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MASTER

A CROSS-HOLE INVESTIGATION OF A ROCK MASS SUBJECTED TO HEATING

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ABSTRACT

A cross-hole high-frequency acoustic investigation of a granitic rock mass subjected to sustained heating is reported. Compressional and shear-wave velocity measurements along four different paths between four vertical boreholes made prior to turning on the heater, during 398 days of heating and after the heater was turned off correlated well with the presence of fracture zones, in which the fractures were closed by thermal expansion of the rock upon heating. When the rock mass cooled, the velocity measurements indicated a greater intensity of fracturing than had existed prior to heating. Laboratory compressional and shear-wave velocity measurements have been made on intact rock specimens obtained from the site and subjected to axial stress. When used to interpret the increases in velocities measured in the field upon heating the rock mass, increases in horizontal normal stresses to between 30 and 40 MPa were inferred. Increases of these magnitudes agree with stress measurements made by the other techniques. The ratio of measured compressional to shear-wave velocity appears to provide a sensitive measure of the fraction of crack porosity containing water or gas.

KEYWORDS

Rock mechanics; ultrasonics; acoustic velocities; thermal stresses; dynamic moduli; static moduli; rock mass characterization.

INTRODUCTION

One of the more promising methods developed in the past few years for geotechnical site investigation and the characterization of rock masses is the higher-frequency acoustic wave technique. The high frequencies employed permit detection of discontinuities and the outlining of zones having different physical properties between boreholes or behind surface boundaries in much more detail than the conventional low-frequency seismic methods.

Price, Malone and Knill (1970), McCann, Grainger and McCann (1975) and Auld (1977) describe the use of acoustic measurements between boreholes for geotechnical purposes. Price and colleagues employed the results of their study to determine the optimum rock-bolt pattern to stabilize a rock mass. McCann and colleagues used the between-hole technique to delineate interfaces between homogeneous media, to detect localized, irregular features and to estimate the degree of fracturing in the rock mass. Auld used between-hole acoustic measurements to determine the elastic properties of the rock mass.

Acoustic techniques employed within a borehole have been described by Geyer and Myung (1971), Myung and Baltosser (1972) and by King and colleagues (1975, 1978). The application of acoustic borehole logs in detecting fractures, for rock classification and in determining the *in situ* elastic properties of rock have been discussed by these workers and by Carroll (1966, 1969) and Coon and Merritt (1970).

In this paper are described the results of a research project involving cross-hole acoustic measurements in a fractured granite rock mass subjected to thermal stresses. The acoustic research project is itself part of a comprehensive rock mechanics and geophysics research programme associated with large-scale heater tests in an abandoned iron-ore mine in central

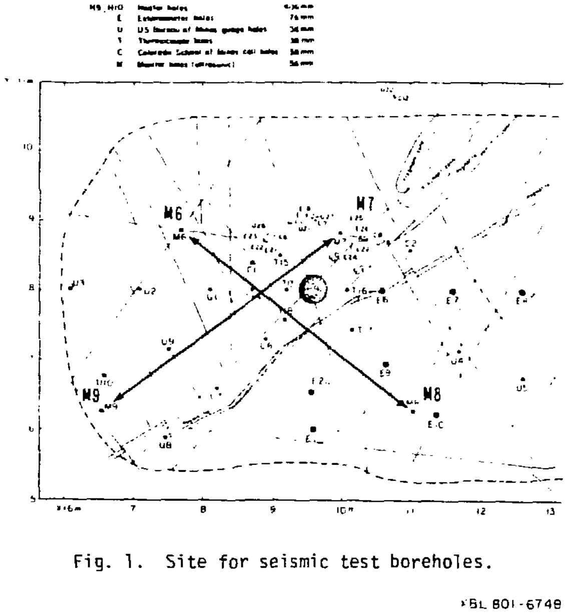

Fig. 1. Site for seismic test boreholes.

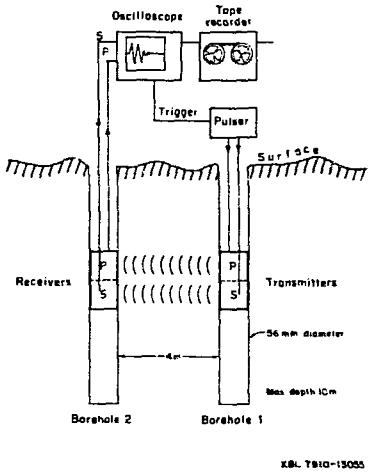

Fig. 2. Block diagram of acoustic equipment.

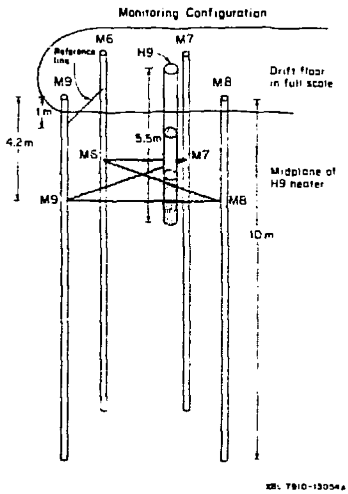

Fig. 3. Monitoring configuration.

Sweden, as described by Witherspoon and colleagues (1979).

EXPERIMENTAL PROCEDURES

The cross-hole acoustic measurements were made between four vertical monitor boreholes of 10m depth in the vicinity of a vertical heater borehole in the floor of a drift in the iron-ore mine, at a subsurface depth of 340m, as indicated in Fig. 1. Small volumes of water were found continually to seep into the four boreholes, but they were blown out regularly to keep them dry.

The acoustic measurements involved transmitting and receiving pulses of compressional and shear waves between pairs of boreholes, employing equipment shown in block form in Fig. 2. The equipment and operational procedures have been described by Nelson and colleagues (1979). The compressional and shear-wave received signals were recorded in analogue form for later harmonic analysis in the laboratory. Both compressional and shear wave arrivals may be picked precisely, enabling velocity measurements to be made with a precision of ±0.2 percent.

The acoustic measurements described here fell into two categories. The first consisted of cross-hole monitoring of the rock mass during the heating experiment. The transducers were placed at the midplane level of the heater to monitor changes in the compressional and shear-wave velocities as a function of changes in thermally-induced stresses and displacements with time. The second consisted of cross-hole surveys of the rock mass, for which the transmitters and receivers were placed at the same horizontal level at the upper end of a pair of boreholes and then moved down together at 0.25 or 0.50m intervals between measurements of the compressional and shear-wave velocities. An isometric view of the four monitor boreholes and heater borehole, with the heater midplane cross-hatched, is shown in Fig. 3. Also indicated are the four paths over which the velocities were monitored.

A plan view of the floor of the mine drift in which the experiments were performed is shown in Fig. 1. This shows also a simplified version of the detailed fracture map of the drift floor. Also shown are the instrumentation boreholes around the heater, the core from which provided excellent control of the structural geology and fractures present within the volume of rock monitored, as described by Paulsson and Kurfurst (1980). The two arrows between monitor boreholes M6 - M8 and M7 - M9 indicated only two of the six paths which were utilized in the rock mass characterization.

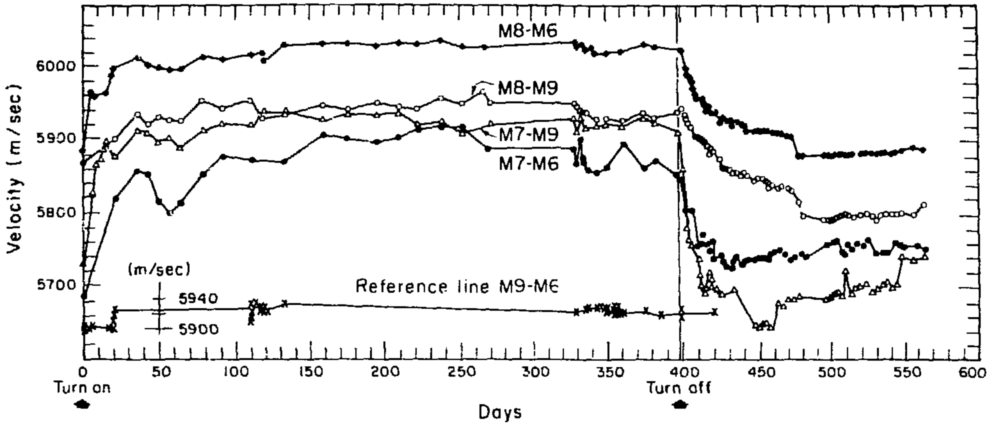

Fig. 4. Monitoring of P-wave velocity.

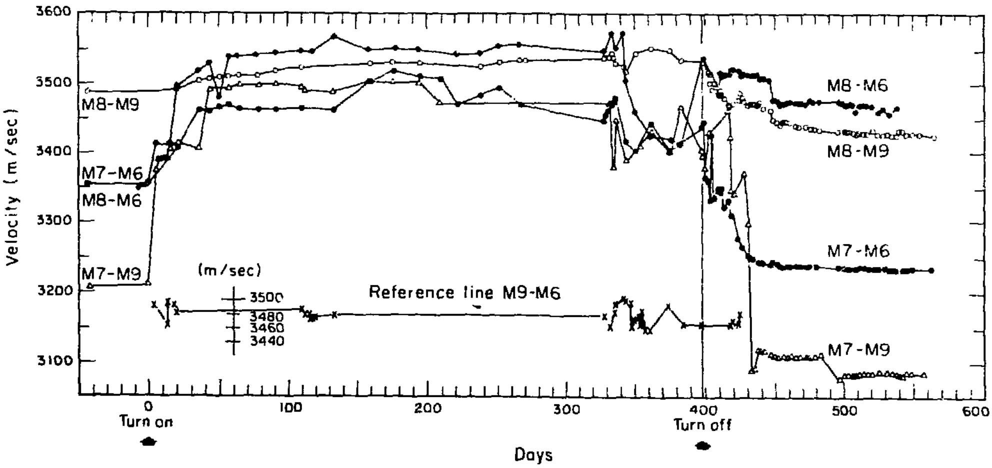

Fig. 5. Monitoring of S-wave velocity.

RESULTS AND DISCUSSION

Field Tests

The full-scale heater (No.H9) was turned on 24 August, 1978, and turned off 27 September, 1979, after 398 days of heating the rock mass.

Almost immediately upon turning on the heater the compressional and shear-wave velocities increased sharply, as shown in Figs. 4 and 5. Then followed a period of less rapid increase to approximately 150 days after turning on the heater, after which the velocities remained fairly constant. It will be observed that between 40 and 100 days there were reductions in compressional-wave velocities, particularly for the path M7 - M6. Since this path is the closest to the heater, it appears that the reduction was probably due to the conversion of water to steam in the cracks along part of the path. This explanation is consistent with the behavior of compressional-wave velocity in water and gas-saturated granite observed in the laboratory, and noted later in the paper.

Upon turning off the heater after 398 days, sharp decreases in compressional and shear-wave velocities were observed. The changes in velocity observed during the experiment appear to be closely related to the directions and magnitudes of the principal virgin field stresses reported by Carlsson

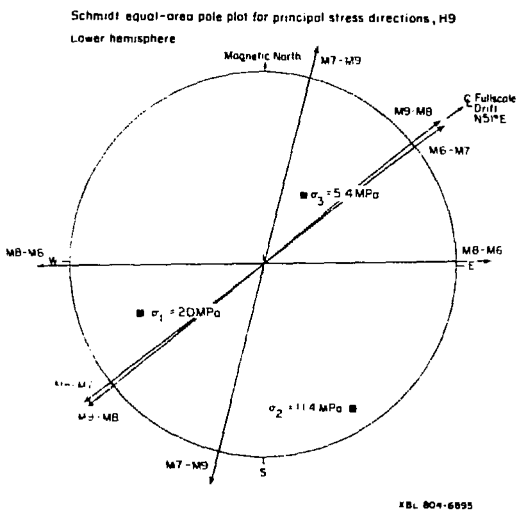

Fig. 6. Principal stresses and monitor line directions.

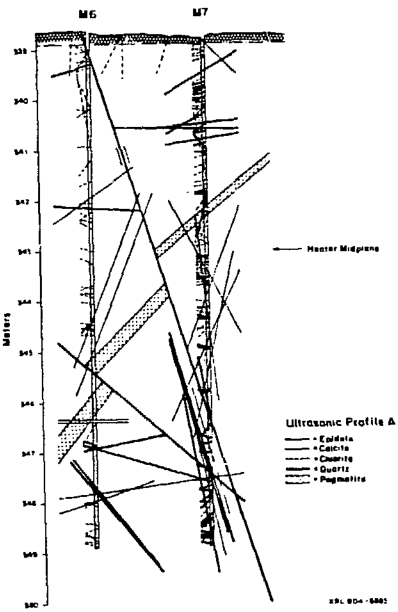

Fig. 7. Geologic cross section between M6 - M7.

(1978) and shown in Fig. 6. The highest velocities before, during and after the heater experiment were observed over the path M8 - M6, which happens to coincide most closely with Carlsson's reported major principal axis of stress.

Noticeable differences in behavior of the velocities over the four paths were observed after the heater was turned off. The velocities over paths M8 - M6, M8 - M9 and M7 - M6 show more gradual reductions than those over path M7 - M9, which drop almost instantaneously. The behavior of the velocities over the path M7 - M9 can probably be explained by its relationship to the direction of the minor pricipal axis of stress. The effect of heating the rock mass will be to increase the horizontal stresses in such a manner as to cause them to approach each other in magnitude; the reverse will be true when the heater is turned off.

The four acoustic monitor boreholes were all core-drilled and the core oriented. This made it possible to reconstruct the fracture system between the boreholes. An example of the fracture system between boreholes M6 and M7 reconstructed from core data is shown in Fig. 7. A detailed discussion of the fracture system in the vicinity of the heater borehole H9 is provided by Paulsson and Kurfurst (1980).

The compressional and shear-wave velocities from monitoring the heater mid-plane for path M6 - M7 have been used to calculate the dynamic values of Young's modulus and Poisson's ration using the rock bulk density reported by Swan (1978) and the classical expressions for homogeneous, isotropic, elastic media. The results are plotted in Fig. 8, which shows Young's modulus (E) and Poisson's ratio (ν) plotted as a function of time. The fact that the Young's modulus returns after the heater is turned off to a value which is lower than that before the heater was turned on, and that Poisson's ratio increases over the same interval of time, indicates that there are more open fractures on cooling than existed before the heater was turned on.

The second category of acoustic cross-hole measurements consisted of moving the transmitters and receivers down a pair of boreholes in unison. In this way the rock mass was surveyed between pairs of boreholes from the surface to a depth of 10m. This was performed over the path M7 - M6 on three occasions during the heater experiment. The first survey was performed prior to the heater being turned on, the second after 344 days of heating and the third 27 days after the heater was turned off. The results of these surveys are shown in Figs. 9 and 10. The velocities have been used in conjunction with the rock bulk density reported by Swan (1978) to calculate the dynamic Young's modulus and Poisson's ratio. These values are plotted for the three surveys in Fig. 11.

It will be observed from the reconstructed geologic cross section shown in Fig. 7 that an abundance of calcite fractures have been logged over the interval 342 - 345 m subsurface. This interval corresponds to the low velocity layer observed in Figs. 9 and 10 prior to turning on the heater. It is

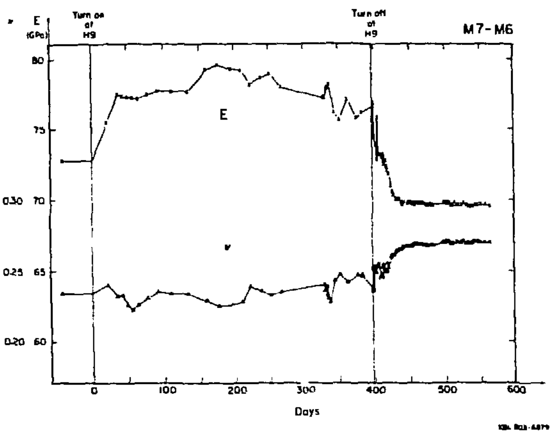

Fig. 8. Young's modulus and Poisson's ratio as a function of time.

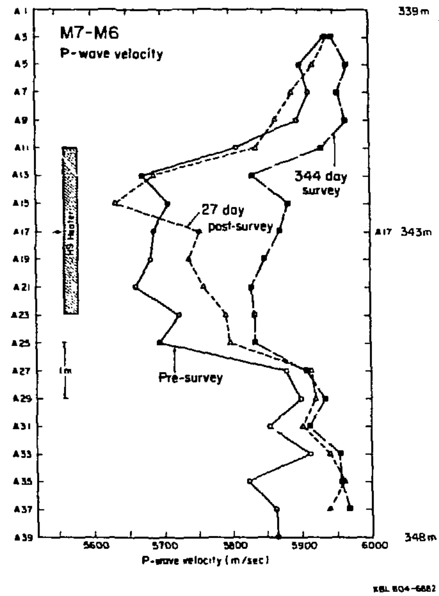

Fig. 9. P-wave velocity as a function of depth and time.

interesting to observe that the velocities measured 344 days after the heater was turned on were, however, more uniformly distributed over the depth of the depth of the boreholes, indicating a more homogeneous rock mass as the fractures were closed by thermal expansion.

Paulsson and Kurfurst (1980) analyzed the degree to which different fractures were opened by drilling. Whereas 30 percent of all fractures were opened by drilling, they observed that 90 percent were opened in the case of calcite fractures and only 10 percent for epidote fractures. These observations provide an indication that calcite fractures are probably the weakest of all. They are also considered to be most likely to conduct water.

Laboratory Tests

A limited number of laboratory tests on intact samples of granite from the test site were performed to complement the field tests. Ultrasonic compressional and shear-wave velocities were measured as a function of axial stress on intact cylindrical specimens of 45mm and 51mm diameter in the manner described by King (1970). Measurements were made at room temperature on 21 specimens prepared from samples cored from the vertical acoustic monitor boreholes and horizontal extensometer boreholes in the vicinity of the H9 heater borehole.

The specimens were tested dry (vacuum-oven dried at 105°C and 20 microns Hg for 24 hours) and in the fully water-saturated state (24 hours saturation under vacuum, followed by 24 hours pressurizing at 10 MPa in distilled water). The results obtained from tests on specimens from vertical and horizontal boreholes indicated no significant anisotropy. The mean values of the measured velocities are shown in Fig. 12 as a function of axial stress to 40 MPa.

The 21 cylindrical specimens were weighed in their dry and water-saturated states to obtain the bulk density and interconnected porosity. The mean bulk densities dry and water-saturated were 2606 and 2611 kg/m^3 respectively, which resulted in a mean porosity of 0.46 percent.

The static Young's modulus and Poisson's ratio were measured on ten of the specimens with length-to-diameter ratios of approximately 2:1, first dry and then water-saturated. A strain-measuring yoke consisting of five C-gauge sensors (three axial and two lateral) was used for this purpose. The specimens were enclosed in a thin rubber membrane during the tests to prevent gain or loss of moisture. The results showed that the granite behaved in an elastic manner, with virtually no hysteresis occuring between ascending and descending axial stresses to 80 MPa. The stress-strain relations were, however, non-linear with the slope increasing as the stress was increased. This observation is in agreement with that reported by Swan (1978) for granite from the same site.

The results are shown in Table I and Fig. 13, where the mean static Young's modulus and Poisson's ratio dry and water-saturated are plotted as a function of axial stress to 40 MPa. It should be noted that the static values plotted are the mean tangent values measured at each of the axial stresses.

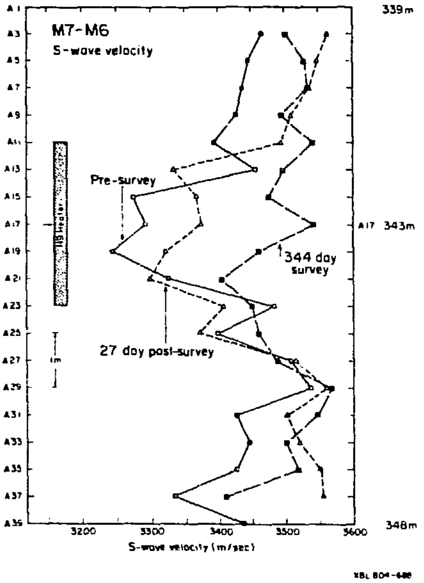

Fig. 10. S-wave velocity as a function of depth and time.

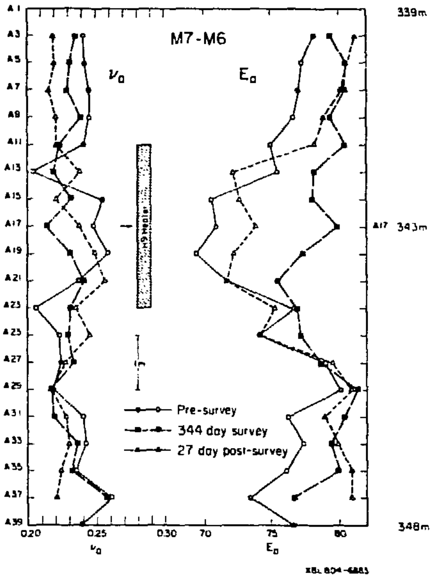

Fig. 11. Young's modulus and Poisson's ratio as a function of depth and time.

The dynamic values for the dry specimens (calculated from the ultrasonic velocities and the dry density) are also shown for comparison. It will be observed that there is excellent agreement between the static and dynamic Young's modulus dry, and fair agreement between the static and dynamic values of Poisson's ratio.

TABLE 1 Static Elastic Moduli

Axial Stress	Young's Modulus, 10^9Pa Saturated		Dry		Poisson's Ratio Saturated		Dry	
MPa	Secant	Tangent	Secant	Tangent	Secant	Tangent	Secant	Tangent
3.5	56.8	61.7	63.3	67.8	0.13	0.16	0.14	0.16
7.0	60.0	65.2	66.2	70.9	0.15	0.19	0.16	0.17
14.0	63.4	68.9	69.3	74.3	0.17	0.21	0.18	0.20
21.0	65.5	71.1	71.2	76.3	0.19	0.23	0.19	0.22
40.0	69.0	74.9	74.3	79.6	0.22	0.26	0.21	0.24

Relations Between Laboratory and Field Tests

It is clear from the laboratory results that the acoustic velocities for granite are influenced by the state of saturation of the crack porosity even though the specimens tested were intact. This is more pronounced for the compressional-wave velocity, at low axial stresses particularly, than the shear-wave velocity. Despite the good agreement between the static and dynamic Young's modulus calculated for dry specimens, caution should be exercised in comparing static and dynamic Young's modulus for water-saturated granite. In the latter case, the dynamic Young's modulus will be higher than for the rock dry, because the velocities saturated are appreciably higher than those dry. This is in contrast to the behavior observed for the static Young's modulus dry and water-saturated. The presence of a larger number of cracks and fissures will tend to exacerbate the situation. These observations are consistent with those predicted by the theory developed by Kuster and Toksöz (1974) for elastic wave propagation in dry and water-saturated media containing pores and cracks.

Although the laboratory velocities have been measured under conditions of axial stress only, they are probably close in value to the values measured under all-round confining stresses in the same range.

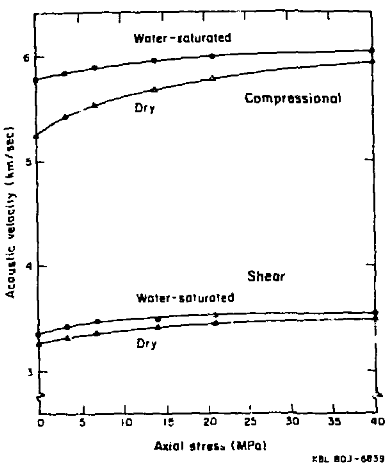

Fig. 12. Acoustic velocities of the Stripa Granite, dry and water-saturated.

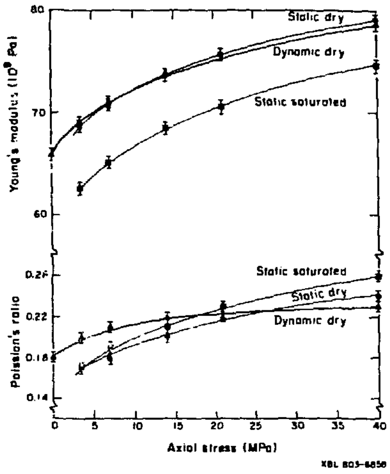

Fig. 13. Static and dynamic elastic moduli Stripa Granite, dry and water-saturated.

Wyllie, Gregory and Gardner (1958) reported an observed insensitivity of compressional-wave velocities to whether the rock specimens were subjected to axial or all-round confining stress at stresses in the range indicated here. This leads to the conclusion that the velocities measured along a particular path in the field are probably influenced most strongly by the component of normal stress acting in the same direction. The laboratory velocities as a function of axial stress probably provide, therefore, an upper bound to those likely to be observed in the field.

Results of the heater midplane monitoring tests indicate increases in compressional-wave velocities on heating from between 5700 and 5900 m/sec to between 5900 and 6000 m/sec, and in shear-wave velocities from between 3200 and 3500 m/sec to between 3450 and 3550 m/sec for the different paths. These increases in velocity are consistent with increases in the corresponding component of normal stress to between 30 and 40 MPa, based on the laboratory measurements. Stresses of these magnitudes were also indicated by other rock mechanics measuring techniques.

The ratio of compressional-wave to shear wave velocity is suggested by the laboratory results to be a sensitive indicator of the degree to which the crack porosity is water or steam-saturated. This point has already received attention earlier in the paper. It is expected that laboratory tests performed on dry and water-saturated granite specimens containing open discontinuities will exhibit an even more pronounced effect of this nature.

CONCLUSIONS

It is concluded that the cross-hole, high-frequency acoustic wave velocity technique provides a promising method for monitoring changes in stress and for detecting the presence of inhomogeneities such as fracture zones and joints in a crystalline rock mass, although the method is probably site specific. The ratio of compressional-wave to shear-wave velocity appears to be a sensitive measure of the fraction of crack porosity occupied by water and gas.

Considerably more laboratory measurements are still required of acoustic velocities in rock specimens containing natural and artificial discontinuities and subjected to different states of stress and pore fluid pressure. This information will provide for better interpretation of the field data.

ACKNOWLEDGEMENTS

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