Pageoph, Vol. 116 (1978), Birkhäuser Verlag, Basel

Velocity Anomalies: An Alternative Explanation Based on Data from Laboratory Experiments

By D. A. LOCKNER and J. D. BYERLEE[1])

Abstract – Locations and velocities were calculated for microseisms occurring in samples of rock subjected to triaxial loading and injection of pore fluid. This was accomplished by analyzing arrival times of acoustic emission using an automatic first arrival picker. Apparent velocity anomalies were observed prior to both failure of intact samples and violent slip in samples containing saw cuts. Further analysis revealed that these fluctuations in calculated velocity were not due to changes in the true seismic velocity. Instead, variations in calculated velocity are shown to be related to sampling errors in picking first arrivals. The systematic picking of late first arrivals for small magnitude events was found to be a persistent bias resulting in low calculated velocities. This has encouraged the reexamination of earthquake records to determine how important sampling biases are in contributing to reported velocity anomalies.

Key words: Velocity anomalies; Microfractures; Stick-slip.

Introduction

Numerous studies have used small earthquakes to estimate *in situ* material velocities prior to larger earthquakes. The material velocity anomalies inferred by various adaptations of this technique (AGGARWAL *et al.*, 1973; WHITCOMB *et al.*, 1973; ROBINSON *et al.*, 1974) constitute much of the positive evidence for the dilatancy model for earthquake precursors (NUR, 1972; SCHOLZ *et al.*, 1973).

LOCKNER and BYERLEE (1974) reported an apparent drop in averaged calculated velocities prior to failure of intact samples of sandstone. In subsequent experiments with both intact samples and samples containing saw cuts, a 5 percent drop in average calculated velocity prior to failure was commonly observed. When looked at more closely, low calculated velocities were found to be correlated with low amplitude microseisms. We intend to demonstrate in this paper that with careful choosing of the data, this biasing can be greatly reduced. When this is done, fluctuations in the calculated velocities are also reduced.

In our experiments, first arrivals are picked automatically by an electronic device. Although hand-picked arrivals are more reliable, LINDH *et al.* (1978) have shown that they are still subject to the same sampling bias that we have observed for our automatic

---

[1]) U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA.

picker. This is especially true for small magnitude events with emergent first arrivals. For this reason the authors feel that the results reported in this paper will be of interest to seismologists as well as to experimentalists.

Experimental method

A cylindrical sample of Westerly Granite, 19.05 cm long by 7.62 cm in diameter, was prepared for laboratory tests. The sample was cut in half along a plane oriented at an angle of 30° to its axis to model a crustal fault. Six piezoelectric transducers were cemented to the sample to monitor the acoustic emission produced during the experiment (Fig. 1). The sample was mounted in a pressure vessel and confining pressure of 1000 bars was applied. An additional differential stress could be applied by advancing a piston against the end of the sample. Oil (Shell Tuellus Oil #5) was injected onto the fault plane through a 0.24 cm diameter bore hole drilled down the axis of one-half of the sample (Fig. 1). Acoustic emission in the sample was monitored for differential stresses ranging from 1.3 to 2.23 kb and bore hole pressures ranging from 0 to 820 bars.

The six piezoelectric transducers cemented to the sample have a resonant frequency of 600 kHz. However, due to the manner in which they were mounted, their overall response was actually about 300 kHz. A complex electronic timing system was used to monitor the output of the transducers. In this system, a threshold level is set on each input channel. When the absolute value of the transducer signal on any of the channels rises above the threshold level, timers are started on the other five channels that record the relative arrival time of the acoustic signal to ±0.05 μsec accuracy. Thus the first arrivals are picked according to signal amplitude. These six relative arrival times, as well as the maximum amplitude seen on each channel, are digitized and written on magnetic tape for computer analysis. Figure 2 shows traces for two acoustic emission events recorded by the system.

The three-dimensional location of each microfracture as well as the velocity of the acoustic wave traveling from the source are calculated from the relative arrival times. The calculation is accomplished using techniques employed by seismologists in locating earthquake hypocenters, and was described for this experimental set-up by BYERLEE and LOCKNER (1977). Briefly, the method uses the six relative arrival times to estimate location, origin time and wave velocity by means of a least-squares fit. The ±0.05 μsec timing error for the arrival times limits the accuracy of locating each event to approximately 0.1 cm. It also limits the resolution of the velocity of each acoustic wave to about 0.05 km/sec. The amplitudes associated with each event are recorded in arbitrary units over a range from 1 to 99. The electronic timing system is capable of recording continuously at a rate of 300 events/sec and for short bursts of up to 32 events at a repetition rate of 25 kHz.

Because the location technique uses six measurements to estimate five unknowns,

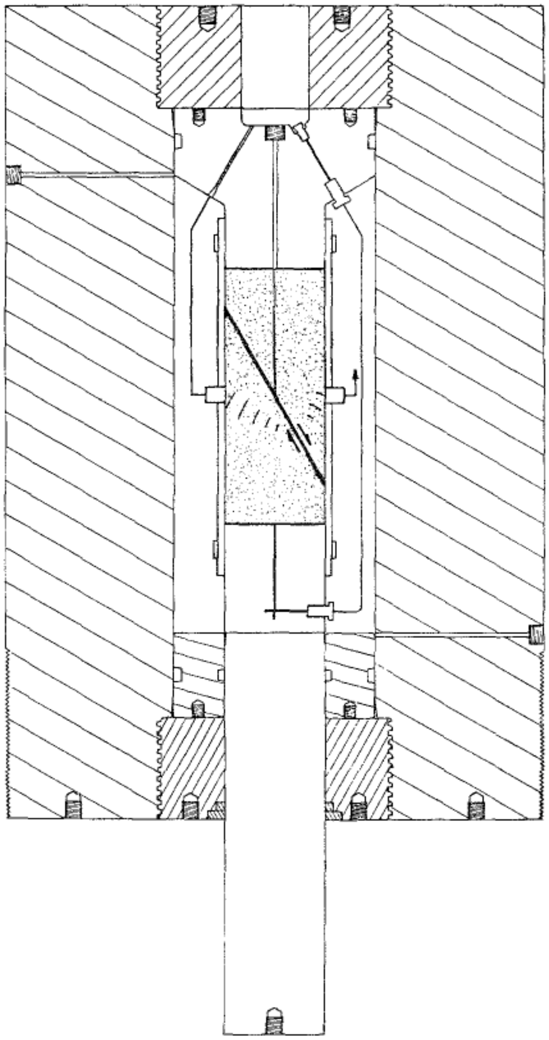

Figure 1
Schematic diagram of sample mounted in pressure vessel. Confining pressure and differential stress are first applied to the sample. Injection of fluid onto the fault plane results in unstable slip. Microseismic events are monitored by six transducers cemented to the sample (two of which are shown in this view).

we are restricted in our ability to estimate the reliability of any individual measurement. Errors in estimating velocity tend to be correlated with errors in the estimated origin time. Because of this we can expect to see velocity errors much larger than the 0.05 km/sec limit. Working in our favor is the fact that whereas seismologists typically work with a population of tens of earthquakes, we normally locate between hundreds and tens of thousands of microseisms. Thus, random errors in estimating velocity can be reduced by simple averaging. Non-random biases, as will be shown in this paper, must be dealt with more carefully.

One such bias that is a potential problem stems from the fact that the estimating technique assumes an isotropic velocity field. Independent measurements of compressional velocity under stress conditions, similar to those of this experiment, show that velocity anisotropy remained less than 2 percent. This could introduce an error of at most ±0.06 km/sec.

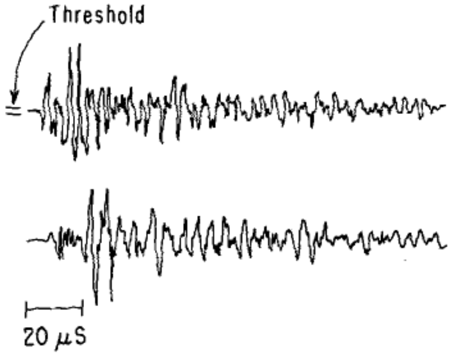

Figure 2
Traces of two acoustic emission events recorded by the electronic timing system. Threshold level required to trigger timers is shown in front of the upper trace.

Laboratory results

During the laboratory experiment, 742 microseismic events that had amplitudes in the range of the recording equipment were recorded. The majority of these events were located near the fault plane (saw cut) in the center of the sample. We will first look at a group of 140 of these events that occurred over an interval of 20 seconds prior to a single slip event on the saw cut. During this time, pore pressure was 500 bars, confining pressure was 1000 bars and differential stress rose approximately 15 bars to a maximum of 2.23 ± 0.01 kb. The slip event was accompanied by a stress drop of 680 bars. Averages of calculated velocities for microseisms that are greater than 4.5 km/sec are plotted in Fig. 3. Circles are the means of groups of twenty events. Error bars show 1 standard deviation. These averaged velocities change by about 0.3 km/sec giving a 6 percent change in velocity. Standard *f* and *t*-tests performed on the maximum and minimum of these mean velocities shows that they are significantly different at the 95 percent confidence level, even though they differ by less than 1 standard deviation. A remarkable result is that this variation is substantially reduced by using only those events for which all six receiver stations recorded a first arrival amplitude greater than 4 (out of a range of 1 to 99). Averages for groups of ten of these events are plotted in Fig. 3 as square symbols. These velocities are consistently higher, agreeing with independent measurements of P velocity in Westerly granite at these stresses. The variation in velocity for these events is now less than 3 percent. Thus, we have shown in Fig. 3

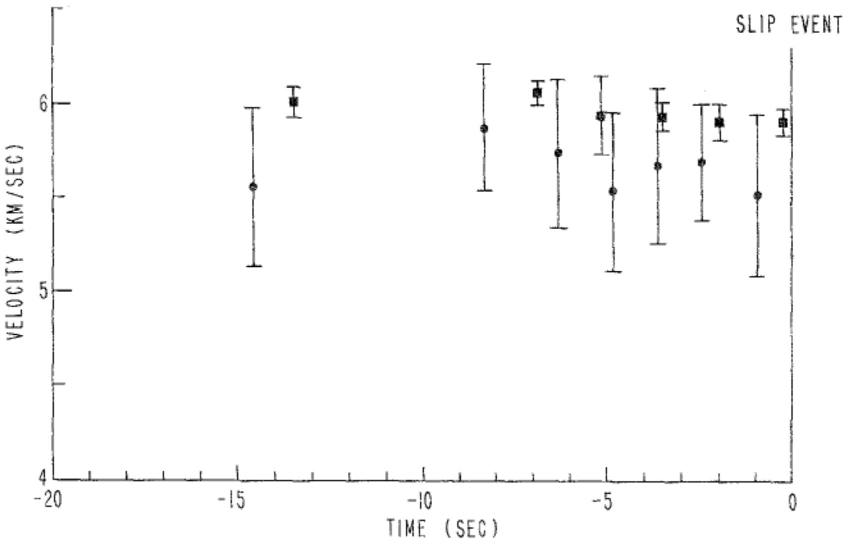

Figure 3

Averages of calculated velocities for microseisms occurring prior to a violent slip event. Average of events of all amplitudes; average of events that had an amplitude greater than 4 on all stations. Error bar is 1 standard deviation.

that the use of small amplitude signals increases the likelihood of picking late arrivals, producing consistently low estimated velocities. This effect can also introduce fluctuations in the mean velocity which appear statistically significant. However, we have shown that this is due in fact to the introduction of measurement bias into the data.

The errors introduced into the calculated velocities can be studied in a different way. Figure 4 is a plot of the distribution of the calculated velocities for all 742 microseismic events in this experiment. In Fig. 4 we have divided the events into two groups: those events having amplitudes between 1 and 9.9 (units are arbitrary) and those events having amplitudes between 10 and 99. The peak in the distribution in Fig. 4 corresponding to a velocity of 5.9 km/sec is in agreement with independent measurements of *P* velocity for Westerly granite at these stresses (Roger Stewart, personal communication). We therefore assume that this represents the true *P* velocity in this experiment. The large peak at 2.3 km/sec is too low to be the *S* velocity and may be due to a reflected arrival. Note that many events give velocities that are significantly different from the true *P* velocity. This deviation cannot be explained by the 0.05 μsec timing errors at the stations. We will next discuss how this can occur.

Discussion

As stated in the preceding section, Fig. 4 shows the distribution of calculated velocities for large and small amplitude events. We explain the salient features of Fig. 4

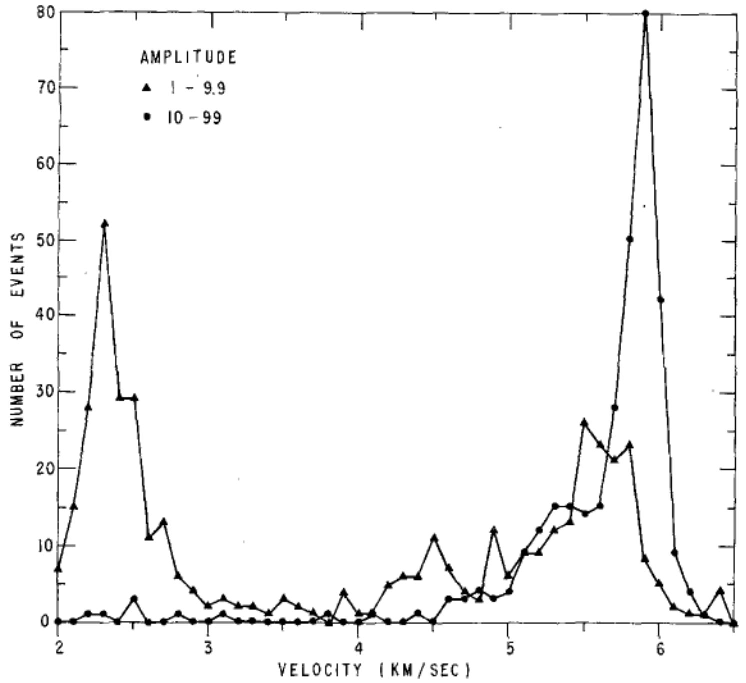

Figure 4

Calculated velocities are shown for seismic waves produced by microfractures occurring in sample. Velocities are divided into two groups having amplitudes (in arbitrary units) of 1 to 9.9 and 10 to 99.

by studying the manner in which arrival times are picked by our electronic timing apparatus. First note that nearly all velocities below 4.5 km/sec are found only for small amplitude events. We suggest that for those events that give such low velocities, the *P* arrival at the stations is too small in amplitude to trigger the system. Consequently, the larger amplitude *S* arrival or a reflected mode is the first signal to be recorded. For large amplitude events, the *P* arrival is apparently large enough to trigger the timers.

A remarkable result seen in Fig. 4 is that the peak in the distribution of small amplitude events for the *P* velocity is about 0.2 km/sec lower than the larger amplitude peak. Our explanation of this phenomenon is based on the attenuation of the acoustic wave as it propagates away from the source region. By the time the wave has traveled to the farthest stations, the first arrival has been attenuated to such a degree that it is of too low amplitude to trigger the timing system. As a result, the far stations will trigger on a later part of the wave form than the near stations. This will result in an apparent lower velocity. A 0.2 km/sec shift corresponds to a timing error of between a half and a full wavelength at the distant stations.

This argument is further supported by the shape of the *P* velocity distributions for both the small and large amplitude events. If the scattering in the velocities were due to random timing errors, we would expect them to be symmetrically distributed about the mean. Instead, both large and small amplitude distributions are skewed towards lower velocities. If the acoustic waves are attenuated as they travel to the distant stations, there are two possible results. First, the signal will be of large enough amplitude that even after being attenuated, the first arrival will be picked. Alternatively, the signal will be of small enough amplitude that the first arrival will be missed and the station will trigger late. In the first case, the true *P* velocity will be obtained, and in the latter case, lower velocities will result, producing skewed distributions as in Fig. 4.

An alternative explanation for the skewed velocity distributions could be related to the radiation pattern of the acoustic waves. If a station happens to be located near a node in the *P*-wave radiation pattern, the resulting low amplitude signal could be triggered on a late arrival. This would result in a calculated velocity lower than the true *P* velocity. However, the distribution of calculated velocities for events that registered large amplitudes at all stations is still skewed the way the distributions in Fig. 4 are. This indicates that effects due to the radiation pattern are not sufficient to explain our results.

It should be noted at this point that independent measurements of *P*- and *S*-wave velocities have been conducted for the stress levels used in this experiment. These measurements indicate that the stress changes alone cannot explain the observed velocity variations and that we are compelled to postulate an alternative explanation such as wave attenuation. *P* velocity anisotropy in Westerly granite for this range of differential stress was found in subsequent tests to be less than 2 percent.

GLADWIN and STACEY (1974) reported that for acoustic pulses traveling in massive rock, pulse rise time is proportional to time of propagation and increases with increasing attenuation. This effect can be directly extended to the first full wave arrival. Consequently, the arrival of the second peak will be delayed more and more as the wave moves away from the source. This delay will look like a decrease in velocity when in fact it is due to attenuation of wave form. If attenuation increases as the rock approaches failure, the resulting delay of the arrivals (especially for emergent first arrivals) could contribute to an apparent drop in velocity.

Conclusion

In our laboratory experiments we have observed apparent velocity anomalies prior to failure in intact samples and slip events in samples containing saw cuts. After closer analysis, we found that all of these velocity anomalies are correlated with changes in the relative number of small amplitude microfractures. When this happens, as seen in Fig. 4, the average *P* velocity will also appear to change. However, as we have shown, such a velocity fluctuation is due to errors in the sampling technique and not to a lowering of the intrinsic *P* velocity in the rock. If this same effect occurs in the field, as demonstrated by LINDH *et al.* (1978), it could provide an alternate explanation for many velocity anomalies reported there. This suggests that it may be more appropriate to look for changes in *b*-value as a precursory phenomenon. Unfortunately, this would require a sizable foreshock population.

The most critical result of this study is as follows: Due to the large variation in calculated velocities, it is not surprising that a simple averaging of velocities would occasionally give variations that could be called 'anomalous'. However, by picking events of similar amplitude and in similar locations, these anomalies disappear. Even though seismologists are more sophisticated at picking first arrivals than an amplitude-only algorithm such as the one employed in this experiment, it is still possible with hand picked events to introduce the same sort of bias; especially when dealing with small magnitude events that have emergent first arrivals.

When attempting to demonstrate the presence of a velocity anomaly one generally starts with a scarcity of data. To enlarge on an existing data set, one is forced to look at small magnitude events, thus increasing the likelihood of picking late arrivals and consequently erroneously low velocities. We do not mean to imply that this will happen in every search for velocity change precursors. It is, however, an effect that must be taken into account when inferring velocities from arrival time data. The burden of proof must be on anyone attempting to demonstrate the presence of a velocity anomaly to first show that the data is free of such biases.

Acknowledgement

We wish to thank Frank Stacey for his encouragement in presenting this paper.

REFERENCES

AGGARWAL, Y. P., SYKES, L. R., ARMBRUSTER, J. and SBAR, M. L. (1973), *Premonitory changes in seismic velocities and prediction of earthquakes*, Nature *241*, 101–104.

BYERLEE, J. D. and LOCKNER, D. *Acoustic emission during fluid injection into rock*, in Proceedings First Conference on Acoustic Emission in Geologic Structure and Materials, p. 87 (Trans. Tech. Publications, Claustal, W. Germany, 1977).

GLADWIN, M. T. and STACEY, F. D. (1974), *Anelastic degradation of acoustic pulses in rock*, in Physics of the Earth and Planetary Interiors, *8*, 332–336.

LINDH, A. H., LOCKNER, D. A. and LEE, W. (1978), Velocity Anomalies an alternative explanation, Bull. Seis. Soc. Amer. (in press).

LOCKNER, D. A. and BYERLEE, J. D. (1974), *Acoustic emission in rock during failure in compression* (abs.), Am. Geophys. Union, Fall Ann. Mtng., Prog. p. 22.

NUR, A. (1972), *Dilatancy, pore fluids, and premonitory variations of ts/tp travel times*, Bull. Seis. Soc. Amer. *62*, 1217–1222.

ROBINSON, R. R., WESSON, R. L. and ELLSWORTH, W. L. (1974), *Variation of P-wave velocity before the Bear Valley, California earthquake of February 24, 1972*, Science *184*, 1281–1283.

SCHOLZ, C. H., SYKES, L. R. and AGGARWAL, Y. P. (1973), *Earthquake prediction: A physical basis*, Science *181*, 801–810.

WHITCOMB, J. H., GARMANY, J. D. and ANDERSON, D. L. (1973), *Earthquake prediction: Variation of seismic velocities before the San Fernando earthquake*, Science *180*, 632–635.

(Received 7th February 1978)