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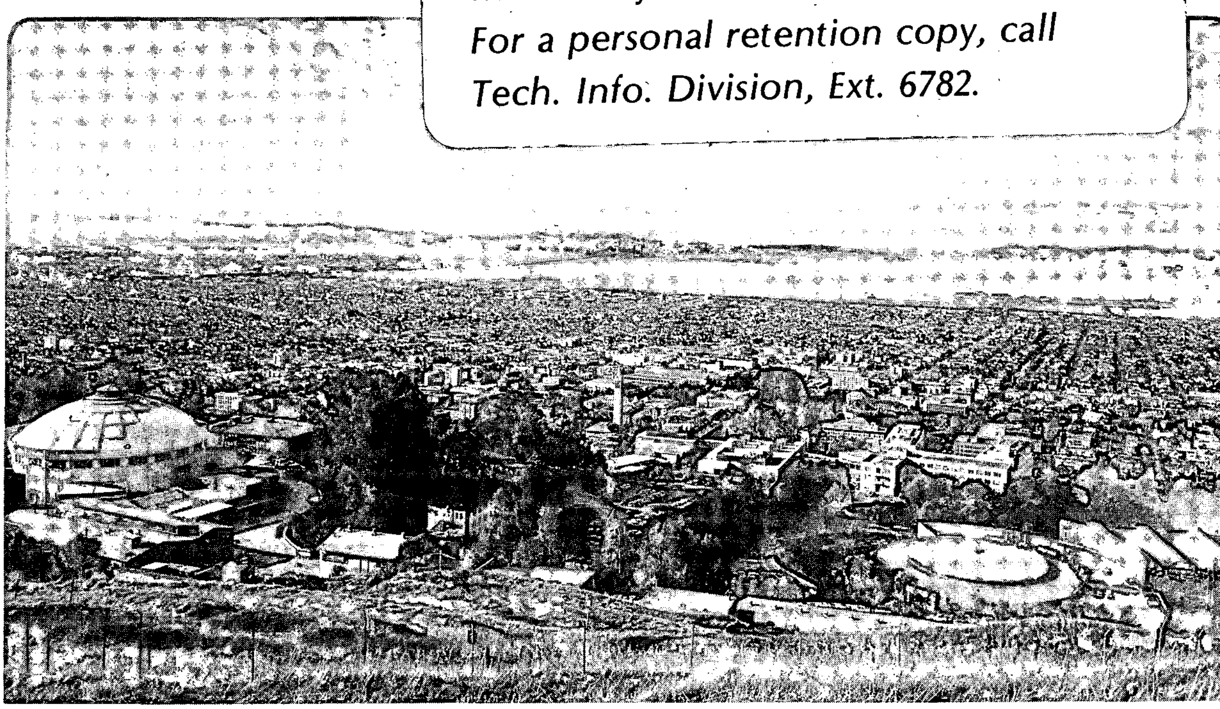

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Seismic Velocities and Attenuation in an Underground Granitic Waste Repository Subjected to Heating

by

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The behavior of a granitic rock mass subjected to thermal load has been studied by an acoustic cross-hole technique between four boreholes, over a period of some two years. Velocities between boreholes were obtained from the times-of-flight of pulses of acoustic waves between transducers clamped to the borehole wall. The attenuation was obtained by a spectral ratios technique. When the heater was turned on, the velocities increased rapidly to an asymptotic value. When the heater was turned off, the velocities decreased rapidly to their original values or below. Velocities along a particular profile were found to increase linearly with the mean temperature in the profile tested. The attenuation showed little correlation with changes in temperature or the associated thernmal stresses, but there was a good correlation of attenuation with water content and the related changes in pore pressure.

Nous avons étudié le comportement d'une masse de granite soumise à une charge thermique à l'aide d'une technique acoustique. Les mésures etaient faites entre quatre trous de forage pendant une periode de deux années. Nous obtînmes les vélocités par la mésure du temps de passage d'une impulsion acoustique, l'attenuation etait calculée par la technique des rapports des spectres. Les vélocités augmentaient rapidement au commencement du chauffage, atteignant bientôt leur valeurs assymptotiques. A l'arrêt du chauffage les vélocités sont revenues très vite à leur valeur d'origine. Les vélocités lelong d'un profil donné démontrent une variation linéaire avec la temperature moyenne du profil. L'attenuation ne semble pas être reliée aux changements de temperature ou de la charge thermique. Cependent on note une bonne correlation entre l'attenuation et le contenu en eau de la roche.

Das Verhalten einer granitischen Gesteinsmasse bei Aufheizung ist mit Hilfe akustischer Transmission zwischen vier Bohrloechern ueber einen Zeitraum von ueber zwei Jahren untersucht worden. Schallgeschwindigkeiten zwischen Bohrloechern wurden aus der Ankunftszeit von akustischen Pulsen in an der Bohrlochwand angebrachten Mikrofonen ermittelt. Die Abschwaechung wurde mit einer Methode spektraler Intensitaetsverhaeltnisse ermittelt. Nach Anschalten der Heizgeraete wurde ein schneller Geschwindigkeitsanstieg zu einem asymptotischen Wert beobachtet. Nach Abschalten der Heizung fielen die Geschwindigkeiten schnell auf ihren urspruenglichen Wert oder darunter. Geschwindigkeiten in einer bestimmten vertikalen Ebene nahmen in linearer Abhaengigkeit mit der mittleren Temperatur zu. Die Abschwaechung war kaum mit Temperaturaenderungen und den damit verbundenen thermischen Spannungen korreliert, aber Abschwaechung zeigte eine gute Korrelation mit Wassergehalt und den damit zusammenhaengenden Aenderungen im Wasserdruck in den Gesteinsporen.

INTRODUCTION

The velocities of compressional and shear waves and their attenuation in crystalline rocks containing fissures, fractures and joints have been observed to be influenced strongly by the state of stress, changes in temperature, and degree of water saturation in the rock mass. Nur and Simmons (1969a) have shown that at effective stress levels below 100 MPa the elastic properties of crystalline rocks are controlled mainly by the properties of microcracks, and that the application of uniaxial stress to a sample of granite caused elastic-wave anisotropy, with a higher compressional-wave velocity in the direction of the applied stress. Anderson et al (1974) found that a preferred orientation of open cracks had a marked effect on seismic velocities, with the major reduction in velocity observed perpendicular to the plane of open fractures. Nur and Simmons (1969b) and King (1984) determined the effects of degree of water saturation on elastic-wave velocities in crystalline rocks, and showed that an increase in water saturation increased the velocities of compressional and shear waves in granite. King and Paulsson (1981) have discussed the changes in compressional-wave velocity observed in a heated block of granite subjected to uniaxial stress.

The use of acoustic measurements made between parallel boreholes for characterizing a rock mass and monitoring changes in rock mass quality have been described by a number of researchers. Grainger and McCann (1977) provided two case histories of cross-hole acoustic measurements for site investigations in rock masses. McCann and Baria (1982) described cross-hole acoustic measurements applied in assessing the quality of a granitic rock mass for radioactive waste storage. McKenzie et al (1982) reported a research program aimed at the in situ assessment of rock properties and quality at a number of Australian mine sites, employing a cross-hole acoustic system to obtain compressional-wave velocity and attenuation. Gladwin (1982) used the same system described by McKenzie et al to monitor stress changes in an underground support pillar in a copper mine. Wong et al (1982, 1983) described an acoustic system using stacking of waveforms for cross-hole seismic imaging in crystalline rocks at ranges of 100's of m.

Described in this paper are the results of a cross-hole acoustic investigation of a granitic rock mass subjected to heating. This particular study was performed as 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 (Witherspoon et al, 1979). The experimental setting and some preliminary results of the cross-hole acoustic investigation have been described by Paulsson and King (1980).

EXPERIMENTAL PROCEDURES

The investigation was performed in a fractured granitic rock mass (quartz monzonite) at a subsurface 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 Fig. 1 at the plane of the heater center-line. The acoustic monitoring boreholes are marked M6, M7, M8 and M9. The heater is marked H9. 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, as referred to by

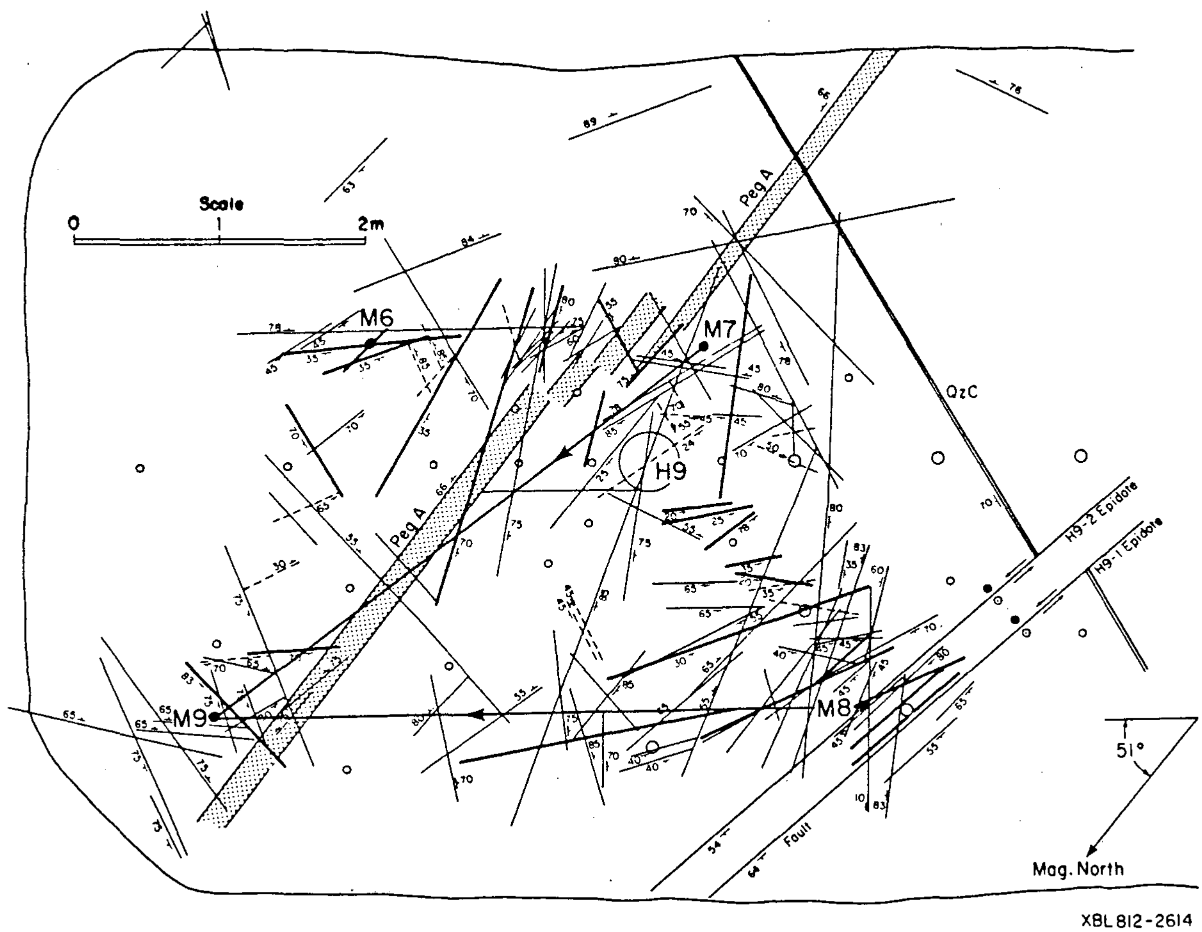

Figure 1. Plan view of borehole locations and geological features below drift floor at plane of heater centerline.

Paulsson and King (1980). Separate compressional (P) and shear (S) wave transducers of nominal 200 kHz resonant frequency were used as transmitters and receivers of pulses of acoustic energy in boreholes of 56 mm dia. The transducer holders were jacked mechanically against the borehole wall at the required depth. The The P- and S-wave signals were displayed on an oscilloscope screen and recorded in analogue form on an instrumentation tape recorder for later harmonic analysis in the laboratory. The accuracy of the velocity measurements is estimated to be ± 0.1% (Paulsson, 1983), resulting in a resolution of ± 6 m/s in P-wave velocities.

The acoustic monitoring tests referred to here fell into two categories: (1) between-hole 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; and (2) between-hole monitoring, for which the transmitter and receiver were positioned in each pair of boreholes at the level of the heater mid-plane. A reference line was chosen between a pair of boreholes (M6-M9, 1 m below the drift floor) well away from the heater to provide a check on transducer performance and the reproducibility of results.

RESULTS AND DISCUSSION

In this paper we shall discuss the velocity and attenuation behavior over two lines only between the four monitor boreholes shown in Fig. 1. These lines are M8-M9 and M7-M9; 4.5 m and 4.2 m apart respectively. The maximum temperature reached at day 398 (the last day of heater operation) in each of the two lines was quite different. The maximum temperature reached in M8-M9 was slightly more than 40°C, as shown in Fig. 2, while the maximum temperature in M7-M9 was 128°C, as shown in Fig. 3. The reason for these differences is that the two lines are at different distances from the heater borehole wall. The nearest point from the heater to the M8-M9 line is 1.32 m, while the nearest point of the M7-M9 line is only 0.2 m from the heater borehole wall. The temperature field for the two cross-sections on the last day of heating can be seen on the left hand side of Figs. 2 and 3. The high temperatures were confined to the immediate vicinity of the heater, where there were sharp thermal gradients. The differences in temperature between the two sections is reflected in large differences of the velocity and the attenuation behavior in space and time. The second active process which influenced the elastic behavior of the rock was dewatering of the rock mass. Dewatering was performed daily by pumping water from the 43 instrumentation boreholes around the H9 heater, as described by Nelson and Rachiele (1982). The dewatering process decreased the pore pressure from its ambient value of approximately 1 MPa (Wilson et al., 1983) to some lower value. The dewatering was performed in all the boreholes, and affected the whole rock mass around the heater.

The velocities measured during the preheating survey, shown in the center of Fig. 2, show no large anomalies. The velocities actually decreased slightly with depth, which could be caused by the decreasing tangential stress away from the drift opening. At day 343 the P-wave velocities had increased by approximately 100 m/s at most depth levels. The uniform increase of the velocity cannot have been caused by the

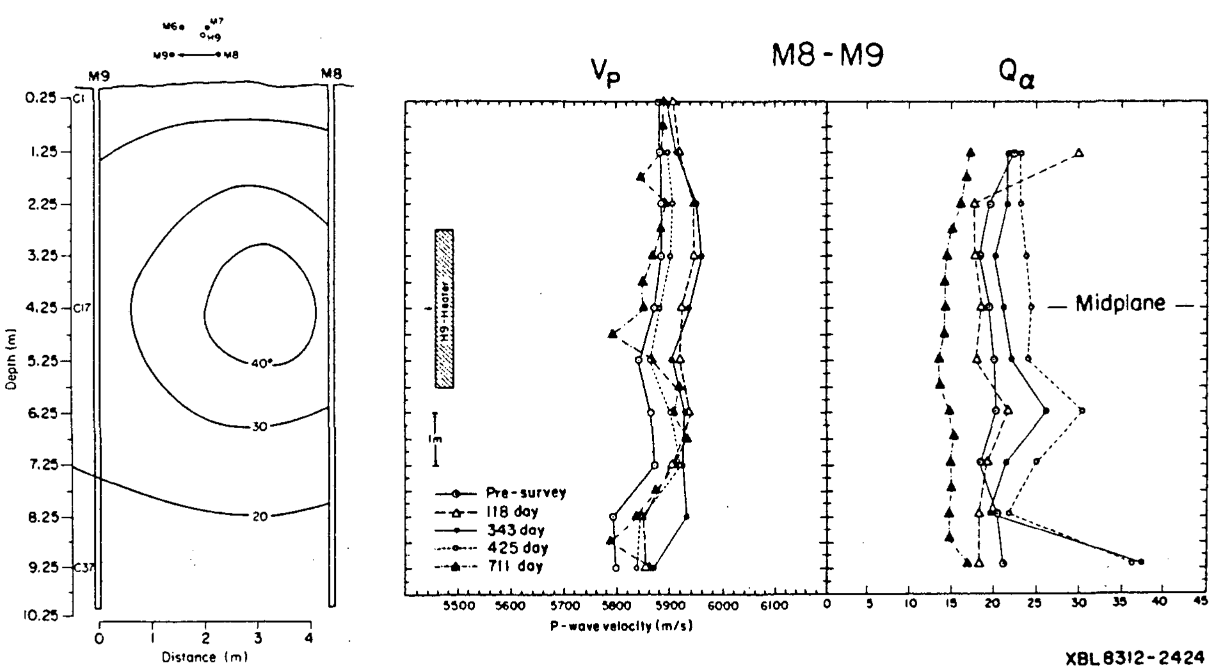

Figure 2. Temperature distribution (°C) immediately prior to heater shut-off, and P-wave velocity (V_P) and quality factor (Q_α) between boreholes M8 and M9 before, during, and after heating.

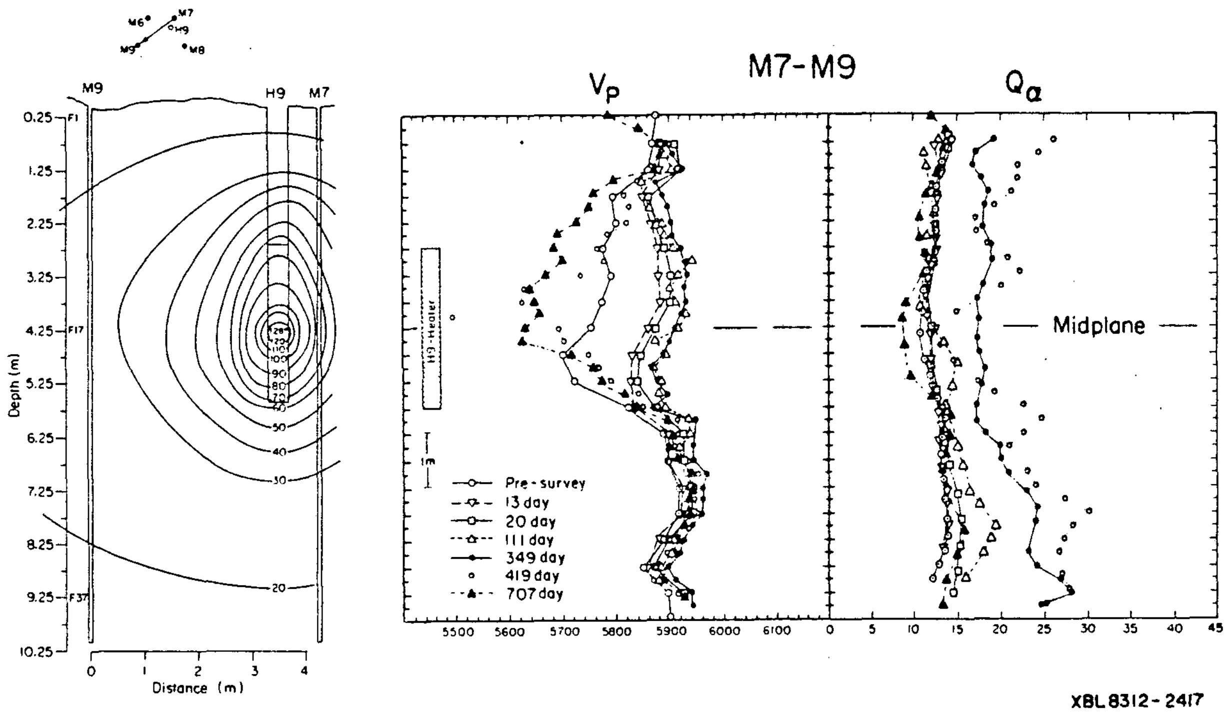

Figure 3. Temperature distribution (°C) immediately prior to heater shut-off, and P-wave velocity (V_P) and quality factor (Q_α) between boreholes M7 and M9 before, during, and after heating.

heating, which was localized to the levels of the heater. The velocity increase in this profile is inferred instead to have been caused by the decrease of pore pressure, which led to a higher effective stress. This inference is confirmed by the near uniform increase of the P-wave quality factor Q_α. The quality factor Q is inversely related to the attenuation. Details of the calculations of Q_α by a spectral-ratios technique are given by Paulsson (1983). This uniform increase of Q_α with depth is not seen in the section M7-M9 shown in Fig. 3, where the velocities and Q_α-values for the M7-M9 section are plotted. In this section the Q_α-values are fairly constant with depth for the preheating survey. The attenuation did not change until the survey performed at day 111. The Q_α-values continued to increase even after the heater was turned off at day 398. For the two surveys conducted at days 349 and 419 in the M7-M9 cross-section, the smallest Q_α increase occurred at the level of the heater. This indicates that the heated zone was a relatively high attenuation zone. This high attenuation was probably caused by a large build up of pore pressure, due to the large thermal expansion of water and a heat-induced sharp reduction in permeability. Morrow et al (1981) have discussed the reduction of permeability of granite observed as a result of temperature increase. Paulsson (1983) has shown that due to this process the pore pressure could exceed the tensile strength of the unfractured rock (15 MPa: from Swan, 1978) for quite modest temperature increases, as indicated in Fig. 4. The only depth level at which the Q_α-values decreased after the heater was turned off was at the level of the heater. This was most likely due to a rapid thermal contraction of the

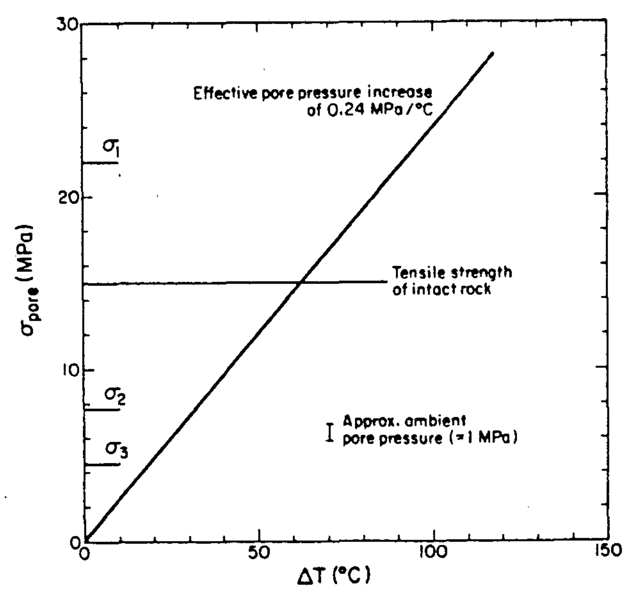

Figure 4. Calculated pore pressure increase as a function of temperature increase for Stripa granite. Virgin field principal stresses σ_1, σ_2, and σ_3 at level of drift, and tensile strength of intact rock are indicated.

rock adjacent to the heater borehole at that time. It is inferred that the rapid contraction of the rock did not permit full resaturation, and the rock became only partially water saturated. The zone of low Q_α at the depth of the heater for the survey at day 707 indicates that the rock had been fractured; probably due to thermal hydrofracturing. The two peaks of the Q_α-values for the survey at day 419 for the M7-M9 line were probably due to water flow into the partially saturated, relatively permeable zone opposite each end of the heater. The P-wave velocities prior to the heating reveal a broad negative anomaly from 1.25 m below the drift floor to a level parallel to the bottom of the heater. This low-velocity zone was caused by a combination of the presence of a concentration of weak calcite fractures at this level and heavy vibrations during the drilling process. These low velocities indicate that a rock mass can be fractured during the drilling of a large borehole, if there are weaknesses present.

The highest temperatures were observed in the heater midplane, as expected. The average temperatures for the two lines M8-M9 and M7-M9 are shown as function of time in the upper part of Fig. 5. The difference in the time constant for the temperature increase is apparent. Again, this is due to the difference in distance from the heater wall to the two lines. While the temperature quickly reached the maximum average temperature in line M7-M9, it took 350 days before the temperature increase leveled off in line M8-M9. The P-wave velocities for the two lines are shown in the center part of Fig. 5. The velocities in the line M7-M9 increased rapidly after the turn-on of the heater. The increase in the line M8-M9 was smaller and more gradual. The same difference in behavior is seen in the decrease of the velocities following the turn-off of the H9 heater. Note however that the temperature decrease in the M8-M9 line follows that of the M7-M9 line. The Q_α-values for the two lines are shown in the lower part of Fig. 5. For line M8-M9 the Q_α-value increase continued from heater turn-on, with two exceptions, until 90 days after heater turn-off. The Q_α-values in M7-M9 in the heater midplane were considerably less regular. There was only a small change the first 100 days followed by a large increase, after which there was a gradual decrease until day 225. This was followed by an increase in Q_α until the heater was turned off; then the Q_α-values decreased rapidly to levels below those found prior to the heating. The reference line showed very similar behavior with respect to Q_α to that found in the other two lines discussed in this paper. The reference line between boreholes M9 and M6 is only 1 m below the drift floor in an area where the temperature increased to only 20°C due to the heating. This Q_α behavior for the reference line indicates that the attenuation decrease with time was a pervasive phenomenon over the entire rock mass, and was primarily due to dewatering rather than heating.

The velocities and the attenuation were both affected by heating and dewatering the rock mass. In Fig. 6 the velocities and the attenuation have been plotted for line M8-M9 as functions of temperature, using the results shown in Fig. 5. In the upper part of Fig. 6 the spatial change of velocity with temperature is also indicated, using the temperature distribu-

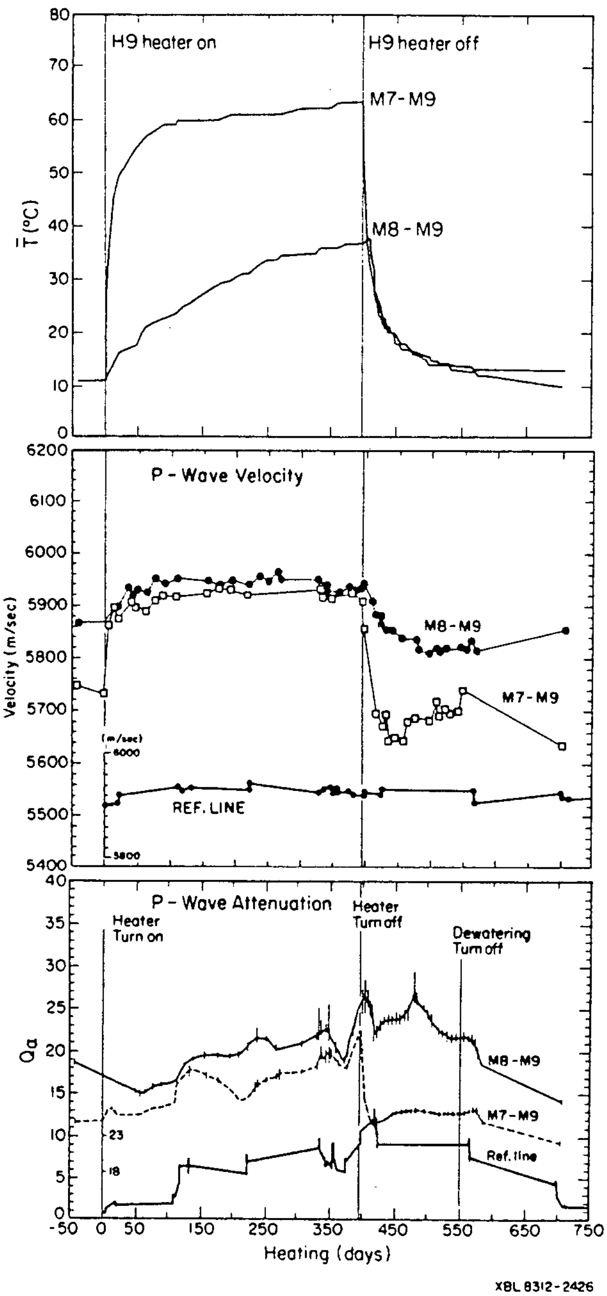

Figure 5. Average temperature, P-wave velocity and quality factor (Q_α) over profiles M8-M9 and M7-M9 as a function of time.

tion in Fig. 2 and the survey data from day 343 (from Paulsson, 1983). The velocity increase with temperature can be divided into two distinct phases: first, where the velocity increase has a sharp gradient with temperature (to 10°C), and second where the velocity increases more slowly. The velocity gradient of the second phase is approximately the same as the gradient of the spatial velocity increase. The lower part of Fig. 6 indicates that for the Q_α-values there is apparently no correlation with temperature.

The temporal and spatial velocity changes with

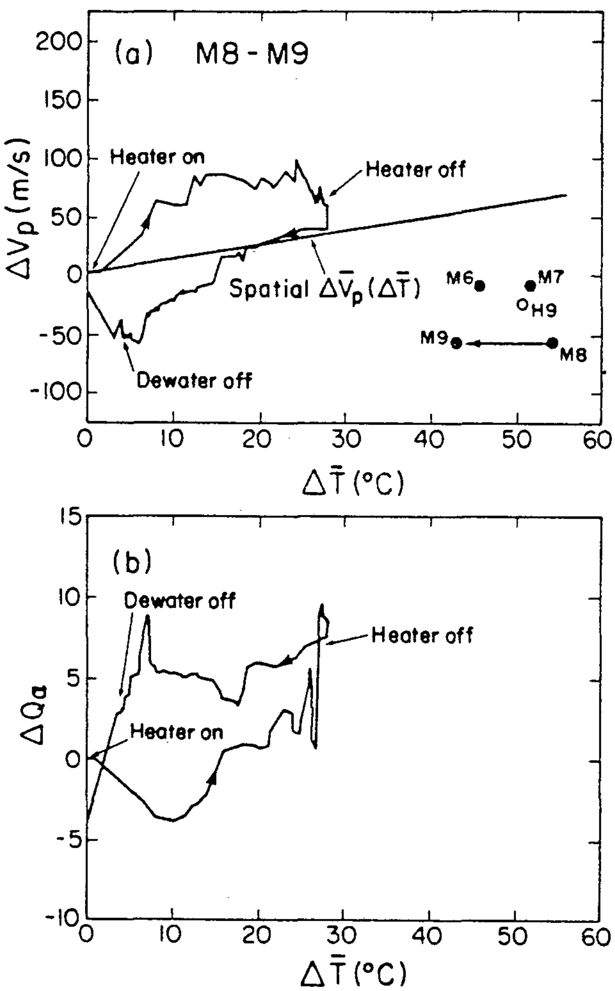

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Figure 6. Changes in P-wave velocity (ΔV_P) and quality factor (ΔQ_α) as a function of temperature change for profile M8-M9.

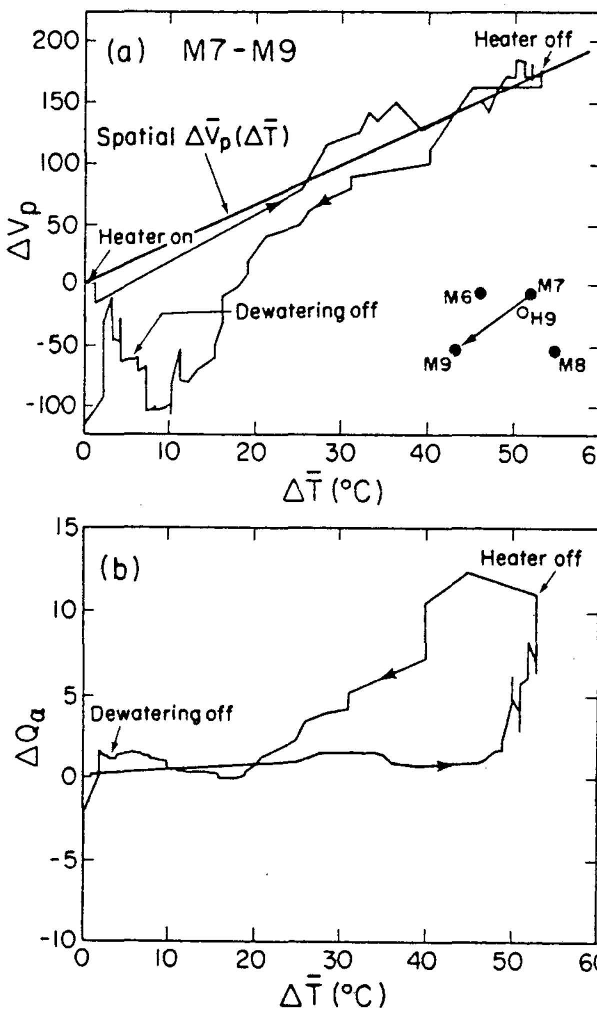

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Figure 7. Changes in P-wave velocity (ΔV_P) and quality factor (ΔQ_α) as a function of temperature change for profile M7-M9.

temperature for section M7-M9 are shown in Fig. 7. The average temperature in the heater midplane for this profile rose rapidly to a maximum value, as indicated in Fig. 5. For this profile the velocity increase was due only to the change in temperature, and was unaffected by the dewatering process. It can be seen that the velocity increase is approximately the same as the gradient of the spatial velocity increase, using the temperature distribution in Fig. 3 and the survey data from day 349 (Paulsson, 1983). Again, the lower part of Fig. 7 indicates that for the Q_α-values there is apparently no correlation with temperature.

Figs. 6 and 7 clearly indicate that when the temperature changes dominated (as with the rapid rise shown for section M7-M9), the velocity increase was linear with temperature. This behavior had also been reported by King and Paulsson (1981) for a small-scale heated block experiment. When the temperature increase was much less rapid (as observed for section M8-M9), the dewatering process also played its part: the velocity then increased more rapidly, due to the reduction in pore pressure increasing the effective stress. These figures also indicate that the attenuation is relatively unaffected by changes in temperature alone. Only when changes in pore pressure occurred (as when dewatering was terminated) were there changes in Q_α.

CONCLUSIONS

Measurements of the velocity and attenuation properties of high-frequency ultrasonic waves transmitted between boreholes in a heated crystalline rock mass constitute an effective seismic technique for detailed rock mechanics investigations around an underground opening. Compressional-wave velocities can be employed to assess thermal damage of the rock mass, and the extent of the disturbed zone due to heating. Attenuation properties of compressional waves can provide important information on thermal damage caused by high pore pressures in conjunction with heat-induced reductions in permeability.

The research has demonstrated that a comparatively small-scale field experiment can be successful in monitoring parameters of the rock which can not be obtained in the laboratory. As such it can provide a prototype data base for the implementation of high-frequency acoustic monitoring programs in full-scale waste repositories where the medium integrity must be known and maintained.

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