Modern and ancient hiatuses in the pelagic caps of Pacific guyots and seamounts and internal tides

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ABSTRACT

Incidences of nondeposition or erosion at the modern seabed and hiatuses within the pelagic caps of guyots and seamounts are evaluated along with paleotemperature and physiographic information to speculate on the character of late Cenozoic internal tidal waves in the upper Pacific Ocean. Drill-core and seismic reflection data are used to classify sediment at the drill sites as having been accumulating or eroding or not being deposited in the recent geological past. When those classified sites are compared against predictions of a numerical model of the modern internal tidal wave field (Simmons, 2008), the sites accumulating particles over the past few million years are found to be away from beams of the modeled internal tide, while those that have not been accumulating are in internal tide beams. Given the correspondence to the modern internal wave field, we examine whether internal tides can explain ancient hiatuses at the drill sites. For example, late Cenozoic pelagic caps on guyots among the Marshall Islands contain two hiatuses of broadly similar age, but the dates of the first pelagic sediments deposited following each hiatus do not correlate between guyots, suggesting that they originate not from ocean chemical changes, but from physical processes, such as erosion by internal tidal waves. We investigate how changing conditions such as ocean temperature and basin physiography may have affected internal tides through the Cenozoic. Allowing for subsequent rotation or uplift by plate tectonics, ancient submarine ridges among the Solomon, Bonin, and Mariana island chains may have been responsible for some sediment hiatuses at these distant guyot sites.

INTRODUCTION

Within the subject of paleoceanography, much effort has been expended investigating the ocean structure of large-scale currents from paleontological, isotopic, and geochemical evidence. Much less is known about water movements of shorter periods, such as those associated with eddies, barotropic tides, internal waves, and surface waves, although these movements may have been significantly different in the geological past, for example, because wind and temperature regimes and physiography of the oceans and landmasses were different. Furthermore, the maximum current is commonly more important locally than the mean current for resuspension and transport of particles and thus for influencing the sedimentary record. The amplitudes of current oscillations should therefore be of interest to paleoceanography, although they are not well known for the geological past.

Hiatuses in pelagic sediments of the deep abyssal ocean floor have been interpreted from sediment cores (Barron and Keller, 1982; Keller and Barron, 1983; Moore et al., 1978). Hiatuses are formed by either physical removal of material by currents or dissolution of soluble components of the sediment. They can be difficult to recognize, being complicated by incomplete recovery of stratigraphy by coring and requiring missing biostratigraphic zones to be identified (Moore et al., 1978). For pragmatic reasons we use low accumulation rates (condensed sections) as signs of breaks in sedimentation, which are loosely referred to as hiatuses, although they may not strictly speaking be hiatuses in the sense originally intended. Individual hiatuses have been attributed to changes in deep-ocean circulation originating from tectonic changes of gateways and changes in production of deep water at high latitudes (Barron and Keller, 1982; Keller and Barron, 1983). The presence of microfossils out of stratigraphic sequence is evidence that hiatuses can be at least partly caused by physical movements (Thiede, 1981). Barron and Keller (1982) noted that Miocene hiatuses correlate with sea-level lowering, greater 18O in benthic foraminifera, and cool faunal assemblages, consistent with intensified deep-water production and circulation. However, Moore (2013) argued that the general circulation was likely too sluggish to explain reworked radiolaria around the Eocene-Oligocene boundary in deep-water samples, suggesting that higher frequency motions such as from internal waves may have been involved.

The sediments deposited in the summits of guyots and seamounts potentially record changing physical conditions within the upper ocean. Watkins et al. (1995) noticed that pelagic cap thicknesses on guyots decline going north from the equator, diminishing to zero at ~25°N, a trend also found in seismic data (van Waasbergen and Winterer, 1993). Watkins et al. (1995) noticed that pelagic caps on guyots among the Marshall Islands contain two hiatuses of broadly similar age, but the dates of the first pelagic sediments deposited following each hiatus do not correlate between guyots, suggesting that they originate not from ocean chemical changes, but from physical processes, such as erosion by internal tidal waves. We investigate how changing conditions such as ocean temperature and basin physiography may have affected internal tides through the Cenozoic. Allowing for subsequent rotation or uplift by plate tectonics, ancient submarine ridges among the Solomon, Bonin, and Mariana island chains may have been responsible for some sediment hiatuses at these distant guyot sites.
that pelagic cap development proceeds from an early barren stage to first accumulation under the influence of currents, allowing sediments to accumulate only in the center of the platform, followed by progressive expansion of that deposit to the platform edges under more quiescent conditions.

Increasing sophistication of physical oceanographic models, combined with more accurate estimates of basin shape (Smith and Sandwell, 1997) and ocean density structure, have allowed increasingly more accurate estimates to be made of physical conditions at the modern seabed. In addition, the GeoMapApp software tool (www.geomapapp.org) has provided easy access to a revised consistent stratigraphy of the drill cores recovered by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) (Fig. 1). This combination now allows an exploration of the spatial correspondence between internal tidal wave propagation across the Pacific predicted by numerical modeling (Simmons, 2008) (Fig. 2) with modern seabed hiatuses. Although the model and the geologic data represent markedly different time scales, we suggest reasons why the internal wave field may not have changed greatly over the past few million years. Furthermore, assessing the presence or absence of hiatuses using seismic and drill-core data together effectively provides estimates over large spatial and temporal scales, which can be preferable to overcome local variability likely to affect individual shallow cores. Given the modern correspondence, we speculate on earlier conditions in the late Cenozoic upper ocean. Although it is not possible to infer the ancient pattern of the internal wave field from the limited sedimentary information, we highlight some tectonic movements that might have affected the wave field and might explain some hiatuses.

This issue is complex, so we devote the following section to describing the nature of internal waves (how they are generated and propagate) and other flow phenomena over seamounts and guyots that may also affect sediment deposits. We then introduce the data sets and provide an interpretation of them, bearing in mind the physical oceanographic results. In the discussion, the origins of the earlier hiatuses are considered speculatively in terms of evidence for changing water temperatures and changing basin physiography, which affected the conversion of barotropic tides into internal waves.

**BACKGROUND**

**Internal Tidal Waves**

Observations and modeling have improved understanding of internal waves over the last decade. When tidal currents cross submarine ridges, they excite oscillations (internal tides, i.e., internal waves at the barotropic tide frequency) in the density gradient of the upper ocean (pycnocline). The resulting energy transfer from the $M_2$ barotropic tide (the principal lunar semidiurnal tide) into internal waves is significant in the Pacific Ocean, where tidal currents cross major ridges, in particular the Hawaiian Ridge, Tuamoto Archipelago (Tahiti), Aleutians, and Izu-Bonin Arc (Egbert and Ray, 2003).

Based on numerical modeling and observations, internal tides propagate away from major topographic features such as the Hawaiian Ridge, forming beams in plan view (Holloway and Merrifield, 2003; Merrifield et al., 2001). The waves have been revealed from satellite altimetry to radiate thousands of kilometers from the Hawaiian Ridge and the Aleutians (Ray and Cartwright, 2001), but even these long distances may be underestimates because the altimetric method only detects waves that are in phase with the barotropic tide. More direct measurements from moorings and ships show that internal tides can continue farther with remarkably little loss of power (Alford, 2003; Alford et al., 2007, Zhao et al., 2010), reaching 2400 km in one locality (Alford and Zhao, 2007). The altimeter data and modeling suggest that the Hawaiian Ridge
data are shown in Figure 4, although information was considered insufficient for classification. Sediment erosion thresholds (circles) in Figure 2, including the French Frigate Shoals and Kaena Ridge in the Hawaiian Islands. Other important sites are ridges underlying the Kuril, Aleutian, Bonin, and Mariana Islands and a gap between Bougainville and New Ireland, where the barotropic tide exchanges between the Solomon Sea and the Pacific Ocean.

**Sediment Erosion Thresholds**

To evaluate the importance of the current magnitudes, it is useful to be aware of resuspension thresholds for pelagic sediments. Unless winnowed by currents, carbonate pelagic sediments typically found on guyot summits contain nannofossils and foraminifera. Their grain sizes range from clay to sand, usually dominated by clay and silt sizes by mass (e.g., Leg 55 Scientific Staff,
1980). Aside from organic components usually removed by oxidation, the primary input of particles falling from surface waters is expected to have this wide particle size range. Because particles have low densities due to calcite or aragonite compositions and porous structures, they are susceptible to erosion by currents. Critical erosion thresholds measured in laboratory experiments range from 7 to 10 cm s⁻¹ for freshly deposited calcareous material to 15–20 cm s⁻¹ after being deposited a few hours in a flow 5–6 cm deep (Southard et al., 1971) (the experimental 10 and 20 cm s⁻¹ is equivalent to 18 and 36 cm s⁻¹ at 1 m above bottom when corrected for the boundary layer effect). Phyodetritus has been found to have smaller erosion thresholds by approximately half or less (Beaulieu, 2003; Mitchell and Huthnance, 2013; Thomsen and Gust, 2000) compared with the Southard et al. (1971) values. Before degradation of organic and phytodetritus and associated inorganic particles may be susceptible to resuspension by currents as small as 5 cm s⁻¹ or less, allowing any embedded solid tests (microfossil skeletons) to be advected away.

Local Flow Patterns over Seamounts and Guyots

Turnewitsch et al. (2013) summarized some of the various flow patterns found over seamounts. Rotational current patterns have been predicted and observed over seamounts and guyots (Lavelle and Mohn, 2010), which are relevant to the patterns of sediment deposition in the seismic data that we describe herein. A steady current in a density-stratified ocean is predicted to produce a rotating body of water above seamount summits (Chapman and Haidwogel, 1992; Verron and Le Provost, 1985; Zhang and Boyer, 1991) (the so-called “Taylor cap” after Taylor, 1923). Simulations show semi-diurnal tidal currents amplified where they interact with seamounts (Beckmann and Haidwogel, 1997). Other simulations show how seamounts can produce lee-side eddies when impacted by steady currents (Zhang and Boyer, 1991).

Above Fieberling Tablemount in the subtropical northeast Pacific (where the summit shoals above 500 m depth), weak radial currents but significant azimuthal mean currents increasing to 10 cm s⁻¹ at the summit rim have been observed (Brink, 1995; Kunze and Tooie, 1997). A similar rotational current pattern with ~10 cm s⁻¹ speeds has been found above Cobb Seamount farther north in the northeast Pacific (summit reaching to only 24 m below sea level) (Codiga and Eriksen, 1997; Freeland, 1994), with semi-diurnal currents reaching 20–40 cm s⁻¹ (Eriksen, 1991). Current fields with a rotational component have been observed on other seamounts (Mohn et al., 2009; Mourino et al., 2001) and inferred in sediment geochemical data (Turnewitsch et al., 2004). A drifter experiment around the Emperor Seamounts discovered eddies attached on one side of the seamounts, with movements of 20–40 cm s⁻¹ at 120 m depth (Bograd et al., 1997). These various motions typically involve intensified flow near the summit margins of the seamounts or guyots with speeds that are comparable with the suspension thresholds of pelagic sediments and thus can be expected to lead to thin deposits or bare rock toward the summit margins.

Oceanographic and Geological Observations on Horizon Tablemount

Studies of Horizon Tablemount are useful for illustrating the sedimentary effects of internal tidal waves. The guyot is an east-northeast–to west-southwest–oriented ridge that was sampled by the DSDP. Figure 3 shows an interpretation of a seismic record through Site 44 (Shipboard Scientific Party, 1971), suggesting erosional truncation of strata at the seabed. This pattern of erosion around the sides of the sedimentary cap is as would be expected from the kinds of rotational flows described here. Recovered shallow cores contain mostly fine to medium foraminiferal sand of Eocene and Quaternary particle (Lonsdale et al., 1972; Schwab et al., 1988), produced by removal of finer particles by current winnowing. Sediment bedload movements are suggested by the presence of current ripples and dunes in bottom photographs and high-resolution sonar images (Lonsdale et al., 1972). Schwab et al. (1988) and Kayen et al. (1989) assessed slope stability using geotechnical parameters measured from cores to infer that shallow slumping (a further cause of erosion) is possible on the pelagic cap during shaking by rare earthquakes, particularly if internal wave activity has overconsolidated surface sediments while leaving underlying sediments normally consolidated. Slumping could also be promoted by the undermining of the edges of the sediment cap by currents.

Current and temperature data obtained from a 9 month mooring deployment 213 m over the summit recorded internal tides (Cacchione et al., 1988; Noble et al., 1988). Those data revealed 15–18 cm s⁻¹ peak semi-diurnal currents and 15–20 cm s⁻¹ peak low-frequency flows occurring during spring, which Cacchione et al. (1988) showed together could exceed the threshold of motion of the bed sediments. From the phase of the currents compared with the surface (barotropic) tide, the currents were shown to be locally generated internal tidal wave currents.

Figure 3. Interpretation of seismic reflection record over Horizon Tablemount through Deep Sea Drilling Project Site 44 (adapted from Shipboard Scientific Party, 1971). Numbers above profile are seabed gradients (m/m) of the sides of the pelagic cap. Value c next to site number is the local semi-diurnal wave characteristic gradient computed for the site depth (see text).
DATA COMPILATION

Seismic reflection and scientific drilling data were compiled for guyot or seamount pelagic caps in the central and western Pacific (Fig. 1). Scientists from Columbia University have revised the absolute age data of DSDP and ODP site stratigraphy available within the GeoMapApp software (www.geomapapp.org; W.B.F. Ryan, 2009, personal commun.; Gradstein and Ogg, 2004). Those ages are plotted along with depth below seabed in Figure 4. However, many of the sites were drilled close to the summit margins, where the onsets of pelagic sedimentation likely occurred later than the onsets in the pelagic cap centers. Furthermore, core recovery was limited in the early stages of DSDP, so biostratigraphic resolution is likely to be nonuniform. Figure 4 is used only to gauge general trends.

Pearson (1995) developed a high-resolution biostratigraphy for ODP Sites 871, 872, and 873 on three guyots in the Marshall Islands; his dates are shown versus depth below seabed as small solid circles in Figure 5 (lower panel), along with his interpreted hiatus depths and other data for comparison.

The benthic δ¹⁸O record contains both a salinity and temperature signal, so estimates of deep ocean temperatures are instead based on Mg/Ca ratios of benthic foraminifera. Gray squares in Figures 5 and 6 (top graphs) represent estimates of global temperatures derived from deep-sea sites (Lear et al., 2000). Discrepancies between sea surface paleotemperature proxies have been attributed in part to recrystallization of calcite foraminiferal tests, making δ¹⁸O-based temperature estimates unreliable (Pearson et al., 2001). Pearson et al. (2001, 2007) and Stewart et al. (2004) argued that pelagic foraminifera recovered from impermeable shales in Tanzania are sufficiently well preserved that original compositions can be extracted from them. Those data are displayed with various symbols in Figures 5 and 6.

Seismic and sediment profiler records were extracted from the ODP reports. A selection was chosen where sites were drilled away from summit margins and where high-resolution stratigraphy data were available. Figure 7 shows three seismic profiles crossing Allison guyot (ODP Site 865) and Figure 8 shows profiles crossing Wodejebato, Lo-En, and Limalok guyots.

Figure 9 shows temperature-depth profiles (upper graphs) from CTD (conductivity-temperature-depth instrument) deployments over Allison, Horizon, Limalok, Lo-En, and Wodegebato guyots, as well as on the equator (accessed...
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Figure 5. Lower three graphs show the sediment age variation with depth below seabed for three sites on guyot pelagic caps among the Marshall Islands. Points are individual age constraints from the biostratigraphy of Pearson (1995); gray bars represent his interpretations of the sediment depths of hiatuses (points within bars may represent persistently slow sedimentation). Circles mark the oldest biostratigraphic age of sediment immediately overlying each hiatus. Solid black bar marks the seabed at each site. Above that bar, labels include drill site number, latitude (°N), water depth (m), and guyot or seamount name. Vertical bars with NH and PH labels are the Neogene hiatuses and one Paleogene hiatus identified by Keller and Barron (1983) converted to the stratigraphic time scale adopted in the GeoMapApp database (GeoMapApp.org) (bars located at approximate centers of each missing interval). To the right of these graphs are shown percent sand (solid circles) and percent of biogenic particles classed as foraminifers (x symbols) from the smear slide analyses for Sites 871 and 872 (gray bars mark the hiatuses of Pearson, 1995). Also shown are estimated Cenozoic carbonate compensation depth (CCD) (Pälike et al., 2012), stack of benthic foraminifera δ18O obtained from Deep Sea Drilling Project and Ocean Drilling Program cores (Zachos et al., 2008), and ocean paleotemperatures from Figure 6. Note that the δ18O data are inverted so that isotopic shifts associated with sea-level lowering are down the page.

These data appear generally to record an initial period of very slow deposition or nondeposition, followed by a period of intermittent pelagic accumulation. The onset of the pelagic stage was interpreted from these data, referring to the drilling reports. The onset dates plotted in the middle graph in Figure 6 (x symbols) show no obvious correlation with other parameters, such as phases of changing sea level or paleotemperature.

In the data of Pearson (1995) shown in Figure 5, the onsets of pelagic accumulation following hiatuses (circled) have different dates in the three sites.

through the GeoMapApp.org data portal). Seawater potential densities were computed from these values using the procedure in Joint Panel on Oceanographic Tables and Standards (1991) and are shown in the lower graphs in Figure 9. From the mean density and density gradient with depth of each profile at the depth of the drill sites, the characteristic gradient (c) of internal semidiurnal waves was computed using Equation 1. Those values given in Figures 3, 7, and 8 are almost uniform between sites due to the uniformity of ocean temperature in the tropics and similar depths of the guyot summits. In most of the cases, c is smaller than the gradients of the pelagic cap sides shown in the figures, so internal waves, if present, are likely to break and intensify (Cacchione and Drake, 1986; Cacchione et al., 2002) as waves pass from the slopes to the summit. For comparison, Cacchione et al. (1988) estimated a modestly different c = 0.085 for Horizon Tablemount.

### OBSERVATIONS

**Depth-Age Graphs**

The low-latitude Sites 871–873, 202, 200 and 171 show recent steady accumulation, but low sedimentation rates in earlier periods (Fig. 4). Some other sites show low sedimentation rates at the seabed but earlier periods of more steady accumulation, such as Sites 865, 44, and 866; of these, Site 866 is close to a summit margin and 171 is within a topographic saddle, so they are not considered further.

Of the Emperor Seamount Chain sites, many are also close to summit margins (1206, 308, 1205, 432). Of the remainder, Site 430 shows no significant recent accumulation, whereas Site 433 shows a 10 m.y. period of recent accumulation following a long period of slow accumulation. The pelagic interval in the Detroit Rise sites is beneath a sediment drift, the lower boundary of which is marked by dashed lines in Figure 4. Prior to drift sedimentation, pelagic sediments accumulated following a barren stage.
Three periods occur where hiatuses apparently overlapped in time between the three sites (at 8, 14, and 24 Ma), although we cannot be sure that intervening deposits have not been removed by the erosion, so we concentrate more on the accumulation onset dates following each hiatus. As noted by Pearson (1995), the onset dates do not correspond between the sites. The hiatus termination at 5 Ma at Site 873 lags that at Site 872 by ~2 m.y., whereas while there is a termination age at Site 871 similar to that at 872, the Site 871 record has two further small hiatuses until steady accumulation resumed at 2 Ma. The next-oldest hiatuses terminated ca. 13 Ma at Site 873, 15 Ma at Site 872, and 13 Ma at Site 871. Hiatuses at 872 and 871 also occurred ca. 20 Ma, but the weaker biostratigraphic age constraints at Site 871 may have made identification of hiatuses difficult in this part of the section.

Between these hiatuses, the sediments are winnowed foraminiferal oozes, with foraminifers accounting for as much as 90% and some microfossils out of stratigraphic sequence (Watkins et al., 1995), in contrast to the Pliocene and Quaternary sediments above the last hiatus, which are nannofossil oozes. A tendency for foraminifers to be more resistant to erosion has been confirmed in laboratory experiments (Black et al., 2003). The lower right graphs in Figure 5 suggest that the transition from coarse particles toward ~60% sand or foraminifers at the modern seabed occurred gradually at Site 872 since the last hiatus. Because of incomplete data in the Site 871 record, the transition there cannot be interpreted, but it nevertheless also shows a change to finer sediment toward the seabed. Although smear slide data are often considered only rough indicators of sediment composition because of effects of dissolution, test fragmentation, and interpreter bias, these trends seem clear and the analyses were carried out during a single drilling expedition.
Figure 6 (solid circles in middle graph) shows that the pelagic onset depths compensated for subsidence. To compute these depths, we found subsidence relationships (Detrick and Crough, 1978) unreliable, so only sites where an age of drowning of the platform is available were used, allowing the depth of initial sedimentation to be estimated by interpolation. Three of the sites shown are from Pearson (1995). Reef limestone growth at Site 433 on Suiko Guyot (McKenzie et al., 1980) terminated in the early Eocene on the basis of nannofossils (Koizumi et al., 1980) (biostratigraphic zones NP 7–10) and is assigned a date of 50 Ma in the GeoMapApp database (GeoMapApp.org). According to Winterer et al. (1995), the limestone platform of Allison guyot emerged above sea level and subsequently drowned after the Albian, but before the mid-Turonian. Within the GeoMapApp database, an age of 100 Ma has been assigned. We have used that date and 93 Ma (the Turonian-Cenomanian boundary) to represent a possible range of drowning times. With these data, the reconstructed depths of onset of pelagic sedimentation are 753–816 m (Allison) and 1430 m (Suiko). The average onset depth of all five sites is 928 m. The remaining sites had ambiguous evidence of shallow-water deposits and therefore drowning ages (two sites are therefore shown merely with modern depths).

Seismic and Profiler Records

In Figure 7A (Allison guyot), seismic reflections that are roughly horizontal within the upper part of the section appear truncated where they reach the seabed, and the seabed reflection has a slightly stepped structure, as would be expected for erosion of strata of varied geotechnical properties and hence...
resistance to erosion. In Figures 7B and 7C, the reflections within the pelagic cap are somewhat convex upward but still terminate at the seabed, and the seabed reflection in Figure 7C is also slightly stepped. Winterer and Sager (1995) and Winterer et al. (1995) interpreted these sequences as pelagic sediments overlying an atoll or karstic limestone basement. A small collapse structure typical of karst topography can be observed on the left of Figure 7C. The very low sedimentation rates for the past 20 m.y. in Figure 4 for Site 865 correspond with apparent seabed erosional evidence in these seismic data.

In Figure 8A (Wodejebato guyot), the seabed forms a low-relief, smooth surface. Internal reflections are difficult to interpret from this profile, but a thin layer is consistent with only ~50 m of pelagic sediment recovered at Site 873 (Fig. 5).

In Figure 8B (Lo-En guyot), the seabed to a few tens of milliseconds comprises laminated sediment with reflections subparallel to the seabed. Below that, a series of reflections can be observed dipping down from right to left in the profile. The boundary between these two sets of reflections is not visible but is suspected to be an unconformity. The depth of the youngest hiatus in the analysis of Pearson (1995) is marked by the topmost red bar, which almost corresponds to the proposed unconformity. Similar features are observed in the seismic data in Figure 8C, although the irregular reflection observed just above the top red bar in Figure 8B is not visible.

In Figure 8D (Limalok guyot), near-surface reflections are also subparallel with the seabed. Below the near-surface reflections, the section is more transparent (lacking reflections) down to a prominent reflection ~200 ms below the seabed. Although discordant reflections cannot be interpreted here, the base of the near-surface reflections approximately corresponds with the first hiatus of Pearson (1995). A mound-like feature is observed within the otherwise transparent sediments south of Site 871.

### INTERPRETATIONS

#### Spatial Patterns of Erosion or Deposition and Currents above the Seamounts and Guyots

The profile shapes of the pelagic caps and near-surface stratigraphy partly reflect how accumulation rates of the clay and silt size components of primary input have been modulated by the currents (spatial variations in the vertical spacing of reflectors indicate how time-averaged accumulation rates have varied spatially). McCave and Swift (1976) showed how an earlier empirically determined relation for fine particle accumulation rates (Odd and Owen, 1972) was compatible with a model in which accumulation was dictated by capture of particles within a viscous boundary layer. The data predict the instantaneous accumulation rate \( R \):

\[
R = C w_s \left( \frac{l - \tau_s}{\tau} \right),
\]

where \( C \) is the mass concentration in the bottom waters, \( w_s \) is the particle settling velocity for a particular grain size component, \( \tau \) is the bed shear stress due to the current and \( \tau_s \) is a limiting stress above which no deposition occurs (increasing with grain size and \( w_s \)). Although current intermittency and various effects modulating resistance to resuspension are also important (McCave, 1984), the shapes of the near-surface reflection spacings should broadly follow how the currents have modulated the bed shear stress \( \tau \) and thus \( R \) in a time-averaged sense. Grain size and other data are generally lacking so quantitative interpretation of those spacings is not possible. However, given that \( R \) is proportional to \( (\tau - \tau_s) \) in Equation 3 and \( \tau_s \) is proportional to the current squared \( (\tau = u^2) \), the patterns of time-averaged deposition rates should indicate where \( u \) has been small in a time-averaged sense, provided that \( C \) and the other factors in Equation 3 have not varied greatly over these structures. Thus, the reflections in Figures 8B and 8D paralleling the seabed suggest these sites have recently experienced conditions that were uniform as well as quiescent. The dipping reflections in the lower part of the pelagic cap in Figure 8B imply deposition under a current with a strong unidirectional component producing asymmetric bed shear stress. In contrast, the package of reflections in the uppermost 30–40 ms of reflective stratigraphy in Figure 8B thins modestly to the southeast, suggesting that the unidirectional component has reversed direction. Erosion occurs when stresses rise above a threshold (McCave, 1984), so the truncation of reflections around the margins of Allison guyot and Horizon Tablemount (Figs. 3 and 7) imply greater current stresses around the sides of the caps than over their summits, consistent with strong rotational components to the current fields there.

A gravity effect on cyclically agitated bedload particles can lead to a small down-gradient flux, which, combined with considerations of continuity, produces a diffusion of the seabed topography if it acts alone (Mitchell and Huthnance, 2008). Because the bed gradients of the guyot caps are small (Figs. 7 and 8) and the primary input is mostly finer than sand grade, this mechanism is unlikely to dominate, though the convex-upward shapes of the sediment caps are similar to the parabolas expected of steady-state solutions to the diffusion equation for the geometry and boundary conditions (Mitchell, 1995). Gravity effects on bedload may be important around summit margins where gradients are steeper and where the sediment has been strongly winnowed, leaving mainly sand.

#### Relationships to the Modern Internal Wave Field

Ten sites (larger symbols in Fig. 2) were deemed sufficiently well characterized to allow them to be classified as having been accumulating sediment particles or being eroded and/or not undergoing deposition in the past few million years. The pelagic cap around Site 44 has already been shown to be the latter (Cacchione et al., 1988; Lonsdale et al., 1972). Also eroding or not undergoing deposition are Allison guyot, indicated by its seabed unconformity (Fig. 7), and Ojin Guyot, where drilling to 14 m below seafloor (bsf) recovered...
only pebbly mudstone including Holocene to Eocene shallow-water fossils (Shipboard Scientific Party, 1980a). The seismic data collected over Oin Guyot were of poor quality but appear to rule out a thick, draping pelagic cap. The first three cores recovered at Site 865 on Allison guyot contained winnowed foraminiferal sand (Shipboard Scientific Party, 1993a), suggesting a recently energetic environment. A pelagic section to 3.2 mbsf was sampled at Site 878 on Mit Guyot and includes nannofossils (Shipboard Scientific Party, 1993c).

However, the limited thickness of this unit and the lack of pelagic sediment visible in the seismic and 3.5 kHz profiler data collected over the guyot summit led us to classify this site as generally not undergoing deposition. Site 866 was drilled 1.5 km from the edge of Resolution Guyot (Shipboard Scientific Party, 1993b). Pelagic sediment thicknesses of only 0.9 m at Site 866A but 23.5 m at Site 866B2 were found, extending in age to Maastrichtian. The 3.5 kHz profiler data show a transparent unit ~40 ms thick (~30 m) at Site 866, thinning into the platform. The drilling report mentions only a thin pelagic cover. We classify this as weakly sedimented and report it separately from the other two classifications.

The accumulating sites include Wodegebato, Lo-En, and Limalok guyots on the basis of seabed-following seismic reflections in the latter two sites and the stratigraphy in Figure 5 being relatively continuous toward the seabed. Suiko Guyot was also classified as accumulating sediment, on the basis of its depth-age graph (Fig. 4) and of >50 m of Holocene to Miocene pelagic sediments recovered (Shipboard Scientific Party, 1980b). The seismic data published in the Site 433 drilling report suggest that pelagic sediments overlie a lagoonal complex, possibly within a graben structure, but have been accumulating asymetrically, suggesting possible influence of a steady current on the seamount. This site is less convincing than the others classified as accumulating. Site 200 was drilled somewhat near the summit margin of Ita Mai Tai Guyot, but nevertheless the presence of thick sediments in seismic data across the summit and the lack of truncation of strata at the seabed show that it has been accumulating sediment (Shipboard Scientific Party, 1973), and this has continued recently (Fig. 4). According to the site report, the sediments here include winnowed foraminiferal ooze, so this site is not as quiescent as some of those in the Marshall Islands.

Although the time scales of deposition here are long compared with those of many physical oceanographic processes, conditions have probably not changed greatly in the past few million years (for reasons discussed herein). Modeling by Egbert et al. (2004), for example, shows little change in the Pacific barotropic tide between the present day and the Last Glacial Maximum when sea level was much lower. The classified sites are plotted in Figure 2 over the modern internal wave field of Simmons (2008), with unfilled circles for accumulating sites and filled circles for eroding and/or nondepositional sites. Despite the irregularities in the computed wave field, the accumulating guyots in the Marshall Islands (Ita Mai Tai, Wodegebato, Lo-En, and Limalok) are all away from the beams of internal wave energy emanating from the Mariana Islands and Solomon Sea–Pacific gateway. Of the eroding and/or nondepositional sites, Allison arguably is on crossing long-range beams originating from the Bonin Islands and Hawaiian Islands. Horizon does not appear to be on a beam of propagated wave energy, but is known to experience locally generated waves (Cacchione et al., 1988; Noble et al., 1988). Resolution is within waves originating from the Bonin Islands but was marginally classified as accumulating. Suiko and Oin Guyots less obviously relate to internal wave beams.

The internal wave model results were sampled at the site locations. All eroding and/or nondepositional sites were found to be separated from all depositing sites by a kinetic energy flux magnitude of 104 W m–1. Although that separation may not be so significant given irregularities in the model and some site classification issues, their mean values are markedly different, 544 and 1924 W m–1 for depositing and eroding sites, respectively. The value for the Resolution Guyot site is anomalous, 2513 W m–1. Nevertheless, aside from that site, the pattern of erosion and deposition on the sediment caps appears compatible with the modern internal tidal field despite the different time scales represented by the data and model.

**DISCUSSION**

**Origins of the Older Hiatuses**

Prior to carrying out this analysis, the incidence of erosion and/or nondeposition and accumulation was anticipated not to correspond exactly to the internal wave field because of the other types of currents that can occur in the mid-ocean. However, for the pelagic caps studied here, internal waves seem to be important for elevating bed stress above the erosion threshold. In light of this, the origins of hiatuses lower in the stratigraphy are considered. The youngest sediment immediately overlying each hiatus in Figure 6 varies in age between the sites, a strong clue that the hiatuses had a physical, rather than chemical origin, which would likely be more synchronous. We evaluate some circumstantial evidence for chemical origins.

Hiatuses appear throughout the late Cenozoic stratigraphy of the abysal Pacific Ocean sediments (Barron and Keller, 1982; Keller and Barron, 1983; Moore et al., 1978). The central ages of the hiatuses identified by Keller and Barron (1983) were updated to the time scale used in GeoMapApp.org (Gradstein and Ogg, 2004) and are shown by vertical bars in the lower graph of Figure 5 (e.g., NH 7). No particular correspondence is observed with the guyot hiatuses. Ujiié (1984) attributed one abyssal hiatus to mesoscale eddies, which typically occur with ocean boundary currents; however, many of the sites examined here are away from boundary currents. The northward drift of the Pacific tectonic plate has been ~0.25° of latitude m y–1 for the past 40 m y. (Mitchell, 1998), so the Marshall Islands guyots currently at 5.6°–11.9° N were at the equator at 48–22 Ma. Measurements with current meters have recorded flows of 10–20 cm s–1 at 300 m depth at 4°N (Hayes et al., 1983), 40 cm s–1 at ~1000 m depth at 1°N, 150°W (Taft et al., 1974), and a standard deviation of zonal current of 10 cm s–1 at 900 m depth at the equator at 159°W (Firing, 1987).
These currents are sufficient to resuspend silt grain sizes and, if present prior to 20 Ma, equatorial currents may help to explain the delayed start of pelagic accumulation on the Marshall Island guyot summits (Sites 871–873) compared with Allison and Horizon, for example (Fig. 4). The sequence of onsets is not simply as expected from equatorial provenance, because the northernmost of the Marshall Island sites, Wodejebato, started accumulating later (Fig. 6) rather than earlier, as might be expected given its latitude. Nevertheless, the onsets of Ita Mai Tai, Lo-En, and Limalok are in the correct order for this interpretation.

The occurrences of pelagic cap hiatuses are compared with the carbonate compensation depth (CCD) in Figure 5 because, although the CCD was persistently deeper than the pelagic caps, the lysocline (dissolution gradient) extends perhaps ~2000 m shallower than the CCD (Berger et al., 1976) and waters at 1000 m depth are undersaturated with respect to carbonate (Peterson, 1966). Although the onset dates of hiatuses are uncertain due to erosion (so we cannot rule out chemical erosion caused by the shoaling of the CCD playing a role at 10 Ma), the terminations of the hiatuses are not associated with CCD deepening. Furthermore, the earlier two major hiatus termination phases do not correspond with CCD deepening. The lack of correlation is consistent with the view that carbonate loss above the lysocline arises mainly from oxidation of organic matter (Peterson and Prell, 1985), which depends on the organic to inorganic carbon ratio of the sediment input and may not be related to the CCD.

Further work on carbonate saturation state based on Li/Ca and Mg/Ca ratios of benthic foraminifera corroborate these observations of CCD shifts. The foraminiferal Li/Ca ratio has been shown to vary with carbonate saturation state (carbonate ion concentration relative to concentration expected at saturation) in modern environments (Lear et al., 2010; Lear and Rosenthal, 2006) and a model-based calculation can be carried out with the aid of Mg/Ca ratios to estimate past carbonate saturation states. Li/Ca ratios from the equatorial Pacific show no obvious shift at the time of the terminations of the younger (10–8 Ma) hiatuses in Figure 5 (Lear and Rosenthal, 2006). Saturation states computed from data over the period corresponding with the earlier hiatus show a general peak in saturation rather than a trough ca. 15 Ma, corresponding to the middle hiatus phase (Lear et al., 2010).

Although chemical effects may have played some roles in developing these hiatuses, physical effects seem more likely to have dominated. The declining thickness of sediment caps north of the equator noted by Watkins et al. (1995) can be explained by the migration of sites across successive internal tidal wave beams as they migrated northward (Fig. 2). We attempt to identify possible changes affecting the Cenozoic ocean that could explain the varying pattern of accumulation, in particular on the Marshall Islands guyots.

**Ocean Tides and Sea Level**

To address whether internal tides were different in the past, the forcing by barotropic tides also needs to be considered, though they are not well known for earlier in the Cenozoic. The power acquired by the modern tide from the Moon and Sun is mainly dissipated by friction in the shallow waters of continental shelves. Modeling by Egbert et al. (2004) suggests that the deep-water Atlantic tidal range was in places twice as large during the Last Glacial Maximum as during the present day because dissipation on the shelves was smaller when coastlines had extended seaward with a lower sea level. This variable dissipation effect was more limited in the Pacific where continental shelves are narrower. A lack of amplification of the tide by sea-level lowering has probably persisted for much of the Cenozoic because subduction zones (regions that are tectonically mobile and therefore unlikely to develop wide shelves through coastal erosion) have persistently ringed the basin. Prior to the Pleistocene, sea-level variations were also smaller (from δ18O in Fig. 5), implying less varied shelf dissipation effects. Furthermore, there is no obvious correlation between sea-level changes and the hiatus terminations in Figure 5. For example, if the terminations ca. 15–13 Ma at the three ODP sites were associated with sea-level rise and a more attenuated tidal range, they should be accompanied by a decrease in δ18O, not the increase observed.

Deep-water tides in the earlier Cenozoic are more difficult to determine. Plate tectonic reconstructions show that the seaway between the American plates remained small (Meschede and Frisch, 1998), whereas others (Briden et al., 1981; Hilde et al., 1977) show that a 3000-km-wide seaway between Australia and Indonesia progressively closed from 60 Ma to the present day. Tides in the Pacific may have therefore been influenced by the Indian Ocean tide, but overall it seems unlikely that there were larger amplitude or more variable tides in the past.

**Changes in Ocean Temperature Structure**

Estimates of tropical paleotemperatures of the ocean surface and bed provide bounds on likely changes in the Pacific pycnocline. For the abyssal ocean, the Mg/Ca-based data in Figure 6 suggest a generally declining trend of $>$10 °C over the past 50 m.y. with stages of stasis. The surface ocean temperature data (Figs. 5 and 6, upper graphs) have been more controversial. Zachos et al. (2002) suggested that the Eocene record for Tanzania may have been affected by a warm western boundary current, and noted potential effects of its continental shelf location on salinity and δ18O. However, Pearson et al. (2002) argued that a salinity effect is likely to be only 2 °C and that the site was on a narrow shelf and steep margin. The paleotemperature data suggest that surface waters declined by only a few degrees since 50 Ma, while benthic temperatures declined by >10 °C. Using a constant salinity of 35 ‰, seawater potential densities ($\rho_p$) were calculated for temperatures of 32 °C and 27 °C (50 and 0 Ma, respectively) and deep-water temperatures of 13 °C and 0 °C using the equations of Joint Panel on Oceanographic Tables and Standards (1991); the resulting values (1021.0, 1022.7, 1026.4, and 1028.1 kg m$^{-3}$, respectively) suggest that the density difference due to temperature has remained a constant 5.4 kg m$^{-3}$ to the present day.
The thermocline (vertical temperature gradient) of the upper ocean results mainly from advection of surface heat by turbulence created by surface wind stress (Apel, 1987). Changing wind stress through the Pleistocene implied by varying halite and dust in ice cores (Mayewski et al., 1994) suggests that there may have been varied upper ocean mixing. However, there is evidence from organic proxies of sea surface temperature that the interzonal air temperature gradients driving trade winds were less than half in the early Eocene compared to today and strengthened progressively through the middle Eocene (Bijl et al., 2009). Wind-driven mixing may therefore have been less efficient in the early Eocene and the pycnocline may have been less steep at ~1000 m proximal to the early tops of the guyots (Fig. 6), though we cannot know by how much. This also implies a smaller N (Brunt-Vaisala frequency) and therefore larger wave characteristic gradient c (Equation 1). Whereas the temperature difference between abyss and surface ocean implies relatively little change in the maximum density difference and therefore effect on internal waves, wind stress changes may have made it somewhat less likely that breaking internal waves occurred on the guyot summits in the Eocene.

Plate Tectonic Motions and the Changing Internal Wave Field

The sills currently creating internal wave beams (Fig. 2) are around the Pacific basin (largely island arcs) and some within the basin (ocean island hotspot chains such as that forming the Hawaiian Ridge). While it is difficult to reconstruct accurately the paleogeography of these areas, the depths of these sills probably changed with tectonics of the subduction zones and with lithospheric thermal subsidence in the case of ocean island hotspot chains. Other wave-generating sills may have existed previously but were lost as seaways closed by tectonic uplift. Here we speculatively link tectonic changes with depositional changes within the guyot caps. The purpose is not to reconstruct the wave field, but to highlight plausible origins of changes in the sediment record.

Solomon Sea–Pacific Site

At present, the seaway between the Solomon Sea and Pacific Ocean extends down to ~1000 m north-northwest of Bougainville Island (Fig. 1), creating a wide band of internal wave energy extending northeast (Fig. 2), originating from the barotropic tide traveling from the Solomon Sea into the Pacific Ocean. Although the dating of vertical tectonic movements is too coarse and paleogeography too uncertain to explain individual hiatuses in Figure 5, known solid-earth movements within the Solomon Islands area are broadly coincident with some of the sedimentary changes in the Marshall Island guyots. Sites 871–873 have no island or shallow bank topography blocking potential internal waves arriving from the Solomon Islands, and local physiography (Ryan et al., 2009) suggests they are open to waves from that direction.

The Solomon Islands are above a subduction zone that switched sense from previously subducting the Pacific plate beneath the islands (then attached to Indo-Australia), to subducting the Indo-Australian plate beneath the islands (now attached to the Pacific plate). This change occurred prior to 6 Ma (Schuth et al., 2009), or ca. 5 Ma (Mann and Taira, 2004). Based on the known geology of the islands and plate tectonic reconstructions of Mann and Taira (2004), we suggest the following possible paleogenerators of internal wave energy. Figure 10 shows how the relationship between the drill sites and the Solomon Islands changed since 8 Ma, based on the reconstructions.

First, an internal-wave generation site may have existed in the vicinity of Choiseul Island (C in Fig. 10), where Pleistocene limestone is now found to 335 m above sea level (asl) (Coleman, 1962). The New Georgia Island Group (NG, Fig. 10) has been uplifted rapidly during the late Quaternary, locally as much as 75 mm yr⁻¹, because of subduction of the Woodlark Basin spreading center and associated seamounts (Crook and Taylor, 1994; Mann et al., 1998) and may not have existed to block propagation of the barotropic tide into the Pacific much earlier. Before the 335 m of Pleistocene uplift, the eastern third of Choiseul Island would probably have been below sea level, with it and the adjacent seaway extending to Santa Isabel (SI, Fig. 10), forming a sill at ~300 m depth. This feature was roughly perpendicular to Sites 872 and 873.

Second, Malaita Island (M, Fig. 10) is an uplifted anticlinorium (Petterson et al., 1999) or accretionary prism (Mann and Taira, 2004). A transition between open ocean pelagic carbonate rocks and higher energy terrigenous clastic rocks occurred at 5.8 Ma (Musgrave, 1990). Guadalcanal Island (G, Fig. 10) has significant relief (2400 m asl) and is unlikely to have been below sea...
level during the late Cenozoic, but late Cenozoic marine sedimentary rocks (Thompson and Hackman, 1969) nevertheless suggest that some uplift occurred. Thus, the seaway currently between Guadalcanal and Makira (MA, Fig. 10) marked by the lowermost dotted circle in Figure 10 would have been wider, with the eastern shelf of Guadalcanal deeper, forming a ridge possibly capable of generating internal waves. It is interesting that the 5.8 Ma date for the uplift of Malaita Island is similar to the hiatus termination dates of Sites 872 and 873.

Third, plate tectonic reconstructions show that Vanuatu Island (V, Fig. 10) and its associated banks have rotated clockwise and prior to ca. 10–8 Ma they were roughly colinear with the Solomon Islands (Mann and Taira, 2004) (Fig. 10). ODP Sites 871–873 were ~500 km east of their present positions (relative to the Solomon Islands) at 10 Ma; therefore, these banks were roughly perpendicular to Site 871, possibly explaining the hiatuses prior to 15–13 Ma.

**Mariana and Bonin Ridges**

The Mariana Islands are on a ridge that originates beams of internal wave energy currently extending southeast, just missing Ita Mai Tai and the other Marshall Islands guyots (Fig. 2). Two main conversion sites occur at 14°N and 16°N, where submarine banks or ridges are roughly parallel to the arc at these latitudes. In plate tectonic reconstructions (McCabe, 1984; Uyeda and Muyahiro, 1974), the Mariana island arc has become progressively more convex eastward and both it and the Bonin arc have rotated clockwise. If there were no change in incidences or depths of sills, this could have redirected internal wave energy clockwise. Guam and Saipan islands are in the southern Marianas. Paleomagnetic measurements on igneous rocks on Guam (Larson et al., 1975) suggest that 55° average rotation has occurred since the early Miocene. Similar results were obtained by Haston and Fuller (1991), who also reported clockwise rotations of Saipan, although of smaller magnitudes (middle Miocene 28° and Eocene 43°). Clockwise rotations of 30°–90° or more have been documented in Eocene rocks of the Bonin Islands (Keating et al., 1983; Kodama, 1981; Kodama et al., 1983). The consistency of these rotations led Haston and Fuller (1991) to suggest that they occurred by rotation of the entire Philippine plate rather than from local movements; their reconstructions show the ridges 30° and 70° counterclockwise of their present orientations at 10 and 30 Ma, respectively. If there were no change in sill depths and other factors causing internal wave generation, the internal wave beams from the Bonin Islands were directed away from Allison guyot at some point prior to 10 Ma and have since rotated toward it, helping to explain the declining accumulation rates followed by erosion (Fig. 4). Similarly, rotation of the Mariana Islands wave beams so that they intersected the Marshall Islands guyots at some stage since 10 Ma may help to explain the hiatuses in Figure 5.

Complicating this interpretation, however, reef limestones of Miocene age on Guam and of Oligocene–Miocene age on Saipan (Haston and Fuller, 1991) are evidence that significant uplift has occurred locally and the sill configura-

tions are unlikely to have been fixed. Geology of the Bonin Islands summarized by Haston and Fuller (1991) also includes subaqueous-erupted pillow lavas and hyaloclastites as well as pelagic sedimentary rocks, implying uplift.

**Aleutian and Kuril Islands**

The depth-age graph for DSDP Site 433 (Suiko Guyot) shows that pelagic sediment began accumulating only at 10 Ma, while Site 430 (Ojin Guyot) has remained barren. Attributing these changes to tectonic movements in the Kuril Islands and Aleutian Arc is difficult given the lack of information on those islands, but nevertheless large rotations about vertical axes have been reported from paleomagnetic studies (Peckersky et al., 1997), including a 76° post-Eocene rotation in the westernmost Aleutians (Bazhenov et al., 1992).

Detroit Rise (Fig. 1) started accumulating pelagic sediments ca. 60 Ma (Fig. 4). Paleomagnetic data on 81–75 Ma Late Cretaceous igneous basement rocks reveal a paleolatitude at that time of 34.4° (Doubrovine and Tarduno, 2004); the seamount was at a subtropical location when the pelagic cap began accumulating. The Pacific Ocean was then much larger, with Detroit more remote from subduction zones (Scotese et al., 1988) and hence possible arc sources of internal waves.

**Hawaiian Ridge**

Subsidence of ocean island chains is more predictable than that of arc island chains, so changes in internal tide generation should also be more predictable. According to K-Ar dates compiled by Ciauge and Dalrymple (1989), volcano ages at the two internal wave generation sites highlighted in Figure 2 are 13–10 Ma. The French Frigate Shoals and Kaena Ridge–Kuau Channel, known to generate internal waves here (Merrifield and Holloway, 2001), are marked with asterisks in the cross sections (lower right inset, Fig. 1). Prior to 13 Ma, the French Frigate Shoals and other banks east of there would not have existed, a date that is later than when deposition slowed at Site 171 but coincides roughly with the last pelagic deposition on Site 44 (Fig. 4).

After vertical motions associated with lithospheric loading by new islands have occurred, subsidence tends to follow the thermal subsidence of the underlying lithosphere after its reheating during the impact of the mantle plume (Crough, 1983; Detrick and Crough, 1978). Profiles C and D in Figure 2 (lower right inset) are 1000–2000 from Kilauea and include 22–12 Ma volcanoes (Clague and Dalrymple, 1989). Besides a bank on the far eastern side of C, they show relatively little evidence of shallow sills between edifices. Using the Detrick and Crough (1978) relationship, the amount of subsidence expected over 10 m.y. is a modest ~200 m. Therefore, the western Hawaiian Ridge was unlikely to have been a generator of significant internal waves. On Allison guyot, periods of nondeposition or erosion started just prior to 20 Ma (Fig. 4), so we suspect other sources of internal waves or other currents affected it.
SUMMARY

In the subject of paleoceanography, large-scale motions of water in the oceans have been worked out from paleontological, chemical, and isotopic changes in pelagic sediments. However, physical movements of bottom waters occur with many higher frequency components, and these physical movements are commonly important for modulating particle accumulation or erosion and thus the sedimentary record. In this study we examined data on the pelagic caps of seamounts and guyots, which are in shallow water so that chemical dissolution of carbonate is likely to be muted and physical effects on deposition are more likely to dominate. Internal waves provide a significant oscillation in the upper ocean in these areas. Such waves are generated where the barotropic tide passes over shallow ridges, producing oscillations in the pycnocline that travel away from the ridges in beams that are predictable for the modern ocean.

Incidents of nondeposition and/or erosion and accumulation on guyot summits over the past few million years characterized from scientific drilling and seismic reflection data are, respectively, on and off the modern beams of internal waves predicted using a global model (Simmons, 2008). Away from boundary currents and sources of strong eddy motions, many of the hiatuses within the pelagic caps of guyots and seamounts were possibly also generated by internal wave motions. The differing termination dates of hiatuses at the different sites suggest that they did not have a chemical origin, but rather a physical origin. Their most likely explanation, it seems to us, is plate tectonics. Rotation of the Bonin and Mariana Islands arcs recorded in paleomagnetic data has likely changed the orientations of beams from their ridges, although this requires a reconstruction of sill depths to evaluate more fully. The Solomon Islands has provided sources of internal waves to the Marshall Islands guyots that can possibly explain hiatuses found there; uplift of several islands documented in the literature combined with plate reconstructions (Mann and Taia, 2004) suggest that shallow sills previously were orthogonal to Sites 871–873.

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