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Erosion and Slope Instability on Horizon Guyot, Mid-Pacific Mountains

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Abstract

Seismic-reflection profiles, sediment cores, and current velocities were assessed to study the impact of erosion and sediment redistribution on the pelagic sediment cap of Horizon Guyot, a flat-topped submarine volcanic ridge in the Mid-Pacific Mountains. These processes seem to concentrate their effect around the rim of the sediment cap. Sediment slumping occurs on the northwest perimeter of the guyot's sediment cap. Slope stability analysis suggests that if overconsolidation on Horizon Guyot is the result of current reworking or if local undercutting by bottom currents steepens the sea floor declivity, the sediment cap may be unstable during infrequent earthquake loading, transporting sediment from the guyot summit to the abyssal sea floor.

Introduction

Horizon Guyot is a 300-km long, 75-km wide northwest-southeast trending volcanic ridge whose gently sloping summit is characteristic of guyots (Heezan and others 1971, Lonsdale and others 1972, Winterer and others 1973) (Fig. 1). Seismic-reflection data delineate a pelagic sedimentary deposit, as much as 160 m thick, capping an irregular volcanic basement and thus enhancing the flatness of the summit area (Karig and others 1970). Seamounts capped or draped by unconsolidated sediment have been noted from many other areas of the world ocean (e.g., Taylor and others 1975, Uchupi and others 1970). However, the current conditions and other processes that resuspend or locally transport these sediment are poorly understood.

This investigation of erosion and slope instability on Horizon Guyot was largely motivated by earlier results by Lonsdale and others (1972). On the basis of current-speed data from Savonius* rotor-type meters moored at three sites within 12 m of the bottom in about 1,675 m water depth, Lonsdale and others (1972) reported tidal-current speeds of up to 17 cm/s in the same area where sand waves and ripples were observed on side-scan sonographs and bottom photographs. They argued that the bedforms on the sediment cap and erosional features, such as truncated sedimentary units and scours along the guyot's rim, were probably caused by internal tidal currents that intensify along the guyot's surface.

This report and the companion paper by Cacchione and others (1988) present new data and interpretations that support and expand the findings of Lonsdale and others (1972) and should directly apply to a better understanding of the dynamics of the environment around mid-plate volcanoes. We present high-resolution seismic-reflection profiles (Fig. 1) and paleontologic and geotechnical analysis of sediment gravity cores. In addition, evidence for the occurrence of mass movement on the sediment cap is presented with suggestions of possible causes of this instability. Current-speed data and implications for sediment transport are presented in Cacchione and others (1988).

Data

Horizon Guyot was surveyed and sampled on U.S. Geological Survey (USGS) cruises L5-83-HW (Hein and others, 1985) and L9-84-CP (Schwab and Bailey,

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*Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

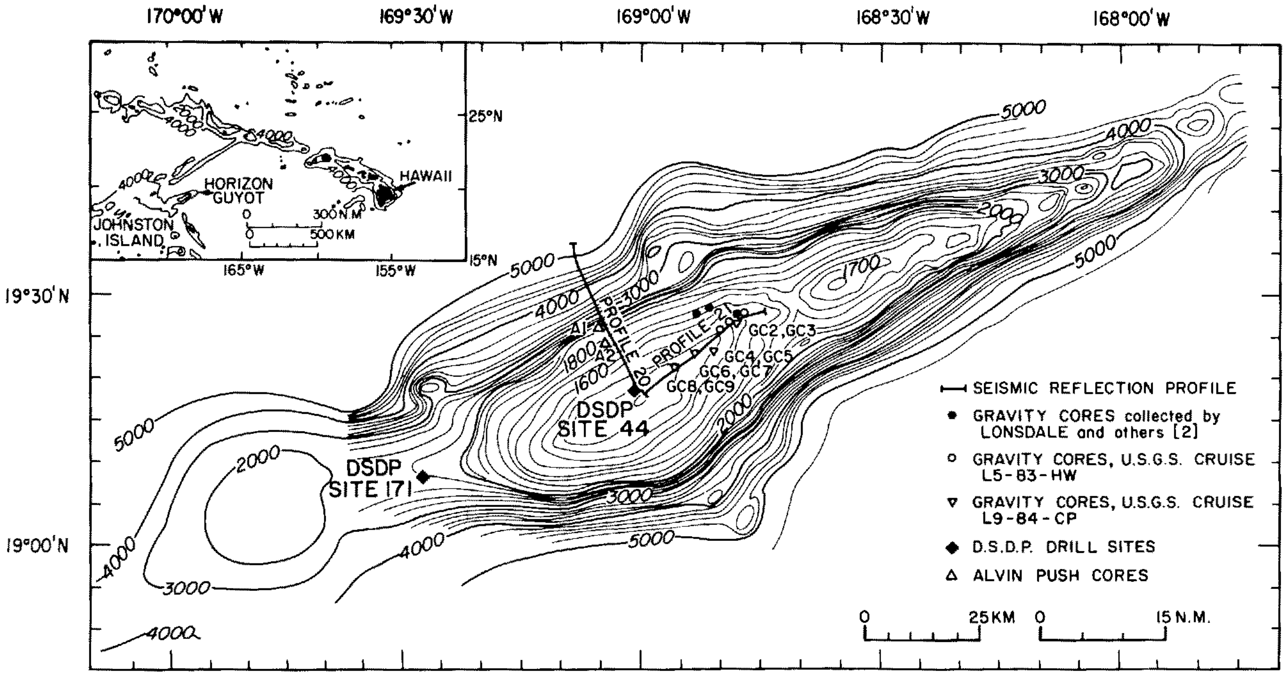


Figure 1. Sample locations, DSDP drill-sites, and the locations of seismic-reflection profiles on Horizon Guyot (modified from Lonsdale and others (1972)).

1985) using the research vessel *S.P. Lee*. For a list of all samples, sediment physical index properties, geotechnical testing, and geophysical and physical oceanographic data collected, refer to Hein and others (1985) and Schwab (1986). The geophysical data include 12 kHz, 3.5 kHz, and 80 in^3 airgun seismic-reflection profiles and bottom camera surveys (Fig. 1). Physical oceanographic data include CTD-0_2 probe profiles, and current-meter data as reported by Cacchione and others (1988).

Geologic Setting

The recovery of shallow water limestone, subaerially erupted basalt, and plant remains in the Upper Cretaceous sequence of Deep Sea Drilling Project (DSDP) Site 171 indicate that Horizon Guyot was subaerially exposed from at least early Cenomanian to late Turonian or early Coniacian time (Winterer and others 1973). Submergence of the guyot was well underway by Coniacian time and continued through the remainder of the Cretaceous and Tertiary.

Horizon Guyot presently is capped by an acoustically transparent blanket of Tertiary nannofossil-foraminiferal ooze and intercalated chert layers (Lonsdale and others 1972). The thickness of the blanket varies from 160 m on top of the summit platform to a thin veneer around the perimeter of the summit, to 287 m at DSDP site 171 (Lonsdale and others 1972, Winterer and others 1973). Sediment from the cap has spilled over the guyot's flanks, covering about 50 percent of the upper flanks; seismic-reflection profiles indicate that sediment and rock debris form talus deposits at the base of the northwest and southeast flanks (Hein and others 1985).

Lonsdale and others (1972) suggested that the 1.6° to 4.0° sea floor declivity around the perimeter of the summit platform (water depth = 1,570 to 2,000 m) was created by current-induced erosion of the pelagic sediment. This erosion exposed underlying Cretaceous volcanic terraces along the northwest and southeast summit rim and truncated the almost flat-lying intercalated chert layers. The orientation of asymmetric ripples, asymmetric sand waves, scour marks, lee deposits, and modified ripple patterns around exposed fragments of rock indicate a net upslope bedload transport.

Interpretation of Geophysical Data

The USGS high-resolution seismic-reflection data and bottom photographs show erosional processes acting on the sediment cap of Horizon Guyot (Hein and others 1985, Schwab 1986). A chert layer identified by Lonsdale and others (1972) crops out in the survey area shown in Figure 2 (identified as "B") and can

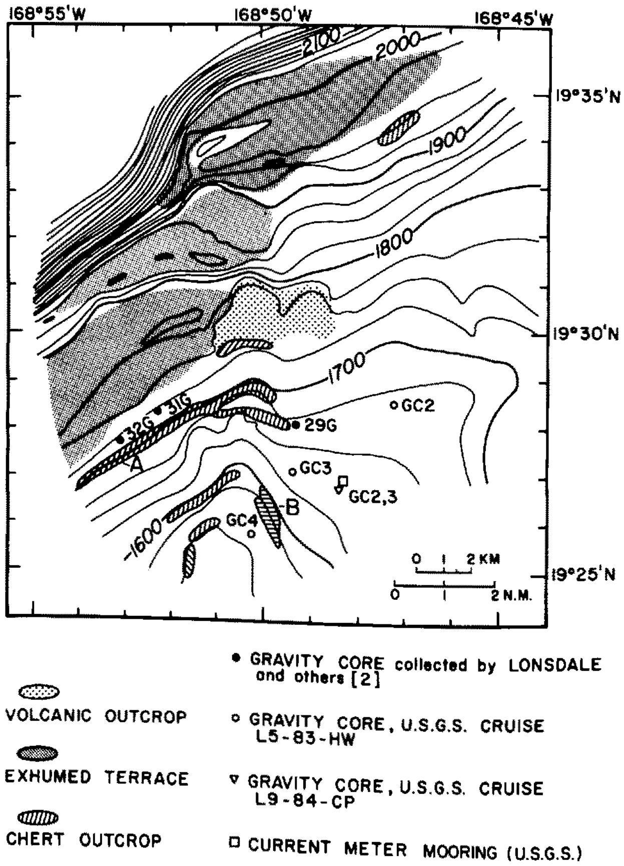


Figure 2. Sample locations, outcrop lithologies, and the location of the USGS current meter mooring (modified from Lonsdale and others (1972) with additional data from Cacchione and others (1988) and Hein and others (1985).

be recognized and followed upslope for 10 km under the pelagic sediment on profile 21 (Fig. 3). Chert layer B crops out again at a water depth of 1,513 m due to erosion of the overlying sediment. Interpretation of profile 21 suggests that erosion of the sediment cap extends upslope to a water depth of at least 1,472 m, where the same chert layer is exposed. Thus, erosion of the summit platform of Horizon Guyot appears to be more extensive than the 1,570- to 2,000-m-isobath limit previously recognized (Lonsdale and others 1972). Bottom photographs (Hein and others 1985, Lonsdale and others 1972) show that long-crested symmetrical ripples with wavelengths of 10 to 35 cm are present across the summit platform. In water depths greater than approximately 1,600 m, these ripples are well-formed and according to Lonsdale and others (1972) indicate contemporary bed-load transport. However, in water depths less than 1,600 m, ripples are severely degraded by biologic activity (previously reported as "unrippled sea floor" by Lonsdale and others (1972) which argues against the existence of a highly mobile bed layer. Thus, sediment transport and erosion may intermittently affect a large portion of the summit platform. However, these processes are apparently concentrated around its perimeter.

A group of large linear hummocks near the southeast margin of the sediment cap were previously interpreted to be erosional features (Lonsdale and others 1972). Profile 20 (Fig. 4) shows that similar hummocks on the northwest perimeter of the sediment cap are caused by sediment slumping. A recent investigation of these slump blocks by the principal author using the DSV *ALVIN* (Dive 1807) showed them to be discrete, having a relief of 6 to 10 m, with nodular chert beds outcropping along the headwall scarp of the individual rotated blocks. Here, mass movement has occurred on an average sea floor slope of 1.6° and extends from an exhumed volcanic terrace (water depth of 1,845 m) to a water depth of 1,458 m. This slope failure has affected the pelagic sediment to a maximum subbottom depth of approximately 40 m.

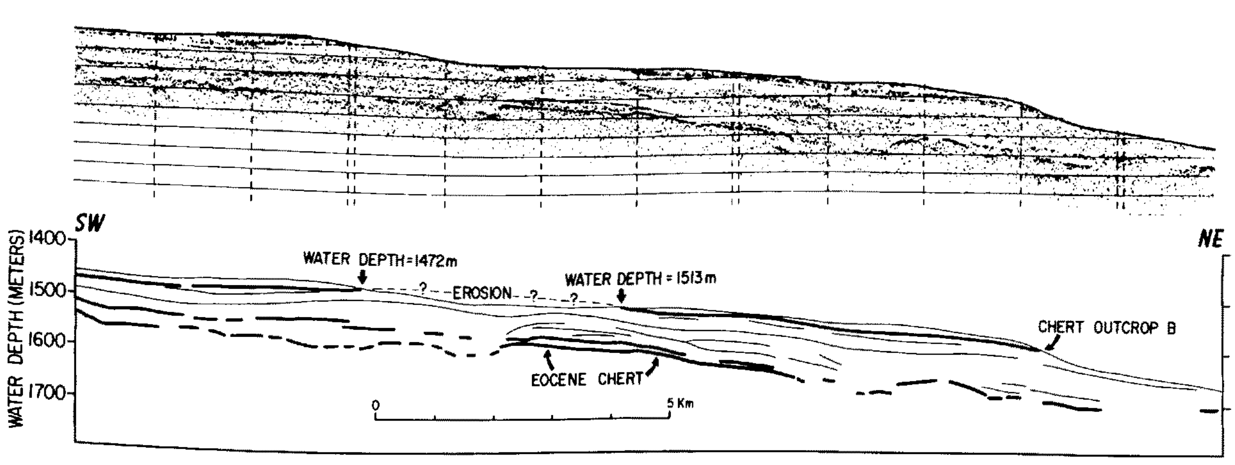
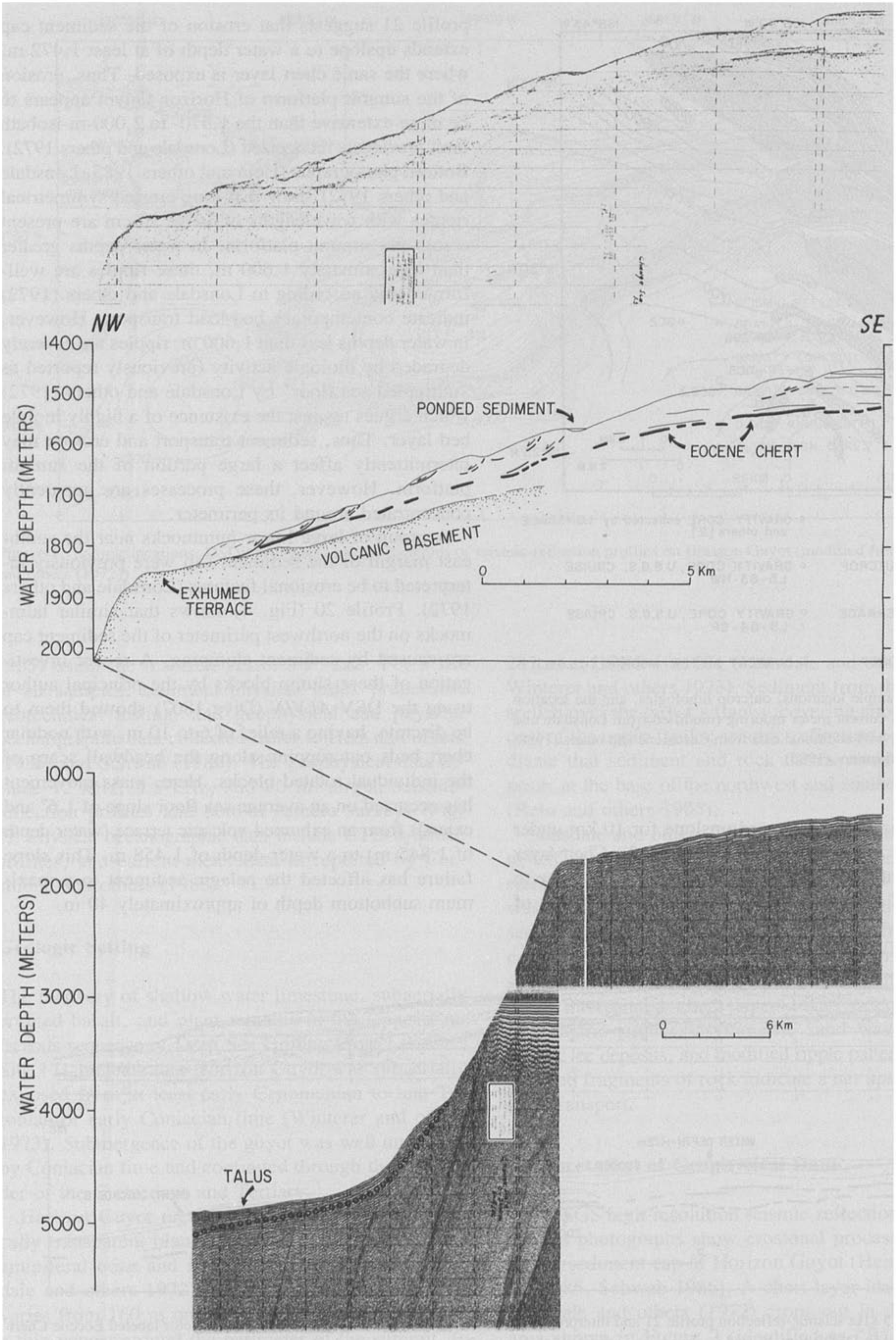


Figure 3. 3.5 kHz seismic-reflection profile 21 and interpretive sketch. For the location see Figure 1. The reflector labeled Eocene Chert was identified at DSDP Site 44 and is shown as outcrop A on Figure 2.


NW
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WATER DEPTH (METERS)
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PONDED SEDIMENT
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5 Km
WATER DEPTH (METERS)
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2000
3000
4000
5000
0
6 Km
TALUS

Analysis of Sediment Gravity Cores

Textural and micropaleontologic analyses of gravity cores collected on the sediment cap of Horizon Guyot support the interpretations based on seismic-reflection profiles and bottom photographs of erosion and sediment transport. Sediment drilled at Deep Sea Drilling Project (DSDP) Site 44 is predominantly nannofossil ooze with a foraminiferal-sand content averaging 3.5 percent Pimm (1971). Sediment gravity cores collected by Lonsdale and others (1972) (Fig. 2) contained sediment with a foraminiferal-sand content as high as 93%, composed of mixed Eocene and Quaternary foraminifers. Lonsdale and others (1972) suggested that this sand content, relatively high in comparison to sediment collected at DSDP Site 44, was produced by current winnowing. In their hypothesis, erosion of an initial ooze proceeded by transporting the fine nannofossil fraction out of the area in suspension while leaving a lag deposit of foraminiferal sand which became mixed (in age) during bed-load transport.

Textural and micropaleontologic analyses of sediment cores collected on Horizon Guyot by the U.S. Geological Survey are summarized on Figure 5. In comparison to sediment collected at DSDP Site 44, anomalously high sand contents, greater than 35 percent are found in the upper 215 cm of core GC2, the upper 55 cm in core GC5, and the entire lengths of cores GC6 and GC9. These gravity cores were qualitatively analyzed for planktonic foraminifers and nannoplankton to determine the ages of the sediment and detect reworking (Schwab 1986). For most samples, the planktonic foraminifers and nannofossil ages are in agreement. The fine-grained sediment (sand content less than 10 percent) encountered in the deeper section of core GC2 and the middle section of core GC5 is late Oligocene in age. Coarser-grained sandy sediment found in the upper sections of cores GC2 and GC5 and throughout cores GC6 and GC9 range in age from early Miocene to late Pliocene or early Pleistocene (Fig. 5). These sandy sections contain reworked Eocene foraminifers estimated to range from less than 1 percent to approximately 12 percent of the planktonic fauna and in the Pliocene to early Pleistocene age samples, trace amounts (less than 3 percent) of reworked Miocene foraminifers are found. Thus, in agreement with the hypothesis of Lonsdale and others (1972), the sandy sediment deposit composed of mixed age foraminifers is thought to be winnowed above a subbottom depth of 215 cm in core GC2. Similarly, winnowing is present to 55 cm in core GC5. Cores GC6 and GC9 show a more uniform grain-size distribution with increasing subbottom depth than in cores GC2 and GC5. The anomalously high sand content and mixed age of the sediment in these cores suggest winnowing throughout.

Active erosion of the sediment cap of Horizon Guyot limits the sediment accumulation. Therefore, the presence of Oligocene sediment at 70 cm below the sea floor (Fig. 5) is not surprising. The common occurrence of reworked Eocene foraminifers and the possible uncomformable contact between Oligocene and Pliocene sediment in cores GC2 and GC5 suggest that erosion and redistribution of sediment was common during Tertiary time (Schwab 1986). The anomalously young age (late Pliocene to early Pleistocene) and high sand content of sediment from the lower section of core GC5 (subsample from a subsurface depth of 180 cm) indicates either that this core was collected in slumped material or that the core barrel penetrated the sediment twice. If core GC5 represents a slump deposit, then mass movement may be more extensive on the sediment cap than just the area of slope instability identified on profile 20 (Fig. 4).

Geotechnical Analysis

A suite of geotechnical and index property tests was conducted on subsamples from USGS gravity cores (GC4, GC7, and GC8) to understand the causes of the slope failure and slumping on Horizon Guyot. Note that these cores are duplicates of cores GC5, GC6, and GC9 (Fig. 1). Although these samples were not collected in the area of slope instability, we assume that the sediment tested is similar to that which has slumped. Sediment samples A1 and A2 (subsurface depth = 0 to 15 cm), collected in the slump area (Fig. 1) using DSV *ALVIN* (Dive 1807), are late Pliocene to early Pleistocene in age, are composed of nannofossil-foraminiferal ooze, and are texturally similar to the early Miocene to late Pliocene-early Pleistocene sandy sediment of cores GC2, GC5, GC6, and GC9. Sample A1 is composed of 66 percent sand, 26 percent silt, and 8 percent clay; A2 has 88 percent sand, 9 percent silt, and 3 percent clay. The critical parameter derived in the geotechnical testing program was the undrained shear strength, that is, the strength that is mobilized in a short period of time with no pore water drainage or inflow. We used the normalized strength parameter (NSP) approach (Ladd and Foott

Figure 4. 80 cu. in. airgun seismic-reflection profile 20 with a segment of the 3.5 kHz profile collected over an area of slumping and interpretive sketch. For location see Figure 1.

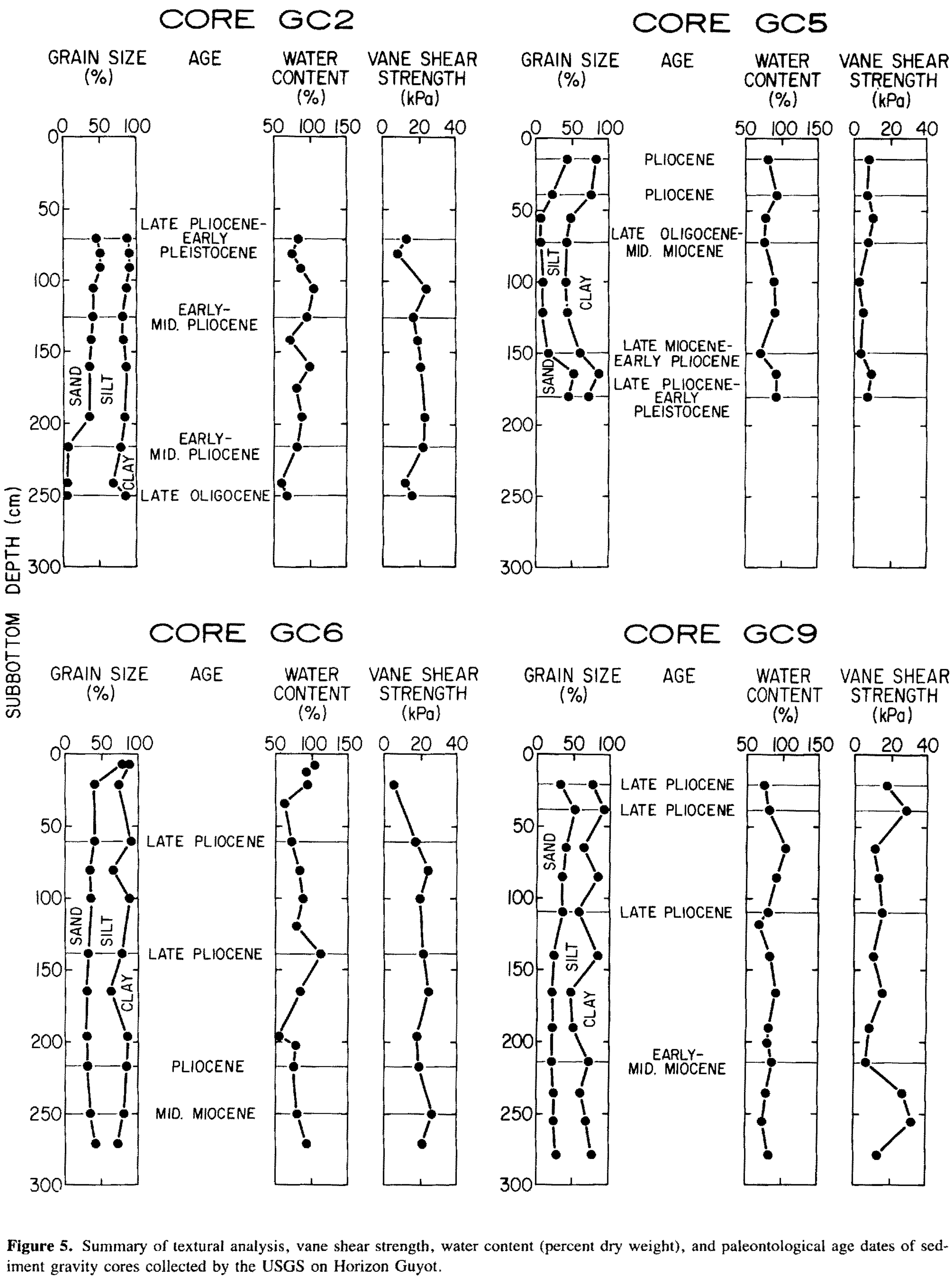

Figure 5. Summary of textural analysis, vane shear strength, water content (percent dry weight), and paleontological age dates of sediment gravity cores collected by the USGS on Horizon Guyot.

1974) to measure the undrained shear strength. The principal assumption of the NSP approach is that sediment behavior depends primarily on three factors: (1) the general sediment type (grain size, mineralogy, etc.); (2) the stress state (overburden and lateral stress); and (3) the overconsolidation ratio (greatest effective stress that the sediment has experienced divided by the present effective overburden stress). Relations between stress state, overconsolidation ratio (OCR), and undrained shear strength were established through seven static triaxial compression tests, four cyclic triaxial tests, and nine consolidation tests using the procedures outlined in Schwab (1986).

Consolidation Properties

The OCR is derived by dividing the maximum past effective stress (σ_{vm}') by the in-place overburden effective stress, (σ_v'). An OCR of 1.0 indicates normally consolidated sediment whereas sediment having an OCR greater than 1.0 is considered to be overconsolidated. Overconsolidation of sediment is caused by erosion or overburden removal. However, submarine sediment often displays pseudo- or apparent overconsolidation (Lee 1986); such sediment appears to have been preloaded, although no geologic evidence exists to suggest removal of overburden. Apparent overconsolidation is mainly displayed in the upper few meters of the sedimentary deposit and is expressed by relatively high strength and maximum past stress. Apparent overconsolidation may be caused by, among other reasons, disturbance of the sample due to the coring process, cementation, or reworking by bottom currents (Lee 1986).

Overconsolidation ratios of Horizon Guyot sediment range from 32 to 57 (Schwab 1986). These exceedingly high values of OCR are thought to result, at least in part, from apparent overconsolidation.

Strength Properties

The in-place static (s_{us}) and cyclic undrained shear strengths (s_{ur}) were estimated through triaxial testing and the NSP approach using the methodology of Lee and Edwards (1986). The sediment type and index characteristics must remain roughly constant with increasing subbottom depth, and the OCR at any depth must be predictable for the calculations derived from this methodology to accurately describe the characteristics of the sedimentary deposit. Even though the OCR distribution with depth is not well known, analysis of the consolidation test data, visual inspection of the cores, and nearby DSDP drilling results (Heezen and others 1971) suggest these two premises likely hold for the Horizon Guyot sediment cap (Schwab 1986). Therefore, we assume that the measured shear strength parameters and index properties are probably representative of deeper sediment. During the consolidation phase of the triaxial tests, isotropic consolidation stresses were elevated to levels approximately four times the maximum past stress. This high confining stress partly avoids the complications of sample disturbance and thereby allows a more accurate evaluation of in-place conditions (Ladd and Foott 1974).

Sediment slope failure occurs when the shear stress acting downslope exceeds the sediment shear strength. The three dominant mechanisms generating downslope shear stresses in the marine environment are gravity, storm waves, and earthquakes (Lee and Edwards 1986). The great water depth of Horizon Guyot precludes slope instability resulting from wave loading. Also, static loading (gravity) is unlikely to cause slope failure because of the relatively high sediment strength and the slight sea floor declivity. Therefore, in the simplified slope stability analysis used in this paper, the undrained shear strength of the sediment under earthquake loading, s_{ur}, is considered.

The parameter s_{ur} may be estimated at a particular subbottom depth, z, by the following equation, modified from Lee and Edwards (1986);

$$s_{ur} = \sigma_v' A_c A_r S[(\sigma_v' + \sigma_e')/\sigma_v']^m \qquad (1)$$

where σ_e' is the excess effective consolidation stress and is equal to σ_{vm}' minus σ_v'; S is the normally consolidated normalized static shear strength of the sediment (this factor is a constant for a given sediment and is equal to the measured s_{us} for a normally consolidated sediment divided by σ_v'); m is a normalized strength behavior parameter that is constant for similar sediment; A_c corrects isotropically consolidated triaxial test results to agree with the anisotropic stress state in the field; and A_r is a cyclic strength degradation factor used to account for strength loss from cyclic loading. The static shear strength, s_{us}, can be calculated from equation 1 by setting A_r equal to 1.

Values of s_{ur} were calculated from equation 1 using parameters obtained from physical index properties, static triaxial testing, and cyclic triaxial testing. The excess effective stress (σ_e') within the subbottom depths that were sampled was determined from consolidation tests. Variation of σ_e' with depth below the level of sampling is unknown but two bounding assumptions about the distribution can be made: (1) Overconsolidation effects are caused by erosion; that is, σ_e' is constant with increasing subbottom depth and equal to the average measured σ_e'; and (2) the sediment is normally consolidated below a "transition zone"; that is, $\sigma_e' = 0$ at depth. Assumption 2 implies that the observed overconsolidation within the tested samples is caused by apparent overconsolidation in the surficial sediment.

Cementation is probably not a cause of overconsolidation of Horizon Guyot sediment (Schwab 1986). In fact, it was difficult capping the core sections while at sea because the sediment had the tendency of flowing out of the core liner after the slightest disturbance. The high values of OCR obtained from consolidation testing are either a result of sediment erosion, in which case assumption 1 applies, or a result of an increase in sediment bulk density caused by bottom-current activity, where assumption 2 applies. In the later case, currents would rearrange sediment particles into a more close-packed configuration. As this higher-density sediment is buried below the level of current-generated movement, it begins to approach a state of normal consolidation. Insufficient evidence exists to select either assumption.

Slope Stability Analysis

Lee and Edwards (1986) present a simplified method for evaluating the relative stability of submarine slopes using:

$$k_c = (\rho'/\rho)UA_cA_rS[(\sigma_v' + \sigma_e')/\sigma_v']^m - (\rho'/\rho)\sin\alpha \quad (2)$$

where k_c is the pseudo-static earthquake acceleration (in g's) required to induce slope failure; ρ' is the buoyant sediment density; ρ is the sediment bulk density; U is the degree of consolidation (equal to 1 for slowly deposited sediment such as that on Horizon Guyot); and α is the average slope angle. The term k_c is a measure of relative stability given a uniform seismic environment. The lower the value of k_c, the less stable a given slope will be during an earthquake. Lee and Edwards (1986) determined characteristic values of k_c corresponding with the transition between observed failed and unfailed slopes. For the seismically active continental shelves and slopes of Alaska and California, the transition value of k_c was 0.14 g. A similar study of a failed slope off the less seismically active southwest coast of Oahu yielded a k_c transition value of 0.07 g (Winters and Lee 1982). Although the seismicity of Horizon Guyot was not determined as part of this study, it is probably less than that of California and Alaska and more like that of Oahu.

We use the following values to evaluate k_c for the Horizon Guyot sediment cap: $\rho = 14.7$ kN/m^3 (1.5 g/cc) and $\rho' = 4.9$ kN/m^3 (0.5 g/cc); $A_c = 0.80$ based on previous work (Lee and others 1981 and 1983, Mayne 1985); $A_r = 0.85$ on the basis of cyclic triaxial test results; $U = 1.0$ as discussed above; $S = 0.35$ on the basis of static triaxial test results; $\sigma_v' = \rho' \times 40$ m $= 196$ kPa, assuming a failure plane at a subbottom depth of 40 m, the greatest subbottom depth of slumping observed on seismic profile 20 (Fig. 4); $\sigma_e' = 399$ kPa, using assumption 1 (average for core GC8 from which A_r was derived), or $\sigma_e' = 0$ kPa, using assumption 2; $m = 0.8$ based on previous work (Ladd and others 1977, Lee and others 1981 and 1983, Mayne 1980, Winters and Lee 1982); and $\alpha = 0.6°$ to 4° (Figs. 1 and 4).

Four values of k_c were calculated: (1) $k_c = 0.184$ g (assumption 1, $\alpha = 1.6°$); (2) $k_c = 0.170$ g (assumption 1, $\alpha = 4°$); (3) $k_c = 0.070$ g (assumption 2, $\alpha = 1.6°$); and (4) $k_c = 0.056$ g (assumption 2, $\alpha = 4°$). The values of k_c obtained using assumption 2 are comparable to those for the failed slope off Oahu, the others obtained using assumption 1 are like those off Alaska and California. Therefore, if we disregard the overconsolidation of the near-surface sediment and assume that it is lost with burial (assumption 2), the sediment cap of Horizon Guyot is likely to be unstable during infrequent earthquakes. However, if assumption 1 is valid, the slopes are likely to remain stable. The level of shaking needed to cause slope failure under assumption 1 would be greater than that causing failure off California or Alaska. Perhaps localized slope failure could occur under the conditions of assumption 1 if bottom-current activity had eroded and oversteepened a local slope before an earthquake event.

The sediment cap of Horizon Guyot is almost certainly stable during static loading. To represent static loading, k_c is taken as 0 and A_r as 1. Thus, equation 2 reduces to:

$$\sin\alpha \text{ (at failure)} = A_cUS[(\sigma_v' + \sigma_e')/\sigma_v']^m \quad (3)$$

For the values given above, α (at failure) equals 42.1° using assumption 1 and 16.3° using assumption 2. In comparison, the actual slopes are 1.6° to 4.0°. The factor of safety (resisting force/driving force) against static gravitational failure is between 4 and 10 for assumption 2 and higher for assumption 1 conditions.

Summary and Conclusions

Analysis of high-resolution seismic-reflection profiles and textural and micropaleontologic analyses of sediment gravity cores show that erosion and redistribution of sediment are important processes affecting the sediment cap of Horizon Guyot. Internal tidal current velocities as high as 43 cm/sec are thought to be the cause of this erosion (Cacchione and others 1988). Although these processes may periodically affect the entire summit of Horizon Guyot, they are apparently concentrated around its perimeter (Lonsdale and others 1972).

Bottom photographic and seismic-reflection surveys and bottom samples on the northwest and southeast flanks of Horizon Guyot indicate that sediment from the cap has spilled over the guyot's flanks onto the abyssal sea floor (Schwab and Bailey 1985). Was this sediment transported from the cap to the guyot's flanks and adjacent sea floor by bottom currents or did sediment transport result from mass movement? Slope stability analysis suggests that if the measured overconsolidation of sediment is produced by erosion or overburden removal and is constant with increasing subbottom depth, the sediment cap is most likely stable during earthquake loading, unless bottom-current activity erodes and oversteepens a local slope before the earthquake event. However, if the overconsolidation is produced by current reworking of surficial sediment while the sediment at depth is actually normally consolidated, the sediment cap of Horizon Guyot may be unstable during earthquake loading. Such a scenario is a possible cause of the observed sediment slumping on the northwest perimeter of Horizon Guyot's sediment cap, and offers a mass-movement mechanism for the removal of sediment from the rim of the guyot summit to the abyssal sea floor.

Acknowledgments

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