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The effect of stress-relief on ambient microcrack porosity in core samples from the Kent Cliffs (New York) and Moodus (Connecticut) scientific research boreholes

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ABSTRACT

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As part of crustal stress studies in the northeastern U.S., two suites of core samples were examined in order to understand the effect of stress-relief on the development of microcrack porosity. Porosity and ultrasonic velocity were measured as functions of confining pressure in cores from the Kent Cliffs, N.Y., borehole, and volumetric strain and ultrasonic velocity were measured as functions of confining pressure in cores from the Moodus, Conn., borehole. Under ambient conditions, properties of the cores are dominated by a microcrack porosity which tends to increase with sample depth from values near zero to approximately 0.6%. This ambient porosity closes at laboratory confining pressures roughly equal to or less than the maximum in situ stress, and is interpreted as forming on relief of stress by drilling. The results of this study suggest that the in situ core microcrack porosity is no greater than 0.05%.

The core samples are dominantly granitic gneisses, schists and amphibolites which exhibit moderate to well-developed foliations, oriented subvertically in Kent Cliffs cores and subhorizontally in Moodus cores. Foliation controls the orientation of the stress-relief microcracks, as indicated by the largest linear crack strain occurring normal to the foliation plane. This fabric-control of crack orientations precludes the use of microcrack analysis for estimating directions of maximum, intermediate and minimum in situ principal stress components. However, the general linear increase in ambient porosity with depth correlates with the increase in mean stress with depth as measured by hydraulic fracturing at the two sites. Two cores recovered from highly fractured zones at depth exhibit low stress-relief microcrack porosities which are believed to reflect locally low mean in situ stresses.

Introduction

Recovery of core from deep wells initiates expansion of the rock to a new volume which is stable at atmospheric pressure. This expansion, called strain relaxation, is a complex reaction of an elastic aggregate to stress-relief. Following relaxation, the aggregate is often filled with microcracks which may have existed in situ prior to coring or may have nucleated and propagated upon coring. Both the new microcracks, termed stress-relief cracks, and any pre-existing cracks open upon strain relaxation to form a crack volume at atmospheric pressure called the ambient microcrack porosity. Strain relaxation as a function of time may be divided into two parts: an instantaneous relaxation and a time-dependent relaxation. Elastic expansion of the component minerals and the bulk of the microcrack expansion occurs rapidly, long before cores reach the surface (Brown, 1989). Time-dependent expansion, which is relatively small compared with the instantaneous expansion, may be associated with the opening of pre-existing microcracks (Engelder and Plumb, 1984). However, if the rock is relatively free of a pre-existing microcrack and mineral fabric, then the orientations of the principal time-dependent expansions may be controlled by

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stress-relief microcracking and therefore correlate with principal components of the in situ stress field (Teufel and Warpinski, 1984). In the latter case the measurement of time-dependent relaxation is a technique for estimating in situ stress magnitudes and directions.

Strains induced by the rapidly opened microcracks cannot be measured directly upon cutting the cores. However, a preferred orientation of the ambient microcrack fabric can correlate with in situ principal stress orientations and magnitudes, as indicated by Differential Strain Analysis (DSA) (Wang and Simmons, 1978) and crack-induced velocity anisotropy measurements (Ren and Hudson, 1985). In relatively homogeneous and isotropic rocks, the directions of maximum, intermediate, and minimum microcrack strain correspond with maximum, intermediate, and minimum in situ principal stress directions, respectively (Strickland and Ren, 1980). Thus, examination of ambient microcrack porosity in core samples may provide an additional method of estimating in situ stress.

In many cases, however, the relationship between microcracks and in situ stress is not as straightforward as in the cores studied by Strickland and Ren (1980). For example, cores from Iceland contain both a stress-relief and a pre-existing microcrack porosity (Kowallis et al., 1982), and local stress relaxation caused by natural fracturing in situ apparently affected the resulting ambient microcrack porosity in cores from Illinois borehole UPH-3 (Carlson and Wang, 1986).

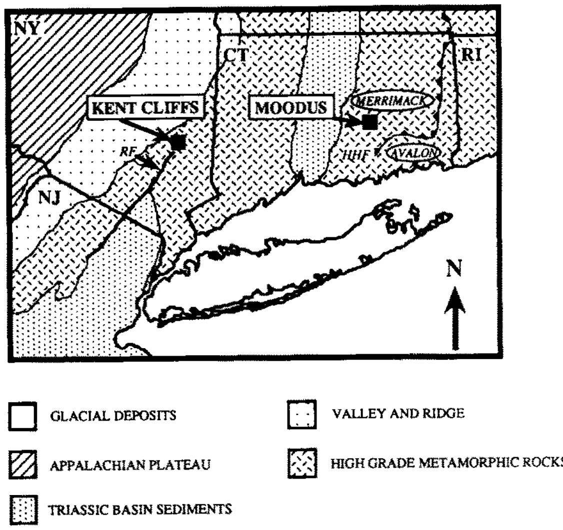

Fig. 1. Generalized geologic map with site locations of the Kent Cliffs (N.Y.) and Moodus (Conn.) scientific research boreholes. *RF* = Ramapo fault, *HHF* = Honey Hill-Lake Char fault.

Our study examines ambient microcrack porosity in core samples which are *not* mechanically homogeneous and isotropic. Two suites of foliated crystalline cores were examined as part of comprehensive studies of crustal stresses at the Kent Cliffs (N.Y.) and the Moodus (Conn.) scientific research boreholes (Fig. 1). Laboratory measurements of porosity, strain, and ultrasonic velocity were used to characterize microcracks in the cores, and the microcrack populations were then examined as possible indicators of in situ stresses.

The Kent Cliffs borehole is located at the northern end of the Ramapo fault zone (Ratcliffe, 1971) within the Precambrian crystalline rocks of

TABLE 1

Dominant mineral composition of selected portions of Kent Cliffs core *

Mineral	Volume fraction (%)						
Core No.:	2	3	4	5	6	7	8
Quartz	10	25	25	25	25	30	30
Plagioclase	15	30	30	28	30	30	25
K-feldspar	–	20	20	20	18	25	27
Biotite	–	10	10	7	15	8	10
Muscovite	–	5	8	4	3	2	2
Amphibole	68	–	–	–	8	–	–
Epidote	3	9	5	5	–	4	5

* Data from Woodward-Clyde Consultants, 1986.

the Reading Prong. Seven of the eight core samples recovered (from depths up to 1 km as shown in Fig. 2) were examined in this study. The shallowest sample examined (core No. 2) is an amphibolite with a slight foliation defined by oriented amphiboles. The six deeper samples are granitic gneisses of coarse grain size (0.1–3 mm), with a strong foliation defined in part by layers of platy minerals (Woodward-Clyde Consultants, 1986). This foliation strikes approximately E–W and dips steeply to the south in all but sample No. 6 (513 m). Petrographic analyses of selected portions of core (Woodward-Clyde Consultants, 1986) indicate that composition is fairly uniform among all the gneiss cores recovered (see Table 1). These analyses are not of the specific samples used in this study.

Core No. 6 intersects a major shear zone in which the rock has been mylonitized, forming a phyllonite within the parent gneiss. Intersecting this zone is a fault, traceable to surface outcrop, which cuts the phyllonite roughly parallel to the schistosity (Woodward-Clyde Consultants, 1986). Sample No. 6 was taken from the gneiss adjacent to the phyllonite. The foliation in this gneiss sample strikes NW–SE and dips steeply to the south.

The Moodus borehole is located in an area of anomalous, shallow, low-level seismic activity in south-central Connecticut (Ebel et al., 1982). The borehole penetrates two distinct geologic terranes separated by a major ductile fault system known as the Honey Hill fault. This fault, intersected at approximately 800 m, places the Merrimack terrane over the Avalon terrane. The Merrimack terrane is characterized by a suite of metamorphosed marine sediments, possibly early Paleozoic in age. The Avalon terrane consists of late Precambrian metamorphosed volcanic and plutonic rocks (Woodward-Clyde Consultants, 1988).

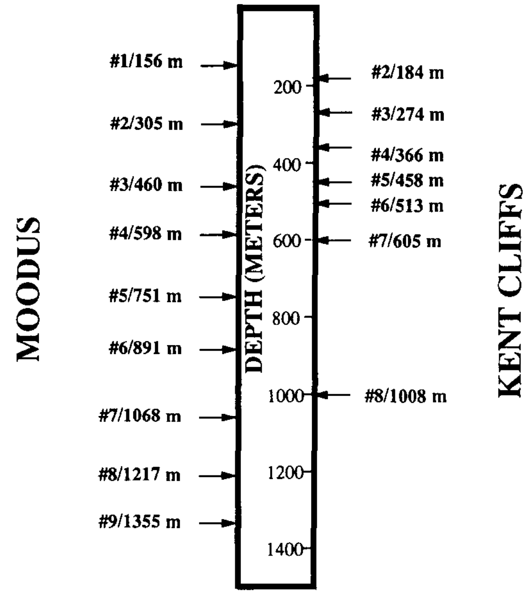

Fig. 2. Depths of drill-core specimens studied.

Nine core sections were recovered from depths up to 1.4 km (Fig. 2). The Merrimack cores are dominantly schists and granitic gneisses with a

TABLE 2

Dominant mineral compositions of selected portions of Moodus core *

Mineral	Volume fraction (%)									
Core No.:	1	2	3	4	5	6	7	8	9A	9B
Quartz	35	35	30	34	30	37	40	34	30	14
Plagioclase	35	35	34	31	35	38	42	40	45	25
K-feldspar	–	–	–	30	–	–	–	–	–	–
Biotite	20	25	25	5	35	15	10	5	10	20
Muscovite	–	–	10	Tr.	Tr.	–	–	–	–	–
Amphibole	1	–	–	–	–	10	8	20	15	40
Pyroxene	9	3	–	–	–	–	–	–	–	–
Epidote	–	–	–	Tr.	–	Tr.	Tr.	–	–	–

* Data from Woodward-Clyde Consultants, 1988.

subhorizontal foliation. The Avalon cores are dominantly gneisses, amphibolites, and granites with a subhorizontal foliation (Wintsch and Aleinikoff, 1987). Core No. 7 was recovered from an intensely fractured zone within the Avalon rocks, at a depth of 1068 m. Petrographic analyses of selected portions of core are presented in Table 2 (Woodward-Clyde Consultants, 1988). Two compositions are indicated for core No. 9. Both lithologies, the gneiss and amphibolite, were examined.

Methods

Kent Cliffs

Samples from the Kent Cliffs borehole were cut into 1-inch cubes with sides parallel and perpendicular to the subvertical foliation. The cubes were hand-lapped and dried in a vacuum oven at 50°C for 24 hrs. Although even moderate drying temperatures may induce thermal cracks (H. Wang, pers. commun., 1989), both Kent Cliffs and Moodus samples were prepared in the same manner, and therefore the variations among samples cannot be accounted for by this mechanism.

PZT compressional transducers with 1 MHz resonant frequency were attached using silicon grease and held in place with cement, and the sample was coated with rubber sealant to exclude the pressure medium (hydraulic oil). Measurements of travel times were taken successively as the sample was pressurized hydrostatically to 20.7 MPa (corresponding to lithostatic pressure at approximately 800 m depth) and then decompressed. Velocities were calculated from sample lengths and time-of-flight measurements made using the method outlined by Mattaboni and Schreiber (1967). Measurements are repeatable to within 0.04 km/s.

Ambient porosity was estimated by immersing samples in acetone, and calculating the porosity from the weight of acetone absorbed. These measurements are repeatable to within 0.02% porosity on the same specimen. This technique measures both microcracks and larger aspect ratio cavities, provided they are connected to the surface of the sample.

Moodus

Cores from the Moodus borehole were cut into 2-inch cubes with one side parallel to the subhorizontal foliation, and the two vertical faces striking N80°E and N170°E. These directions mark the approximate orientations of the maximum (N80°E) and minimum (N170°E) horizontal principal stresses measured by hydraulic fracturing (Zoback and Moos 1988).

Samples were polished using a surface grinder, then dried under a vacuum at 50°C. Strain gauge rosettes of 350 Ω nominal resistance were attached on three perpendicular faces. PZT compressional 1 MHz transducers were attached using epoxy, and the samples were coated with rubber sealant. A separate section of core was prepared for an additional measurement of linear strain normal to the foliation. Those samples were hand lapped, rather than surface ground. Measurements were made approximately every 10 MPa on loading and unloading to a maximum hydrostatic confining pressure of 140 MPa (corresponding to lithostatic pressure at approximately 5400 m depth). Ambient microcrack porosity in core No. 5 is not presented because the sample jacket was breached under pressure. Core No. 8 was highly disked during coring and several attempts at measuring strains were unsuccessful.

Microcrack strain was determined by fitting a line to the linear segment of the strain curve (above 100 MPa confining pressure) which is interpreted as reflecting primarily the compression of component minerals. Assuming the minerals exhibit linear elastic behavior, the zero-confining pressure intercept of the fitted line yields the total strain contributed by closure of microcracks over that interval (Simmons et al., 1974). Crack porosity was determined by summing the crack strains of a sample in three mutually perpendicular directions (Siegfried and Simmons, 1978). This method does not account for larger aspect ratio cavities which have closure pressures above 140 MPa.

Results

Velocity

An example of a complete pressurization cycle is shown in Fig. 3 for Moodus core No. 1, with the velocity measured normal to the gneissic foliation. The non-linear increase in velocity at low confining pressures reflects the closure of microcracks. As confining pressure increases the velocity curve becomes linear. The pressure at which the curve becomes linear is termed the maximum crack closure pressure; above that pressure, changes in velocity primarily reflect the compression of mineral components (Birch, 1960).

Compressional wave velocities measured perpendicular and parallel to the foliation are summarized in Table 3, and are plotted as functions of sample depth at ambient and maximum confining pressure in Figs. 4 and 5. In both suites of core, ambient velocities are low and tend to decrease with increasing initial sample depth. The application of confining pressure causes an increase in velocity as microcracks close. In the Moodus cores, the maximum velocities (V_{max}) are significantly higher than ambient velocities (V_{min}), and the V_{max} do not decrease with initial depth. In the Kent Cliffs cores, the decrease in velocity with sample depth persists at 20.7 MPa, indicating the microcracks have not closed completely in the deeper samples. However, the trend of decrease in velocity with sample depth is less pronounced at maximum pressure than at ambient pressure.

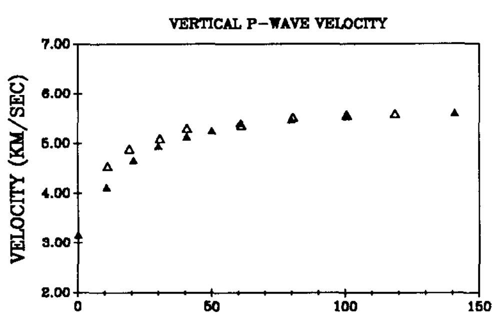

Fig. 3. Example of velocity versus hydrostatic confining pressure cycle for Moodus core No. 1 (184 m) measured normal to the foliation. Closed symbols represent measurements made on loading, open symbols on unloading.

TABLE 3

Compressional wave velocities *

Core No.	Core depth (m)	V_{min} par. (km/s)	V_{max} par. (km/s)	V_{min} perp. (km/s)	V_{max} perp. (km/s)
Kent Cliffs					
2	183.6	7.05	7.11	6.46	6.55
3	273.9	5.30	5.72	4.94	5.54
4	365.7	5.61	5.82	5.09	5.57
5	458.1	5.04	5.51	4.71	5.32
6	513.3	5.73	5.95	5.68	5.94
7	605.0	5.29	5.80	4.51	5.32
8	1007.5	4.28	5.00	3.89	4.93
Moodus					
1	155.6	4.84	6.21	3.17	5.61
2	305.4	4.28	6.30	2.79	5.64
3	460.1	4.68	6.49	2.31	5.56
4	597.9	3.89	5.70	2.53	5.18
6	891.0	3.82	6.33	1.84	5.96
7	1067.6	4.72	6.30	3.94	5.84
8	1217.0	–	–	0.61	–
9	1354.2	3.74	6.14	2.05	5.88

* Compressional wave velocities measured parallel (par.) and perpendicular (perp.) to the foliation in core samples. Minimum pressure is ambient; maximum confining pressure for Kent Cliffs cores is 20.7 MPa; maximum confining pressure for Moodus cores is 140 MPa.

In both suites of core, the velocity anisotropy between the directions parallel and perpendicular to foliation is largest at ambient pressure and decreases at the maximum pressures. In every case the direction normal to the foliation has the lower velocity.

Compressibility

An example of a linear strain-confining pressure curve as a function of orientation is shown in Fig. 6 for Moodus core No. 9A (1355 m). This example shows strain measured in three directions on the vertical face with strike N80°E: vertical strain (normal to the gneissic foliation), horizontal strain (parallel to the foliation), and strain at 45° to the foliation. The strain curves show that sample compressibilities are initially large but decrease rapidly with further application of confining pressure. Above pressures of approximately 50–70 MPa, the intrinsic compressibility of the

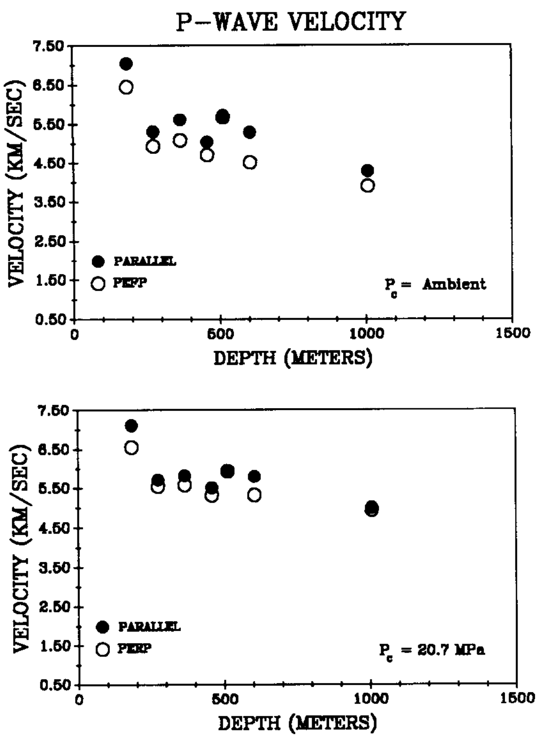

Fig. 4. Compressional wave velocities measured at ambient pressure and 20.7 MPa hydrostatic confining pressure in the Kent Cliffs samples, plotted as a function of sample depth. Measurements perpendicular to the foliation are plotted in circles; measurements parallel are plotted in dots.

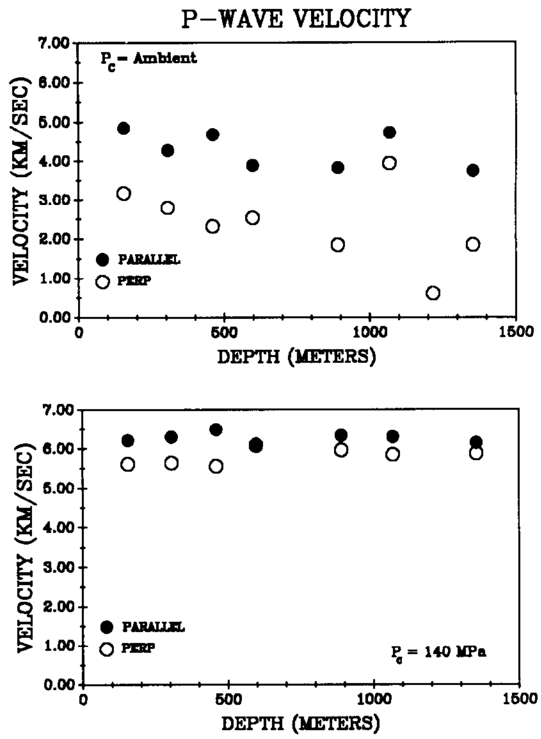

Fig. 5. Compressional wave velocities measured at ambient pressure and 140 MPa hydrostatic confining pressure in the Moodus samples, plotted as a function of sample depth. Measurements perpendicular to the foliation are plotted in circles; measurements parallel are plotted in dots.

sample is approached. In all samples the low-pressure compressibilities are largest normal to the foliation.

Figure 7 shows cumulative microcrack strains in the vertical direction for all Moodus samples, plotted at their respective depths. The circles represent measurements made on mutually perpendicular vertical faces of the cube, and the squares represent the additional vertical measurements made on separate samples, as discussed in the "Methods" section. With the exception of core No. 7 (1068 m), cumulative microcrack strain increases in a reasonably linear manner with increasing initial sample depth. Despite inhomogeneities within core segments and even within samples, the cumulative microcrack strains in cores from a given depth are repeatable to within a few percent, and thus appear to be insensitive to core mineralogy. The calculated ambient microcrack porosities have precision on the order of 0.05% porosity.

These cumulative strain measurements were averaged, as were the horizontal cumulative strains measured in directions N80°E and N170°E, and plotted in Fig. 8. The horizontal cumulative crack strains, shown in circles and diamonds, are only

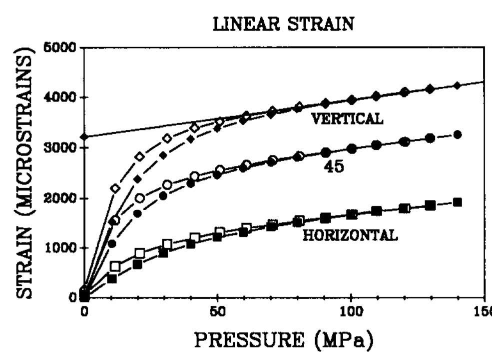

Fig. 6. Example of confining-pressure–strain curves for Moodus core No. 9A from ambient pressure to 140 MPa. Strains measured are parallel, perpendicular and at 45° to the horizontal foliation on a vertical face. Closed symbols represent measurements made on loading, open symbols on unloading.

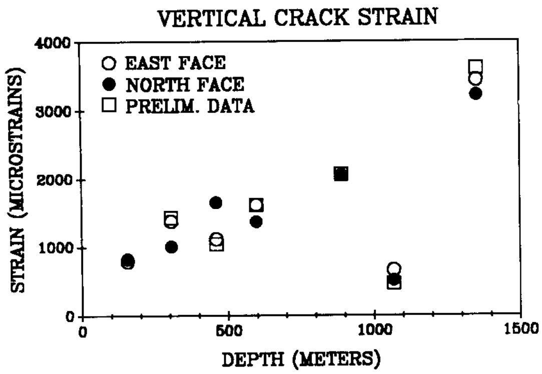

Fig. 7. Cumulative crack strains measured in the vertical direction for all Moodus cores, plotted as a function of sample depth. Circles represent measurements made on two perpendicular vertical faces; squares represent measurements made on a separate segment of core from the same depth interval.

one third to one half the magnitude of vertical crack strains and are virtually independent of direction. Ambient microcrack porosity for a given sample is obtained by summing the values of the average linear crack strain measured in these three mutually perpendicular directions.

Ambient porosity

Ambient porosities for both suites of core are plotted against initial sample depth in Fig. 9. Porosity is essentially absent in Kent Cliffs core No. 2 (184 m); it ranges from roughly 0.15% to 0.38% in the deeper Kent Cliffs cores and generally increases with initial sample depth. Kent Cliffs core No. 5 (458 m) has a higher ambient porosity than would be expected from its velocity properties. This sample contains a macroscopic healed

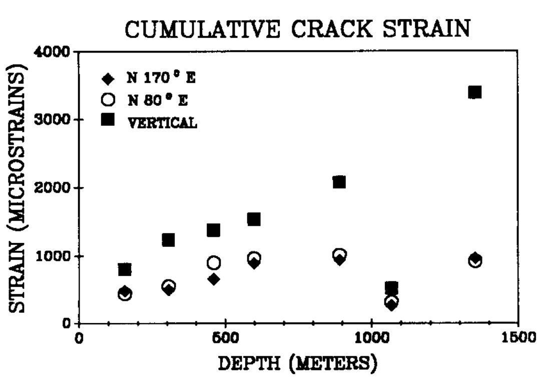

Fig. 8. Average of cumulative crack strains (Moodus cores) measured vertically (squares), horizontal N80° E (circles) and horizontal N170° E (diamonds).

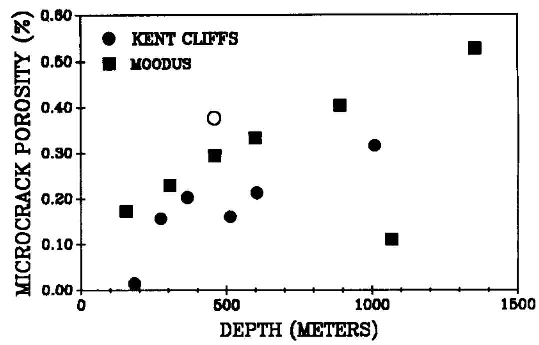

Fig. 9. Total porosity measured in Kent Cliffs cores (by immersion) and in Moodus cores (from strain measurements). The open circle is Kent Cliffs core No. 5, as discussed in text.

fracture of roughly 1 mm aperture, suggesting there is some open volume within this fracture contributing to the higher porosity. This is not believed to reflect a distributed microcrack porosity.

Ambient microcrack porosities in the Moodus cores range from 0.09% to 0.57%. As with the Kent Cliffs cores, ambient porosity tends to increase with initial sample depth, with the exception of Moodus core (1068 m) which has a very low microcrack porosity.

Though porosity in the two core suites were measured using different techniques, the results are consistent in magnitude with each other and with other measurements of porosity in crystalline rocks. The data show a general linear increase in porosity with initial depth. The exceptions are Kent Cliffs core No. 6 (513 m) and Moodus core No. 7 (1068 m), which were recovered from known fracture zones in situ (Zoback, 1986; Plumb and Hornby, 1988). Kent Cliffs core No. 2 (156 m) has an extremely low porosity as well, which may be related to a fractured zone several meters above it.

Discussion

The velocity measurements suggest that both core suites contain an ambient microcrack porosity which is larger in the deeper samples. In both suites, the velocity anisotropy predicts that the largest contribution to ambient microcrack porosity is from crack planes subparallel to the foliation. Closure of microcracks occurs at confining pressures roughly equal to or less than those found in situ, resulting in increased velocity and decreased anisotropy. Our porosity measurements confirm that the deeper cores contain a larger ambient porosity. Furthermore, cumulative microcrack strain measurements in the Moodus cores confirm that the largest contribution to sample porosity comes from microcracks subparallel to the foliation plane.

Two characteristics of the ambient microcrack porosities in these samples, the low crack closure pressures and the increasing porosity with initial core depth, are typical of a stress-relief crack porosity. Kent Cliffs core No. 5 is an exception, in that its high measured ambient porosity may have a component from a large pre-existing crack, rather than from stress-relief microcracks alone. Volumetric expansion of cores on removal of high in situ stresses is a process analogous to thermal expansion on increase in temperature. Elastic expansion of component minerals results from stress-relief, and, where compressibility mismatch occurs, high local stress causes microcracks to propagate. A significant portion of these stress-relief microcracks propagate along pre-existing planes of weakness, including grain boundaries (Brown, 1989; Teufel, 1989) and possibly mica cleavages (Meglis, 1987), thus accounting for the correlation with foliation in the Kent Cliffs and Moodus samples.

In samples of Illinois Granite from borehole UPH-3 ambient microcrack porosity formed by stress-relief increases with increasing in situ mean stress (Carlson and Wang, 1986). Preferred orientations of stress-relief cracks in isotropic rocks can reflect the orientation of in situ principal stresses (Strickland and Ren, 1980; Ren and Hudson, 1985), with the largest microcrack strain parallel to the maximum in situ stress. When the preferred orientation is controlled by rock anisotropy, as with the Moodus and Kent Cliffs cores, the relationship of microcrack orientation to in situ principal stresses is obscured. Cumulative microcrack strains in the Moodus cores measured parallel to the maximum in situ stress component (horizontal, oriented N80°E) are indistinguishable from strains measured normal to the maximum stress (horizontal, N170°E), and both are significantly lower than the vertical microcrack strains, measured parallel to the minimum in situ stress. However, the overall expansion of the cores results from relief of the total stress present in situ, and therefore the ambient microcrack porosity may correlate with some measure of the total in situ stress field, such as the mean stress.

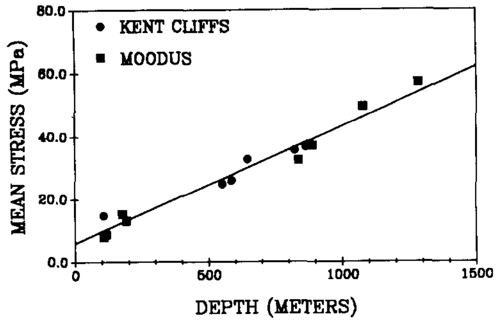

Fig. 10. Mean stress versus depth in the Kent Cliffs and Moodus wells. (Data from Zoback, 1986; Zoback and Moos, 1988).

Results of hydraulic fracturing measurements reported by Zoback (1986) and Zoback and Moos (1988) at both Kent Cliffs and Moodus are plotted as mean stress versus depth in Fig. 10. These data show that mean stress increases linearly with depth in both wells, consistent with the general trends of porosity in the two core suites. A linear regression of mean stress versus depth for the combined data sets shows a fit of:

$$\sigma_m = 5.9 \text{ MPa} + (0.037 \text{ MPa/m}) \times z \text{ (m)} \quad (1)$$

where σ_m = mean stress and z = depth; $r^2 = 0.97$.

This relation was used to estimate the mean stress at the depth of the samples studied in all but the cores recovered from fractured zones and Kent Cliffs core No. 2. The estimated mean stress was plotted as a function of sample porosity, as shown by the solid symbols in Fig. 11. A linear regression of these data shows a fit of:

$$\sigma_m = -3.13 \text{ MPa} + (110.56 \text{ MPa}) \times n \quad (2)$$

where σ_m = mean stress and n = % porosity; r^2 = 0.82.

The zero-pressure intercept of eqn. (2) is 0.028% porosity. Since this value is approximately equal to the precision reported for the porosity measurements, it may represent either error introduced in individual measurements during sample recovery

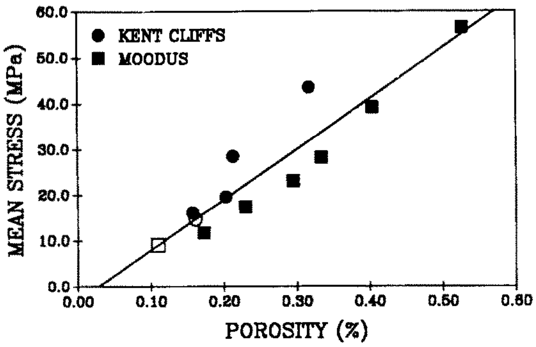

Fig. 11. Estimated mean stress at depth plotted as a function of porosity in the Kent Cliffs and Moodus cores. Linear regression of closed symbols is plotted as a line. Open symbols indicate samples recovered from fracture zones. These points were not included in the regression; rather, porosity in these samples was used to estimate mean stress in the fractured zones.

and preparation, or the fraction of porosity which exists in situ.

Carlson and Wang (1986) were the first to recognize that cores recovered from fractured zones generally have low porosities, reflecting locally lower mean stress in situ. Equation (2) was used to predict the mean stress in the fractured zones from which Kent Cliffs core No. 6 and Moodus core No. 7 were recovered. Those values are plotted in Fig. 11 as open symbols. In both cases, the predicted mean stress is significantly lower than the mean stress outside the fractured zones, and is lower than the mean stress if all three principal stresses are equal to overburden. Ambient porosity in Kent Cliffs core No. 2 is so low that a prediction of mean stress was meaningless.

One of the more surprising aspects of this study was the lack of dependence of the vertical crack strain on core mineralogy in the deepest Moodus sample. In fact, the trends in porosity versus stress for the Moodus and Kent Cliffs cores are remarkably consistent with each other. It should be noted that the two core porosities were measured using different techniques. However, the possibility remains that stress-relief crack porosity can be calibrated within a given borehole to yield magnitude of in situ mean stress. In homogeneous and isotropic rocks, in situ principal stress magnitudes and orientations could then be calculated from the principal crack strain ratios if the mean stress and the overburden are known.

Implications

One important implication of this study is that the bulk of microcrack porosity found in the cores is not expected to be present in situ. Open fluid-filled fractures are known to exist, and there is evidence of crack healing in cores, suggesting that now and in the past, fluid has had access to these rocks. However, at any given time the existing porosity in situ is expected to be low and localized within fractured zones such as those intersected by the boreholes. Our observations of the trends of porosity in the cores predict that a zone of microcracking exists at the borehole wall, which has undergone radial stress-relief (from in situ stress magnitudes to hydrostatic stress) in a manner similar to the cores. This zone is not expected to extend far from the borehole wall, and any resulting microcracks are expected to form as vertical planes subparallel to the borehole wall. Such cracks could interact with the concentrated stresses around the borehole and influence the formation and characteristics of borehole breakouts. Observations of breakouts formed experimentally in blocks of rock (Zheng et al., 1989) support this hypothesis. Breakouts had larger cross sections when holes were drilled in pre-stressed blocks than when holes were drilled before stressing. Apparently the amount of stress-relief at the borehole wall is at least as important as the magnitude of applied stress in determining breakout characteristics.

Although the correlation of ambient core microcrack porosity with both in situ stress magnitudes and even principal stress orientations has been established in many cases, the nature and cause of the correlation remains unknown. The formation of microcracks in cores on unloading indicates that grain configurations are locked in under stress at depth. Yet, those locked configurations are somehow reflective of the present-day stress field, suggesting that the grains have adapted to current stress conditions. Ductile relaxation of grains is unlikely, since temperatures are less than 10°C above ambient at the depths from which the cores were recovered. Adjustment may result from brittle fracturing and healing in situ, although low temperatures and low in situ porosities impede the rapid healing of microcracks (S. Brantley, pers. commun., 1989). This hypothesis is the more likely one, and is supported by observations of crack healing and alteration of minerals in cores recovered from the stress-relieved fractured zones in situ (A. Brown, pers. commun., 1989). One implication which would follow is that a significant porosity may be created and filled during stress-relief by geologic unloading, even under very shallow crustal conditions. Clearly the relationship between ambient core microcrack porosity and in situ stress is not straightforward, and further work in this area can address not only the use of microcracks for prediction of in situ stress, but also the nature of deformation mechanisms acting in the shallow crust on geologic timescales.

Conclusions

The results of this study suggest that ambient microcrack porosity in cores is linearly related to the in situ mean stress, even when the distribution of those microcracks is controlled by factors other than the in situ stress state. Core studies hold promise of being able to map in situ stresses at a very fine scale, particularly in fractured zones where hydraulic fracture measurements are not feasible.

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