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BETWEEN-HOLE ACOUSTIC SURVEYING AND MONITORING OF A GRANITIC ROCK MASS

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INTRODUCTION

In the fields of geotechnology and mining, seismic and, to a growing extent, higher-frequency acoustic techniques are increasingly being employed for site investigation, characterization, and evaluation. The promise held by these techniques lies in their ability to detect the presence of discontinuities, to outline zones having different physical properties and to interpret these physical properties between boreholes or behind surface boundaries.

The classification of rock mass quality and site evaluation by seismic methods have been described by Cratchley et al (Ref.1), La Porte et al (Ref.2) and Sjogren et al (Ref.3). Stephansson et al (Ref.4) have discussed applications of the seismic method to determine the depth and degree of fracturing of a rock mass near a free surface. Recent developments in the use of seismic channel waves in coal-mine exploration have been discussed by Dresen and Freystatter (Ref.5) and Mason (Ref.6). Of particular relevance, Mason describes a computer-aided algebraic reconstruction of the seismic velocity field in a coal mine panel, which is based on an algorithm similar to that developed for medical tomography. Buchanan et al (Ref.7) have described the location of faults in coal seams by channel-wave seismology.

Higher-frequency acoustic techniques employed within a borehole have been described by Geyer and Myung (Ref.8), Myung and Baltosser (Ref.9) and King et al (Refs.10,11). The applications 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 (Refs.12,13) and Coon and Merritt (Ref.14).

The use of acoustic measurements between boreholes for geotechnical purposes has been described by Price et al (Ref.15), McCann et al (Ref.16), and Ault (Ref.17). Price et al employed the results of their study to determine the optimum rock-bolt pattern to stabilize a rock mass. McCann et al used the between-hole technique to delineate interface between homogeneous media and to detect localized, irregular features. They also discussed a means for interpreting their data to estimate the degree of fracturing in the rock mass. Auld has described instrumentation for, and presented field results of, between-hole acoustic measurements which he then used to determine the elastic properties of the rock mass.

Computer-aided algebraic reconstruction of the seismic velocity and attenuation fields from detailed between-hole measurements are described in Lytle (Ref.18). Potential contributions to the three-dimensional characterization of rock masses from medical imaging techniques are discussed by Johnson et al (Ref.19).

The purpose of this technical note is to present preliminary results of an acoustic monitoring study performed as part of a comprehensive rock mechanics and geophysics research program (Ref.20) associated with large-scale heater tests in an abandoned iron-ore mine in central Sweden.

EXPERIMENTAL PROCEDURES

The investigation was performed in a fractured granitic rock mass at a sub-surface depth of 340 m, in a drift adjacent to the original iron-ore mine workings. Acoustic monitoring took place between four empty, dry, vertical boreholes of 10 m depth spaced in the vicinity of a vertical heater borehole in the floor of a drift, a plan of which is shown in Figure 1. Small volumes of water were found continually to seep into the four boreholes, but they were blown out regularly to keep them dry. Oriented core from a large number of vertical and horizontal instrumentation boreholes drilled in the vicinity of the heater provide excellent control of the structural geology and fractures within the volume of rock monitored (Ref.2).

A block diagram of the equipment is shown in Figure 2 (Ref.22). Separate compressional (P) and shear (S) wave transducers of nominal 200 kHz resonant frequency are used as transmitters and receivers of pulses of acoustic energy in boreholes of 56 mm diameter. The transducer holders are jacked mechanically against the borehole wall at the required depth. The P- and S-wave received signals are displayed on an oscilloscope screen and recorded in analogue form on an instrumentation tape recorder for later harmonic analysis in the laboratory. Typical oscilloscope traces for boreholes 2.8 m apart are illustrated in Figure 3. It will be observed that both P- and S-wave arrivals are sharp and may be picked precisely.

The acoustic monitoring tests referred to fall into three categories: (1) between-borehole surveys, for which the transmitter and receiver were positioned at the same depth in a pair of boreholes and then moved down together at 0.25 m intervals between each reading; (2) between-hole monitoring, for which the transmitter and receiver were positioned in each pair of boreholes at the level of the heater midplane, as indicated in Figure 4; and (3) computer-aided reconstruction of the P- and S-wave velocity and attenuation fields between a pair of boreholes 4.2 m apart, with velocity and attenuation measurements made over the paths shown in Figure 5.

PRELIMINARY RESULTS AND DISCUSSION

Results of the between-hole surveys for boreholes M8-M6, whose profile passes close to the heater, are shown in Figure 6. This shows P-wave velocities prior to turning on the heater, 21 days, 118 days, and 342 days after turning on the heater, and finally 21 days after turning off the heater. The precision of the velocity measurements is estimated to be ±0.15%. The survey conducted prior to heater turn-on indicates a major velocity anomaly above the heater midplane. This anomaly appears to correlate with the presence of an abundance of calcite-filled fractures in the granite. By 21 days after heater turn-on, most of the velocity anomaly has disappeared. At 118 days, the velocities had increased slightly and were fairly uniform, except for a significant increase opposite the heater. Between 118 days and 342 days after turning on the heater, there appears to have been little change in velocity, except for a slight increase at the lower end of the profile. By 21 days after turning off the heater, the velocities at the upper end of the profile has returned to, or below, their original values prior to heater turn-on, but had not done so at the lower end of the profile. It is intended to interpret the acoustic survey results in conjunction with the measured temperature, stress, and displacement fields interpolated to points on planes containing the pairs of boreholes, and with laboratory velocity measurements on intact and fractured specimens of the granite subjected to temperatures and stresses in the range experienced in the field.

Results of between-hole monitoring at the heater midplane level are shown in Figure 7, where P-wave velocities for four between-hole paths are plotted as a function of time after the heater was turned on. It will be observed that there was a sharp initial increase in velocity. The velocities then increased more slowly until about 150 days after heater turn-on, after which they remained fairly constant until the heater was turned off after 398 days. The reduction in velocity (most pronounced for path M7-M6) observed between 40 and 100 days has not yet been explained, but preliminary laboratory acoustic-velocity measurements indicate that this behavior is possibly due to the conversion of water in the fracture pore space to steam over part of the travel path. This aspect will be studied in conjunction with the measured temperature and stress fields and results of further laboratory tests. Upon turning off the heater, the velocities at first fell sharply. It is yet too early to comment on the asymptotic values to which the velocities appear to be falling. It is instructive, however, to compare the behavior of the velocities as a function of time in Figure 7 with that of the displacement and stress measured in two vertical boreholes approximately 1 m from the heater, shown in Figure 8. In all three cases, the behavior is remarkedly similar.

Harmonic analysis has been performed on a few selected records which have been digitized from the analogue tapes. Amplitude spectra of P-wave signals recorded over one path at three different times during the heater midplane survey are shown in Figure 9. It will be seen that there is an increase in higher frequency components of the signal as a function of time, indicating a decrease in attenuation as the rock is heated. Amplitude spectra of P-wave signals recorded over different paths between one pair of boreholes during a survey conducted before the heater was turned on are shown in Figure 10. It will be seen that the higher frequency components of the signal are much lower in relative amplitude for the path passing through the highly fractured zone than for that passing through the less fractured zone.

The results of the acoustic research program that have so far been analyzed appear to indicate that the presence of fractures, particularly those filled with calcite, contributes significantly to reductions in the seismic velocities and increased attenuation observed in the unheated rock. As the rock mass is heated, it is clear that thermal expansion tends to close open fractures and to increase the normal stress across those already closed. This results in a considerably more homogeneous rock mass upon heating with correspondingly more uniform mechanical properties. The expected reduction of elastic modulus of the intact rock due to an increase in temperature appears to be overridden by the concomitant increase in modulus due to closure of fractures present in the rock mass.

Tentatively, it might be concluded that the between-hole acoustic technique provides an excellent method for monitoring changes in stress and for detecting the presence of inhomogeneities such as fracture zones and faults.

ACKNOWLEDGEMENTS

The research reported here comprises part of an extensive rock mechanics and geophysics program to explore the possibilities of using a large crystalline rock mass as a geologic repository for nuclear waste, sponsored by the Swedish Nuclear Fuel Supply Company (SKBF) and the U. S. Department of Energy through the Office of Nuclear Waste Isolation under Contract B511-0900-1. In particular, the authors wish to acknowledge the continued support and encouragement provided by Mr. Lars-Bertil Nilsson of the Swedish Nuclear Fuel Safety Program (KBS), Dr. Philip Nelson of Lawrence Berkeley Laboratory, and Professors Frank Morrison and Shimon Coen of Engineering Geoscience at the University of California, Berkeley. The generosity of Hagbybruk AB and VIAK during drilling and surveying the test boreholes is gratefully acknowledged, as were the conscientious efforts of Messrs. Lennart Andersson and Gunnar Ramqvist in assisting with data collection. We are indebted also to Terra Tek, Inc., Salt Lake City, who designed the cross-hole seismic equipment and took an active part in designing the experiment; to Margot Harding, who drafted the text figures; and Martha Manqueros, who typed the manuscript.

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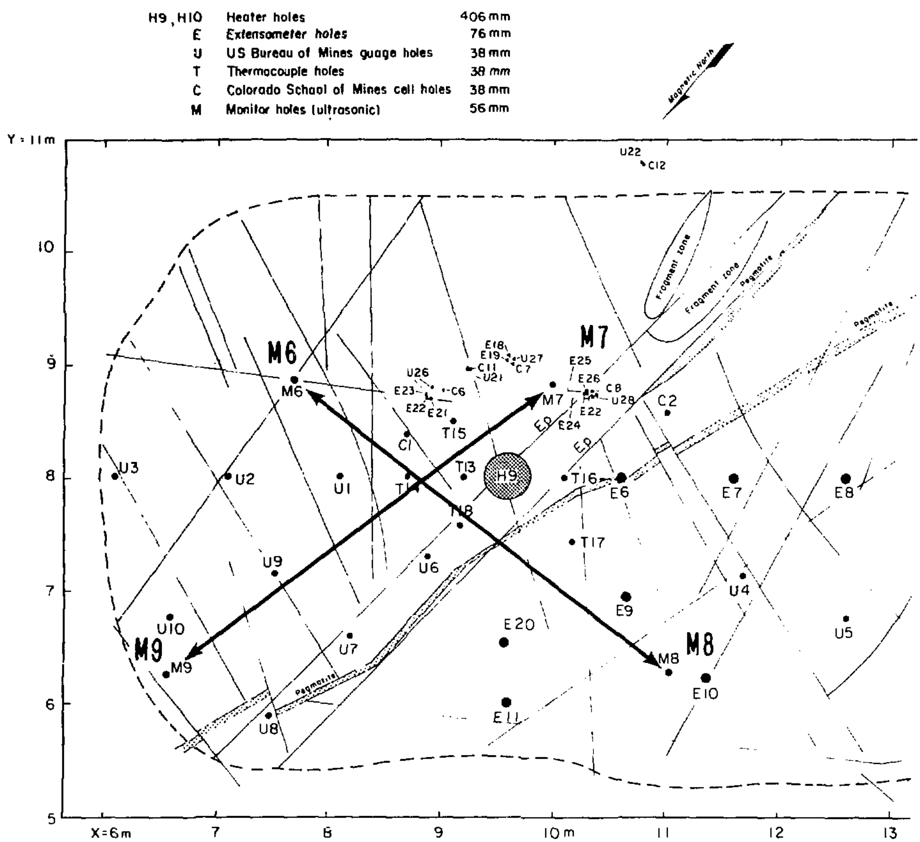


Fig. 1. Sites of seismic test boreholes in heater drift.

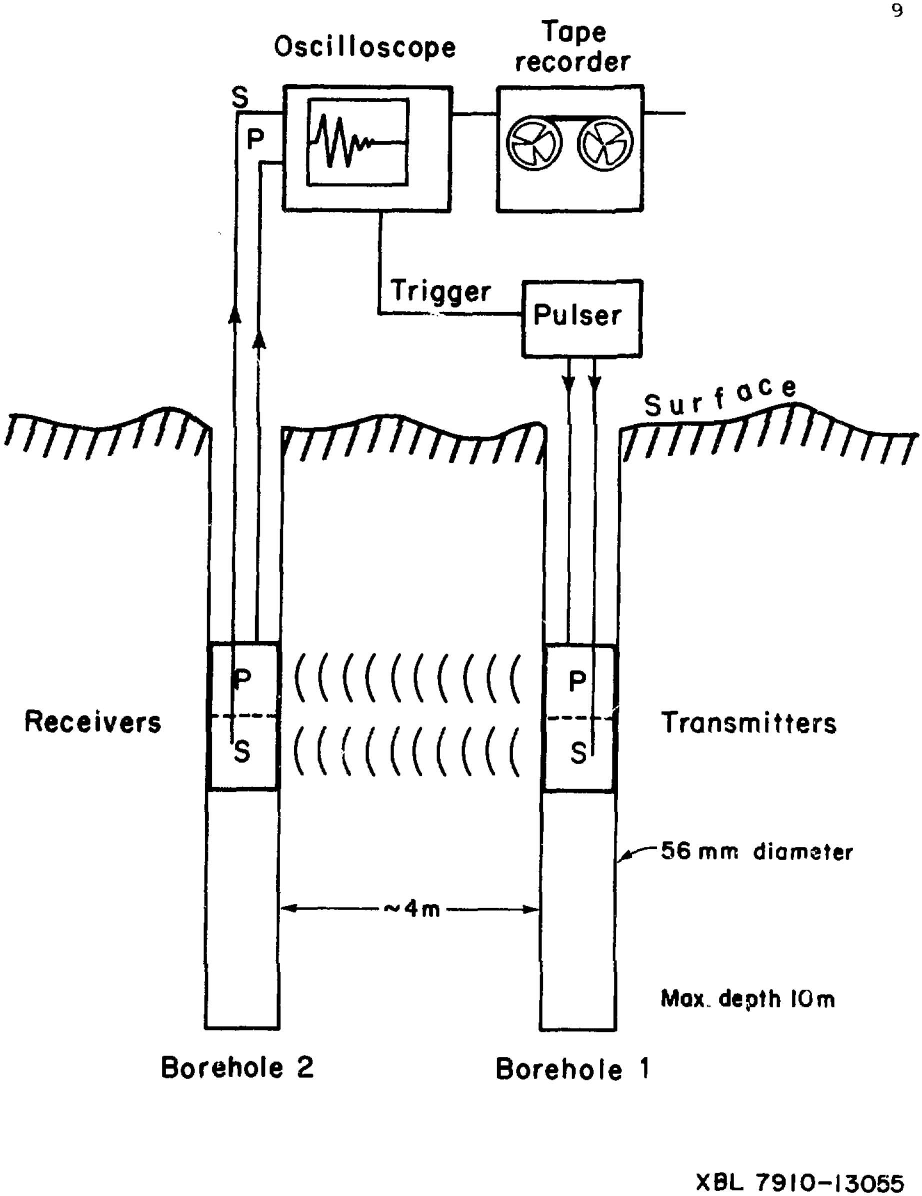
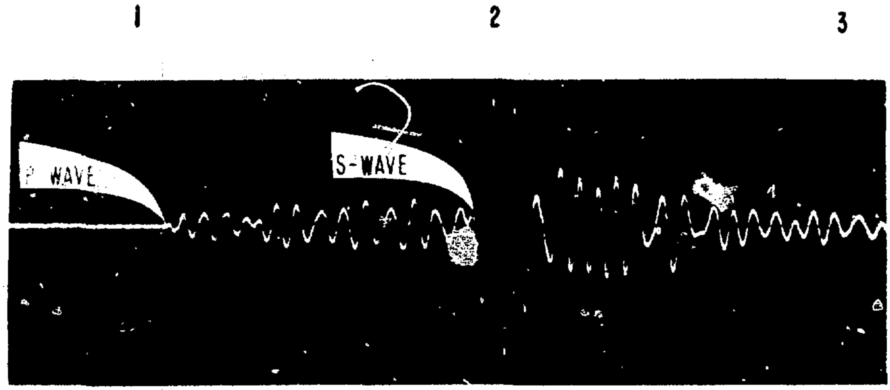


Fig. 2. Block diagram of between-hole seismic equipment.



Arrival time P: 0.4755 m sec 0.2V/div 50μsec/div M9-M6
S: 0.8125 m sec

Arrival time: 0.4755 msec 1V/div 50μsec/div M9-M6

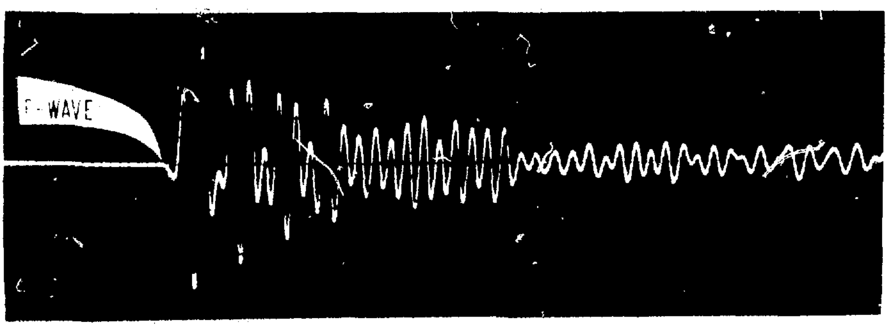


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Fig. 3. Oscilloscope traces of received seismic signals.

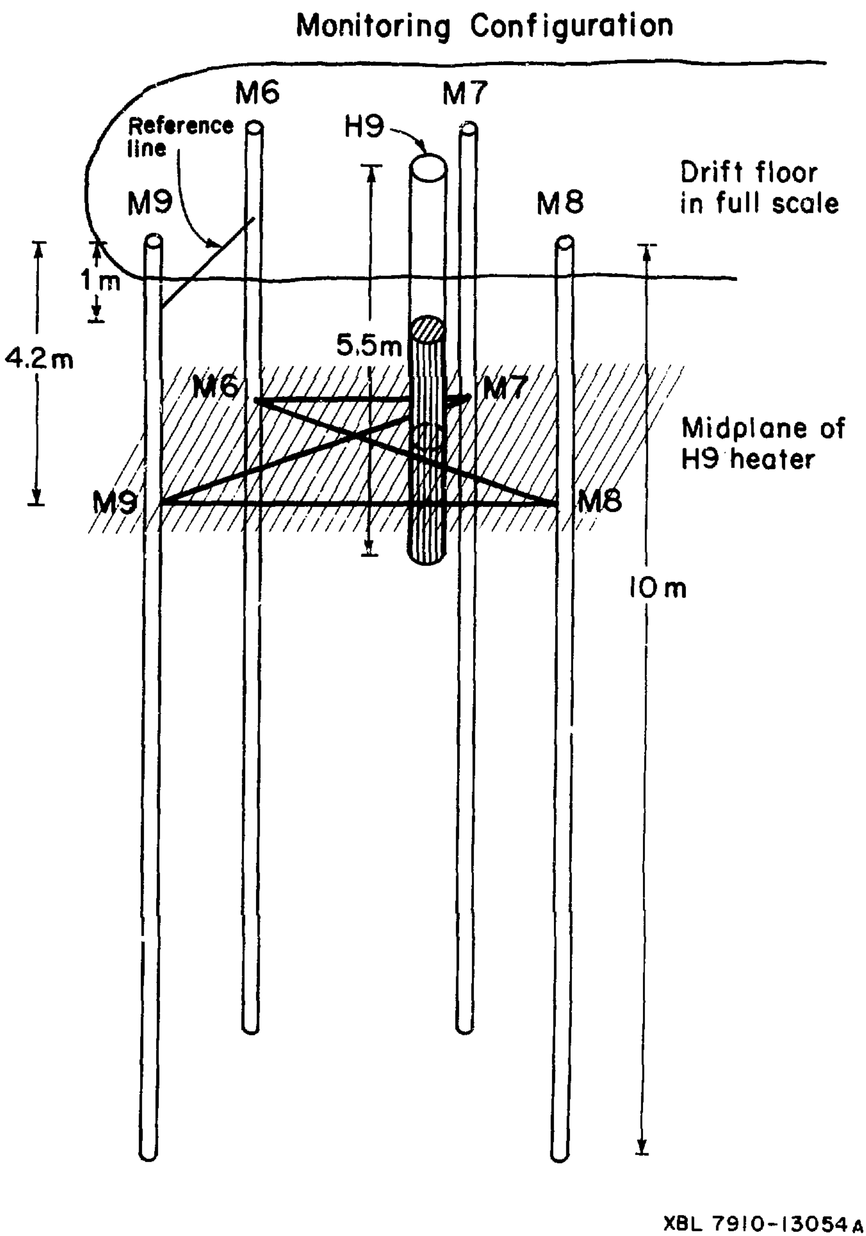

Fig. 4. Between-hole monitoring configuration at heater midplane.

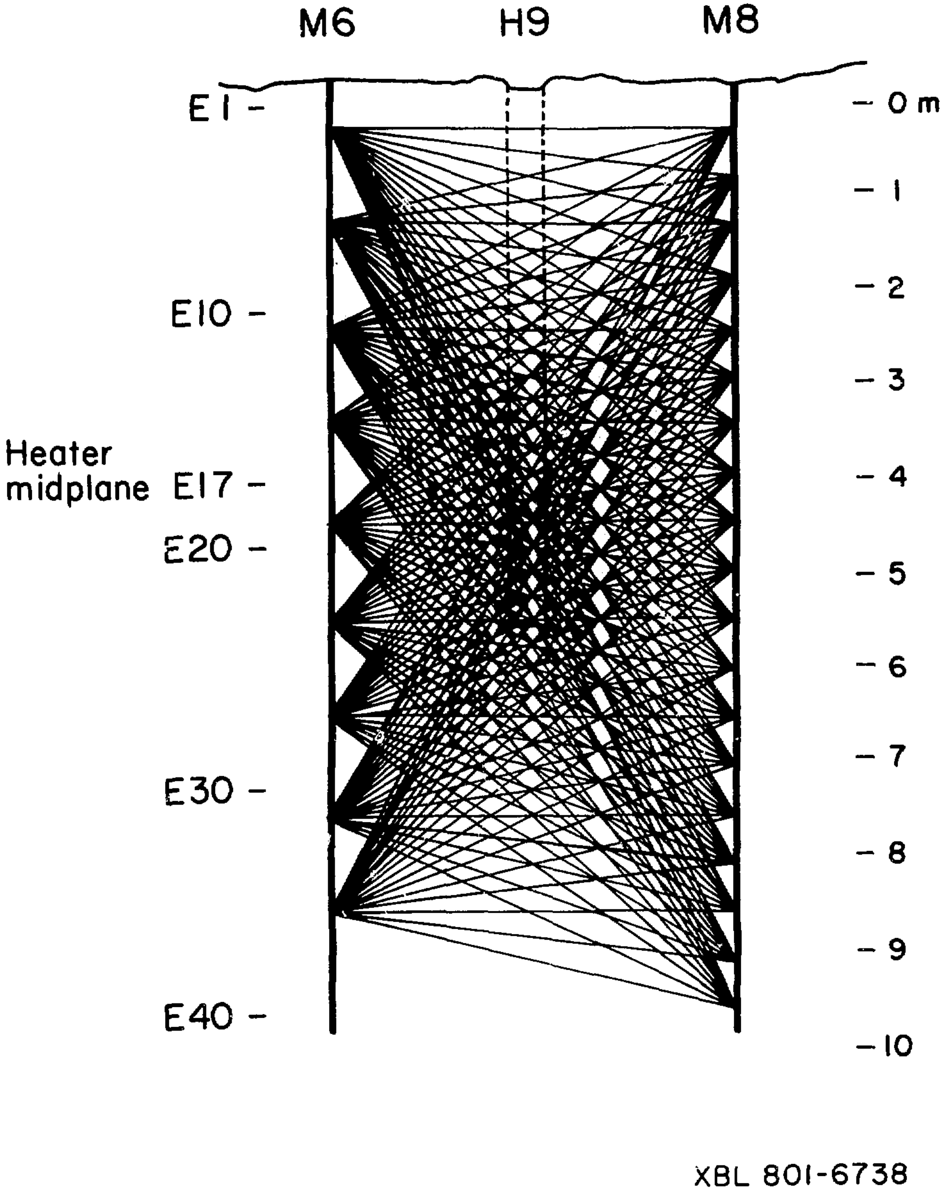

Fig. 5. Ray paths for between-hole tomographic experiment.

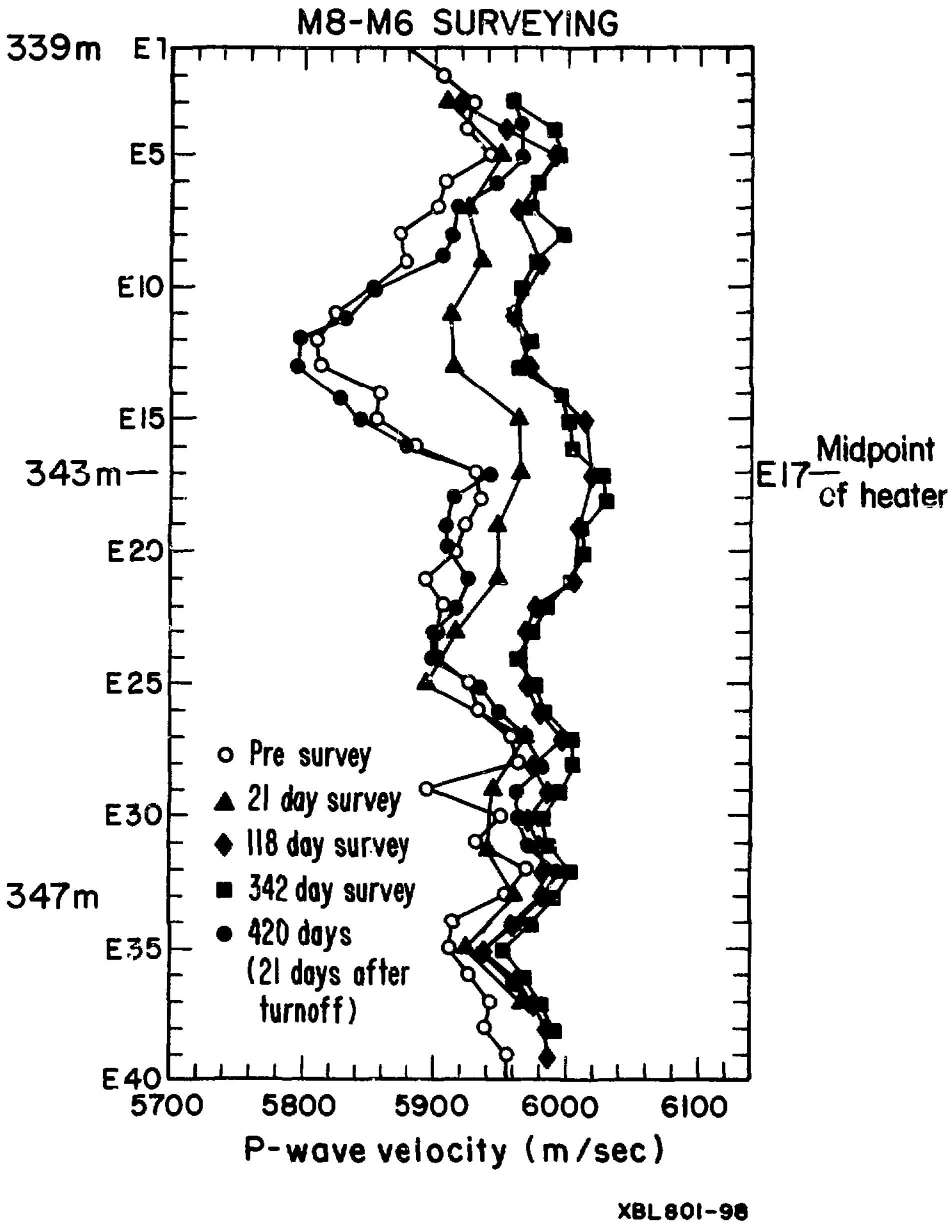

Fig. 6. Compressional wave velocity as a function of time for between-hole survey.

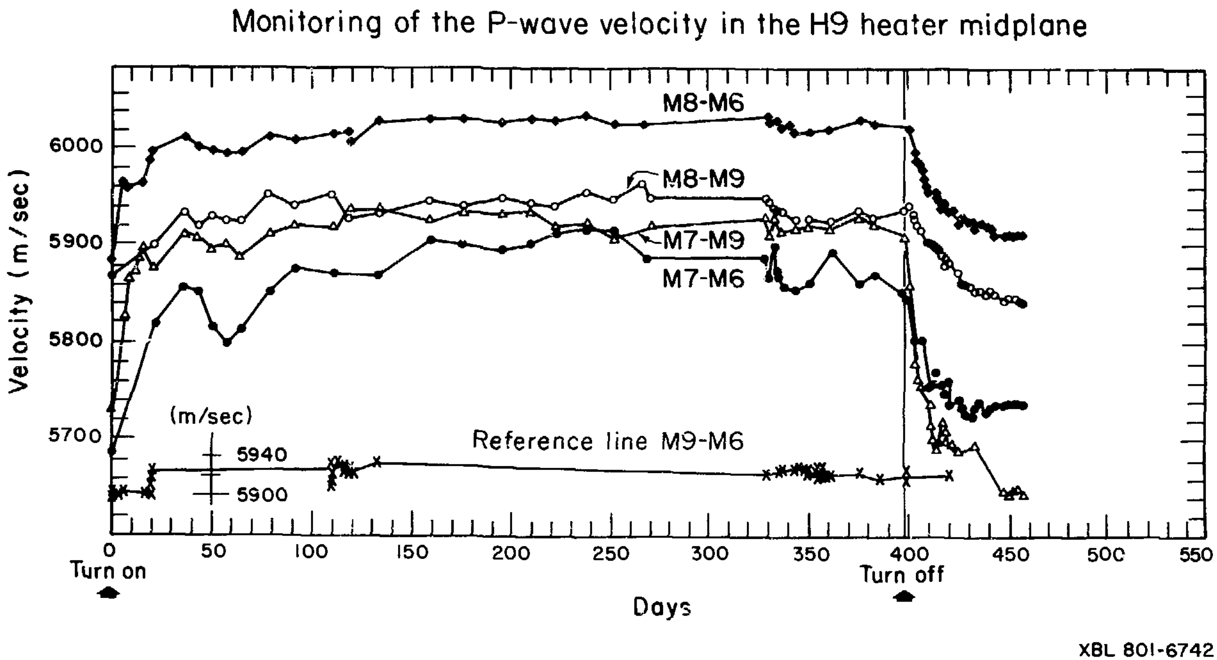

Fig. 7. Compressional wave velocity as a function of time for heater midplane monitoring.

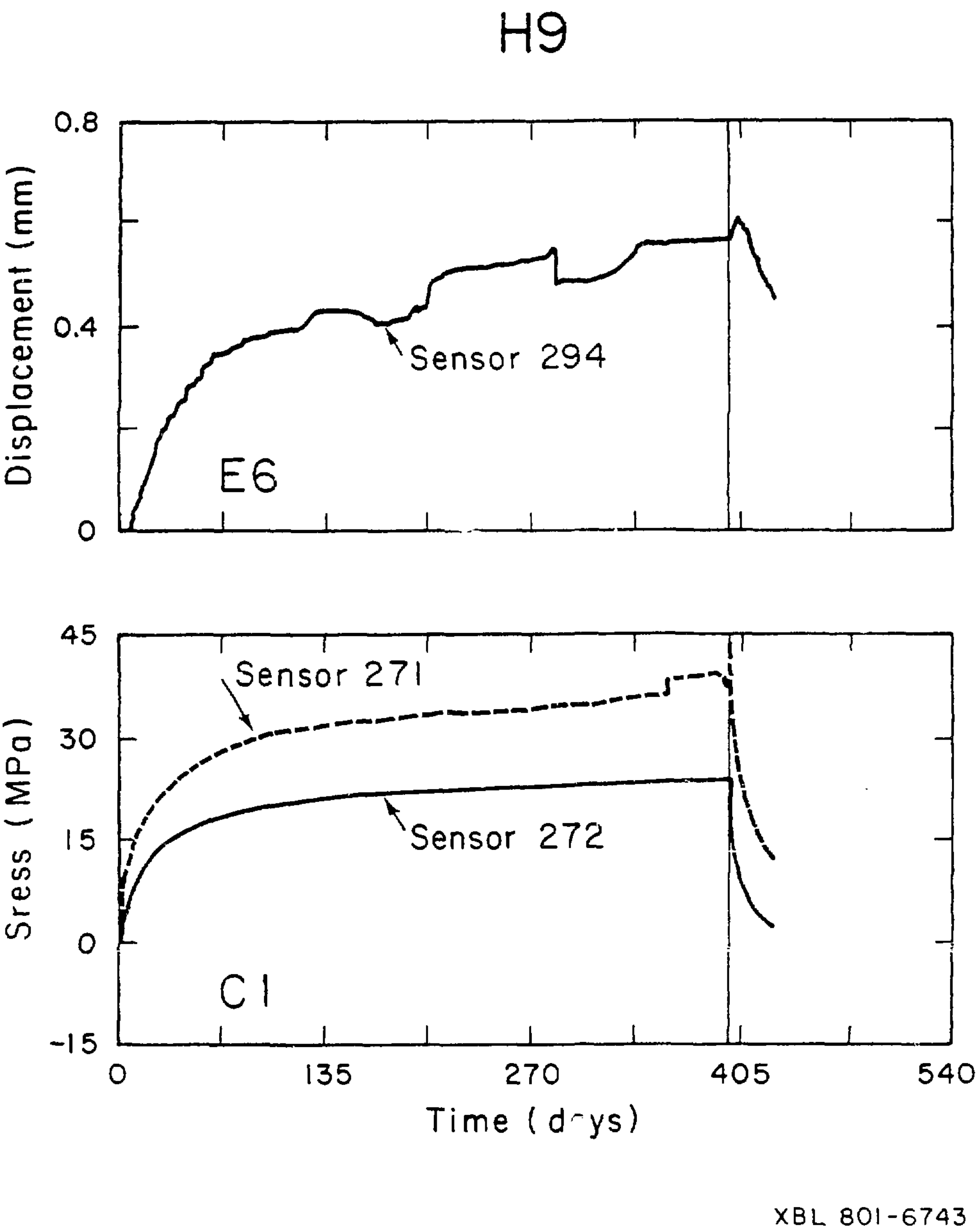

Fig. 8. Measured vertical displacement and horizontal stress in the vicinity of the heater as a function of time.

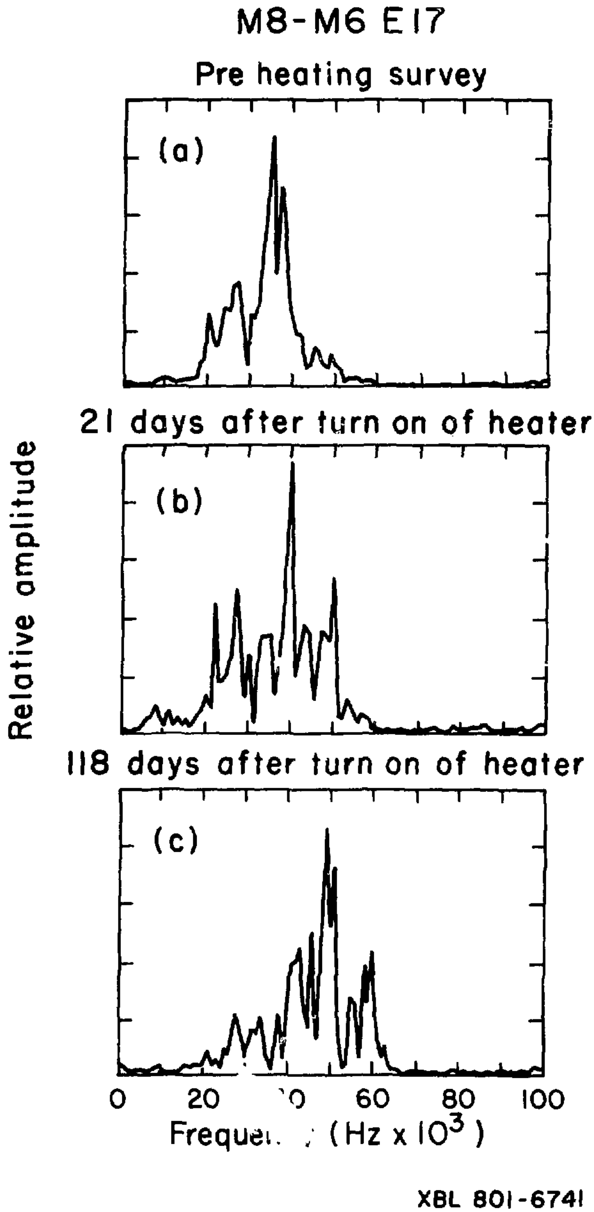

Fig. 9. Amplitude spectra of between-hole survey before and after heater turn-on.

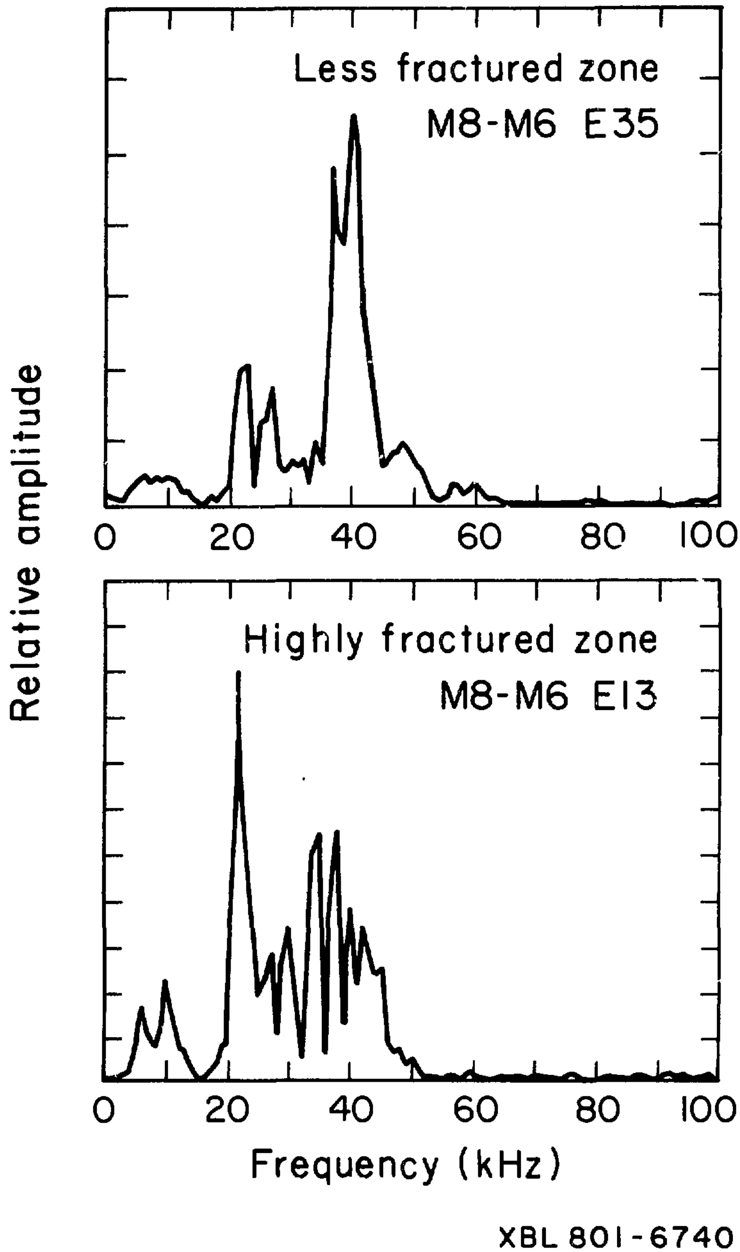

Fig. 10. Amplitude spectra of between-hole survey in highly fractured and less fractured rock mass.