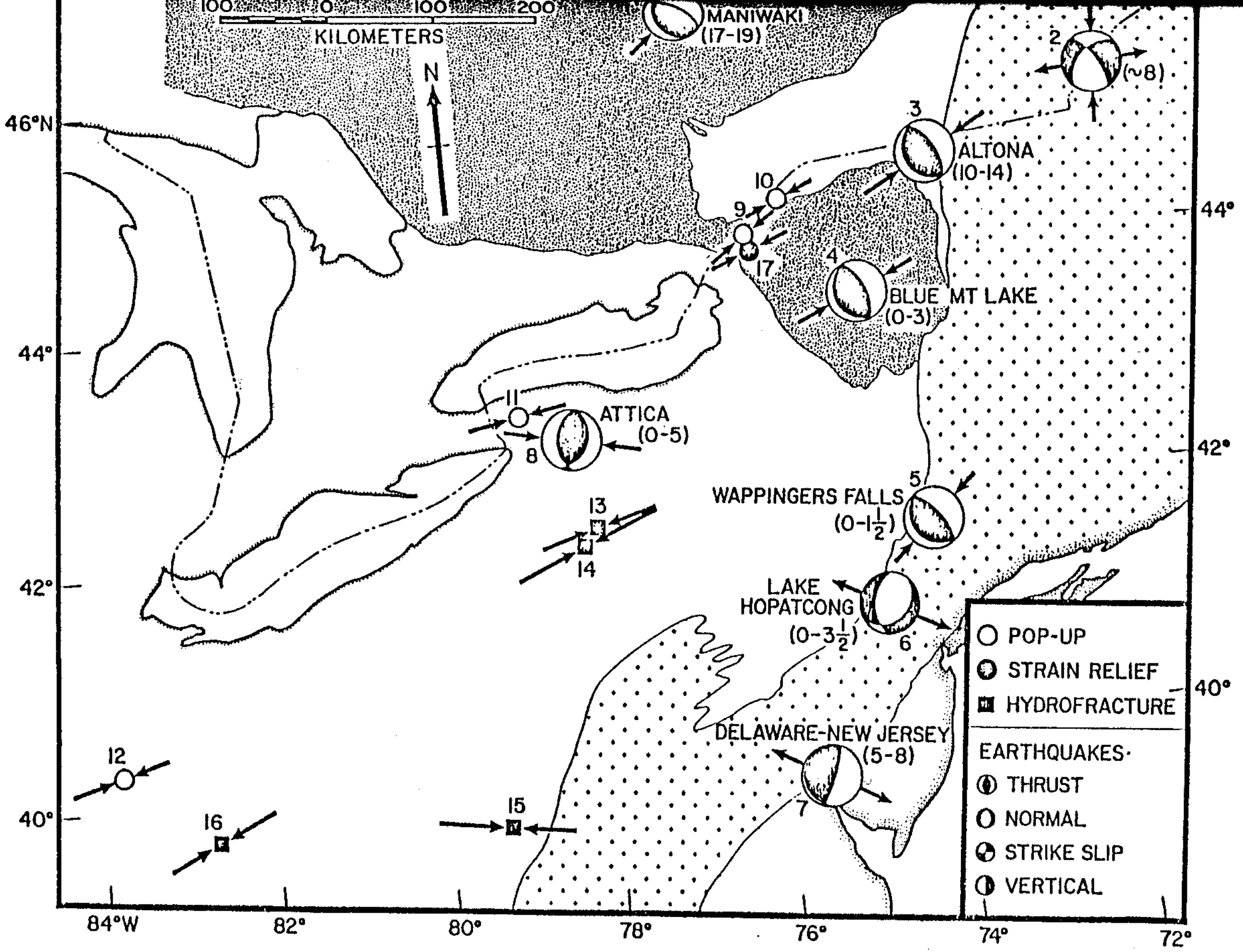

Figure 1. Fault-plane solutions, hydrofracture, selected strain-relief measurements, and pop-ups in northeastern United States and southeastern Canada (Sbar and Sykes, 1977).

In addition we measured strain relaxation in two areas where seismicity is very low: central Pennsylvania and northern Vermont. In central Pennsylvania we hoped to study the effect of high amplitude folds on residual strain. In northern Vermont we sought to map strain relaxation between two areas which have distinctly different orientations for the fault-plane solutions of earthquakes.

The long-term goal of our strain relaxation measurements is to determine the spatial variation of tectonic stress in eastern North America. This knowledge is important for predicting the location of future intraplate earthquakes. Presumably future destructive earthquakes will occur at sites where there is the fortuitous combination of high deviatoric stress and faults oriented for slip within the stress field. A clear understanding of the magnitude and orientation of crustal stresses is potentially possible through studies such as reported here.

II. PROCEDURES FOR FIELD EXPERIMENTS

A) Strain Relaxation by 6"-Overcore

Techniques for surface strain relaxation measurements have been described extensively in the 1976 Annual Technical Report to the New York State Energy Research and Development Authority (Engelder and Sbar, 1976a). Brief descriptions of the technique appear in Engelder and Sbar (1976b), Engelder and Sbar (1977), and Engelder, Sbar, and Kranz (1977). The techniques used during the 1976 field season remain the same as previously described. Basically a strain gauge rosette is bonded to an outcrop. Strain is monitored several days before overcoring to establish a thermal drift. A 6" core is cut around the strain gauge which is then monitored for several days after overcoring to establish the nature of time-dependent relaxation. The strain relaxation discussed here is the combination of instantaneous and time-dependent strain.

B) Strain relaxation by Double Overcoring

Residual strain, which exists in some rocks even in the absence of boundary loads, influences the strain relaxation of rocks. An extensive discussion of residual strain is presented in Appendix I. One technique for measuring residual strain is to cut a 3" core inside a 6" core which has no boundary loads by virtue of having already been cut loose from the outcrop. Any strain recovered from the three-inch core is associated with the relaxation of residual strain. Data from many tests shown in this report include the strain relaxation of a double overcore.

C) Triple Overcore

To further test the nature of strain relaxation following the cutting of a 6" core, we made triple overcores by making an initial cut with a 9" diameter core barrel. We followed the 9" overcore with a 6" diameter overcore coaxial with the 9" core and then a 3" overcore coaxial with the 6" core. In this experiment the strain relaxation of both the 6" diameter overcore and the 3" diameter overcore are associated with residual strains. This experiment yields information on the influence of the size of the overcore on the relaxation of residual strain. Residual strain data following the 6" overcore can then be used to compare with data from 6" overcores which were initially cut into the outcrop.

III. LABORATORY TECHNIQUES

Laboratory analyses are necessary to understand the nature of strain relaxation in the field. Basically an understanding of the mechanical properties of rocks give clues about the presence of residual strain and the role of residual strain in the relaxation of rocks.

Laboratory techniques described in our previous technical report (Engelder and Sbar, 1976a) include sonic velocity tests, uniaxial deformation tests and petrofabric analyses. In addition to these tests we developed two new lab tests during 1976-1977.

A) Radial Squeezer

In order to further tests our _in situ_ strain samples for a mechanical anisotropy, we constructed a test chamber which applies a uniform radial load to a 1 7/8" diameter cylinder cut along the axis of a 6" diameter core (Figure 2). The top of the 1 7/8" diameter cylinder has the same strain gauge rosette which was bonded to the outcrop in the field. Essentially,

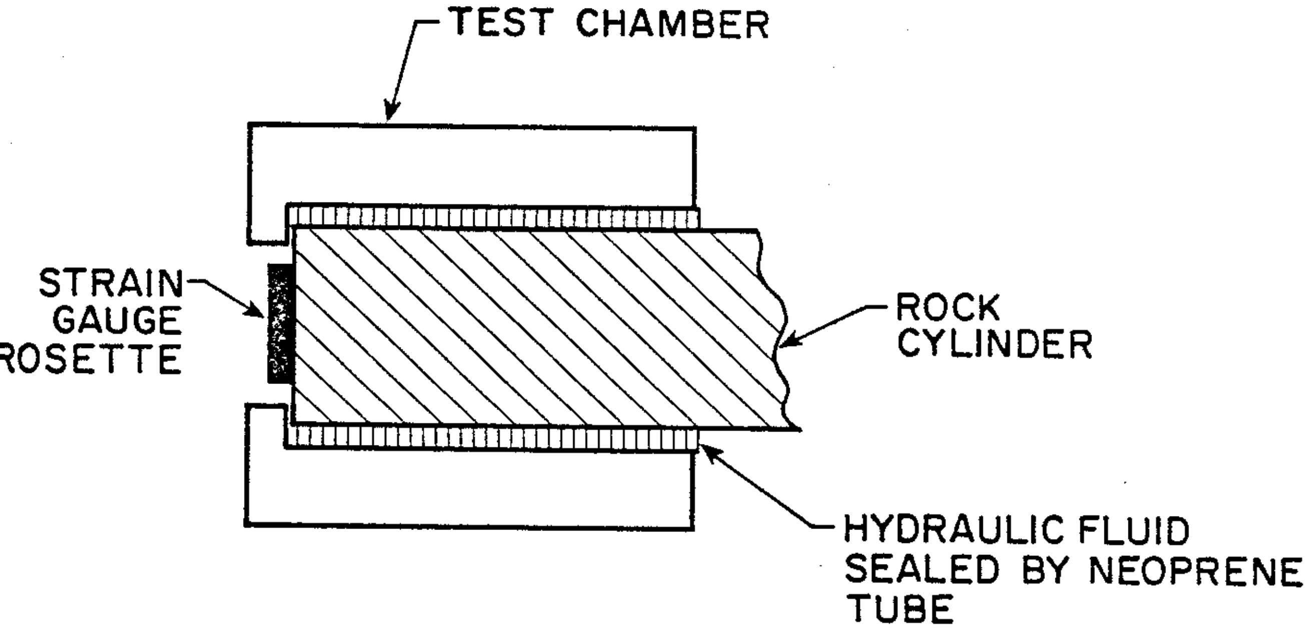

Figure 2. Cross-section of a test chamber designed to apply a radial load on an NX core (1 7/8" diameter).

we are reloading the same rock which was relieved by overcoring.

The test chamber consists of a 4" long hollow cylinder with an inside diameter of 2 1/8". A neoprene tube is sealed to the inside wall of the test chamber. An Enerpac hand-pump is used to pressurize hydraulic fluid between the neoprene tube and the test chamber, thereby creating a uniform radial load around the rock cylinder. The radial load is measured with a pressure gauge and the radial strain is measured using the strain rosette to the end of the cylinder.

The test chamber allows us to identify the orientation and relative strength of any mechanical anisotropy affecting in situ strain relaxation. This anisotropy may then be correlated with fabric elements of the sample. A linear compressibility may be estimated for directions along which strain gauges are bonded. Finally the in situ stress may be estimated by measuring the load necessary to restore the strain relieved by overcoring.

B) Microfracture Analysis

Rocks contain many microcracks which affect their mechanical properties. Such microcracks are either open or clay-filled. To estimate the effect of microfractures on the linear compressibility of rocks we measured fracture orientation and density in thin sections from strain relaxation samples. Microfractures whose normal orientation is in or near (±30°) to the principal axes of strain relaxation are most likely to have influenced strain relaxation. Therefore, we cut thin sections parallel to the plane of strain relaxation (the outcrop surface) and measured the azimuth of those microcracks which dipped between about 60° and 90°. Because a flat-stage microscope with an X-Y mount was used for our measurements, we could measure the azimuth of microcracks rapidly but we could never be sure we were measuring only those microcracks which dipped between 60° and 90°. The X-Y mount allowed us to measure only those microcracks in grains falling under a grid at 2 mm intervals. We found that grains under each stop had between 0.5 and 4 microcracks. This microcrack density was determined from a sample of 100 or more points.

To calculate the possible effect of microcracks on linear compressibility for each _in situ_ strain sample, we assumed that each open or clay-filled crack affected the stiffness of the grain which enclosed the microcrack. We arbitrarily assigned a stiffness anisotropy to each grain containing a microcrack by assuming the grain was ten (10) times stiffer parallel to the strike of the microcrack than normal to the microcracks. A relative stiffness was estimated for each sample of microcracks by using a tensor superposition technique. Here, we assume that the stiffness anisotropy of the sample is determined by the superposition of microcracks.

Each microcrack was treated as a 2 x 2 second-order tensor with principle axis ratio of 10:1. Each crack was transformed to a N-S coordinate system. Next, a mean of each of the transformed tensor elements was made. A new tensor whose elements were composed of these means was transformed to principal axes. From this we obtain an axial ratio and orientation of an average stiffness for the sample. This average stiffness calculated from microcrack orientations was then used to determine if the relaxation of microcracks contributed to the strain relief of a specimen. Likewise, this calculated stiffness anisotropy was compared to the anisotropy determined by the radial squeezer. If the anisotropy determined by the radial squeezer compared with the anisotropy calculated from the microcrack analysis, we can attribute the sample anisotropy to microcracks.

IV. FIELD EXPERIMENTS: BLUE MOUNTAIN LAKE

A) Geology and Geography

The area of our study is 50 km southwest of the high peaks in the Adirondack Mountains. Our sites are located approximately between the towns of Racquette Lake and Tahawas, New York and in the vicinity of Blue Mountain Lake and Long Lake. In general all sites were located in areas with less than 500 m of relief.

Four rock types dominate the outcrops of the central Adirondacks: hornblende-biotite gneiss; pyroxene-hornblende gneiss; anorthosite; and layered metamorphic rock (Figure 3). Sites named Dillon, Sagamore, Prospect, and Rock Lake are metasediments; those named Reed, Seaman, Sagamore and Windfall are pyroxene-hornblende gneiss; and Rifle is an anorthosite (Table I).

Parts of the central Adirondacks have been mapped by DeWard (personal communication) who finds highly deformed nappe-like structures in the metasediments. In the Blue Mountain Lake area the foliation of the metasediments and gneiss strike about east-west. There are local instances where the

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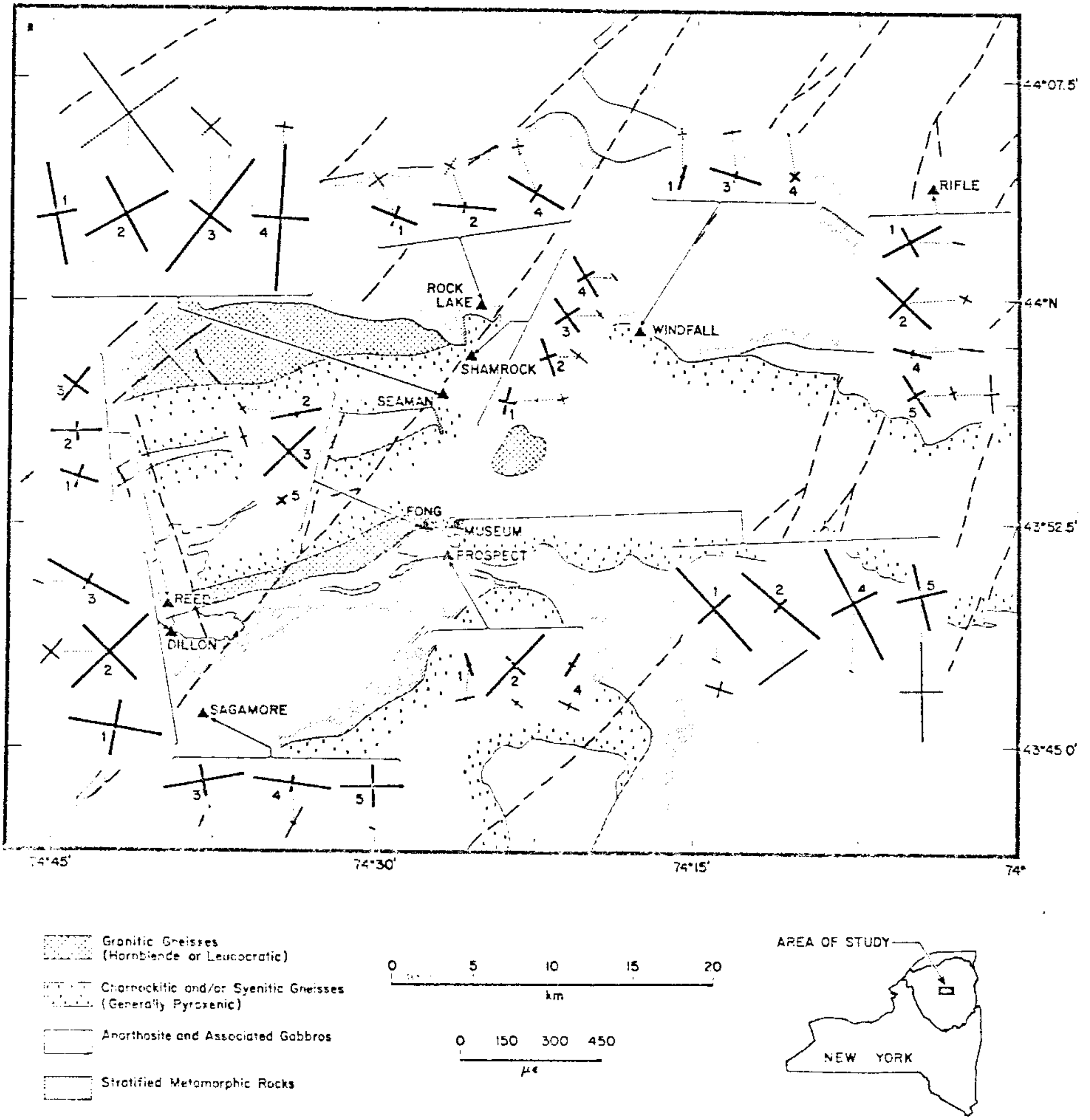


Figure 3. Strain relaxation data from the Blue Mountain Lake area. Eleven overcoring sites are referred to by name on a map showing the geology of the central Adirondacks. Maximum and minimum expansion and orientation are shown for both initial overcores (dark crosses) and double overcores (light crosses). A strain relief scale is given in microstrain (με). The number beside each data set is an arbitrary number assigned to each strain gauge rosette on the outcrop.

maximum expansion. An interpretation of these initial strain relaxation measurements is only possible after extensive analysis of the mechanical properties of the samples from the Blue Mountain Lake area.

2) Double overcore

The largest relaxations following the cutting of a 3" core inside a 6" core occurred on samples from Museum and Seaman. The orientation of the maximum expansion at each site varied. Only the double overcore from Rock Lake yielded consistent magnitudes and orientation within 45°. However, the Rock Lake data are unusual because small contractions followed the double overcoring. The double overcore data are poor, and reveal no obvious trend in residual strain of rocks in the Blue Mountain Lake area.

3) Triple overcore

At Museum, Shamrock, and Rifle an initial overcore was made using a 9" core barrel. Inside these three 9" cores were cut concentric 6" and then 3" cores. In all three cases the magnitude and orientation of the relaxation following the 9" core was comparable to relaxation following initial 6" cores made elsewhere on the outcrop. The subsequent 6" overcore within the 9" core relieved very little strain. Strain relaxed by a 3" core cut into the 6" core was larger than that relaxed by the 6" core. We conclude that if a core has been cut from the outcrop, a 3"

TABLE I. COMPOSITION OF CENTRAL ADIRONDACK ROCKS

					(Percent)			
Site	Rock Type	Qtz	Plag	K-Spar	Biot	Amph	Pyrox	Acc
Dillon	Stratified metamorphic	15	11	51	8	10	3	2
Prospect	Stratified metamorphic	35	3	50	3	9	-	-
Rock Lake	Stratified metamorphic	38	-	57	-	5	-	-
Sagamore	Stratified metamorphic	12	10	70	2	5	-	2
Fong	Hornblende-biotite gneiss	20	5	73	-	3	-	-
Museum	Hornblende-biotite gneiss	10	2	79	2	5	-	2
Reed	Pyroxene-hornblende gneiss	12	7	78	2	-	1	-
Seaman	Pyroxene-hornblende gneiss	16	11	68	-	1	-	4
Shamrock	Pyroxene-hornblende gneiss	5	16	66	1	-	10	2
Windfall	Pyroxene-hornblende gneiss	19	7	69	1	-	-	4
Rifle	Anorthosite	0			0	0	0	

overcore in that block will relieve larger components of residual strain than a 6" overcore.

The strain relaxation following an initial cut by a 6" overcore is much larger than strain relaxation following the cutting of a 6" core into a 9" core. This difference suggests that strain measured after an initial 6" overcore was not residual but the recovery of strain imposed by loads external to the 6" overcore.

C) Laboratory Analyses

Cores from each of the eleven strain relaxation sites were subjected to a battery of tests to determine their mechanical characteristics. Here we present the results of laboratory tests with emphasis on any information which may help us understand the significance of the strain relaxation of Adirondack rocks.

1) Composition

Using thin sections, the composition of the rock at each site was determined (Table I). Those rocks mapped as stratified metamorphic rocks by Rickard and Fisher (1970) were characteristically lower in feldspar than other rock-types in the central Adirondacks. The anorthosite contained the most feldspar.

2) P-wave velocity

Maximum velocity, minimum velocity, and orientation of maximum P-wave velocity are presented in Table II. These data were measured using a pulse-superposition technique described by Mattiboni and Schreiber (1967). Velocities were measured in six directions parallel to the plane of strain relaxation using 3-inch cylinders obtained by double overcoring. The relation between seismic velocity and total feldspar content is shown in Figure 4a. With only one exception, each distinct rock type clusters in a group in the seismic velocity - % total feldspar plot.

3) Strain from a uniform radial load

Seven samples were subjected to a uniform radial load of 1000 psi for which load the maximum and minimum strain plus orientation of the minimum strain are given in Table II. At 68 b radial load the maximum strain varied from 95 με for the sample at Sagamore to 312 με for the sample from Shamrock. The radial load data for a sample from Dillon are shown in Figure 5.

4) Microcrack fabric

Microcrack orientations and densities were measured from thin sections of samples taken from all sites. From these data the influence of the cracks on a modulus was calculated. Table II gives the ratio of the high

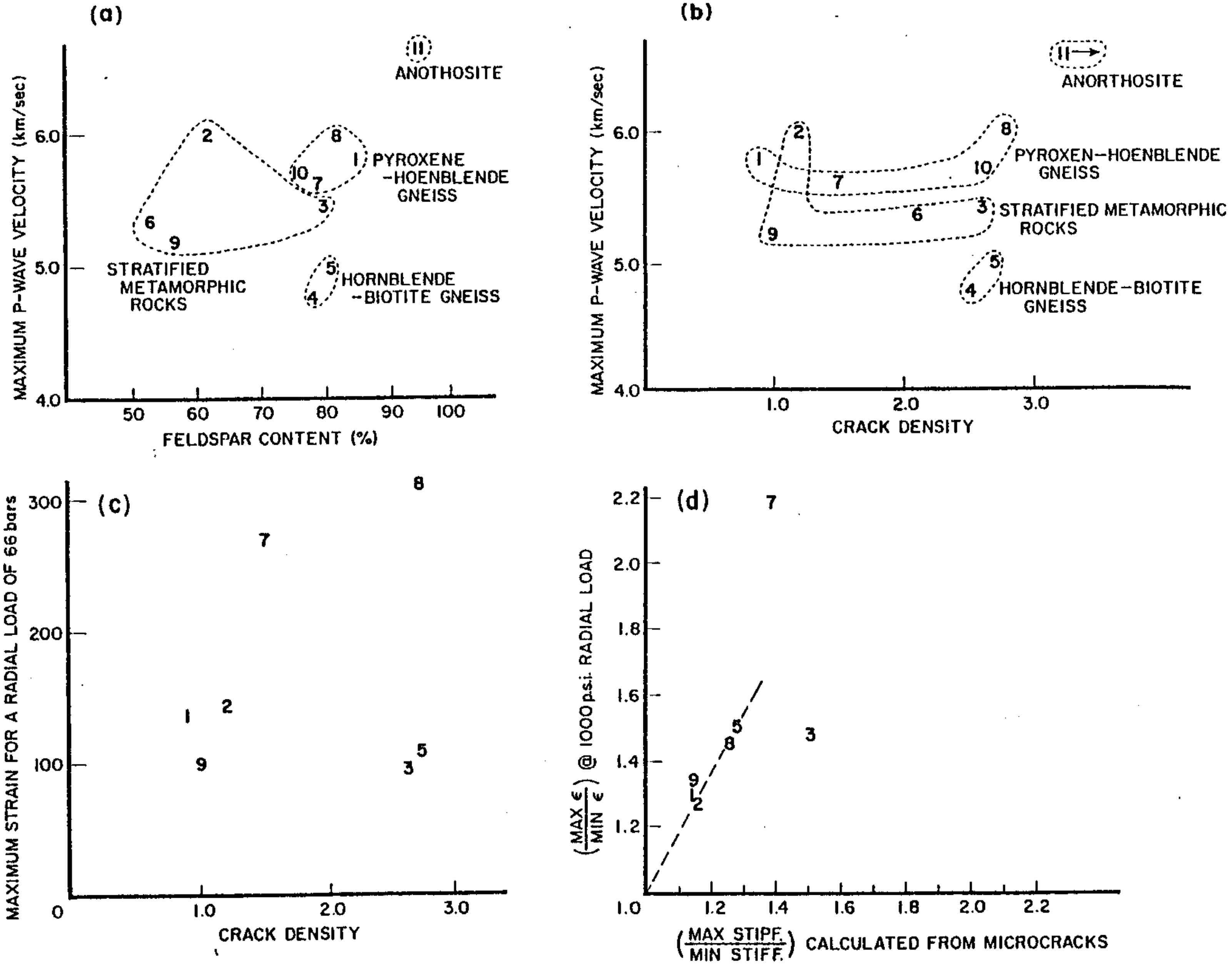


Figure 4. Mechanical data for Adirondack sites identified as: Reed = 1, Dillon = 2, Sagamore = 3, Fong = 4, Museum = 5, Prospect = 6, Shamrock = 7, Seaman = 8, Rock Lake = 9, Windfall = 10, Rifle = 11. a) Maximum P-wave velocity versus feldspar content when similar rock types are enclosed by a curve. The four groups are stratified metamorphic rocks, hornblende-biotite gneiss, pyroxene-hornblende gneiss and anorthosites. Only Sagamore (3) falls outside its appropriate group; b) Maximum P-wave velocity versus crack density; c) Maximum strain under a 66 bar radial load versus crack density; d) Axial ratio of strain (x 10^{-6}) for a 66 bar radial load versus axial ratio of stiffness calculated from microcracks.

TABLE II. MECHANICAL PROPERTIES OF ROCKS FROM CENTRAL ADIRONDACKS

Site	Tensor Average of Initial Overcores			Radial Strain with Radial Load of 68 b			P-Wave Velocity km/sec			Calculated Stiffness Based On Microcracks		Bearing of Foliation	Average Stress (Bars)		
Name & Number	Max (με)	Min (με)	Bearing Max	Max (με)	Min (με)	Bearing Min	Max (km/sec)	Min (km/sec)	Bearing Max	Stiffness Ratio	Bearing Stiff	Hand Specimen	Max (b)	Min (b)	Bearing Max
illon (2)	281	188	105	143	113	129	5.98	5.70	120	1.16	112	120	167	89	115
ong (4)	141	98	69	-	-	-	4.75	4.64	60	1.18	33	75	93	51	62
useum (5)	313	142	141	108	72	62	4.99	4.77	30	1.28	45	70	216	138	144
rospect (6)	117	42	37	-	-	-	5.33	4.87	90	1.27	132	90	66	29	33
eed (7)	142	112	81	136	106	97	5.78	5.56	60	1.14	137	75	89	57	89
ifle (11)	161	113	113	-	-	-	6.63	6.08	90	1.33	0	-	90	71	140
ock Lake (9)	182	72	124	105	78	117	5.21	4.68	90	1.15	125	90	160	40	123
agamore (3)	187	77	73	95	64	140	5.42	5.38	120	1.51	129	105	149	77	89
eaman (7)	345	237	03	271	124	143	5.62	5.40	90	1.39	55	66	148	67	156
hamrock (8)	118	73	157	312	215	105	5.99	5.90	30	1.26	125	15	32	18	134
indfall (10)	69	36	53	-	-	-	5.69	5.60	150	1.79	123	150	31	22	84

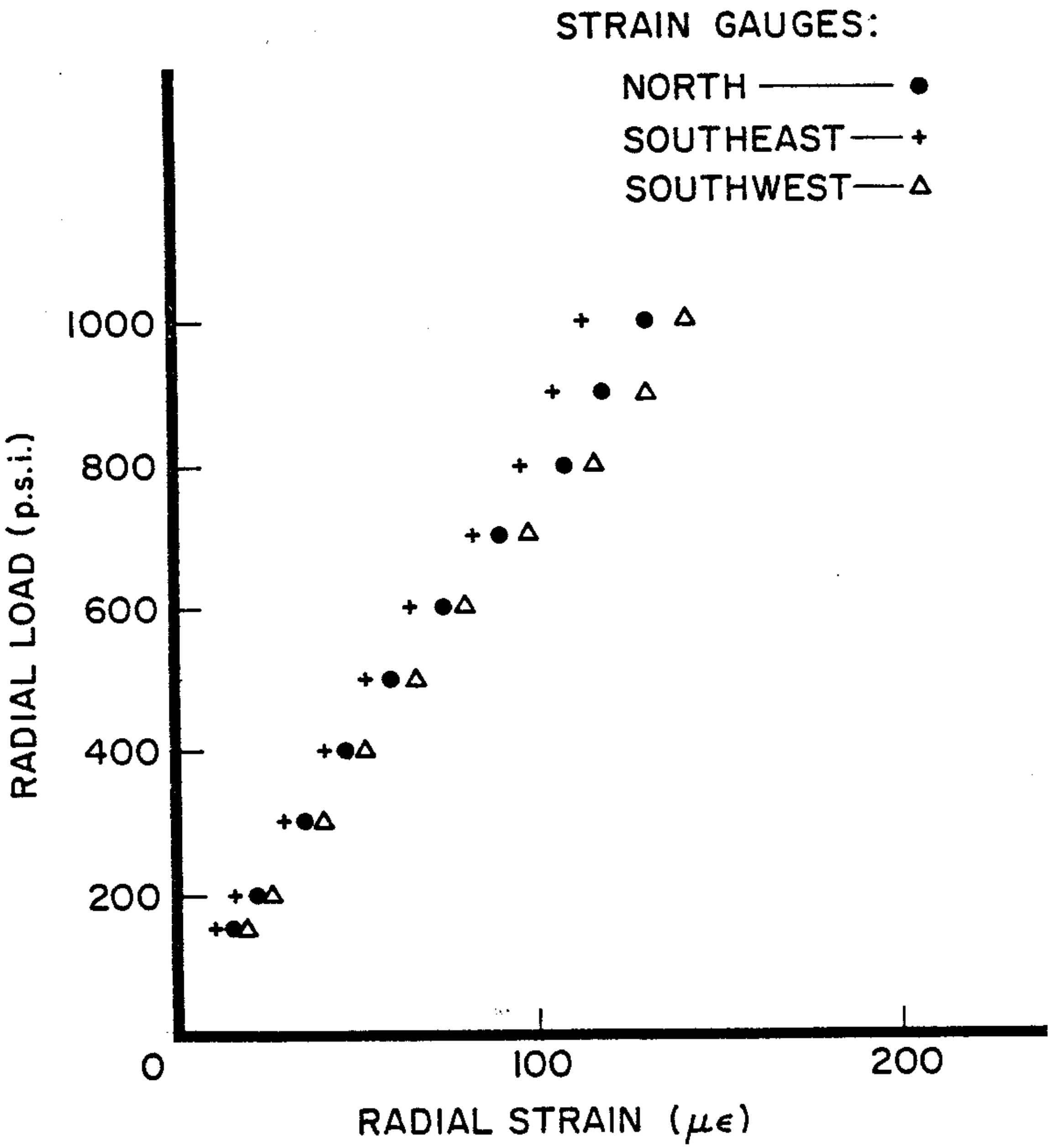


Figure 5. Radial load versus radial strain for an NX core (1 7/8" diameter) from a metasediment sampled at the site Dillon (2).

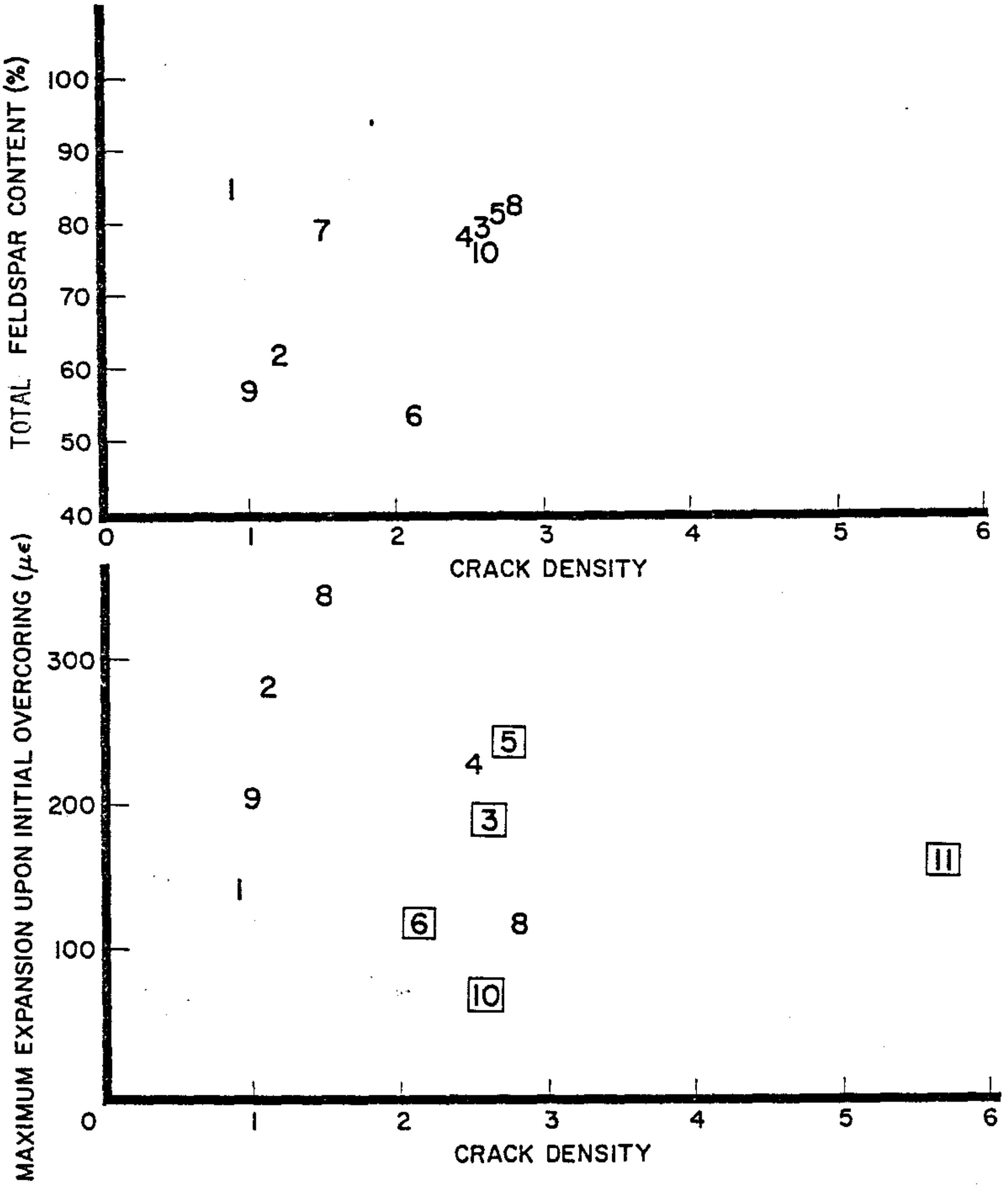
to low modulus and the orientation of the high modulus (stiff direction) in a plane parallel to the plane of strain relaxation.

One important characteristic of the rocks from the central Adirondacks is that most open microcracks are clay-filled and found in feldspar grains. The microcrack density is approximately proportional to the total feldspar content of the rocks (Figure 6a). Samples from Reed, Seaman and Prospect have crack densities which do not fit this trend.

5) Interaction of mechanical properties

The cause of the mechanical anisotropy is of greatest interest because the principal axes of strain relaxation generally correlate with the principal axes of the mechanical anisotropy for central Adirondack rocks (Table II). A mechanical anisotropy may be attributed to either of two fabric elements in the rocks: 1) a foliation caused by the alignment of minerals and; 2) an alignment of microcracks.

The relationship between crack density and other mechanical properties is predictable although there is some scatter in our data. Because the crack density is a function of total feldspar, it is also a function of rock type (Figure 6a). Most of the layered metamorphic rocks have a lower feldspar content and lower crack density. The anorthosite has the highest crack density. The stiffness of the samples varies roughly with the crack density as displayed in Figure 4c. The rocks with low crack densities appear to strain less for an equivalent load. Samples from Museum and Sagamore are exceptions to this rule. Crack density does not



igure 6. Mechanical data for Adirondack sites: a) Crack density versus total feldspa ontent. Rocks placed in three groups with only Sagamore, a metasediment, falling outide its appropriate group; b) Maximum expansion upon initial overcoring (με) versus rack density. Rectangles note those samples with a maximum expansion more than 50° fr he strike of the calculated stiff direction based on microfracture orientation.

seem to affect seismic velocity in any systematic manner (Figure 4b). P-wave velocity strongly depends on total feldspar content. The increase in velocity because of feldspar content apparently masks any decrease in velocity which might be expected for an increased fracture density. For example, Rifle has both the highest fracture density and highest velocity.

We observe a strong correlation between the orientation of the calculated microcrack anisotropy and the mechanical anisotropy. For five out of the seven samples for which we have radial squeeze data, we find that the stiff direction determined by the radial squeeze is within 20° of the stiff direction calculated from microcracks (Table II and Figure 7). Here it is of significance to note that the same sample was not used for radial squeeze and microcrack analyses. This demonstrates that mechanical properties do not vary on the outcrop scale. The exceptions are Reed and Seaman where the stiff directions differ by 40° and 70°, respectively. At Seaman there was scatter in the overcoring data, suggesting that mechanical properties vary within this outcrop.

To further emphasize the correlation between strain associated with a uniform radial load and the calculated microcrack fabric, we plot the ratio of stiffnesses calculated from microcracks against the ratio of stiffnesses measured from a uniform radial load (Figure 4d). Four out of six samples fall on a line. Seaman does not fall on this trend because of variation in mechanical properties on the outcrop scale. Again, Sagamore falls off of this trend for unknown reasons.

The velocity anisotropy correlates with the calculated microcrack anisotropy in seven out of eleven cases. The calculated stiff direction is the high

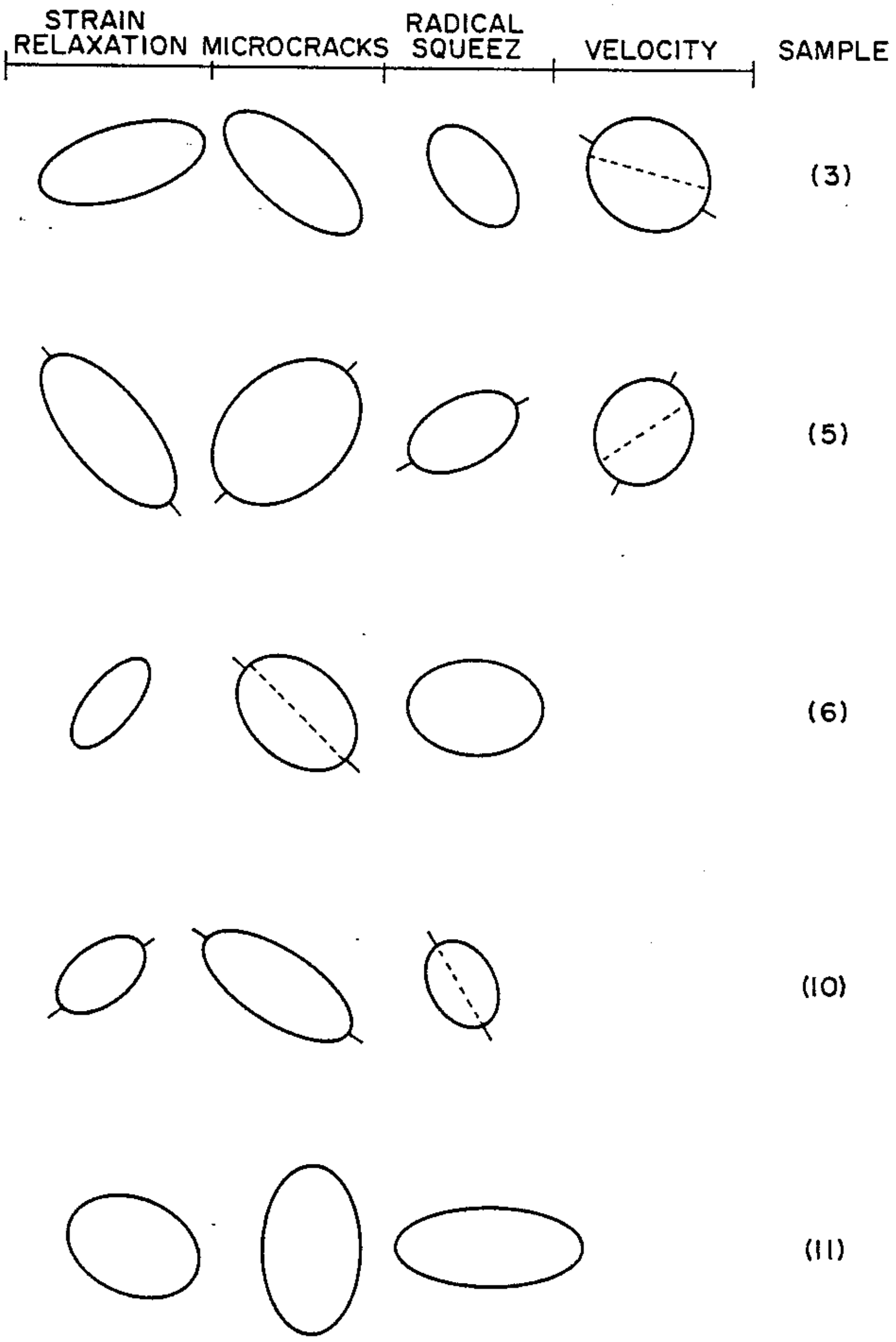
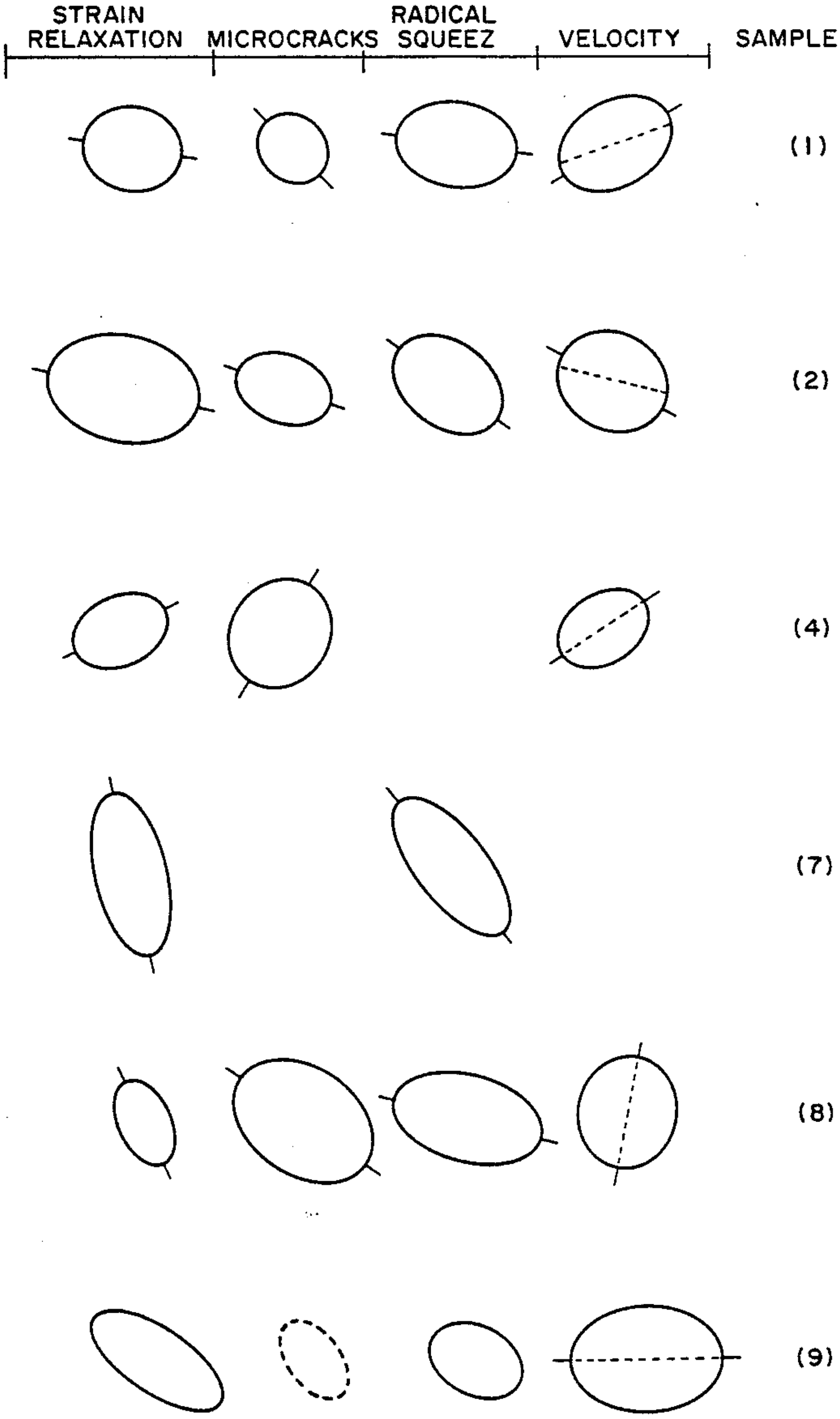


Figure 7a. Strain relaxation and mechanical data for samples that relaxed normal to their stiff direction. Shown for each site are tensor averages of initial overcoring, microcrack orientation, radial load strain anisotropy and velocity anisotropy. The dotted insets show test sample foliation. The various data are represented by ellipses whose ellipticity indicates relative axial ratio range and size indicates relative magnitude (see Figure 7c).



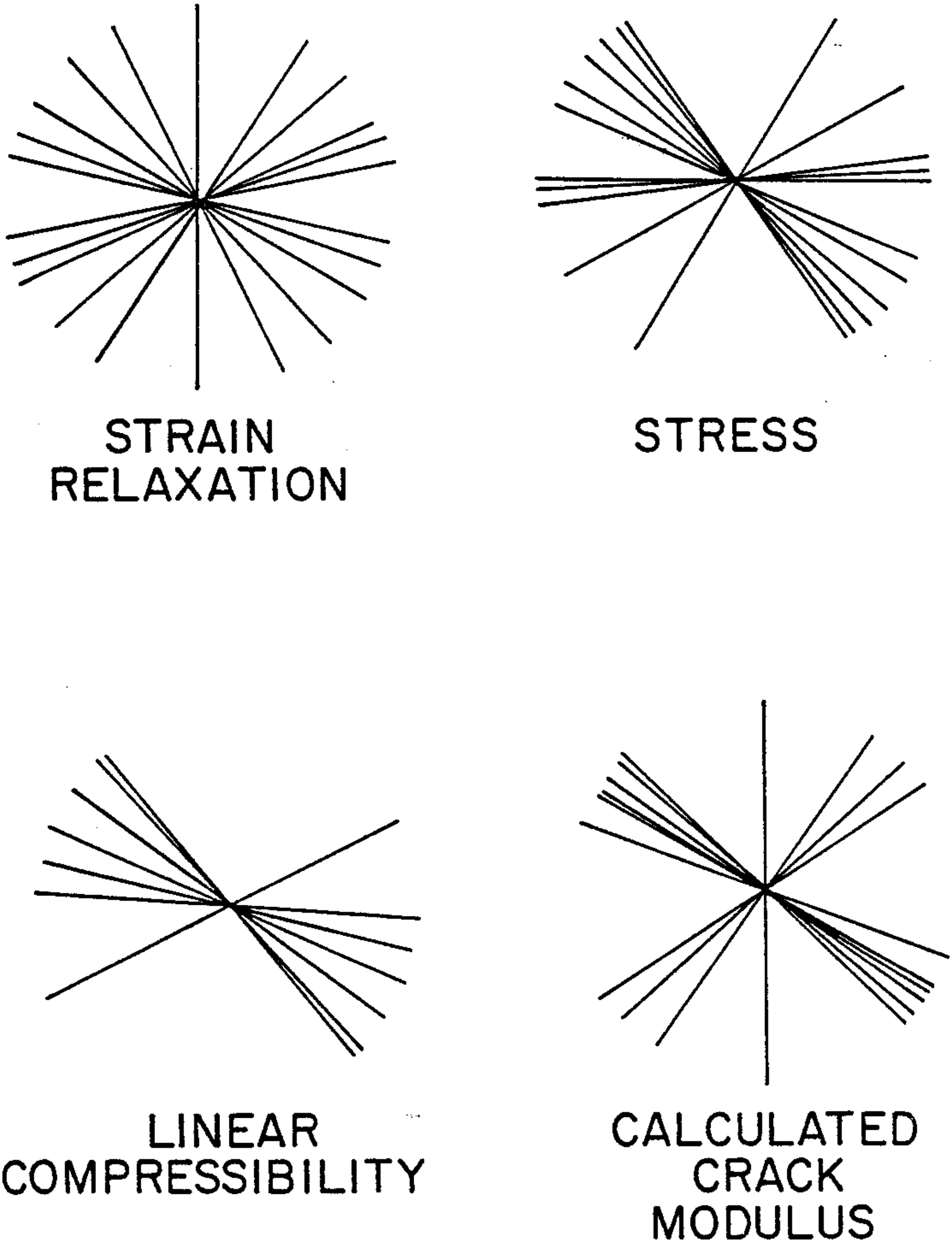
gure 7b. Strain relaxation and mechanical data for samples that relaxed parallel th their stiff direction.

velocity direction (± 30°). At Reed, Shamrock, and Rock Lake, the velocity anisotropy follows the foliation with the high velocity direction parallel to a visible foliation in the rock (Figure 7). Reed and Rock Lake have the lowest crack density and, so, cracks are least likely to control the seismic velocity anisotropy (Figure 4b). Shamrock has a very strong foliation which dominates any microcrack anisotropy.

D) Interpretation of Strain Relief in the Central Adirondack Mountains

In order to facilitate interpretation of the strain relief measurements from the central Adirondacks, we have calculated an average for the initial strain relaxation from each outcrop. The average is obtained from the superposition of the tensors representing each initial overcore data. The resulting tensor is divided by the number of data to obtain a tensor average for each outcrop (Table II and Figure 7). We have also calculated a stress for each outcrop by using the measured linear compressibility. The strain relaxation in each of the three strain gauge rosette directions is divided by the linear compressibility in that direction to obtain three components of stress. From the three components of stress we obtain orientation of principal stresses (Table II).

The orientations of the tensor average for the maximum expansion and the maximum compressive stresses for all eleven outcrops are shown in Figure 8. The rose diagram for tensor averages of strain relaxation shows no preferred orientation; however, a trend is indicated by the rose diagram



STRAIN RELAXATION

STRESS

LINEAR COMPRESSIBILITY

CALCULATED CRACK MODULUS

Figure 8. Orientation diagrams for pertinent data from the central Adirondack Mountains: (1) Orientation of tensor average for maximum expansion of strain relaxation for eleven outcrops; (2) Orientation of tensor average for stress from eleven outcrops; (3) Orientation of minimum linear compressibility for seven samples; (4) Orientation of stiffest direction for samples as calculated from crack anisotropy.

for the orientations of maximum compressive stress. Strain relaxation is sensitive to an east-west to northwest maximum compressive stress. The anisotropy in linear compressibility of rocks from the Adirondack Mountains apparently affects the strain relaxation. Although the raw strain relaxation data in Figure 3 show no trend, there is a stress field in the rocks of the Adirondacks which affects surface outcrops with a WNW maximum compression (Figure 8).

We have distinguished two data sets (Figure 7a and 7b). Figure 7a shows all sites where the initial strain relaxation was parallel to the stiff direction of the sample as determined by radial loading tests and microcrack calculations. Figure 7b shows these samples where strain from the initial overcore was greater than 30° from the stiff direction of the sample.

In situ strain at Rock Lake, Reed, and Dillon have stiff directions oriented about east-west (Figure 7a). Seaman, Fong and Shamrock have north-south trending strong directions with N-S maximum expansions upon initial overcoring. *In situ* strain at Museum, Prospect and Windfall is apparently controlled by the opening of microcracks with the maximum expansion normal to the sample's stiff direction (Figure 7b). Maximum expansion at Rifle and Sagamore were at about 45° to the mechanically strong direction.

In general the mechanical anisotropy is oriented with a strong direction between NW and E-W. The exceptions are Fong and Museum with a strong direction in toward the NE and Seaman with a strong direction N-S. A tensor average for strain in the entire central Adirondack area gives a maximum expansion of N59°W. This is equivalent to a maximum expansion in the stiff direction of most Adirondack rocks. Previous experience suggests that if microcracks or other elements of rock anisotropy influence the strain relaxation, the maximum expansion will occur in the weak or least stiff direction of the sample. Residual strain generally relaxes a paleostress which in the central Adirondacks may have been a N-S direction Grenville age deformation. We found no evidence for a WNW paleostress. Thus we conclude that the WNW-directed maximum expansion is related to a regional applied load. We think it to be significant that this WNW maximum expansion falls in the compression quadrant of fault-plane solutions for earthquakes from Racquette Lake and Blue Mountain Lake.

We calculated a deviatoric stress of 27 bars from the tensor averages of the eleven outcrops sampled in the Blue Mountain Lake area. The maximum compressive stress is N60°W. Although the maximum stress rose diagram clusters in the WNW direction and the strain relaxation rose diagram does not (Figure 8), the orientation of the tensor average for both maximum expansion and maximum compression are within 7° of each other.

V. FIELD EXPERIMENTS: PENNSYLVANIA AND VERMONT

In addition to our experiments near Blue Mountain Lake, we performed field experiments in central Pennsylvania and northwestern Vermont. These experiments were designed to measure strain relaxation in areas of the northeastern United States which had not been visited in past summers.

A) Central Pennsylvania

Our central Pennsylvania experiment was concluded in the folded Appalachian Mountains in the vicinity of Williamsport, Pennsylvania (Figure 9). This region was selected because the orientation of the residual strain due to the Appalachian deformation should be easily discerned in central Pennsylvania and may thus be distinguished from any applied components. Very few earthquakes were reported in this region, so we might suspect that the applied stress may be low in comparison with that in northern New York. This area consists of first order folds with amplitudes of more than 1 km and wave lengths of more than 15 km. Most of the Paleozoic section between the Cambrian carbonates and the Carboniferous sandstones of the central Appalachians are exposed within 100 km of Williamsport. The rock type of each _in situ_ strain site is listed in Table III.

The strain relaxation data from central Pennsylvania are ambiguous (Figure 9). Initial overcore strains were very low and contractions were measured at some sites. At most sites the orientation of the maximum expansion was not reproducible. Likewise the maximum expansion of double overcores was low.

The results from the strain relief measurements were surprising in light of the tectonic deformation in the Williamsport area. We expected to measure a very strong trend in residual strain based on our experience

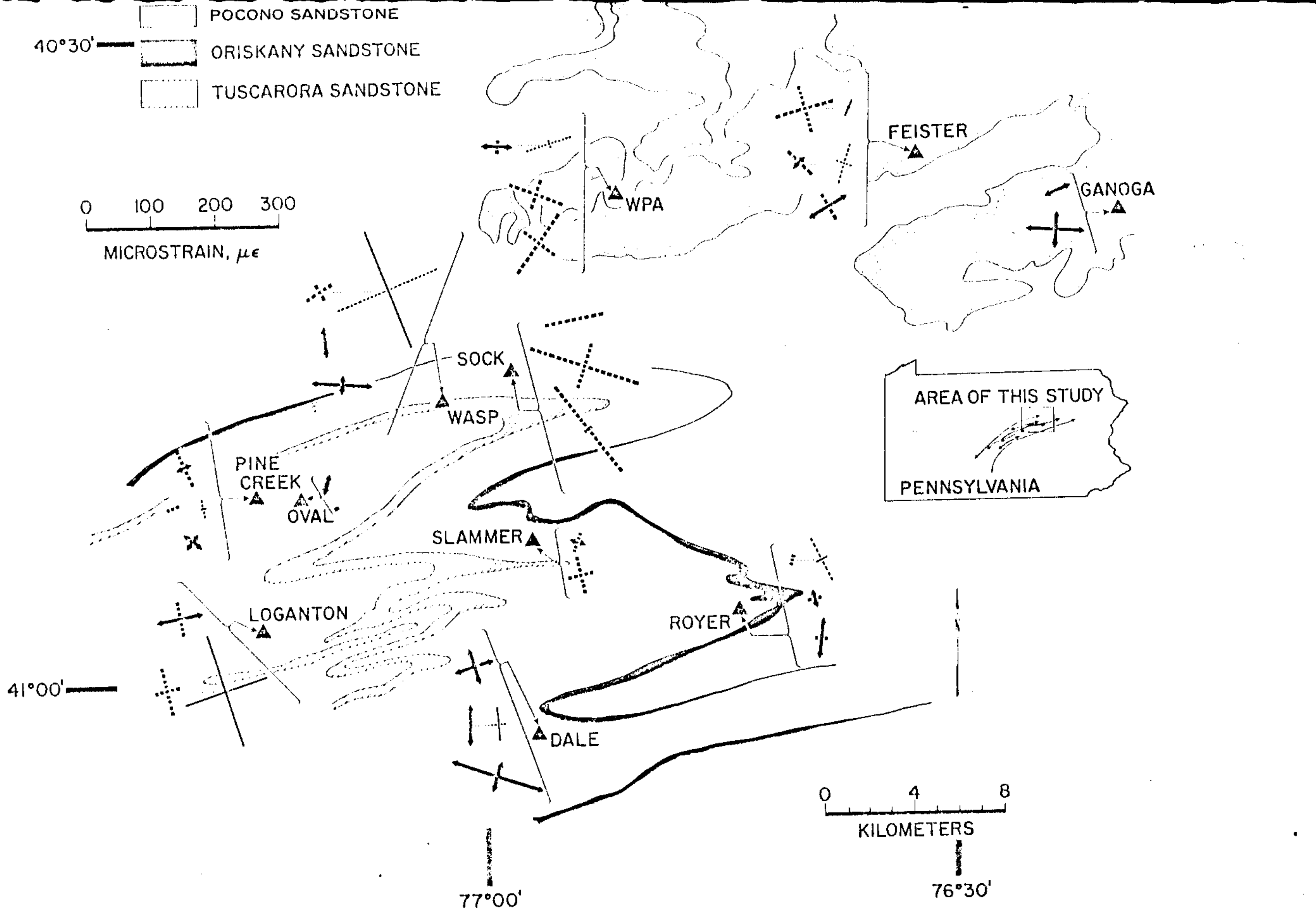


Figure 9. Strain relaxation data from central Pennsylvania. Eleven overcoring sites are referred to by name on a map showing the location of three Paleozoic sandstones that outcrop in central Pennsylvania. Maximum and minimum strain relief are shown for both initial overcores (dark crosses) and double overcores (light crosses). Solid lines represent expansions and dashed lines represent contractions. A strain relief scale is given in microstrain (με).

TABLE III. ROCK TYPE OF CENTRAL PENNSYLVANIA

Site	Rock Type	Age
Ganoga	Sandstone	Pennsylvanian
Fiester	Sandstone	Pennsylvanian
W.P.A.	Sandstone	Devonian
Loyalsock	Sandstone	Devonian
Dale	Carbonate	Silurian
Slammer	Carbonate	Silurian
Royer	Carbonate	Silurian
Wasp	Sandstone	Silurian
Loganton	Carbonate	Ordovician
Oval	Carbonate	Ordovician
Pine	Carbonate	Ordovician

in western New York where maximum expansion was oriented parallel with the compression of the Appalachian folds. The inconsistent nature of our initial strain relaxation data from central Pennsylvania suggests that any applied strain was so low that we could not recognize it with our surface technique.

By comparing and contrasting the velocity and overcoring data from western New York (Engelder and Sbar, 1976a) and central Pennsylvania, we can suggest why residual strain relaxation was low and seems inconsistent in central Pennsylvania. In western New York the sandstones expanded parallel to the maximum velocity direction (NNW) and the maximum compression of the Appalachian folds. Table IV shows that sandstones from central Pennsylvania have a maximum velocity oriented E-W or normal to the maximum compression of the Appalachian folds. The sandstones of central Pennsylvania are greywackes with clay which has been metamorphosed to white micas. These micas give the sandstone a slight E-W foliation and seem to control the velocity anisotropy. When the sandstones expanded upon initial overcoring their maximum expansion was E-W in most cases (Wasp, W.P.A., Feister, and Ganoga). This expansion is parallel to the high velocity direction as it was in western New York. The data suggest an expansion parallel to a weak foliation but it was not reproducible except at Ganoga.

The carbonates show a high velocity direction normal to the fold axes near Williamsport (Table IV). This mechanical anisotropy was not reflected in the overcoring data. We suggest that the level of metamorphism to which the carbonates were subjected was high enough to anneal the rock and remove

TABLE IV. VELOCITY OF ROCKS FROM CENTRAL PENNSYLVANIA

			Velocity (km/sec)					
		Velocity	Bearing					
Site	Rock	Ratio	0	30	60	90	120	150
Royer	Carbonate	-	6.29	6.30	6.30	6.28	6.31	6.30
Dale	Carbonate	1.02	6.34	6.25	6.26	6.29	6.33	6.37
Pine	Carbonate	1.03	6.10	6.11	6.00	5.97	6.13	6.14
Wasp	Sandstone	1.19	4.09	4.33	4.73	4.87	4.64	4.24
W.P.A.	Sandstone	1.13	3.97	4.22	4.32	4.19	3.92	3.81

any residual strain which may have once been impressed on the carbonates. The net effects are incoherent strain relaxation data.

B) Northwestern Vermont

Strain relief measurements were made at seven sites in metamorphic rocks of Ordovician and Cambrian age near Burlington (Figure 10). This region was selected since it is within a region of low seismicity between areas of higher seismicity in northern New York and central and southern New Hampshire. Fault-plane solutions to the west of Vermont indicate an ENE maximum compressive stress while one fault-plane solution to the east of Vermont indicates a N-S maximum compressive stress (Figure 1). Thus this study area is ideally situated to investigate the transition from one stress orientation to another.

The rocks sampled include the Monkton quartzite, Dunham dolomite, and Cheshire quartzite of Cambrian age and the Ordovician Shelborne marble. All are folded and metamorphosed with fold axes trending north to NNE. Petrofabric and detailed fault and joint analysis of the Monkton quartzite by Stanley (1974) indicates that this formation underwent deformation during the Taconic and Acadian orogenies, with different orientations for the maximum compressive stress in each case. The Cheshire quartzite has a strong, steeply-dipping foliation and strikes generally north-south. In the areas sampled, Hayes, Georgia, Irish and Wright, the quartzite grades toward a phyllite. The outcrop of Shelborne

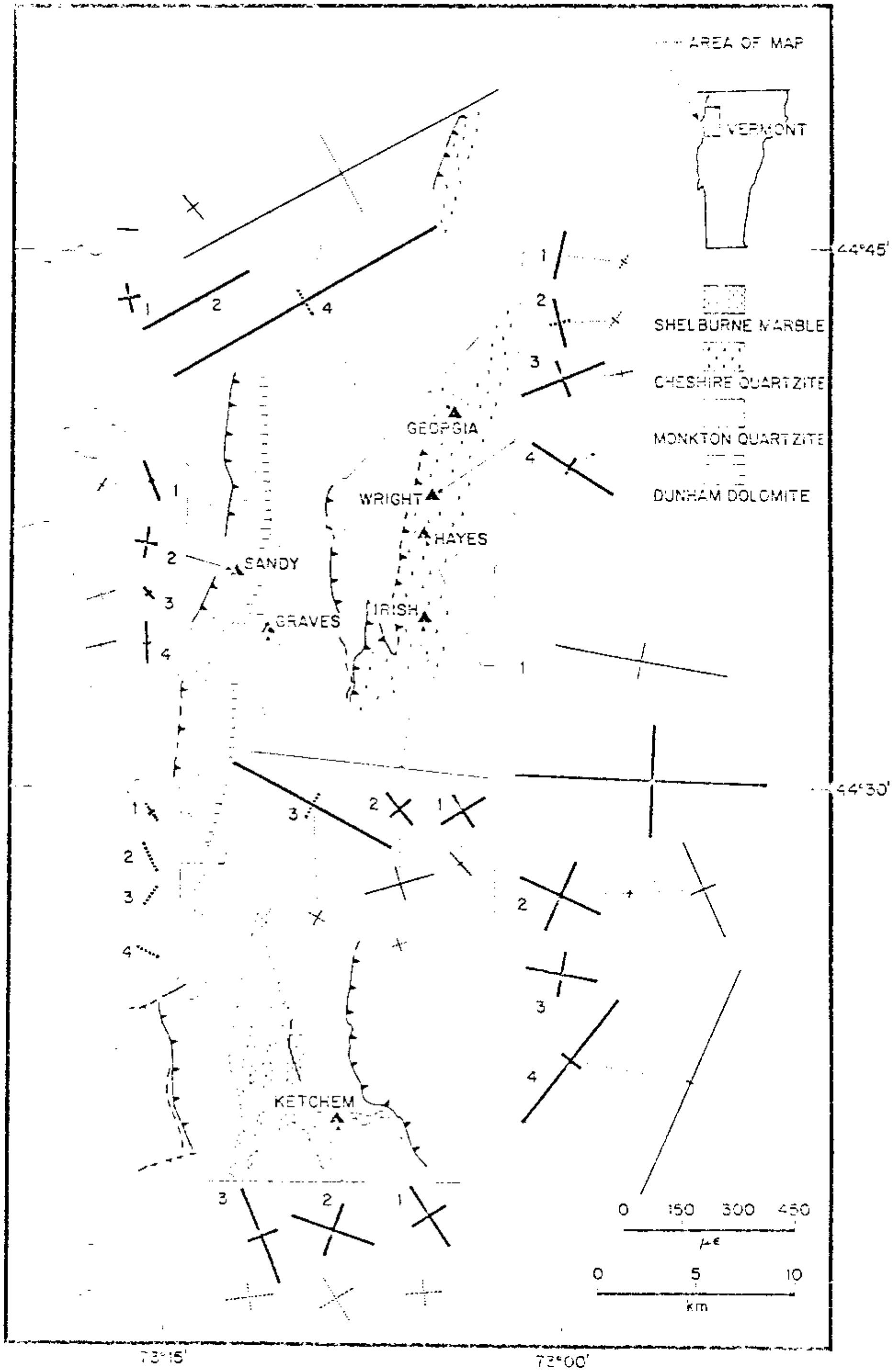


Figure 10. Strain relaxation data from northwestern Vermont. Eight overcoring sites are referred to by name on a map showing the location of four geological units. Maximum and minimum strain relief are shown for both initial overcores (dark crosses) and double overcores (light crosses). Solid lines represent expansions and dashed lines represent contractions. A strain relief scale is given in microstrain (με).

marble at Ketchem showed several phases of deformation. Structure is not apparent in the cores taken, instead the rock appears homogeneous and fine-grained. Because of the fine-grained nature of the rock, no calcite twin lamellae were observed.

Graves was the only site on Monkton quartzite. The data obtained here were poor. The strain relieved upon overcoring was small and should be disregarded. This is most probably because the site was too close to the edge of a 30 m cliff, which would relieve the strain at that site. Other sites could not be found in that formation since in most places it was too fractured or dipped too steeply.

Sandy was the only location where we were able to bond to dolomite. Topographically it is not ideal. There were 5 to 10 m of relief on two sides. The gauges were placed more than 10 m from slopes, so the effect of the relief should be minimal but still present.

The strain relief on the four Cheshire quartzite sites does not appear to be controlled entirely by the foliation. If this were so, one would expect the maximum elongation to be perpendicular to the strike of the foliation. Large values of strain relief were obtained at Georgia and Hayes and may be due to the opening of microcracks.

The Adirondacks. We have measured _in situ_ strain at four localities in the vicinity of the Adirondacks (Figure 11). Rocks at all localities show a predominant maximum expansion upon overcoring WNW-ESE to NE-SW. Our present interpretation is that rocks at at least two localities where detailed analysis has been performed are responding to a maximum compression from an applied stress oriented somewhere between E-W and NE-SW. This is similar in orientation to that of the compression axes of focal mechanisms for earthquakes in the vicinity of the Adirondack Mountains [(1) Blue Mountain Lake earthquakes; (2) Racquette Lake earthquake, and (3) Altona earthquake (Sbar and Sykes, 1977)]. This same region about 250 km in diameter is presently undergoing rapid uplift; at the center of the Adirondacks, the rate is 3.7 mm/yr (Isachsen and Wold, 1977). Although it is tempting to suggest that rapid uplift, earthquakes, and uniformly oriented _in situ_ strain may be related to the same anomalous stress in the lithosphere, proof of a common source for the three phenomena is not yet at hand. At two sides on the south and northeast side of the Adirondack Mountains we have not demonstrated a relationship between _in situ_ strain and an applied load. We include these in our set of four Adirondack sites because of the similar orientation of maximum expansion at all four sites.

Western New York. Strain relaxation in the vicintiy of Brockport, New York is oriented with a maximum expansion N-S to NNW-SSE (Figure 11). This orientation is the same as the compression of the Appalachian foreland fold and thrust belt. That such a compression reached the vicinity

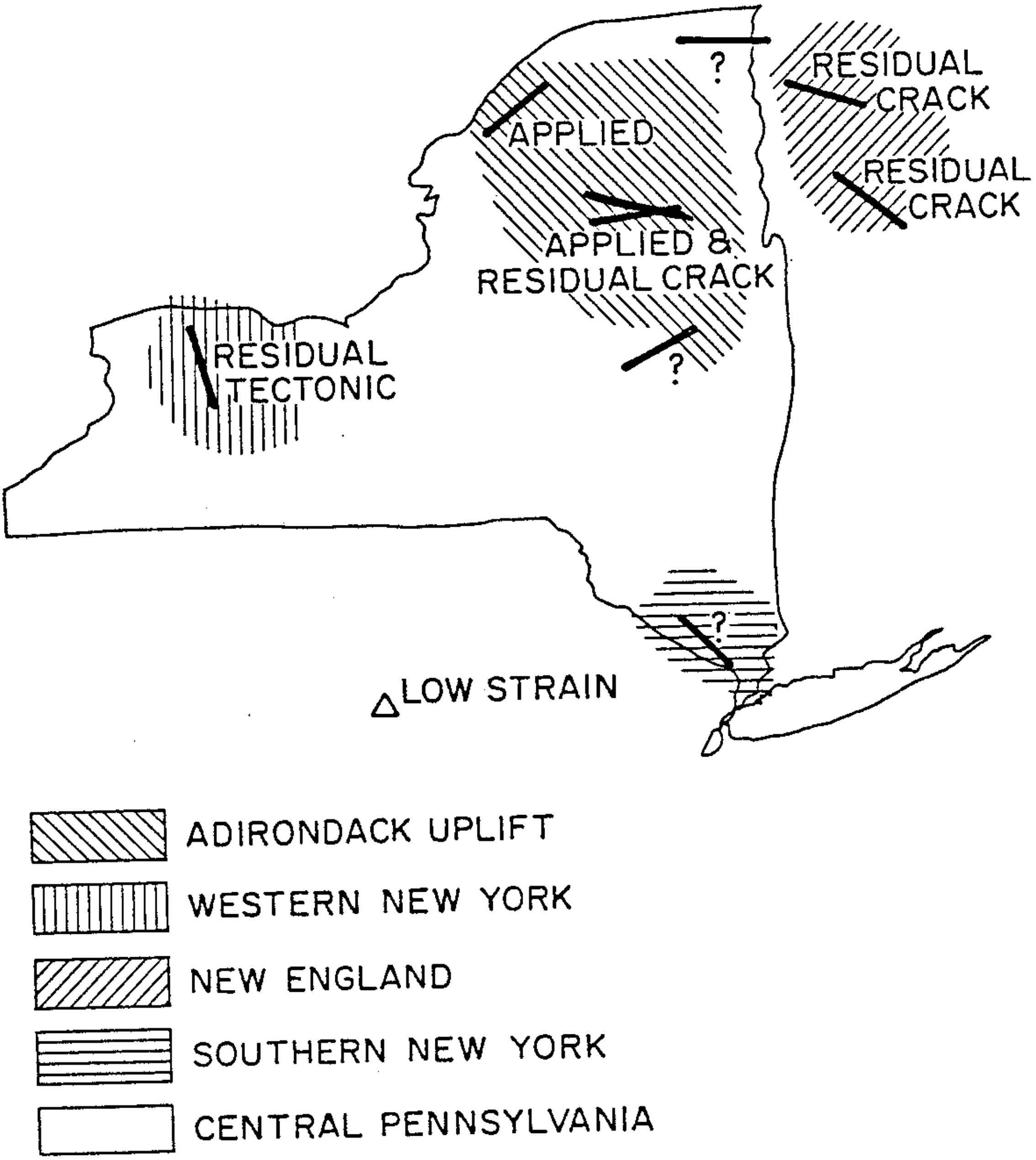


Figure 11. Five areas in which strain relaxation had similar orientations and perhaps similar mechanisms for strain. The orientation for maximum expansion is indicated by strike symbols.

of Buffalo, New York had not previously been recognized (Engelder, 1977; Engelder and Engelder, 1977). In addition to recoverable strain (*in situ* strain relaxation) nonrecoverable strain indicated by deformed fossils and calcite deformation twins also demonstrates the existence of a late Paleozoic tectonic stress oriented N-S to NNW-SSE. Our interpretation is that the strain relaxation in western New York is the recovery of a residual strain locked in the rocks from late Paleozoic. In Figure 11 we label this strain as a residual-tectonic strain. It is conceivable that a uniformly-oriented residual strain such as that in western New York may be relaxed by an earthquake slip. Until residual strain can be discounted as a source of energy to be released seismically, it must be considered in *in situ* stress studies.

Northwestern New England. In two localities in this area we have measured a maximum expansion oriented NW-SE to E-W (Figure 3). The predominant mechanism of strain relaxation in both areas was a relaxation of microcracks associated with a foliation in meta-sediments or a rift in Devonian granites. Our interpretation was that the strain associated with microcracks could be treated as a residual strain. In Figure 11 this is called a residual-crack strain. The NE-SW to WNW-ESE compression we measured in the vicinity of the Adirondacks did not seem to affect the rocks in New England. In fact, the one focal mechanism from New England does not have the same orientation for compression axes as observed in the Adirondack area (Sbar and Sykes, 1977). Our measurements fit Sbar and Sykes' (1977) conclusion that the stress field in New England is different from that in the Adirondack vicinity.

Southern New York. We have made just three measurements in one quarry in the vicinity of Nyack, New York (Figure 11). That set of measurements indicated a NW-SE oriented trend for maximum expansion which is the same general trend as for the compression axes of focal mechanisms from the vicinity of the Ramapo fault (Aggarwal, personal communication, 1977). We suspect that if these earthquakes and strain relaxation measurements are related and are associated with crustal stresses and strains, these stresses and strains are not far reaching.

Central Pennsylvania. Strain relaxation measurements in central Pennsylvania showed very low magnitude expansions upon overcoring with no obvious trend from site to site. These data imply that any residual strain accompanying the compression of the Appalachian Mountains in the late Paleozoic had relaxed. Metamorphic micas are observed in the greywacke sandstones. We suggest that residual strain of the type observed in western New York relaxed during the elevated temperatures necessary for the growth of micas. Yet the rock does not possess a strong enough metamorphic foliation to relax in the manner of rocks from northwestern New England. We detected no hint of a modern tectonic stress as was found in the Adirondack area. Our observation of little tectonic strain correlates well with the lack of seismicity in the central Pennsylvania area.

Residual strain. In addition to defining areas which have unique strain relaxation characteristics, we have made progress in measuring and understanding the mechanisms of residual strain. (Appendix I contains a detailed discussion of residual strain.) First in western New York we have measured a residual strain which is unequivocally left from a late Paleozoic deformation. Residual strains are stored for geologically significant lengths of time. Figure 12a is a schematic for the storage of residual strain. We use a symbol which looks like a spring to denote residual-tectonic strain. The orientation of the compression causing the residual strain is shown by the orientation of the spring. Strain relief would cause a maximum expansion parallel to the springs as indicated by the orientation of the arrows denoting strain relaxation. A simple model for _in situ_ strain in western New York is that of a set of aligned springs. If residual strain of uniform magnitude and orientation can be relaxed by slip along a fault, it may contribute to the seismicity of an area.

In New England we measured a strain relaxation which we attribute to the opening of microcracks (Engelder, Sbar and Kranz, 1977). The mechanism for this type of residual strain relaxation is shown in Figure 12b. This _in situ_ strain situation is equivalent to grains with microcracks in a preferred orientation surrounded by a uniform distribution of springs. The relaxation of strain in this type of rock results in a maximum expansion normal to the preferred orientation of the microcracks.

In the northwest portion of the Adirondack uplift we measured a strain relaxation which resembled the relief of an applied load. A schematic of that situation is shown in Figure 12c where grains are loaded at their boundary as indicated by the black arrows. Relief of

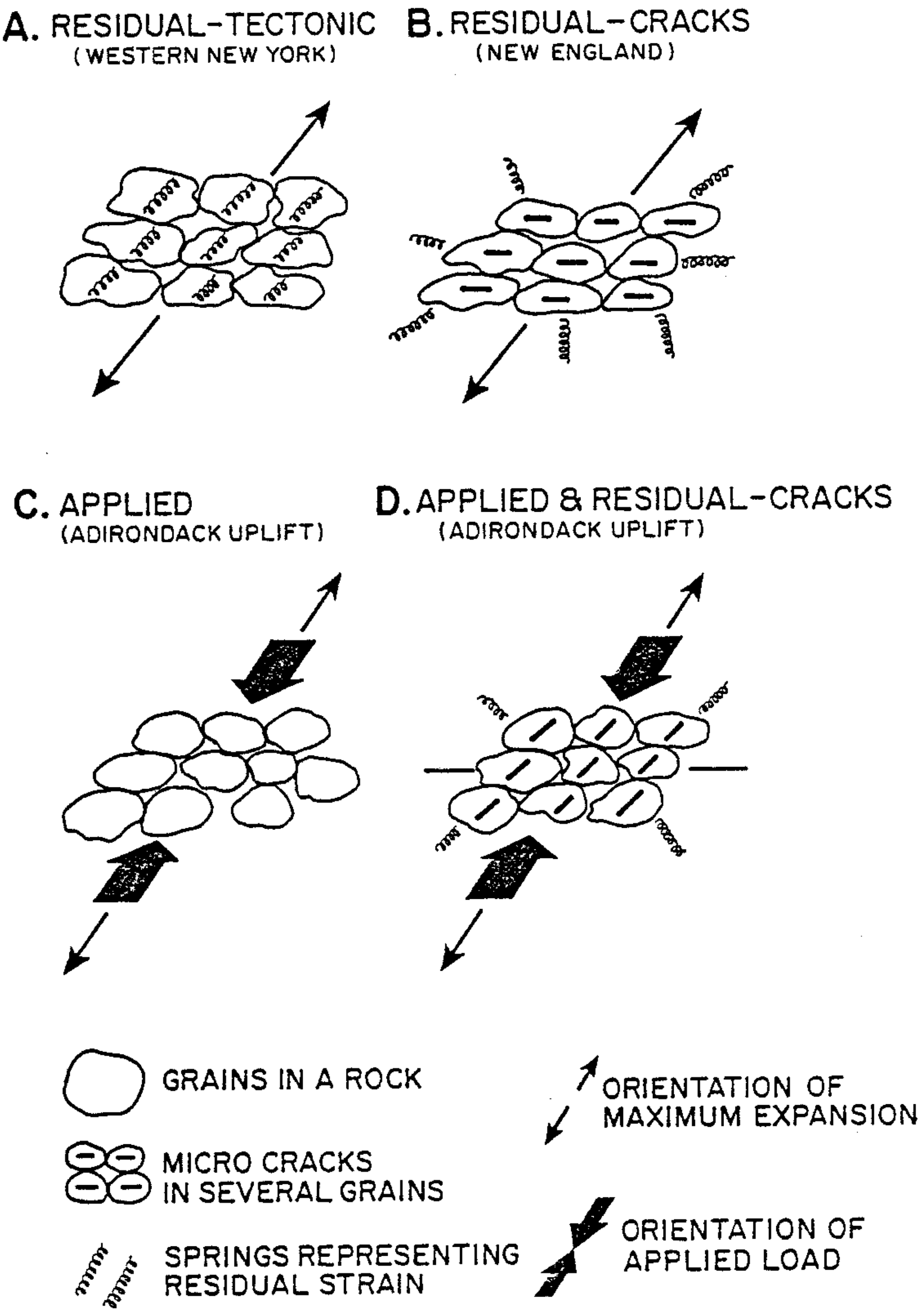


Figure 12. Schematic for mechanisms of strain relaxation in rocks containing a residual strain and/or subjected to boundary loads.

these grains would result in a maximum expansion parallel to the applied load.

In the Adirondack uplift area we also distinguished a strain relaxation which is attributed to the opening of microcracks normal to foliation (Figure 12d). The same mechanism for strain relaxation was found in the Barre granite of Vermont (Engelder, Sbar and Kranz, 1977). For the Blue Mountain Lake area the foliation strikes E-W so that the associated maximum expansion is north-south. However, we also distinguished an WNW-ESE expansion which we suggest is related to the same stress inferred from fault-plane solutions from the Blue Mountain Lake and Racquette Lake earthquake swarms. The important point concerning our Blue Mountain Lake experiments is that despite the recovery of residual strain in one of our sample areas, we were still able to detect the recovery of another type of strain which had the same orientation as the compression axes of earthquake focal mechanisms.

VII. PROJECTS IN PROGRESS

At the time of writing this technical report we have several incomplete projects which will be carried to completion with future <u>in situ</u> strain studies.

A) Down-hole technique

During the summer of 1976, we started to develop the capability of measuring strain relaxation at the end of a borehole. This technique for strain relief at the end of a borehole at depths up to 5 m was first developed by Leeman (1971) and is commonly known as a "doorstopper" strain relief measurement. We have built a gauge and setting tool for placing the gauge at the end of a vertical 5 m deep borehole. Because the technique was developed during the fall of 1976 and winter of 1977, we have not gathered sufficient data to report meaningful results. This technique will be used extensively in a study of the Palmdale uplift, California.

B) Continuous Recorder

During the fall 1976 and winter 1977 we developed a battery-powered recorder which will allow us to monitor strain gauges in remote places for periods of up to one month. To date we have tested the recorder in a diabase quarry in West Nyack, New York. We recorded strain before and after overcoring. The records show two trends in strain with time. One trend cycles every 24 hours and is a record of thermal expansion of the rock with the diurnal temperature variation. The other trend is a time dependent recovery of strain following overcoring. These trends are still poorly understood because we have not yet had the time to establish a good data base. Future work with these continuous recorders will clarify the time-dependent relaxation of rocks and the thermal-mechanical interaction within rocks.

VIII. APPENDIX I: RESIDUAL STRAIN

One fundamental problem with the interpretation of rock stress measurements is that rock contains residual strains as well as those due to current externally applied boundary loads. Residual strains are locked into the rock during its thermal history, tectonic history and burial, causing a residual strain that may persist even when the rock is free of boundary loads (Friedman, 1972). Boundary loads cause an applied strain which results from modern tectonics, including the collision of drifting plates and intraplate deformation, present topography, and man-made structures.

A proper interpretation of all stress measurements within the crust of the earth demands that components of applied strain be distinguished from residual strain. This distinction is particularly important to assessing seismic risk of a region. Once relieved during an earthquake, residual strain cannot be recovered whereas applied strain may be recovered by continued application of tectonic forces.

A simple model for residual strain in a body with many elastic components is that of a set of springs of different lengths and spring constants hooked between two plates (Treuting, 1952). Some springs are in compression and others are in tension. The sum of the strain energy of those in compression equals the sum of the strain energy of those in tension so that the entire body of two plates and springs is in static equilibrium. If one of the springs is cut, the body changes shape to reestablish static equilibrium. Here the shape change occurs without the benefit of external loads.

The model of springs in tension balanced against springs in compression helps to visualize residual strain which appears on both the macroscopic and microscopic scale in rocks. Springs hooked between two plates contain strain domains with dimensions comparable to the size of the model. Each spring contains one strain domain with a large-scale uniform strain which may be relieved individually. Macroscopic residual strain domains in rocks may be cut or measured individually. A single uniform domain may be as large as a single outcrop. In contrast, the individual domains may be so small that we can't measure or cut them individually. For example, single grains in a sand aggregate may constitute one domain. Static equilibrium will be reestablished if many microscopic springs are cut but here the residual strain measured is a composite of the relief of many microscopic springs.

Voight and St. Pierre (1974) present a model for the relation between the stress history of a rock and its residual stress. They point out that the horizontal compressive stress on a sediment during burial is a function of gravity loading through a Poisson's ratio and thermoelastic expansion. At depth the horizontal compressive stress is carried by the grains without support from pore spaces. Because the grains occupy a major fraction but not the entire volume of the sediments, the average intragranular stress is higher than the average stress on the entire volume. Here Voight and St. Pierre refer to the intragranular stress as microscopic where the average stress on a large volume of rock is a macroscopic stress.

Once the sediment is lithified, its elastic properties change mainly because unsupported pore space is filled with cement. At depth, the cement is stress-free, but once the macrostress systems change, a comparable change in the intragranular stress is resisted by the cement which is now under stress. If the macrostress is completely removed from the sediment, stresses which are called residual will remain in the cement and grains. An important characteristic of this microscopic residual stress is that the integral of stresses in the cement and grains is zero because the volume of rock is in static equilibrium. The cement and grains are microscopic springs which abut each other in tension and compression. Gallagher and others (1974) present a photoelastic model which illustrates the distribution of residual stress on the microscopic scale.

Voight and St. Pierre (1974) and Haxby and Turcotte (1976) point out that the primary effect of denudation of a lithified sediment is due to thermal cooling during which the horizontal stresses become tensile. Thus they conclude that denudation alone cannot account for large horizontal compressive stresses. Tectonic stresses must be superimposed on burial and thermal stresses in order to maintain horizontal compressive stresses following denudation. Here the tectonic stress (a macrostress) which places a denuded sediment in horizontal compression may be either applied or residual. In either case, the macrostress may be treated as a boundary load and a small volume of rock may be cut free from this boundary load. However, a microscopic residual stress may still remain within this small volume.

On the microscopic scale, residual strain is manifested by elastic distortions of both grains and cement (Friedman, 1972). If for some reason the residual strain in the grains and cement is not balanced, there will be a net strain which must be balanced on some larger scale. In addition, Swolfs and others (1973) have suggested that there may be a layer of compressive strain at the surface balanced by a tensile strain at depth. This compressive strain is on the order of less than a meter thick and may be treated as a macroscopic residual strain which may be completely relieved by cutting all boundaries. Again, cutting boundaries may only partially relieve microscopic residual strain.

Residual strain on a larger scale may be attributed to the accumulation of sediments in a downwarping basin of elliptical shape (Price, 1974). Strain are greater parallel to the long axis of the basin. Likewise, it is conceivable that large blocks of crust abut and are locked in such a manner that each block is a single residual strain domain.

On an even larger scale, strain domains may be set up within continental and oceanic plates from the collision of plates while drifting on a convecting mantle. We refer to such tectonic strains as applied. It is our goal to detect these tectonic or applied strains and distinguish these from various residual strains.

APPENDIX II. COMMENTS ON THE SURFACE OVERCORING TECHNIQUE AS A TOOL FOR EVALUATING POTENTIAL SITES FOR POWER PLANTS

This project was funded for the specific purpose of aiding those who have to license power plants. In this regard it is appropriate to make some pointed comments concerning the usefulness of the surface overcoring technique as a tool for evaluating potential power plant sites.

Should the surface overcoring technique described within this and previous reports (Engelder and Sbar, 1976b) be recommended to agencies or consultants involved with specific power plant siting studies? No! The surface overcoring technique is not an engineering tool from which the state of stress at a specific site may be directly obtained. This tool gathers data on the strain relaxation of rocks; the mechanisms of strain relaxation are complicated, only indirectly related to a tectonic stress within the vicinity of the site. Most operators are not likely to recognize the various mechanisms for strain relaxation and, therefore, incorrectly interpret their data. There are aspects of strain relaxation that even the experts don't understand.

What are specific limitations in acquiring field data and interpreting their significance? There are several limitations! The greatest problem in making surface stress measurements is finding suitable outcrops. Ideally homogeneous, unfractured flat-lying rock is most suitable. These conditions are rarely met. In addition some rock types such as shale and schists are impossible to use. The major limitation is interpreting the significance of the measurement is that relaxation is influenced by at least three mechanisms: 1) tectonic stress, 2) residual strain, and 3) microcrack fabric.

What is our evaluation of surface overcoring as a tool for determining tectonic provinces? As this report indicates, we have delineated several regions in which the strain relaxation of rocks seems to be unique (see Figure 11). We have, in fact, defined a set of tectonic provinces. However, we have yet to demonstrate what, if any, relationship there is between our strain relaxation regions and regions of higher or lower seismic risk. Care must be used in the definition of a tectonic province.

What specific contributions have our surface overcoring techniques made toward proper site evaluation? 1) We have shown that local sites (outcrops) contain a great deal of strain energy (residual strain) which may be activated by cutting rocks free from the outcrop (Engelder, Sbar, and Kranz, 1977); 2) In some cases microfracture fabric controls the orientation of strain relaxation (Engelder, Sbar, and Kranz, 1977); 3) Outcrop stresses (strains) vary as a function of fracture density (Engelder and Sbar, 1977); 4) There are large areas (> 100 km^2) of uniformly oriented <u>in situ</u> strain (Engelder and Sbar, 1976a); 5) Stress orientations indicated by fault-plane solutions do not necessarily correlate with near-surface stress measurements (Blue Mountain Lake, this report); 6) Residual strain can be correlated with past tectonic events such as the late Paleozoic compression of western New York (Engelder and Sbar, 1976b).

The state of stress in the crust and its relationship with seismic risk is complicated. No single technique is going to provide all the answers which might arise concerning stress and seismic risk. However, continued funding of basic research such as represented by this report will provide a means of obtaining answers to some of the problems perplexing those who license power plants.

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