Velocity Anisotropy in Gulf Coast Carbonates

by

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ABSTRACT

Compressional-wave velocities were measured parallel and perpendicular to bedding in five Gulf Coast carbonate samples at atmospheric pressure. In general, the horizontal velocities exceeded the vertical velocities, with anisotropy ranging from 0 to 7%. The fabric of the most anisotropic sample, while weak, appears to be related to the velocity behavior.

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I wish to gratefully dedicate this work
to my parents.
They raised me up to love God, seek His
will, and live in it. They also first
introduced me to the world of research.

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INTRODUCTION

Among modern geophysical methods, the seismic method stands as one of the most heavily used. The seismic method is used to obtain information about the subsurface by studying the behavior of sound energy propagated through the earth. In the analysis of seismic data, the assumption is commonly made that the subsurface behaves isotropically with respect to the velocity of acoustic waves.

Studies of the acoustic properties of carbonate sediments from the deep sea indicate that the sediments are anisotropic with respect to seismic velocity (Carlson and Christensen, 1977, 1979). Anisotropy in this situation means that the sound velocity varies depending on the direction of travel through the material. In deep sea carbonates (Carlson and Christensen, 1979), velocities in the horizontal direction are as much as 0.45 km/s faster than those in the vertical direction at 0.1 kbar confining pressure. This is enough anisotropy to effect depth determinations made from seismic methods.

In a rock with a random orientation of crystals, cracks and pores, the velocity would behave isotropically. Anisotropy caused by aligned cracks and pores would decrease with depth of burial as the cracks and pores were closed. Because the anisotropic behavior was observed to increase with depth for the deep sea carbonates (Carlson and Christensen, 1979), it has been suggested that the anisotropy is controlled by the orientation of calcite crystals which are the main constiuents of carbonates.

Objective

This text follows the format of the Journal of Geophysical Research.

This study was done using a suite of five detrital carbonate sediment samples deposited in a nearshore environment. They are all from the East Texas basin.

The questions the study sought to address were whether these nearshore sediments show the same sort of anisotropic behavior observed in the deep sea sediments and, if so, whether the anisotropy can be related to the orientation of the calcite crystals in the rock.

To study the behavior of the samples with respect to seismic velocity, compressional-waves were employed. These waves oscillate along the direction of wave propagation.

The fabric study was done using a universal stage to determine the orientation of the crystallographic c axes in the calcite. These were then plotted on a stereographic projection and contoured to show dominant orientations.

PREVIOUS WORK

It has been shown (Birch, 1960; Christensen and Crosson, 1968; Christensen, 1966a, 1966b) that most metamorphic and ultrabasic rocks exhibit seismic anisotropy, and Christensen (1966b, 1971) demonstrated that the anisotropy relates to a preferred orientation of crystals in such rocks. Seismic anisotropy in sedimentary rocks, however, has only recently come under investigation.

Some of the most recent work on sedimentary rocks and their behavior with respect to seismic velocity involved calcareous sediment samples from the Deep Sea Drilling Project, Leg 39. Carlson and Christensen (1979) found that compressional-wave velocities parallel to the bedding plane may be as much as 0.45 km/s faster than the vertical velocities at 0.1 kbar hydrostatic confining pressure. Carlson (personal communication) noted this anisotropy is also apparent at zero pressure. Observing that anisotropy increased with depth (Figure 1), Carlson and Christensen (1977) suggested that the phenomenon may reflect a preferred orientation of calcite grains in the sediment.

Calcite has a trigonal symmetry with one three-fold axis which is also the crystallographic c axis (Figure 2). Peselnick and Robie (1967) demonstrated that compressional-wave velocities parallel to the calcite c axis are much lower than velociteis in the plane perpendicular to the c axis.

The velocity along the c axis is only 5.5 km/s compared to 7.1 km/s along an a axis (Figure 3). This can be explained by the fact that atoms in the plane of the a axes are more closely spaced than those along the c axis.

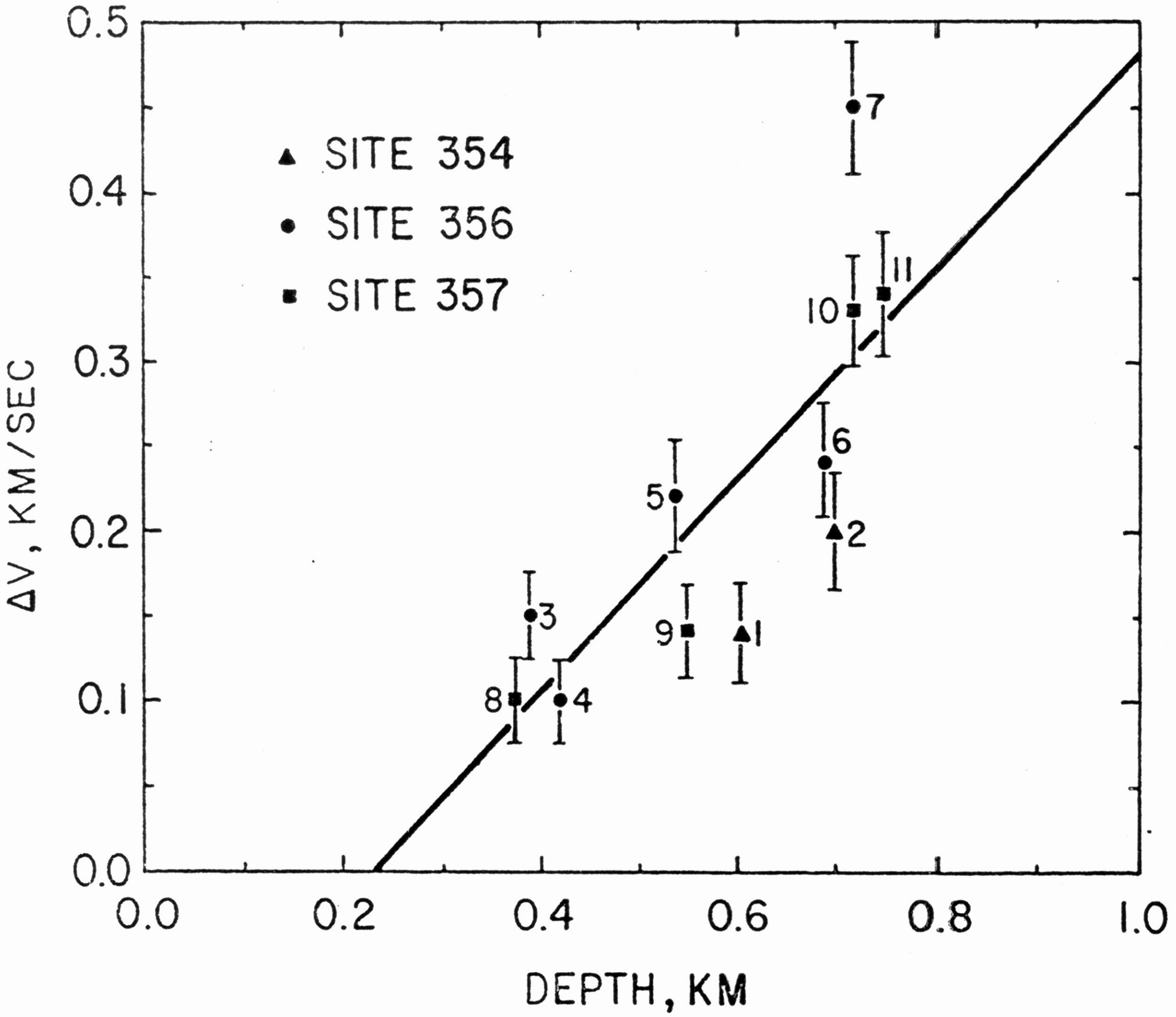


Fig. 1. Velocity difference ($\Delta V = V_h - V_v$) versus depth of sample recovery. Error bars are computed assuming a 2.0% error in measured velocity. The regression equation, relating the velocity difference to depth is

$$\Delta V = 0.62(\pm 0.16)d - 0.15(\pm 0.10)$$

where V_h is the velocity in the bedding or horizontal plane and V_v is the velocity in the direction perpendicular to bedding.

(From Carlson and Christensen, Velocity anisotropy in semi-indurated, calcareous, deep sea sediments, J. Geophys. Res., 84, 205, 1979.)

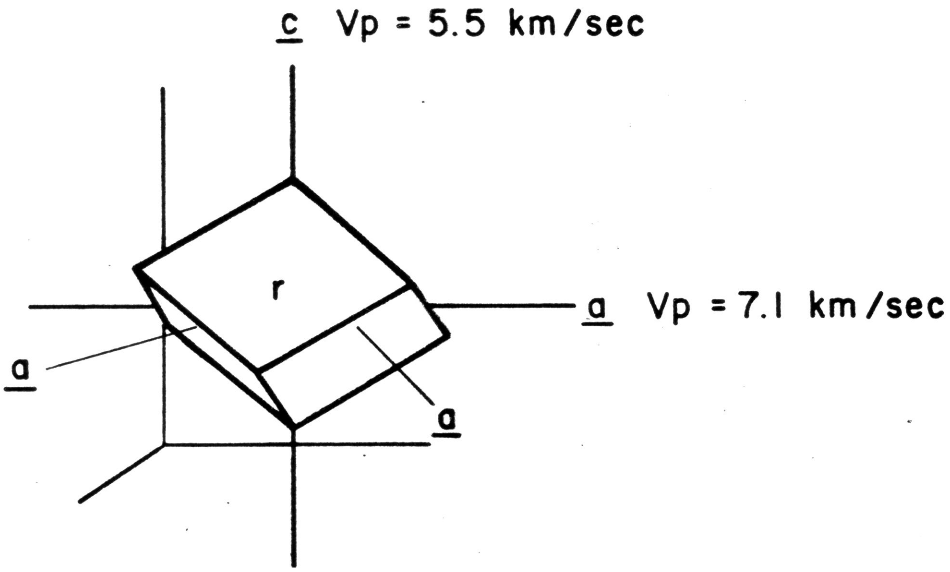


Fig. 2.
Compressional velocities in a single crystal along a and c crystallographic axis.

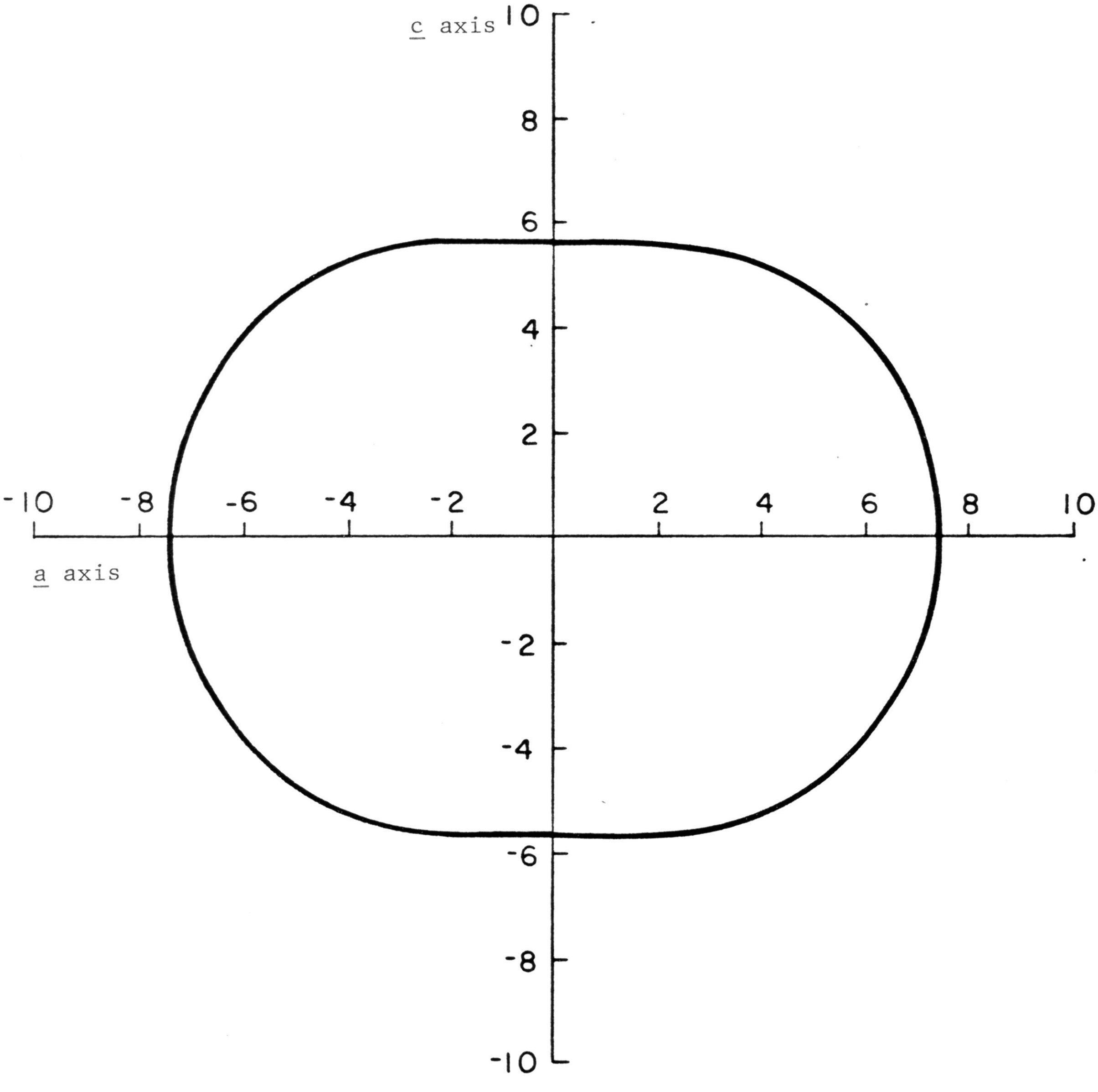
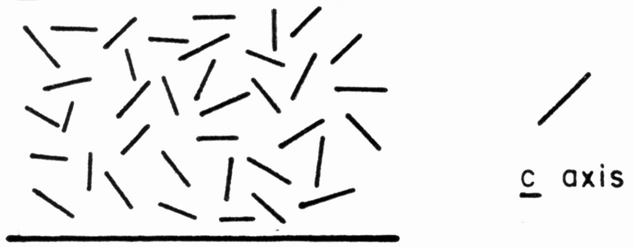


Fig.3.
Compressional-wave velocity profile in the calcite 010 plane.

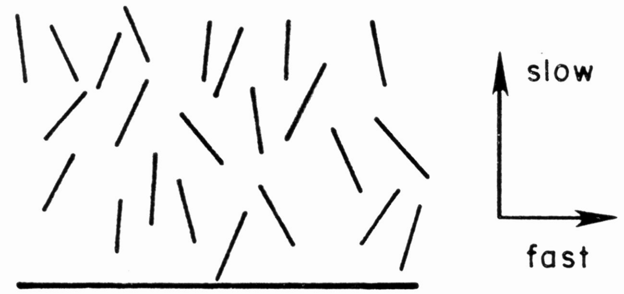
Based on this information Carlson and Christensen (1979) suggest an alignment of calcite c axes perpendicular to bedding as the cause of the observed anisotropy pattern. They further suggest that the development of the fabric is related to compaction and lithification processes. The sediments the studied consist almost exclusively of accumulated calcareous microfossil remains, some of which are known to have highly ordered arrangements of calcite crystallites. Compacting this biogenic detritus should cause alignment such that the calcite c axes are normal to bedding (Figure 4). This fabric might be further enhanced by epitaxial growth.

In practical application on a large scale, Kleyn (1956) found certain sedimentary rocks showed anisotropic behavior on his data from a seismic refraction study. The section of rock included limestones at 1800 m below the surface which had a horizontal velocity 1.04 times the vertical velocity.

Richards (1960) studied wide angle reflection data taken through limestone structures and experimentally determined a horizontal/vertical velocity ratio of 1.10 for those limestones. Thus, velocity anisotropy is a common characteristic of calcareous rocks.



c axis with random orientation: isotropic



c axis with preferred orientation: anisotropic

Fig.4. Suggested relationship of calcite c axis orientation and velocity behavior.

SAMPLE DESCRIPTION

The samples used in this study were all nearshore carbonate sediments taken from wells in the East Texas basin. They are composed of detritus (mechanically eroded carbonate fragments such as carbonate sands) deposited in the neritic zone of the ocean (low-tide level out to 600 feet). The deposition occured in Jurassic and Cretaceous time. The samples were all buried at depths between 10,000 and 20,000 feet when recovered.

Four of the samples are limestones and one is a dolomite. Dolomite is identical to limestone in basic make-up with the exception that some of the calcium in the calcite that makes up both rocks is replaced by magnesium in dolomite. The limestones tend to be more fine grained than the dolomite. Table 1 includes a summary of the descriptions and depositional environments of the samples.

Preparation

For use in the study, two oriented cylinders were cut from each sample, one perpendicular to the bedding plane and the other parallel to the bedding plane. The ends were then lapped smooth and parallel. Pieces cut from the cylinder ends in the bedding plane were used to make the thin sections for the fabric study.

Table 1
Acoustic Properties

Sample #	Compressional Velocity (km/s)	Anisotropy (%)	Description
1	H* 5.90 V 5.94	0	Limestone; large crystals in finer mass; from 100' tidal banks
2	H 3.86 V 3.59	7	Dolomite with metallic oxide; nearshore deposit; less than 100' of water
3	H 6.26 V 6.12	2.2	Fine-grained limestone; nearshore deposit
4	H 6.30 V 5.97	4.3	Fine-grained limestone; outer shelf deposit; 100+' of water
5	H 4.10 V 3.92	4.8	Fine-grained limestone; outer platform; about 100' of water

*H denotes propagation parallel to bedding; V denotes propagation perpendicular to bedding.

VELOCITY MEASUREMENTS

Compressional-wave velocities through the samples were measured using a pulse transmission technique (Figure 5). A transducer is placed on each end of the suspended cylindrical sample. The sending transducer takes an electrical pulse from the pulse generator and converts it to a mechanical one. Simultaneous with sending the pulse, the generator triggers the oscilloscope sweep, displaying the input pulse. Then the receiving transducer takes the mechanical pulse at the other end of the cylinder and turns it back into an electrical signal which is amplified, filtered, and also displayed on the oscilloscope screen. The output of the oscilloscope drives a X-Y plotter which provides a hard copy of the data (Figure 6). One μsec time marks are also recorded on the hard copy to allow the determination of exact travel time.

The compressional-wave velocities are then calculated using the measured sample length and the travel time, which is corrected for electronic delay.

The measurements were repeated several times to guard against errors. The final results are shown in Table 1, and indicate that the amount of anisotropy in the samples ranged from total isotropy to 7% anisotropy. The velocity in the isotropic sample was measured at various angles along the bedding plane and remained constant in all directions measured.

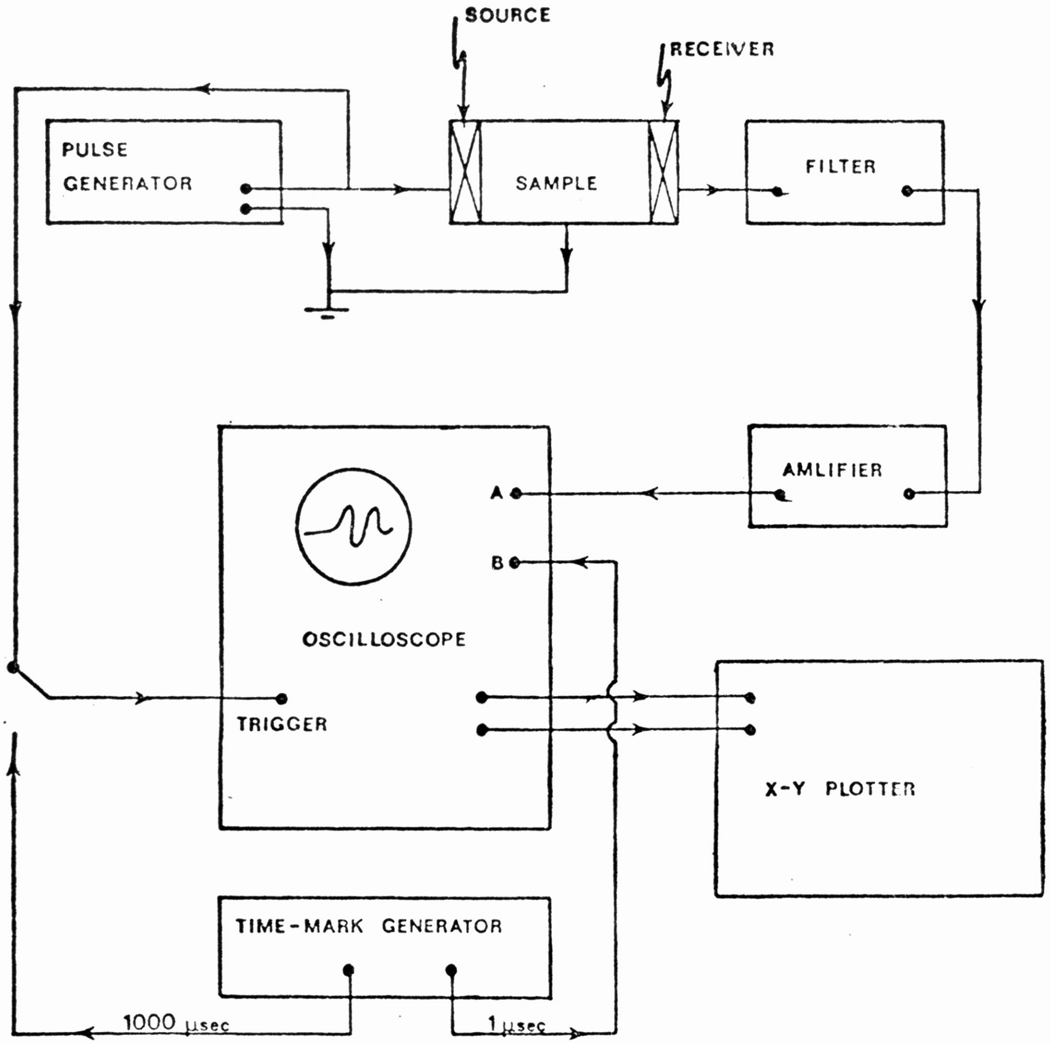
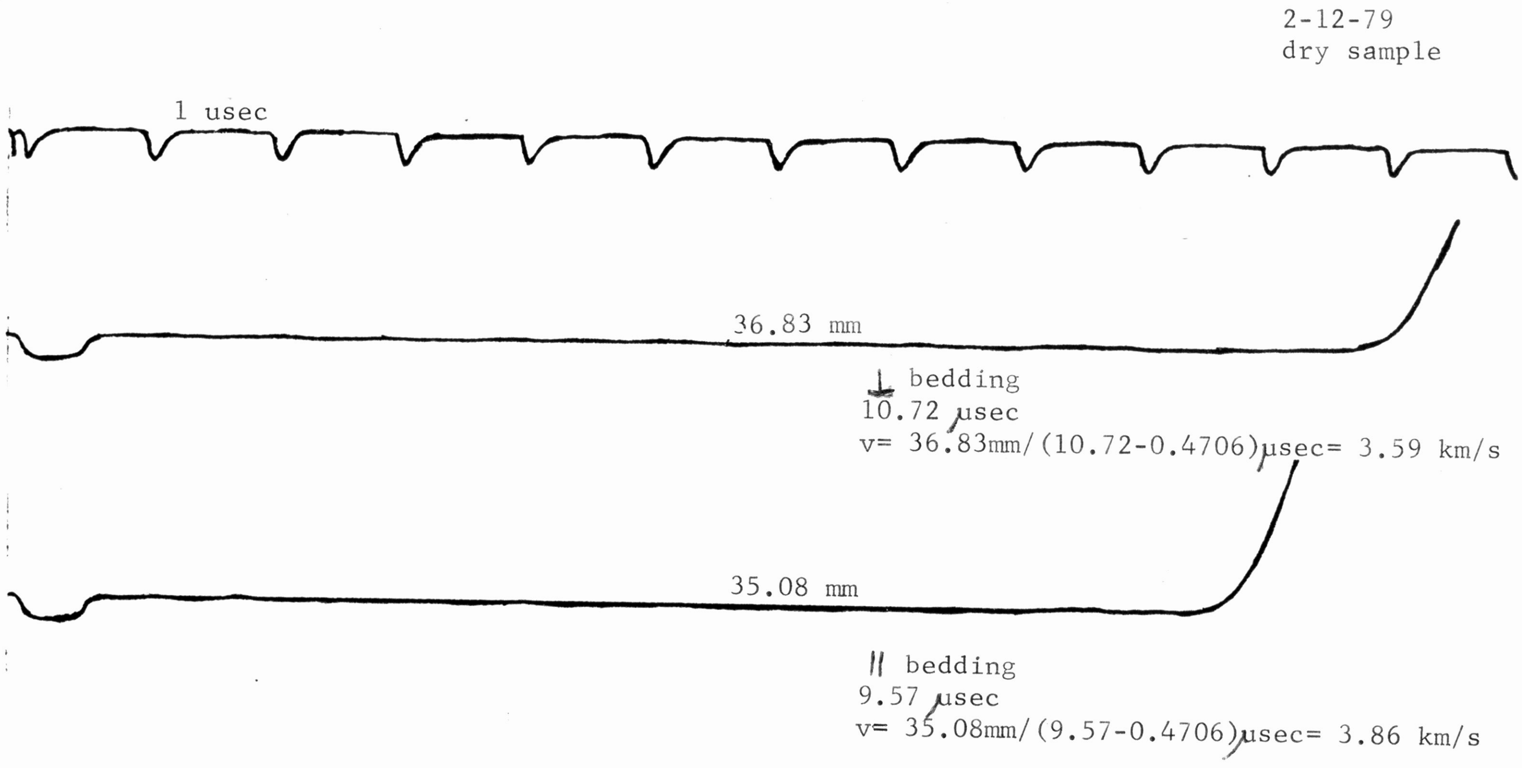


Fig. 5. Schematic diagram of system used to measure acoustic velocities.



2-12-79
dry sample

⊥ bedding
$10.72\ \mu\text{sec}$
$v = 36.83\text{mm}/(10.72-0.4706)\mu\text{sec} = 3.59$ km/s

∥ bedding
$9.57\ \mu\text{sec}$
$v = 35.08\text{mm}/(9.57-0.4706)\mu\text{sec} = 3.86$ km/s

Fig.6. Hard copy of velocity measurements through the most anisotropic sample.

FABRIC STUDY

The fabrics of the samples which behaved the most anisotropically and isotropically with respect to velocity were used in looking for possible relationships between velocity anisotropy and fabric (c axis orientation).

The study was done on a four-axis universal stage microscope. The orientation of the calcite c axis was determined for each of 100 grains in a sample.

The orientation of the c axis of calcite can be determined optically because calcite is anisotropic with respect to optical properties (Emmons, 1943). The extinction positions of a calcite crystal give the exact c axis orientation.

The fabric diagrams (Figure 7) are shown contoured from stereographic projections of the c axis orientations. On such a projection, a point at the center indicates a vertical c axis, while a point on the edge indicates a c axis lying in the bedding plane. Other points indicate c axis inclined at some angle, those nearer the center being more nearly vertical. The contour interval on the diagram is 1% with 2%-6% contour lines shown.

Figure 8 shows the sample that behaved isotropically with respect to velocity as viewed under a microscope. The few large grains were used to determine the fabric as the ground mass is too fine grained for optical work. Though the sample appears to have some very weak fabric (Figure 7) this can be anticipated statistically and is not reflected in the velocity measurements. Since only a small portion of the total material in the sample was used in the fabric study,

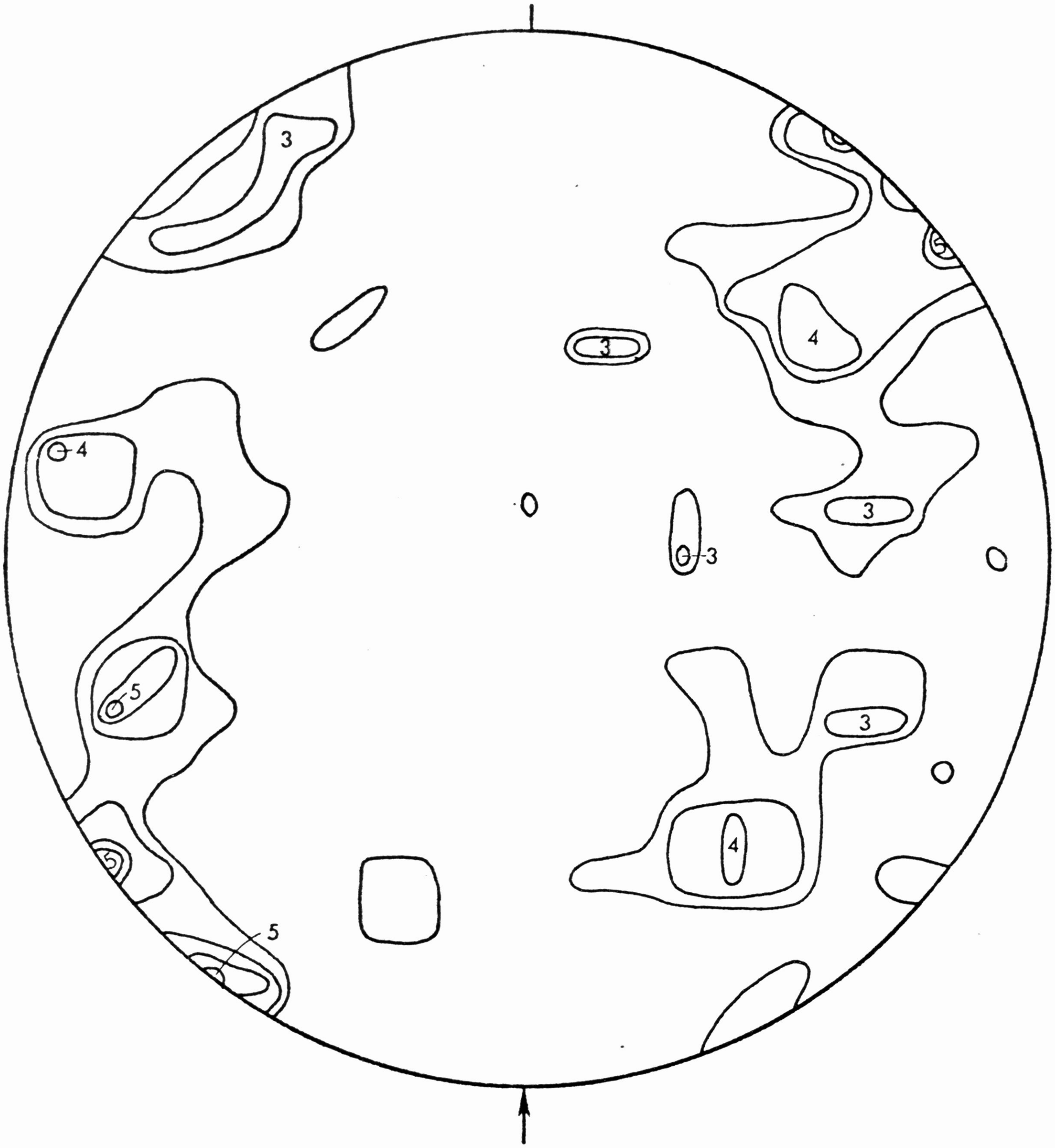


Fig.7. Calcite c axis orientation diagram for 100 grains in isotropic sample. Contours 5%, 4%, 3%, and 2% per 1% area.

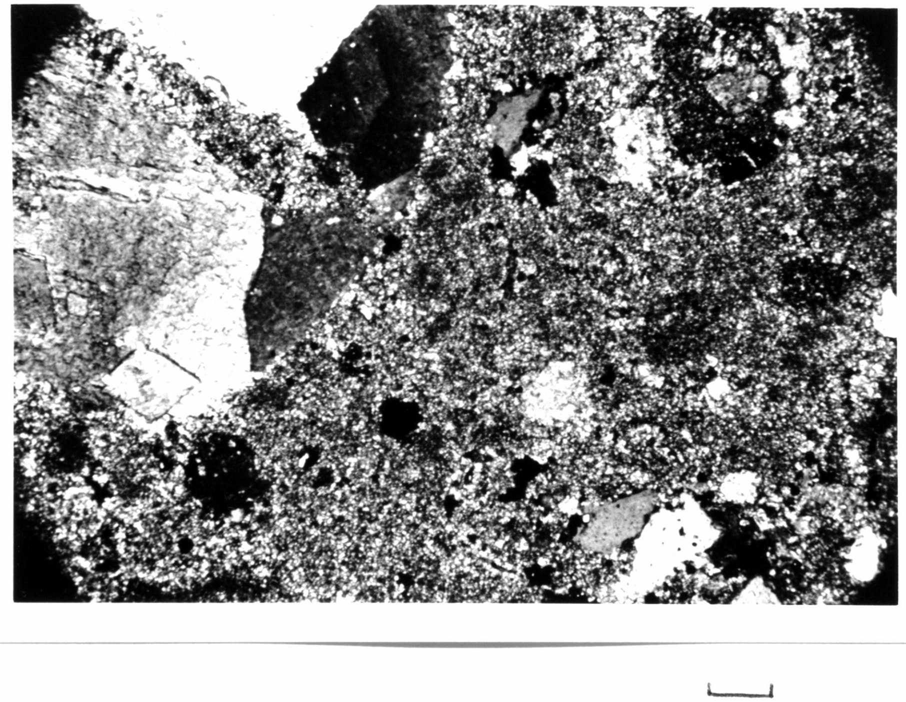


Fig.8. Photomicrograph of the isotropic sample. This is a limestone with a fine grained mass and a few large crystals. (Plane-polarized light, scale equals 0.08 mm.)

a portion which did not reflect the total rock composition, it is probable that the fabric determined by that portion is not reflective of the overall rock fabric.

In comparison to the first sample, the sample which behaved most anisotropically with respect to velocity appears under a microscope to be much more homogeneous in composition (Figure 9). However, this homogenity of composition is associated with a directionally dependent velocity and a fabric stronger than that of the first sample studied. The fabric, shown in Figure 10, indicates some concentration of calcite c axes at angles near the vertical. It is possible that because the single calcite crystal behaves with such strong anisotropy with respect to velocity, that a strong fabric may not be necessary for a carbonate rock to behave anisotropically.

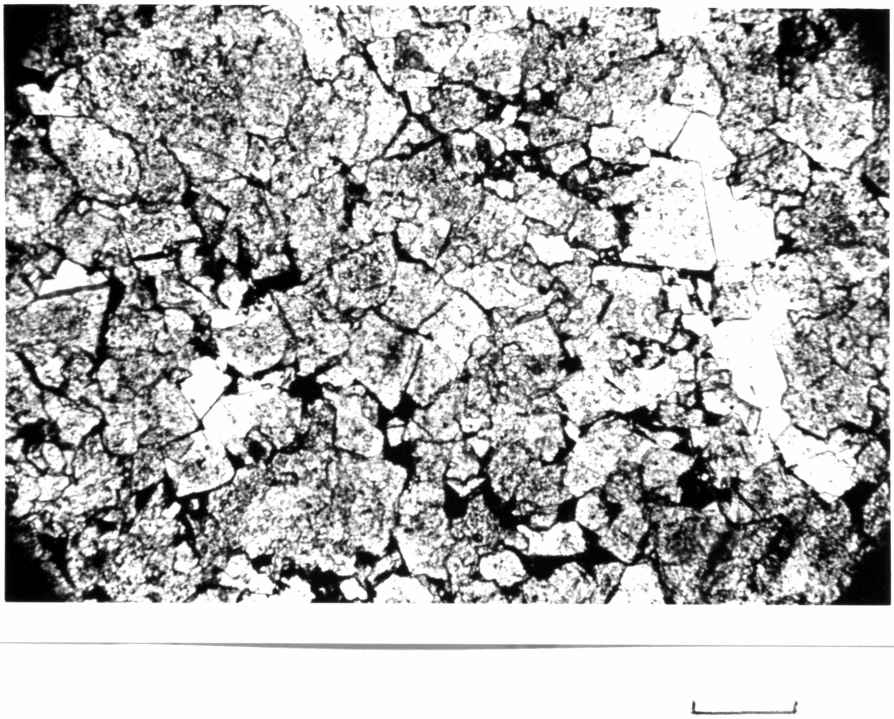


Fig.9. Photomicrograph of the most anisotropic sample, a dolomite.(Plane-polarized light, scale equals 0.16 mm).

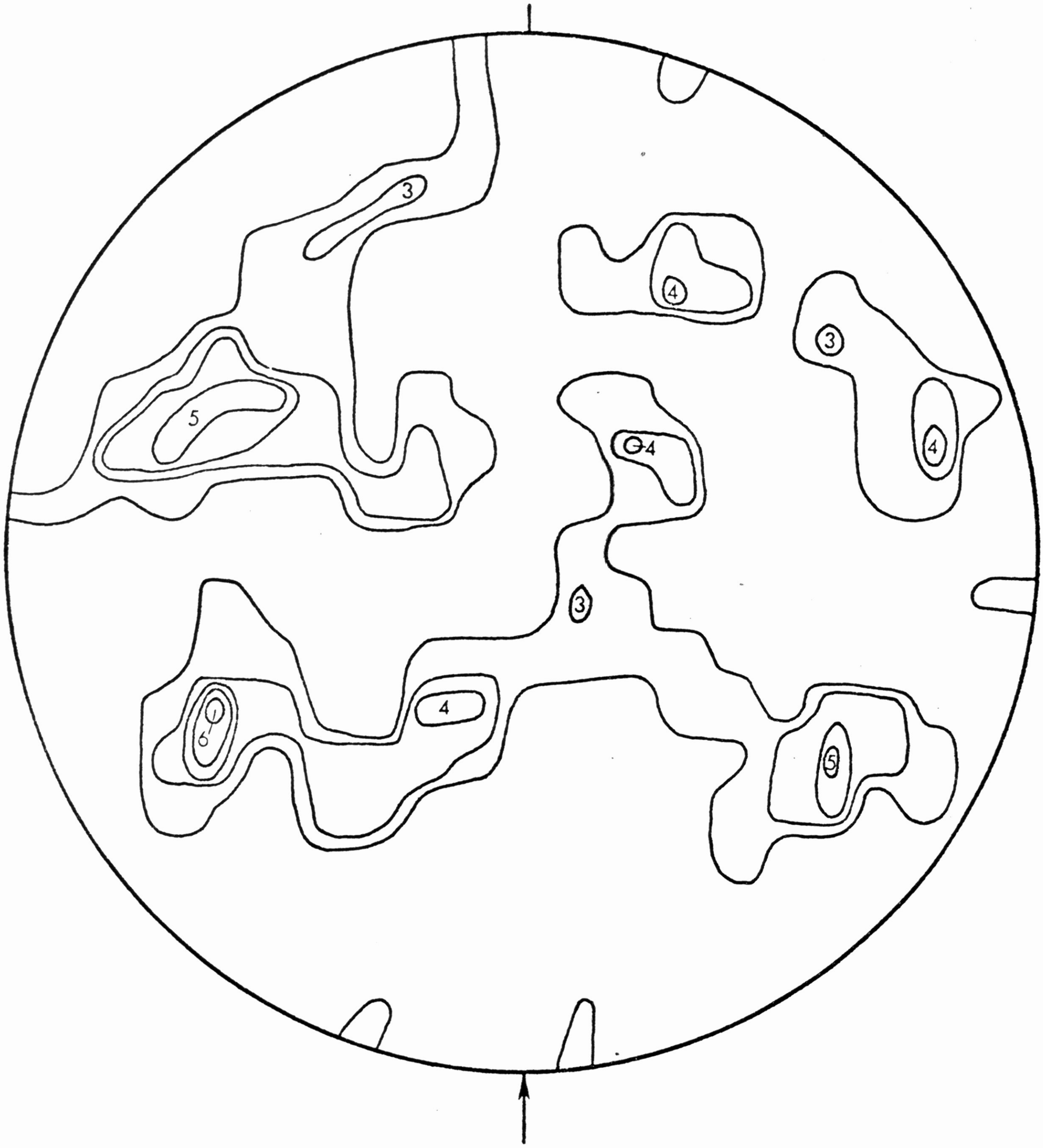


Fig.10. Calcite c axis orientation diagram for 100 grains in most anisotropic sample.Contours are 6%, 5%, 4%, 3%, and 2% per 1% area.

CONCLUSION

From the results of my research, it is evident that some near-shore carbonate sediments behave anisotropically with respect to velocity. That these are non-biogenic carbonates is interesting since they lack the skeletal orientations of calcite *c* axes thought to be important in the deep sea carbonates.

The fact that the fabric of the most anisotropic sample appears to relate to anisotropy is significant, though the origin of the fabric remains unknown.

REFERENCES

Birch, F., The velocity of compressional waves in rock to 10 kilobars, 1, J. Geophys. Res., 65, 1083, 1960.

Carlson, R.L., and N.I. Christensen, Velocity anisotropy and physical properties of deep-sea sediments from the western South Atlantic, in Supko, P.R., K. Perch-Nielson, et al., Initial Reports of the Deep Sea Drilling Project, 39, Washington (U.S. Government Printing Office), 555-559, 1977.

Carlson, R.L., and N.I. Christensen, Velocity anisotropy in semi-indurated calcareous deep sea sediments, J. Geophys. Res., 84, 205-211, 1979.

Christensen, N.I., Shear wave velocity in metamorphic rock at pressure to 10 kilobars, J. Geophys. Res., 71, 3549, 1966a.

Christensen, N.I., Elasticity of ultrabasic rock, J. Geophys. Res., 71, 5921, 1966b.

Christensen, N.I., Fabric, seismic anisotropy and tectonic history of the Twin Sisters Dunite, Washington, GSA Bull., 82, 1681-1694, 1971.

Christensen, N.I., and R.S. Crosson, Seismic anisotropy in the upper mantle, Tectonophysics, 6, 93-107, 1968.

Emmons, R.C., The Universal Stage, GSA, Memoir 8, Geologic Society of America, New York, 202 pp., 1943.

Kleyn, A.H., On seismic wave propagation in anisotropic media with applications in the Betun area, South Sumatra, Geophys. Prospecting, 4, 56-69, 1956.

Peselnick, L., and R.A. Robie, Elastic constants of calcite, J. Applied Phys., 33, 2889-2892, 1963.

Richards, T.C., Wide angle reflections and their application to finding limestone structures in the foothills of western Canada, Geophysics, 25, 385-407, 1960.