32. ORIGIN OF "VEIN STRUCTURE" IN SLOPE SEDIMENTS ON THE INNER SLOPE OF THE MIDDLE AMERICA TRENCH OFF GUATEMALA[1]

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ABSTRACT

Partly consolidated lower Miocene to Quaternary hemipelagic muds recovered at Sites 496 and 497 contain abundant, vertical to subvertical veins that are generally less than 2 mm thick and are spaced from one to several millimeters apart. Veins are parallel, planar to curviplanar structural discontinuities (restricted to subhorizontal zones), which appear on the faces of cut cores as dark linear, curved, or sigmoidal traces. Vein fillings are mineralogically and texturally similar to surrounding matrix, but very fine-grained platy phyllosilicates within are preferentially oriented parallel to vein boundaries. Veins are interpreted as water-escape conduits that are geometrically analogous to extension fractures. They formed as horizontal confining pressure was preferentially relaxed in one direction, allowing water from interbedded, unconsolidated sandier layers to escape upward. Deformation, which imparted a penetrative foliation to muds, may have occurred in response to modest gravity-driven downslope extension of part of the blanket of sediments on the upper slope of the Middle America Trench.

INTRODUCTION

One of the goals of Leg 67 was to document styles of deformation across a convergent plate boundary in an effort to resolve the relative importance of gravity-driven versus subduction-driven processes. In addition, a wide variety of small- and large-scale structures have been described in on-land exposures of presumed subduction complexes, but there are few examples from presently active systems for actual comparisons. The purpose of this article is to describe a small-scale structure, herein called "vein structure" or "veins," which I interpret to record *in situ* dewatering and possibly downslope creep of consolidating sediments mantling the slope landward of the Middle America Trench. Veins are defined as subparallel planar structural discontinuities, generally less than 2 mm thick, which appear on the faces of cut cores as dark linear, curved, or braided traces, typically oriented parallel to or within 30° of the (vertical) core axis. Morphologically analogous structures were described in cores obtained from the inner slope of both the Japan Trench on Leg 57 (Arthur et al., 1980) and the Middle America Trench off Oaxaca, Mexico, on Leg 66 (Lundberg and Moore, in press).

The following descriptions are based on shipboard observations and photographs of cut cores and on thin-sections prepared and examined at the University of Washington. Wet samples were immersed in acetone to displace pore water and gradually impregnated with epoxy resin by dissolving epoxy in the acetone. Standard thin sections were cut after allowing the epoxy to harden for 3 weeks.

MORPHOLOGY AND GEOMETRY OF VEIN STRUCTURE

Vein structure occurs in partly consolidated, hemipelagic mud at Site 496 (first noted in Core 29, Section 4, at about 269.5 m sub-bottom depth; abundant in Core 30 and those below) and Site 497 (first noted in Core 17, Section 3, at about 153 m sub-bottom depth; abundant from Core 25, at about 225.5 m sub-bottom depth, to the bottom of the hole) (Figs. 1 and 2). The mud is generally dark olive gray and locally rich in diatoms, calcareous nannofossils, and volcanic ash. It ranges in age from early Miocene to Quaternary. Sandy mud is common, and unconsolidated layers of fine to coarse sand up to 19 cm thick are locally abundant, especially at Site 497 (Plate 1, Fig. 1). Mud at both sites is progressively more consolidated with depth, as manifested not only by measurements of physical properties (Faas, this volume) but also by the characteristic change in drilling-induced deformation from swirling in the upper cores to drilling biscuits at depth. Biscuits are short (averaging 5 cm), coherent sections of core separated by horizontal disk fractures induced by drilling. Veins are apparently absent in the mushy, least-consolidated shallow sediments and instead occur below the first appearance of biscuits.

In a typical example (Plate 1, Figs. 1–3), many 1- to 4-cm-long veins occur in subhorizontal zones, within which veins are subparallel and spaced from one to several millimeters apart. They are conspicuously darker than their monotonously olive gray host. The longest veins we noted, up to 15 cm in vertical height, are in Section 497-38-1, but most zones containing veins average 2 to 3 cm in thickness. In three dimensions, veins are planar or curviplanar features and, taken together, they define a subvertical, semipenetrative foliation parallel to which the mudstone flakes preferentially and easily. Some individual veins are approximately constant in thickness (Plate 1, Fig. 1) but many sigmoidal veins (Plate 1, Fig. 3) are thicker in the center than at the ends. Other veins are delicately braided, resembling anastomosing channels in a braided river system (Plate 1, Fig. 2). At their ends, these veins typically branch into progressively thinner tributaries. All vein zones are restricted to partly consolidated mud; none was observed

[1] Aubouin, J., von Huene, R., et al., *Init. Repts. DSDP*, 67: Washington (U.S. Govt. Printing Office).

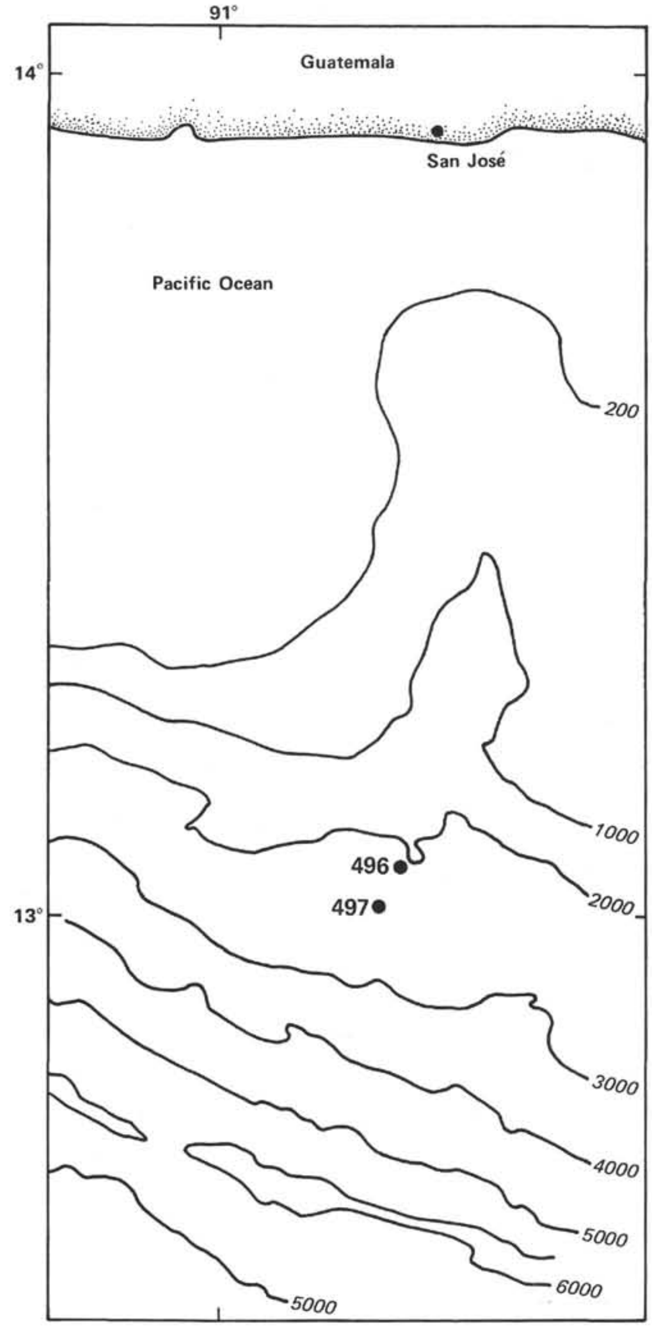

Figure 1. Bathymetry (in meters) in vicinity of Leg 67 transect (modified from Ladd et al., 1978). (Closed 6000-m contours represent the trench axis.)

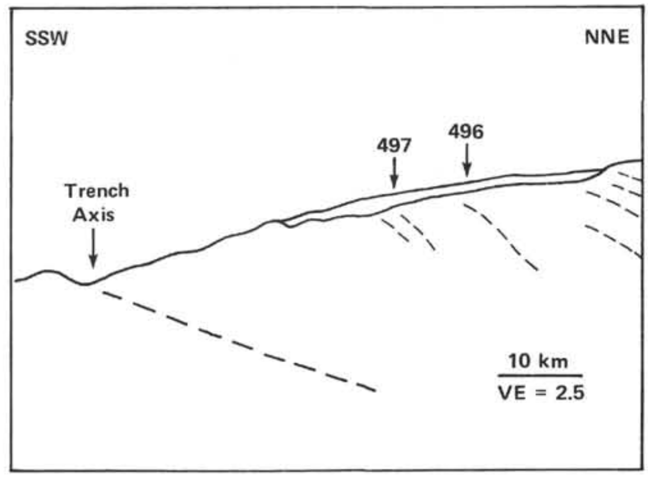

Figure 2. Topographic profile along seismic reflection line GUA-13, nearly coincident with Leg 67 transect (from Ibrahim et al., 1979). (The solid line below the seafloor denotes the approximate lower limit of slope sediments, on the basis of the character of reflections and refraction velocities. Dashed lines represent landward dipping reflectors.)

in clean sands. In some zones (Plate 1, Fig. 1), nearly all veins terminate at the contact separating mud from an adjacent layer of muddy, very fine-grained sand, although one or two veins extend part way into or completely across the 2-cm sand bed in the sample illustrated.

Along most veins we were unable to document any displacement parallel to the veins themselves. In a few instances, however, burrows, bedding laminations, and other veins show separations of 1 mm or less, but any such offsets are negligibly small compared to the length of the veins in question. Where cores are broken apart along veins, the surfaces are typically smooth. In one sample (496-35,CC; Plate 1, Fig. 4), vein surfaces are shiny and locally finely grooved, as if they were polished by vein-parallel shear. Thin-section analysis, discussed later, showed that platy clay minerals within veins are preferentially oriented parallel to vein boundaries. This microfabric is probably responsible for the relative smoothness of vein surfaces, although small amounts of slip may have accentuated this feature.

Bedding is indistinct in most cores from Sites 496 and 497. Where observed, it is generaly horizontal, but in some sections it dips as much as 15°. Vein-rich zones, restricted to mud layers, are likewise horizontal to subhorizontal. Within an individual zone, all veins typically have a similar shape and orientation, but there is a considerable range in these attributes, even within a single section of core. Most straight (planar in three dimensions) veins are approximately normal to zone boundaries and therefore oriented subvertically *in situ*, but acute angles between 90° and 45° were noted as well. The ends of most curved (curviplanar) veins, especially the sigmoidal variety, are inclined at angles of 45° to 75° to zone boundaries. In some sets of sigmoidal veins, individual members are connected to adjacent veins by delicate "tributaries."

MICROSTRUCTURE

Thin sections (Figs. 3 and 4) show that platy phyllosilicates within veins are preferentially oriented parallel and subparallel to vein boundaries. Detrital silt- and clay-sized platy minerals in these slope sediments are principally montmorillonite, mixed-layer clays, and illite; minor amounts of kaolinite and chlorite are also present (Heinemann and Füchtbauer, this volume). Individual grains are visible only with crossed nicols (Fig. 4). The strongest preferred orientation characterizes the thinnest veins, which are generally less than 0.05 mm wide. When viewed in plane light, mud matrix is darker

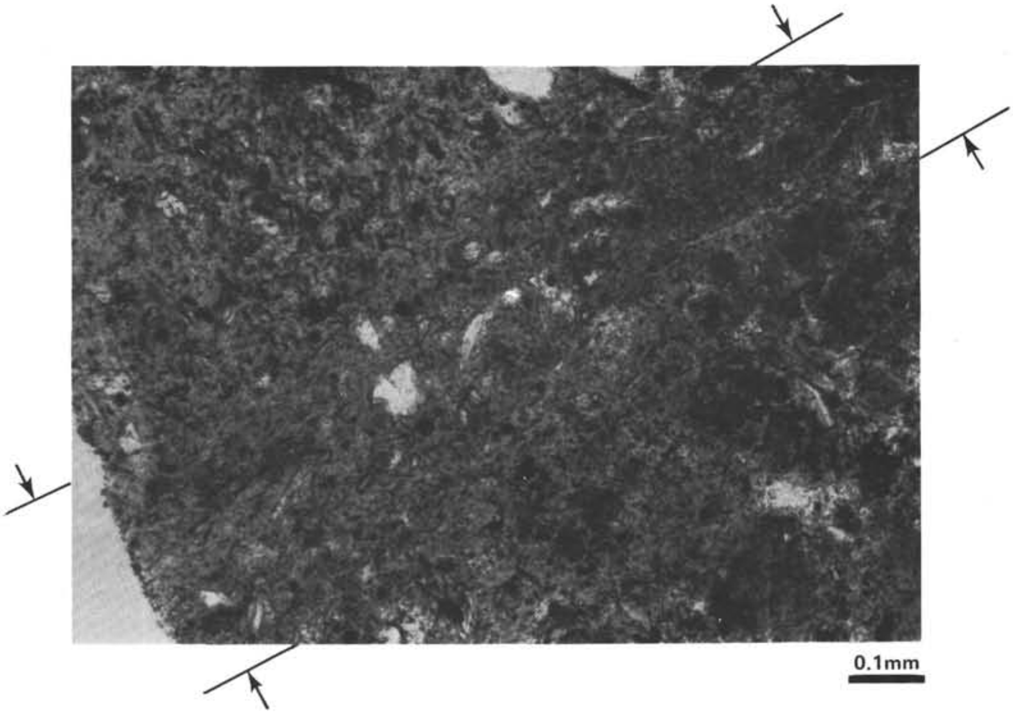

Figure 3. Photomicrograph of impregnated thin section of Sample 497-25-4, 75–77 cm (plane light). (Approximate vein boundaries are indicated by arrows.)

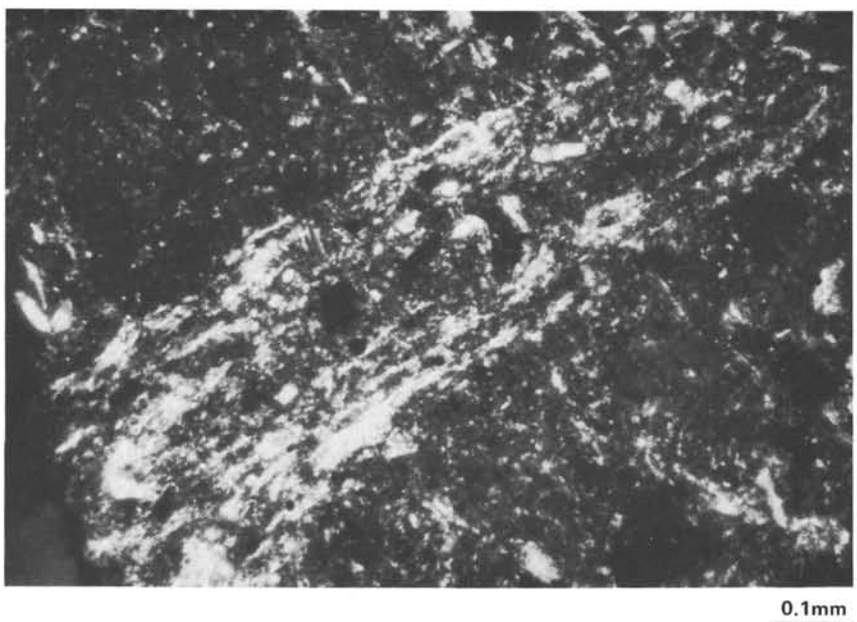

Figure 4. Same field (Sample 497-25-4, 75–77 cm) as in Figure 3, but with crossed nicols. (Bright, elongate grains in the vein are subparallel, platy phyllosilicates viewed at 45° off extinction. Note that, other than this preferred orientation, the range in grain sizes and shapes is similar both within and outside of the vein.)

than vein filling (Fig. 3), but this color contrast is apparent only in parts of each thin section. Otherwise, I could detect no differences in grain size, texture, or composition between veins and matrix. Both are light to medium brown and contain about 5% silt- and sand-sized grains of quartz and feldspar scattered randomly throughout. Variously sized tests and fragments of diatoms and foraminifers are ubiquitous. I ascribe the darker brown color of matrix to a higher content of submicroscopic organic matter, which seems to have been selectively removed from the veins. Sand grains, microfossils, and sponge spicules within and adjacent to veins are perfectly preserved and have not been broken, fractured, or abraded. It is not known why veins are darker than matrix in fresh, wet cores. The color difference becomes less distinct as the mud dries. On shipboard, we guessed that veins consist of finer-grained material than their muddy and silty host, but petrographic work failed to substantiate this hypothesis.

Small-scale structures that are morphologically similar to vein structure were encountered on Leg 57 at Sites 438 and 439 on the deep-sea terrace landward of the Japan Trench, and on Leg 66 at Site 489 on the upper slope of the Middle America Trench. "Veins" encountered on Leg 57 are darker than surrounding matrix, apparently because they contain finer-grained clay minerals, quartz, and minor pyrite (Arthur et al., 1980). Thin, subparallel structures encountered on Leg 66, termed "spaced foliation" by Lundberg and Moore (in press), are defined by darkened sediment possibly stained by precipitates from migrating fluids or by insoluble residues. In cores from both Legs 57 and 66, fine-grained, platy minerals are preferentially oriented parallel to the boundaries of individual veins and spaced foliations.

ORIGIN OF VEIN STRUCTURE

The veined zones in cores from Sites 496 and 497 are interpreted as localized zones of deformation in which muds were consolidated enough to respond to imposed nonhydrostatic stresses by mesoscopically brittle fracture. The near absence of evidence for vein-parallel slip indicates that veins are not shear fractures. Instead, the parallel or en echelon arrangement of veins within zone boundaries strongly resembles the geometry of extension fractures ("tension gashes") in hard rocks on land. The consistent parallelism of veins within zones and their predominantly vertical orientation required a dynamic, nonhydrostatic stress field ($\sigma_3 < \sigma_2 < \sigma_1$) in which σ_3, the least principal stress, was oriented subhorizontally, and σ_1 subvertically. If σ_2 had equalled σ_3 and both were horizontal, vertical extension fractures could theoretically have formed with any azimuth.

Extension fractures in rock on land are typically filled with calcite or quartz, because fluids in the deforming rock migrated into the voids and in effect held them open while solid phases were being deposited. However, vein fillings in these cores apparently are mineralogically identical to matrix, although they may contain less optically irresolvable organic matter. Thus it is doubtful that the "fillings" contain much extraneous material that was deposited as fractures opened. I suggest that the strongly oriented phyllosilicates simply rotated in response to water streaming through veins as the horizontal confining pressure was preferentially reduced in one direction. Flowing water modified the microfabric in dewatering conduits, which were localized along incipiently formed extension fractures. Arthur et al. (1980) also interpreted veins encountered on Leg 57 as dewatering structures and suggested that preferred orientation in veins and fractures was the result of fracture-parallel slip or the movement of fluids. I favor the "streaming fluid" hypothesis for veins encountered on Leg 67 in view of the lack of evidence for significant amounts of offset and slip along them.

It is significant that veins are typically restricted to semiconsolidated mud layers and terminate at contacts with sandy layers. A certain amount of compaction must occur for the muds to acquire a fracture strength. Furthermore, both clean and muddy sands in these cores are softer and less consolidated than interbedded muds. It is probable that sands serve *in situ* as reservoirs for fluids in shallow, consolidating sediments and thus tend to compact more slowly than dewatering muds. As interlayered sands and muds were shortened vertically and extended horizontally, muds fractured, whereas high pore pressures in loose sands facilitated intergranular movement and suppressed brittle behavior (Handin et al., 1963). Elevated fluid pressures in muds may have further decreased effective horizontal confining pressures, allowing the mud to fracture at abnormally shallow depths. The possible role of methane in this process is not clear, but if it existed in a gaseous state because of phase changes in clathrates, it could have contributed to total fluid pressure during deformation (Dengo, this volume). Neither the distribution nor mechanical effect of methane in gas hydrates is understood at present.

The ultimate cause of the deformation at Sites 496 and 497 is imperfectly understood. Both Arthur et al. (1980) and Lundberg and Moore (in press) interpret possibly analogous structures in cores from Legs 57 and 66 to have formed in the vicinity of dip-slip faults cutting slope sediments. In other words, they are a localized, small-scale response to stresses near larger structures, and Arthur et al. (1980) imply that tectonically elevated fluid pressures are responsible for the initial development of veins and associated fractures. I suggest, as an alternative hypothesis, that vein structure is a small-scale response to slow, downslope creep of part of the blanket of slope sediments. The consistent subvertical orientation of veins records a relaxation of effective confining pressure in a horizontal direction, just as would occur in the slope blanket if it were allowed to extend itself slightly, parallel to bedding in a downslope direction.

There is further evidence that deformation was distributed throughout the veined section during and perhaps after the veins developed. En echelon veins within some zones initially may have formed perpendicular to zone boundaries and then passively rotated in response to noncoaxial progressive simple shear parallel to both bedding and veined zones. Also, the geometry and systematically variable thickness of many sigmoidal veins indicate that they continued to grow at their ends while the deforming mud was undergoing progressive simple shear parallel to zone boundaries. Ramsay and Graham (1970) analyzed the kinematics of this process and illustrated how earlier-formed central sections of extension fractures possibly rotate and continue to expand as the fractures distally extend (Fig. 5).

Seismic data (see profiles in the site reports, this volume) are not adequate to resolve the question of whether faulting or more penetrative strain is responsible for vein structure of Leg 67 samples. Actually, normal dip-slip faulting and pervasive, incipient extension fracturing may both be expressions of an overall regime characterized by downslope, layer-parallel extension. I

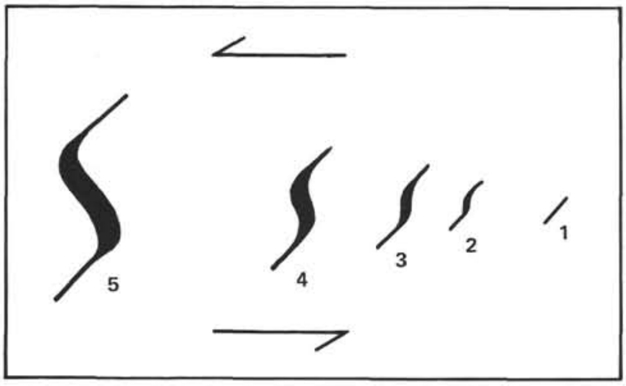

Figure 5. Idealized example of how extension fractures both grow and rotate during progressive noncoaxial simple shear in a zone delimited by arrows. (Stage 1 [earliest] represents the initiation of a fracture at 45° to zone boundaries. Stage 2 depicts the same fracture after an added increment of noncoaxial strain. In 3, 4, and 5 [final stage], the fracture progressively expands in its central, earlier formed section as it extends itself at its ends. Compare with actual examples in Plate 1, Figs. 2 and 3).

found only two other examples of veinlike structures described in the literature. Ogawa (1980) illustrates remarkably similar "beard-like veinlet structure" in Neogene tuffaceous siltstones in Japan, which he interprets as having formed during dewatering and contemporaneous normal faulting. Einsele et al. (1974) describe analogous drainage channels, in muds deposited in laboratory experiments, that are deflected downslope or deformed into sigmoidal shapes by bedding-parallel creep in tilted layers.

The weight of the evidence cited tends to discount other hypotheses for the origin of veins. Simple compaction, or "hydrofracturing" resulting from drastically elevated fluid pressures, in a hydrostatic stress field can be ruled out, because water-escape features and fractures would theoretically form in random, rather than subvertical, orientations in these nondynamic situations. Also, the veins are not drilling induced because (1) veins that extend to the boundary of a drilling biscuit are truncated sharply (Plate 1, Fig. 3); (2) veins have no apparent geometrical relation to the core-barrel axis or to radial drilling stresses; and (3) the vein filling is not the soft, plastic mud surrounding biscuits that is remolded and mobilized by drilling.

CONCLUSIONS

The prevalence of vein structure in muds at Sites 496 and 497 indicates that part of the blanket of hemipelagic mud and interbedded sand covering the slope is characterized by a pervasive mesoscopic fabric recording postdepositional deformation. Veins are interpreted as water-escape features paralleling incipient extension fractures in semiconsolidated muds. Their orientation is determined by an imposed, nonhydrostatic stress field developed either in the vicinity of faults or perhaps in response to downslope extension. Plate 1, Figure 4 emphasizes the penetrative nature of the subvertical foliation in these muds. This early-formed anisotropy may strongly influence the character of succeeding fabrics developed during subsequent deformational events. For example, Arthur et al. (1980) imply that early-formed veins are small-scale zones of weakness that foster the development of more pervasively fractured and brecciated mudstone. There is no evidence that veins at Sites 496 and 497 formed in response to convergence-related, tectonic stresses communicated from the toe of the trench slope where active underthrusting must be occurring; vein structure may instead be an entirely surficial phenomenon.

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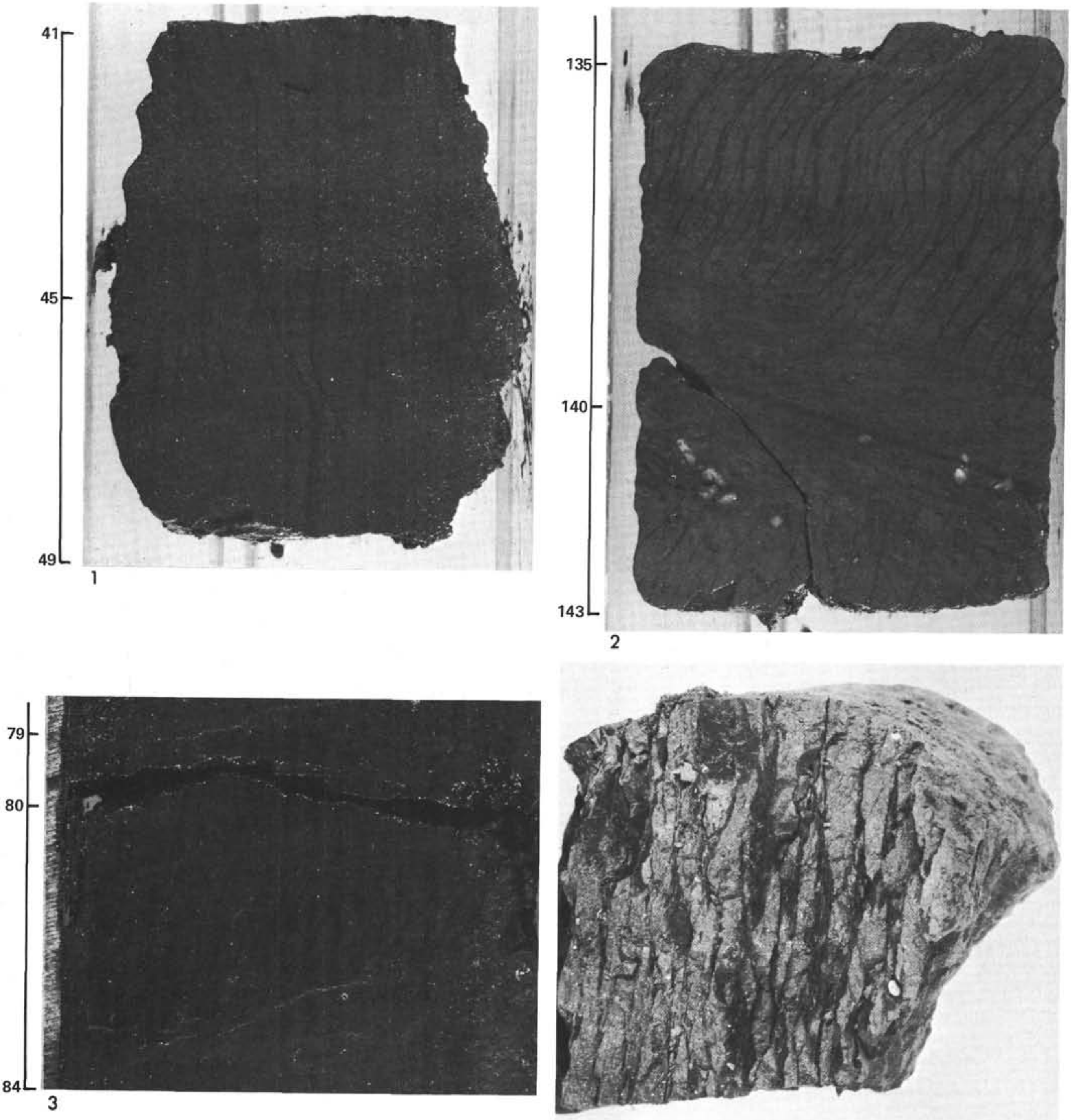

Plate 1. Examples of vein structure in cores from Leg 67. 1. Sample 497-39-3, 41–49 cm. Olive-gray hemipelagic mud, containing abundant dark veins, overlain by nearly vein-free fine-grained muddy sand. (Note the vertical orientation of subparallel, anastomosing veins. Most terminate at the sedimentary contact between sand and mud.) 2. Sample 497-42-2, 135–143 cm. Bioturbated nannofossil mudstone containing delicately braided, gently sigmoidal veins. (Note that the prominent contact near the center of the sample, which may represent bedding, has been offset < 1 mm by some of the veins cutting across it.) 3. Sample 497-25-4, 79–84 cm. Pronounced sigmoidal veins with thick centers in a 4-cm-thick drilling biscuit of partly consolidated mud surrounded by soft mud remolded by drilling. (Compare with Fig. 5 in the text.) 4. Sample 496-35,CC. (Part of the core-catcher sample was split by hand on a roughly horizontal surface normal to the axis of the core barrel. This photo was taken looking down on the broken surface and, therefore, parallel to not only the core axis but also a prominent foliation defined by subvertical veins. Curved surfaces of anastomosing veins are darker and appear polished [''pseudo-slickensides''] because of the strong preferred orientation of clay minerals as revealed in thin sections. Note the large, unbroken foraminifer test in the lower right corner.)