VOL. 81, NO. 17 JOURNAL OF GEOPHYSICAL RESEARCH JUNE 10, 1976

Evidence for Uniform Strain Orientation in the Potsdam Sandstone, Northern New York, From In Situ Measurements

J. T. ENGELDER AND MARC L. SBAR

Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964

Twelve strain relief measurements were made at five sites on Potsdam sandstone northeast of the Adirondack Mountains, New York, to test Sbar and Sykes's (1973) suggestion that the upper crust in a large area of eastern North America is currently in a state of compression with the maximum principal stress (σ_1) east-northeast. In situ strain was relieved by overcoring and detected by using strain gages bonded to the sandstone at the surface. The average of nine measurements at four sites in the Late Cambrian Keeseville member of the Potsdam sandstone indicates that compressive stresses were relieved upon overcoring with an average direction of maximum expansion of N78°W. These nine measurements also indicate that stress can be consistent in orientation over areas of tens of square kilometers. The average of three measurements at one site in the Nicholville member 11 km from the other four sites indicates a maximum expansion oriented N18°E. At several sites, residual strain was recovered when specimens free of boundary loads were overcored. We suggest that the residual strain measured in the Nicholville member may be related to a late Proterozoic (Hadrynian) or Early Cambrian stress field.

INTRODUCTION

Recent compilations of a variety of stress measurements within the interiors of lithospheric plates delineate large regions within which stress has a consistent orientation [*Ahorner and Schneider*, 1974; *Sbar and Sykes*, 1973; *Raleigh*, 1974]. Results from such diverse techniques as hydrofracturing, fault plane solutions, recent crustal deformations, and strain relief tests compiled by *Sbar and Sykes* [1973] all indicate that west of the Valley and Ridge province of the Appalachian Mountains and east of the Mississippi embayment the maximum principal stress (σ_1) is compressive and oriented approximately east-northeast. The orientations of the stress fields within and east of the Valley and Ridge province [*Hooker and Johnson*, 1969] and within the Mississippi embayment [*Street et al.*, 1974] are not consistent with this pattern but suggest that different and possibly more complex stress fields exist. The data that we present here represent the first step in our program designed to delineate more clearly the state of stress in the crust in eastern North America and to understand the mechanisms causing intraplate stresses within the crust of the earth.

Intraplate stresses may be related to the gravitational loading of sedimentary basins [*Gay*, 1972; *Price*, 1974], differences in crustal thickness [*Artyushkov*, 1973], thermoelastic strains [*Turcotte*, 1974], and/or local tectonic histories [*Voight*, 1969, 1971; *Sykes and Sbar*, 1973, 1974]. One fundamental problem with the interpretation of intraplate stresses is that measurements in rock are influenced by residual stresses as well as those due to current externally applied boundary loads. Residual stresses are locked into the rock during its thermal history, tectonic history, or burial and cause 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, 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 in assessing seismic risk of a region. Once relieved during an earthquake, residual strain cannot be recovered, whereas applied strain may be recovered by continued shifting within the earth's crust.

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 parallel 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 equilibrium. If one of the springs is cut, the body changes shape to reestablish equilibrium. Here the shape change occurs without the benefit of external loads.

Likewise, residual strain in rocks requires the internal balance of forces in static equilibrium [*Friedman*, 1972; *Varnes and Lee*, 1973]; regions in compression are in equilibrium with regions in tension. 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 [*Swolfs et al.*, 1974]. Residual strains must balance themselves regardless of whether or not boundary loads are present. The internal equilibrium of residual strains will be reestablished upon overcoring a rock containing residual strains [*Varnes and Lee*, 1973; *Nichols*, 1975] and result in changes of shape and volume.

EXPERIMENTAL PROCEDURE

Our purpose was to make a number of measurements within a selected area of about 100 km². Such a sampling program requires a stress measurement technique which

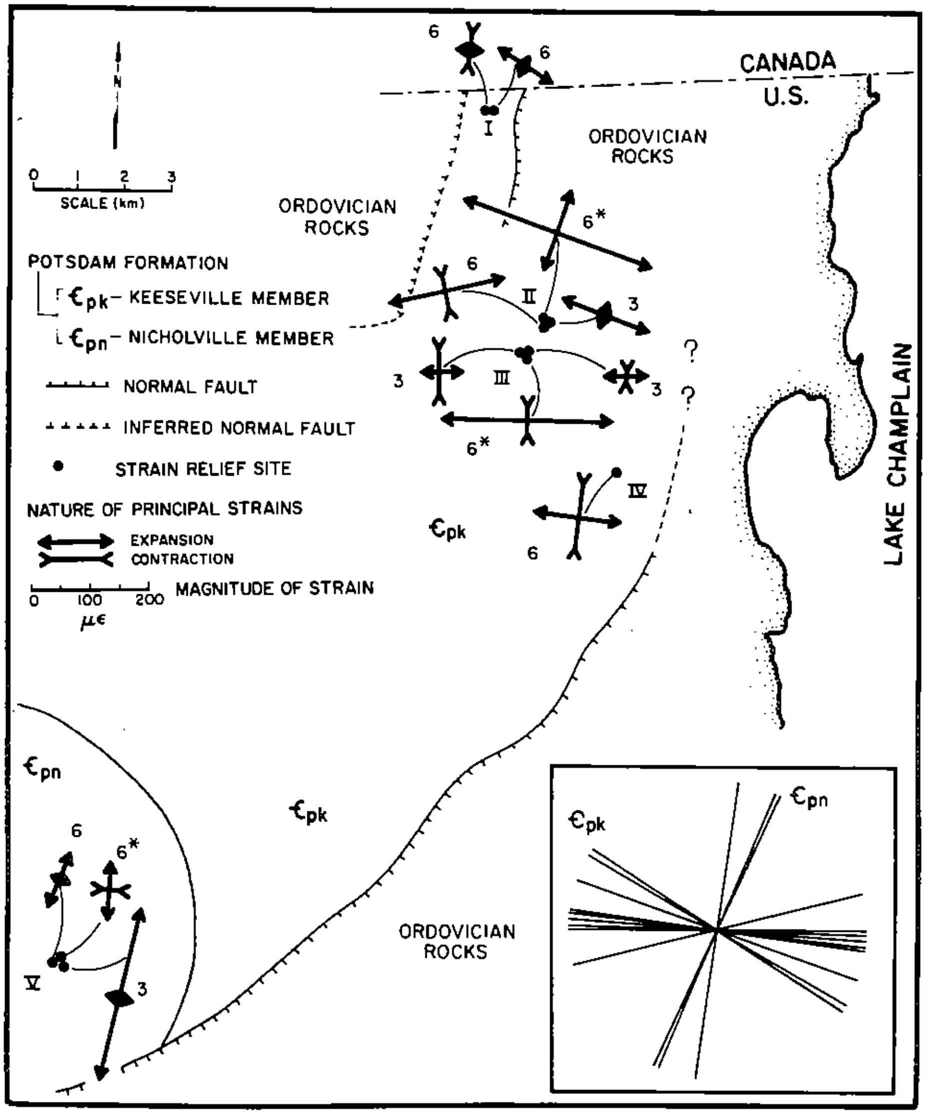

Fig. 1. Location, magnitude, and orientation of horizontal strains from in situ strain relief measurements in Potsdam sandstone. Five sites are designated by Roman numerals. Arabic numerals accompanying each datum indicate the diameter (in inches) of initial overcore. The asterisks about some Arabic numerals designate those 15.2-cm (6 inch) cores which were relieved a second time by a 7.6-cm (3 inch) core. The rose diagram in the lower right corner represents the orientation of the axes of maximum expansion of the 12 measurements in the Potsdam sandstone.

is both quick and inexpensive. The measurement of horizontal in situ strain by overcoring foil resistance strain gages bonded directly to surficial rocks is most suitable [*Friedman,* 1972; *de la Cruz and Raleigh,* 1972; *Swolfs et al.,* 1974].

Criteria which influenced our choice of rock formation and sample localities include the following: (1) the formation should not be affected by large inelastic strains (underformed), (2) the formation should outcrop over a relatively large area, (3) it should be statistically isotropic and reasonably homogeneous over the outcrop area, and (4) it should be coupled as well as possible to elastic strains which may occur deeper in the crust. The Potsdam sandstone, which outcrops on the north side of the Adirondack Mountains, meets these criteria [*Fisher,* 1968].

Five sites were selected for strain relief measurements along a 24-km line northwest of Plattsburgh, New York (Figure 1). Three measurements were attempted at each site; however, poor bonding or poor electrical contacts made three of 15 rosettes unusable. Measurements were made as far away as possible from vertical fractures on outcrops with the least weathering. We bonded three-component rosettes, a compensation gage, and temperature sensor to surfaces ground flat and horizontal at each site. One rosette was overcored per day with either a 15.2-cm (6 inches) or 7.6-cm (3 inches) diamond core barrel; all holes were vertical. The biaxial strain change due to relief of a core of rock was determined by taking the difference in resistance of the gages in a rosette before and after overcoring. The thermal drift of the other rosettes and the temperature sensor are used to subtract the effect of thermal drift on the overcored rosette. Using this technique, we are able to measure strain to $\pm 1 \times 10^{-5}$; 1 $\mu\epsilon$ equals a strain of 1×10^{-6}.

To measure the horizontal component of residual strain [*Hoskins and Daniells,* 1970; *Friedman,* 1972; *Nichols,* 1975], several strain gage rosettes were overcored first with a 15.2-cm and then a 7.6-cm core barrel without breaking the rock cylinder from the outcrop. Presumably the 15.2-cm overcore relieves both applied strains and part of the residual strains, whereas a 7.6-cm overcore relieves just residual strains. The idea is that the residual strains obtained with the second overcore may enable us to separate the residual effects from the combination of applied and residual strains relieved during the first overcore.

STRAIN RELIEF OF THE POTSDAM SANDSTONE

The Potsdam sandstone consists of three members in ascending order: (1) the Nicholville, (2) the Ausable, and (3) the Keeseville. The oldest and youngest members were sampled in our study. The Nicholville member is a coarse- to medium-grained arkose which is believed to be late Proterozoic (Hadrynian) (D. W. Fisher, personal communication, 1975). The Keeseville is a Late Cambrian medium-grained quartz sandstone representing a high-energy intertidal zone [*Fisher*, 1968].

The nine in situ strain measurements within the Keeseville member have an average direction of maximum expansion of N78°W (Figure 1). This average does not account for differences in magnitude. The rose diagram inserted in Figure 1 indicates the variation in direction of the maximum expansion. The second axis of the strain recovery ellipse is either the axis of least expansion or an axis of contraction. The three measurements within the Nicholville member indicate a maximum expansion of N18°E or a maximum expansion at about 90° to the trend established within the Keeseville member.

Reproducibility of orientation of the surface strain relief measurements varies from site to site. In all cases the rosettes at one site are placed within two meters of other rosettes, but in some cases they are separated by vertical fractures with a spacing of 1–3 m. The orientation of the principal axes of relieved strain for three measurements at a site varies by as little as 4° at site III, to 18° at site V, and 45° at site II (Figure 1). The bisectors of the acute angle between the two most divergent directions of maximum expansion at site II and site III have about the same direction: N86°W for the former and N88°W for the latter.

Reproducibility of the magnitude of the strains is not good. The maximum elongation for relieving strain with a 15.2-cm core barrel varies more than 50% on some outcrops, and this variation was similar with the 7.6-cm overcore. Since the measurements are made at the surface, we expect that the magnitude of the strains may be modified by the effects of weathering and jointing, although we have not verified this. This kind of variation is similar to that reported by *Handin* [1970], using the same technique [*Friedman*, 1972]. Handin also reported a variation of 25° in orientation of the major strain axes upon overcoring three strain gage rosettes in the same outcrop. Using photoelastic bar rosettes, *Brown* [1974] found that the azimuth of the major strain axes varies about 20° for a series of overcore measurements at Rangely, Colorado.

To check for residual strain, a 7.6-cm overcore was placed inside some of the 15.2-cm overcores. The greatest deviation in the orientation of the axis of maximum expansion between 15.2-cm and 7.6-cm overcore was 27° (Table 1). In all cases the contraction occurred along the minor axis of the strain ellipse. In directions of expansion the expansions were much less than the expansions after the first overcores.

RELATION BETWEEN IN SITU STRAIN AND TECTONIC HISTORY OF POTSDAM SANDSTONE

The axes of maximum expansion of the Nicholville member are nearly perpendicular to those within the Keeseville member. This suggests that either (1) we detected large components of residual strain in at least one member of the Potsdam sandstone, (2) residual strains have different origins for each member of the Potsdam, or (3) applied strain domains are less than 100 km^2 in area. It appears that both members are not coupled to a common boundary load which strained the Potsdam sandstone in a common direction.

We speculate that the tectonic history of the Potsdam sandstone explains the orientation of the residual strain in the Nicholville member. This latter sandstone is believed to have filled a late Proterozoic (Hadrynian) fault graben. The orientation of the fault grabens filled by the Nicholville member is thought to be parallel to the north-northeast lineaments, which have been mapped by *Isachsen* [1976] in the Proterozoic (Helikian) rocks of the Adirondack Mountains (D. W. Fisher, personal communication, 1975). This orientation is the same as that inferred for grabens formed during the opening of a Proto-Atlantic in the late Proterozoic or earliest Paleozoic time. If the Nicholville sand in a Proto-Atlantic fault graben was subjected to east-west extensional tectonics, the greatest compressive stress in the horizontal plane (actually the true intermediate principal stress σ_2) would be parallel to the axes of the graben.

Cementation of the sand while still subject to an extensional stress field would result in locking a residual stress into the sandstone [*Friedman*, 1972; *Voight and St. Pierre*, 1974]. If this residual stress is not affected by subsequent tectonic events and not totally relieved by jointing, we

TABLE 1. Data From Concentric Overcores

Site	Overcore, cm	Maximum Expansion, $\mu\epsilon$	Minimum Expansion, $\mu\epsilon$	Orientation of Maximum Expansion	Difference in Orientation, deg
II	15.2	201	51	N76°E	17
II	7.6	−44	−105	N59°E	
III	15.2	286	−62	N89°W	
III	7.6	−13	−70	N61°W	27
V	15.2	108	−17	N14°E	
V	7.6	2	−64	N2°W	16

The 15.2-cm overcore preceded the 7.6-cm overcore. Difference of orientation of maximum expansion relieved after first and second overcore is indicated.

should detect it. This residual stress would result in a maximum expansion parallel to the axis of the graben upon relief by overcoring. Our data do indeed indicate axes of maximum expansion parallel to the probable axes of grabens of the Proto-Atlantic and strongly suggest that this ancient stress field still persists to this day.

In contrast to the Nicholville, the Keeseville member was deposited during a marine transgression upon a stable continental shelf. This Late Cambrian sand was not subject to tectonic stress until after the Proto-Atlantic had expanded to nearly its maximum width near the end of the Early Ordovician. The first tectonic stress felt by the Keeseville was probably extensional, as manifested by a regional uplift with block faulting at the end of the Early Ordovician [*Fisher*, 1968]. To the east, the block faulted miogeosyncline sagged and filled with sediments [*Bird and Dewey*, 1970]. By late Medial Ordovician time the area was subject to an east-west compression as indicated by low-angle thrusts less than 5 km east of our sample localities. If the strain that we measured in the Keeseville is residual, it is more easily related to the east-west compression which would result in a maximum east-west expansion upon overcoring.

The preceding speculation is based on an assumed time of cementation; alternate explanations are possible. For example, different regions may have been subject to different stress histories after both members were deposited. If this is the case, strain would be independent of lithologic boundaries.

DISCUSSION AND CONCLUSIONS

A major component of the in situ strain which we measured is residual strain. The presence of residual strain in the Potsdam sandstone was confirmed by overcoring the sandstone after boundary loads were removed by an initial overcore. Both the orientation and the magnitude of the strain recovered from a specimen free of boundary loads differed from the in situ strain as measured after an initial overcore (Table 1). It is possible to explain this difference between in situ strain and strain change following the double overcore in more than one way. If the sandstone was free of all applied loads, the difference may be attributed to the reestablishment of internal equilibrium of residual strain following the initial overcore. By analogy the initial overcore had the same consequence as cutting one spring in the plates and spring model for residual strain. Strain within the body was redistributed to achieve equilibrium. If the in situ strain includes a component of externally applied strain, the difference in strain recovered between the initial overcore and the double overcore results from both the elimination of the applied strains and the reestablishment of equilibrium of residual strain.

The possible presence of a component of applied strain in the Potsdam sandstone is suggested by the numerous earthquakes in northern New York. The stress orientation inferred from fault plane solutions of two of these shocks indicates that the maximum compressive stress is horizontal and nearly east-west trending. It is thus possible that there is a component of applied strain in the measurements from the Keeseville member of the Potsdam formations. It is less likely in the Nicholville member, since the 15.2-cm and 7.6-cm overcores in that member relieved north-south maximum elongations. However, at the present time we are unable to conclude that we are detecting applied strains.

We conclude that there are regions at the surface of the Potsdam sandstone which contain uniformly oriented strain fields. There is, however, still the worrisome problem of determining whether we measured only residual strain or both applied and residual strain. Here we have suggested possible interpretations of our data and indicated some difficulties in interpretation. Many more measurements using this and other stress measuring techniques will be necessary before intraplate stresses will be understood.

Acknowledgments. The work was supported by the New York State Energy Research and Development Authority and the National Science Foundation grants GA 43295 and DES-03640. We benefited from discussions with D. W. Fisher, Y. W. Isachsen, T. C. Nichols, W. L. Prell, and H. Swolfs. Early versions of our manuscript were critically reviewed by M. Friedman, C. H. Scholz, H. S. Swolfs, L. R. Sykes, and B. Voight. Lamont-Doherty Geological Observatory contribution 2288.

REFERENCES

Ahorner, L., and G. Schneider, Herd Mechanismen von Erdbeben in Oberrhein-Graben und in seinen Randgebirgen, Approaches to Taphrogenesis, *Sci. Rep. 8*, pp. 104–117, Interunion Comm. on Geodynamics, Karlsruhe, West Germany, 1974.

Artyushkov, E. V., Stresses in the lithosphere caused by crustal thickness inhomogeneities, *J. Geophys. Res., 78*, 7675–7708, 1973.

Bird, J. M., and J. R. Dewey, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogeny, *Geol. Soc. Amer. Bull., 81*, 1031–1060, 1970.

Brown, A., Photoelastic measurement of recoverable strain at four sites, *Tectonophysics, 21*, 135–164, 1974.

de la Cruz, R. V., and C. B. Raleigh, Absolute stress measurements at the Rangely anticline, northwestern Colorado, *Int. J. Rock Mech. Miner. Sci., 9*, 625–634, 1972.

Fisher, D. W., Geology of the Plattsburgh and Rouses Point, New York-Vermont, quadrangles, *N. Y. State Mus. Sci. Serv. Map Chart Ser.*, no. 10, 51 pp., N. Y. State Mus. of Sci., Albany, N. Y., 1968.

Friedman, M., Residual elastic strain in rocks, *Tectonophysics, 15*, 297–330, 1972.

Gay, N. C., Virgin rock stresses at Doornfontein gold mine, Carletonville, South Africa, *J. Geol., 80*, 61–80, 1972.

Handin, J., Studies in rock fracture, *Quart. Tech. Rep. 12*, Tex. A&M Res. Found., College Station, Tex., 1970.

Hooker, V. E., and C. F. Johnson, Near-surface horizontal stresses, including the effects of rock anisotropy, *U.S. Bur. Mines Rep. Invest., 7224*, 29 pp., 1969.

Hoskins, E. R., and P. A. Daniells, Measurements of residual strain in rocks (abstract), *Eos Trans. AGU, 51*, 826, 1970.

Isachsen, Y. W., Fracture analysis of New York State using multistage remote sensor data and ground study; Possible application to plate tectonic modeling, in *Symposium Volume of Utah Geological Association, Proceedings of First International Symposium on New Basement Tectonics*, edited by R. F. A. Hodgson, Utah Geological Association, Salt Lake City, Utah, in press, 1976.

Nichols, T. C., Deformations associated with relaxation of residual stresses in a sample of Barre granite from Vermont, *U.S. Geol. Surv. Prof. Pap. 875*, 32 pp., 1975.

Price, N. J., The development of stress systems and fracture patterns in undeformed sediments, in *Advances in Rock Mechanics, Proceedings of 3rd Congress of ISRM*, vol. 1, pp. 487–496, U.S. Committee for Rock Mechanics, National Academy of Sciences, Washington, D. C., 1974.

Raleigh, D. B., Crustal stress and global tectonics, in *Advances in Rock Mechanics, Proceedings of 3rd Congress of ISRM*, vol. 1, pp.

593–597, U.S. Committee for Rock Mechanics, National Academy of Sciences, Washington, D. C., 1974.

Sbar, M. L., and L. R. Sykes, Contemporary compressive stress and seismicity in eastern North America: An example of intraplate tectonics, *Geol. Soc. Amer. Bull., 84,* 1861–1882, 1973.

Street, R. L., R. B. Herrmann, and O. W. Nuttli, Earthquake mechanics in the central United States, *Science, 184,* 1285–1287, 1974.

Swolfs, H. S., J. Handin, and H. R. Pratt, Field measurements of residual strain in granitic rock masses, *Advances in Rock Mechanics, Proceedings of 3rd Congress of ISRM,* vol. 2, pp. 563–568, U.S. Committee for Rock Mechanics, National Academy of Sciences, Washington, D. C., 1974.

Sykes, L. R., and M. L. Sbar, Intraplate earthquakes, lithospheric stresses and the driving mechanism of plate tectonics, *Nature, 245,* 298–302, 1973.

Sykes, L. R., and M. L. Sbar, Focal mechanism solutions of intraplate earthquakes and stresses in the lithosphere, in *Geodynamics of Iceland and the North Atlantic Area,* pp. 207–224, D. Reidel, Dordrecht, Netherlands, 1974.

Treuting, R. G., The nature, origin and effects of residual stresses, in *Residual Stress Measurements,* pp. 1–41, American Society of Metals, 1952.

Turcotte, D. L., Are transform faults thermal contraction cracks?, *J. Geophys. Res., 79,* 2573–2577, 1974.

Varnes, D. J., and F. T. Lee, Hypothesis of mobilization of residual stress in rocks, *Geol. Soc. Amer. Bull., 83,* 2863–2866, 1973.

Voight, B., Evolution of North Atlantic Ocean: Relevance of rock-pressure measurements, in *North Atlantic—Geology and Continental Drift, Mem. 12,* edited by M. Kay, pp. 955–962, American Association of Petroleum Geologists, Tulsa, Okla., 1969.

Voight, B., Prediction of in situ stress patterns in the earth's crust, in *Determination of Stresses in Rock Masses Symposium,* pp. 111–131, U. S. Committee for Rock Mechanics, National Academy of Sciences, Washington, D. C., 1971.

Voight, B., and B. H. P. St. Pierre, Stress history and rock stress, in *Advances in Rock Mechanics, Proceedings of 3rd Congress of ISRM,* vol. 2, pp. 580–582, U. S. Committee for Rock Mechanics, National Academy of Sciences, Washington, D. C., 1974.

(Received August 25, 1975;
revised November 4, 1975;
accepted November 21, 1975.)