GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 8, PAGES 1101-1104, JULY 1990

THE DARWIN RISE: A CRETACEOUS SUPERSWELL?

M.K. McNutt, E.L. Winterer, W.W. Sager, J.H. Natland, and G. Ito

Abstract. The Japanese Guyots, Wake Guyots, and Mid-Pacific Mountains are part of a broad area of Cretaceous volcanism in the western Pacific termed the "Darwin Rise." Based on Seabeam bathymetric data we classify these drowned volcanic islands as: type "A," those that advanced to the atoll stage before final submergence; type "B," those that drowned at the barrier reef stage; and type "V," those with little or no reef material on their volcanic summits. Widespread evidence for karst topography extending to depths of 200 m on the summits of A and B guyots sheds new light on events leading to the synchronous extinction of reefs on the Darwin Rise in the mid-Cretaceous. We propose that after the formation of the reefs on the A and B guyots, the entire region was elevated at approximately the Aptian-Albian boundary (113 Ma) to form a superswell similar to that existing now in French Polynesia. The type V guyots formed on this anomalously shallow lithosphere. The demise of the reefs was the direct result of the rise of this superswell, although climate factors may have prevented reef recolonization following its later subsidence.

Introduction

The western Pacific contains numerous guyots whose origins and geologic histories are unclear. Most seem to have formed during the Cretaceous on lithosphere that was too shallow at the time of volcanism given its age and have summit depths shallower than expected for the elapsed time since they drowned [*Menard,* 1964]. It has been proposed that these volcanoes formed during widespread volcanic events that marked the Aptian and later Cretaceous stages [*Schlanger et al.,* 1981] associated with anomalously shallow seafloor (the "Darwin Rise" [*Menard,* 1964]). A more recent and uniformitarian view is that the Cretaceous guyots formed in a setting similar to present-day French Polynesia [*Menard,* 1984; *McNutt and Fischer,* 1987]. *McNutt and Fischer* [1987] term this region of elevated seafloor in the South Pacific the "Superswell" and suggest a link to the Darwin Rise based on the similar magnitude of their depth anomalies at the time of volcanism [*Menard,* 1964]; their common high vulnerability to volcanism along short, frequently overprinting, radiogenically enriched hot-spot chains [*Heezen et al.,* 1973; *Duncan and McDougall,* 1976; *Hart,* 1984; *Smith et al.,* 1989]; and absolute plate-motion models which trace the source of the midplate Cretaceous volcanism to the French Polynesian hot spots [*Gordon and Henderson,* 1985].

In 1988 we collected marine geophysical data on cruise *Roundabout Leg 10* of the *R/V Thomas Washington* in the Japanese, Wake, and Mid-Pacific seamount chains (Figure 1) which comprise the northern part of the Darwin Rise. Here we address three issues with the data from this expedition:

1) Does the paleodepth/age curve for the Darwin Rise support the hypothesis that it formed in a Cretaceous setting very similar to that of the present-day Superswell? If so,
2) Does the superswell model account for the sea-level history of the carbonate reefs of the northern Darwin Rise, particularly the deep karsting we observed on the reef surfaces and their eventual drowning?
3) What is the long-term fate of the Superswell as inferred from the present-day morphology of the Darwin Rise?

Paper number 90GL00746
0094-8276/90/90GL-00746$03.00

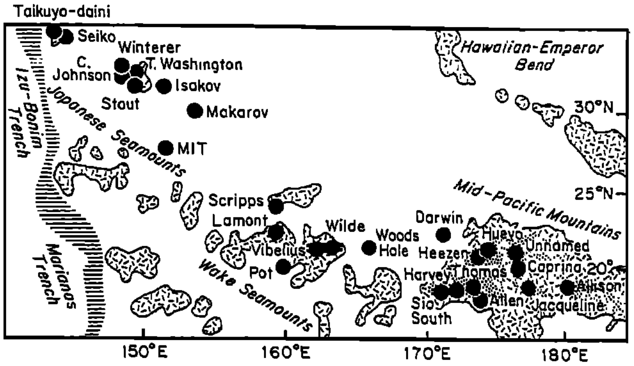

Fig. 1. Location of guyots of the northern Darwin Rise in the Western Pacific used in this study.

The Data

Table 1 summarizes information on guyots used in this study. The morphologic and sediment-thickness data for the first 22 guyots were collected during *Roundabout Leg 10*; the data for the other four guyots of the Mid-Pacific Mountains were taken from *Kroenke et al.* [1985] and *Nemoto and Kroenke* [1985]. For the Japanese and Wakes, present age of the plate was taken from *Nakanishi et al.* [1989]. For the Mid-Pacs, where Mesozoic series lineations have been obliterated by volcanism on the MidPacific plateau, we assign generous bounds on lithospheric age as bracketed by identified magnetic lineations on its perimeter [*Winterer and Metzler,* 1984].

Lithospheric depth is measured at the base of each guyot and isostatically corrected for the thin pelagic sediments using watergun profiles. Correction for any flexural moats is unnecessary, because gravity and seismic data reveal that they have been filled with acoustically opaque material to the regional depth of the surrounding seafloor. For the MidPacs, the depth is taken at the edge of the plateau upon which the guyots are superimposed. The summit depth is the last, highest sea-level stand recorded on each guyot. Taikuyo-daini and Seiko lie on the flexural arch of the Japan Trench. Their summit depths and lithospheric depths have been increased by 300 m to remove this effect as calculated from unpublished multi-channel seismic profiles from Lamont-Doherty crossing the arch just north and just south of these two guyots.

Based on summit morphology, each guyot is classified as type "A", for atoll (rim enclosing a shallow depression); type "B", for barrier reef (rim surrounding central volcanic pinnacle); or type "V", for volcanic (gently convex-upward summit with no acoustic penetration). A velocity of 2600 m/s was assumed in converting airgun profiles to sediment thickness. In no place did we fail to observe basement beneath the reefs. All of the B and several of the A guyots show evidence of limestone dissolution on their summits. On B guyots, the floor of the lagoon lies at least 180 m below the reef rim, compared to values of 20 to 40 m for modern-day atolls, suggesting that sediments have been dissolved or eroded from the lagoon. The only sediment detected on B guyots by the the profiling system consists of isolated pockets in topographic lows. Clear evidence for sink holes and dolines was observed on MIT (Figure 2), Vibelius, Huevo, and Allison (the latter even has a low-stand terrace 200 m below the reef rim). Given that no Seabeam data exist for Sio South, Harvey, Thomas, and Allen and that summit surveys for most

Table 1. Darwin Rise Guyots

Seamount Group	Guyot Name	Lith Age (Ma)	Lith Depth (m)	Summit Depth (m)	Type	Sed Thick (m)	Karst Depth (m)	Smt Age (Ma)	Mag Polarity *	Paleomag Age (Ma)
Japanese	Taikuyo-daini	142	5800	1750	B	50	180		N	(?)
	Seiko	142	5800	1720	B	100	180	102±3	N	85-120
	Winterer	146	5800	1450	V	0			N	
	C Johnson	150	5900	1750	B	130	180		(?)M	>118
	Stout	152	5800	1580	V	0			N	85-120
	T Washington	152	5900	1500	V	0			N	85-120
	Isakov	150	6000	1460	V	0			N	85-120
	Makarov	157	6000	1390	V	0		94±1	N	85-120
	MIT	160	6100	1390	A	650	200		R	>118
Wakes	Scripps	160-169	5800	1300	V	0		98±3	N	85-120
	Lamont	160-169	5600	1330	V	0		87±4	N	
	Pot	160-169	5700	1390	V	0			N	
	Vibelius	160-169	5800	2000	A	650			N	
	Wilde	160-169	5600	1410	V	0		86±2	N	85-120
	Woods Hole	160-169	5600	1130	V	0			N	85-120
Mid Pacs	Darwin	155	5850	1350	A	500	none		R	>118
	Heezen	135-156	5850	1300	A	850			N	(?)
	Huevo	135-156	5850	1320	A	1000	100			
	Unnamed	135-156	5850	1650	A	450				
	Caprina	135-156	5850	1650	A	780				
	Jacqueline	135-156	5850	1650	A	650			(?)M	
	Allison	135-156	5850	1650	A	600	200			
	Sio South	156-169	5850	1270	A	750	no data		(?)N	>120
	Harvey	156-169	5850	1050	A	(?)	no data		N	(?)
	Thomas	156-169	5850	1287	A	910	no data		N	>120
	Allen	135-156	5850	1376	A	585	no data		N	>120

*N=normal; R=reversed; M=mixed

of the other type A guyots concentrated on the more resistant reef rim, it may be that karst surfaces are more widespread amongst the drowned atolls than indicated by Table 1.

Radiometric ages in Table 1 are presently available for only a very few volcanoes [*Ozima et al.*, 1970, 1977; R. Duncan, pers. commun.]. Paleontological estimates of minimum ages from rudists, molluscs, and planktonic assemblages are reported in *Matthews et al.* [1974], who conclude that the Japanese and MidPacs are Aptian age or older and that the Wakes are older than Eocene but younger than Aptian. Magnetic character and paleopole positions relative to the Pacific apparent polar-wander path [*Sager and Pringle*, 1988; *Sager*, 1989] were used as additional age constraints. Based on paleopole postions, the A guyots are the oldest (>118 Ma), whereas the type V are the youngest (80-120 Ma). Similarly, their magnetic anomalies fall into two categories. The V's have large amplitude anomalies and normal polarities, implying formation during the Cretaceous Long Normal Period. The A's have smaller, often complex anomalies suggestive of formation during the period of reversing polarity that preceeded the Quiet Period. Of the three type B guyots, Charlie Johnson has an anomaly typical of the A type, whereas Seiko and Taikuyo-Daini have anomalies similar to the V types.

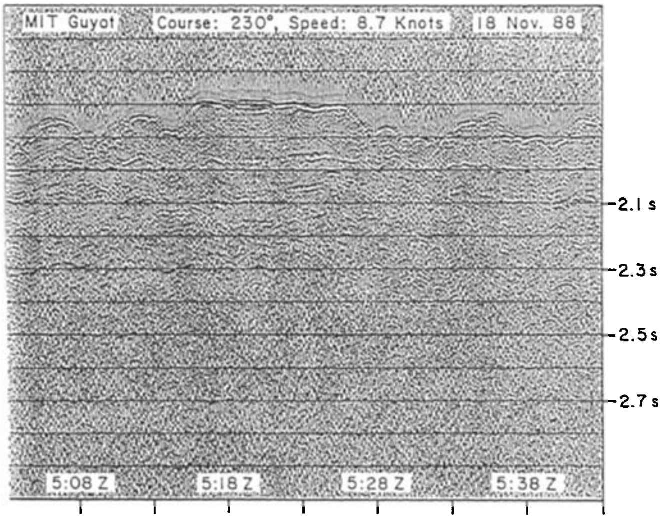

Fig. 2. Processed seismic section (automatic gain control, bandpass 40-110 Hz) across the summit of MIT guyot, showing lagoonal layers cut by an erosional surface with a total relief of 100 m. Maximum depth of sinkholes from Seabeam records elsewhere on this guyot is 180 m. We interpret the strong reflector at 2.3 s to be the top of basaltic basement.

Paleodepth Versus Age

Assuming that these guyots were all formerly islands eroded at sea level soon after formation, the height of the volcanic summit (beneath any sediment) above the surrounding seafloor is a measure of the depth of the lithosphere at the time of volcanism [*Menard*, 1964]. Despite the loose age constraints as outlined above, the depth-age relationship at the time of volcanism for the type A and B guyots using information from Table 1 is consistent with *Parsons and Sclater*'s [1977] depth-age relationship for normal seafloor in the North Pacific (Figure 3). In contrast, the paleodepths for the type V guyots follow the present-day depth versus age for the Superswell [*McNutt and Fischer*, 1987], well above the standard curve.

The foregoing analysis assumes that the reefs on the guyots are totally uncompensated, i.e., the weight of a reef cap does not cause a seamount to subside. This assumption does not affect the paleodepth/age relationship for the type B and type V guyots, with little or no sediment at present. Allowing for rebound of the summits of the type A guyots after sediment removal increases their paleodepths by several hundred meters (Figure 3), and thus strengthens the conclusion that the type A guyots did not form on anomalously shallow lithosphere.

History of the Darwin Rise

The evidence from paleodepths that a superswell may have existed at the time of formation of the type V seamounts, but not earlier, leads to the following scenario for the vertical

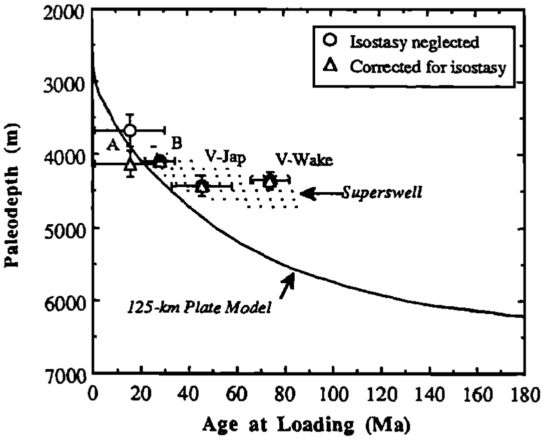

Fig. 3. Paleodepth versus age of the lithosphere at the time of loading for the guyots of the Darwin Rise. "A", "B", "V-Jap", and "V-Wake" refer to the average paleodepth and age values for all guyots with that classification. Error bars on paleodepth reflect only the scatter in the population. Error bars on age reflect scatter in the population as well as uncertainty in the age of the lithosphere as shown in Table 1.

motions in the Cretaceous Pacific (Figure 4). Between 135 and 169 Ma (time t_0), the lithosphere beneath the Darwin Rise was created and subsided as a normal, 125-km-thick thermal plate. At some later time t_1 (about 120 to 140 Ma based on their paleomagnetism and local compensation), the volcanic foundations for the type A guyots erupted. Volcanism was predominantly on the MidPac plateau, probably in a setting much like that of the Tuamotu Islands in the early Tertiary. The Pacific plate was moving slowly southwest [*Winterer and Metzler*, 1984] from a hot spot that was located near Easter Island. Isolated volcanoes (including MIT and Vibelius) formed farther west. It took between 10 to 20 my for their carbonate reefs to form (time interval t_2-t_1 in Figure 4). Towards the end of this time period (110 to 120 Ma), the type B guyots formed. An earlier date would be inconsistent with their paleomagnetism and their small amount of subsidence. Reef caps formed on their subsiding summits until time t_2. The reefs stopped building after time t_2 and by t_3, the reefs were being dissolved subaerially. We believe that reef extinction was caused by a relative fall in sea level that was tectonic, rather than eustatic in orgin, because during this time of long-term eustatic sea level rise [*Haq et al.*, 1987], the reefs of the central Pacific rose at least 200 m above sea level over an area which extends 40° across the Pacific.

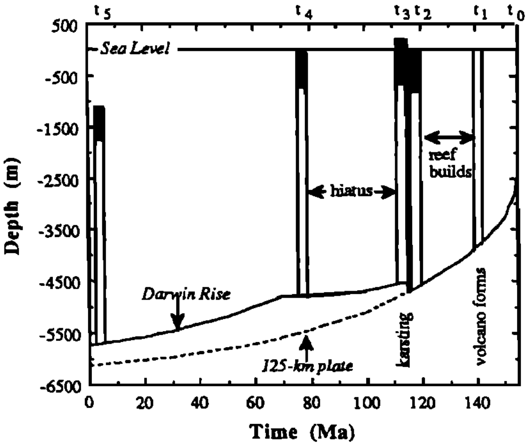

Fig. 4. Schematic model for vertical motions on the Darwin Rise for the specific case of a 140-Ma volcano on 155-Ma lithosphere. Between times t_0 when the lithosphere forms and t_2, the lithosphere subsides as a 125-km-thick thermal plate. At time t_2 the seafloor is uplifted to form a superswell. Between t_3 and t_4 the lithosphere subsides at the rate of a 75-km-thick thermal plate with effective thermal age at t_3 given by its depth at time t_3. Between times t_4 and t_5 (the present), the plate resumes the subsidence rate of a 125-km-thick plate, with effective age at t_4 given by its depth at t_4.

The present-day Superswell in French Polynesia has similar lateral dimensions [*McNutt and Fischer*, 1987], and the depth anomaly is composed of two parts [*McNutt and Judge*, 1989]. The first component is dynamic uplift of 200-250 m caused by convection in the asthenosphere, affecting the entire region of the Superswell. The uplift could occur in a time period of less than 10 m.y. (comparable to the rise time of the Hawaiian swell) and would lead to emergence of existing shore lines. The second component is lithospheric thinning caused by enhanced heat flux from the mantle and reduced viscosity at the base of the lithosphere that leads to convective instabilities. The lithosphere thinned to approximately 75 km subsides at a slower rate and eventually leads to depth anomalies exceeding 750 m with respect to the 125-km plate model, but never actually elevates sea floor with respect to sea level.

We propose that a thermal disturbance similar to that of French Polynesia occurred beneath the Darwin Rise at time t_2, causing 200-250 m of uplift with respect to sea level for the preexisting atolls and barrier reefs. During the period t_3 to t_4, the Darwin Rise lithosphere subsided at the rate of a 75-km-thick plate, producing anomalously shallow paleodepths for the type V guyots, which erupted during this period on the thin, vulnerable lithosphere. For the A and B guyots, this period is marked by a 20- to 25-m.y. hiatus in sedimentation on their summits until the accumulated subsidence of the 75-km thick plate exceeded the initial uplift. Because the Darwin Rise does not presently display geoid and surface wave anomalies indicative of a thinned lithosphere and a hot, low-viscosity asthenosphere [*McNutt and Judge*, 1989], at some time t_4 in the past the lithosphere of the Darwin Rise began to thicken again and subside at the rate of a 125-km-thick plate. The change in thermal regime may have resulted from motion of the plate with respect to the upwelling asthenosphere or a reorganization of the convection pattern.

The geological and geophysical data from the Darwin Rise allow us to constrain the absolute ages of the events t_2, t_3, and t_4, which must be synchronous for all guyots. Lacking firm dates on the ages of the A and B guyots, the time t_2 of reef extinction can be estimated in two ways (Figure 4). For the A guyots on well-dated lithosphere, t_0-t_1 and t_1-t_2 are estimated from the paleodepth and thickness of reef cap, respectively. For A guyots on poorly dated lithosphere (most of the MidPacs), the estimate of t_2 is less sensitive to the assumed t_0 if the present summit depth of the guyot is used to estimate the time interval t_3-t_5. In backtracking the present summit depths to time t_2, we assume that t_2-t_3 is small (only a few million years) and that t_4 must be greater than 70 Ma based on the present-day lithospheric depth and less than 80 Ma based on the ages and paleodepths for the youngest type-V guyots.

The time of extinction of the reefs calculated in these two ways is remarkably synchronous at 113±8 Ma (except for Vibelius, which has an anomalously deep summit probably caused by flexural loading from the younger nearby volcano, Wilde). This result is consistent with the 118-Ma age for the youngest guyot-derived, shallow-water sediments drilled at DSDP site 463 on a fan of Huevo [*Sayre*, 1981] and fits well with the Cenomanian to Turonian age (97-87 Ma) for pelagic chalks dredged from Jacqueline Guyot that could only be deposited after the 20- to 25-m.y. hiatus (Figure 4) following uplift [*Matthews et al.*, 1974]. Assuming t_2=113 Ma and t_4=70 Ma also provides a good fit to the paleodepths and present-day summit depths of the type V guyots of known age.

The existence of an ancient superswell in the mid-Cretaceous coincides with the time period when the Darwin Rise lay over the same region of mantle presently beneath French Polynesia [*Gordon and Henderson*, 1985], and its initiation may be linked to a shift in plate motion, perhaps even more dramatic than the one recorded by the Hawaiian-Emperor bend. The pole of rotation migrated to a position 90° away from the South Pacific, the angular rate of rotation doubled, and the plate started moving rapidly to the northwest (~80 mm/yr) along an azimuth defined by the Japanese and Wake seamount lines.

This model still does not explain why the A and B guyots did not later reestablish reef communities, why the Japanese type-V reefs died almost immediately, and why the Wakes never bore reefs. Subsidence rates due to cooling of the plate (0.01 mm/yr), motion with respect to the dynamic mantle upwelling (0.1 mm/yr), and even collapse of the dynamic component (10 mm/yr) all occur at rates too slow to outstrip the present-day estimate of coral growth under favorable circumstances, although Cretaceous rudist reefs may have grown more slowly. Climatic factors linked to sea-surface temperature, species-dispersal patterns, or true eustatic sea-level rise may still be invoked to explain why, when some 20 my earlier the type A reefs flourished, they were not able to reestablish communities when they once again sank below the sea surface.

Conclusions

The paleodepth/age relationship for the type V guyots in the Japanese and Wake seamount chains supports the hypothesis that they formed on an ancient superswell. The uplift of the superswell occurred at about 113±8 Ma (Aptian-Albian time) based on the reef thicknesses and current summit depths of the guyots. The uplift of this Cretaceous superswell can explain the 200-m emergence and karsting of the reefs on the MidPacs and the other isolated older guyots. The present-day depth of the Darwin Rise is shallower than normal lithosphere of similar age, but the depth anomaly can be explained as the residual effects of mid-Cretaceous reheating. This result suggests that the depth anomaly in French Polynesia is also transient. As soon as the plate drifts off the mantle upwelling (or the upwelling itself turns off), the lithosphere will begin to subside as a normal, 125-km-thick plate. The fact that the oldest lithosphere in the Pacific is also lithosphere affected by superswell-type volcanism may not be a coincidence. The residual thermal effects of plate reheating, as well as the locally thickened crust beneath the seamounts and plateaus, may counteract the negative buoyancy that facilitates subduction of extremely old lithosphere.

Acknowledgements. We thank Sy Schlanger for comments. This work was supported by NSF-ODP-8717826-OCE to MKM, NSF-ODP-8717079-OCE to ELW, and NSF-ODP-8715733 to WWS. GI was supported by NSF's Reseach Experiences for Undergraduates Program through MIT.

References

Duncan, R.A. and I. McDougall, Linear volcanism in French Polynesia, *J. Volcan. Geotherm. Res.*, *1*, 197-227, 1976.

Gordon, R.G. and L.J. Henderson, Pacific plate hot spot tracks, unpub. preprint, 1985.

Haq, B.U., J. Hardenbol, and P.R. Vail, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present), *Science, 235*, 1156-1167, 1987.

Hart, S.R., A large-scale isotope anomaly in the Southern Hemisphere mantle, *Nature* , *309*, 753-757, 1984.

Heezen, B.C., J.L. Matthews, R. Catalano, J. Natland, A. Coogan, M. Tharp, and M. Rawson, Western Pacific guyots, *Init. Rep. DSDP, 20*, B.C. Heezen and I.D. MacGregor, eds., U.S. Gov. Printing Office, Washington, D.C., 653-723, 1973.

Kroenke, L., J.N. Kellogg, and K. Nemoto, Mid-Pacific Mountains revisited, *Geo-Marine Letts.*, *5*, 77-81, 1985.

Matthews, J.L., B.C. Heezen, R. Catalano, A. Coogan, M. Tharp, J. Natland, and M. Rawson, Cretaceous drowning of reefs on Mid-Pacific and Japanese guyots, *Science, 184*, 462-464, 1974.

McNutt, M.K. and K.M. Fischer, The South Pacific superswell, in *Seamounts, Islands, and Atolls*, B.H. Keating, P. Fryer, R. Batiza, and G.W. Boehlert, eds., Geophysical Monograph 43, American Geophysical Union, Washington, D.C., 1987.

McNutt, M. K., and A.V. Judge, The Superswell and mantle dynamics beneath the South Pacific, *Science*, in press, 1990.

Menard, H.W., *Marine Geology of the Pacific*, 271 pp., McGraw-Hill, New York, 1964.

Menard, H.W., Darwin Reprise, *J. Geophys. Res.*, *89*, 9960-9968, 1984.

Nakanishi, M., K. Tamaki, and K. Kobayashi, Mesozoic magnetic anomaly lineations and seafloor spreading history of the Northwestern Pacific, *J. Geophys. Res.*, *94*, 15437-15,462, 1989.

Nemoto, K. and L.W. Kroenke, Sio Guyot: a complex volcanic edifice in the western Mid-Pacific Mountains, *Geo-Marine Letts.*, *5*, 83-89, 1985.

Ozima, M., M. Honda, and K. Saito, ^{40}Ar-^{39}Ar ages of guyots in the western Pacific and discussion of their evolution, *Geophys. J.R. astr. Soc.*, *51*, 475-485, 1977.

Ozima, M., I. Kanoeka, and S. Aramaki, K-Ar ages of submarine basalts dredged from seamounts in the western Pacific area and discussion of oceanic crust, *Earth Planet. Sci. Letts.*, *8*, 237-249, 1970.

Parsons, B. and J. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res.*, *82*, 803-827, 1977.

Sager, W.W., Seamount ages estimates from paleomagnetism and their implications, in *The Geology and Offshore Mineral Resources of the Central Pacific Basin*, B. Keating and B. Bolton, eds, submitted, 1989.

Sager, W.W. and M.S. Pringle, Mid-Cretaceous to Early Tertiary apparent polar wander path of the Pacific plate, *J. Geophys. Res.*, *93*, 353-369, 1987.

Sayre, W.O., Preliminary report on the paleomagnetism of Aptian and Albian limestones and trachytes from the Mid-Pacific Mountains and Hess Rise, Deep Sea Drilling Project Leg 62, *Init. Rep. DSDP*, *62*, J. Thiede and T. L. Vallier, eds., U.S. Gov. Printing Office, Washington, D.C., 983-994, 1981.

Schlanger, S.O., H.C. Jenkyns, and I. Premoli-Silva, Volcanism and vertical tectonics in the Pacific basin related to global Cretaceous transgressions, *Earth Planet. Sci. Letts.*, *52*, 435-449, 1981.

Smith, W.H.F., H. Staudigel, A.B. Watts, and M.S. Pringle, The Magellan Seamounts: early Cretaceous record of the South Pacific isotopic and thermal anomaly, *J. Geophys. Res.*, *94*, 10501-10523, 1989.

Winterer, E.L. and C.V. Metzler, Origin and subsidence of guyots in Mid-Pacific Mountains, *J. Geophys. Res.*, *89*, 9969-9979, 1984.

G. Ito, 6013 E. Mineral, Englewood, CO 80112
M. McNutt, 54-826, MIT, Cambridge, MA 02139
J. Natland and E.L. Winterer, Geoloical Research Division, Scripps Institution of Oceanography, La Jolla, CA 92093
W. Sager, Department of Oceanography, Texas A&M University, College Station, TX 77843

(Received November 30, 1989;
revised March 12, 1990;
accepted March 15, 1990)