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Simultaneous Monitoring of Stress and Strain in Massive Rock

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Abstract – Continuous measurements of ultrasonic pulse transit times over 10 m baselines between fixed points in each of three mutually perpendicular directions are made routinely in solid rock. The most significant current experiment is in a large underground support pillar (30 m × 30 m × 200 m high) 700 m below ground level in an active mine. Velocity measurements to a precision of 2 parts in 10^6 allow stress changes of order 1 kPa to be monitored, and compared with simultaneous strain measurements (for which a capacitance strain sensor is used) to examine the mechanisms of large scale stress relief processes. Characteristic stress relief cycles (of magnitude 200–3000 kPa) are found to migrate through the pillar as impressed loads are accommodated by the rock mass.

Key words: Stress in situ; Seismic velocity anisotropy; Creep.

1. Introduction

Numerous strain monitoring techniques have been developed for geophysical use. In most instances strain measurements are used to infer stress conditions, and an in situ elastic modulus must be observed or assumed. However, in many cases observed strain is not directly related to the accumulation of elastic energy, since stress is almost invariably accompanied by anelastic creep and redistribution of block boundaries. These relief processes are particularly relevant on the long time scales of the monitoring programmes for shallow earthquake studies and are important also in mining situations.

In the present experiment, the stress dependence of acoustic velocity, which accompanies the phenomenon of pore closure at low ambient stress levels (<2 k bar), is used to monitor stress in a large underground mining support pillar as part of a cooperative programme (Bridges *et al.*, 1976). The stress dependence of acoustic velocity has not yet been widely used for monitoring, probably because early workers (Kanamori, 1970; Fedotov *et al.*, 1970; Eisler, 1969) concentrated on long base line measurements which necessitated the use of explosive sources, and which have a low total path sensitivity to stress since for most of the ray path the conditions of

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hydrostatic pressure ensure that pore closure is essentially complete. Short baseline measurements are not subject to these limitations, and routine continuous monitoring at much higher sensitivity, using boreholes up to 100 m apart is quite feasible.

REASENBERG and AKI (1974) presumably recognized this in their use of timed pulse trains from an air gun in water. However, in this experiment and in the previous work of DE FAZIO, AKI and ALBA (1973), implausibly high apparent sensitivity of velocity to stress (20 % per bar) was obtained, quite out of line with laboratory measurements and our own better controlled observations. Their very high sensitivities are due partly to the fact that observations are made at the surface at low ambient stress levels, partly to the ambiguity in separating the chosen Rayleigh wave arrival maximum from the *p*- and *s*- wave codas but more particularly because their observation (which is essentially a phase velocity measurement) is subject to amplitude variations on all of the multiple paths which reach the detection point (GLADWIN and STACEY, 1974). Their observations appear to be limited to ± 0.15 ms in 170 ms ($\approx 0.1\,\%$) and, as inferred in their summary, resolution at this level is of little significance for geophysical observations at reasonable depths. Observation of *p*-wave first arrivals is not subject to such limitations.

Ultimate stress sensitivity in such a system is determined by the accuracy of timing of individual pulse transits. This is limited by the degradation of pulse rise time with distance from the transmitter, but it can be shown [GLADWIN and STACEY, 1974] that this rise time is actually proportional to travel time, so that the relative precision of a velocity measurement is independent of travel time provided no instrumental limitation is imposed by the timing electronics. Demonstrations that multiple sampling of acoustic pulse arrivals reproducibly improves the timing precision in an almost perfect statistical ($\sqrt{N}$) manner have been reported (GLADWIN, 1973; GLADWIN and STACEY, 1974) and are here confirmed. By averaging travel times of 10^4 pulses at 20 ms intervals, the averaged readings (obtained at 200 sec. intervals) are found to be reproducible to several nanoseconds although individual pulses over 5 m paths (about 900 μs travel time) can be timed only to about 0.2 μsec.

Experiments of this kind in tunnels of the Snowy Mountains Hydroelectric Authority and in both lead and copper ore bodies at the Mount Isa mine in North Queensland, in which tunnelling and mining operations have produced stresses which were believed to be approximately known, have all yielded velocity changes corresponding satisfactorily with the velocity stress sensitivities established by laboratory measurements.

The most recent experiment uses an orthogonal array of velocity monitors in a pillar in the copper ore body at Mount Isa. Simultaneous measurements of strain are being made with a borehole capacitance strain meter developed for the project from the highly linear displacement transducer previously reported (STACEY *et al.*, 1969; GLADWIN and WOLFE, 1975). Apart from providing routine analysis of the state of stress of the pillar (of which a reasonably large volume (10^4 m^3) is sampled), comparison with the independent strain measurements allows both the elastic and inelastic components of the loading sequence to be isolated. The pillar, which is to be taken through an extended stage of vertical uniaxial compression as part of a mining sequence, provides a very large scale quasi-laboratory experiment which should allow conclusions to be drawn on the mechanisms of stress relief and redistribution in massive rock.

2. *Ultrasonic stress monitoring*

Changes in pulse travel time due to changes in compressional wave velocity in the direction of propagation are proportional over a limited range to changes of stress in the rock. For most sites in massive rock the stress sensitivity of pulse velocity is of order 1 part in 10^6 per kilopascal (1 part in 10^4 per bar) allowing stress change of 5 kPa (1/20 bar) to be resolved easily. The system is sensitive to changes of either hydrostatic or deviatoric stress. Each installation consists of a magnetostrictive transmitting transducer (resonant at 37.5 kHz) and two piezoelectric detectors set in three parallel 90 mm boreholes. For spot monitoring (required by mining personnel) a portable measurement package is used to produce a mean travel time averaged over any number of pulses chosen by the operator (typically 10^3 or 10^4). For the current continuous monitoring experiment in the Mt. Isa copper ore body, a number of installations are multiplexed into a single timing module and the travel times are digitally serialized via a telephone line to a 7 track incremental magnetic tape recorder (in an air conditioned control room). Four paths are being monitored, two in the vertical direction and two at right angles to each other in the horizontal plane. A significant improvement and simplification of the technique, as originally described (GLADWIN 1973), has been obtained by timing the first zero crossing of the p-wave arrival instead of using an arbitrary discriminator level on the leading pulse. A histogram of standard deviations of hourly readings over a six day period for a particular station (travel time 905 μs) shown as Fig. 1, indicates the reproducibility of observations. More than 50 % of all the data show hourly standard deviations of 2 nanoseconds or less, i.e., a timing precision of 2 parts in 10^6. It should be noted that these data have been obtained in a site with very high ambient noise, in an active mine, within 100 m of routine drilling operations. This is accomplished because the rapid spatial attenuation of mine-generated high frequency noise allows a good signal to noise ratio at the chosen frequency. This precision could not in principle be achieved using techniques such as those of REASENBERG and AKI (1974), who do not use first arrivals, but is necessary for stress monitoring in sites which have realistic velocity-stress sensitivities.

Calibration of the ultrasonic stress monitor for each particular site is achieved by direct comparison of observed velocity changes with the long term stress changes observed by over-coring of soft borehole inclusion strain meters every few months and by direct comparison with strain observations. Laboratory observations on the elastic properties of the rock which is a strong recrystallized breccia of compressive strength 170 MPa have also been made.

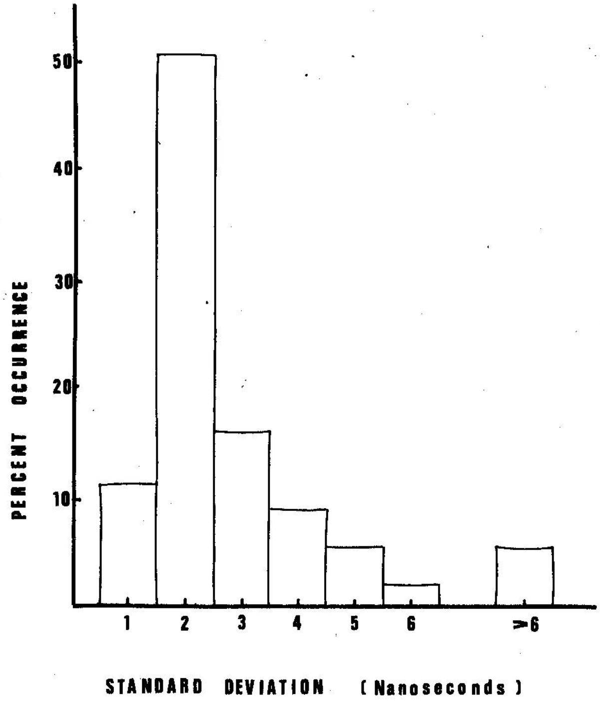

Figure 1
Histogram of hourly standard deviations of time of flight readings for a 5 m path ($t = 905$ μs) in the Mt. Isa copper ore body over a six day period in February 1976.

Recordings during 1974 in the Mt. Isa lead ore body yielded the following results:

(1) Changes of velocity of predictable magnitudes, totalling up to 7% at one site, occurred as loading was increased through approximately 40 MPa (400 bars).

(2) Velocity anisotropies of up to 3% were observed in extreme cases.

(3) Stress relief processes occur by episodal relief events. These are characterized by gradual increase of velocity in the direction of increased stress toward a reasonably constant level representing the maximum which the rock can withstand, followed by a more dramatic decrease in velocity accompanying local failure and stress relief. An example is shown in Fig. 2.

(4) Relief events, when they occur, typically give stress drops in the range 500–3000 kPa (5–30 bars). These values are estimated from laboratory measurements of stress sensitivity and are consistent with known long term total loading figures and overcore measurements.

(5) The stress relief events are not instantaneous but typically occur over periods of 4 to 6 hours.

(6) Stress relief events in the direction of maximum principal stress are not simultaneously transmitted to the minor stress axes in nearby areas.

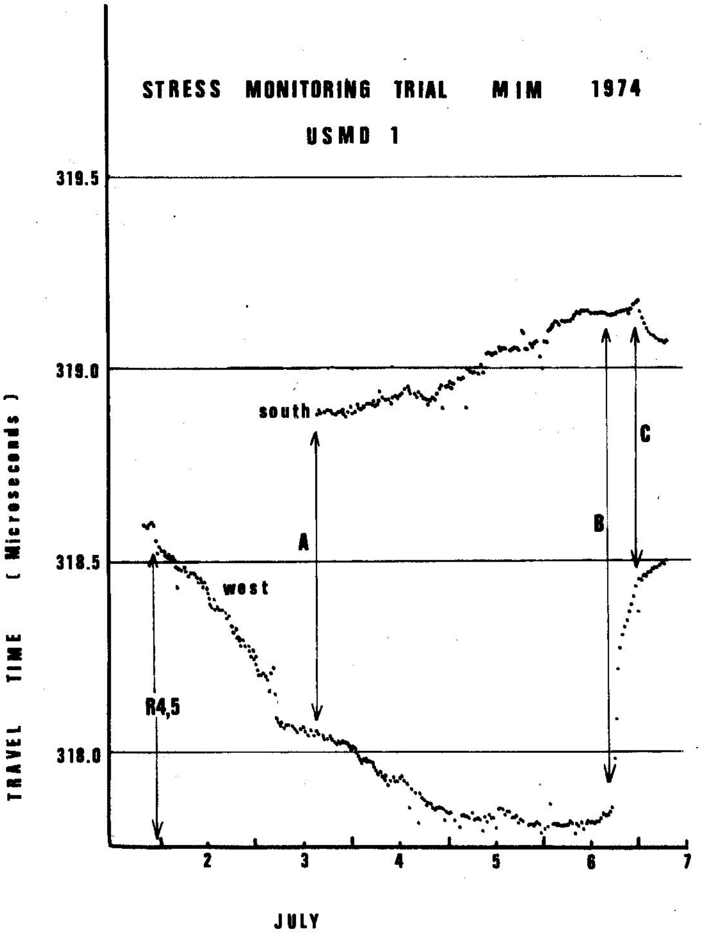

Figure 2
A stress relief event in the Mt. Isa lead ore body. Raw travel times for two short paths at right angles to each other are shown over a six day period. The stress release initiated at B on the lower plot has a magnitude of approximately 30 bars.

(7) The number of stress-relief events per unit time tends to increase prior to massive failure of the whole rock body.

Measurements of stress (as distinct from strain) are notoriously difficult to make in a mining environment. Thus the stress relief events observed in this experiment are of particular interest. The one reproduced in Fig. 2 is representative. Two nearly perpendicular paths are shown. The one marked WEST coincided with the near-vertical maximum principal stress and showed an increase in stress initiated by firing at the time marked (R4,5) of two rings of explosive which removed adjacent supporting rock. The second path (SOUTH) was displaced by 5 m from the West path, but in the absence of inelastic effects would be expected to show a simultaneous reduction in stress. At the time of firing no marked changes in velocity occurred. However, the expected velocity changes occurred over the next few days. At the point marked B, after the west path had reached what seemed to be a steady state, a stress relief event (increase in travel time) occurred at a time unrelated to mining activity. At this time the south path showed no response, but about 7 hours later (C in Fig. 2) an increase in stress is indicated, evidently when the relieved stress on the west path was transferred to the region sampled by the south path. The inferred stress relief of the west path was 3000 kPa (30 bars).

3. *Simultaneous strain monitoring*

The 1974 velocity observations in the Mt. Isa lead ore body were not accompanied by well controlled strain measurements. In the current programme in the copper ore body, use is made of a new borehole strain meter based on the capacitance displacement technique developed in this department (STACEY *et al.*, 1969); MCKAVANAGH and STACEY, 1973; GLADWIN and WOLFE, 1975; DAVIS and STACEY, 1976). The strain meter measures plane strain perpendicular to a 90 mm borehole approximately 8 m long. Each instrument has three independent sensors with strain sensing axes at 120° to each other. On each axis the change in diameter of the borehole is monitored using a three plate capacitor with centre plate mounted from one end of the diameter and outer plates mounted from the opposite end. Strain is routinely recorded to 1 part in 10^8. The strain meter probe is located close to the ultrasonic stress monitor.

During 10 months of continuous operation a systematic strain rate of about 3×10^{-8} per day has been observed. During periods of stress accumulation (as measured by increase in ultrasonic pulse velocity) this strain rate tends to decrease. An example of simultaneous stress and strain data is shown in Fig. 3. The mining extraction sequence which will ultimately put the pillar into uniaxial compression is in its early stages, so that only small loading events are available for study so far. The strain step (magnitude 9×10^{-7}) at midnight of 30 July, was triggered by a major blast at that time. A decrease in travel time over an ultrasonic path with the same orientation as the strain sensor occurred over the next five days, as the load was redistributed in the pillar. At the end of this time, (August 5), a stress relief event occurred without a strain increment and the strain trend returned to the normal long term drift rate. The July 31 strain step (on the upper plot) would, if elastic, correspond to a stress change of order 50 to 70 kPa (0.5 to 0.7 bars). The total associated velocity change over the next 5 days was 0.44 microseconds. With the approximate velocity-stress sensitivity of 2×10^{-6} per kPa (2×10^{-4} per bar), the corresponding stress change would be 240 kPa (2.4 bar). It may be possible that the stress sensitivity is increased to approximately 7 parts in 10^4 per bar by microcracks, but in any case the observations are obviously not explicable in terms of elastic deformation. The stress relief event on August 5 is a striking example of effects observed many times in both the lead and copper ore bodies at Mt. Isa. None of the observed events appear as straightforward elastic deformation.

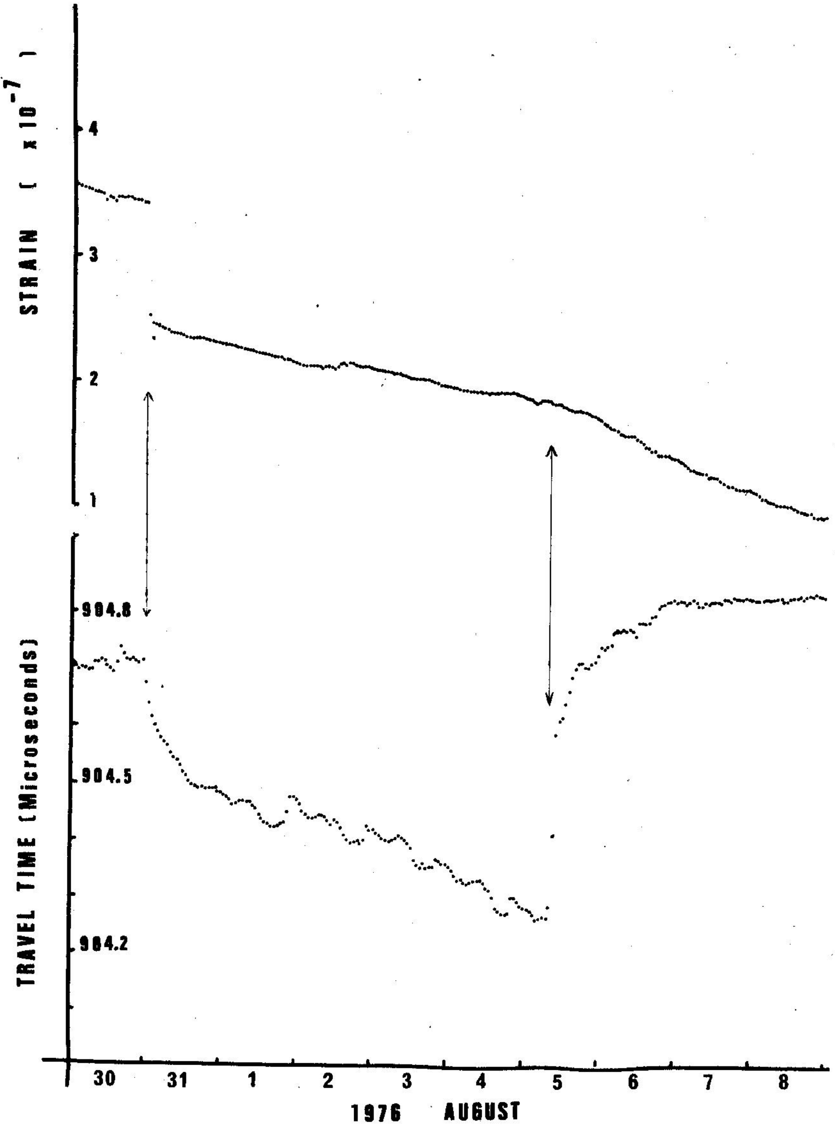

Figure 3

Hourly average values of strain and of ultrasonic travel time (inferred stress) at a particular site in the copper ore body at Mt. Isa. The increase in velocity associated with the strain step on July 31 occurred over a period of five days during which an anomalous strain rate was also observed. A typical stress relief event, accompanied by a change in the strain rate, occurred on August 5.

4. *Summary*

Simultaneous monitoring of stress and strain allows the separation of elastic and inelastic processes of rock deformation. In the experiments reported here, in situ deformation of rock is found to be so dominated by inelastic processes that we are doubtful of the validity of stresses inferred from strain observations. Use of ultrasonic stress monitoring would be a valuable extension to many current strain monitoring programmes.

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