

SEDIMENTOLOGICAL SIGNIFICANCE OF STRAIN AND SONIC VELOCITY ANISOTROPY IN FINE-GRAINED TURBIDITIC AND HEMIPELAGIC DEEP-SEA SEDIMENTS — AN EXAMPLE FROM THE MISSISSIPPI FAN

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Abstract

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In visually homogeneous and compositionally similar argillaceous sediment of the Mississippi Fan, depositional processes (turbiditic versus hemipelagic sedimentation) are reflected in the anisotropy of strain as well as in sonic velocity. The correspondence between the mode of deposition and anisotropy was observed in single beds as well as in entire depositional sequences.

In single beds, the turbiditic part (as opposed to the pelagic portion) is characterized by an anisotropy within bedding and a comparatively low anisotropy between vertical and horizontal directions; as current influence decreases, anisotropy within bedding disappears, while anisotropy in vertical versus horizontal directions increases. Because of rapid sedimentation, the sediments are not influenced by bioturbation that would distort the primary fabric.

In depositional sequences, the anisotropy pattern depends on the type of sequence; in fining-upward sequences, anisotropy in vertical versus horizontal directions increases upsection and anisotropy within bedding is less frequent. This pattern is explained by the decreasing influence of turbidity currents on sediment fabric and an increasing proportion of quietly accumulated, hemipelagic deposits. In coarsening-upward sequences the inverse trends are found.

The general correspondence between trends in lithology and anisotropy only documents relative changes in the predominant depositional process within a specific fan sub-environment. On an absolute scale, values of both types of anisotropy differ from site to site; a clear pattern within the fan is found. Thus, anisotropy determinations provide useful supplementary information for interpreting fan environments.

Compaction generally leads to an increasing anisotropy, but the relative differences in anisotropy between turbiditic and hemipelagic sediments are not significantly affected.

Introduction

Anisotropy refers to the variation of properties in relation to the direction in which they are measured. Anisotropy of physical properties in sediments corresponds to preferred particle/pore orientation that results

from depositional, compactional, and/or diagenetic processes (Rees, 1965; Oertel and Curtis, 1972; Carlson and Christensen, 1977; Gravenor and Coyle, 1985). In this study, only anisotropy related to depositional processes is considered.

The arrangement of particles, and hence, the formation of pore space, varies with environmen-

tal conditions (e.g., Osipov and Sokolov, 1978; Moon and Hurst, 1984). Although particle/pore orientation in fine-grained sediments reaches a higher degree of parallelism due to compaction, relative differences in fabric are preserved, as shown by O'Brien et al. (1980) for turbiditic and hemipelagic deposits. Consequently, relative differences in anisotropy should also be maintained during compaction in such deposits.

However, deciphering depositional processes in fine-grained sediments becomes increasingly difficult, inasmuch as (1) sediment is compacted, and (2) differences in grain size are smaller, i.e. the frequency of silt-sized particles decreases. Indirect methods for fabric analysis are then useful, for instance, in the determination of anisotropy.

The purpose of this investigation is to relate the pattern of anisotropy to the mode of deposition by studying fine-grained sediments in both turbiditic and hemipelagic Mississippi Fan deposits that are mostly unbioturbated. The significance of anisotropy was consequently investigated for single argillaceous beds as well as for entire depositional sequences that characterize the general trends of deposition in submarine fan deposits (Mutti and Ricchi Lucci, 1972). Anisotropic behavior of the sediment was determined by both strain and sonic velocity. Determination of sonic velocity anisotropy is a well known technique used to obtain indications of the internal structure of sediments (Nacci et al., 1974; Carlson, 1981).

In contrast, the utilization of strain for this purpose is not yet established, even though it, too, provides useful information on particle orientation and pore geometry of unindurated muddy sediments (Wetzel, 1984). The determination of strain is a simple method in terms of necessary equipment as well as necessary measurements. Determination of strain has the advantage of providing data for the whole sample tested and not just for a specific part as is the case in SEM or X-ray-based fabric studies.

Material and methods

The sedimentological significance of anisotropy was investigated in sediments drilled at eight sites during Leg 96 of the D.V. "Glomar Challenger" on the middle and lower Mississippi Fan (Fig.1).

Area of investigation

The Mississippi Fan extends almost 600 km from near the present Mississippi River Delta onto the Gulf of Mexico abyssal plain. It is a broad, thick, arcuate accumulation of Pleistocene shallow water sediments that were deposited mainly by sediment gravity flows into the deep-sea. The Mississippi Fan is built up by seven elongate sediment bodies — so-called "fan lobes". The two youngest fan lobes were investigated during Leg 96. They were mainly formed 12,000–85,000 and 85,000–127,000 yrs B.P., respectively.

At four sites, sediments of the middle fan were studied. Sites 621 and 622 are situated in the central midfan channel, Site 621 in the thalweg of the channel, and Site 622 on the inside concave or "point bar" side of the channel. Both sites were drilled to a subbottom depth of about 200 m, and the sediments show similar lithologic characteristics, although deposits at Site 622 tend to be more fine-grained than at Site 621. The cored channel-fill sequences show an overall fining-upward trend from pebbly mudstone (lag deposits on the channel floor) through alternating sand, silt, and thin-bedded mud to thick-bedded mud. However, this general trend is superimposed by variations in the lithologic composition which are reflected by bed thickness trends that were derived from processed gamma-ray well-log data.

Site 617 was drilled to 191 m subbottom depth in a swale on the western side of the midfan channel. Three units capped by a thin, foraminiferal mud were encountered: (1) a lower, 108 m thick, coarsening-upward sequence composed primarily of mud; (2) 38 m thick, uniform, silt-graded mud; and (3) an

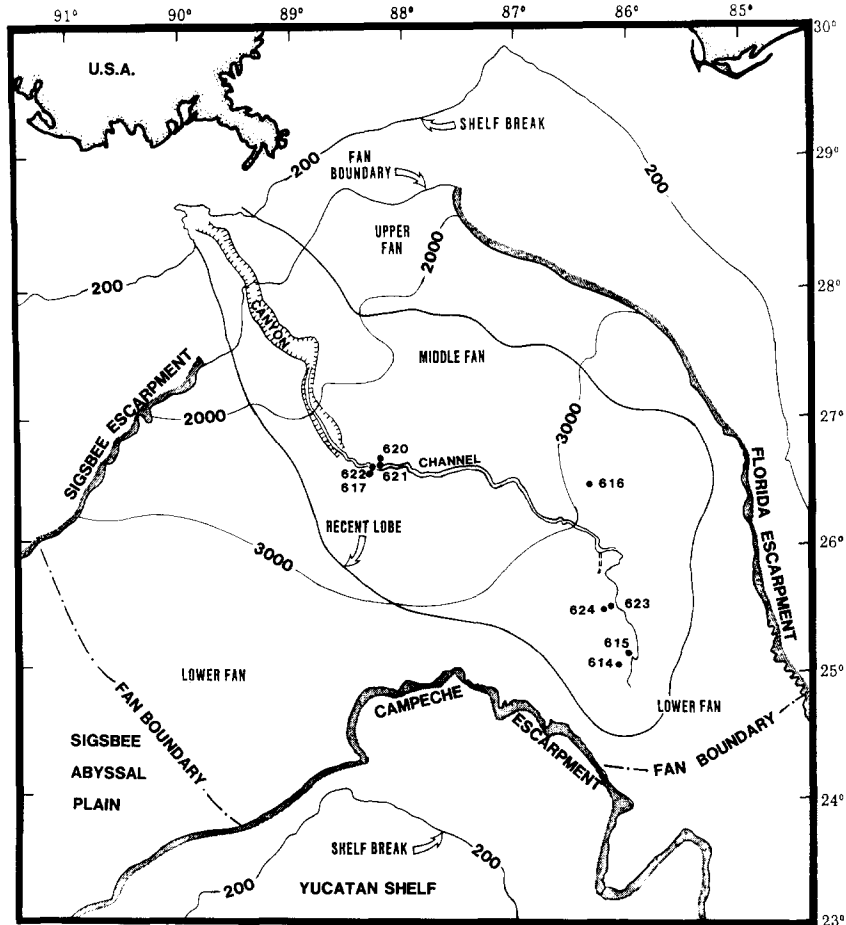


Fig.1. Location of Mississippi Fan drill sites.

uppermost fining-upward sequence consisting of mud with some silt laminae.

Site 616 was drilled 55 km east of the central midfan channel on the easternmost flank of the Mississippi Fan. The 371 m deep hole penetrated, from bottom to top: (1) a lower, 121 m thick mud unit; (2) 110 m of sand-rich material fining upward in its upper part; (3) a 55 m thick, fining-upward mud sequence; and (4) 95 m of slumped, muddy sediment showing some fining-upward trends in its upper section.

Four sites are situated on the lower fan. Sites 623 and 624 are located on the margin of the lower fan channel. They were drilled to a depth of about 200 m subbottom. Sediments

at both sites consist of alternating 10–20 m thick, sand-rich, fining-upward channel-fill and 20–60 m thick, muddy overbank deposits that are poorly defined, coarsening-upward sequences.

Site 615 is situated on the western edge of the lower fan channel near its termination; it was drilled to 523 m subbottom depth. The modern fan lobe sediments recovered at this site are 202 m thick, whereas the underlying fan lobe is 274 m thick. Both fan lobes are characterized by a general coarsening-upward trend. The upper fan lobe contains less sand and is generally more thickly bedded than the underlying fan lobe. However, these general

trends are superimposed by short-term variations in grain size as well as bed thickness.

At Site 614, 150 m of fan-lobe sediments similar to those recovered at Site 615 were penetrated.

Sediments drilled at neighboring sites are similar in terms of lithology as well as depositional processes, and hence, they show similar trends in physical properties. Therefore, for Sites 614 and 615, 621 and 622, and 623 and 624 the obtained results are drawn only for one site in each group.

Methods

In this study, only fine-grained, pelitic sediments of similar composition were investigated in respect to their anisotropic behavior, since sandy material was too disturbed to make reliable measurements of physical properties.

Anisotropy was determined from measurements of strain and compressional-wave velocity as well as SEM fabric studies. Composition of the sediments was estimated by determination of specific surface area. In order to avoid the influence of grain-size variations (Curtis et al., 1980), only sediments of similar composition were tested (see below; specific surface area). The following methods were applied.

Strain measurements

A cylindrical sample of known dimension (2.5 cm diameter and 2.0 cm height) was taken with its rotational axis perpendicular to bedding (Fig.2). The sample was dried for 24 h at 110°C. After drying, the precise diameter and height of the sample were determined (error approximately $\pm 1\%$). These measurements were used to calculate linear strain values perpendicular to bedding (ϵ_z) and parallel to bedding (ϵ_x) and (ϵ_y), mutually perpendicular to each other and to ϵ_z :

$$\epsilon_i (\%) = (l_0 - l_d) \times 100 / l_0 \quad (1)$$

where ϵ_i = linear strain in direction "i" ($i = x, y, z$), l_0 = length of the wet sample in direction i , and l_d = length of the dried sample in direction i .

Based on the linear strain values, the

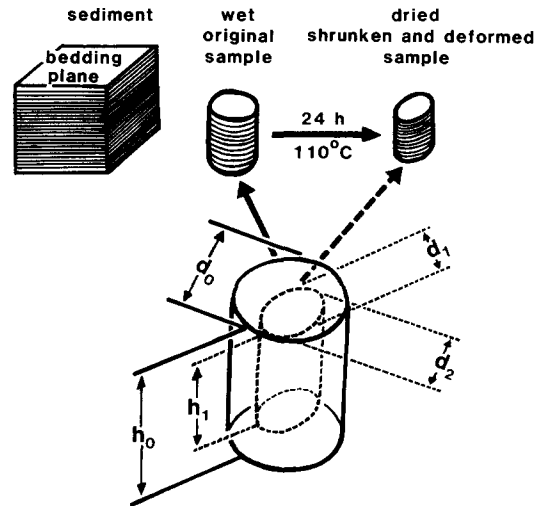


Fig.2. Measurements necessary for determination of strain. d_0 = diameter, and h_0 = height of a water-saturated undeformed cylinder sample taken with its rotational axis perpendicular to bedding. For the dried and deformed sample the height (h_1) and the smallest (d_1) and largest (d_2) diameter are indicated.

anisotropy of strain was calculated between vertical and horizontal directions (ϵ_{av}) and within bedding (ϵ_{ah}) by the formulas:

$$\epsilon_{av} = \epsilon_z / (\epsilon_x + \epsilon_y) \quad (2)$$

and:

$$\epsilon_{ah} = 2(\epsilon_x - \epsilon_y) / (\epsilon_x + \epsilon_y) \quad (3)$$

that is analogous to eq.4.

Strain due to shrinkage and its implications

Sediment shrinkage can be explained by the forces that develop in a capillary system due to water loss (Brinch Hansen and Lundgren, 1960). As long as a sample is completely saturated with water and no osmotic effects occur, the tension of the water within the pore system does not exceed the strength of the fabric. Inasmuch as water evaporates from the surface of a sample, the tension within the pore water increases, because it adheres to the surfaces of the mineral grains. Thereby, the forces within the pore water are hydrostatic and act in a similar way as an external

pressure (Terzaghi and Peck, 1967). Thus, the forces within the pore water are isotropic. When the tension within the pore water exceeds the fabric strength, the sample starts to shrink. Then, during a certain period of drying, water loss is roughly compensated by volume loss of the sample until at a marked water content — the so-called shrinkage limit — the sample maintains a constant volume.

Under the isotropic tension conditions within the pore water, the deformation of an uncemented sample depends mainly on the arrangement of particles that define the direction of dewatering (Krizek et al., 1975). Consequently, the measured dimensional changes occurring during drying are directly related to the microstructure. The relationship between strain due to shrinkage and the arrangement of particles was proven in several ways: (1) strain anisotropy of the original sample was compared to that of a sample remolded at the same water content; the original sample shows a strain anisotropy, whereas the remolded sample was deformed isotropically (Wetzel, 1984); (2) samples with the same area of specific surfaces, i.e. similar grain-size composition (Rabitti et al., 1983), show different strain anisotropies; and (3) SEM investigations demonstrate the correspondence between strain anisotropy and fabric parameters; the pore anisotropy calculated from pore height and pore length (see below; investigation of fabric) is clearly related to strain anisotropy (Fig.3).

Sonic velocity

Compressional-wave velocity was determined on board ship using a Hamilton frame (Boyce, 1976). The measurements were carried out on the same samples that were later used for strain measurements. When the sediment was stiff enough to take subsamples, sonic velocity was measured parallel as well as perpendicular to bedding on sediment cubes $2 \times 2 \times 4$ cm in size. For sediments of Sites 614–622, sonic velocity was determined perpendicular to bedding and in only one direction within bedding. For deposits of Sites 623 and 624, sonic velocity was also measured in a

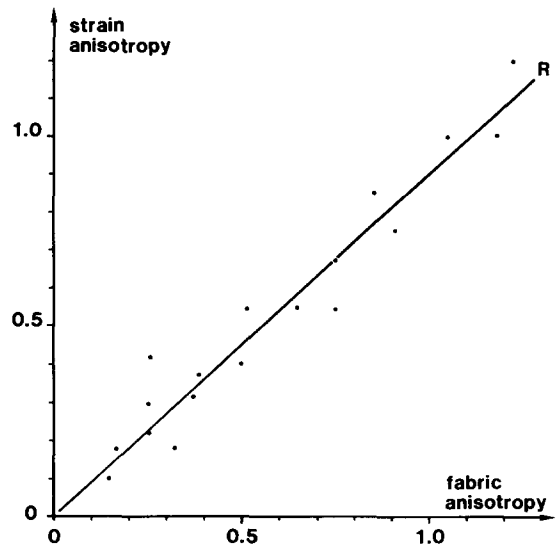


Fig.3. Correspondence between anisotropy of strain and anisotropy of fabric expressed as anisotropy of pores. Measurements were carried out on various samples ranging from sea floor sediments to highly compacted mudrocks. The regression line (R) follows $y=0.902x$. The correlation coefficient is 0.96. Anisotropy was calculated by eqs.3 and 5.

second direction parallel to bedding, perpendicular to the other directions.

Anisotropy of compressional-wave velocity (sv_a) was calculated using the formula given by Carlson and Christensen (1977):

$$sv_a(\%) = 200(sv_m - sv_n)/(sv_m + sv_n) \quad (4)$$

Depending on the type of anisotropy which is determined, indices refer to different measurements: (1) in case of anisotropy in vertical versus horizontal direction, sv_m is sonic velocity in horizontal direction and sv_n in vertical direction; (2) for anisotropy within bedding, sv_m is the highest measured value parallel to bedding and sv_n the lowest. When sonic velocity was determined in two directions within bedding, anisotropy in vertical versus horizontal direction was calculated separately for both of these measurements, and then a mean value was calculated from both.

Specific surface area

In order to estimate the grain-size composition of pelitic sediments, the specific surface area was determined by the BET method using a Ströhlein Areameter II for measuring N_2 adsorption at the temperature of fluid nitrogen. Based on the investigations of Rabitti et al. (1983) it is assumed that sediments with a similar specific surface area have a similar grain-size composition. In this study, most sediments tested have specific surface areas of about $40 \text{ m}^2 \text{ g}^{-1}$.

Investigation of fabric

The arrangement and orientation of particles were studied using a scanning electron microscope (SEM). The investigated samples were freeze-dried. Fabric anisotropy (pa) was calculated as the mean value of the ratio of pore height (ph) to pore length (pl) of about 100 pores. The formula used is analogous to eqs.3 and 4, respectively:

$$pa = 2(pl - ph)/(pl + ph) \quad (5)$$

Accuracy of measurements and calculations

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

Sedimentological significance of anisotropy

In uncompacted sediments, anisotropy phenomena result mainly from preferred orientation within fabric, and hence they are related to depositional processes. Therefore, such anisotropies have sedimentological significance and may be useful as indicators of environmental conditions. This will be demonstrated for single beds as well as for sedimentary sequences.

Anisotropy in single beds

In pelitic beds of the Mississippi Fan, that are normally unbioturbated, both types of anisotropy (1) in vertical versus horizontal direction, and (2) within bedding were observed. Strain measurements show changing anisotropy phenomena in much more detail than sonic velocity determinations do. Therefore, the former are discussed extensively whereas sonic velocity anisotropy is only described briefly.

Strain

In most of the studied fine-grained (parts of) turbidites, strain anisotropy shows a typically graded profile like that in Fig.4. Above a coarser-grained, silty section, two parts can be distinguished:

(a) The lower part shows both types of anisotropy, within bedding (ϵ_{ah}) and perpendicular to bedding (ϵ_{av}). However, anisotropy within bedding is typical for this part; just above the basal layer, anisotropy within bedding (ϵ_{ah}) is highest and decreases upwards. Anisotropy perpendicular to bedding, on the other hand, increases upwards.

(b) The upper part is characterized by an increasing anisotropy perpendicular to bedding and the absence of anisotropy within bedding. This pattern of anisotropy phenomena is interpreted as follows:

(1) Anisotropy within bedding indicates a preferred particle/pore orientation even in fine-grained sediments, as deduced from the relationship between fabric and strain anisotropy (see above). Pores are elongate in the current direction, which was determined from the orientation of silt grains in the basal part (Rees, 1965). SEM studies of bedding planes show a fabric deformation of 2–10% when related to average pore measurements (Fig.5).

The value of anisotropy within bedding decreases upwards; this is interpreted as a result of currents diminishing during deposition of a fine-grained (part of a) turbidite. To relate anisotropy to current direction, the orientation of long axes of silt grains orien-

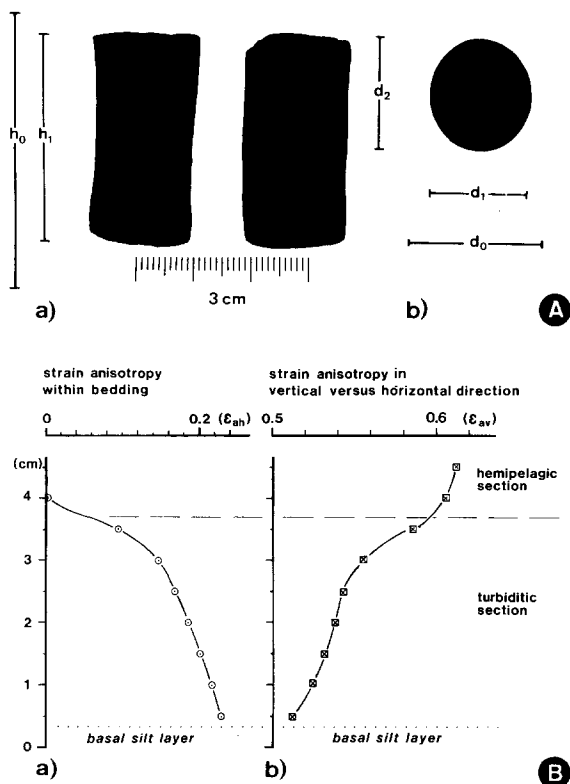


Fig.4. Strain anisotropy within argillaceous sediments from the Mississippi Fan; DSDP Site 616, Core 1-1, 132–137 cm depth in sediment. (A) Photograph of the tested sample, (a) view of sample in the d_1 and d_2 plane as defined in Fig.2, and (b) cross-section. (B) Profile of strain anisotropies of the sediment sample shown in (A); Hemipelagic and turbiditic section differ significantly in their strain pattern: turbiditic section shows a marked anisotropy within bedding (ϵ_{ah}) and a low value of anisotropy in vertical versus horizontal directions (ϵ_{av}) whereas in the quietly accumulated, hemipelagic section, ϵ_{ah} is lacking and ϵ_{av} is higher than is the turbiditic part.

tated predominantly parallel to current direction was determined in the basal part of a turbidite (Rees, 1965).

Hence, the anisotropy within bedding can be produced mainly in three ways: (i) A continuously flowing or pulsating current induces some shear stress into the sediment boundary layer (McCave, 1984) — this leads to a slight deformation of fabric whereby the pores become stretched in the current direction; (ii) it might also be that flocs of clay minerals

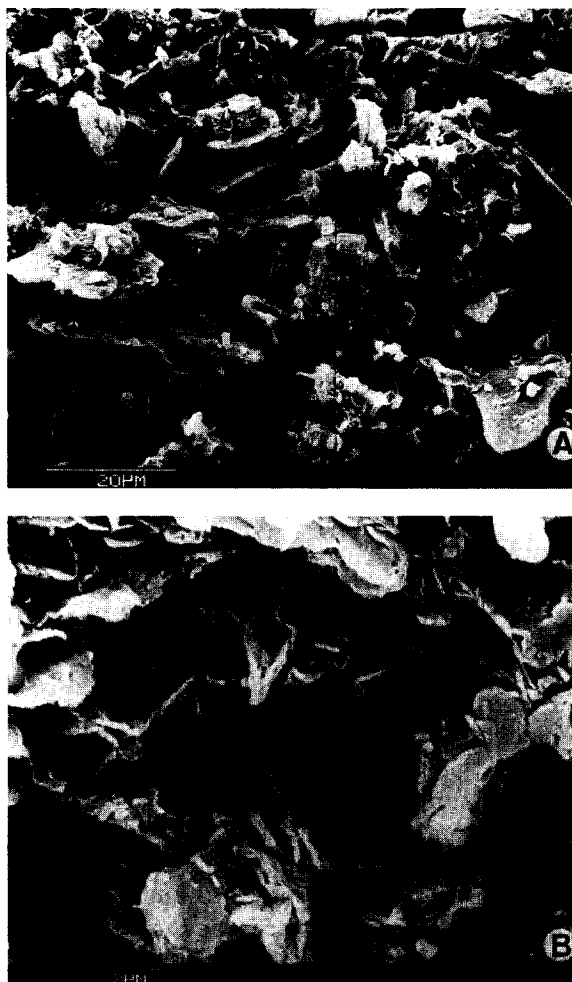


Fig.5. SEM microphotographs of fabrics observed in sediments that show a strain anisotropy within bedding. Both photographs show a section parallel to the bedding plane of the same sample shown in Fig.4: DSDP Mississippi Fan drill Site 616, Core 1-1.

(A) Basal silt layer (136.5 cm depth in sediment); the long axis of silt grains are oriented in the direction of flow (Rees, 1965), in this case from left to right or right to left. This coincides with the lowest strain value. (B) Cardhouse-like microfabric of clay minerals within the turbiditic section (134 cm depth in sediment); note elongation of pores in current direction.

become slightly elongate during their transport through the boundary layer before deposition, so that the anisotropy of particle and pore orientation would occur by long-axis particle (floc) alignment in the same way as for

silts; (iii) finally, processes (i) and (ii) may act simultaneously.

(2) Anisotropy perpendicular to bedding increases upwards (Fig.4). This grading indicates an increasing degree of parallelism of particles, and it is interpreted as follows: As long as currents are acting, near-surface shear stresses within the suspension prevent a parallel orientation of particles to the bedding as exemplified by the depositional model of Stow and Bowen (1978). Under such conditions only a low degree of anisotropy perpendicular to bedding is reached. Since flow diminishes and settling conditions become more quiet, the orientation of particles within this section shows an increasing degree of parallelism reaching "optimal" orientation under absolutely quiet settling conditions, thereby resulting in a high value of vertical anisotropy.

Sonic velocity

Determinations of sonic velocity reveal a considerable degree of anisotropy parallel to bedding; parallel variations can reach the same magnitude as differences between measurements perpendicular and parallel to bedding in the Mississippi sediments (Wetzel, 1986). The determinations were carried out on sediment cubes that were randomly cut because there were no visual criteria for the mode of deposition. Thus, maximum and minimum values of sonic velocity can not always be measured (Fig.6). Consequently, anisotropy determinations parallel to bedding often show less than maximum values. This is the case when the angle of the cutting planes varies 0–90° from the current direction (Fig.6). Therefore, for the estimation of maximum and minimum sonic velocity, at least more than four determinations on one sample were necessary.

The anisotropy of compressional-wave velocity is interpreted in the same way as the corresponding strain anisotropy; currents produce an elongation of pores in the direction of flow. Then the minimum value of sonic velocity occurs in the current direction.

A grading of sonic velocity anisotropy was

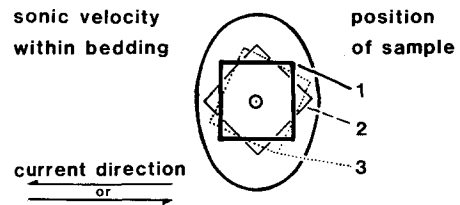


Fig.6. Influence of subsampling procedure on the value of sonic velocity anisotropy as determined from sediment cubes collected from turbiditic deposits. When measurements are carried out on sediment cubes, maximum and minimum values are not always determined with certainty (see text). The ellipsoid 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, and in 3 an intermediate maximum and minimum value is measured.

not directly observed because the transducers used cover too large an area to measure a detailed profile across the sample. However, grading of sonic velocity anisotropy should also exist because of the following reasons: (1) samples of similar composition and depth of burial show varying anisotropy values; this can be explained best when anisotropy shows grading and the actual position of transducers is different for each sample; and (2) the correspondence between strain anisotropy and fabric suggests that fabric parameters also govern sonic velocity anisotropy.

In summary, the evident variations of anisotropies are related to the change from current-influenced, turbiditic to quiet, hemipelagic sedimentation that was not influenced by bioturbation due to rapid accumulation. However, this obvious pattern may be enhanced by slight variations in grain size (Curtis et al., 1980). The boundary between these two modes of deposition are indicated by the disappearance of anisotropy within bedding and by a clear increase in anisotropy perpendicular to bedding.

The relationships found between anisotropy, fabric, and mode of deposition in single beds are in good agreement with the results of other authors; observations of fabric changes from turbiditic to hemipelagic deposits are reported

by O'Brien et al. (1980), and magnetic anisotropy within bedding resulting from currents acting during deposition of fine-grained parts of varves were described by Gravenor and Coyle (1985).

Anisotropy pattern within sequences

Sedimentary sequences in submarine fans are built up by a large number of single beds with various values of anisotropy. Thus, properties of single beds govern the anisotropy pattern of entire sequences. The influence of the mode of deposition on anisotropy should be evident when the observed anisotropy patterns are compared with the theoretically expected, general downhole trend. Namely, in uniformly composed, quietly accumulated, fine-grained deposits, particle/pore orientation should become more regular with increasing overburden pressure (e.g., Heling, 1970). At the same time, fabric should become increasingly anisotropic (Oertel and Curtis, 1972). However, anisotropy does not show this expected general trend within the visually and compositionally similar argillaceous sediments from most of the Mississippi Fan drill sites. Consequently, the observed variations of anisotropy probably result from differences in the mode of deposition. This was proven by comparing the anisotropy pattern with lithologic sequences that reflect general trends in the mode of deposition (Mutti and Ricchi Lucci, 1972).

Anisotropy of strain and sonic velocity are discussed separately.

Strain anisotropy

Strain anisotropy data are often scattered, obliterating the general trends somewhat (Fig.7). However, this scattering must be ascribed mainly to two reasons: (1) the depositional processes vary considerably throughout a lithologic section, i.e. general lithologic trends are superimposed by short-term fluctuations of bed thickness, etc. (see below); and (2) random sampling technique, unavoidable because there were no visual criteria to distinguish between turbiditic and hemipelagic fine-

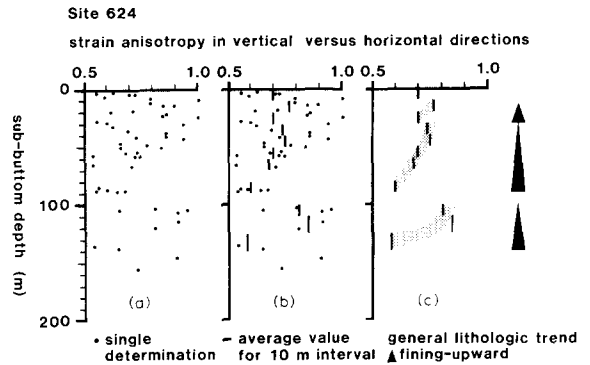


Fig.7. Determined strain data of Site 624 are shown in (a). Scattering of data is mainly due to two factors, namely random sampling technique (see text) and fluctuating intensity of turbidity currents by the pelitic bed thickness that is also reflected (see for example Fig.9). Average values of anisotropy for 10 m intervals are shown in (b) and enhanced in (c). When compared with the general observed lithologic trend (black arrows on the right-hand site), a good correspondence between average value of anisotropy in vertical versus horizontal direction can be stated.

grained deposits, which significantly differ in their anisotropic behavior (Fig.4). In order to compensate for these effects, average values were calculated for 10–20 m long core intervals for anisotropy perpendicular to bedding. In contrast, for anisotropy within bedding only the percentage of samples that show this phenomenon was calculated, because ϵ_{ah} can vary significantly within one bed. However, the significance of the percentage values decreases as the number of tested samples decreases. Therefore, the relationship to lithology is not as clear as for anisotropy perpendicular to bedding.

When comparing lithologic sequences and anisotropy pattern, the following trends are obvious: in coarsening-upward sequences, average values for 10 m intervals of anisotropy in vertical versus horizontal direction generally decrease upsection, whereas anisotropy within bedding occurs more frequently. In fining-upward sequences, the inverse trend is found (Fig.8).

The observed correspondence between average values of anisotropy and lithology is substantiated by three other general upward

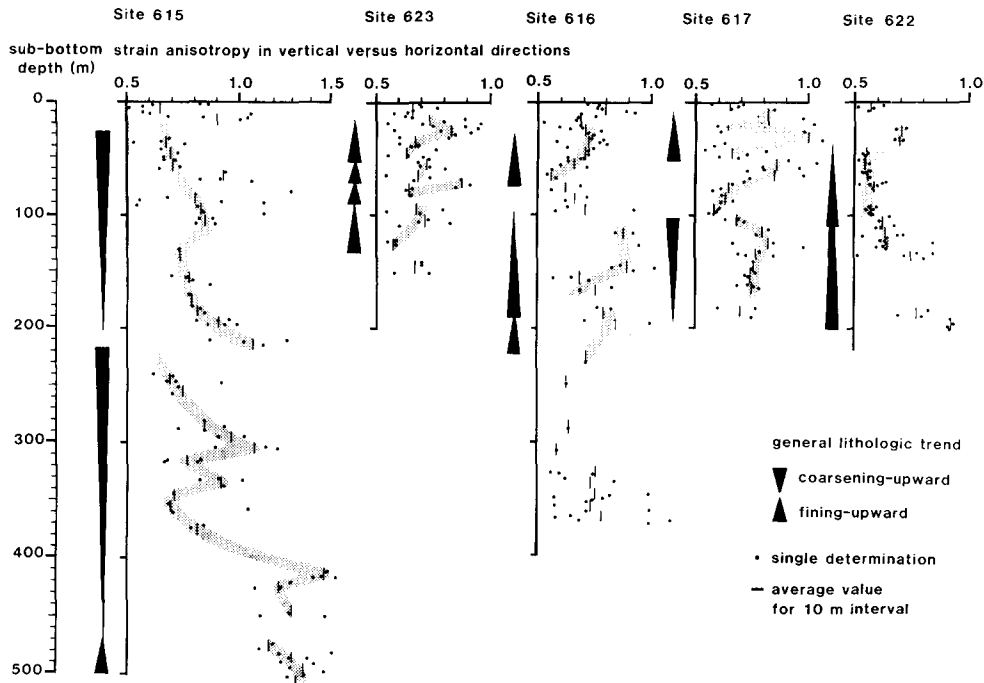


Fig.8. Correspondence between strain anisotropy determined in vertical versus horizontal directions and lithologic sequences. Average values were calculated for strain anisotropy over depth intervals of about 10 m. Lithologic sequences are characterized by general fining- or coarsening-upward trends. In general, fining-upward sequences show increasing strain anisotropy due to a greater degree of parallel particle/pore orientation which is related to the increasing proportion of hemipelagical quietly settled sediments. Coarsening-upward sequences show the inverse trend because of predominant turbidite sedimentation.

trends that are immanent in coarsening-upward turbiditic sequences (Nelson and Nielsen, 1984): (1) the frequency of turbidites very probably increases; (2) the intensity and velocity of turbiditic flows depositing those turbidites normally increases; and (3) more frequent and more intense flows lead to greater erosion of underlying material deposited on top of the preceding turbidite. The combination of these three factors together significantly raises the probability that in a coarsening-upward sequence the proportion of pelitic material deposited by turbidity currents increases up-section. Therefore, the probability of sampling such material is similarly greater and is expressed in the average values; in fining-upward sequences the inverse trend should be true. Consequently, average values of aniso-

tropy over longer core sections allow determining general depositional trends.

The sequences defined in cores do not necessarily reflect the in-situ lithologic situation because of uncomplete recovery. Therefore, to get information about missing intervals, well logs were run. Gamma-ray logs were found to be especially suitable for this purpose. Processing these data allows estimating bed thickness trends (Coleman et al., 1986); for this study only the thickness of pelitic beds (API value < 20) were used. As Fig.9 shows, the variations of the clay bed thickness indicate fluctuating depositional processes (which were also derived from strain anisotropy data). In contrast to these individual data, average values for 10 m depth intervals do not differ considerably from the general lithologic

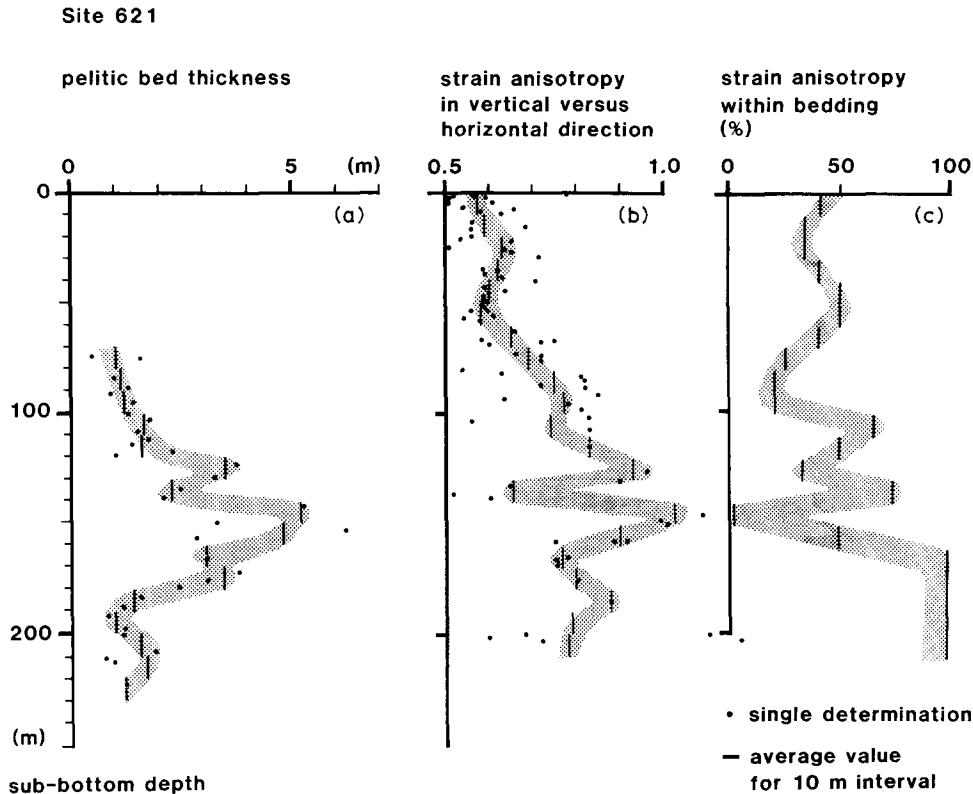


Fig.9. Correspondence between bed thickness of "clay beds" (a) and anisotropy (b) in vertical versus horizontal directions as well as (c) within bedding. For all data average values for 10 m depth intervals were calculated in order to smooth scattered points and to show general trends. It is evident that "clay-bed thickness" as well as anisotropy scatter; because of this correspondence fluctuating intensity of turbidity currents is assumed to be the reason for such a pattern. The latter data were derived from processed gamma-ray well-log data, "clay" is indicated by an API value < 20 (Coleman et al., 1986).

trends, but show a more differentiated pattern. Thereby, pelitic bed thickness is related in the same way to turbidity current intensity as anisotropy: inasmuch as turbidity current frequency increases, the proportion of fine-grained, hemipelagically deposited material decreases. This trend is true when relative changes are compared. However, on an absolute scale considerable differences occur between the sites (see below).

Acoustic measurements

Anisotropy of compressional-wave velocity shows a similar downhole pattern in the studied Mississippi Fan sediments as strain anisotropy: (1) there is no steady increase of

anisotropy with depth of burial; for a given sediment composition, only maximum values of anisotropy follow such a trend, whereas anomalously low anisotropy values occur within deeper deposits; and (2) a clear correspondence to lithology is found; in coarsening-upward sequences anisotropy of sonic velocity decreases, whereas the inverse trend is found when sediment becomes finer-grained upwards. These two trends are found in deposits of similar composition. However, they are enhanced when sediments of varying composition within a sequence are considered (Fig.10).

The clear correspondence between lithology and anisotropy of sonic velocity is similar to that between lithology and strain anisotropy.

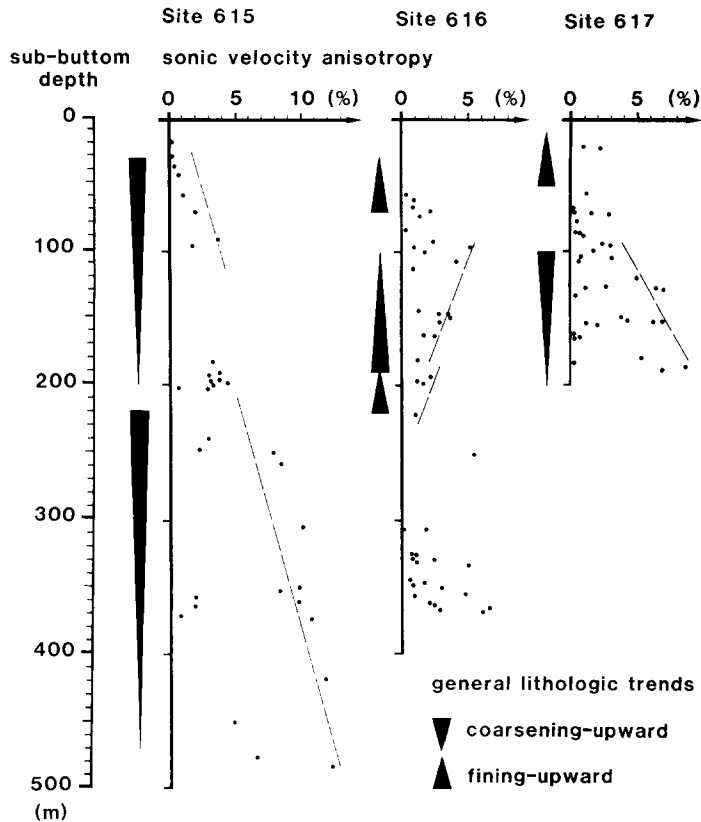


Fig.10. Downhole trends of sonic velocity anisotropy at Sites 615, 616 and 617. The maximum values correspond to the identified lithologic sequences (shown as arrows at the left side of each diagram). Values less than maximum show scattering, that is due to subsampling procedure (see Fig.6).

Therefore, it is explained by the same processes as strain anisotropy (see above).

In order to evaluate the relationship between sonic velocity anisotropy and lithology in more detail, compressional-wave velocity was also determined for sediments of two sites (623 and 624) in two directions within bedding perpendicular to each other (Fig.11). This was based on the assumption that the fabric of the measured pelitic sections is influenced by turbidity currents, resulting in a fabric anisotropy within bedding similar to that indicated by strain anisotropy. These determinations reveal a considerable degree of sonic velocity anisotropy parallel to bedding; parallel variations can reach the same magnitude as differ-

ences between measurements perpendicular and parallel to bedding (Fig.12). However, the values of compressional wave velocity were not always maximum because the determinations were carried out on sediment cubes that were randomly cut (see above; Fig.6).

Significance for fan systems

The validity of the concept of turbidite facies associations for interpreting ancient submarine fan environments (Mutti and Ricchi Lucci, 1972) was considered tenuous by Shanmugan et al. (1985) for three main reasons, which are related to: (1) lacking comparisons between subenvironments in modern and

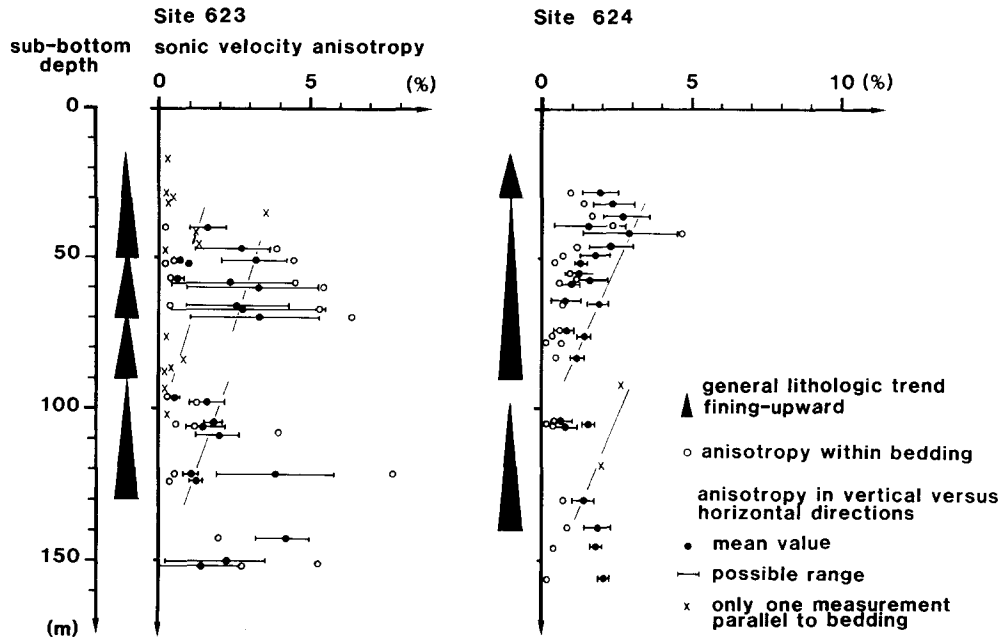


Fig.11. Anisotropy of sonic velocity versus depth at Sites 623 and 624; anisotropy parallel to bedding significantly affects the anisotropy in vertical versus horizontal directions. Sediment cube samples analyzed do not always have maximum and minimum values measured parallel to bedding, depending on the orientation of the cube to the current direction (see Fig.6). However, those samples that did have maximum and minimum values of anisotropy reveal a clear trend that corresponds to the identified lithologic sequences.

ancient fans, because the facies association scheme is based exclusively on observations in outcrops, whereas the correspondence between facies and fan environments was not confirmed in modern fans; (2) the differences in size between modern fan systems and ancient fans, from which the "fan facies concept" was derived; and (3) a lack of observations of ancient channel levee systems comparable in size to their modern counterparts.

The facies scheme of Mutti and Ricchi Lucci (1972) is based mainly on the succession and type of coarse-grained beds that form typical sequences. The mode of deposition of fine-grained material was not considered because the predominant depositional processes can barely be determined due to the visual homogeneity of the material. However, observations of the anisotropy of pelitic sediments allow the recognition of the processes acting during the accumulation of fine-grained sediments, hence,

this information can additionally be used for interpretation of fan facies. So, trends in anisotropy and identified lithologic sequences correspond when relative changes are considered. On an absolute scale, however, anisotropy values differ from site to site (Table 1 and Fig.12).

In order to avoid the effect of different depth of burial on values of anisotropy in the vertical versus horizontal directions, only sediments with a similar state of compaction should be compared. Therefore, for all sites only the upper 200 m are considered. For this interval average values were calculated. To show the sedimentological significance of the anisotropy values, their pattern within the fan is discussed in respect to environmental setting distinguishing sand-rich and mud-dominated sections.

(1) Sand-rich sediments were observed on channel floor and within the depositional lobes of the Mississippi Fan. Generally, the channel

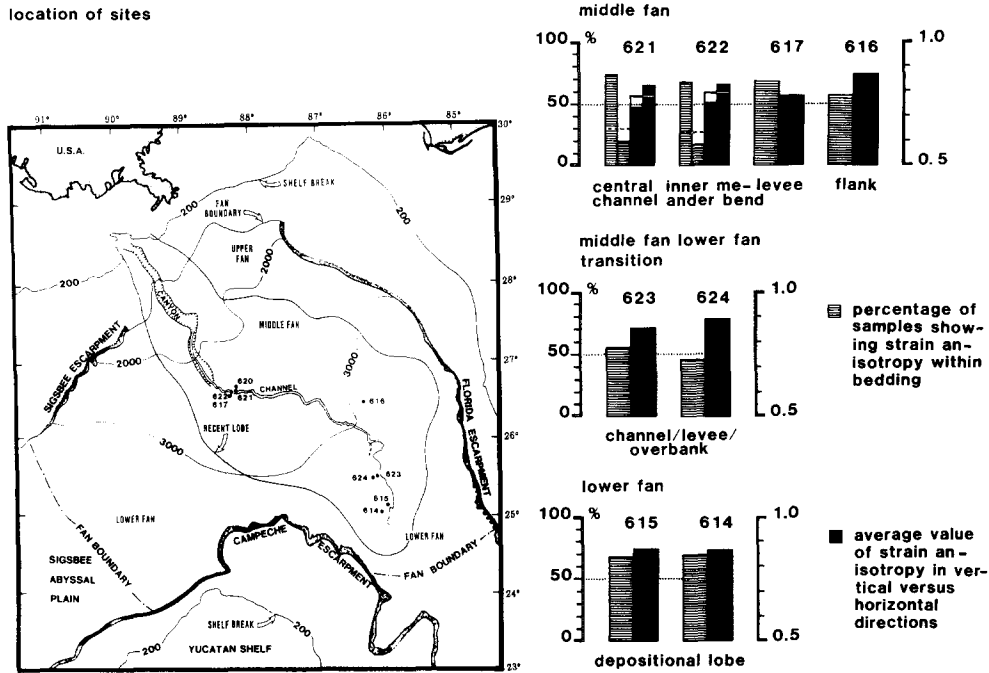


Fig.12. Pattern of strain anisotropy values within the Mississippi Fan. Average values for the upper 200 m of all sites are shown. Each fan sub-environment is characterized by two strain anisotropy values determined in vertical versus horizontal directions and within bedding (data are given in Table 1). This pattern of anisotropy values provides useful supplementary information to interpret submarine fan deposits.

TABLE 1

Pattern of anisotropy values determined on the sediments of the Mississippi Fan drill sites

Depositional environment	Site	Anisotropy in vertical vs. horizontal direction	Anisotropy within bedding	
Central channel	621	muddy fill	0.66 (mean) (0.70)	15 (25)
		sandy fill	0.83	70
Channel (inner meander bend)	622	muddy fill	0.57 (mean) (0.62)	18 (30)
		sandy fill	0.65	72
Levee	617	0.62	73	
Flank	616	incl. slump	0.77	57
		excl. slump	0.75	53
Mid fan/lower fan transition	623	0.70	53	
	624	0.76	47	
Depositional lobe	615	0.77	56	
	614	0.70	68	

floor deposits are characterized by a low anisotropy in the vertical versus horizontal direction and a very high anisotropy within bedding. In contrast, in the depositional lobe setting anisotropy within bedding occurs less frequently, and the proportion of quietly settled material is higher.

(2) Mud-dominated sediments are found as (passive) channel fill, levee, overbank and flank deposits. These sediments are visually very similar to each other, but they clearly differ in their anisotropies. Levee deposits are characterized by a very high value of anisotropy within bedding and a low value of anisotropy in the vertical versus horizontal directions. Such extreme values only occur in sandy channel fill deposits. Towards the flanks and downfan, anisotropy in the vertical versus horizontal directions increases markedly; at the same time, anisotropy within bedding occurs less frequently. The rate of change in anisotropy per distance unit is considerably lower in the channel direction than perpendicular to the channel axis.

This pattern of the values leads to the following interpretation in terms of depositional processes: A turbidity current moving downchannel forms a suspension cloud above it. This suspension flows downchannel as well as perpendicular to the channel axis. The downchannel flow is more highly concentrated and moves faster than the suspension moving flankwards, as indicated by the different rates of change in anisotropy values. Consequently, anisotropy determinations can provide supplementary information for interpreting fan environments because depositional processes of fine-grained sediments can also be taken into account for facies analysis.

Conclusions

(1) In visually homogeneous argillaceous sediments of the Mississippi Fan, two types of anisotropy occur: (1) anisotropy in vertical versus horizontal directions; and (2) anisotropy within bedding. Strain as well as compressional wave velocity were used to deter-

mine anisotropy. The anisotropy pattern of these properties correlates with lithology, that is, with the microfabrics as well as with entire depositional sequences. The sediment fabric was normally not distorted by animals due to rapid sedimentation.

(2) Strain measurements are based on sample deformation which occurs due to experimentally increased pore water tension. While the tension within the pore fluid is isotropic, strain is governed by the direction of dewatering, i.e. the geometry and arrangement of pores as indicated by other experimental studies.

(3) In single beds, both types of anisotropy occur. The lower part of a bed is characterized by a comparatively low value of type 1 anisotropy and a marked anisotropy of type 2 resulting from minimum values of strain/sonic velocity in the current direction and maximum values perpendicular to it. In the upper, quietly accumulated, hemipelagic portion only a high value of type 1 anisotropy is observed.

Based on the correspondence between lithology and anisotropy, this pattern is interpreted thus: Particles settling from a moving suspension cloud can not reach their optimal degree of parallelism, and they are oriented in the current direction to form elongated pores. As the currents decline, settling conditions become more quiet and an increasingly parallel fabric is formed. This interpretation is supported by SEM fabric studies.

(4) Anisotropy parallel to bedding leads to the difficulty that maximum and minimum values of compressional wave velocity can not always be reliably determined. This affects determinations of both anisotropies, type 1 and type 2.

(5) In depositional sequences, coarsening-upward trends correspond to a decreasing value for type 1 anisotropy and an increasing proportion of type 2 anisotropy. This anisotropy pattern is found by determination of strain and sonic velocity. It reflects the influence of increasing frequency and intensity of turbidity currents on the fabric of argillaceous sediments. In fining-upward sequences the inverse trend is true.

(6) The general correspondence between trends in lithology and anisotropy only documents relative changes in the predominant depositional process within a specific fan sub-environment. On an absolute scale, values of both types of anisotropy differ from site to site; a clear pattern within the fan is found. Thus, anisotropy determinations provide useful supplementary information for interpreting fan environments.

(7) Although type 1 anisotropy increases downwards due to compaction and rearrangement of particles, relative differences of type 1 anisotropy between hemipelagic and turbiditic sediments are preserved. Consequently, both sediment types seem to differ in their compactional behavior.

(8) High-resolution seismic modelling may be affected by the anisotropy parallel to bedding, because in pelitic dominated fans about 50% of a sequence can show differences in sonic velocity in a horizontal direction which that can reach 10% or more when seismic lines are run parallel and/or perpendicular to the prevailing direction of the turbidity currents.

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