Time Lapse Monitoring of Acoustic Emissions with Coda Wave Interferometry

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Summary

The coda of a waveform consists of that part of the signal after the directly arriving phases. At late times the coda is dominated by multiply scattered waves. Small changes in a medium, which would have no detectable influence on the first arrivals, are amplified by the multiple scattering and may be seen readily in the coda. We have exploited ultrasonic coda waves to study the non-linear temperature dependence of velocity in granite. This non-linearity is irreversible and is related to acoustic emissions during thermal cracking. With this *Coda Wave Interferometry* we can measure velocity differences of the order of 0.1% with an error of 0.02%. There are many other possible applications of Coda Wave Interferometry in geophysics, including dam and volcano monitoring, time-lapse reservoir characterization, and rock physics.

Introduction

Geophysicists investigate the structure of the subsurface by making indirect measurements on the surface and relating them to those predicted by theoretical earth models. The Earth, however, is a highly complex system, and we almost always have to simplify our models in order to make them computationally tractable. In many applications, this simplification means treating unmodeled physics as noise, with the result that information contained in the data is discarded. For seismic data, coda waves are the tail of a seismogram. (In music the coda is the concluding passage of a movement or composition (Latin cauda, tail).) In this study we use coda waves to make inferences about thermally induced changes in granite. Those waves are the multiple scattered waves that arrive much later than the major wave types such as P, S and surface waves. Geophysical applications based on coda waves include earthquake prediction (Aki, 1985; Sato, 1988), volcano monitoring (Aki, 2000; Fehler et al., 1998) or monitoring of temporal changes in the subsurface (Chouet, 1979; Revenaugh, 1995).

In recent years, applied geophysicists have spent much effort on time-lapse seismics to monitor hydrocarbon reservoirs during recovery operations. Hydrocarbons move in the subsurface, reservoir rocks are artificially fractured, water-oil horizons move and steam propagates through the reservoir (Lumley, 1995; Wang, 1997). The high sensitivity of coda waves to small perturbations of the medium, makes them a powerful tool to monitor these kinds of changes.

We present a laboratory experiment in which we monitor the change in velocity resulting from a temperature change in a sample of Elberton granite. We excite and record ultrasonic waves and extract the velocity change from the coda waves. Furthermore, we monitor acoustic emissions that result from heating the granite sample and correlate them to non-linear changes in seismic velocity.

Introduction to Coda wave interferometry

Coda wave interferometry uses multiply scattered waves to detect temporal changes in a medium, by using the multiple scattering medium as an interferometer. For a change in the wave velocity, for quasi-random perturbations of the point scatterer location, or for a change in the source location, we can estimate this perturbation from multiply scattered waves by a cross-correlation in the time domain (Snieder et al., 2002). For a constant change δv in seismic velocity and fixed locations of the scatterers, the mean travel time perturbation of the multiply scattered waves is given by

$$\langle \tau \rangle_{(t,T)} = -(\delta v / v)\, t. \tag{1}$$

where $\langle \tau \rangle_{(t,T)}$ is the mean travel time perturbation in a time window centered at time t with duration $2T$ and $\delta v/v$ is the relative velocity change. When the time window is small ($T \ll t$). The velocity change follows from the time of the maximum t_{max} of the time-shifted cross-correlation function :

$$\frac{\delta v}{v} = \frac{t_{max}}{t}. \tag{2}$$

More details about the theory of Coda Wave Interferometry can be found in Snieder et al. (2002). Furthermore, Snieder (2002) derives the application of Coda Wave Interferometry to elastic media.

Monitoring Thermally Induced Velocity Change and Acoustic Emissions in Granite

In the ultrasonic experiment we use a Elberton granite cylinder with a height of 11 cm and a diameter of 5.5 cm. The sample is equipped with a sonic source on one side and a single receiver on the other. The transducer sends a pulse through the sample and the receiver, records the impulse response of the sample, with a sampling interval of 1μs (the dominant frequency is 100 kHz.) Ten traces are stacked to reduce the noise level. Two typical

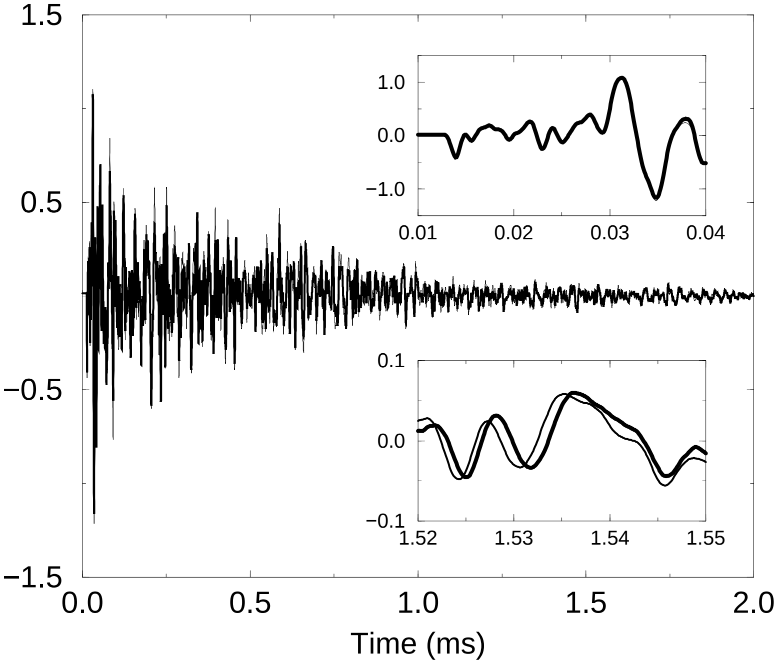

Fig. 1: Wave-forms recorded in the granite sample for temperatures of $45^o C$ (thin) and $50^o C$ (thick) respectively. The insets show details of the wave-forms around the first arrival (top) and in the late coda (bottom.)

records for a cylindrical sample are shown in Figure 1. To apply a controlled change in the medium over time, the aluminum sample is equipped with a heating element in a central borehole. The temperature is monitored by a thermocouple glued to the side of the sample.

While increasing the temperature from $25^o C$ to $90^o C$, the sonic measurement is repeated for every $5^o C$ increase in temperature. Then the sample is cooled to room-temperature and the sonic experiment is repeated again for every $5^o C$ in temperature decrease. In addition, acoustic emissions are counted for every temperature interval.

In many laboratory experiments, the change in the seismic velocity is measured for a temperature change of about $100^o C$ (Kern et al., 2001; Timur, 1977; Peselnick and Stewart, 1975; Hughes and Maurette, 1956). For a 11 cm small sample and a temperature difference of only $5^o C$, there is no significant travel-time difference for the first arriving waves (see top inset of Figure 1). Therefore, these first arriving waves do not provide any information about velocity changes. In a late time window (bottom inset of Figure 1), we see a distinct time shift of the wave-forms. This information can be used to infer the change of sonic velocity with temperature.

For each change of $5^o C$ in temperature the relative change in velocity is estimated from equation (2), with 20 different time windows of the coda waves each with a length of 0.1ms. Every window provides an independent estimate of the relative velocity change. This provides a consistency check of the method. Since we have multiple estimates of $\delta v/v$ we can calculate the mean and variance of the relative velocity change.

During the heating phase the velocity decrease for temperatures below $70^o C$ is constant, however for every $5^o C$ increase above that temperature, the velocity change increases (Figure 2). Note, that we are dealing with a velocity change of 0.1% and an accuracy of 0.02% . $70^o C$ corresponds to the critical fracture temperature for granite (Johnson et al., 1978; Fredrich and Wong, 1986). Thermal cracking results from the internal stress concentration induced by thermal expansion anisotropy or thermal expansion mismatch between minerals or grains (Boley and Weiner, 1960). Fredrich & Wong (1986) show that thermal cracking in rocks occurs principally along mineral or grain boundaries. The thermally induced cracks can influence significantly both the mechanical and transport properties, as well as thermoelastic moduli (Simmons and Cooper, 1978).

In addition we use a third ultrasonic transducer in order to detect acoustic emissions in the granite due to thermal cracking. Figure 2 also shows the count of acoustic emissions versus temperature. There is a small amount of acoustic emissions at low temperatures. However, there is a significant increase in acoustic emissions between $70^o C$ and $75^o C$. The increase in velocity change and the jump in the number of acoustic emissions correlate well.

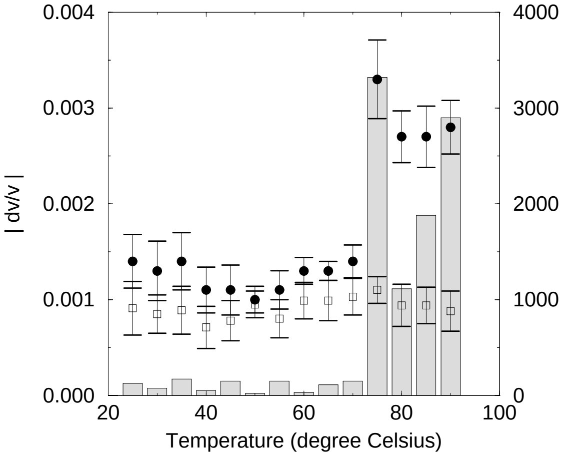

Fig. 2: Absolute values of $\delta v/v$ in Elberton granite, for 5^oC temperature intervals from 25^oC to 90^oC. Circles correspond to the heating phase and rectangles to the cooling phase. The histograms show the count of acoustic emissions for a given temperature interval.

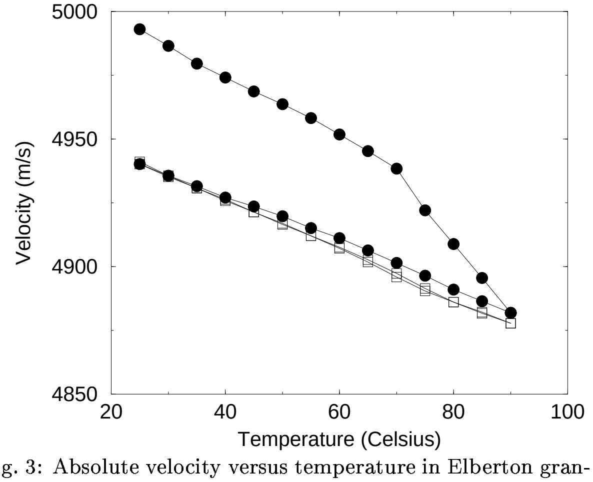

Fig. 3: Absolute velocity versus temperature in Elberton granite, for two heating cycles. Filled circles represent the first heating cycle and rectangles the second. Note that on the second heating cycle the temperature dependent velocities during the heating and cooling phase are virtually indistinguishable.

Irreversible Change in Velocity Due to Thermal Cracking

In the 1930's, Kaiser found that during repeated loading of metals, little or no acoustic emissions occurred until previously applied stress levels where exceeded. Since then, this effect has been known as the "Kaiser effect." Later, it was found that the Kaiser effect is a common phenomenon for various materials including rocks (Kurita and Fujii, 1979). Thus, the maximum stress applied in the previous cycles is 'memorized' in rocks.

During the cooling phase of the granite, there is no non-linear velocity change at 70^oC and there is only few acoustic emissions over the entire period. The seismic velocity does not increase back to its initial value. This difference in velocity is due to irreversible damage done to the rock by thermal cracking (Figure 3).

Todd (1973) studied the acoustic emissions of Westerly granite during cyclic heating. He noted that if a sample was re-heated to the same maximum temperature, few acoustic emissions occurred. Similarly we find in a second heating cycle up to the same maximum temperature (90^oC) for the same granite sample, only few acoustic emissions events occur and there is no non-linear velocity decrease around 70^oC. Furthermore, the velocity increases back to the value before the second heating cycle when cooled down (Figure 3). Note, that there is a small difference in relative velocity change between the cooling phase of the first heating cycle and the second cycle. Thirumalai & Demou (1973) studied the residual strain in a granitic rock produced by cyclic heating, and showed that predominant damage took place during the initial exposure to heating and the damage reached a steady state after three successive heating cycles.

This indicates that two different mechanisms drive the temperature induced velocity change. The first mechanism is the change in bulk elastic constants with temperature, which is linear and reversible. This explains the constant velocity change with temperature during the second heating cycle during heating and cooling. The second mechanism is the damage done to the granite due to thermal cracking, which explains the non-linear velocity change at the critical fracture temperature during the first heating cycle.

In (1937) Ide found the same temperature dependence of velocity in Quincy granite. By means of first arrival travel time, he obtained 7 measurements over one heating cycle, with a peak temperature of 300^oC. With Coda Wave Interferometry we are able to measure twenty times more points over the same temperature interval.

Conclusions

Due to the extreme sensitivity of coda wave interferometry, we are able to study temperature effects on small rock samples to a high level of precision. It is often assumed that seismic velocity depends linearly on temperature up to a temperature of about 300^oC. We show that under laboratory conditions (atmospheric pressure, unconfined sample), this is not the case. Furthermore, we can relate the non-linearity to thermal cracking.

The velocity estimation based on the coda waves requires only a single repeatable source and a single receiver. This means that one can monitor minute changes in-situ. The laboratory experiment is closely related to important problems in time lapse hydrocarbon reservoir monitoring, where cracking allows fluids to move around. In coda wave interferometry we have a inexpensive, automated and precise technique to monitor a hydrocarbon reservoir.

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