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Ultrasonic Stress Monitoring in Underground Mining

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Stress changes induced in a large (40 × 40 × 120 m) underground support pillar by mining development have been monitored over a period of 2 yr in the 1100 copper orebody at Mt Isa Mine, Australia, using an ultrasonic stress monitoring device (USMD). Results are compared with estimates from in situ *absolute stress measurements and with continuous strain recordings at a nearby site. Sensitivity to deviatoric stress changes of 0.01 MPa has been achieved. Propagation of stress relief cycles through the pillar were observed, and a number of creep events were documented. Many events of potential interest detectable in continuous strain measurements were examined in the stress domain. The large increases in vertical stress field expected as the pillar was progressively isolated did not occur since the pillar yielded by shear on pre-existing fractures. Most of the deformation of the pillar which was observed in strain records occurred without significant stress change demonstrating the need for simultaneous stress and strain data. Stress relief events propagate slowly through a rock mass on time scales of several days.*

INTRODUCTION

The stress sensitivity of the velocity of acoustic pulses in rock has been documented extensively in the laboratory. Early measurements by Birch [1, 2] have been repeated more recently by Anderson & Liebermann [3]. For most rocks, hydrostatic pressure increase from 0 to 200 MPa produces significant increase of compressional and shear velocities. At higher pressures the effect diminishes rapidly toward the much smaller effect characteristic of the intrinsic elastic parameters of the individual mineral crystals. The effect is explained by the presence of pores and microstructure in rocks at low hydrostatic pressure. Typical behaviour for a broad suite of rock types is shown in Fig. 1, where the profiles have been extracted from the data of Anderson & Liebermann [3] and apply to intact dry samples jacketed in hydrostatic pressure bombs. The superposition of axial compressions at low hydrostatic pressure is accompanied (Volarovich *et al.* [4]) by velocity changes similar to those produced by corresponding increments in hydrostatic pressure and results in an anisotropy in velocity. The sensitivity to deviatoric stress decreases strongly with increasing hydrostatic stress [5]. This velocity sensitivity of rock to stress has been the basis of many unsuccessful seismic studies in earthquake prediction and was the basis of the present stress change monitoring programme in the M538 mine pillar at Mt Isa. The technique is successful in the mining environment because of the low ambient hydrostatic stress levels.

The stress sensitivity under study is a microstructure property in intact rock. Though visible with the aid of a petrographic microscope, study of the existence, aspect ratio and response to stress of these microcracks has been well documented only recently using the scanning

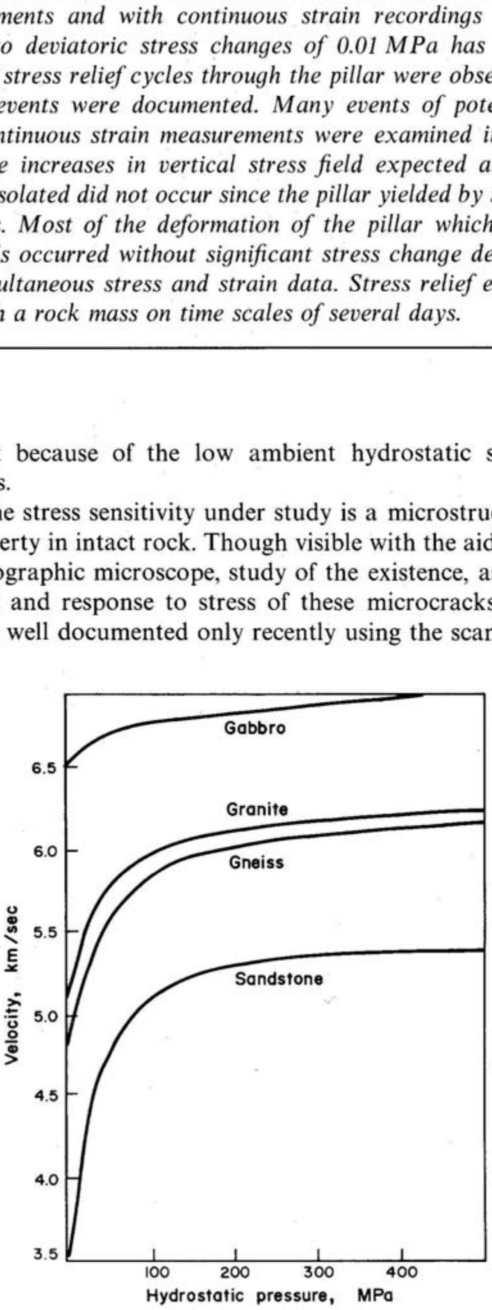

Fig. 1. Typical compressional wave velocity variation with hydrostatic pressure.

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electron microscope. Kranz [6] has shown that in Barre granite microcracks of typical aspect ratio (crack width divided by crack length) less than 0.05 and with average length in the range 10–200 μm appear to be continuously generated by ambient stress loading. Macrocracks (interconnected microcrack structure) and joints will produce a velocity stress sensitivity of an enhanced amplitude, but are not necessary for a stress diagnostic.

The ultrasonic technique described here is therefore termed a stress change monitoring system since a stress sensitive parameter is measured. Many commonly used "stress monitors" are in fact strain devices, the stress being implied via a modulus. Such devices are in principle unable to isolate elastic from plastic deformation. Typical velocity stress sensitivities are shown in Fig. 2. For dry granite the values range from a maximum of about 40 m/sec/MPa at zero hydrostatic pressure and decrease by an order of magnitude at depth of a few kilometers. Changes of velocity due to changes in stress are measured in the present system by a change in pulse transit time between a transmitter and two detectors. This change of travel time is not caused by the change of physical dimension of the path due to the change of stress. For a typical hard rock environment with a Young's modulus of order 50 GPa, the strain induced change of travel time is almost two orders lower than the effect under discussion.

Changes of acoustic compressional velocity in field or laboratory environments can also be caused by variation of moisture content. King & Paulsson [15] give in their Fig. 5 a recent typical example of this type of variation for granite. Sensitivity of velocity to ambient stress change is usually highest for "dry" samples, and decreases by up to a factor of two as saturation is approached. In field environments control of moisture content is normally not possible. In any case the actual stress sensitivity of acoustic velocity in a given site must be measured before stress changes can be quantified. The technique here described assumes supportive measurements from time to time (e.g. flat-jacks or strain rosettes) from which the stress sensitivity is evaluated. For the present experiment in massive recrystallized dolomitic breccia at 900 m depth, variation of water content is assumed negligible, since the area is essentially 'dry', and all paths monitored were buried at depths of at least 7 m from any access tunnels.

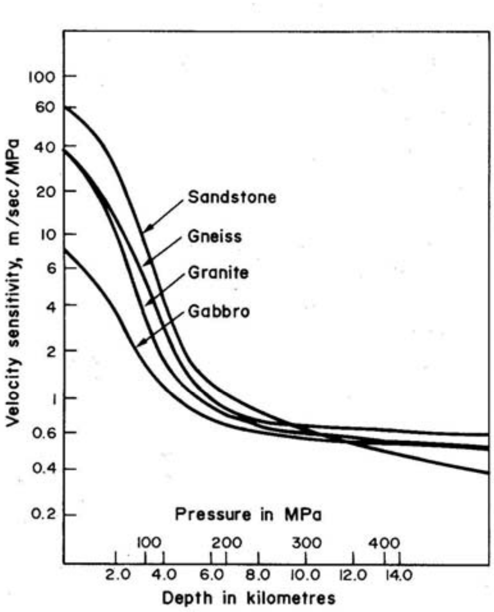

Fig. 2. Variation with confining pressure of velocity sensitivity (in m per sec per MPa) for intact samples. In the mining environment ambient stress levels less than 100 MPa are expected.

Data presented later will show the value of monitoring stress and strain independently and simultaneously. In particular, and with regard to mine stability, stress increase and relief are of great significance if separable from simple strain and creep phenomena which are also quite widespread in the time scale of mining operations.

In a mining environment, at lithostatic stresses of up to 60 MPa the expected sensitivity of velocity to deviatoric stress is shown on Fig. 2. Thus, relatively high precision of velocity monitoring is necessary to provide useful information on stress conditions. The accuracy of a pulse velocity measurement is limited by the sharpness in the time domain of the pulse arrival. It can be shown (Gladwin & Stacey [7]) that the definition of the pulse onset is controlled by the selective attenuation of high frequency components of the spectrum. The rise time of the pulse increases linearly with travel time [7, 8]. This effect increases the timing uncertainty in travel time measurement so that the relative precision of a measurement of velocity between two fixed points is in principle constant and independent of distance [9]. The relative precision is of course dependent on the attenuation characteristics of the rock mass.

Electronic limitations on the timing of the pulse transit become significant only at very short paths (below 0.1 m) so that for paths in the range of interest to mine stress change monitoring (1–30 m) timing precision is in practice limited by mine generated noise over which the pulse must be observed. In this range it is possible to use repetitive non-destructive pulse sources and signal enhancement techniques by multisampling to overcome this problem.

The present instrument is designed to operate in either of two modes. In the survey mode the operator visits the monumented sites at times of interest and plugs the transducers into a portable battery operated timing module. He then takes a series of quasicontinuous measurements over a period of about 10 min for each path. In the continuous mode the timing module is powered at the site by a power supply and a pulse coded output module is used to remotely record the travel time data via a normal telephone line.

INSTRUMENTATION

The instrumentation includes a pulsed magnetostrictive transducer as a non-destructive source, two detectors separated by a fixed distance in the range 1–10 m, multiple transmission paths (in this case four)

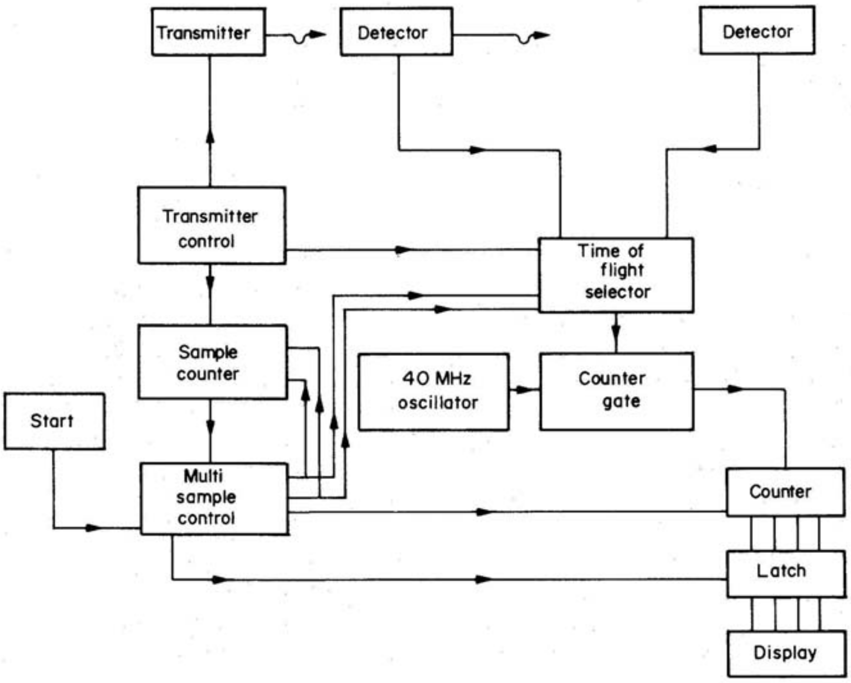

Fig. 3. Schematic diagram of the ultrasonic stress monitoring system used in this study. Time of flight of a pulse between two detectors is averaged allowing variations of a 1 msec travel time to be measured to a few nanoseconds.

oriented for best detection of the expected stress changes and a timing control and travel time measurement module. The transmitter is pulsed approximately every 20 msec and produces a pulse spectrum controlled by the mechanical resonance of the magnetostrictive laminations. For typical attenuations ($\simeq 5$ db/m at 40 kHz) the first compressional pulse is detected with signal-to-noise ratio greater than 10 out to about 15 m. Timing uncertainty on a single pulse transit is of order 1–2 μsec. Two detectors are used, one near the transmitter (at about 1–2 m) and the other remote, so that the time of flight measurement is independent of the precise time of transmission. This two detector system is essential where measurements are to be made over a period of years, since ageing of the transmitter bond can introduce significant error.

A block diagram is shown in Fig. 3. For each pulse transit the two detectors are used to gate a crystal clock into a decade counter. Significant improvement in timing precision is obtained by use of a multisampling average on the travel time. It can be shown that for the 40 MHz clock used the uncertainty of the time of flight may be reduced to better than 10 nsec by averages over 10,000 pulse transits. At the end of the averaging period, the time of flight is displayed and in the continuous operating mode serialized via phone lines to the remote recording station. Further averaging over time is then used if very high precision monitoring is required. In the mining environment the stress changes encountered rarely warrant this extra processing.

The changes of pulse arrival typical of those observed in the field are shown in Fig. 4. This composite photograph taken during laboratory testing of the apparatus in a 8 × 0.4 × 0.4 m specially cast concrete beam shows the effect of stress on travel time at 7 m. The lower set of four traces shows the first arrival at four axial stresses, 0.5, 1.5, 2.5 and 3.5 MPa. At higher stress, the pulse amplitude increases and the arrival moves to the left (earlier). The upper set of curves are the same arrivals normalized to an arbitrary amplitude. This upper set shows more clearly the movement forward of the pulse arrival with increase in stress. The time base is 10 μsec per division. It is important to note that though a change in amplitude is clear on the lower set due to increasing axial stress, the arrivals, after normalization, show a remarkably constant pulse shape. This pulse shape is in fact used in a technique of *in situ* rock characterization [10].

In this laboratory experiment, the dominant frequency at pulse transmission was 37.5 kHz. The beam was balanced in air at its centre to prevent changes of attenuation due to changes of surface contact during compression. During propagation to the detectors, the higher frequency components have been significantly attenuated. The lateral dimension of the beam (0.4 × 0.4 m) also have the effect of spreading the first arrival by any low order internal multiple reflections which can delay the arrival by less than one half cycle. This 'wave guide' effect is of course absent in the field environments reported later. Figure 4 is presented by way of clear illustration of the effects of stress on pulse velocity and on pulse amplitude. Elimination of the effect of pulse amplitude variation with stress is essential in stress monitoring.

GEOLOGICAL SETTING

The monitoring project at Mt Isa Mines was set up in 1975 to examine the behaviour of rock in and

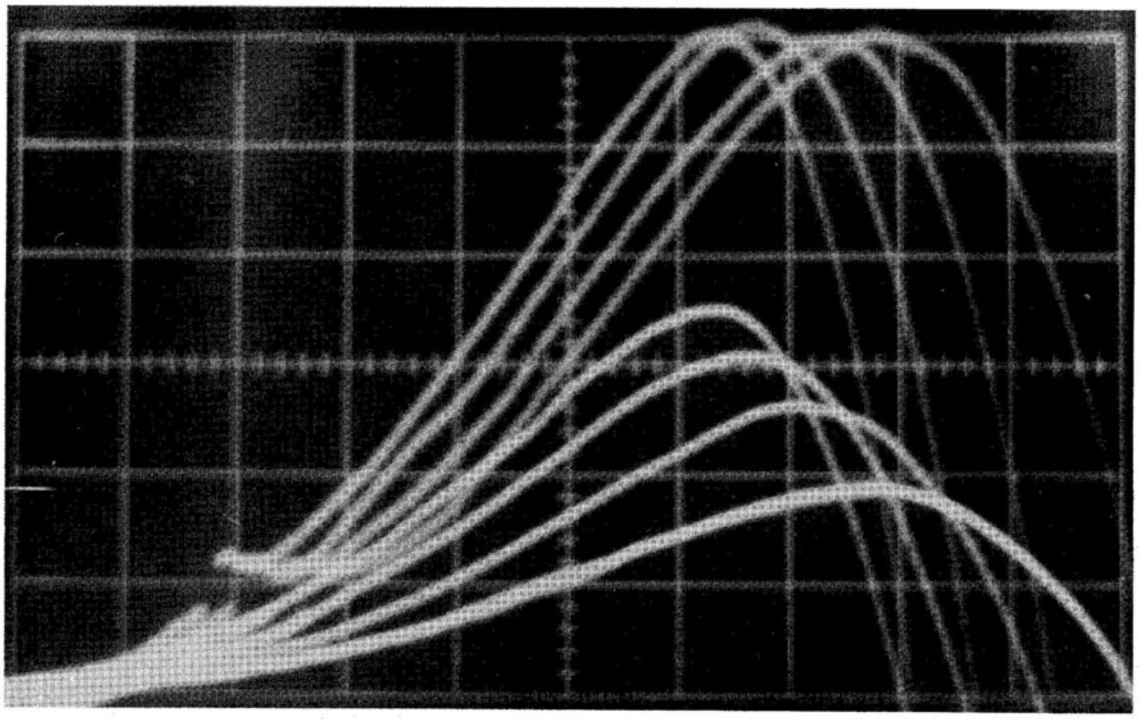

Fig. 4. Composite photograph of typical pulse arrivals. The lower set of arrivals shows change of amplitude and arrival time at four axial loads in a 8 m test block at stresses (right to left) 0.5, 1.5, 2.5 and 3.5 MPa. The upper set of curves are the same arrivals after normalisation to fixed amplitude showing the invariance of pulse shape with stress.

around a large vertical pillar as it was isolated [11]. The host rock for the copper ore body is strong (uniaxial compressive strength 170 MPa) massive recrystallized dolomitic breccia. Below the pillar (dimensions 40 × 40 × 120 m) is a weak (70 MPa) greenschist separated by a carbonaceous mylonitic fault (Fig. 5). The lower half of the pillar was used for the ultrasonic stress monitor since it was dominantly composed of

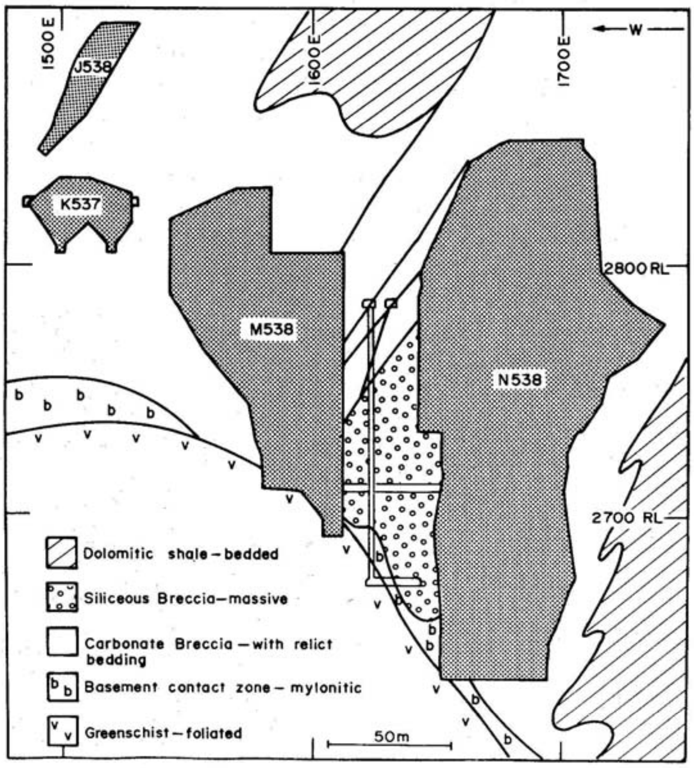

Fig. 5. Section facing north through the M538 pillar showing the bored raise and geological setting. The bedding planes shown in the top half of the pillar dominated response to stress.

unstructured silicified dolomite. The top half of the pillar was more dolomitic and had relic bedding planes developed through it. Movement on these bedding planes dominated the stress relief processes observed.

A 1.8 m dia raise had been bored near the centre of the pillar for installation of various devices (Figs 5 and 6). Four ultrasonic stress monitoring paths were located near the base of the pillar; two in the vertical direction, one east–west and one north–south. The system sampled a volume of dimension approximately 10 × 10 × 10 m in the pillar. Near the centre of this volume a set of borehole capacitance strain monitors [12] was located to allow comparison of stress and strain fields. At critical times during the excavation sequence soft inclusion [13] and pin rosette overcoring [14] strain measurements were made by M.I.M. personnel. These point measurements were in part aimed at providing control on the ultrasonic stress monitor which must be calibrated *in situ* for high reliability. It is not possible to measure the absolute stress from velocity measurements or to infer from composition the velocity stress sensitivity of a particular site. The absolute stress must be obtained from another technique, and though the velocity stress sensitivity can be measured in a laboratory sample such a figure is of questionable value as an average for a whole rock mass.

RESULTS

The performance of the ultrasonic stress monitor during periods of the excavation in which no obvious loading events were occurring allows some estimate of the intrinsic precision of the velocity measurement and of the stress sensitivity of the system. Table 1 shows a synopsis of one such period (21 days of data on all channels). The data quality varies somewhat from channel to channel, being controlled mainly by anisotropic attenuation in the pillar. The standard deviations of data over each hour were calculated and the table shows the number of hour averages in 24 days which occurred in each time interval.

Thus for this location good paths have standard deviation over hour data of order 5 nsec in travel time of order 1 msec. This implies that stress changes of order 0.01 MPa are observable. Changes of stress of order several megapascals occurred in the course of the experiment giving more than adequate resolution.

TABLE 1. SAMPLE STANDARD DEVIATIONS OF HOURLY DATA ON ALL CHANNELS

Standard deviation 1 hr data	Down	Across	Up	Along
0–1 nsec	0	88	3	8
1–3 nsec	2	237	60	52
3–5 nsec	23	188	272	174
5–9 nsec	216	37	145	249
10–20 nsec	255	17	48	73
>20 nsec	80	9	48	20

The mining sequence opposite the M538 pillar is shown in Figs 6 and 7. In the course of ore recovery the upper part of the M538 pillar (in particular the zone of bedding plane shear in Fig. 5) was isolated on the south side by the removal of the M534 pillar in February/March 1977, during mining sequence number 2. Retreat direction was to the east. Expected vertical stress increase during the mining sequence did not occur. The data presented below indicate that the period from August 1976 to December 1977 produced general increase of travel time on all paths. This implied destress of the pillar was confirmed on all other data (Lee *et al.*, in preparation). Rod extensometers across the basement contact actually revealed a rebound shear of 2 mm. Bedding plane shearing in the top of the pillar up to 25 mm was observed with about 70% occurring by the end of April 1977. 'Absolute' stress measurements in the pillar showed in general little change from the premining values (e.g. vertical from 22 ± 1 to 16 ± 2 MPa after the sequence), at four of the five sites measured. At one site below the ultrasonic system an abnormally high N/S component (59 ± 11 MPa compared with typical figures of 16 ± 1 MPa) was measured. There is no evidence at the USMD site that any such anomaly occurred, and all stress drops were less than 10 MPa over the measurement period.

The first major destress of the pillar was recorded by the vertical component and it was accompanied by smaller stress decreases on the E/W and N/S channels. These changes are consistent with initiation of shearing on bedding planes shown in the top of the pillar (Fig. 5). In late April the M541 pillar was undercut opposite the M538 pillar by mining sequence number 4 accompanied on all three channels by further destressing at the USMD site. Figure 8 shows the destress episode in late April. It is important to note that the stress relief process is not "instantaneous', and that it does not occur by a continuous (plastic like) deformation. The mechanism is clearly a sequential series of stress accumulation and relief episodes producing a slow net secular change of stress level.

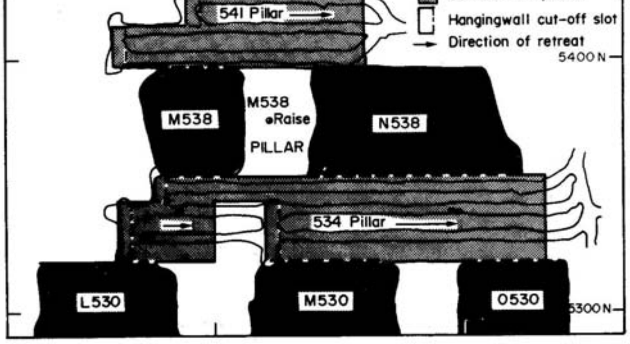

Fig. 6. Plan view of experimental site, showing the bored raise in the M538 pillar.

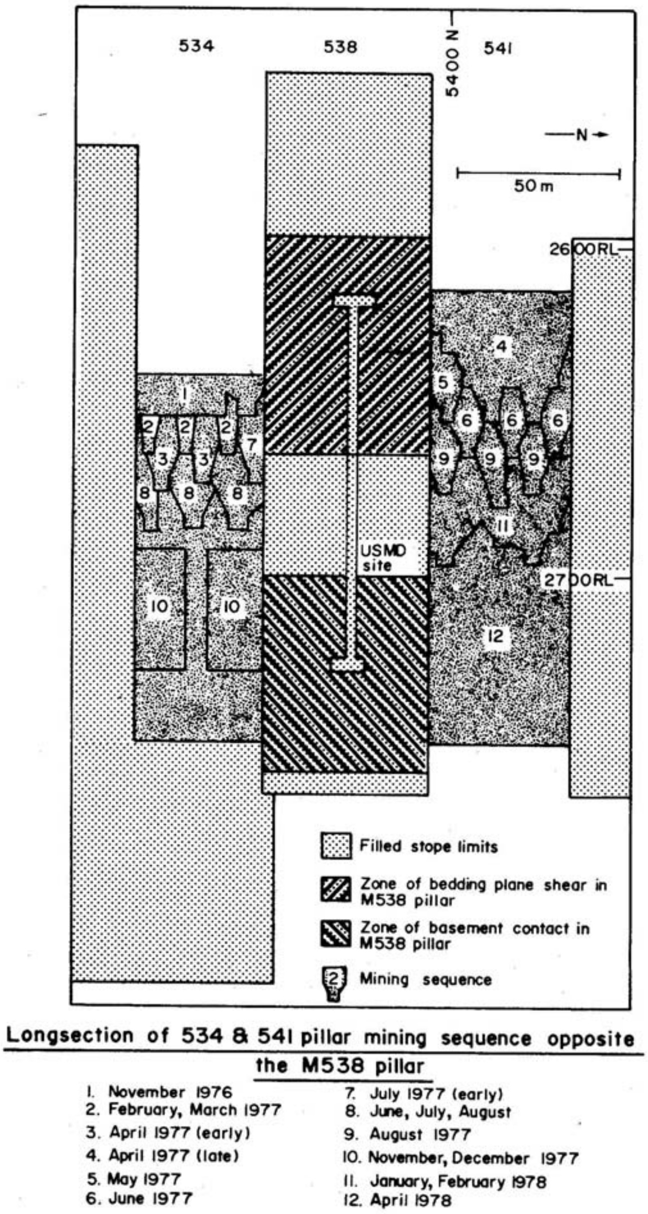

Fig. 7. Mining sequence opposite the M538 pillar giving times of major recovery blasts.

This record is particularly interesting in that within the volume of rock sampled the relief response on the E/W axis did not begin until nearly 10 days after the N/S and vertical axes had begun to destress on April 18. Stress loading from the other two axes into the E/W path is evident until on 28th April, the E/W path began a destress event producing nearly 2 μsec travel time change in 752 μsec travel time, over a 4 day period to May 1st.

Further changes occurred as mining sequences 5, 6, 8, 9 and 11 increased the common exposure height of the pillar from 5 m after sequence number 5, to 40 m after sequence number 11. Figure 9 gives another example presentation of the nature of this relief process for a series of events in July 1977. Of particular significance in this figure is the close correlation of the observed velocity changes with the borehole strain monitor output (channel 5). This instrument is totally independent eletronically and has totally different principles of operation. The ultrasonic travel time changes are accompanied by strains of more than 2×10^{-5} over the period shown in this figure. Correlations of this nature give increased confidence in the reality of signals observed on the stress monitor. In this record stress relief episodes were generally simultaneous with strain relief events.

A detail from Fig. 9 is reproduced in Fig. 10 to permit closer comparison of the stress/strain data. The strain relief event shown on BCSM 5 is seen to be composed of a series of strain steps (which usually occur at or near blast times and which are assumed triggered by the nearby blasts). These are connected by continuous strain accumulation in the direction of the trend line of the whole event. It could perhaps be inferred on elastic grounds, that the strain relief is accompanied by a decrease of stress. Examination of the N/S travel time data however, indicate clearly that between the instantaneous stress relief events (associated with blasts) ultrasonic travel time is constant indicating that the strain is occurring at constant stress. This is shown by the strong departures from the trend line of the travel time data through the episode (e.g. July 19, 1977), which shows nearly constant velocity during the continuous sections of the strain events. Hence since stress remains approximately constant and strain is accumulating we have an environment better described as a steady state creep interrupted by elastic relief events triggered by routine blasting.

Simultaneous monitoring of stress and strain allows estimates of *in situ* elastic and plastic moduli to be made. In simple cases these depend on some independent absolute stress estimate such as is provided by soft inclusion cells measured at or near significant events. The continuous stress monitor is then calibrated between fixed points and permits detailed stress concentration or relief mechanisms to be examined. The travel time data is integrated over time to produce an accumulated stress estimate which is calibrated against the point stress measurements. The data of Fig. 10 for example, shows a strain change from July 17 to 22 of approximately 2×10^{-5} indicating significant strain relief without massive failure.

In the absence of absolute stress measurements, the *in situ* stress sensitivity of the rock mass can always be estimated with fair confidence by analysis of the instantaneous relief events shown on Fig. 10. If we accept the measured modulus of order 80 GPa as typical of the whole pillar and that the *instantaneous* events are dominantly elastic, the measured strain steps represent stress increments of order 0.1–0.2 MPa. Thus, by direct observation of the travel time steps associated with each strain step we can deduce an average velocity stress sensitivity ($\Delta V/V$/MPa) for the area of 2.77×10^{-3} per MPa, which is quite typical for the rock type. The event sequence on July 17–22 (Fig. 7) thus rep-

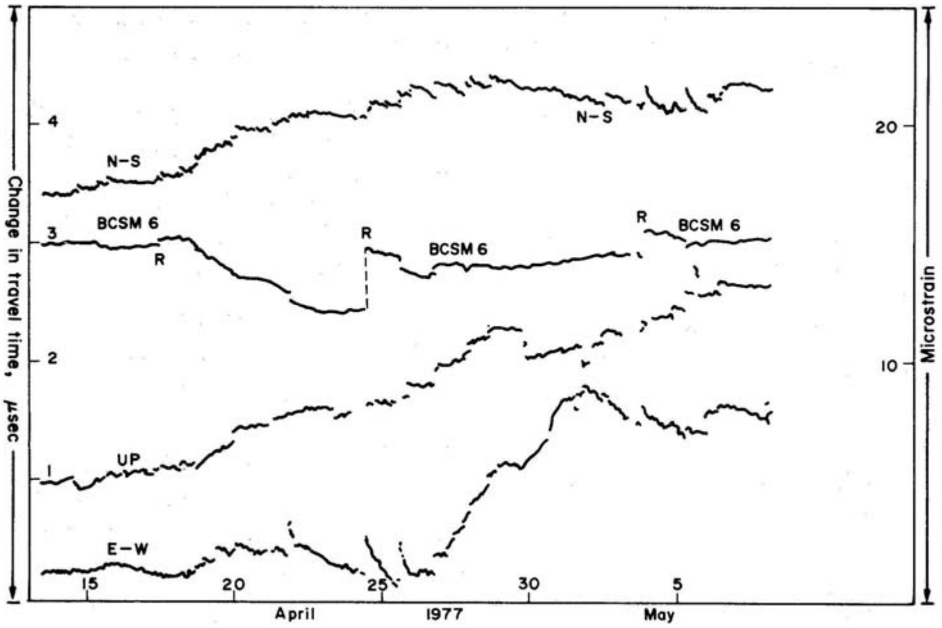

Fig. 8. Ultrasonic travel time data for three axes (vertical, north–south, and east–west) for the period April 15, 1977 to May 8, 1977. Travel time change is shown in microseconds. The stress relief is seen to occur by a series of triggered instantaneous events separated by recovery sequences. Note the delayed response of the E/W component. The fourth trace is the borehole strain monitor for which full scale strain response is 2.5×10^{-5}.

resents a stress relief of approximately 0.8–0.9 MPa. From the total strain accumulation (elastic plus plastic) over the period 18–22 July we can then infer that the pillar modulus (*in situ*) is nearer to 40 GPa. This can also be inferred by noting that nearly half of the observed strain in the pillar is non-elastic. Future studies will concentrate on better determination of elastic/plastic behaviour and measurement of moduli.

CONCLUSIONS

Where rock quality permits its use, ultrasonic stress monitoring allows immediate isolation of elastic from plastic deformation processes in mining recovery sequences. Stability criteria based on stress monitoring should be able to provide valuable supplement to normal strain monitoring.

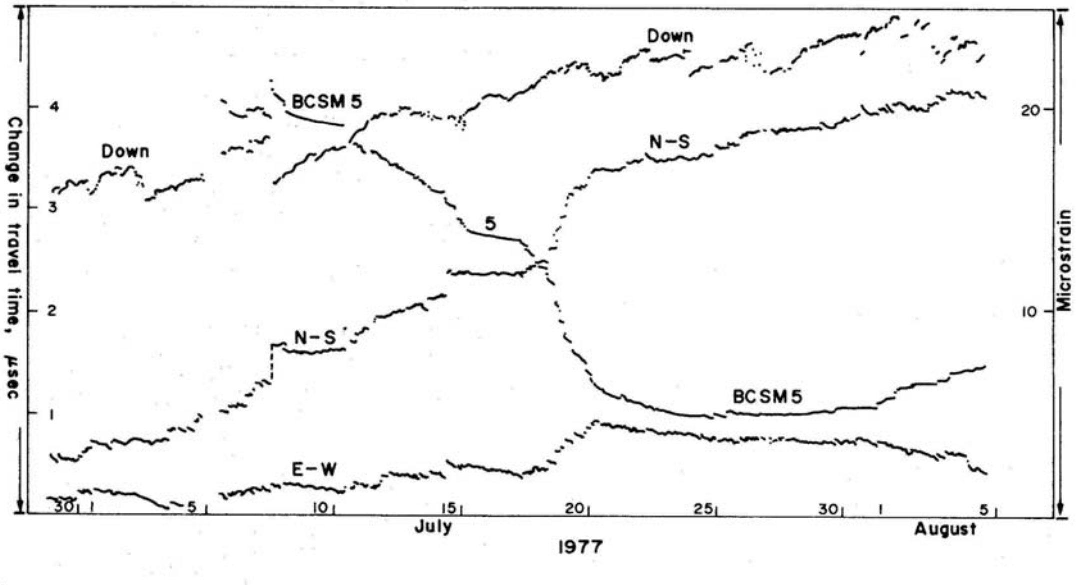

Fig. 9. Another stress relief sequence. Here all components remain synchronous. The total stress event is approximately 0.9 MPa on the N/S axis. The strainmeter (BCSM5) is included for comparison.

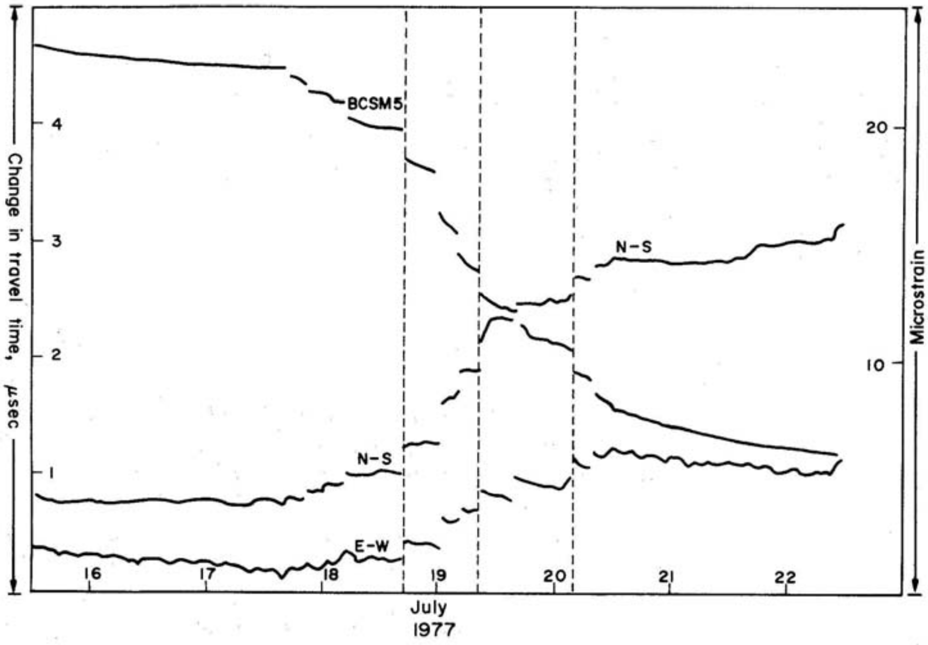

Fig. 10. Detail of Fig. 9 in which the mechanism of strain accumulation at near constant stress followed by elastic failure is clearly shown. Elastic and plastic modulus for this region can be distinguished.

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