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Title

ULTRASONIC AND ACOUSTIC EMISSION RESULTS FROM THE STRIPA HEATER EXPERIMENTS. PART I: A CROSS-HOLE INVESTIGATION OF A ROCK MASS SUBJECTED TO HEATING. PART II: ACOUSTIC EMISSION MONITORING DURING COOL-DOWN OF THE STRIPA HEATER EXPERIMENT

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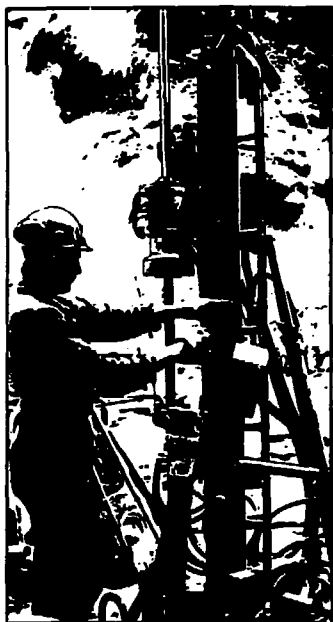
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SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK

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ULTRASONIC AND ACOUSTIC EMISSION RESULTS FROM THE STRIPA HEATER EXPERIMENTS

Part I: A Cross-Hole Investigation of a
Rock Mass Subjected to Heating

B. N. P. Paulsson and M. S. King

Part II: Acoustic Emission Monitoring During
Cool-Down of the Stripa Heater
Experiment

R. Rachiele

December 1980

A Joint Project of

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Fack 10240 Stockholm, Sweden

Operated for the Swedish
Nuclear Power Utility Industry

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720, USA

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Part I: A Cross-Hole Investigation of a Rock Mass Subjected to Heating

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Part II: Acoustic Emission Monitoring During Cool-Down of the Stripa Heater Experiment

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December 1980

Part I of this paper was presented at the Symposium on Subsurface Space, "Rockstore 80," in Stockholm, June 1980.

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PREFACE

This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory.

The principal investigators are L.B. Nilsson and O. Degerman for SKBF, and N.G.W. Cook, P.A. Witherspoon, and J.E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previous technical reports in this series are listed below.

1. Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns by P.A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).
2. Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test by Lars Lundstrom and Haken Stille. (LBL-7052, SAC-02).
3. The Mechanical Properties of the Stripa Granite by Graham Swan (LBL-7074, SAC-03).
4. Stress Measurements in the Stripa Granite by Hans Carlsson (LBL-7078, SAC-04).
5. Borehole Drilling and Related Activities at the Stripa Mine by P.J. Kurfurst, T. Hugo-Persson, and G. Rudolph (LBL-7080, SAC-05).
6. A Pilot Heater Test in the Stripa Granite by Hans Carlsson (LBL-7086, SAC-06).
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8. Mining Methods Used in the Underground Tunnels and Test Rooms at Stripa by B. Andersson and P.A. Halen (LBL-7081, SAC-08).
9. Theoretical Temperature Fields for the Stripa Heater Project by T. Chan, Neville G.W. Cook, and C.F. Tsang (LBL-7082, SAC-09).
10. Mechanical and Thermal Design Considerations for Radioactive Waste Repositories in Hard Rock. Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Waste by N.G.W. Cook; Part II: In Situ Heating Experiments in Hard Rock: Their Objectives and Design by N.G.W. Cook and P.A. Witherspoon (LBL-7073, SAC-10).
11. Full-Scale and Time-Scale Heating Experiments at Stripa: Preliminary Results by N.G.W. Cook and M. Hood (LBL-7072; SAC-11).

12. Geochemistry and Isotope Hydrology of Groundwaters in the Stripa Granite: Results and Preliminary Interpretation by P. Fritz, J.F. Barker, and J.E. Gale (LBL-8285, SAC-12).
13. Electrical Heaters for Thermo-Mechanical Tests at the Stripa Mine by R.H. Burleigh, E.P. Binnall, A.O. DuBois, D.O. Norgren, and A.R. Ortiz (LBL-7063, SAC-13).
14. Data Acquisition, Handling, and Display for the Heater Experiments at Stripa by Maurice B. McEvoy (LBL-7062, SAC-14).
15. An Approach to the Fracture Hydrology at Stripa: Preliminary Results by J.E. Gale and P.A. Witherspoon (LBL-7079, SAC-15).
16. Preliminary Report on Geophysical and Mechanical Borehole Measurements at Stripa by P. Nelson, B. Paulsson, R. Rachiele, L. Andersson, T. Schrauf, W. Hustrulid, O. Duran, and K.A. Magnussen (LBL-8280, SAC-16).
17. Observations of a Potential Size-Effect in Experimental Determination of the Hydraulic Properties of Fractures by P.A. Witherspoon, C.H. Amick, J.E. Gale, and K. Iwai (LBL-8571, SAC-17).
18. Rock Mass Characterization for Storage in Nuclear Waste in Granite by P.A. Witherspoon, P. Nelson, T. Doe, R. Thorpe, B. Paulsson, J.E. Gale, and C. Forster (LBL-8570, SAC-18).
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26. Part I: Some Results from a Field Investigation of Thermo-Mechanical Loading of a Rock Mass When Heater Canisters are Emplaced in the Rock by M. Hood. Part II: The Application of Field Data from Heater Experiments Conducted at Stripa, Sweden for Repository Design by M. Hood, H. Carlsson, and P.H. Nelson (LBL-9392, SAC-26).
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28. A Laboratory Assessment of the Use of Borehole Pressure Transients to Measure the Permeability of Fractured Rock Masses by C.B. Forster and J.E. Gale (LBL-8674, SAC-28).
29. Thermal and Thermomechanical Data for In Situ Heater Experiments at Stripa, Sweden by T. Chan, E. Binnall, P. Nelson, O. Wan, C. Weaver, K. Ang, J. Braley, and M. McEvoy (LBL-11477, SAC-29).
30. The Effect of Radon Transport in Groundwater Upon Gamma Ray Borehole Logs by P.H. Nelson, R. Rachiele, and A. Smith (LBL-11180, SAC-30).
31. Strength and Permeability Tests on Ultra-Large Stripa Granite Core by R. Thorpe, D.J. Watkins, W.E. Ralph, R. Hsu, and S. Flexser (LBL-11203, SAC-31).

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PART I

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

B.N.P. Paulsson

M.S. King

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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 were made prior to turning on the heater, during 398 days of heating, and after the heater was turned off. These measurements 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 before heating. Laboratory compressional and shear-wave velocity measurements were also 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, these measurements implied increases in horizontal normal stresses to between 30 and 40 MPa. Increases in 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.

1. 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, et al. (1970), McCann, et al. (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), by Myung and Baltosser (1972), and by King et al. (1975, 1978). The application of acoustic borehole logs to detect fractures, to classify rocks, and to determine 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 the results of a research project involving cross-hole acoustic measurements in a fractured granite rock mass subjected to thermal stress are described. This acoustic research is part of a comprehensive rock mechanics and geophysics research program associated with large-scale heater

tests in an abandoned iron-ore mine in central Sweden, as described by Witherspoon et al. (1979).

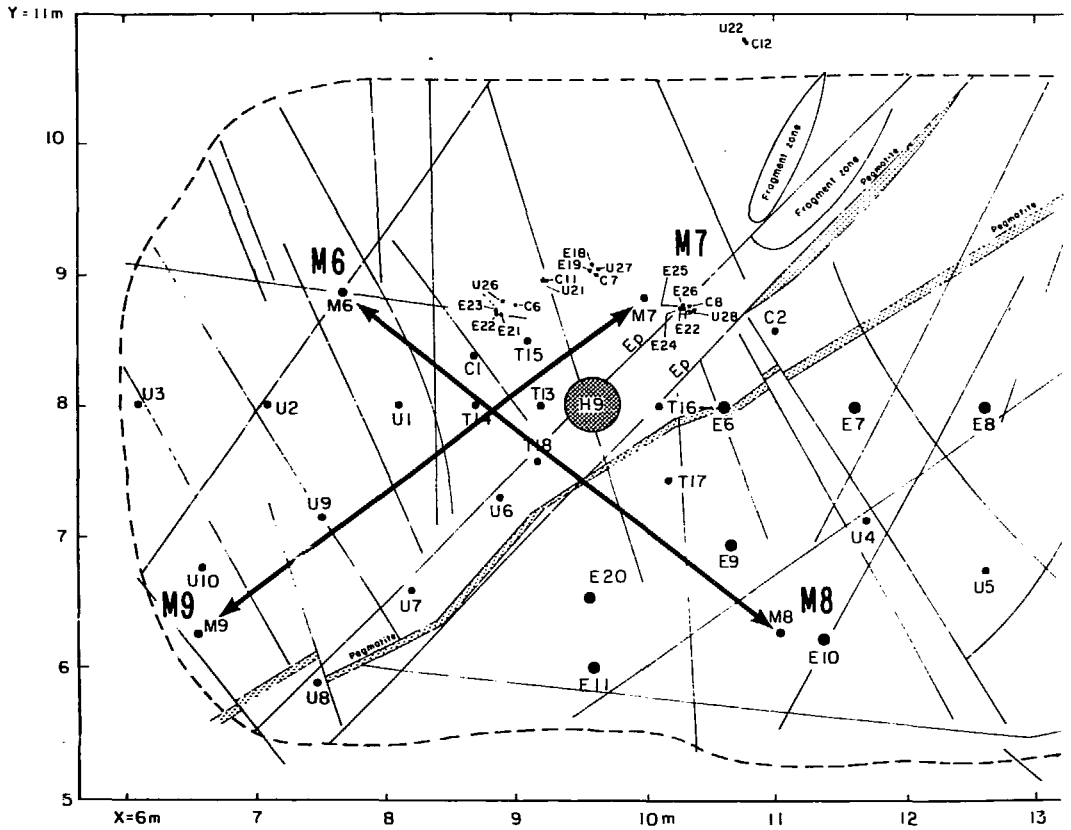
2. EXPERIMENTAL PROCEDURES

The cross-hole acoustic measurements were made between four vertical monitor boreholes of 10 m depth near a vertical heater borehole in the floor of a drift at a subsurface depth of 340 m, as indicated in the plan view of Fig. 1. The four holes are labeled M6, M7, M8, and M9. During testing, small volumes of water continually seeped into the four boreholes, but they were blown out regularly to keep them dry.

Figure 1 also shows a simplified version of the fracture map of the drift floor and the instrumentation boreholes around the heater. The cores from these boreholes provided excellent control of the structural geology and fractures present within the volume of rock monitored, as described by Paulsson et al. (1980). The arrows between monitor boreholes M6 - M8 and M7 - M9 indicate two of the six paths used in rock mass characterization.

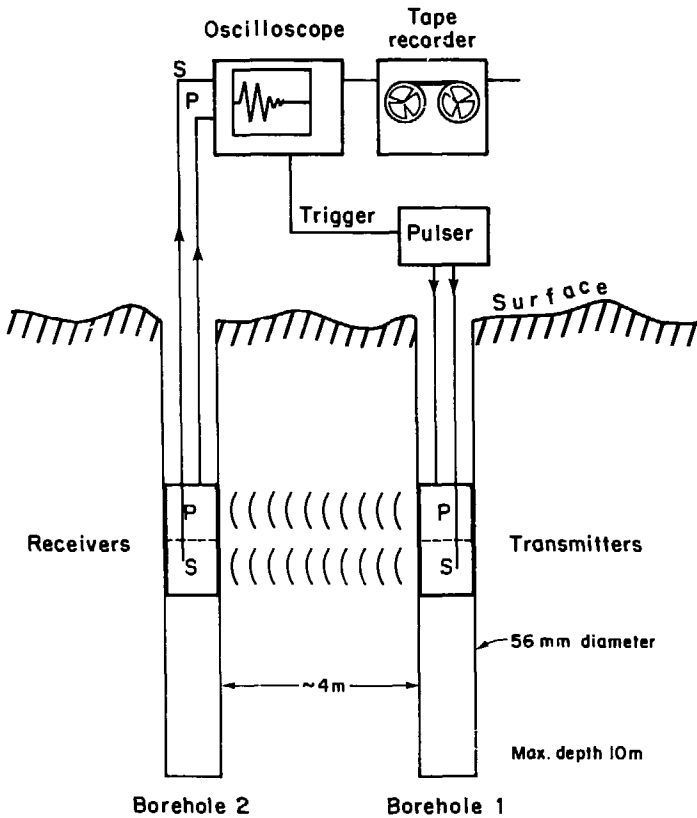
The acoustic measurements involved transmitting and receiving pulses of compressional (P) and shear (S) waves between pairs of boreholes, employing equipment shown in block form in Fig. 2. The equipment and operational procedures have been described by Nelson et al. (1979). The received compressional and shear-wave signals were recorded in analog 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 $\pm 0.2\%$. This precision is an estimate based on repeatability of arrival times in the referenced profile. A more thorough error analysis will be made when all the data from the crosshole experiment is available for analysis.

H9, H10	Heater holes	406 mm
E	Extensometer holes	76 mm
U	US Bureau of Mines gauge holes	38 mm
T	Thermocouple holes	38 mm
C	Colorado School of Mines cell holes	38 mm
M	Monitor holes (ultrasonic)	56 mm



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Fig. 1. Site for seismic test boreholes.

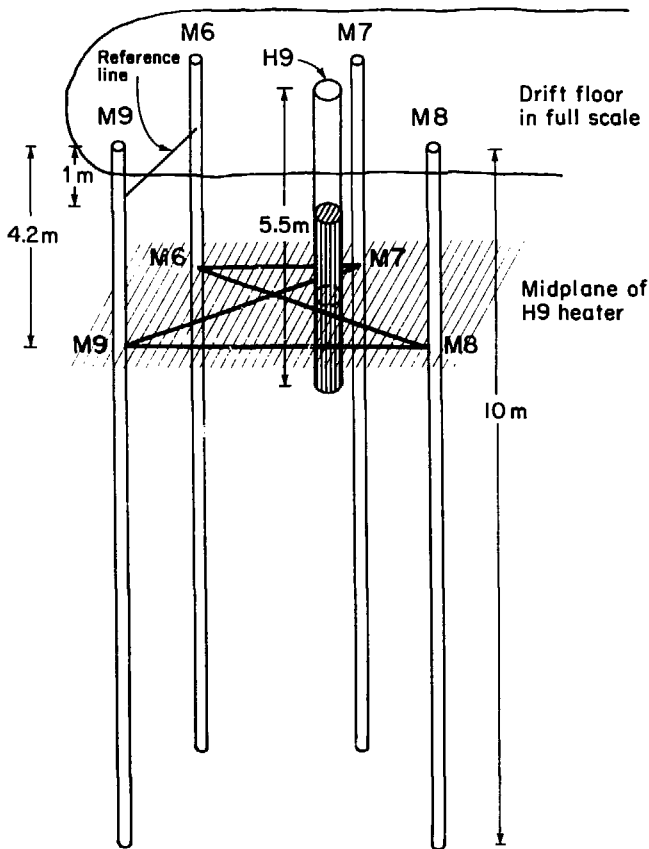


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Fig. 2. Block diagram of acoustic equipment.

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 0.50 m intervals, depending on the profile between measurements of the compressional and shear-wave velocities. An isometric view of the four monitor boreholes and the 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.



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Fig. 3. Monitoring configuration.

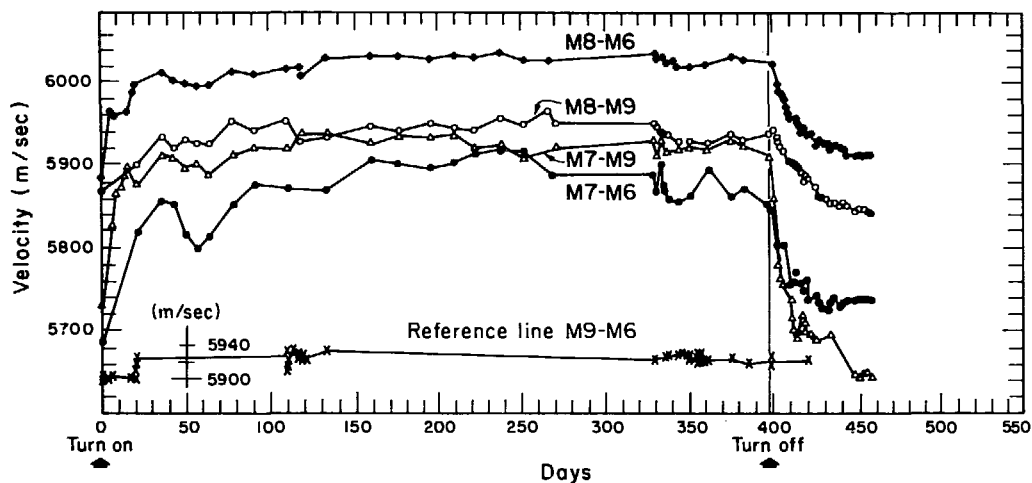
3. RESULTS AND DISCUSSION

3.1 Field Tests

The full-scale heater H9 was turned on 24 August, 1978, and turned off 27 September, 1979, after 398 days of heating the rock mass.

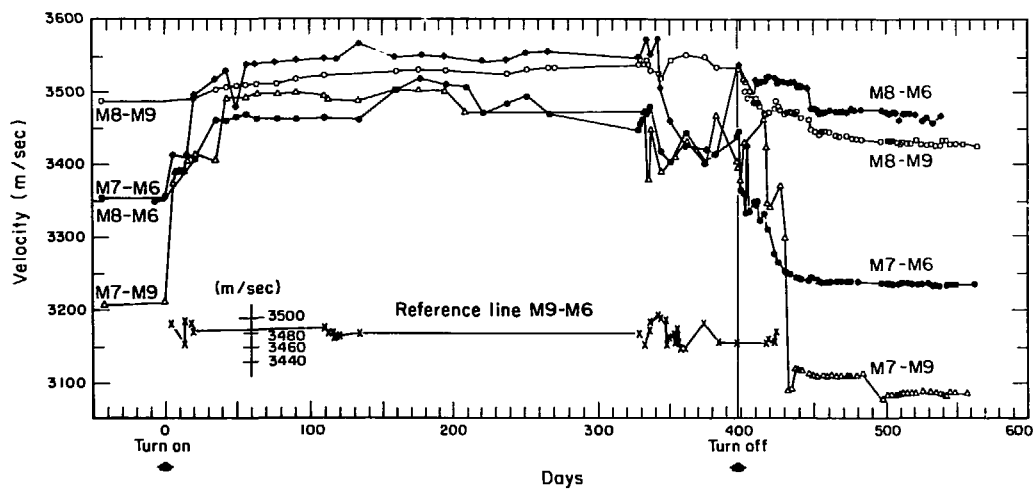
Almost immediately upon turning on the heater, the compressional and shear-wave velocities increased sharply, as shown in Figs. 4 and 5. Then followed a period of less rapid increase to approximately 150 days after turning on the heater, after which the velocities remained fairly constant. It will be observed that between days 40 and 100 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 the 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 (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.



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Fig. 4. Changes in compressional (P) wave velocity in the H9 heater midplane.



XBL 804-6884

Fig. 5. Changes in shear (S) wave velocity in the H9 heater midplane.

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 the 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 principal 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.

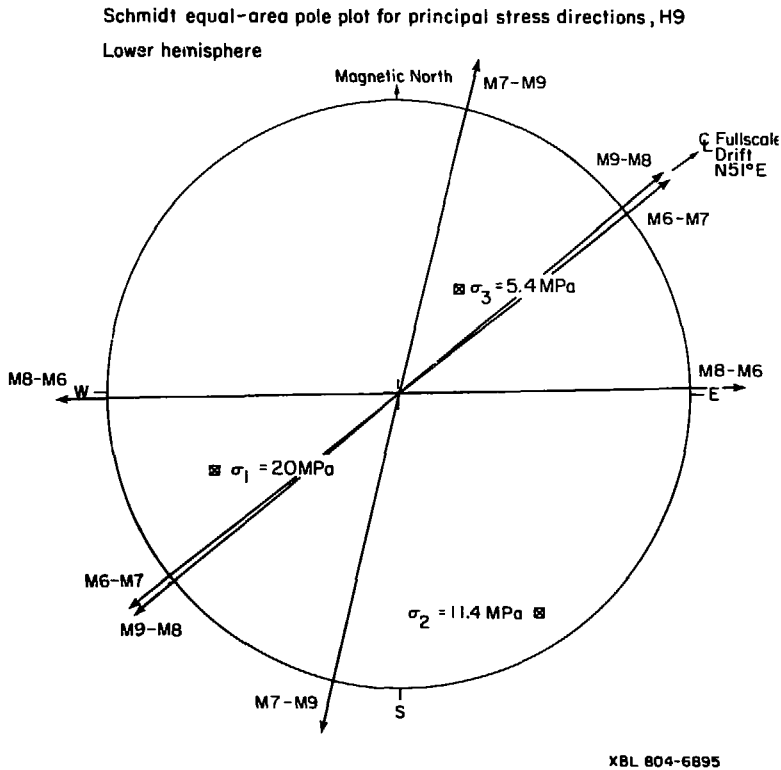
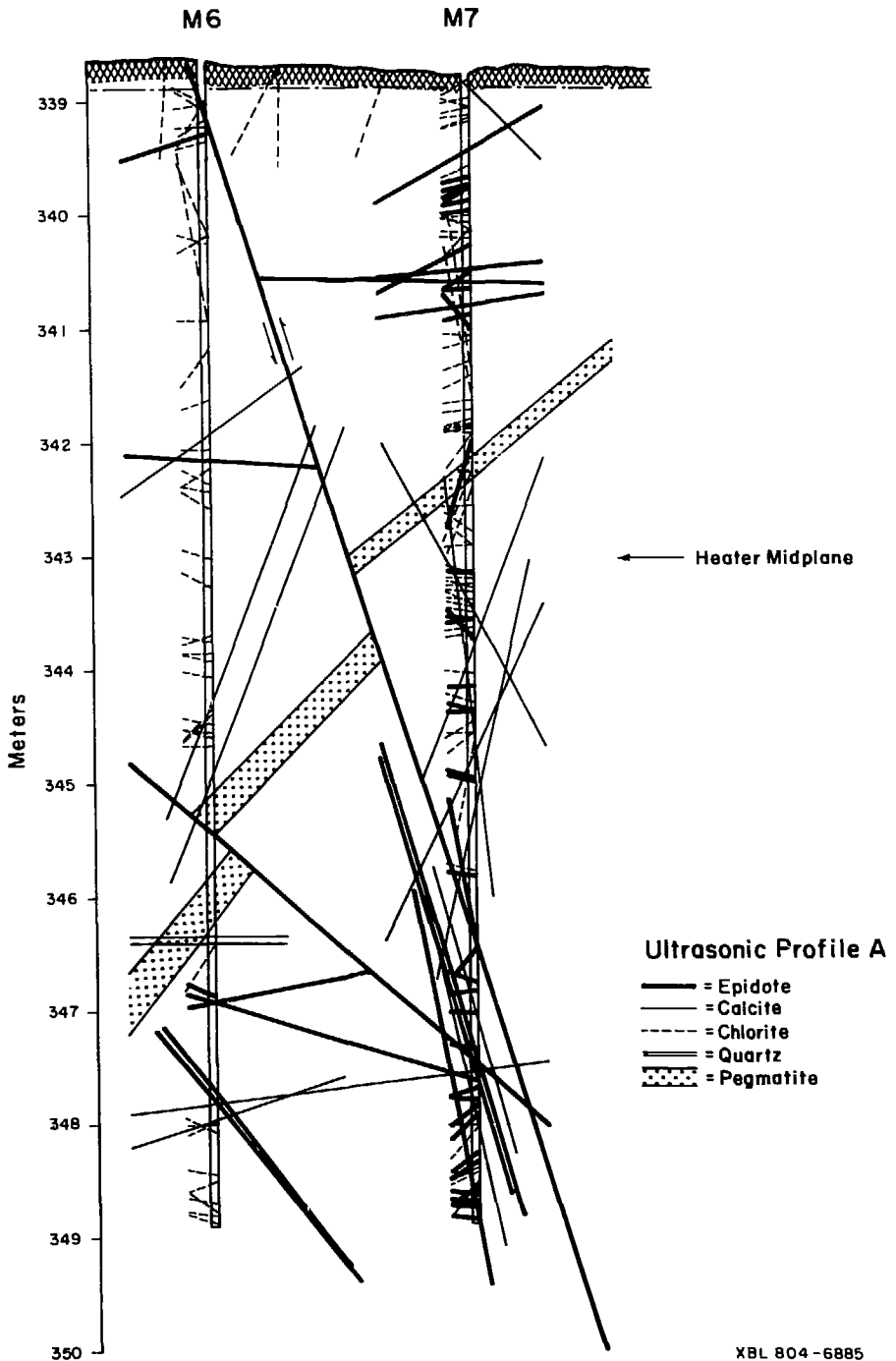


Fig. 6. Principal stresses and monitor line directions for H9 area.

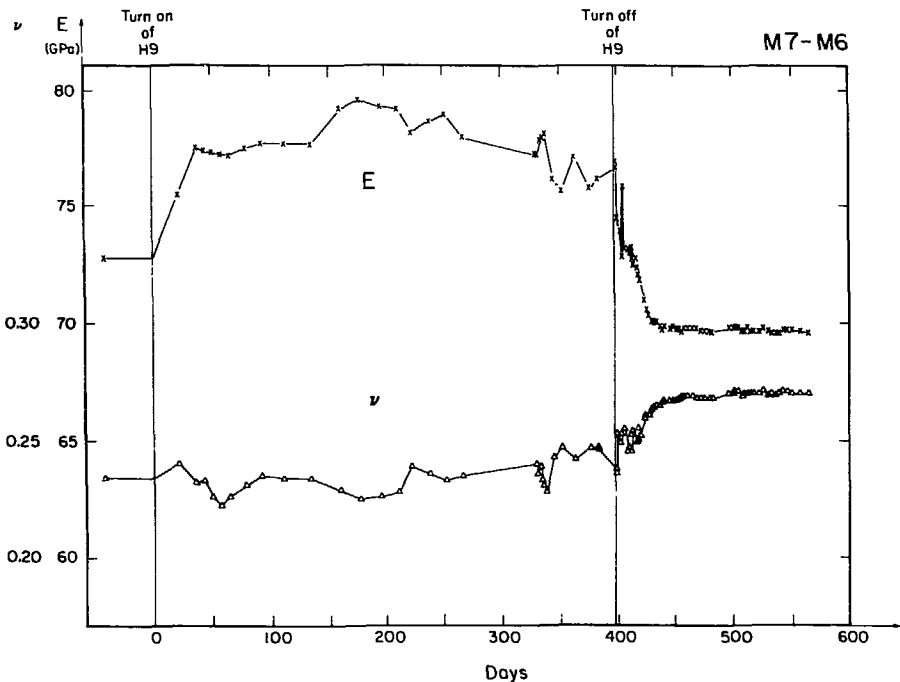


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Fig. 7. Geologic cross sections between M6 - M7.

The four acoustic monitor boreholes were all core-drilled and the orientation of each piece of core was marked. This made it possible to reconstruct the fracture system between the boreholes. An example of the fracture system between boreholes M6 and M7, as 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 et al. (1980).

The compressional and shear-wave velocities from monitoring the heater midplane for paths M6 - M7 have been used to calculate the dynamic values of Young's modulus and Poisson's ratio 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)



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Fig. 8. Young's modulus (E) and Poisson's ratio (ν) as function of time.

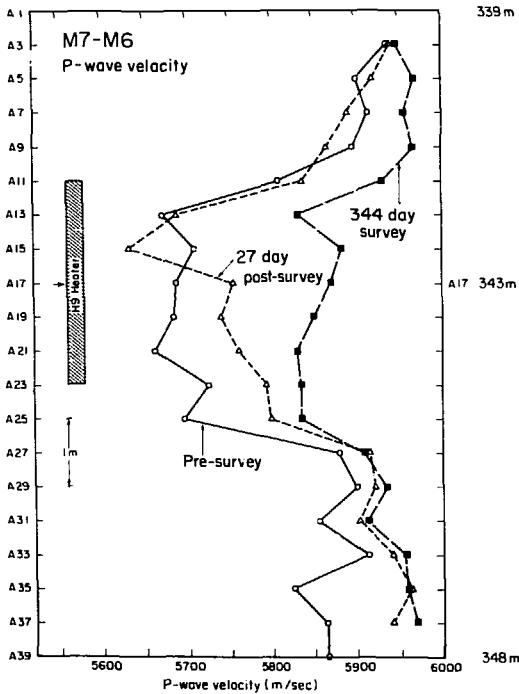
and Poisson's ratio (ν) plotted as a function of time. This plot shows that Young's modulus declined, after heater turn-off, to a value lower than that before the heater was turned on, and that Poisson's ratio increased over the same interval of time. These facts indicate that more open fractures existed on cooling than 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 10 m. This was performed over the path M7 - M6 on three occasions during the heater experiment. The first survey was performed before the heater was 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.

The reconstructed geologic cross-section of Fig. 7 shows an abundance of calcite fractures logged over the 342 - 345 m subsurface interval. This interval corresponds to the low-velocity layer observed in Figs. 9 and 10 for the period before heater turn-on. The velocities measured 344 days after the heater was turned on were, however, more uniformly distributed over the depth of the boreholes. This indicates a more homogeneous rock mass as the fractures were closed by thermal expansion.

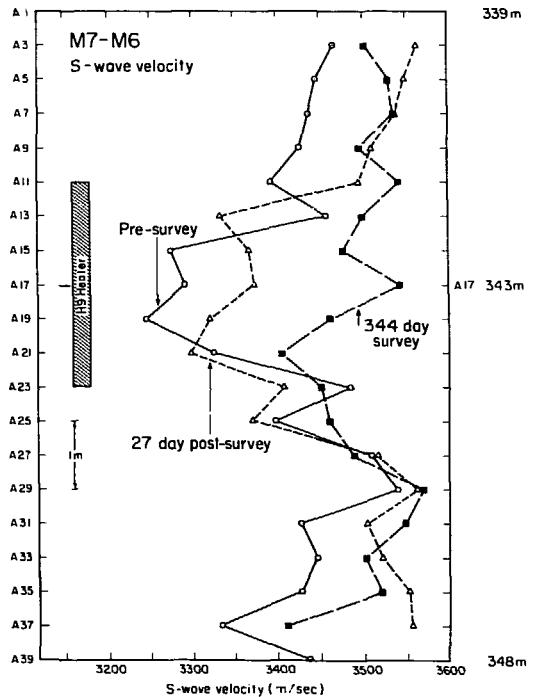
Paulsson et al. (1980) have analyzed the degree to which different fractures were opened by drilling. They observed that whereas 30% of all

fractures were opened by drilling, 90% of calcite-coated fractures were opened by drilling while only 10% of epidote fractures were opened. 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.



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Fig. 9. Compressional (P) wave velocity as a function of depth and time.



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Fig. 10. Shear (S) wave velocity as a function of depth and time.

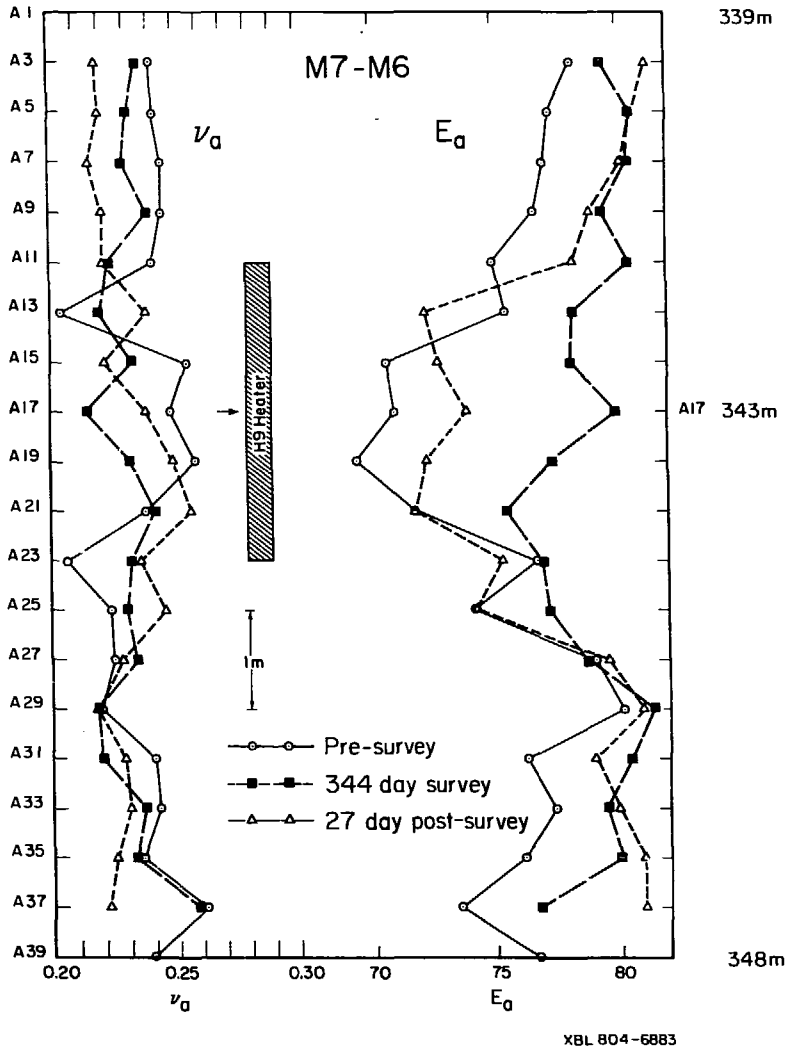


Fig. 11. Young's modulus (E) and Poisson's ratio (ν) as function of depth and time.

3.2 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 45 mm and 51 mm diameter in the manner described by King (1970). The measurements were made at room temperature on 21 samples cored from both the vertical (acoustic monitor) boreholes and the horizontal (extensometer) boreholes near the heater H9 hole.

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 up 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/m³ respectively, which resulted in a mean effective porosity of 0.46%.

The static Young's modulus and Poisson's ratio were measured on 10 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. 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 occurring between ascending and descending axial stresses in the range 0 to 80 MPa. The stress-strain relations were, however, nonlinear, 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 1 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. 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.

3.3 Relationship 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

Table 1. Static elastic model.

Axial Stress MPa	Young's Modulus, 10^9 Pa				Poisson's Ratio			
	Saturated		Dry		Saturated		Dry	
	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

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 in saturated rock are appreciably higher than those in dry rock. 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 of Kuster and Toksoz (1974) for elastic wave propagation in dry and water-saturated media containing pores and cracks.

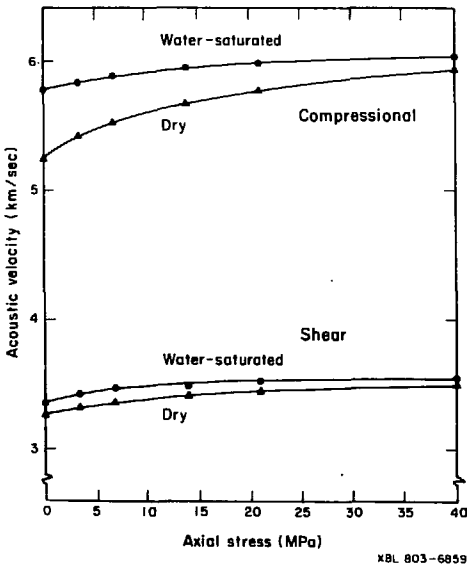


Fig. 12. Acoustic velocities of the Stripa granite, dry and water-saturated.

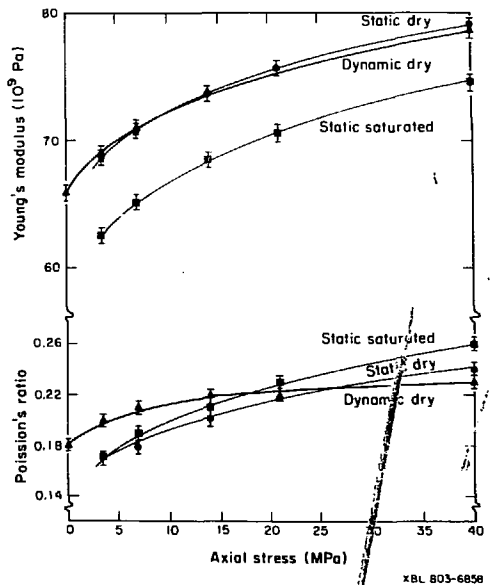


Fig. 13. Static and dynamic moduli of the Stripa granite, dry and water-saturated.

Although the laboratory velocities have been measured under conditions of axial stress only, they are probably close to the values measured under all-round confining stresses in the same range. Wyllie, et al. (1958) reported an observed insensitivity of compressional-wave velocities to whether the rock specimens were subjected to axial or to 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.

Since, as mentioned, crack saturation influences the acoustic velocities, and since these velocities also depend, of course, on the type of rock, the ratio of compressional-wave to shear-wave velocity may therefore be a sensitive indicator of the degree to which the crack porosity is water or steam-saturated. 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.

4.0 CONCLUSIONS

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

ACKNOWLEDGMENTS

This research 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. The program is sponsored by the Swedish Nuclear Fuel Supply Company (SKBF) and the U.S. Department of Energy through the Office of Nuclear Waste Isolation, Battelle Memorial Institute, under Contract No. W-7405-ENG-48. In particular the authors wish to acknowledge the continued support and encouragement provided by Mr. L.B. Nilsson of the Swedish Nuclear Fuel Safety Program (KBS) and Dr. P. Nelson of Lawrence Berkeley Laboratory, University of California. The generosity of Hagby Bruk AB and VIAK during drilling and surveying the test boreholes is gratefully acknowledged, as are the conscientious efforts of Messrs. L. Andersson and G. Ramqvist in assisting with data collection. We are indebted also to TerraTek, Inc. of Salt Lake City, which designed the cross-hole acoustic equipment and took an active part in designing the experiment, and Margot Harding, who drafted the text figures. M.S. King wishes to acknowledge the California Institute for Mining and Mineral Resources for partial support of this research and the University of Saskatchewan, Saskatoon, Canada, for providing facilities for conducting the laboratory research reported.

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PART II

ACOUSTIC EMISSION MONITORING DURING
COOL-DOWN OF THE STRIPA HEATER EXPERIMENT

R. Rachiele

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ABSTRACT

A simple acoustic emission system monitored acoustic emission activity during the cooling of the rock in the two full-scale heater experiments at Stripa, Sweden. In each case an increase in acoustic emission activity was noted with heater turn-off. Peak acoustic activity was 5 to 7 days after the beginning of cool-down, whereas stress and displacement measurements exhibited a maximum rate of change immediately after turn-off. Possible causes of this lag in peak activity are explored. At a time well after turn-off, there was a renewed period of acoustic emission activity.

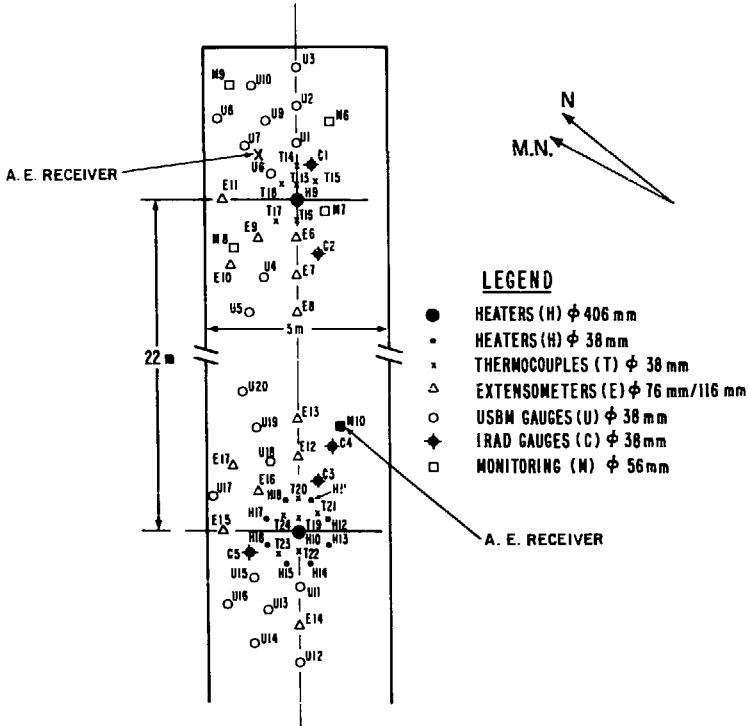
Despite the simplicity of the system, results indicate that acoustic emissions do occur with cooling of the rock, and even greater acoustic emission activity would have been expected with heating of the rock. More sophisticated systems, such as the one presently installed at the Nevada Test Site waste storage experiment, should greatly increase our knowledge of rock movements and the fracturing process associated with the large-scale heating of a rock mass.

1. INTRODUCTION

The mechanical behavior of rock under thermal stress induced by heating is of great interest to researchers associated with the nuclear waste storage program. To study the thermo-mechanical response of hard rock, large-scale heater tests were performed in a granitic rock mass, 340 m below the surface in an abandoned iron mine at Stripa, Sweden (Witherspoon and Degerman, 1978). In these tests, temperature fields, stresses and rock displacements from the heating and subsequent cooling of the rock were monitored. In addition to the conventional rock monitoring techniques, a simple acoustic emission system was employed to record the rock noise expected with the changing stress conditions brought about by the turn-off of the heaters and the consequent cooling of the rock.

Acoustic emission methods have been employed in the past to study cracks and crack formation in laboratory samples under applied stress. In the field, acoustic emission techniques have been used to attempt prediction of rock bursts in deep hard rock mines and roof collapse in coal mines. Thus, acoustic emission monitoring appears to be a promising technique for monitoring a waste repository for stability and for the formation of fractures that would increase the flow of water past waste canisters. A history of the acoustic emission method and examples of its use are discussed in Hardy and Leighton (1977).

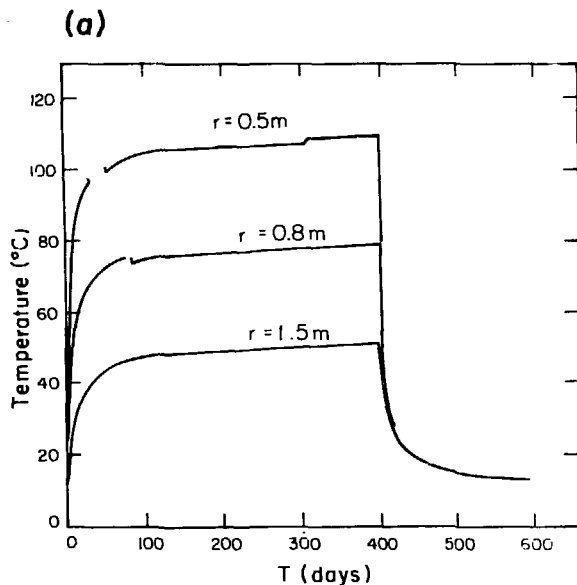
A plan view of the area of the two heater experiments where acoustic emissions were monitored is provided by Fig. 1. The locations of the two AE receivers as well as the locations of some other instruments are shown. The H9 heater (Fig. 1) operated at a power level of 3.6 kW for 398 days before



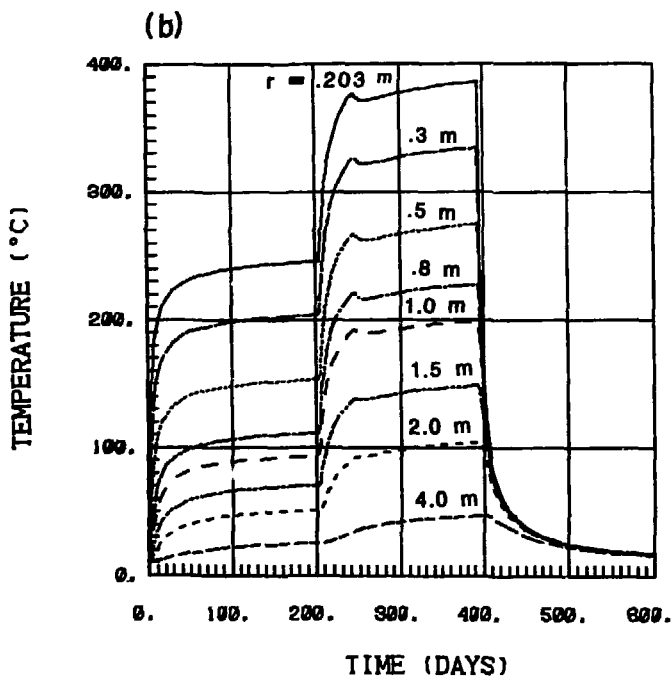
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Fig. 1. Location of acoustic emission receivers, in the full-scale drift.

heater turn-off. For the H10 experiments, the main H10 heater power level was 5 kW for 204 days. Eight surrounding 1.1 kW heaters were then turned on, and all H10 area heaters operated 190 more days before turn-off. Figure 2 shows H9 and H10 area rock temperature versus time for several distances outwards from the main heaters. The acoustic emission monitoring was not part of the original program at Stripa. The system was constructed from existing equipment from other experiments. For this reason, acoustic emission measurements commenced only a short time prior to turn-off, and continued as the rock cooled for both the H9 and H10 experiments.



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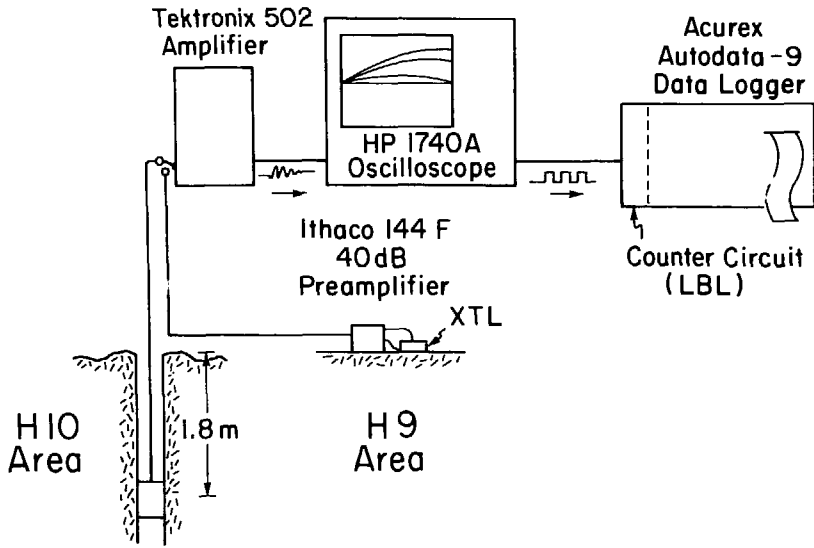
Fig. 2. Temperature vs. time for several radial distances out from the main heaters: (a) H9 measured temperatures (Chan et al., 1980b). (b) H10 predicted temperatures (Chan et al., 1980a), which are close in value to the measured temperatures.

2. INSTRUMENTATION

The acoustic emission instrumentation was composed mainly of spare equipment from the ultrasonic velocity monitoring experiment associated with the H9 heater test (Paulsson and King, 1980). A block diagram of the equipment is shown in Fig. 3. Waveforms from either the H9 or H10 receivers were amplified and band-pass filtered by a Tektronix 502 amplifier. The waveform was then delivered to a Hewlett-Packard 1740A oscilloscope. The oscilloscope was triggered when the preset threshold level was exceeded by a cycle of the waveform (Fig. 4). A pulse was then sent to a counter board, designed and built by LBL, located in the back of an Acurex Autodata-9 data logger, with a pulse being transmitted to the data logger for each cycle that exceeded the threshold voltage. At one-minute intervals, the counter would be reset. If the number of pulses reaching the data logger was five or greater, the time and the number of cycles above threshold were printed on the data-logger tape.

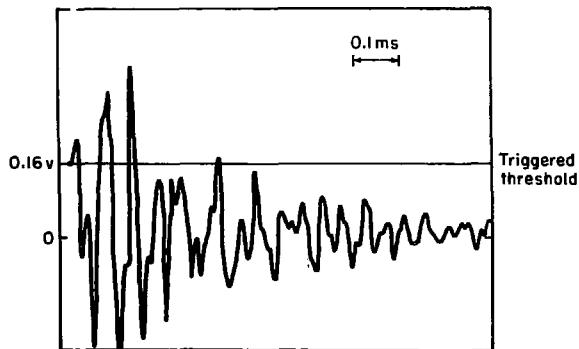
This system differs from the usual method of counting acoustic emission events. Other systems typically count each waveform as one event, even though more than one cycle of the waveform may be above the threshold. With the counting method used at Stripa, there was no way of knowing if the cycles counted during the one-minute sampling period represented one high-amplitude event or several discrete low-amplitude events.

There were slight differences in the H9 and H10 receiver configurations. The H10 receiver consisted of a disk-shaped PZT piezoelectric crystal, 1-1/2 in. diameter x 3/8 in. thick with a resonant frequency of 220 kHz, contained in an aluminum housing that was then jacked against the borehole



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Fig. 3. Block diagram of the acoustic emission monitoring system.



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Fig. 4. Example of an acoustic emission waveform from the H9 area seen on an oscilloscope. The oscilloscope would normally be set to trigger and send a pulse to the datalogger for each cycle of the waveform exceeding the trigger threshold.

wall. A similar piezoelectric crystal was directly clamped to the rock surface in the H9 area to serve as an acoustic emission receiver, with a small amount of silicon oil being added to the rock surface to enhance the acoustic coupling.

For H10, line matching transformers were included in the circuit near the crystal and at the amplifier input terminal. The signal from the H9 receiver was immediately amplified 40 dB by a Ithaco 144F amplifier before reaching the Tektronix amplifier. For both receivers, the total amplification was 60 dB, with single pole band-pass filtering 10 kHz - 300 kHz, and a trigger level of 0.16 volts.

The H9 receiver was considerably more sensitive to acoustic emissions than the H10 transducer due to better coupling to the rock, the doubling of amplitude by the free surface, and the lesser attenuation of surface waves in comparison to body waves. Photographs of acoustic emission waveforms showed the predominant frequency of the H10 receiver to be 60 - 65 kHz. The enhanced coupling of the H9 receiver broadened the predominant frequencies observed for acoustic emission events to 12 - 65 kHz. The H10 receiver was somewhat prone to high-frequency electrical noise, while the H9 receiver, being located at the surface, was susceptible to the noise of the ventilation fan, and thus required that the low-frequency filter be set at 10 kHz.

Sensitivity of the system was checked by measuring the response of a steel ball dropped from a set height onto a polished rock surface in the case of H9, and onto the flattened end of an anchored rock bolt in the case of H10. Tables 1 and 2 are compilations of the calibration data for H9 and H10. The measurements suggest no discernible loss in response for the H9 and

H10 data periods until day 475 for the H9 receiver. However, measuring the amplitudes of the waves from the calibration drops is complicated by the changing shape of the waveform with the cooling of the rock.

Table 1. H10 calibration data obtained by dropping a steel ball onto rock bolt 1.5 m from receiver.

Experiment Day	Amplitude of three largest peaks		
313	2.9	2.7	2.6
	2.1	1.7	1.8
	2.9	2.2	2.0
	3.1	3.2	3.0
368	2.3	2.1	2.0
	2.9	2.5	2.3
443	2.3	2.0	1.7
	2.6	2.3	2.2
	2.4	2.3	2.2
	3.1	2.4	2.2
	2.3	2.2	2.0

Table 2. H9 calibration data, with calibration drop points 0.75 m and 3.05 m from the receiver.

Experiment Day	Amplitude of 3 selected peaks, 3.05 m from receiver			Amplitude of 3 selected peaks, 0.75 m from receiver		
405	2.0	2.3	1.1	2.2	2.7	1.7
	2.2	2.6	1.2	2.1	2.5	1.6
	2.3	2.6	1.2	2.0	2.4	1.5
	2.1	2.7	1.2	2.2	2.7	1.7
421	2.2	2.7	1.1	2.2	2.6	2.4
	2.7	2.9	1.1		2.4	2.3
	2.2	3.0	1.2		2.4	2.3
	2.3	2.7	1.0	2.2	2.7	2.4
435	2.5	3.1	1.0	2.4	2.8	2.8
	2.5	3.1	1.0	2.0	2.3	2.3
				2.1	2.4	2.3
				2.1	2.7	2.4
468				1.9	2.5	2.1
				2.0	2.4	2.2
475	1.9	2.4	.9			
	1.9	2.5	.9			

3. DATA COLLECTION

The recording period for each day was from 1600 hours in the evening to 600 hours the next morning, the period when the mine was unoccupied. Only one acoustic emission channel at a time could be monitored; when data from H9 were being collected, data from H10 were lost. A few recording periods were lost when the data logger tape ran out or when work in the mine continued into the night. Late in the experiment, the H10 receiver became excessively noisy for unknown reasons, so these data were discarded.

As noted earlier, the time and the number of cycles above threshold were printed out on paper tape. This information was reduced by hand for analysis.

4. RESULTS

Figures 5 and 6 are histogram plots of the information printed out by the data logger. On the graphs are plotted the number of one-minute intervals per recording day in which a minimum number of cycles were counted. The shape of the histograms for both H9 and H10 are quite similar. Both exhibit a sudden rise of activity immediately following turn-off of the heaters, but with peak activity not occurring before the passing of several more days. Acoustic emissions then diminished over the next 60 days. This contrasts with the displacement and stress measurements (Figs. 5 and 6) which show a maximum rate of change near turn-off.

Comparing the acoustic emission data with the stress and displacement data has not been rewarding. The almost daily jumps in the displacement curves (Figs. 5 and 6) complicate the correlation of acoustic emission events with rock movements. These jumps are the result of tapping the extensometer heads on working days to release the frictional energy stored in the extensometer rods. Minor offsets were also seen in the curves from many of the stress gauges at Stripa, and are attributable to voltage shifts in the data acquisition system. In addition, a significant proportion of the stress gauges failed, making reliable interpretations of changes in the stress curves difficult.

Figure 7, a graph of the H9 acoustic activity for each minute of 12 recording periods, dramatizes the increase in activity following heater turn-off and shows the distribution of events over time.

An ultrasonic velocity monitoring experiment was performed in association with the H9 heater experiment (Paulsson and King, 1980). The change in

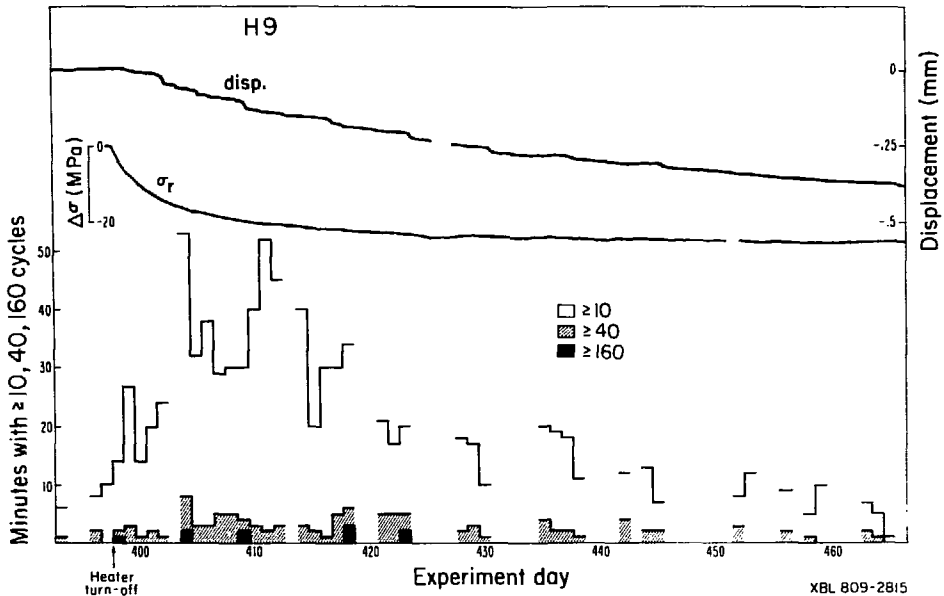


Fig. 5. Acoustic emission activity plotted as the number of minutes per overnight recording period in which a minimum number of cycles were counted during the one-minute sampling interval. Also shown are curves for radial stress and displacement for two holes in the H9 area. H9 heater turn-on is day 0.

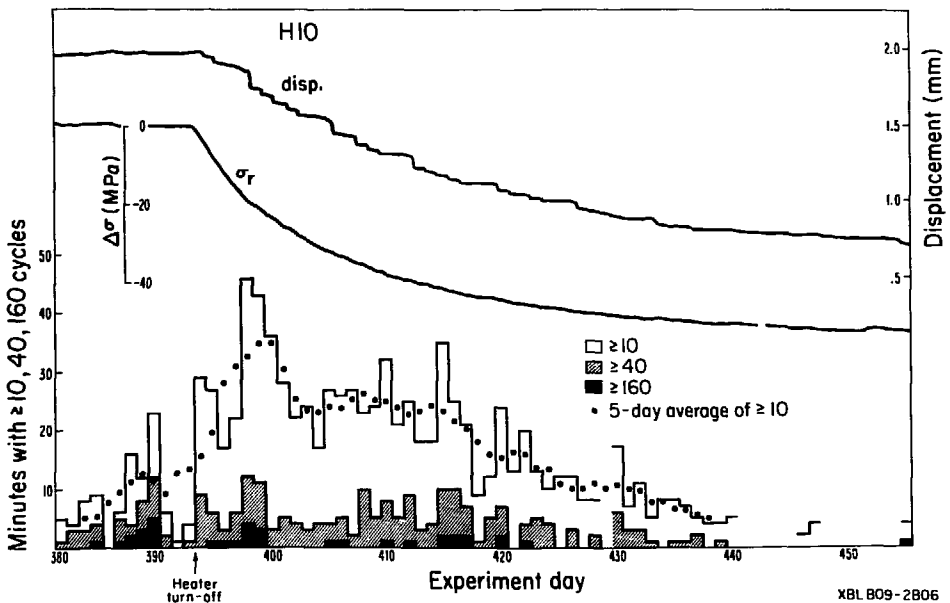
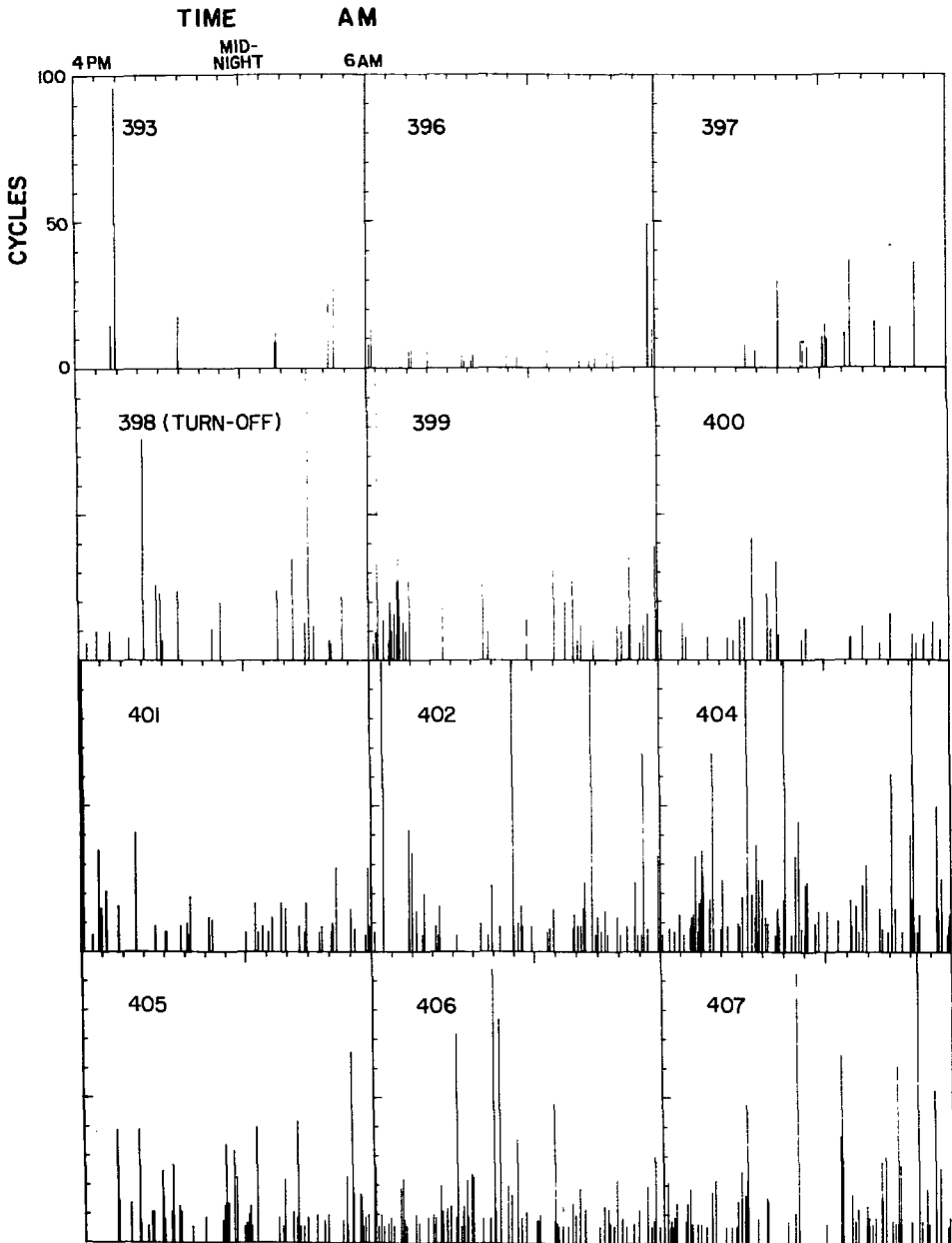


Fig. 6. Acoustic emission activity plotted as the number of minutes per overnight recording period in which a minimum number of cycles were counted. Also shown are the curves for radial stress and displacement for two holes in the H10 area. H10 heater turn on is day 0.



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Fig. 7. H9 acoustic emission activity for the first 12 recording periods, showing the time and the number of cycles recorded for each one-minute period exceeding 4 or more cycles.

compressional velocity with the cooling of the rock is given with the acoustic emission data for the same period in Fig. 8. The shape of the velocity versus time curve is similar to that of the displacement and stress curves. Probably the most interesting section of the graph is around day 480, where there is a renewed burst of acoustic emission activity. No definite changes in the velocities seem to be associated with this new period of activity, nor are there any notable anomalies in the stress and displacement curves for this time.

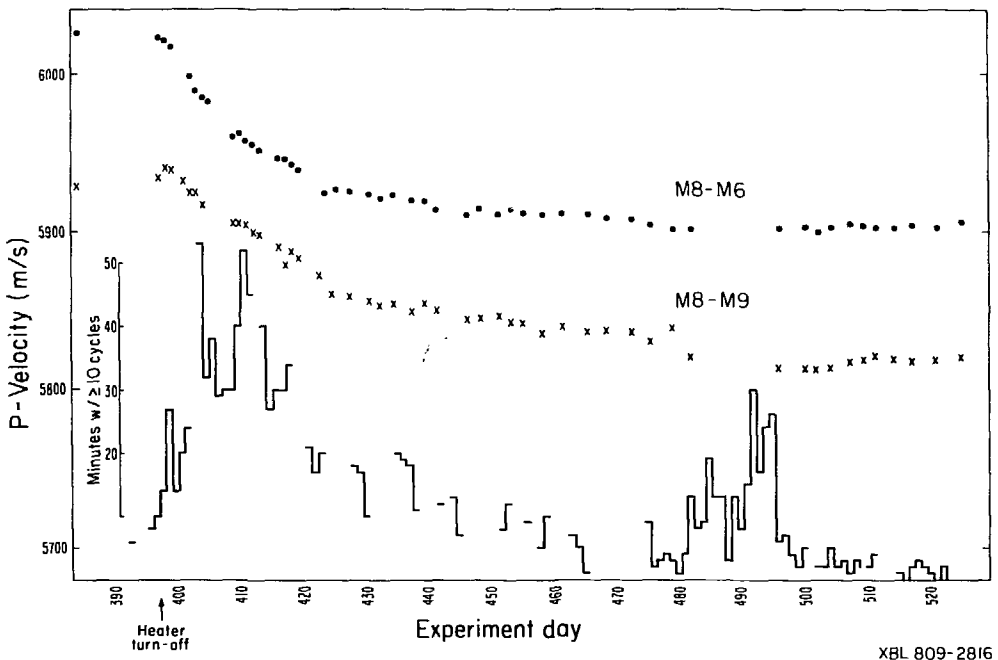


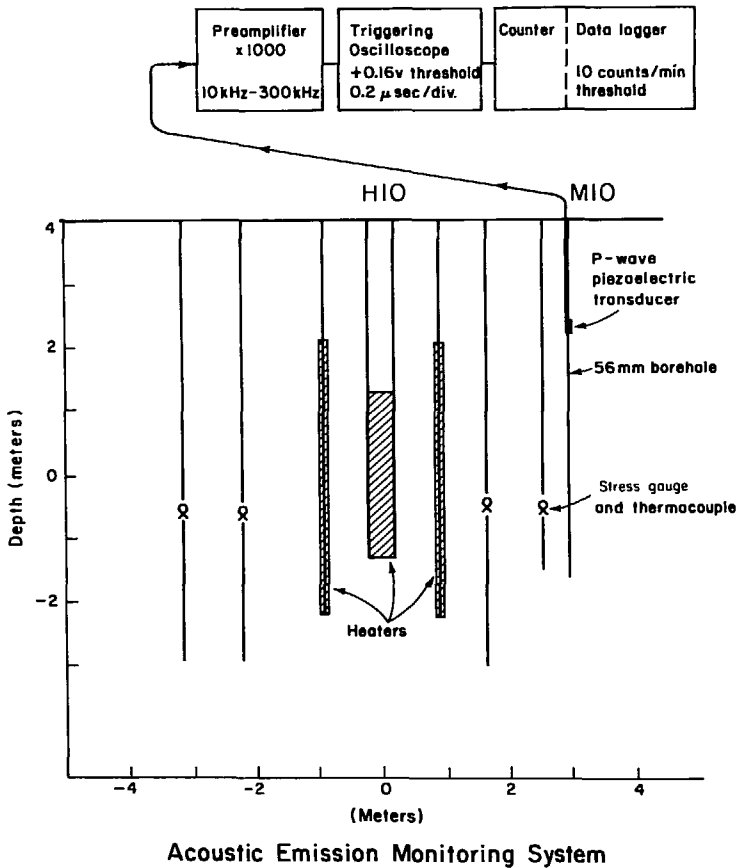
Fig. 8. Acoustic emission activity plotted with compressional wave velocity (from Paulsson and King, 1980) for the H9 area. Note that the time period is extended past the period shown in Fig. 5.

5. DISCUSSION

As noted earlier, the stress and displacement gauges show a maximum rate of change at turn-off, while the acoustic emission activity peaks several days later. However, the stress and displacement gauges are primarily sensitive to the elastic response of the rock, whereas acoustic emissions are usually associated with inelastic material behavior such as crack formation (Scholz, 1968) or frictional sliding (Alheid and Rummel, 1977). Rock movements and stress changes associated with acoustic emission events are likely to be less than the sensitivity of the displacement and stress gauges. Nevertheless, after final calibration and analysis of the stress and displacement gauges, these gauges should provide a measure of the hysteresis experienced by the rock during its heating and cooling.

To explain the lag of peak acoustic emission activity following heater turn-off, a model was constructed relating the temperature decay rate around the H10 heater to the acoustic emission activity. In the model, each point in space around H10 is seen as a source of acoustic emissions. The activity detected by the receiver from any point is assumed to be proportional to the temperature decay at that point modified by the distance from the point to the receiver in order to include the effects of spherical spreading and attenuation of the seismic energy. This elemental acoustic emission activity is integrated over the volume for the time period following turn-off.

It should be noted that the model to be developed is for an infinite medium with only the main heater included. This model is thus only an approximation to the real physical situation pictured in Fig. 9.



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Fig. 9 Cross-sectional view of the H10 area showing the location of the acoustic emission receiver in hole M10, and the location of the main peripheral heaters.

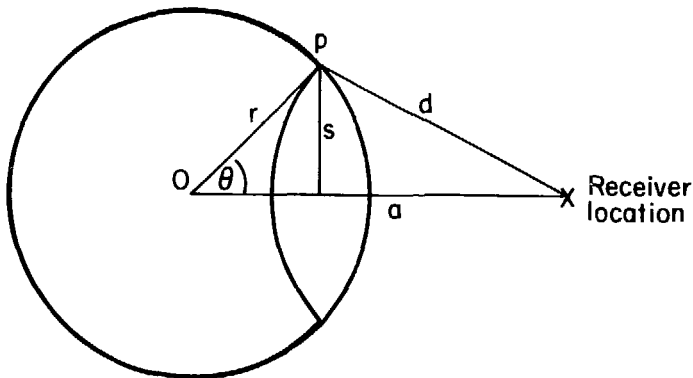
For a point heat source located at the origin (see Fig. 10), the acoustic emission activity can be written as a volume integral:

$$W(\alpha, t) = \int \dot{T}(r, t) F(\alpha, d) dV \quad (1)$$

where $\dot{T}(r, t)$ is the rate of temperature change as a function of time and

radial distance from the point source; $F(\alpha, d)$ is the amplitude function expressing the attenuation occurring over the source-receiver path length d .

Time-dependent temperature fields for the 5 kW main H10 heater can be approximated by modeling the heater as a line source. This line source can be further approximated by many closely-spaced point sources. With a point heat source, the isotherms are spherical, and can easily be incorporated into an "acoustic emission" model that will account for the decrease in seismic energy from spherical spreading of waves and from attenuation loss in the rock. The activity function $W(\alpha, t)$ of Eq. (1) is an intermediate result, and $W(\alpha, t)$ for each point along the heater center-line must be summed



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Fig. 10. Diagram showing integration over the sphere surrounding the point heat source to form the weighting function $F(\alpha, d)$.

to produce the total acoustic emission activity function $A(\alpha, t)$.

After turn-off, heat continues to flow out to the surrounding rock from the high-temperature region near the H10 heater. As the heat moves outwards, thermal gradients decrease. Thus with the perturbation of the near steady-state conditions, temperature and temperature gradients, both spatial and temporal, become functions both of distance from the heater and of time. Although other temperature functions than the time derivative, $\dot{T}$, could arguably be used in Eq. (1), $\dot{T}$ is believed to be the best measure of the departure from the established spatial temperature regime already established in the rock as a result of the long heating period.

For a point source, temperature with time in an infinite medium is (Carslaw and Jaeger, 1959):

$$T(r, t) = \frac{q}{4\pi Kr} \operatorname{erfc} \frac{r}{(4Kt)^{1/2}} \quad (2)$$

where K is the thermal diffusivity constant of the Stripa granite and is equal to $1.84 \times 10^{-6} \text{ m}^2/\text{s}$ (Jeffrey et al., 1979), and q is the heat output for the point. To model heater turnoff, a negative heat source is added to the existing positive heat source so that the temperatures following turnoff are $T(r, t_1) - T(r, t_2)$, where $t_1 = 398 \text{ days} + t_2$. The time derivative $\dot{T}$ was approximated by differencing the result over one-day time increments.

If the volume element located at point p in Fig. 10 emits an acoustic event, amplitude decreases with distance by the factor

$$F(\alpha, d) = (1/d) \cdot \exp(-\alpha \cdot d)$$

where the attenuation constant, $\alpha = \pi f/Qv$, and f is the frequency (per sec), Q the dimensionless quality factor, and v the seismic velocity (m/s). For a

resonant transducer, as the H10 receiver appears to be, the number of events detected by the receiver is directly proportional to amplitude (Nakamura, 1977) and the acoustic emission activity for the volume element is proportional to:

$$F(\alpha, d) dV = \frac{2\pi s \exp(-\alpha d) r d\theta dr}{d} \quad . \quad (3)$$

Integration over the sphere begins with the annulus defined by s , dr , $r d\theta$ (Fig. 10), so that the volume of the annulus is $2\pi r \cdot \sin\theta \cdot r d\theta \cdot dr$. The distance from an element of this annular ring to the receiver is d , or $(a^2 + r^2 - 2ar \cdot \cos\theta)^{1/2}$. Hence:

$$F(\alpha, d) dV = \frac{2\pi r^2 \sin\theta \cdot \exp\left[-\alpha \left(a^2 + r^2 - 2ar \cdot \cos\theta\right)^{1/2}\right] d\theta dr}{\left(a^2 + r^2 - 2ar \cdot \cos\theta\right)^{1/2}} \quad (4)$$

Since $\dot{T}$ is independent of θ , Eq. (4) is integrated numerically over $0 \leq \theta \leq \pi$ to yield a modified amplitude function $F'(\alpha, r)$ which is shown in Fig. 11. The remaining step in the evaluation of Eq. (1) is now:

$$W(\alpha, t) = \int_{r_{\min}}^{r_{\max}} \dot{T}(r, t) F'(\alpha, r) dr \quad . \quad (5)$$

The lower limit $r_{\min}$ is 0.2 m, the position of the heater hole wall. The upper limit $r_{\max}$ is set at 7.0 m as a practical outer limit where $\dot{T}$ is small and slowly varying with time. Eq. (5) is evaluated numerically to obtain the activity function W for a single point heat source.

The total acoustic emission activity function is produced by summing over 11 colinear point heat sources which represent the finite length heater.

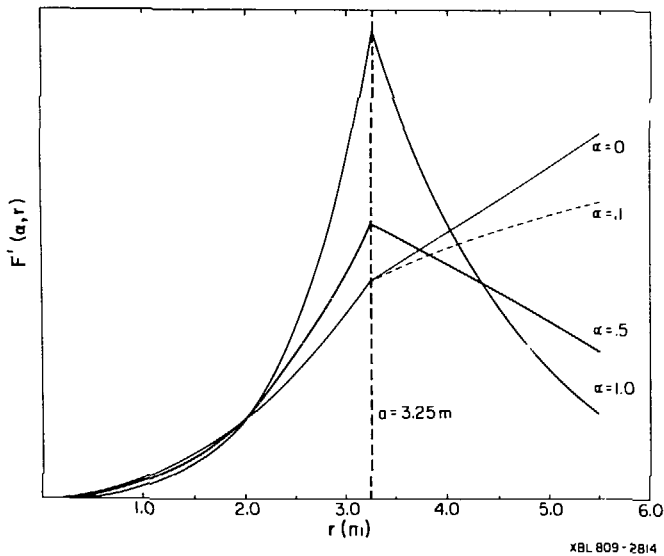
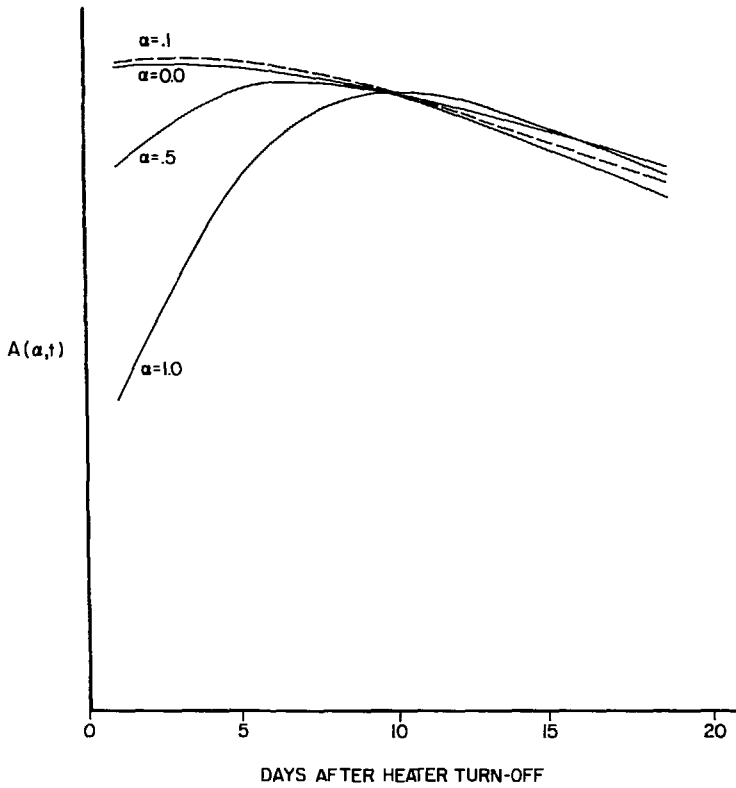


Fig. 11. Value of the weighting function $F'(\alpha, r)$, plotted on a linear scale for different values of the attenuation constant, α . $F'(\alpha, r)$ incorporates the increasing volume of rock with increasing r , and the effect of distance between the receiver and the acoustic emission source. The receiver is located 3.25 m radial distance from the heat source.

Figure 12 shows the resulting function $A(\alpha, t)$ for the H10 heater experiment. For $\alpha = 1.0$, $A(\alpha, t)$ approximates the recorded acoustic emission data in Fig. 6 quite well. For lower values of α , the correspondence is less convincing.

There is some information for choosing a proper range of values for α . For H10, the predominant frequency for acoustic emission events recorded by the system appears to be 60 kHz. In situ velocity determinations for H9 yield 5700 - 5900 m/s for compressional waves and 3100 - 3550 m/s for shear waves (Paulsson and King, 1980). Values for Q in situ have not yet been determined, but tests on one laboratory sample give $Q_{\text{comp}} = 40 - 80$ and $Q_{\text{shear}} = 40 - 60$ (Paulsson, personal communication). Table 3 shows α



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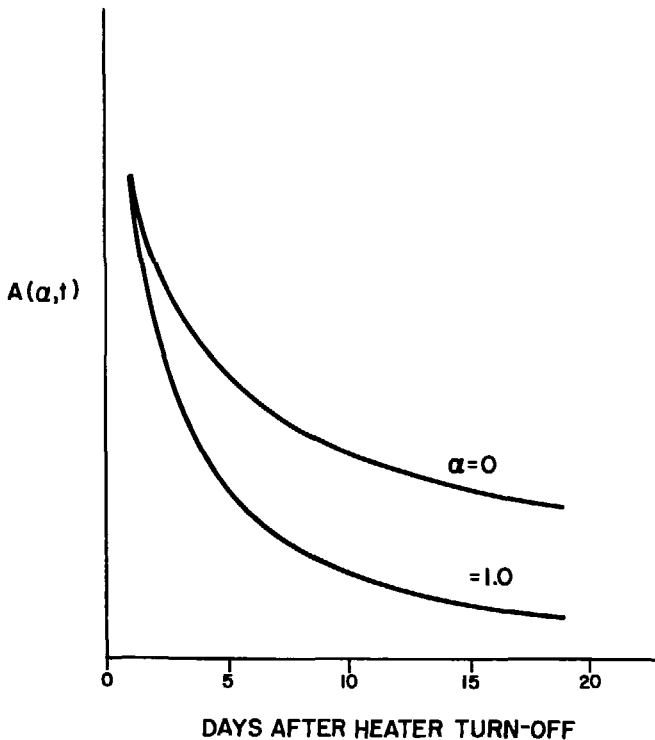
Fig. 12. The acoustic emission activity function $A(\alpha, t)$ for turn-off of the H10 main heater plotted on a linear scale.

Table 3. Values of attenuation constant α with various values of Q , f and v .

Q	$f(\text{kHz})$	$v(\text{m/s})$	α
80	60	5900	0.40
80	12	5900	0.08
50	60	3300	1.14

calculated for several reasonable values of f , Q , and v . Visual inspection of the oscillograph records indicate that the higher (60 kHz) frequencies predominate, so that the higher value for α is preferred.

Even though the model is only an approximation of the H10 cool-down, what should be recognized from the results of the model is the dependence of the shape of the $A(\alpha, t)$ curve on the value of α . What may not be obvious is the dependence of $A(\alpha, t)$ on the receiver location. Figure 13 is a graph of $A(\alpha, t)$ for a hypothetical receiver located at the midpoint of the H10 heater.



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Fig. 13. The acoustic emission activity function $A(\alpha, t)$ for a hypothetical receiver located at the H10 heater mid-point.

In this case, $A(\alpha, t)$ much resembles the shape of the stress and displacement curves in Fig. 6. Such a drastic change in curve shape occurs because of the much greater influence of the cooling rate near the borehole wall upon the hypothetical receiver.

Other possible reasons for the observed lag in peak acoustic emission activity exist. The lag in the data may suggest that a certain amount of cooling or unloading of the rock is required before acoustic emissions result. This lag in acoustic emission activity would then be attributed to the amount of unloading needed for the direction of frictional force to reverse along the joints in the rock. A similar argument was proposed by Walsh (1965) to explain the high value of Young's modulus observed during initial unloading of rock samples in the laboratory. The high Young's modulus was attributed to change in the shear stress direction required before frictional sliding could again occur along the cracks in the rock specimen.

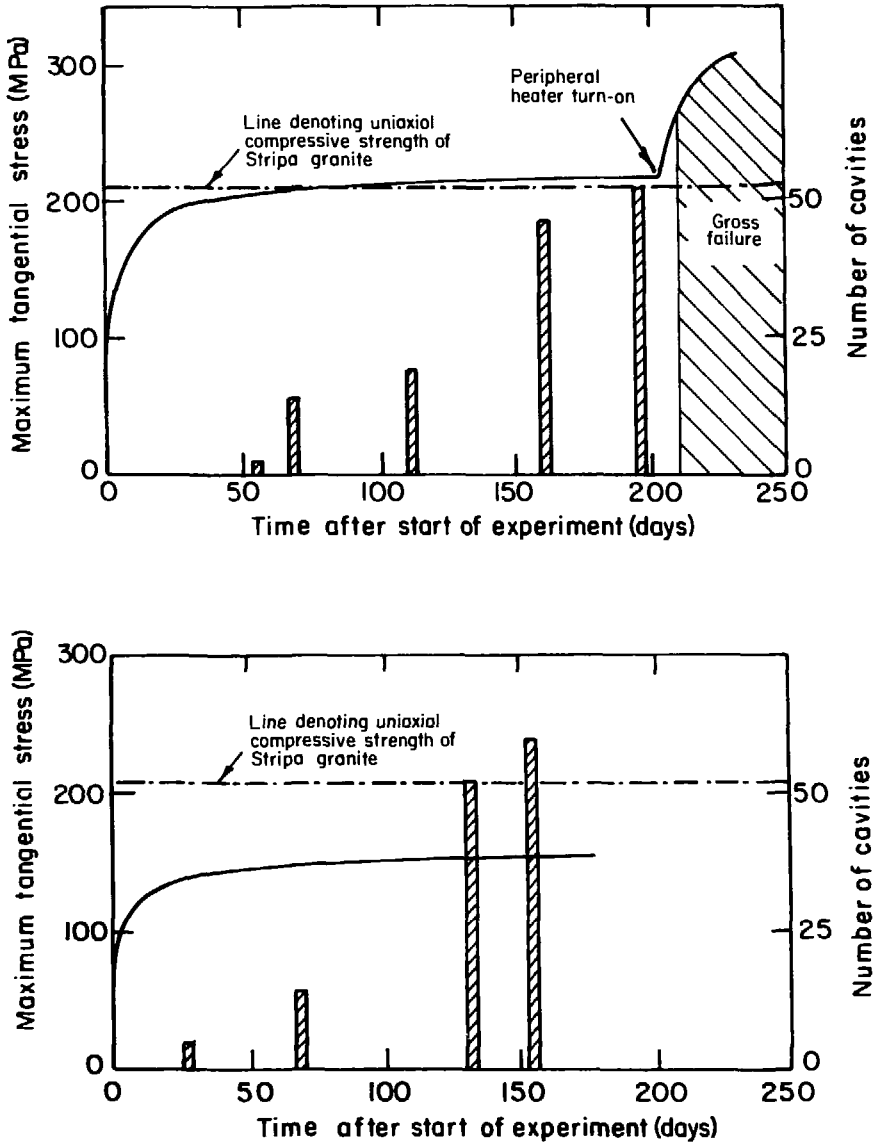
Had the acoustic emission monitoring commenced before the turn-on of the heaters, an even greater acoustic emission activity might have been expected with the heating of the rock. Several processes are present during heating which are not likely to occur upon cool-down.

In laboratory tests on unconfined samples of Westerly granite, acoustic emissions are associated with differential thermal expansion between mineral grains and high thermal gradients (Yong and Wang, 1980). Thermal gradients in heater tests are the steepest shortly after turn-on and are very small as the rock cools.

Spalling of the borehole wall along the heaters was observed in both the H9 and H10 experiments (Hood, 1979). Theory predicts that spalling should occur when the tangential stress at the borehole wall exceeds the unconfined compressive strength of the rock (Cook, 1978). In fact, gross failure of the borehole wall occurred with the turn-on of the peripheral heaters in the H10 area and the surpassing of the unconfined compressive strength by the σ_θ stress. However, at lower stress levels, small chips of rock, 20-30 mm wide and 2-3 mm thick, flaked off the borehole of both the H9 and H10 heaters. Continued formation of these rock chips with time did not correspond with any significant stress increase (Fig. 14) (Hood, 1979). The cause of this phenomenon is being studied. In any case, both the minor spalling and the major failure of the borehole wall are the result of crack-forming processes that should produce acoustic emissions.

A look at the H10 acoustic emission data (Fig. 6), clearly shows a change, upon the start of cooling, in the ratio of minutes recording > 10 cycles to those recording > 40 cycles; that is, the proportion of minutes with > 10 cycles increased relative to those with > 40 . This suggests possible changes, with turn-off of the heaters, in the mechanisms generating acoustic emissions, such as the cessation of spalling on the heater hole wall.

As the system at Stripa employed only one receiver, the amount of information collected on the behavior of the rock was limited. A proper monitoring system for future heater tests or repository sites should at least be capable of locating events and determining their energy. The advantage of such an acoustic emission system would be the ability to monitor the behavior



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Fig. 14. Maximum induced compressive stress at walls of the 5 kW (upper graph) and the 3.6 kW (lower graph) heater boreholes plotted as a function of time, together with lines denoting the uniaxial compressive strength of the rock (from Hood, 1979). Also plotted are the number of cavities induced in the borehole wall as a result of thermal spalling.

of the rock over a large area for instability and fracture formation, as has been demonstrated by acoustic emission monitoring of deep mines. The determination of an area of movement or fracturing is not dependent upon the borehole crossing the affected zone, as it is with an extensometer.

Such a sophisticated monitoring system was developed and installed by LBL at the Nevada Test Site waste storage experiment (Majer et al., 1980). This is an advanced multi-receiver system capable of locating events, recording amplitude, first motion, and characteristics of the frequency spectrum. By employing techniques common to earthquake seismology to analyze the recorded data, the nature of the acoustic emission source--that is, its size and whether it represents shear motion or the development of an extension fracture--may be determined. Ideally, the complete history of the fracturing process can be followed, allowing a close study of fracture formation due to the thermally induced stresses. Also of interest will be the correlation of microseismic events to mapped fractures and faults in the mine.

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