Reports

Slaty Cleavage: Incipient Occurrences in the Deep Sea

Abstract. *Highly deformed Pleistocene mudstones from the inner wall of the Aleutian Trench and from the continental rise of the Gulf of Mexico show incipient slaty cleavage defined by the orientation of platy and elongate detrital minerals parallel to the axial surfaces of folds.*

For more than 150 years geologists have debated the origin of cleavage in deformed rocks (*1*). Early controversy centered around whether the preferred mineral orientation (which defines some varieties of cleavage) was produced by mechanical rotation or by metamorphic recrystallization. Within the last 15 years some students of ancient rocks (*2*) have suggested that the preferred mineral orientation of slaty cleavage is achieved by rotation of particles during deformation related to dewatering in a nonmetamorphic environment. To test this concept of early cleavage formation we have studied cores of deformed Pleistocene deposits recovered by the Deep Sea Drilling Project from the continental rise of the Gulf of Mexico and the inner wall of the Aleutian Trench. At each locality an incipient slaty cleavage, produced by preferred orientation of detrital minerals, occurs parallel to axial surfaces of folds apparently formed by large scale slumping (Gulf of Mexico) and by subduction (Aleutian Trench).

The Sigsbee Wedge comprises an extensive probable slump deposit (*3*) located at the base of the northern continental slope of the Gulf of Mexico. Numerous seismic reflection profiles (*3, 4*) demonstrate that this deposit is composed of seaward-thinning irregularly reflective units locally interbedded between undeformed beds. Drilling along the northern margin of the Sigsbee Wedge (Site 1, Leg 1, Deep Sea Drilling Project) penetrated 770 m of variously deformed late Pleistocene muds and mudstones (*4*). Most cored folds have planar limbs and sharp hinges with wavelengths ranging from 10 to 60 cm. Axial surfaces are subhorizontal; interlimb angles range from more than 150° to less than 15°. In the initial description of these cores, Beall and Fischer (*5*) noted a horizontal hackly fracture pattern apparently parallel to the axial surfaces of folds.

We have studied numerous thin sections cut normal to the axes of folds from the Sigsbee Wedge cores. Fifty percent of the folds with well-defined bedding show some reorientation of platy and elongate minerals from a position parallel to bedding to a position parallel to the axial surface of the fold. Seventy-one percent of the well-defined folds with interlimb angles less than 45° include areas with detrital minerals reoriented parallel to the axial surface of the fold. Thus, the probability of mineral reorientation parallel to the axial surfaces increases with increasing tightness of folding (a crude measure of strain). Similar trends are observed

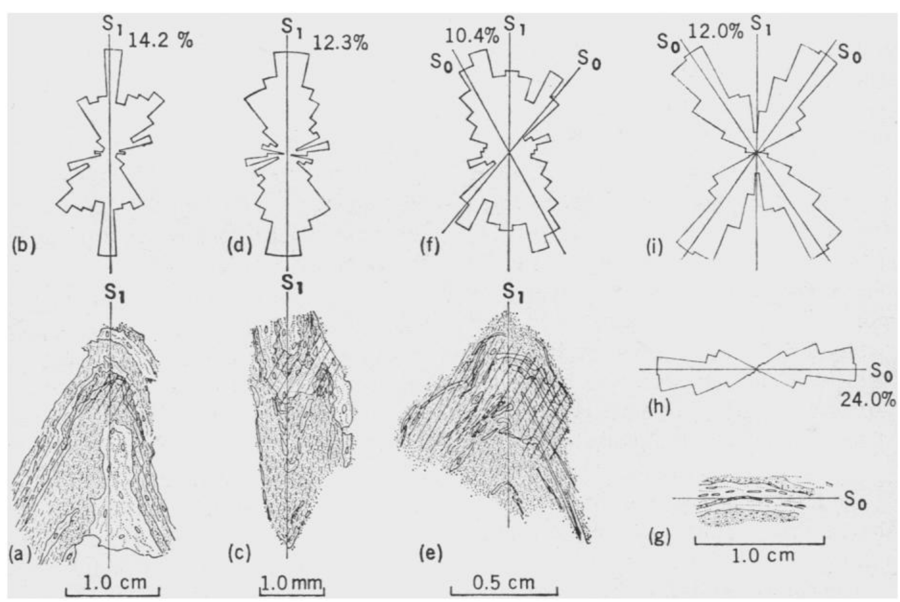

Fig. 1. Sketches and circular histograms of cored folds. Silt- and mud-rich layers, respectively, are indicated by coarse and fine patterns. The histograms sum the orientations of elongate projections of detrital mica and quartz grains; diagonal lines on the sketches cover the area of grain orientation represented in the histograms; grain orientation is summed over 10° intervals. (a) Fold closure from Sigsbee Wedge, Gulf of Mexico. Apparent competent behavior is shown by conjugate fractures on limbs, but irregular bedding indicates flow in the axial zone. (b) Orientation of 200 detrital (mica and elongate quartz) grains from the axial zone of (a). The maximum (14.2 percent) is parallel to the axial surface (S_1). Secondary modes apparently parallel the limbs in the area of grain count. (c) Fold closure from the inner wall of the Aleutian Trench. (d) Orientation of 251 detrital (mica and elongate quartz) grains of (c). Note the strong maximum (12.3 percent) parallel to the axial surface (S_1). (e) Fold closure from the inner wall of the Aleutian Trench. (f) Orientation of 404 detrital micas of (e); the maximum is 10.4 percent. Note that two modes lie slightly within the angle defined by average limb orientations (S_0 lines), also that a secondary mode parallels the axial surface S_1. Both observations suggest an incipient transition from grain orientations parallel to bedding (S_0) to positions parallel to the axial surface (S_1). (g) Unfolded bed, inner wall of the Aleutian Trench. (h) Orientation of 179 detrital mica and quartz grains from the entire area of (g). (i) Simulated grain orientation of (e). The model produces the grain distribution for a simple intersection of planar limbs with no reorientation of particles. Compare with (f) (see text for a more complete explanation).

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in subaerial exposures of deformed rocks. A sketch and a circular histogram (Fig. 1, a and b, respectively) illustrate the style of one of the folds and quantitatively demonstrate mineral reorientation.

It could be argued that the folds we have studied are an artifact of the drilling processes. However, the preservation of undeformed horizontal layers between folded sequences from the Sigsbee Wedge suggests that the deformation is a natural feature. Moreover, the extreme induration and low water content of the folds from the Aleutian locality argue against their rapid artificial development in the presence of high-pressure drilling fluids (*6*).

The continental margin adjacent to the eastern Aleutian Trench has apparently accreted more than 200 km seaward in the last 70 million years. Drilling along the inner wall of the eastern Aleutian Trench (Site 181, Leg 18, Deep Sea Drilling Project) has recovered highly deformed, Pleistocene mudstones which apparently represent one of the latest phases of subduction and accretion (0.92 to 1.3 million years before present) (*7*). The Pleistocene mudstones comprise the core of an irregular ridge which rises 2000 m above the adjacent trench and is covered by a blanket of younger sediments (*6*). These mudstones have unusually low porosity (28 to 33 percent), high densities (2.1 to 2.2 g/cm^3), high seismic velocity (2.02 km/sec), and high shear strengths relative to normally consolidated sediments of equivalent burial (169 to 369 m) (*6, 8*). These factors suggest deformation and dewatering at depths greater than their present overburden.

The folded mudstones from the inner wall of the Aleutian Trench show highly irregular geometry. Orientations of the axial surfaces are variable with respect to the horizontal; wavelengths of individual folds range from more than 40 cm to less than 1 cm; the interlimb angles of folds studied in thin section vary from 150° to 33°.

Thirty percent of all Aleutian folds studied in thin section show some degree of detrital mineral reorientation parallel to the axial surface. Sixty-seven percent of the folds with interlimb angles less than 45° show preferred orientation of mineral particles parallel to their axial surfaces. The fabric may be strongly reoriented (Fig. 1, c and d) or show various transitions from an orientation parallel to bedding to an orientation parallel to the axial surface (Fig. 1, e and f).

In unfolded beds from the inner wall of the Aleutian Trench, 95 percent of the platy and elongate minerals are oriented subparallel to bedding (Fig. 1, g and h). Unfolded deposits from the Sigsbee Wedge display similar trends. The rose diagrams from the noses of tight folds (Fig. 1, b and d) show the maximum orientation of platy and elongate minerals at high angles to the local bedding surface. This observed axial plane-parallel orientation is substantially greater than that expected from primary depositional variation about bedding, which indicates that reorientation must have occurred during folding.

The secondary orientation mode parallel to the axial surface of the moderately open Aleutian fold (Fig. 1, e and f) might be produced by the overlapping pattern of the primary depositional orientation of the fold limbs. In order to test this possibility we have simulated the grain orientation expected from the geometry of this fold. We have summed the intersection of two primary depositional grain orientations inclined at an interlimb angle of 70°. Our model eliminates the zone of dip reversal at the nose of the fold which maximizes the possibility of an overlapping grain orientation parallel to the axial surface. The simulated grain distribution (Fig. 1i) shows modes of 12 percent centered on each limb (S_0) with only 2 percent of the grains oriented parallel to the axial surface (S_1). In the natural fold the modes subparallel to each limb are smaller than expected (10 percent compared to 12 percent) and rotated toward the axial surface. Moreover, the axial plane orientation of the natural fold is four times greater (8 percent compared to 2 percent) than that of the simulated fold. Thus, the platy and elongate grains in the natural fold must have been reoriented during folding and comprise a grain distribution truly transitional to the more strongly oriented fabrics (Fig. 1, b and d).

Consolidation tests suggest that the Aleutian folds have been subjected to a maximum total pressure of at least 120 bars but probably not more than 850 bars (*8*). The overall strain rate during deformation is estimated to have been $10^{-13\pm1}$ sec^{-1}, based on a convergence rate of 6 cm/year and a zone of stress release 10 km thick. The degree of carbonization of organic matter suggests that the Aleutian rocks have been heated to approximately 68°C (*9*). No diagenetic changes were observed in clay mineralogy (*7*).

Deposits of modern oceanic trenches, and continental slopes and rises, have been broadly equated to ancient geosynclines on the basis of lithologic and geometric criteria (*10*). The occurrence of incipient slaty cleavage in deposits of the Sigsbee Wedge and the inner wall of the Aleutian Trench provides a specific structural feature observable both in core section and outcrop, relating modern continental margins and ancient geosynclines. Moreover, the prevalence of slumping at continental margins (*11*) and probable early folding occurring in subduction zones suggest that processes of deformation of semilithified sediments may account for the initial folds and cleavages in many complexly deformed tectonites.

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12. Samples provided by the Deep Sea Drilling Project through the assistance of the National Science Foundation. Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research. We thank R. von Huene and T. Thompson for preprints of (*6–8*) and (*9*), respectively; P. Harrold for laboratory assistance; O. T. Tobisch and A. C. Waters for criticism of the manuscript; and C. A. Burk, A. G. Fischer, and R. E. Garrison for various discussions.

4 June 1973; revised 15 October 1973