52. ANISOTROPY AND MODES OF DEPOSITION OF PELITIC MISSISSIPPI FAN DEPOSITS[1]

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ABSTRACT

The predominant mode of deposition (turbidity current vs. hemipelagic) within entire sequences is related to the general trends in anisotropy, determined by both shrinkage and sonic velocity measurements, of fine-grained sediments cored during DSDP Leg 96 in the Mississippi Fan. Anisotropy increases in fining-upward sequences with decreasing abundances of density-current deposits upsection. In coarsening-upward sequences with increasing abundance of density-current deposits upsection, the inverse trend is found. Increasing compaction generally leads to increasing anisotropy, but the primary differences between turbidites and hemipelagic sediments are not significantly affected.

INTRODUCTION

A sediment behaves anisotropically when its physical properties vary according to the direction in which they are measured. Anisotropy is clearly related to the fabric and orientation of particles and pores in the material. Consequently, it is possible to obtain information on the internal structure of a sample when the anisotropic behavior of specific physical properties is determined.

The orientation of fine-grained particles and the formation of pore space vary according to the mode of deposition as well as the environmental setting (Osipov and Sokolov, 1977), thereby affecting the anisotropic behavior of the material. Anisotropy in marine, clastic sediments increases, in order from (1) to (4) (O'Brien et al., 1980; Moon and Hurst, 1984; Wetzel, 1984) as follows: (1) biologically homogenized, (2) accumulated under current influence, (3) vertically settled in normal marine environments, and (4) deposited under euxinic conditions. Types (2) and (3) occur in the Mississippi Fan sediments recovered during DSDP Leg 96.

In addition, the degree of particle/pore orientation increases with depth of burial (Rieke and Chilingarian, 1974). Nevertheless, the relative differences in anisotropy between depositional processes (2) and (3) seem to be preserved, even as overburden pressure and sediment compaction increase and particle/pore orientation improves (O'Brien et al., 1980).

The purpose of this investigation was to relate the general trends of anisotropy to mode of deposition by studying fine-grained sediments (both turbiditic and hemipelagic) cored during Leg 96 in the Mississippi Fan (Fig. 1). Both shrinkage and sonic velocity were used to determine the anisotropic behavior of the sediment. Determination of sonic-velocity anisotropy is a well-known technique used to obtain indications of the internal structure of sediments (Nacci et al., 1974). In contrast, the utili-

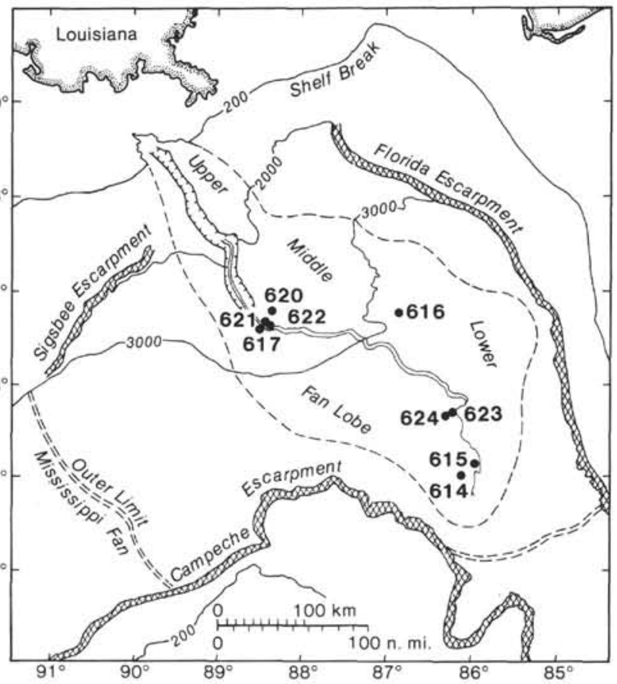

Figure 1. Location of Mississippi Fan sites drilled on DSDP Leg 96.

zation of shrinkage behavior for this purpose is not yet established, even though it too provides useful information on the pore geometry of unindurated muddy sediments (Wetzel, 1984). In order to justify analysis of shrinkage behavior for anisotropy studies, the physical process of shrinkage and its geological implications will be briefly explained next.

SHRINKAGE AS A PHYSICAL PROPERTY

Shrinkage is the result of forces that develop within the capillary system because of water loss. Brinch Hansen and Lundgren (1960) described the principles of shrinkage in pelites in detail. In an ideal case, the tension within pore water normally does not exceed the strength of the fabric as long as a sediment is totally saturated and no osmotic effects occur. However, when wa-

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ter evaporates from the surface of the sample, tension builds up in the pore water. This process can be described by the following equations (Hartge, 1978):

$$\sigma = \gamma/2r \qquad (1)$$

in the case of isometric pores or

$$\sigma = \gamma/(r_1 + r_2) \qquad (2)$$

in the case of pores with an elliptical cross section where σ = tension within the pore water, r = radius of the meniscus (equivalent to pore radius), and γ = surface tension of the pore fluid.

The maximum curvature of the water menisci within the pores depends on the size and geometry of the pores (Hartge, 1978). In the ideal case, additional tension within the pore water is induced from the surface of the sample because of evaporation of the pore fluid. Above the so-called shrinkage limit, the loss of water is compensated by volume loss of the sample, whereby the interior of the sample remains completely or nearly saturated. Within the sample the tension of the pore fluid is hydrostatic. Thus, the occurring volume changes are related to an isotropic all-round pressure (Terzaghi and Peck, 1967; Hartge, 1978). When the tension forces within the pore water exceed the strength of the fabric, the sample shrinks. This deformational process is related to different textural and structural parameters as follows:

1. The amount of volume loss is related to the mineralogical composition, grain size, pore volume, salinity of pore water, and exchangeable cations.

2. Shrinkage anisotropy is related to the arrangement of the particles because an isotropic all-round pressure does not change the relative arrangement of particles (Krizek et al., 1975). Consequently, the measured dimensional changes during drying are directly related to the pre-existing microstructure. In this study only the latter parameter, that of particle arrangement, is dealt with; the pelitic samples studied all had similar mineralogy, grain size, and initial porosity. The relationship between shrinkage and arrangement of particles has been demonstrated by scanning electron microscope (SEM) fabric studies and in several other ways:

a. Shrinkage anisotropy of the original sample was compared with that of a remolded sample containing the same water content. The original sample shows anisotropic shrinkage behavior, whereas the remolded sample shrinks isotropically (Wetzel, 1984).

b. Samples with the same area of internal surfaces (i.e., similar grain size compositions, Rabitti et al., 1983) show different shrinkage anisotropies.

c. The relationship between shrinkage anisotropy and fabric anisotropy of various types of pelites was stated by Merklein (1982).

Shrinkage anisotropy and its implications are discussed extensively in this chapter, whereas the aspects of sonic-velocity anisotropy are described only briefly, since both show the same general trends.

AREA OF INVESTIGATION

Anisotropy measurements were made on samples collected from eight Leg 96 drill sites located in the middle and lower Mississippi Fan (Fig. 1).

We drilled at five sites in the midfan region. Sites 621 and 622 are both situated in the central midfan channel and holes there were drilled to sub-bottom depths of about 200 m. The cored channel fill sequences show overall fining-upward trends from pebbly mudstone (lag deposits on the channel floor) through alternating sand, silt, and thin-bedded mud into thick-bedded mud (see site chapters, this volume). At Site 617, we drilled to 191.2 m sub-bottom depth in a swale on the western side of the midfan channel. Three units capped by a thin foraminiferal mud were penetrated: (1) a lower 108-m-thick coarsening-upward sequence composed primarily of mud, (2) a 38-m-thick uniform silt-laminated mud, and (3) an uppermost fining-upward sequence consisting of mud with some silt laminae (see Site 617 chapter, this volume). Site 620 is located about 20 km northeast of the midfan channel, and 422.7 m of overbank deposits were penetrated. Sediments from Site 620 are not discussed in this chapter because they were rotary cored and therefore show a large degree of drilling disturbance. Site 616 is 55 km east of the central midfan channel on the easternmost flank of the Mississippi Fan. The 371-m-deep Hole 616 penetrated (from bottom to top) (1) a lower mud unit (110 m thick), (2) sand-rich material fining-upward in its upper part (123 m thick), (3) a silt-laminated mud sequence (85 m thick), and (4) a slightly coarsening-upward silt-laminated mud sequence (63 m thick) (see Site 616 chapter, this volume).

We drilled at four sites on the lower fan (Fig. 1). At Sites 623 and 624, on the margin of the lower fan channel, we drilled to depths of about 200 m sub-bottom. Sediments at both sites consist of alternating 10- to 20-m-thick channel fill deposits (fining-upward sequences rich in sand) and 20- to 60-m-thick overbank deposits that are poorly defined coarsening-upward sequences (see site chapters, this volume). At Site 615, we drilled on the western edge of the lower fan channel near its termination to 523.2 m sub-bottom depth. The youngest fan lobe recovered at this site is 199 m thick, whereas the underlying fan lobe is 285 m thick. Both are characterized by a general coarsening-upward trend. Below these two fan lobes occurs a fining-upward carbonate sequence probably derived from the western part of the Florida platform. The sedimentary structures suggest that it was deposited by a debris flow (see Site 615 chapter, this volume; Brooks et al., this volume). At Site 614, we drilled to a sub-bottom depth of about 150 m, penetrating the fan lobe sediments similar to those recovered at Site 615 (see Site 614 chapter, this volume).

The Holocene sediments form only a thin cover of several decimeters at the top of the holes and consist of hemipelagic and pelagic calcareous clay and marly calcareous ooze. In contrast, the underlying late Wisconsin glacial sediments are primarily terrigenous turbidites. In general, none of the sediments are cemented. The consistency of the recovered material ranges from loose sand to soft to stiff mud depending on their grain size and depth of burial.

SAMPLING STRATEGY

Because there were no visual criteria for distinguishing between fine-grained turbidites and hemipelagic deposits, samples were necessarily taken randomly with respect to their mode of deposition. However, there are indirect indications of depositional mode. Specifically, this indirect evidence is based on the following consideration: Within a coarsening-upward sequence, three general upward trends (Nelson and Nilsen, 1984) can be seen: (1) the frequency of turbidites very probably increases upsection, (2) the intensity and velocity of the turbidity flow depositing those turbidites increases, and consequently, (3) more frequent and more intense flows lead to greater erosion of underlying hemipelagic material deposited on top of the preceding turbidite. The combination of these three factors significantly raises the probability that in a coarsening-upward sequence the proportion of pelitic material deposited by turbidity currents increases upsection. Consequently, the probability of sampling such material is similarly greater. In fining-upward sequences the inverse trend should be true.

On the basis of this reasoning, it is possible to utilize randomly collected samples (i.e., samples collected without knowledge of the mode of deposition of the sediment) and calculate average values over larger sections (10–20 m) to determine general depositional trends.

Only pelitic sediments were analyzed in this study, since sandy materials were too disturbed to make sonic velocity or shrinkage anisotropy measurements. Shrinkage anisotropy was determined for sediments from all of the Mississippi Fan sites except for Site 620 sediments, which were disturbed by drilling.

In general, one shrinkage and sonic velocity anisotropy determination was made per core section (1.5 m). A total of about 1500 determinations were made.

METHODS

Shrinkage Measurements

A cylindrical sample of known dimensions (2.5 cm diameter and 2.0 cm height) was collected with its rotational axis perpendicular to bedding. The sample was dried for 24 hr. at 110°C. After drying, the precise diameter and height of the sample were determined (error approximately ±1%). Using these measurements, linear shrinkage values[3] perpendicular to bedding (Sh_z) and parallel to bedding (Sh_y and Sh_x), mutually perpendicular to each other and to Sh_z, were then calculated with the formula

$$Sh_i\ (\%) = \frac{l_o - l_d}{l_o} \times 100 \tag{3}$$

where Sh_i = linear shrinkage in direction i ($i = x, y, z$), l_o = length of the wet sample in direction i, and l_d = length of the dried sample in direction i.

[3] In order to be consistent with other chapters in the Initial Reports (e.g., Bayer, 1983; Einsele, 1982; Wetzel, 1984), the abbreviation "Sh" is used instead of the symbol ϵ normally used in soil mechanics for strain.

Based on linear shrinkage values, the anisotropy of shrinkage (Sh_a) was calculated using the formula

$$Sh_a = \frac{Sh_z}{Sh_x + Sh_y}\,. \tag{4}$$

Sonic Velocity Measurements

Compressional-wave velocity was determined on board ship as described by Boyce (1976) on the same samples that were later used for shrinkage measurements. The data are given in the site chapters (this volume). When the sediment was stiff enough to take subsamples, sonic velocity was measured parallel as well as perpendicular to bedding using sediment cubes (2 × 2 × 4 cm in size). Because the sediment in the upper 20 to 50 m of the holes was too soft to cut sediment cubes, it was not possible to make measurements perpendicular to bedding. Thus, no evaluation of sonic-velocity anisotropy could be conducted in these portions of the sections.

For Sites 614 to 622, sonic velocity was determined perpendicular to bedding and in only one direction parallel to bedding; for Sites 623 and 624, sonic velocity was also measured in a second direction parallel to bedding (perpendicular to the other directions). From these values, the compressional-wave velocity anisotropy (sv_a) was calculated with the formula (Carlson and Christensen, 1977)

$$sv_a\ (\%) = \frac{sv_v - sv_h}{sv_v + sv_h} \times 200 \tag{5}$$

where sv_a = sonic velocity anisotropy, sv_v = sonic velocity perpendicular to bedding, and sv_h = sonic velocity parallel to bedding.

When sonic velocity was determined in two directions parallel to bedding, sonic-velocity anisotropy was calculated separately for both of these measurements.

Accuracy of the Calculations

The error in measurements is about 1% for both shrinkage and sonic-velocity determinations. Resultant errors in the anisotropy calculations were numerically estimated and are 1–2%. For both shrinkage and sonic-velocity anisotropy, anisotropy variations are normally larger than the estimated error.

RESULTS AND INTERPRETATION OF SHRINKAGE ANISOTROPY

In a pelitic sequence of uniform composition, particle/pore orientation becomes more regular downhole because of increasing overburden pressure (Bennett et al., 1981). Thus, samples of similar nature should show a higher degree of anisotropy with increasing depth of burial (Heling, 1970). However, shrinkage anisotropy of the visually and compositionally similar sediment samples from most of the Mississippi Fan drill sites does not show this expected general trend of increasing anisotropy with depth (Figs. 2 and 3). Consequently, the observed variations of shrinkage anisotropy must be influenced by differences in modes of deposition of these samples.

Two general trends are recognized when comparing lithologic characteristics and mode of deposition with shrinkage behavior of the Mississippi Fan sediments.

1. The degree of shrinkage anisotropy of fining-upward sequences increases upward (with the exception of Site 615, below 480 m sub-bottom and Site 622), whereas coarsening-upward sequences show the reverse trend (Fig. 3). These trends can be interpreted in terms of the mode of deposition of the sediment, with fining-upward sequences reflecting the decreasing influence of density currents carrying coarser-grained material and coarsen-

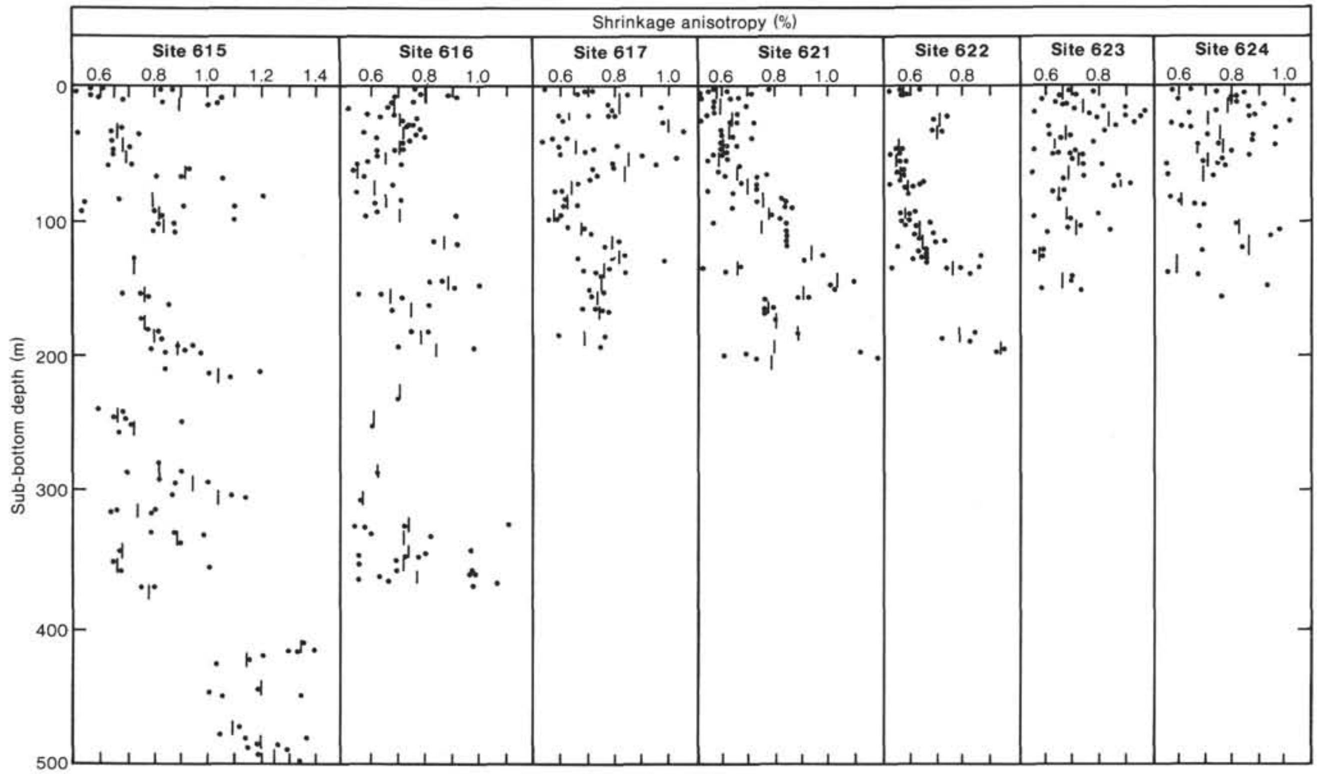

Figure 2. Shrinkage anisotropy versus depth for studied sediments. Points are single determinations, bars are average values.

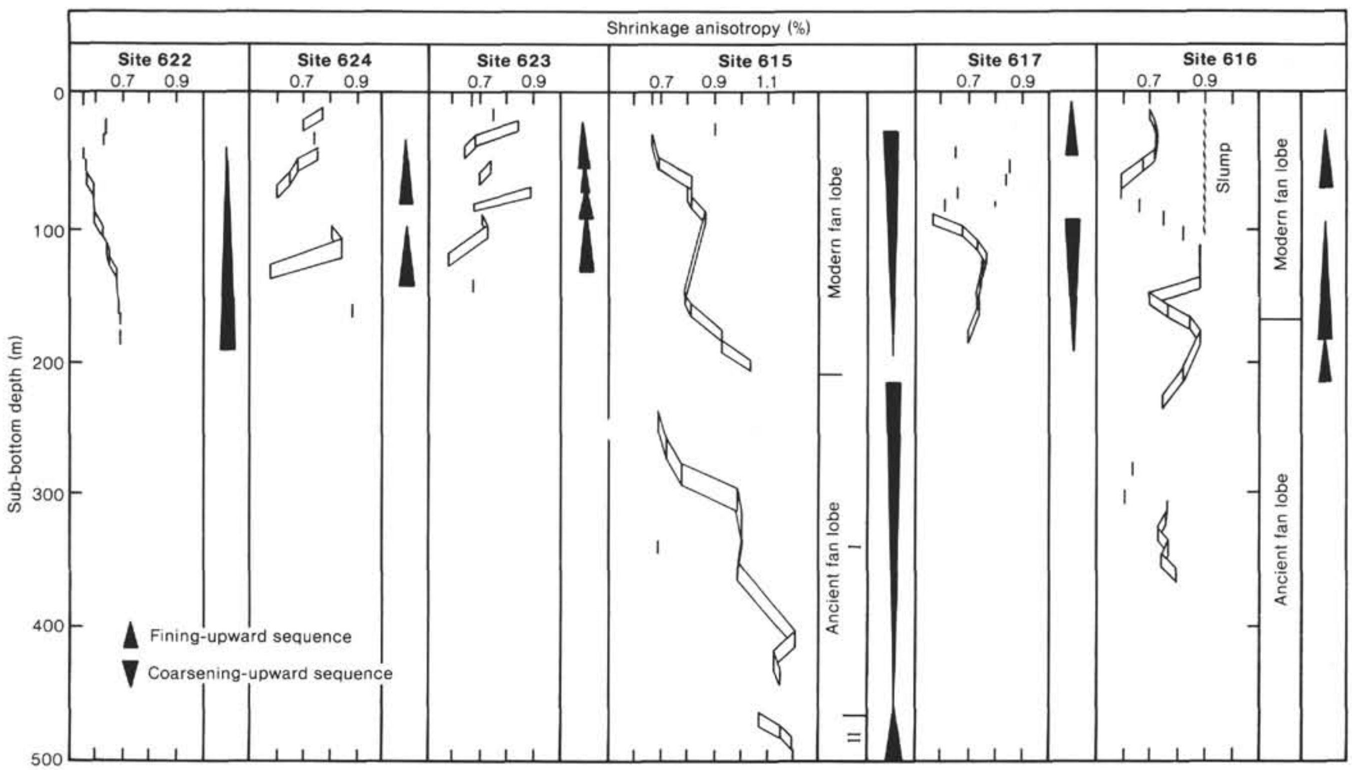

Figure 3. Relationship between shrinkage anisotropy and lithologic sequences. Average values were calculated for shrinkage anisotropy over depth intervals of about 10 m. Lithologic sequences are characterized by general fining- or coarsening-upward trends. In general, fining-upward sequences show increasing shrinkage anisotropy due to a greater degree of particle/pore orientation which is related to the dominant hemipelagic sedimentation. Coarsening-upward sequences show the inverse trend because of the predominant turbidite sedimentation.

ing-upward sequences reflecting the increasing turbidity current activity.

However, the sequences observed in the cores do not necessarily reflect the true lithologic trends because of incomplete recovery. To get information about the missing intervals, well logs were run. Gamma-ray logs provided the best information in the open drill holes. Processed gamma-ray data allow us to recognize bed thickness trends that may correspond to general lithologic sequences (Coleman, Constans, and Bouma, this volume). Based on these data, thickness of pelitic beds (API value <20) correlates well with the general trends of anisotropy: with increasing thickness of pelitic beds a higher degree of anisotropy occurs (Fig. 4).

Turbidite sequences have relatively low shrinkage anisotropy because the particles cannot reach their "optimal" orientation under turbidity current deposition, resulting in a more or less open isotropic fabric (O'Brien et al., 1980).

In contrast, lithologically similar hemipelagic sediments have a higher degree of particle orientation, and therefore a greater degree of shrinkage anisotropy because of the prevailing quiet settling conditions.

There are, of course, transitions between the turbidite and hemipelagic anisotropic end members. An example may be particles that were initially transported by a turbidity current and ultimately settled to the seabed quasi-quietly from a very slowly flowing suspension.

The debris flow deposits at Site 615 (below 480 m subbottom) show a pattern different from the general trends described above. This may be related to this specific mode of deposition. During transport of debris flows, the sediments are subjected to an internal shearing (Middleton and Hampton, 1973) that may lead to a higher degree of particle orientation (e.g., Sonderegger, 1985). The shearing within a slowly moving debris flow normally decreases from bottom to top (Allen, 1984), as is also indicated by a decreasing anisotropy (Fig. 3).

2. The effect of overburden pressure on shrinkage anisotropy can be estimated in the fining-upward channel-fill sequence cored at Site 622. Although the intensity of density currents changes from high concentration to low concentration flows upsection, a turbidity current origin of the major proportion of the channel fill is indicated by the large amount of displaced shallow water fauna (see Site 622 chapter, this volume; Kohl et al., 1985). As-

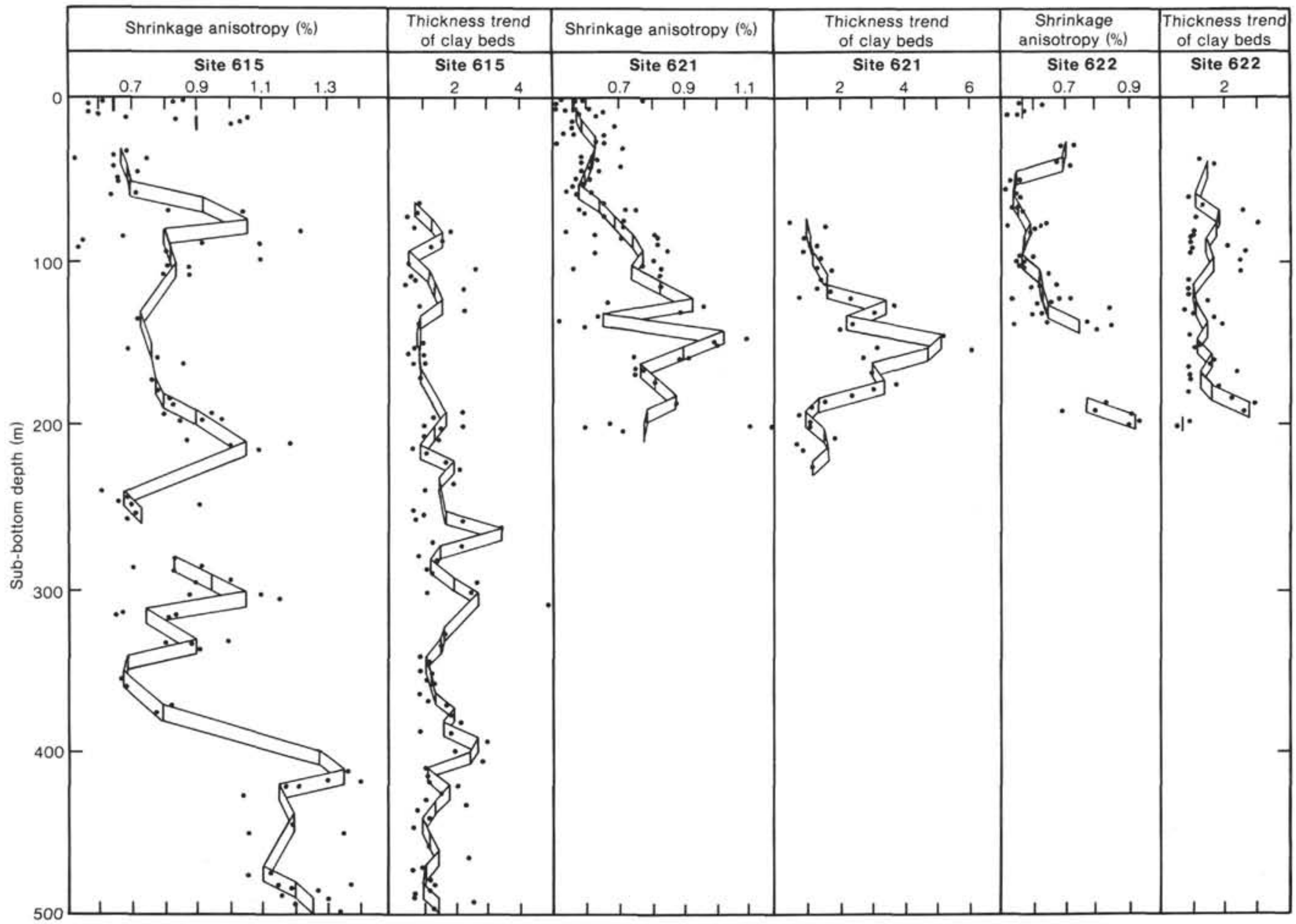

Figure 4. Relationship between shrinkage anisotropy and bed thickness trends of "clay-beds." The latter data are derived from processed gamma-ray well-log data; clays are indicated by an API value <20 (Coleman, Constans, and Bouma, this volume). For both shrinkage anisotropy and clay bed thickness, single values (points) as well as average values for 10-m intervals (bars) are shown.

suming that the depositional processes for the fine-grained material in the lower section of the drilled sequence (200 to 100 m sub-bottom) did not change significantly, the slight increase in anisotropy observed downhole may result from increasing burial depth rather than the effects of varying depositional mode (Fig. 3).

The effect of overburden pressure on shrinkage anisotropy can also be seen in the Site 615 sediments: the basal parts of the coarsening-upward sequences are assumed to be deposited by a similar mode of deposition. The comparison of these sections with each other reveals the same rate of increase of anisotropy with depth as found in the Site 622 sediments.

In contrast to these two general trends found in entire sequences, observations in single beds also show the influence of currents by shrinkage anisotropy parallel to bedding.

Within the bedding plane, the amount of shrinkage parallel to current direction is higher than that perpendicular to it. The phenomenon of anisotropic shrinkage parallel to bedding is interpreted on the basis of the general relationship between shrinkage anisotropy and orientation of particles/pores. Thus, anisotropic shrinkage parallel to bedding implies a preferred orientation of particles/pores with their long axis parallel to current direction. SEM fabric studies support this deduction.

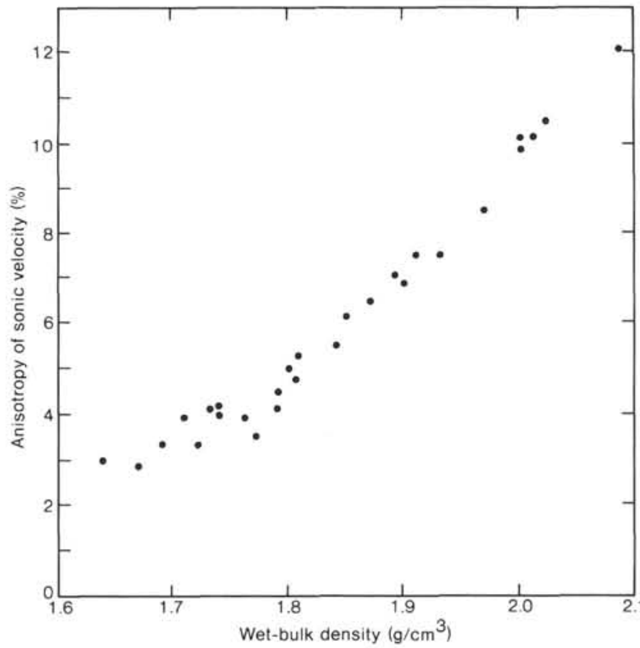

Figure 5. Relationship between maximum values of sonic-velocity anisotropy and wet-bulk density from all Mississippi Fan sites. Sonic-velocity anisotropy generally increases 2.5% per 0.1 g/cm^3 increase in wet-bulk density. For more easily comparable data, only sediments of similar composition (silty mud) were used.

SONIC-VELOCITY ANISOTROPY RESULTS

Sonic velocity and anisotropy increase with decreasing distance between particles; this may occur, for instance, with increasing compaction (Hamilton, 1974; Carlson and Christensen, 1977). At the Mississippi Fan only the maximum values of sonic anisotropy increase at a rate of 3–4% per 100 m below 50 m sub-bottom depth (Fig. 5).

Anomalously low anisotropy values were found in deeper sediment, producing an unsystematic scattering of data points (Fig. 6). To evaluate this scattering, compressional-wave velocity was determined in two different directions parallel to bedding in samples from Site 623 (Fig. 7) and Site 624. This was based on the assumption that the fabric of the measured pelitic sections is influenced by turbidity currents, resulting in a fabric anisotropy parallel to bedding similar to that indicated by shrinkage anisotropy. These determinations reveal a considerable degree of sonic-velocity anisotropy parallel to bedding; parallel variations can reach the same magnitude as differences between measurements perpendicular and parallel to bedding (Fig. 7). Because the determinations were carried out on sediment cubes that were randomly cut (see above implications for sampling), both maximum and minimum values were not always measured parallel to bedding and resultant anisotropy determinations are less than maximum values. This is the case when the angle of the cutting planes varies 0–90° from the current direction (Fig. 8). Because currents produce an elongation of pores in the direction of flow, the minimum value of sonic velocity occurs in the current direction. Accordingly, the maximum value can be found perpendicular to flow direction. This pattern allows the detection of turbidity current flow direction in fine-grained sediments by determining sonic-velocity anisotropy parallel to bedding.

CONCLUSIONS

1. Both shrinkage and sonic-velocity anisotropy demonstrate the same general trends:

a. The degree of anisotropy is related to the mode of deposition when grossly applied to entire depositional sequences. In fining-upward sequences with a decreasing intensity in density currents anisotropy increases upsection, whereas coarsening-upward sequences show the inverse trend.

b. Current influence is also documented by anisotropy parallel to bedding.

c. Anisotropy of sediments that were accumulated under similar conditions increases with depth of burial.

2. Because the relative differences in anisotropic behavior between turbidites and hemipelagic pelitic sediments are preserved with depth, it is likely that these sediments also differ from each other in their compactional behavior.

3. Since the anisotropic character of a sediment has just begun to be used as an indicator of the mode of deposition, it is not yet possible to compare sediment types (that is, depositional modes) with an absolute scale for both entire sequences and single beds. However, because anisotropic behavior seems promising as an aid to identification of depositional mode, further study in this area is necessary in order for these observations to reach their full potential.

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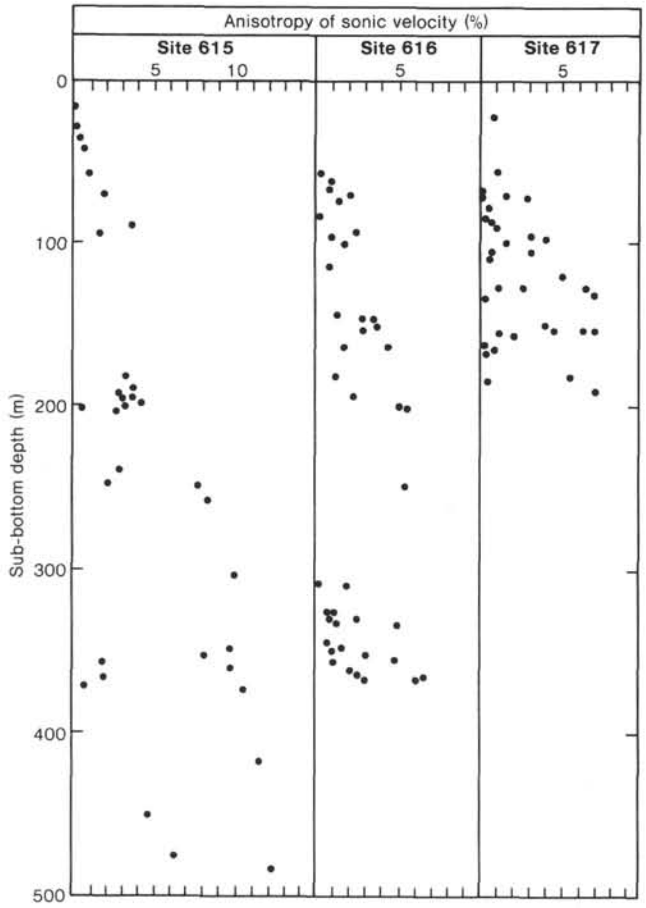

Figure 6. Downhole trends of sonic-velocity anisotropy at Sites 615, 616, and 617. The maximum values show a clear trend, whereas the minimum values are somewhat scattered (for explanation, see text). Other sites reveal similar trends.

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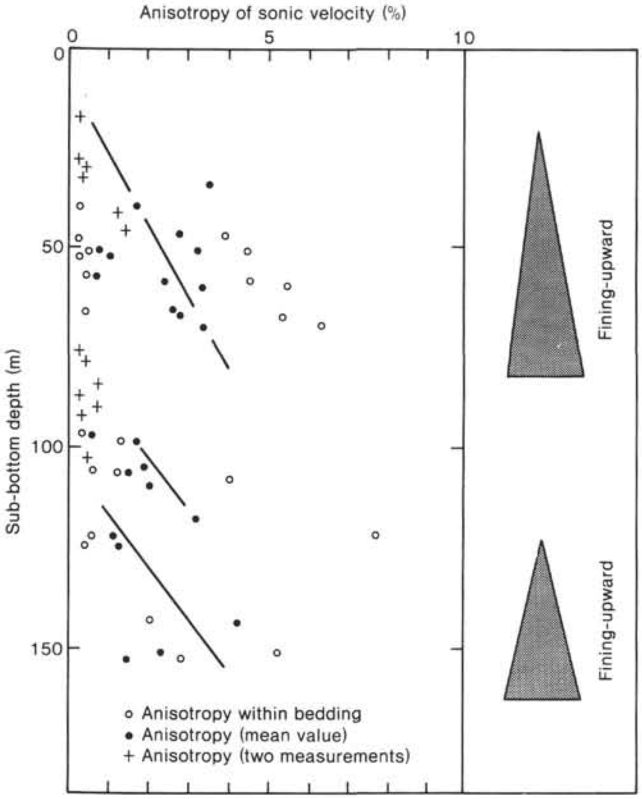

Figure 7. Anisotropy of sonic velocity versus depth at Site 623; anisotropy parallel to bedding significantly affects the anisotropy of the sediment (calculated from vertical versus horizontal measurements). Sediment cube samples analyzed do not always have maximum and minimum values measured parallel to bedding, depending on the orientation of the cube to the current direction. However, those samples that did have maximum values of anisotropy reveal a clear trend (Fig. 3).

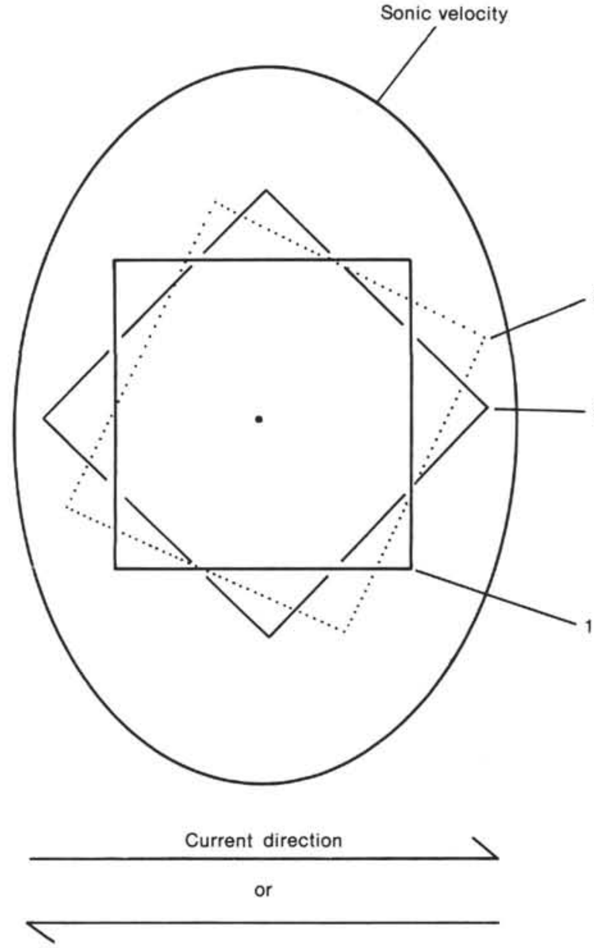

Figure 8. Influence of subsampling procedure on the value of sonic-velocity anisotropy as determined from sediment cubes collected from turbidite deposits. When measurements are carried out on sediment cubes, maximum and minimum values are not always determined with certainty (see text). The ellipsoid refers to sonic velocity measured in sediments influenced by currents. If the cube is cut in orientation (1), maximum and minimum values can be measured; in (2), no extreme values occur; in (3), intermediate maximum and minimum values are measured.