

Measurement of ultrasonic phase velocities in an oil shale and the determination of the elastic stiffnesses

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ABSTRACT

Ultrasonic phase velocities are obtained on an oil shale from the Piceance Basin, Colorado, USA after its composition and structure have been determined. The composition and structure of the oil shale was determined through the use of thin sections, pyrolysis, powder X-ray diffraction, scanning electron microscope, and electron microprobing.

Co-planar arrays of specially constructed near-point ultrasonic transducers of differing polarizations are used to generate and recorded ultrasonic waveforms travelling at a variety of differing angles within a number of differing planes through the finely layered sedimentary rock. Using a well-tested τ - p plane wave decomposition technique an attempt was made to obtain P-wave and S-wave velocities from these ultrasonic waveforms. Due to inhomogeneities in the sample, the well-known pulse-transmission method was used to determine P-wave and S-wave velocities in numerous directions with pressure.

Introduction

The velocity anisotropy and the corresponding elastic constants of a rock are determined not only by the bulk composition of the rock itself but also by how these constituent minerals are organized within the rock. A sample may be composed of many isotropic layers but may still have an anisotropic response caused by the layers themselves (Backus, 1967). As it is well known, some sedimentary rocks such as shales and oil shales are composed of many fine layers. This layering in itself will cause the rock to be anisotropic in nature. The sample of oil shale obtained from the Piceance Creek basin, Colorado will analyzed using a variety of methods in order to determine its composition and structure. The well-tested τ - p method (Kebaili and Schmitt, 1997) and pulse-transmission method (Markham, 1957) will be used in order to determine the velocity anisotropy of the material and how it relates to the composition and structure of the sample.

Sample Analysis

The sample we have chosen for our study is of an oil shale obtained from the Parachute Creek Oil Shale mine in the Piceance Creek basin, Colorado, USA. The sample was originally deposited in Eocene Lake Unita approximately 44 to 53 million years ago. The sample has a bulk density of 1.57 g/cm^3 . The sample

is well laminated and predominantly medium to dark greyish brown with white-cream coloured layers (*Fig. 1*).



Fig. 1: Close-up view of layering present in sample.

The depositional environment is thought to be lacustrine with the presence of volcanoclastic air-falls (Lundel and Surdam, 1975; Mason, 1983). The white-cream coloured layers are thought to be volcanic ash produced by volcanic activity by the Absaroka Volcanic Field in northwestern Wyoming (Mason, 1983).

One of the goals of this work is to determine how the composition and microscopic structure of the sample affect the velocity anisotropy of our material. In order to do this one must first understand what our sample is composed of and what the orientations of the constituent minerals are. To determine the composition and microscopic structure of our sample, numerous tests were performed on our sample ranging including powder X-ray diffraction, pyrolysis, scanning electron microscopy and electron microprobing.

Analysis of thin sections taken both perpendicular and parallel to bedding under polarized light was performed to look for the presence of birefringent minerals and to see if there were preferential orientations of these materials in the various planes. Thin section analysis showed very little brightening or extinction indicating either the absence of or the random orientation of birefringent minerals. However, powder X-ray diffraction of the sample showed the presence of calcite, dolomite, quartz, albite, and pyrite (*Fig. 2*). The X-ray diffraction did not show any definitive results indicating the presence of any clay minerals but did indicate the possible presence of amorphous clay minerals. This indicates that the orientation of birefringent minerals such as calcite is random.

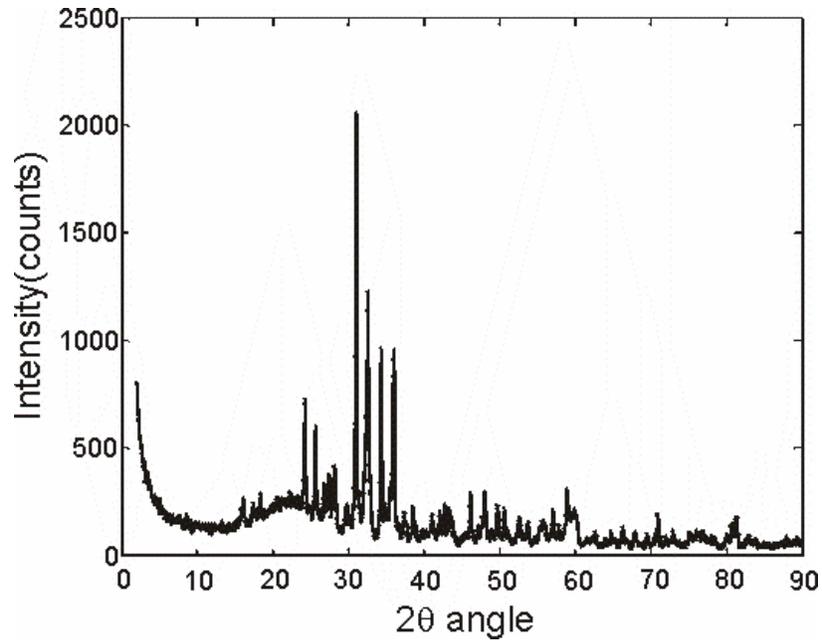


Fig. 2: Powder X-ray diffraction of sample.

The random orientation of the minerals in the sample is confirmed by scanning electron micrography (SEM). Analysis of various areas and orientation of the sample showed no obvious preferential mineral orientations (Figure 3). However, the SEM showed that layers are present in the sample and may be a source of anisotropy in our sample (Backus, 1969).

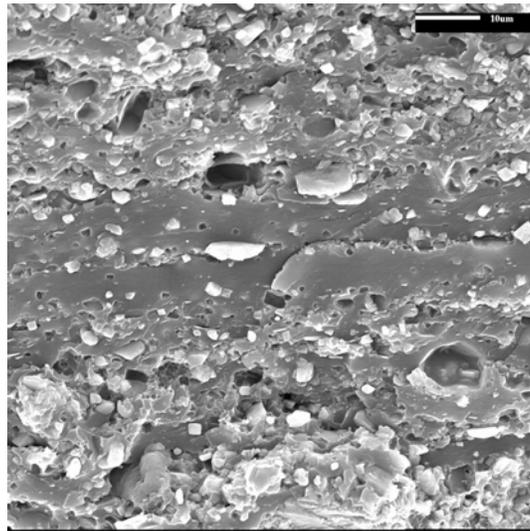


Fig. 3: SEM image of sample showing the layering present.

To determine more about the composition of the layering, electron microprobing of the sample was performed. Electron microprobing showed that layering was predominantly composed of calcite/dolomite rich layers interspersed with

aluminum rich layers (Fig. 4). Continued electron microprobe analysis combined with pyrolysis analysis has shown our sample is composed of albite ($\text{NaAlSi}_3\text{O}_8$), calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), ilmenite (FeTiO_3), orthoclase (KAlSi_3O_8), pyrite (FeS_2), and siderite (FeCO_3) with traces of quartz (SiO_2). From the SEM and electron microprobing of the sample in various directions, it seems the sample is predominantly transversely isotropic in nature.

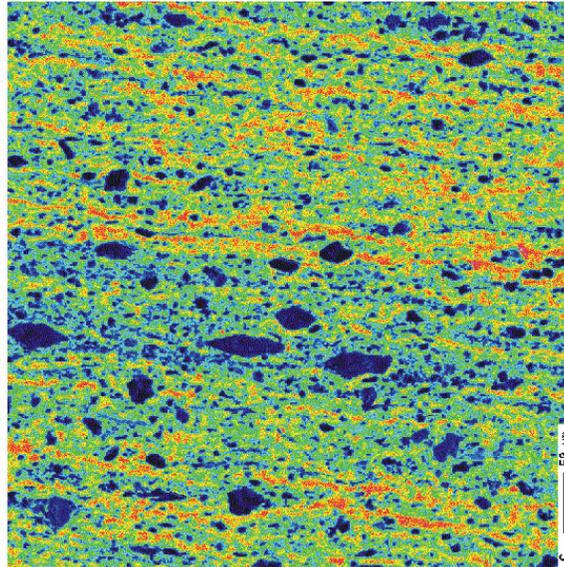


Fig. 4: Electron microprobe of carbon in sample.

Phase Velocity Determination

In order to determine the anisotropy or elastic constants of the sample it is necessary to determine the phase velocities travelling through the sample. Although phase velocities may be close to the group, or ray, velocity as would usually be determined by picking of travel time between a point source and a receiver in anisotropic materials, the group and phase velocities do not in general have the same magnitude (Fig. 5).

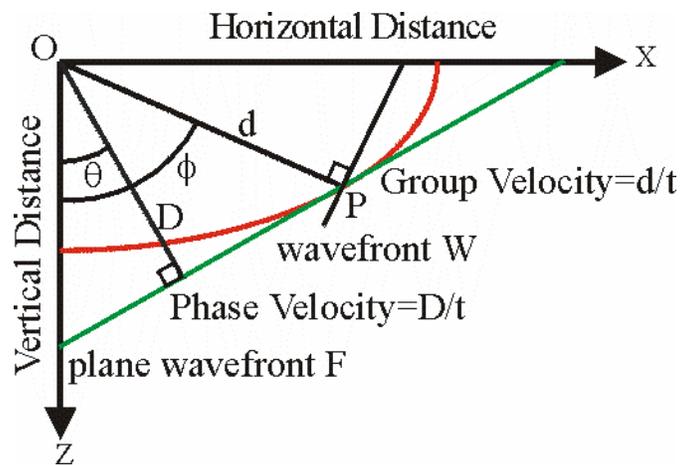


Fig. 5: Distinction between group and phase velocities in anisotropic media.

We employ plane wave decomposition (τ - p transform) to obtain phase velocities from a series of observed traces. The essential components of the phase velocity determination method are previously described (Kebaili and Schmitt, 1997). The method is most easily employed on a rectangular prism of the material. Essentially, a closely spaced linear array of specially constructed P, SV, or SH mode ultrasonic transducers detect the elastic wave pulses from at least two coplanar source transducers on the side of the block. (Fig. 6).

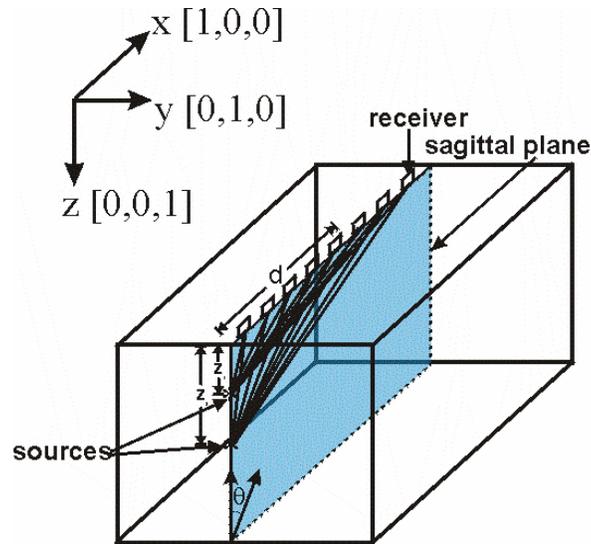


Fig. 6: View of the plane containing sources of known depths and a co-planar array of receivers with ray paths for a homogeneous medium. Ultrasonic transducers act as both sources and receivers on each side of the sample.

This method was applied to our sample in a variety of directions using both P-wave and S-wave ultrasonic transducers. Results for an S-wave source at 4 cm depth (Figure 7) and at 10 bar of pressure shows near-hyperbolic moveout and a fairly large of dispersion.

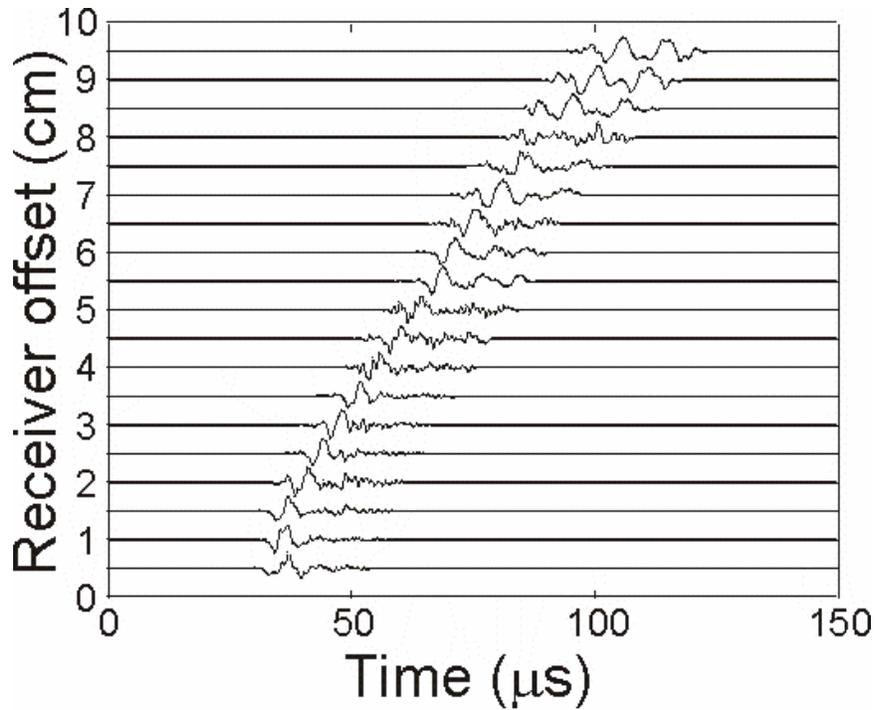


Fig. 7: Recorded S-wave waveforms from a 4 cm source at 10 bar pressure.

Using recorded waveforms from both 2 cm and 4 cm source depths, the phase velocities can be determined as a function of the phase propagation angle from the τ - p transforms of the data (Fig. 8).

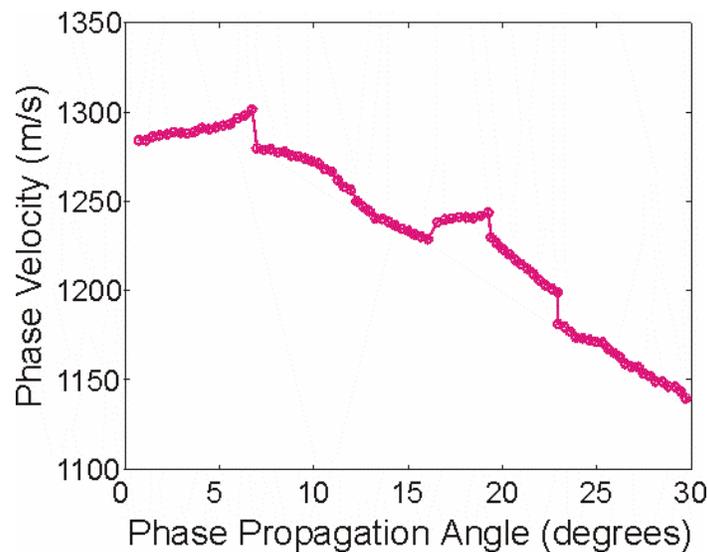


Fig. 8: Phase velocity as function of the phase propagation angle for an S-wave source at a pressure of 10 bar.

As one can see the phase velocities do not vary smoothly as a function of the phase propagation angle. Though this method has been tested on a layered

composite material successfully (Mah and Schmitt, 2001; Mah and Schmitt, 2003), one assumption made was that the sample was homogeneous. One problem with the τ - p method is that if there are large inhomogeneities in the sample, erroneous phase velocities will be determined. One way to check this is to directly calculate the group velocities from the recorded arrivals and see how the group velocities change with receiver offset (Figure 9). As one can see, there is an abrupt change in the velocities at a receiver offset of 6 cm. Visually looking at the sample reveals the presence of a relatively thick white-cream coloured layer. Additional direct pulse transmission tests have revealed this layer has an average P-wave velocity of 3034 m/s while the surrounding rock above and below this layer has an average P-wave velocity of 2413 m/s. The additional direct pulse transmission test showed that the sample is relatively homogeneous outside this white-cream coloured layer. A smaller proportion of the sample that excluded this white-cream coloured layer was used for the rest of the study. However, the τ - p method requires large offsets which is not possible on small samples. So the τ - p method was abandoned in favour of the more well-used direct pulse transmission tests (Markham, 1957; Carlson et al., 1984; Arts et al., 1991; Cheadle et al., 1991; Vestrum, 1994).

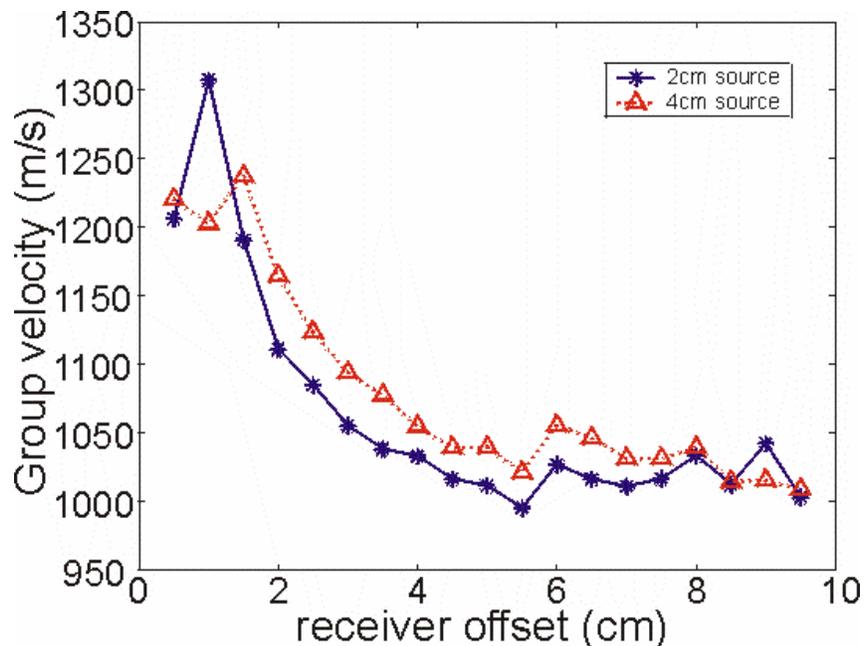


Fig. 9: Group velocity as a function of receiver offset for an S-wave source at 10 bar pressure.

Pulse-Transmission Tests

A variety of pulse-transmission measurements were taken in various directions using various polarization going from 0 bar pressure to 200 bar and back down to 0 bar. These pulse-transmission measurements will then allow for the calculation the elastic constants of the sample and how they change with pressure. As one can see for a P-wave travelling in the Y-direction parallel to the predominant

layering one can see that the travel times decrease with increasing pressure and vice versa (Fig. 10). Further analysis of the P-wave arrivals in Figure 10 shows not only increasing velocity with pressure but as well as the occurrence of velocity hysteresis. This is observed when the pressure is decreased and the velocity measure is slightly higher than the velocity taken at the same pressure (Jones and Wang, 1981). Preliminary analysis of the other P-wave and S-wave data taken shows that the rock is at the very least transversely isotropic in nature and may be weakly orthorhombic. More measurements in well-chosen directions would be necessary in order to delineate a more anisotropically complex material. However, this increased complexity may not be due to more complex anisotropy in the sample but may be due to small inhomogeneities present in the sample. The results so far indicate that anisotropy as determined by the ultrasonic testing of sample is related to the layering as determined by the SEM and electron microprobing.

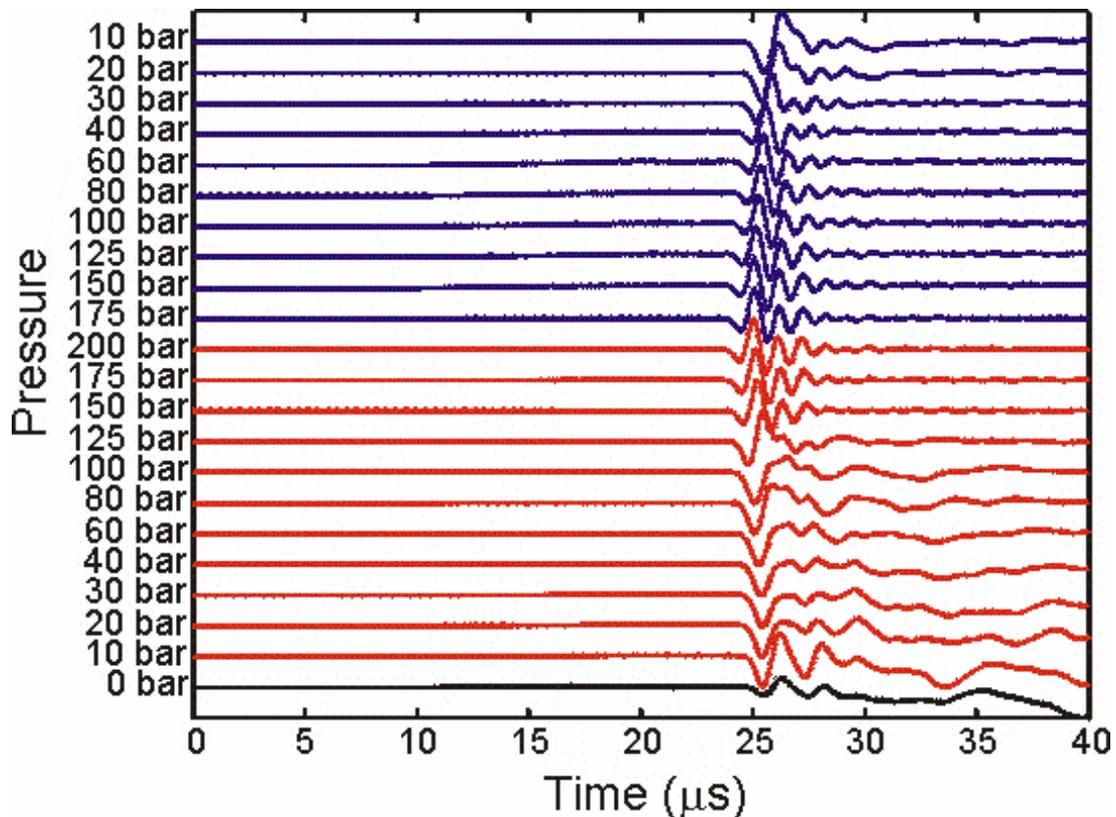


Fig. 10: Recorded P-wave waveforms travelling through sample in the Y-direction at various pressures. Red waveforms are those recorded after an increase in pressure. Blue waveforms are those recorded after a decrease in pressure.

Conclusion

The composition and microscopic structure of an oil shale was analyzed using a variety of techniques ranging from simple powder X-ray diffraction to electron microprobing. Through these tests it was found that the sample was

predominantly transversely isotropic in nature. Initial testing using the well-tested τ - ρ method yielded poor results due to the presence of inhomogeneities in the sample. The well-known method of direct pulse-transmission testing was used instead to investigate the material. It was found that the velocity anisotropy of the sample as determined by the pulse transmission tests was at the very least transversely isotropic in nature but may be weakly orthorhombic. The velocity anisotropy seems to be related to the composition and structure of the material as would be expected. Since these measurements were made at a variety of pressures, the elastic constants of the sample may also be determined as a function of pressure.

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Acknowledgements

This work supported by NSERC and the Petroleum Research Fund administered by the American Chemical Society. Technical assistance and sample preparation was greatly assisted by L. Tober. The work of Drs. Kebaili and Molz prepared the way for the present experiment. The assistance of the Alberta Microelectronics Centre in cutting of the ceramic transducers is greatly appreciated. The use of the computer equipment and software of the Downhole Seismic Imaging Consortium and the Seismic Heavy Oil Consortium at the University of Alberta during the preparation of this paper is acknowledged. The authors would like to thank Sergi Matveev for help in electron microprobing, Diane Caird in powder X-ray diffraction, Dong Chan Li for help with the scanning electron microscope, and Don Resultay for help with thin sections.