

## 14. MASS MOVEMENT ALONG THE INNER WALL OF THE MIDDLE AMERICA TRENCH, COSTA RICA<sup>1</sup>

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### ABSTRACT

The sediments of Deep Sea Drilling Project Site 565 and University of Texas Marine Science Institute Cores IG-24-7-38 to -42 taken on the landward slope of the Middle America Trench exhibit characteristics of material subject to reworking during downslope mass flow. These characteristics include a generally homogeneous texture, lack of sedimentary structures, pervasive presence of a penetrative scaly fabric, and presence of transported benthic foraminifers. Although these features occur throughout the sediments examined, trends in bulk density, porosity, and water content, and abrupt shifts in these index physical properties and in sediment magnetic properties at Site 565 indicate that downslope sediment creep is presently most active in the upper 45 to 50 m of sediment. It cannot be determined whether progressive dewatering of sediment has brought the material at this depth to a plastic limit at which sediment can no longer flow (thus resulting in its accretion to the underlying sediments) or whether this depth represents a surface along which slumping has occurred. We suspect both are true in part, that is, that mass movements and downslope reworking accumulate sediments in a mobile layer of material that is self-limiting in thickness.

### INTRODUCTION

The movement of sediment on the continental slope is usually attributed to turbidity currents and slumping—single events to periodic emplacements of sediments as a result of mass gravity flows (e.g., Doyle and Pilkey, 1979). These mechanisms and other types of mass gravity flows (fluidized-liquidized flow, grain flow, and debris flow) classified by Middleton and Hampton (1976) can be recognized in the sedimentary record by characteristic sedimentary textures and structures (Fig. 1). Commonly these deposits have abrupt or scoured basal contacts with the underlying sediment. Other features such as grading, laminations, dish structures, grain orientation, and grain sorting are variable depending on the mechanism of emplacement. Sediments from the continental slope offshore Costa Rica (DSDP Site 565 and UTMSI cores IG-24-7-38 to -42; Fig. 2) have features similar to a grain flow deposit, but the differences suggest a more continuous mechanism of sedimentation.

Sediments recovered at Site 565 on the the Costa Rican slope are massive and generally lack grading. Although these features are common to a grain flow deposit, the textural homogeneity and paucity of sedimentary structures of the Site 565 sediments suggest a continuously operating sedimentary mechanism: downslope creep. Such a process would disrupt depositional sedimentary features and could produce fabric and textures diagnostic of large-scale sedimentary reworking.

We examined Costa Rican slope sediments from DSDP Site 565 and from five piston cores collected in 1978 during a University of Texas Marine Science Institute (UTMSI) cruise to evaluate continuous downslope mass movement as a significant mode of slope sediment transport and to identify a means of documenting this transport (Table 1). We examined seismic profiles of the slope, sediment texture and structure, physical properties, paleomagnetism, *in situ* and transported benthic foraminifers, and sediment fabric.

Several lines of evidence emerged from our study that indicate the effects of plastic grain flow, or creep: (1) the general lack of sedimentary structures, (2) generally homogeneous texture, (3) overconsolidation of sediment in upper part of the sediment column at Site 565, (4) scattered paleomagnetic orientations indicating a disturbed section, (5) mixed assemblages of benthic foraminifers containing both *in situ* fauna and species transported from upslope, (6) presence of a penetrative fabric here described as a "scaliness," and (7) high sediment accumulation rates such as might be anticipated from amassing sediment from upslope. Thus we envision a simple model of material in continuous creeping movement in the upper sediment of the slope. As transport reworks the sediment it dewateres and approaches its "plastic limit"; as sediment flow is impeded at the base of the more mobile upper meters, the sediment is plastered along the firmer underlying material. Small-scale creep could lead to slope failure and larger-scale slumping events, especially in a tectonically active area such as the Middle America Trench, where earthquake activity will contribute another mechanism for triggering these events.

### GEOLOGIC SETTING

The Middle America slope is an extension of the Central American continental framework that is overlain by

<sup>1</sup> von Huene, R., Aubouin, J., et al., *Init. Repts. DSDP*, 84: Washington (U.S. Govt. Printing Office).

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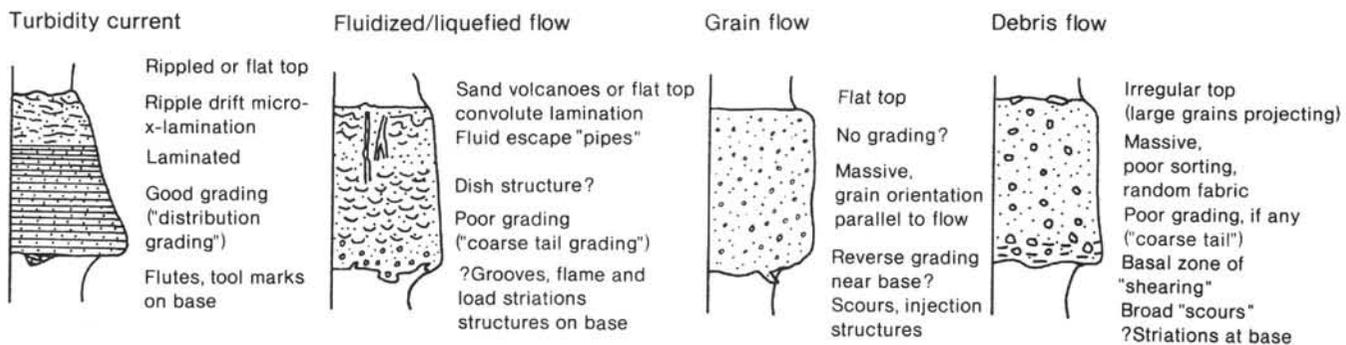


Figure 1. Structure and textures of deposits from single-mechanism mass gravity flows. No vertical scale is implied (from Middleton and Hampton, 1976).

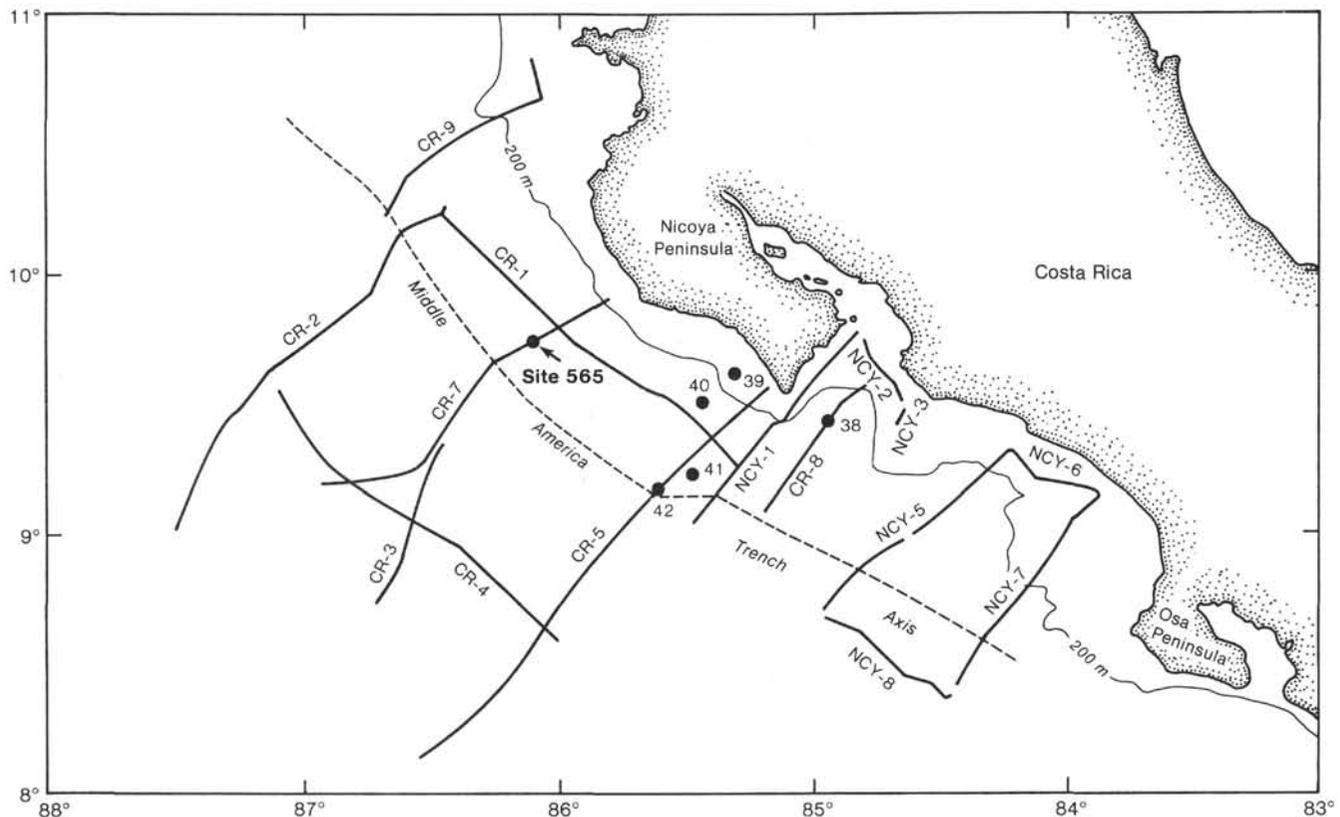


Figure 2. Location map of Site 565 and of track lines and the five piston cores collected during UTMSI Cruises IG 24 and 29.

Table 1. Site and piston core locations.

Piston core or site	Latitude, longitude	Water depth (m)	Recovered sediment (m)
IG-24-7-38	09°22.4' N 84°58.1' W	1179.58	10.09
IG-24-7-39	09°38.0' N 85°19.8' W	104.24	2.70
IG-24-7-40	09°31.0' N 85°27.0' W	1243.58	6.63
IG-24-7-41	09°15.5' N 85°31.2' W	2467.05	9.00
IG-24-7-42	09°9.4' N 85°35.0' W	3427.17	4.93
DSDP Site 565	09°43.69' N 86°05.44' W	3111	287.28

Cenozoic marine sediments. A thick layer of Quaternary and Neogene fine-grained sediments derived from the weathering of onshore Tertiary and Quaternary volcanics drapes over most of the slope. Site 565 from DSDP Leg 84, and the UTMSI piston cores (IG-24-7-39 to -42) are situated on the Costa Rican continental margin between two submarine canyons. UTMSI core IG 24-7-38 was taken in the southernmost of these two canyons.

Site 565 was drilled at a depth of 3111 m and recovered a thick section of Pleistocene through Miocene sediment that comprises a single sedimentary unit of massive mud and mudstone. The Pleistocene section of Site 565 includes the upper 90 to 100 m of sediment (Sections 565-1 to -10) and portions of planktonic foraminiferal Zones N23 and N22 (Stone and Keller, this vol-

ume) and calcareous nannoplankton zones *Emiliana huxleyi* and *Geophyrocapsa oceanica* (Filewicz, this volume). Similar massive Pleistocene and Miocene muds and mudstones were also encountered in the UTMSI cores. The Pleistocene assemblages correlate with planktonic foraminiferal Zone N23. The Miocene assemblage (sample IG-24-7-42, 493 cm) is from a white chalk deposited at abyssal depths under oceanic conditions away from the continental margin and will not be considered further in this study. The UTMSI cores recovered 2.7 to 10.0 m of sediment and were drilled at depths ranging from 104 to 3427 m (Fig. 2; Table 1).

### SEISMIC PROFILES

Seismic reflection profiles of the continental slope at Site 565 (UTMSI Profile CR7) appear in figures 10 and 11 of the Site 565 report (this volume). Drilling penetrated only the upper 328 m of slope sediment. This upper unit shows few bedding reflectors and these are laterally discontinuous and of irregular trend. Other UTMSI profiles of the Costa Rican slope show similarly disrupted bedding in the upper sediments. Thus on a large scale, seismic profiles show a lack of bedding consistent with the massiveness of the mud and mudstones recovered in cores from this site.

### SEDIMENT TEXTURE AND STRUCTURE

Grain size analysis for sediments at Site 565 (Taylor and Bryant, this volume) show a silty clay texture with a gradual trend toward increased clay content with depth. There are a few distinct ash beds, and mottling and burrowing occur throughout the hole. Graded bedding (clayey silt to silty clay) and faint current laminations also occur sporadically. The sand is generally dispersed through-

out the sediment rather than concentrated in specific beds. Small pebbles (under 15 mm in diameter) of semi-consolidated mudstone are also dispersed throughout the massive mud, a characteristic of continental margin debris flow deposits where the strength of the matrix mud prevents internal sorting or grading (Stanley and Unrug, 1972). The unsorted dispersal of sand- and silt-sized grains throughout the sediment sections may be a further expression of matrix strength.

### PHYSICAL PROPERTIES

A rapid change in physical properties occurs in the upper 20 to 30 m, as indicated by a sharp decrease in water content and porosity and increase in bulk density (Fig. 3). Water content decreases from 60 to 40% from the sediment surface to 20 m sub-bottom. Below 20 m the water content decreases to about 30% at a depth of about 45 to 50 m. Contact marked by physical properties occurs at this last depth and is indicated by an abrupt increase in water content that fluctuates around 35% to a depth of 130 m.

The compaction of sediments under gravitational loading results in a decrease of water content and porosity with consequent increases of bulk density and shear strength. Skempton (1970) studied the rate of increasing shear strength as related to burial depth for marine sediments. He defines a range of shear strength versus effective overburden pressure that varies between 0.2 and 0.5 for sediments having undergone normal consolidation. Results of shear strength measurements of Sites 565 when plotted against effective overburden pressure yield a ratio of 0.7. This value is slightly higher than the range defined by Skempton and possibly reflects the effect of another process, such as downslope transport and parti-

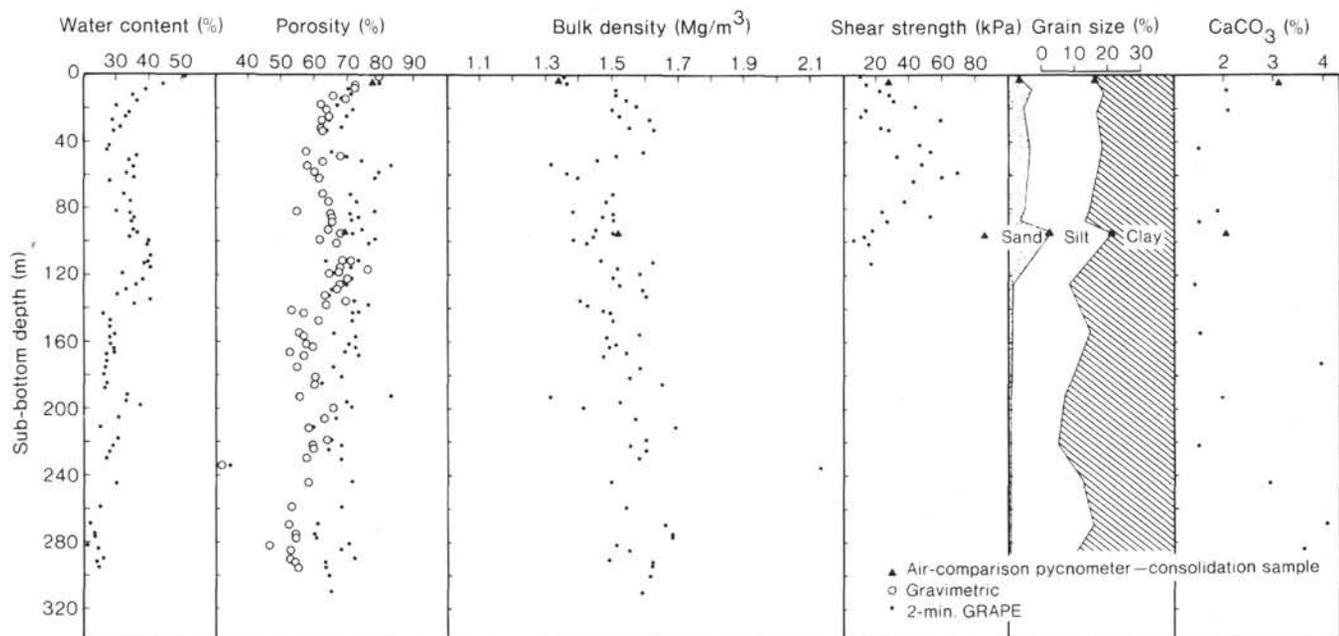


Figure 3. Downhole trend of index geotechnical properties at Site 565 (from Taylor and Bryant, this volume). Profiles of physical properties for samples from DSDP Site 565 reflect the abrupt changes occurring in sediments above an apparent contact at 40 m. The grain size analysis profile exhibits the fairly homogenous texture of sediments recovered from this site.

cle rearrangement, aiding in the consolidation of sediments.

Despite the lithologic homogeneity and massive appearance of the sediment, there is a distinct break in physical properties at a sub-bottom depth of 45 to 50 m. We suspected this was related to plastic reworking of sediment during downslope creep and sought tangible evidence of sediment transport in benthic foraminiferal assemblages.

### PALEOMAGNETICS

Paleomagnetic properties of the sediments at Site 565 are described in the Site 565 report (this volume). The natural remanent magnetism intensities are initially high ( $10^{-5}$  emu) but decrease to  $10^{-6}$  emu at about 20 m sub-bottom. Between 20 and 50 m, the inclinations are scattered and the magnetic intensity decreases; from 50 to 100 m, the intensity decreases rapidly to about  $2 \times 10^{-7}$  emu, and below 100 m intensity is so low that initial demagnetization steps destroyed any measurable remanent magnetism. The absence of measurable magnetic inclination is attributed to the rearrangement of magnetic particles because of bioturbation, slumping, or plastic mass flow of sediments. Such mixing would be expected to destroy the original magnetic orientation, but if the sediment is sufficiently fluid to permit reorientation of magnetic particles, the remagnetization would occur in alignment with the ambient field (Verosub et al., 1979).

Experiments by Verosub et al. (1979) with sediment remagnetization indicate that the critical water content necessary to permit remagnetization is greater than the initial water content of the uncompacted sediment, that is, disturbed sediment will not remagnetize to the ambient magnetic field even if it has a high water content. The reworked sediment of the Costa Rican slope thus probably retains its original magnetic intensity and inclination in the smaller fragments of sediment created during reworking. The addition of magnetic vectors occurring in the smaller sediment fragments could result in cancellation of magnetic vectors and produce the magnetic incoherence observed in these sediments. Whether or not this occurs in the sediment at Site 565, it is interesting that trends are particularly definable in the upper 40 to 50 m of the section.

### BENTHIC FORAMINIFERS

Transported foraminifers are common throughout Site 565 and the UTMSI cores, frequently averaging greater than 50% of the total assemblage. These assemblages indicate transport is the result of both continuous downslope movement and rapid displacement associated with slides, debris flows, or turbidity currents. This conclusion is based on biofacies analysis, which relates water masses, physical properties, water depths, and benthic foraminiferal species or assemblages with specific water depth ranges (Bandy, 1961; Ingle, 1980; Douglas, 1979, 1981; also see McDougall, this volume, for a more complete discussion of the techniques and methods used). Several biofacies may be represented in a single sample, thus, the paleobathymetry is determined by the deepest biofacies present and reflects the minimum depth of de-

position. Paleoecologic interpretations are affected by selective preservation and predation, and by transport, mixing, and environmental changes. Selective preservation and predation alters the species abundances, and can be observed directly from the condition of the tests or by comparisons of species present with dissolution indexes for benthic foraminifers (Corliss and Honjo, 1981). Transport and mixing alters the composition of the assemblages. Although the effects of transport and mixing are suggested by the condition of the tests, they are more easily detected along with environmental shifts by changes in diversity, concentrations of small or similar-sized specimens, or changes in the biofacies patterns. Changes in the biofacies patterns include offsets or lobes of a particular biofacies (Bandy, 1961; Douglas, 1979, 1981; Ingle, 1980). Peak abundances expressed graphically as lobes of shallower water species (Fig. 5) in one or two samples indicate slides or debris flows, whereas offsets or large-scale changes in biofacies abundances tend to reflect environmental shifts or more continuous downslope movement. The Pleistocene section of DSDP Site 565 and the UTMSI cores contain examples of both modes of transport, but a slow gradual downslope movement appears to have been the dominant mechanism.

Biofacies analysis of the UTMSI cores indicates in most cases that there has been little change between the late Pleistocene and the present site of deposition (Figs. 4, 5; Table 2). An environmental change is noted in Core 41 between samples at 300 and 500 cm. Foraminifers suggest that deposition occurred in the abyssal biofacies for samples 500 to 900 cm, and in the lower bathyal biofacies for samples 100 to 300 cm. Although decreasing water depths cannot be discounted, the faunal change in Core 41 between 300 and 500 cm is believed to result from an adjustment of the water masses, following maximum glaciation.

Overall, the biofacies in the UTMSI cores indicate a gradual and continuous downslope movement of benthic foraminiferal faunas (Fig. 5). Shallower water biofacies are represented in each of the cores, but the abundance generally decreases with water depth. There is an increase in abundance of shelf species in core IG-24-7-42, which may be the result of ponding of sediment at the base of the slope and in the Trench. The only inner shelf species that reach the slope are several specimens of *Quinqueloculina lamarkiana*. These are broken and worn, indicating transport. Outer shelf, upper bathyal, and oxygen minimum zone species that reach the lower slope include platelike forms such as *Bolivina bicostata* and *Epistominella bradyana* or fragile thin-walled specimens of *Chilostomella oolina* and *Globobulimina pacifica*. All these species have probably been transported in the water column rather than within the sediment, because the tests are easily suspended and are too fragile to withstand much transport. The larger, heavier tested forms such as *Cassidulina*, *Hoeglundina*, and *Gyroidina* present in the lower slope assemblages often have fragmented or worn tests. The living range of these species (Uchio, 1960; Smith, 1964) indicates some transport was necessary to move these species downslope, but may not have been as great as indicated by the biofacies anal-

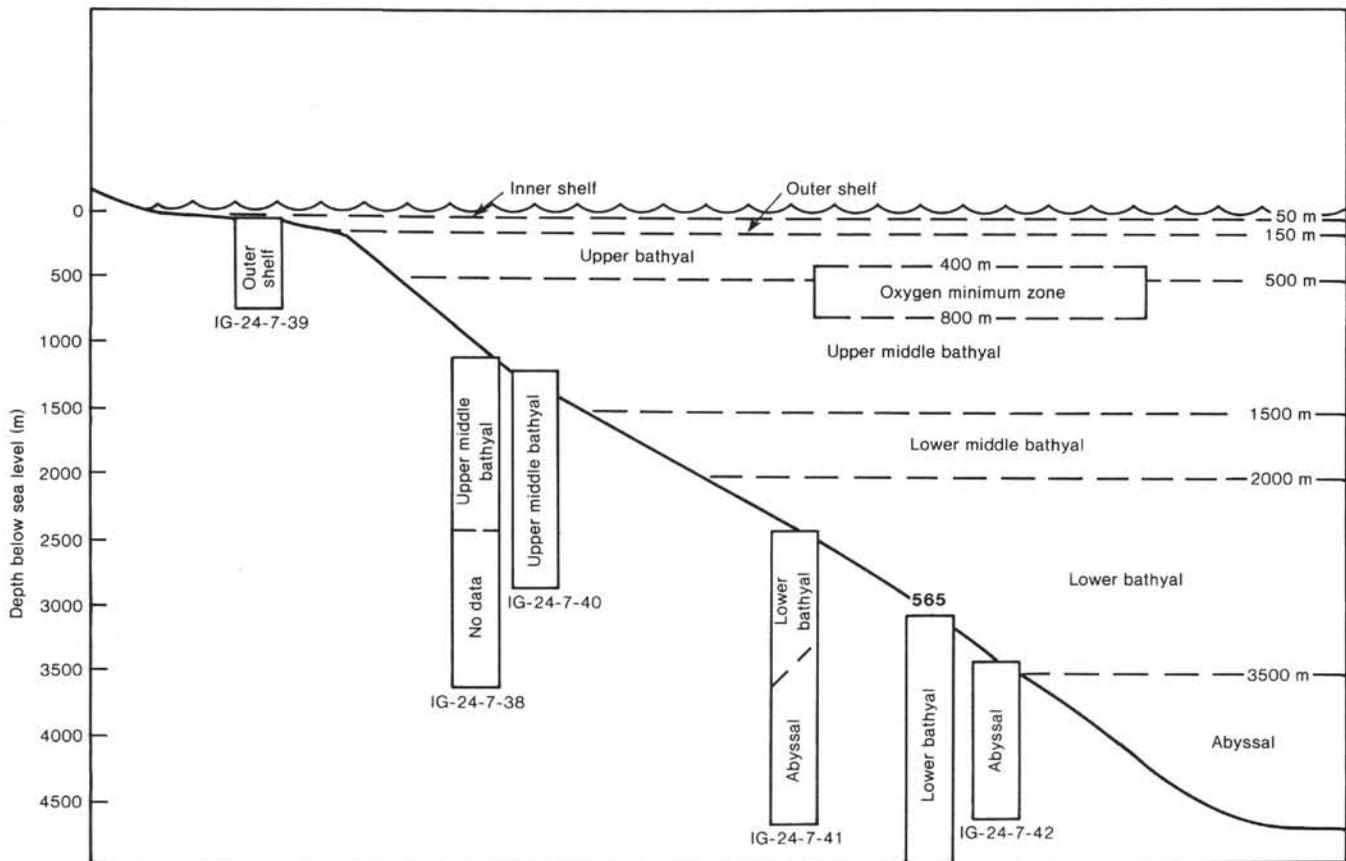


Figure 4. Location of UTMSI piston cores with respect to present benthic foraminiferal biofacies. Depth ranges for the biofacies are taken from studies of recent foraminiferal faunas and physical-chemical properties off Central America (see McDougall, this volume, for discussion and references).

ysis, which considers primarily the upper depth limit of a species. The condition of most of the tests suggests transport occurred as part of the sediment load.

Benthic foraminiferal assemblages from Site 565 (Table 3) indicate deposition occurred within the lower bathyal and abyssal biofacies with paleodepths close to 4000 m and under the influence of both the Pacific Deep Water (PDW) and Antarctic Bottom Water (AABW). Major changes in the benthic foraminiferal faunas correspond to the glacial-interglacial cycles of the late Quaternary and to changes in the water masses. Glacial conditions (cold events, Fig. 6) are correlated with events dated at 0.7 (Core 565-2), 0.9 (Core 565-6), and 1.2 to 2.5 (Cores 565-7 to 565-10) Ma (Ingle, 1967, 1973; Kent, Opdyke, and Ewing, 1971; Bandy, 1972; Olsson, 1974; Shackleton and Opdyke, 1977; Keller and Ingle, 1981). Dissolution associated with the cold events (e.g., Pliocene/Pleistocene boundary, 1.2 to 2.5 Ma cold event) is believed to be the result of expansion of the cold AABW during the glacial maxima. In Cores 565-1, the onset of the warm event and associated transgression is accompanied by a decrease in water depths or more probably an adjustment of the water masses as the production of the AABW declines. Taxonomic notes and paleoenvironmental considerations for Site 565 species are given in McDougall (this volume), and age and paleoceanographic interpretations are discussed by Filewicz, by Stone

and Keller, and by McDougall (this volume) and are summarized in Figure 6.

Transported fauna are common throughout the Pleistocene and average at least 50% of the fauna. Biofacies patterns indicate transported faunas are present as a result of two kinds of downslope movement: a rapid single event (mass gravity flow) usually affecting one biofacies; and a continuous downslope movement, which effects all biofacies. Specimens transported during intervals of rapid downslope movement include platelike bolivinids from the outer shelf-upper slope, cylindrical forms such as *Buliminella* and *Chilostomella* from the upper slope. Abundances of these species are anomalously high in some samples, suggesting rapid downslope movement such as in Sections 565-2-2, 565-2-5, and 565-2-6; 565-3-5; and 565-4-1 (Fig. 6). The larger, more robust transported specimens in these samples tend to be from the adjacent shallower water biofacies and/or have broken or altered tests (molds, fillings, or overgrowths). Continuous downslope transport is recognized by the broader more consistent abundances of biofacies faunas common throughout the Pleistocene (Fig. 6). Transported foraminifers in these intervals include a variety of shapes, sizes, and states of preservation. Shallower water species are represented by continuous low abundances rather than by sporadic peak abundances. Similar patterns were noted in the UTMSI cores.

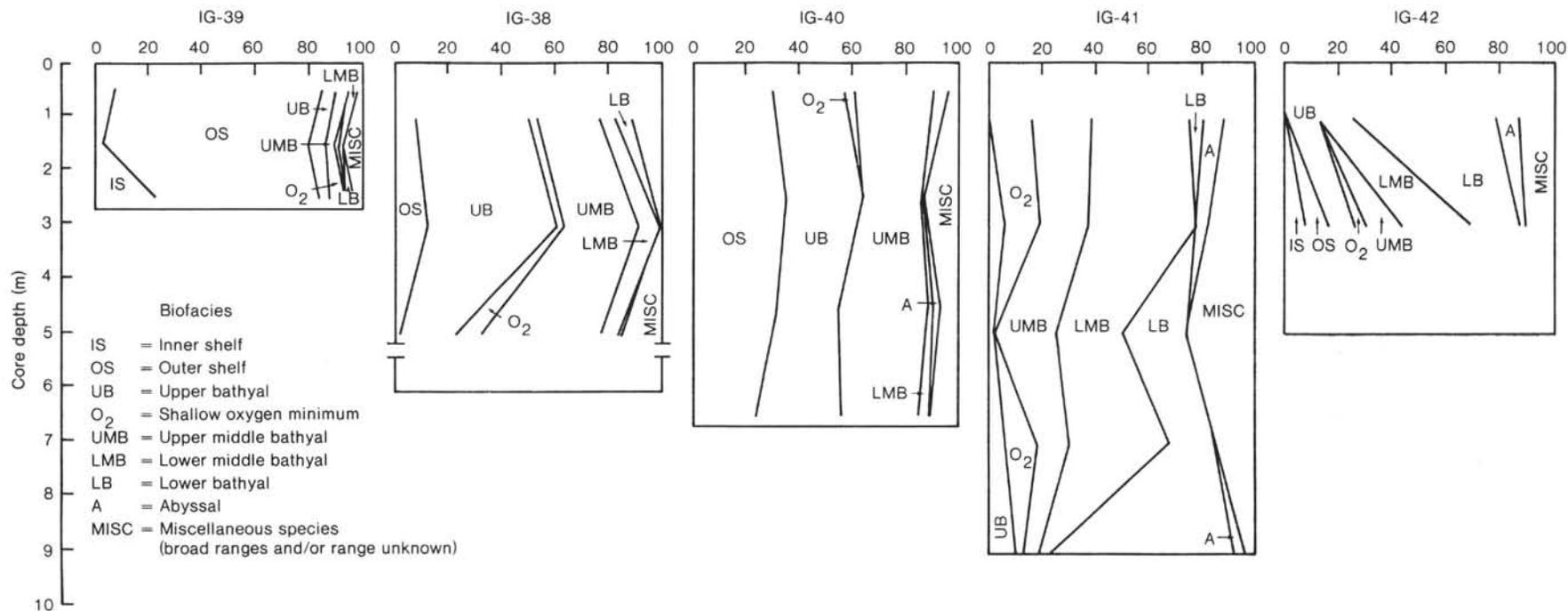


Figure 5. Biofacies trends for the UTMSI cores based on benthic foraminifers. Cores are arranged from shallowest (IG-24-7-39) to deepest (IG-24-7-42). Biofacies groups are the percent of specimens with upper depth limits in that biofacies (Table 2). The distribution and abundance of each biofacies in the IG cores indicate that deposition occurred in the outer shelf (Core IG-24-7-39), upper middle bathyal (Cores IG-24-7-38 and IG-24-7-40), lower bathyal (Core IG-24-7-41, samples at 100 and 300 cm), and abyssal (Cores IG-24-7-41, samples at 500, 700, and 900 cm, and IG-24-7-42).



Table 2. Faunal list, UTMSI cores.

UTMSI samples (core/cm level or interval)	<i>Astrorionion guadalupae</i>	<i>Bolivina acuminata</i>	<i>B. advena</i>	<i>B. alta</i>	<i>B. argentea</i>	<i>B. beyrichi</i>	<i>B. bicostata</i>	<i>B. bradyi</i>	<i>B. floridana</i>	<i>B. foraminata</i>	<i>B. marginata</i>	<i>B. pacifica</i>	<i>B. pseudobeyrichi</i>	<i>B. scabrata</i>	<i>B. seminuda</i>	<i>B. semiperforata</i>	<i>B. cf. B. sinuata</i>	<i>B. spissa</i>	<i>B. striatula</i>	<i>B. subadvena</i>	<i>B. subadvena sulphurensis</i>	<i>B. tongi filicostata</i>	<i>Ruvetella harrisi</i>	<i>Bulimina oboezensis</i>	<i>B. denudata</i>	<i>B. mexicana</i>	<i>B. sp.</i>	<i>B. subacuminata</i>	<i>Buliminella curta</i>	<i>B. subuliformis</i>	<i>Cancris inflatus</i>	<i>C. panamaensis</i>	<i>C. sagra</i>	<i>Castidina californica</i>	<i>C. crassa</i>		
39/49-53	.	.	1	.	.	4	17	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
39/150	.	1	.	.	.	4	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
39/250	.	2	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
38/100	.	.	1	.	11	x	1	.	.	2	.	x	3	.	.	x	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
38/300	.	.	x	x	x	.	.	.	x	.	.	.	.	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
38/500	.	.	2	.	x	2	.	.	.	.	.	.	2	.	6	9	.	.	.	.	.	.	.	.	.	1	.	4	.	4	x	.	.	2	.	.	
40/50	.	.	2	.	3	.	9	.	2	.	.	x	1	.	3	3	.	.	3	.	.	.	.	.	x	.	.	.	.	6	.	.	.	.	3		
40/250	.	.	x	.	4	.	16	1	.	.	.	.	1	.	4	x	12	.	2	.	.	.	.	.	x	.	1	.	3	4	.	x	.	.	.		
40/450	.	.	x	.	6	.	8	.	.	1	.	.	x	.	.	5	.	.	8	x	.	.	.	.	2	.	.	.	1	7	.	.	.	.	.		
40/650	.	.	x	.	4	.	3	.	.	x	.	.	2	.	.	x	16	x	.	3	x	.	.	.	x	.	.	.	4	3	.	.	.	x	.		
41/100	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	
41/300	2	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
41/500	3	.	.	.	.	.	.	.	.	.	2	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
41/700	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
41/900	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
42/100	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
42/300	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Note: Benthic foraminiferal occurrences for the UTMSI cores are given as percent total fauna, and an x indicates a percent of less than 1. Biofacies abundances are also given in percent of total fauna. Dot indicates species is not present.

**SEDIMENT FABRIC**

In contrast to the general uniformity of sediment texture at Site 565, a penetrative fabric best described as a "scaliness" occurs in several intervals of mud and mudstone. The fabric is a primary sedimentary feature rather than a product of drilling disturbance, for it is observed over a range of consolidation from firm mud to undisturbed mudstone blocks in a matrix of drilling-disturbed mud. This fabric was observed in the near-surface sediments recovered in the UTMSI cores as well as at subsurface depths well below 150 m at Site 565.

The scaliness is horizontal to subhorizontal; mud breaks into smooth "polished" concoidal flakes of less than 2 mm in length. Figure 7 illustrates scaly splitting of firm mud. The scaly fabric is striking under very high magnification. Small (under 2-mm) pieces of scaly mud and mudstones were selected from the Site 565 sediments for examination under the scanning electron microscope (SEM). Figure 8A-D shows SEM photographs from this study. Flakes of a montmorillonite clay are aligned in larger stacks incorporating small blocky fragments of other materials. Such alignment is an expected feature of clays because of their phyllosilicate crystalline structure (Burst, 1976), but the size of aligned flakes indicates an agglomeration of clay crystals. In a continental slope setting, current activity could be an agent of earlier horizontal orientation of the clayey sediment, but the incorporation of blocky fragments in the clayey stacks belies sorting and aligning by current activity.

Downslope creep and scaly fabric are described in some soil science texts (e.g., Jackson, 1969), and we suggest that this process occurs here on the Costa Rican slope. Plastic mass flow of sediments downslope would continuously rework materials into a closer-knit fabric, smearing clayey sediment into alignment and grinding other fine materials into the clayey base. Dewatering during this movement would result in the overconsolida-

ted sediment near the top of the sediment column observed at Site 565. On a broader scale, such flow destroys sedimentary bedding, resulting in the massivity evidenced in the seismic profile of the upper unit at Site 565 as well as in the cores recovered at the site.

**DISCUSSION OF SEDIMENTARY PROCESSES**

The upper 45 to 50 m of sediment at Site 565 are lithologically indistinguishable from sediment recovered at greater depths downhole: the entire 328 m is placed in a single lithologic unit. Geotechnical and paleomagnetic properties, however, suggest that different processes are presently occurring in the upper part of the section, and sedimentologic and faunal characteristics suggest that these are related to downslope transport and mixing of sediment.

The unique structure of the upper sedimentary section at Site 565 provides us with the opportunity to try several approaches of characterizing or recognizing a gradual, downslope transport mechanism. The fact that sediments possess different rheological behaviors and shear strength characteristics and rest on various degrees of slopes on continental margins and slopes leads to the conclusion that downslope transport mechanisms can vary from a slow, downslope creep to slumps, debris flows, or turbidity currents. Any one of these transport mechanisms can in turn be the precursor of subsequent catastrophic failures.

The nature of a deposit undergoing mass movement is dependent on the strength characteristics of the sediment resisting the gravitational impulse acting on the pile along a given inclined plane. The possibility of frequent seismic disturbance in the region of the Middle America Trench suggests the gravitational impulse may occasionally be bolstered by stresses resulting from seismic activity. The presence of excess pore pressure generated downhole at Site 565 (see Site 565 report, this volume) may result from the subduction process burying



Table 2. (Continued).

UTMSI samples (core/cm level or interval)	<i>F. staphylearia</i>	<i>F. wiesneri</i>	<i>Fursenkonia bramletti</i>	<i>F. complanata</i>	<i>F. cornuta</i>	<i>F. nodosa</i>	<i>F. rotundata</i>	<i>F. seminuda</i>	<i>Globobulimina barbata</i>	<i>G. pacifica</i>	<i>G. spinifera</i>	<i>Globocassidulina subglobosa</i>	<i>Gyroldina altiformis</i>	<i>G. altispira</i>	<i>G. vandoni</i>	<i>G. lamarckiana</i>	<i>G. multilocula</i>	<i>G. neosoldani</i>	<i>G. nitidula</i>	<i>G. planulata</i>	<i>G. quinqueloba</i>	<i>G. soldani</i>	<i>G. zelandica</i>	<i>Hantzawaia concentrica</i>	<i>Hoglundina elegans</i>	<i>Lagena elongata</i>	<i>L. gracillima</i>	<i>L. striata</i>	<i>L. striatopunctata</i>	<i>L. sulcata</i>	<i>L. vulgaris</i>	<i>Laticarinina pauperata</i>	<i>Lenticulina cushmani</i>	<i>Martinoiella pallida</i>	<i>Melonis affinis</i>			
39/49-53	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
39/150	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
39/250	•	•	•	1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
38/100	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
38/300	•	•	x	•	x	x	x	•	x	•	•	•	39	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
38/500	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
40/50	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
40/250	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
40/450	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
40/650	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
41/100	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
41/300	•	•	x	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
41/500	•	x	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
41/700	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
41/900	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
42/100	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
42/300	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

higher water contents, in turn, shift the rheological nature of the sediment toward a more fluid state such as measured in Section 565-1-4.

Lowe (1979) describes sediment gravity flows in terms of the rheological nature of the deposit. The range of water contents within the liquid-plastic behavior field defined by Atterberg limits for sediments at Site 565 supports the idea of a spectrum of downslope transport processes, going from a viscous creep movement near the base of the 45-m layer to mud flows or cohesive debris flows near the surface.

An illustration of the velocity profile resulting from the envisioned downslope movement mechanism is shown in Figure 10. Conditions defining this velocity profile set the depth of minimum velocity at 47 m, but the point of the figure does not depend on halting the flow entirely. The sediment at the base of this mobile 45 to 50 m is moving much more slowly than the more fluid overlying materials: essentially it is left behind by the faster-moving upper layer. At this level in the sediment section, sediment water content has decreased to below its plastic limit (Fig. 9), providing a second indication that this material will no longer flow.

The nature of the boundary at about 47 m is of interest. The boundary could represent a slowly shifting horizon of sediment accumulation, where overlying clayey sediment is continuously plastered onto it as the sediment reaches its plastic limit. Smearing of clayey sediment could result in a relatively impermeable layer, effectively sealing the upper sediments from the section below. Thus buildup of pore pressure resulting from dewatering of the subducting sediments of the Cocos Plate or from formations of gas hydrates ubiquitous to the sediments on this continental slope (see Organic Geochemistry section, Site 565 report, this volume) could occur in the sediments below the zone of downslope creep. Alternatively, this layer of abrupt change in physical properties could indicate the basal surface of a slump.

Buildup of a pile of sediment too consolidated for plastic flow at its base could result in slope instability and local failure through slumping. This can be enhanced by the buildup of pore pressure at the base of the layer acting to lubricate the slump surface. A shift in the benthic foraminiferal biofacies and diversity at about 47 m sub-bottom indicates a slight unconformity or hiatus (Fig. 6), which supports the possibility of a slump surface at this depth.

We consider the answer to lie in a combination of these alternatives where mass movement and downslope reworking accumulates sediment in a mobile layer of material that is self-limiting in its thickness. At the base of the layer shearing and reworking accretes the clayey material to underlying slope sediments, creating a low permeability boundary of nonflowing clayey sediment that seals the mobile layer from the underlying material. Buildup of pore pressure below and accumulation of a thick pile of sediment above leads to local instability and slumping along the surface. The few laterally discontinuous reflectors in seismic profiles of the Costa Rican slope may represent ancient slump surfaces.

Canyon sedimentation on continental slopes is generally treated in terms of depositional events such as turbidity flows, slumps, or debris flows, but continuous sedimentation processes that could lead to these events are somewhat neglected. The muds and mudstones of the Costa Rican slope are typical hemipelagic deposits of an active margin inner slope cut many canyons. The texture and fabric of sediment in this geologic setting leads us to suggest that downslope creep is a process of sediment transport of greater importance than has been heretofore recognized.

Analysis of benthic foraminiferal assemblages and detection of scaly fabric can be useful documentation of downslope creep, and shifts in physical properties and the paleomagnetic record may be used to define the layer of sediment movement.



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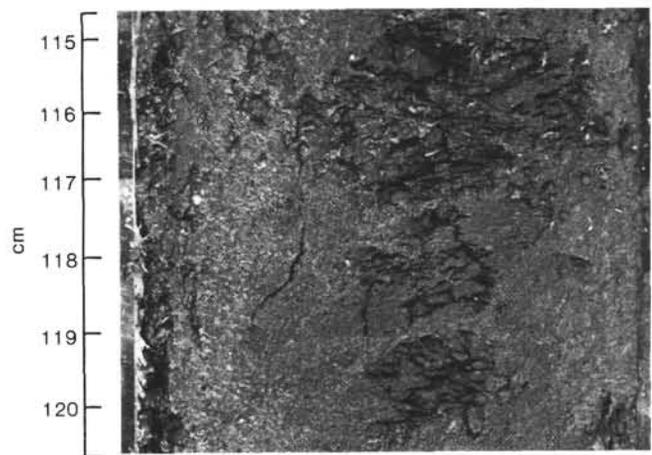


Figure 7. Typical scaly sediment fabric observed at Site 565, Sample 565-16-4, 115-120 cm.

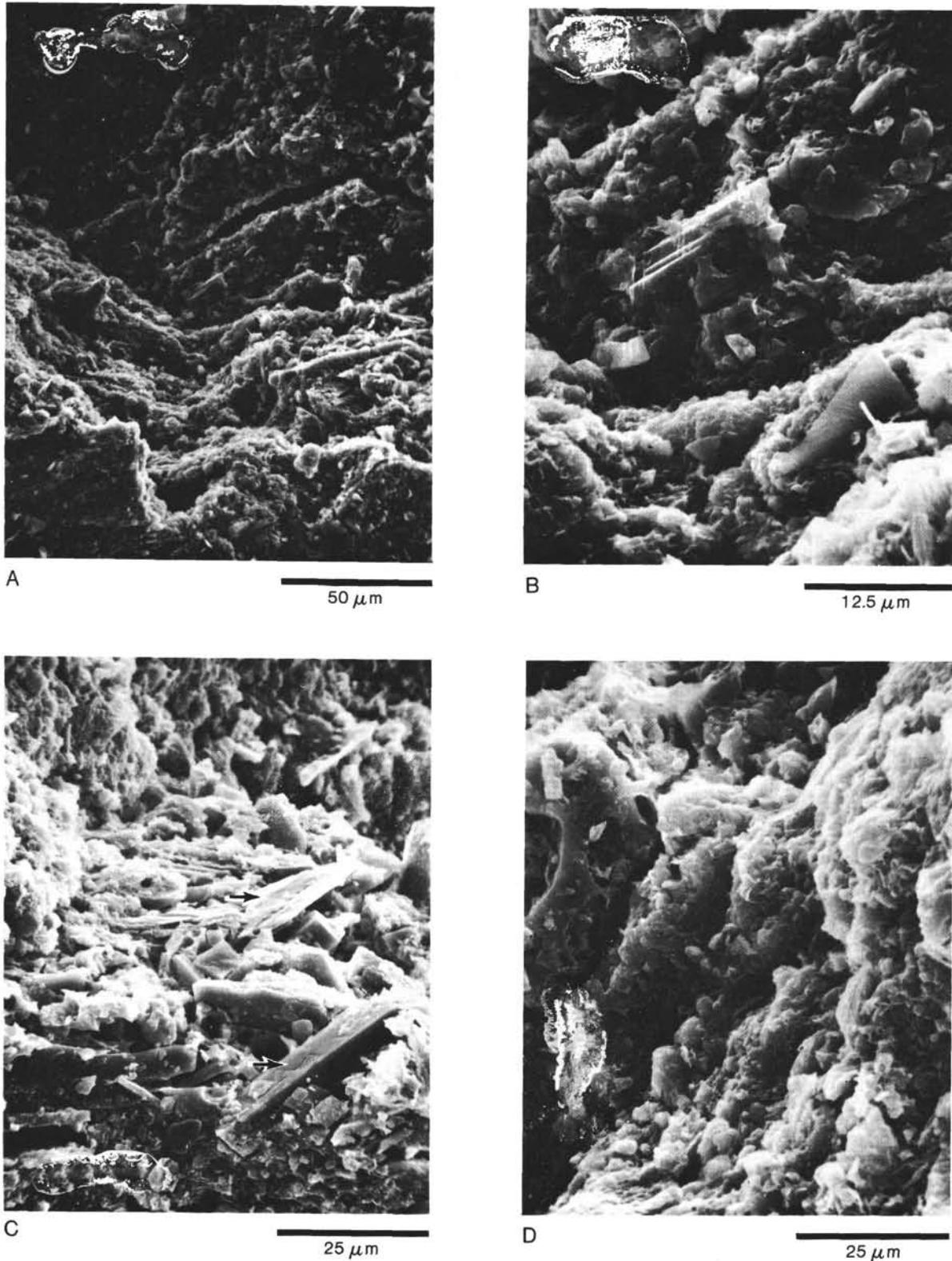


Figure 8. Scanning electron microscope photomicrographs of scaly mud from Site 565. A. Sample 565-11-2, 125 cm. Stacks of clayey sediment incorporating blocky fragments of other sediment constituents including shell fragments. B. Sample 565-11-2, 125 cm. Closer view of the aligned stacks of Figure 8A, illustrating the agglomerate nature of the aligned stacks of sediment. Large crystalline plugs are incorporated into layers of smaller flakes. C. Sample 565-11-2, 52 cm. Tabular and cubic (pyrite?) crystals in clayey stacks. Arrows indicate incipient splitting of larger crystals possibly in response to shearing. D. Sample 565-11-2, 52 cm. Multiple layers with large-scale stacks.

Table 3. Faunal list, Site 565.

Sample (cm interval)	Taxa	<i>Alveolophragmium crassimargo</i>	<i>A. cf. A. nitidula</i>	<i>Anomalinaeides globosa</i>	<i>Astronotium guadalupe</i>	<i>Bolivina acuminata</i>	<i>B. advena</i>	<i>B. alataensis</i>	<i>B. argentea</i>	<i>B. bicostata</i>	<i>B. bradyi</i>	<i>B. beyrichi</i>	<i>B. foraminata</i>	<i>B. globosa</i>	<i>B. pacifica</i>	<i>B. plicata</i> of Resig	<i>B. pseudobeyrichi</i>	<i>B. pseudospissa</i>	<i>B. semiperforata</i>	<i>B. seminuda</i>	<i>B. cf. B. sinuata</i>	<i>B. spp.</i>	<i>B. spissa</i>	<i>B. subadvena</i>	<i>B. woodringi</i>	<i>Bolivinita quadrulata</i>	<i>Bulimina alataensis</i>	<i>B. denudata</i>	<i>B. mexicana</i>	<i>B. pagoda</i>	<i>B. subacuminata</i>	<i>Buliminella curta</i>	<i>B. curta basispinata</i>	<i>B. subfastiformis</i>	<i>B. tenuata</i>	<i>Cancris inflatus</i>			
1-1, 70-74	4						4			4											16																		
1-2, 77-81	5		5																		5		4				4												
1,CC	x																																						
2-1, 70-74	x			x																																			
2-2, 77-81				4	2		1						3									8		1															
2-3, 77-79						1	1			1							3			1	7				2														
2-4, 76-80						x																																	
2-5, 52-56						3																																	
2-6, 70-76						2				1																													
2-7, 30-34																																							
2,CC				2	3		x		x	1																													
3-1, 64-70						2				2																													
3-2, 66-70							2			2																													
3-3, 66-70																																							
3-4, 66-70						2	2		2	2																													
3-5, 66-70																																							
3-6, 64-68						33																																	
3,CC						2																																	
4-1, 10-14							3			3																													
4-2, 10-14							3			x			x																										
4-3, 10-14						2																																	
4-4, 10-14						3				3																													
4-5, 10-14						2	x	2	6																														
5-1, 84-88						4		9	6																														
5-2, 84-88		1		x	x	x	x	2	4	x																													
5-6, 84-88																																							
5-7, 44-48							x			x																													
5,CC						x				1	x	x																											
5 (below)																																							
6-1, 39-43																																							
6-2, 39-43																																							
6-3, 39-43																																							
6-4, 39-43						5																																	
6-5, 39-43																																							
6-6, 39-43							5		x																														
6-7, 39-43							3		2																														
6,CC				x		x			x																														
7-1, 58-62																																							
7-3, 58-62																																							
7-4, 56-62																																							
7-5, 58-62						4			x																														
7-6, 58-62						1			x																														
7,CC						4			4	x																													
8-1, 54-58																																							
8-2, 54-58						3		4	3	24																													
8-3, 54-58																																							
8-4, 54-58																																							
8-6, 54-58																																							
8,CC																																							
9-1, 34-38																																							
9-4, 54-58						x	x			8	4	11																											
9-6, 46-50																																							
9-7, 11-15																																							
9,CC																																							
10-1, 70-74																																							
10-2, 73-74																																							
10-3, 76-80																																							
10-5, 86-90																																							
10-6, 86-90																																							

Note: Benthic foraminiferal occurrences are given as percent total fauna; an x indicates less than 1%. Biofacies abundances are also given in percent total fauna; IS = inner shelf; OS = outer shelf; UB = upper bathyal; O2 = oxygen minimum zone; UMB = upper middle bathyal; LMB = lower middle bathyal; LB = lower bathyal; A = abyssal; dot or blank space indicates species is not present.



Table 3. (Continued).

Taxa	<i>Ellipsogena</i> sp.	<i>Elphidium tumida</i>	<i>Epistominella bradyana</i>	<i>E. exiua</i>	<i>E. pacifica</i>	<i>E. smithi</i>	<i>E. sp. of Resig</i>	<i>E. sp.</i>	<i>Eponides repandus</i>	<i>Ficurina alveolata</i>	<i>F. auriculata</i>	<i>F. carteri</i>	<i>F. cucullata</i>	<i>F. exsculpia</i>	<i>F. Imbraia</i>	<i>F. marginata</i>	<i>F. cf. F. kugleri</i>	<i>F. orbignyana</i>	<i>F. solida</i>	<i>F. spp.</i>	<i>F. spinosa</i>	<i>F. staphylaria</i>	<i>F. subformosa</i>	<i>F. wiesneri</i>	<i>Froncilularia compressa</i>	<i>F. joaquensis</i>	<i>Pursenkoina complanata</i>	<i>F. coronata</i>	<i>F. spp.</i>	<i>F. rotundata</i>	<i>F. seminuda</i>	<i>Gaudryna arenaria</i>	<i>Glandulina</i> sp.	<i>Globobulimina barbaia</i>	<i>G. pacifica</i>		
1-1, 70-74			4																																		
1-2, 77-81				5																																	
1,CC				9																																	
2-1, 70-74				4	2	2																															
2-2, 77-81				14		1																															
2-3, 77-79				1																																	
2-4, 76-80				5																																	
2-5, 52-56			1	1	3	3				x	x																										
2-6, 70-76				12	4																																
2-7, 30-34																																					
2,CC				2	1	2																															
3-1, 64-70				2	2	2	2																														
3-2, 66-70				2	2	2																															
3-3, 66-70				2	2	2																															
3-4, 66-70			2										2																								
3-5, 66-70				12																																	
3-6, 64-68																																					
3,CC				3	6	2						x	x																								
4-1, 10-14				14																																	
4-2, 10-14				9		3																															
4-3, 10-14				2																																	
4-4, 10-14				6																																	
4-5, 10-14				7																																	
5-1, 84-88				7	x	1																															
5-2, 84-88	x	x		2	5																																
5-6, 84-88				x	2	2																															
5-7, 44-48				2		3																															
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6-1, 39-43													6																								
6-2, 39-43																																					
6-3, 39-43				5									5																								
6-4, 39-43					5																																
6-5, 39-43			3																																		
6-6, 39-43			5			1	1																														
6-7, 39-43			2				3						2																								
6,CC	x						x					2																									
7-1, 58-62																																					
7-3, 58-62																																					
7-4, 56-62			2			4																															
7-5, 58-62			3				4																														
7-6, 58-62			3			x																															
7,CC	x		5			x	x																														
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8-2, 54-58			3				3																														
8-3, 54-58			3																																		
8-4, 54-58			2			x	2					1	1																								
8-6, 54-58																																					
8,CC													1																								
9-1, 34-38																																					
9-4, 54-58				5			x																														
9-6, 46-50																																					
9-7, 11-15																																					
9,CC																																					
10-1, 70-74	1		1	3																																	
10-2, 73-74																																					
10-3, 76-80																																					
10-5, 86-90																																					
10-6, 86-90																																					



Table 3. (Continued).

Taxa	<i>N. lamellata</i>	<i>N. obliqua</i>	<i>N. parvifilis</i>	<i>N. sp.</i>	<i>N. siamforthia</i>	<i>Notonella auriculata</i>	<i>N. basispinata</i>	<i>N. incisa</i>	<i>N. labradoricum</i>	<i>N. stella</i>	<i>Oolina</i> cf. <i>O. laevigata</i>	<i>Oridorsalis umbonatus</i>	<i>Oxangularia culteri</i>	<i>Panzissurina</i> sp.	<i>Planulina exorna</i>	<i>Plectrofrondicularia advena</i>	<i>P. californica</i>	<i>P. rathvenmurrayi</i>	<i>P. vaughani</i>	<i>Pleurostomella hierigi</i>	<i>P. alternans</i>	<i>P. brevis</i>	<i>Praglobobulimina auriculata</i>	<i>P. affinis</i>	<i>P. ovata</i>	<i>P. pupoides</i>	<i>Pullenia alacensis</i>	<i>P. bulloides</i>	<i>P. duplicata</i>	<i>P. quinqueloba</i>	<i>P. salisburyi</i>	<i>P. trinitatis</i>	<i>Pyrgo depressa</i>	<i>P. murrhina</i>	<i>P. rotulata</i>		
1-1, 70-74																																					
1-2, 77-81																																					
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2-1, 70-74																																					
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2-5, 52-56																																					
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6-1, 39-43																																					
6-2, 39-43																																					
6-3, 39-43																																					
6-4, 39-43																																					
6-5, 39-43				3	3																																
6-6, 39-43				x																																	
6-7, 39-43																																					
6,CC																																					
7-1, 58-62																																					
7-3, 58-62																																					
7-4, 56-62																																					
7-5, 58-62																																					
7-6, 58-62																																					
7,CC																																					
8-1, 54-58																																					
8-2, 54-58																																					
8-3, 54-58																																					
8-4, 54-58																																					
8-6, 54-58																																					
8,CC																																					
9-1, 34-38																																					
9-4, 54-58	x																																				
9-6, 46-50																																					
9-7, 11-15																																					
9,CC																																					
10-1, 70-74																																					
10-2, 73-74																																					
10-3, 76-80																																					
10-5, 86-90																																					
10-6, 86-90																																					



Table 3. (Continued).

Sample (cm interval)	Taxa		Biofacies								
	Fossiliferous number	Diversity	IS	OS	UB	O <sub>2</sub>	UMB	LMB	LB	A	
1-1, 70-74	25	19	16	16	4	*	20	40	*	*	
1-2, 77-81	20	16	15	5	*	*	20	30	*	*	
1,CC	338	49	4	4	2	12	22	19	22	2	
2-1, 70-74	49	32	*	4	6	*	34	19	18	2	
2-2, 77-81	77	37	*	8	14	1	37	12	8	1	
2-3, 77-79	87	42	*	4	4	7	18	23	16	*	
2-4, 76-80	158	43	*	4	6	2	17	20	33	1	
2-5, 52-56	81	33	*	12	8	8	38	6	16	*	
2-6, 70-76	85	27	*	15	3	5	47	12	4	*	
2-7, 30-34	1	1	*	*	*	*	100	*	*	*	
2,CC	230	64	*	11	8	4	36	16	7	3	
3-1, 64-70	39	28	*	12	2	5	31	19	17	2	
3-2, 66-70	41	24	*	20	7	10	17	4	15	3	
3-3, 66-70	12	7	*	16	*	8	17	16	42	*	
3-4, 66-70	61	30	*	11	10	5	40	8	12	*	
3-5, 66-70	17	10	*	*	18	23	47	12	*	*	
3-6, 64-68	3	3	*	*	*	*	*	33	*	*	
3,CC	126	46	*	5	12	2	34	10	18	3	
4-1, 10-14	35	17	*	6	23	6	52	3	6	*	
4-2, 10-14	107	23	*	4	25	2	45	8	6	*	
4-3, 10-14	46	15	*	28	7	*	61	2	2	*	
4-4, 10-14	35	16	*	26	8	3	54	6	*	*	
4-5, 10-14	232	43	1	9	22	1	43	11	7	*	
5-1, 84-88	285	53	*	7	22	*	40	10	10	*	
5-2, 84-88	384	71	1	8	6	1	32	23	9	2	
5-6, 84-88	249	48	*	*	13	1	23	26	21	1	
5-7, 44-48	199	39	*	1	7	*	34	19	23	*	
5,CC	302	58	*	2	11	1	32	15	19	3	
5 (below)	17	12	*	*	6	*	22	12	30	*	
6-1, 39-43	8	5	*	*	*	*	25	37	38	*	
6-2, 39-43	19	13	*	*	*	*	32	16	21	10	
6-3, 39-43	7	7	*	*	14	*	*	14	29	*	
6-4, 39-43	21	7	*	5	*	*	39	*	52	5	
6-5, 39-43	38	15	*	3	5	*	34	13	37	*	
6-6, 39-43	153	33	*	5	22	*	54	8	2	2	
6-7, 39-43	65	21	*	2	12	*	41	16	14	*	
6,CC	265	44	1	*	2	*	26	24	14	1	
7-1, 58-62	10	7	*	20	*	*	20	10	20	*	
7-3, 58-62	20	11	*	*	5	*	5	15	50	*	
7-4, 56-62	56	21	4	*	*	2	14	24	47	*	
7-5, 58-62	200	40	*	6	4	4	24	11	28	1	
7-6, 58-62	233	47	*	4	5	1	28	16	22	1	
7,CC	580	79	*	10	12	2	35	8	8	2	
8-1, 54-58	7	7	*	*	14	*	43	15	14	*	
8-2, 54-58	123	39	*	16	18	*	25	6	11	*	
8-3, 54-58	33	22	*	3	6	*	36	33	3	*	
8-4, 54-58	200	46	*	7	10	2	31	13	14	2	
8-6, 54-58	23	13	*	*	17	7	43	4	22	*	
8,CC	81	24	3	*	6	*	23	16	20	*	
9-1, 34-38	2	1	*	*	100	*	*	*	*	*	
9-4, 54-58	286	45	1	19	26	*	32	8	5	5	
9-6, 46-50	2	2	*	*	50	*	50	*	*	*	
9-7, 11-15	1	1	*	*	*	*	100	*	*	*	
9,CC	140	25	*	*	4	*	23	23	41	*	
10-1, 70-74	105	30	*	3	3	*	27	23	25	5	
10-2, 73-74	8	2	*	*	*	*	12	*	82	*	
10-3, 76-80	20	10	*	*	15	*	25	20	15	*	
10-5, 86-90	4	3	*	*	*	*	*	25	25	*	
10-6, 86-90	1	1	*	*	*	*	*	*	*	*	

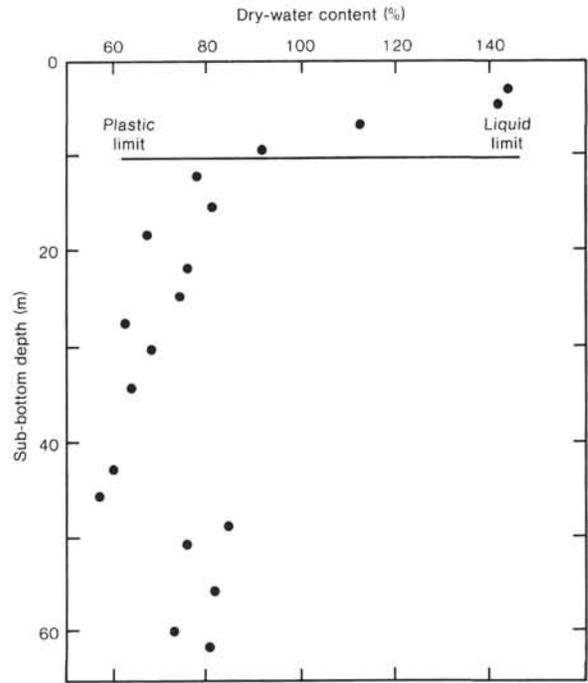


Figure 9. Comparison of natural water content of sediments of Site 565 to liquid and plastic limits of Section 565-1-4.

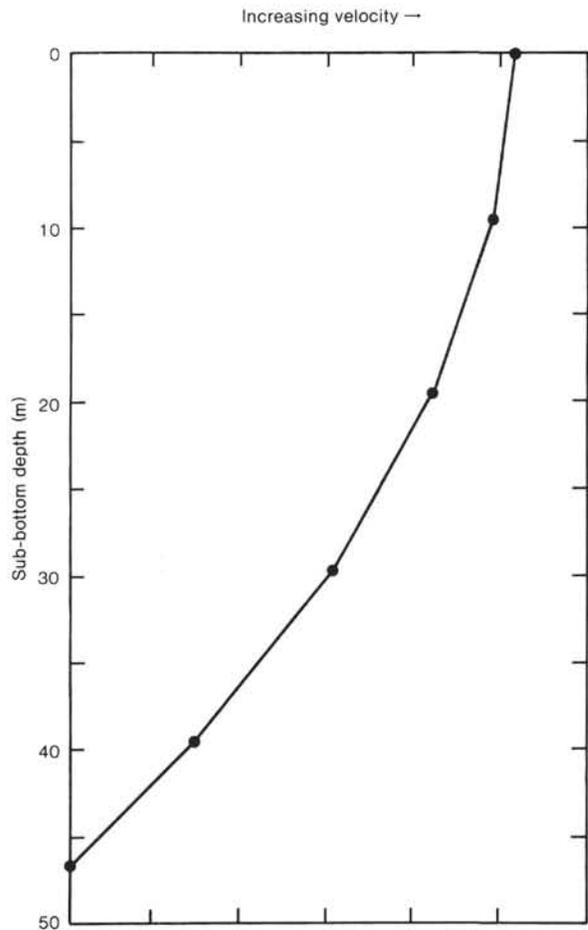


Figure 10. Calculated downslope velocity profile for potential creep for sediments in the upper 47 m at Site 565.