Mid-Cretaceous tectonic evolution of the Tongareva triple junction in the southwestern Pacific Basin

Roger L. Larson
Robert A. Pockalny
Richard F. Viso
Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island 02882, USA

Elisabetta Erba Dipartimento di Scienze della Terra, Università di Milano, 20133 Milano, Italy

Lewis J. Abrams Center for Marine Science, University of North Carolina, Wilmington, North Carolina 28409, USA

Bruce P. Luyendyk Department of Geological Sciences, University of California, Santa Barbara, California 93106, USA

Joann M. Stock
Robert W. Clayton
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA

ABSTRACT

The trace of the ridge-ridge-ridge triple junction that connected the Pacific, Farallon, and Phoenix plates during mid-Cretaceous time originates at the northeast corner of the Manihiki Plateau near the Tongareva atoll, for which the structure is named. The triple junction trace extends >3250 km south-southeast, to and beyond a magnetic anomaly 34 bight. It is identified by the intersection of nearly orthogonal abyssal hill fabrics, which mark the former intersections of the Pacific-Phoenix and Pacific-Farallon Ridges. A distinct trough is commonly present at the intersection. A volcanic episode from 125 to 120 Ma created the Manihiki Plateau with at least twice its present volume, and displaced the triple junction southeast from the Nova-Canton Trough to the newly formed Manihiki Plateau. Almost simultaneously, the plateau was rifted by the new triple junction system, and large fragments of the plateau were rafted away to the south and east. The Tongareva triple junction originated ca. 119 Ma, when carbonate sedimentation began atop the Manihiki Plateau. Subsequent spreading rates on the Pacific-Phoenix and Pacific-Farallon Ridges averaged 18–20 cm/yr until 84 Ma.

Keywords: Pacific Ocean, tectonics, marine geology, submarine geomorphology.

INTRODUCTION AND BACKGROUND

It is generally agreed that the Pacific, Farallon, and Phoenix plates were joined in Early Cretaceous time at a triple junction near the Nova-Canton Trough (Larson and Chase, 1972; Winterer et al., 1974; Joseph et al., 1993; Nakanishi and Winterer, 1998). Magnetic lineation M0 just west of the Nova-Canton Trough (Fig. 1) documents this triple junction's existence until 121 Ma (Larson, 1997). The triple junction evolved toward the southeast and eventually coincided with the magnetic lineation intersections formed by anomaly 34 and younger anomalies (Watts et al., 1988; Cande et al., 1989). The intervening tectonic evolution during a time of constant magnetic polarity (121–84 Ma) (Gradstein et al., 1994) has been unclear because there are no lineated magnetic anomalies to guide interpretations.

Larson and Chase (1972) proposed a simple model of constantly decreasing plate age from north to south. Winterer et al. (1974) and Joseph et al. (1993) proposed a large jump in the triple junction from the Nova-Canton Trough to a location south of the Manihiki Plateau (Fig. 1). Larson and Pockalny (1997) suggested instead that the triple junction jumped to the northeastern corner of the Manihiki Plateau. Basalts from Deep Sea Drilling Project (DSDP) Hole 317A atop the Manihiki Plateau (Fig. 1) have been radiometrically dated as 123.7 ± 1.5 Ma (Mahoney et al., 1993; Larson and Erba, 1999). Thus, the Manihiki Plateau is slightly older than anomaly M0 near the Nova-

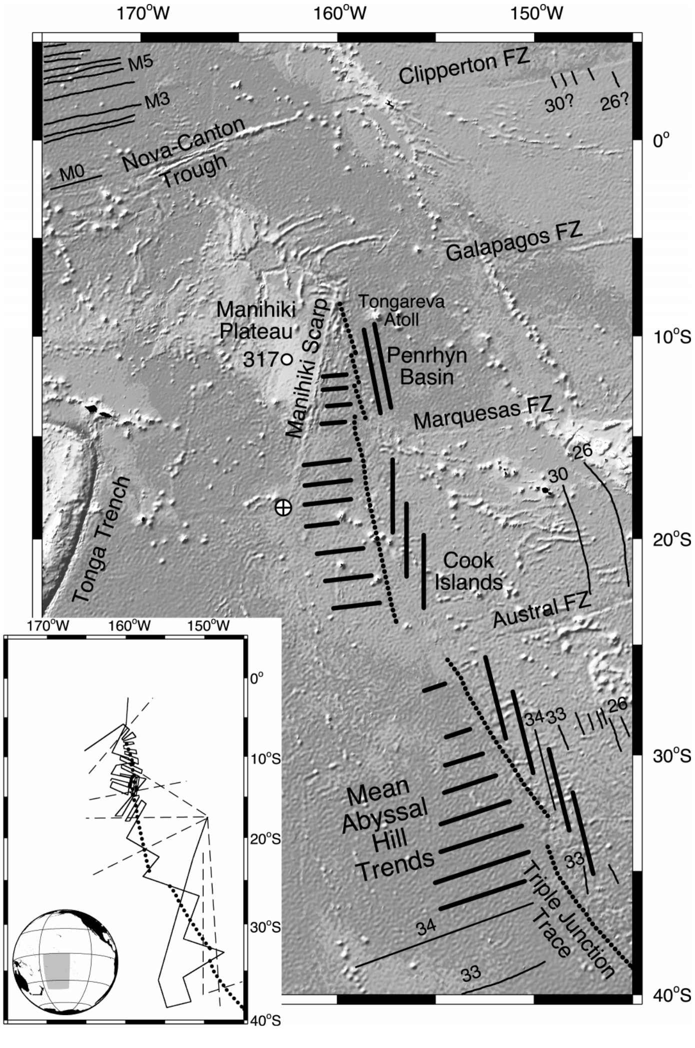

Figure 1. Mean abyssal hill trends (thick solid lines) between fracture zones and trace of Tongareva triple junction (dotted lines) are superimposed on predicted topography from satellite altimetry (Sandwell et al., 1997). Lighter and darker topography depict shallower and deeper features. Thin solid lines indicate magnetic lineations from Cande et al. (1989), and white circle marks Deep Sea Drilling Project Site 317. Circle with cross locates origin of triple junction trace proposed by Winterer et al. (1974) and Joseph et al. (1993). In track chart (inset) solid lines indicate our multibeam surveys and dashed lines indicate previously collected regional multibeam tracks. FZ is fracture zone.

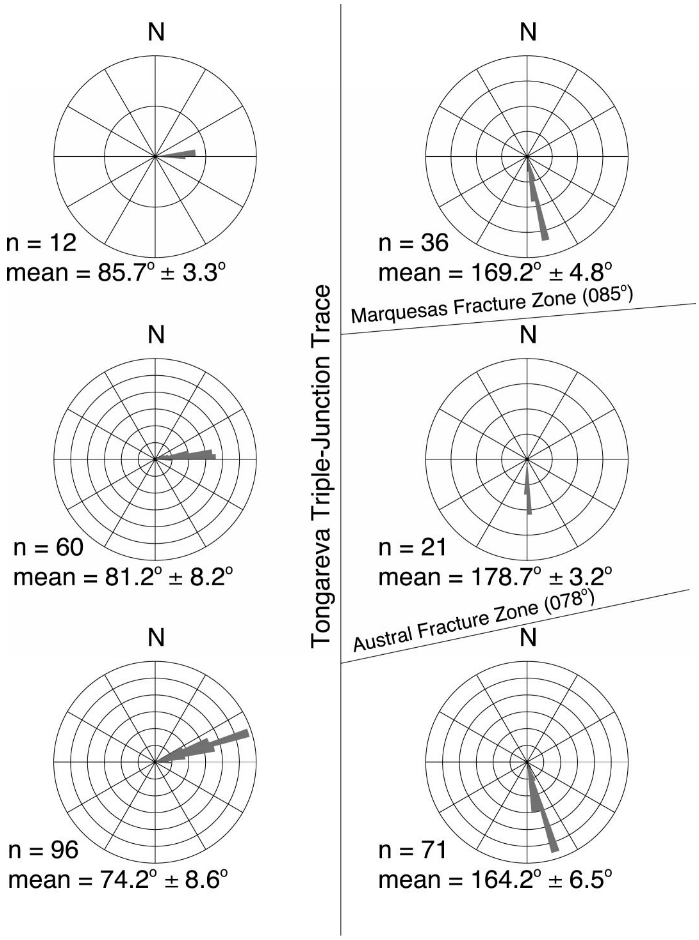

Figure 2. Rose diagrams of abyssal hill trends geographically partitioned into compartments bounded by Marquesas and Austral Fracture Zones or their western extensions on either side of triple junction trace. Trends are all rectified into first two quadrants (0°–180°) for ease of display. Each concentric ring on each diagram indicates five data points; error shown is standard deviation from mean.

Canton Trough, so the reconstruction of Larson and Chase (1972) cannot be correct.

SURVEY RESULTS

We conducted geophysical surveys to map the triple junction trace from the anomaly 34 bight northward to its origin (Fig. 1). We surveyed with multibeam sonar, gravity, and magnetics. The horizontal footprint of each acoustic beam in the multibeam sonar system is 1° × 1°, or ~100 × 100 m directly beneath the ship in ~5 km of water. The deep seafloor in this area is dominated by lineated abyssal hills, which are basaltic ridges formed at and parallel to spreading centers. They are typically 100–500 m high, 1–10 km wide, and 10–100 km long. Our 3.5 kHz echo sounders showed that the seafloor is generally covered with <50 m of draped pelagic sediments, so these basement features are easily resolvable with the multibeam systems.

Two new crossings (Fig. 1) of anomaly 34 west of the triple junction trace show that it is an unbroken lineation trending 069° in a manner slightly different from that shown by Cande et al. (1989). This result and the previously charted anomaly 34 east of the triple junction trace firmly outline the two spreading ridges at 84 Ma. Nearly orthogonal, lineated abyssal hills meet at or very near the trace of the triple junction throughout the survey area (Figs. 1 and 2). The triple junction is commonly marked by a 0.5–1-km-deep trough if it has not been subjected to subsequent volcanism. This trough is especially apparent south of the Austral Fracture Zone. Between the Marquesas and Austral Fracture Zones the triple junction trace cuts across the younger Cook Island chains. There the triple junction trace is between the orthogonal trends of abyssal hills. However, any possible former trough is now filled with volcanics, and smooth seafloor characterizes their intersection.

Winterer et al. (1974) and Joseph et al. (1993) proposed that the triple junction originated south of the Manihiki Plateau (Fig. 1). This hypothesis requires all abyssal hills north and east of that origin point to have formed at the Pacific-Farallon Ridge with north-south trends. Conversely, our surveys and previous data clearly show east-west–trending abyssal hills east of that location. These trends and similar ones to the north in the Penrhyn Basin disprove their hypothesis. The triple junction trough is clearly present in three en echelon segments within the Penrhyn Basin. Lonsdale (1973) discovered the southern segment. The northern segment extends to ~9°S, where it merges with the Manihiki scarp and marks the origin of the triple junction trace just west of the Tongareva atoll. Near the Manihiki scarp, east-west–trending abyssal hills wrap into the scarp in a manner suggesting that the scarp was a transtensional transform fault during formation of the Penrhyn Basin (Stock et al., 1998).

There may be slight but potentially significant differences in the trends of the abyssal hills across the Austral and Marquesas Fracture Zones. We measured the major abyssal hill trends with a protractor on large-scale charts and averaged the results in six groups or fracture-zone compartments (Fig. 2). East of the triple junction trace, the mean values from adjacent compartments are significantly different at the 95% confidence interval. This suggests that slight but significant changes in spreading directions on the Pacific-Farallon Ridge may have initiated the Marquesas and Austral Fracture Zones in a manner similar to that suggested by Menard and Atwater (1968). There are no significant differences between adjacent compartments west of the triple junction trace, suggesting a constant spreading direction on the Pacific-Phoenix Ridge.

Sutherland and Hollis (2001) interpreted the Tongareva structure, as outlined in satellite altimetry data, to be a rift separating crust of different ages. Our data refute that hypothesis. First, the abyssal hills near anomaly 34 closely parallel the magnetic lineations, and anomaly 34 documents the structure as a triple junction. The abyssal hill lineations to the northwest have the same general trends as the ones near anomaly 34, which suggests the same type of structure there. The trends calculated for the triple junction trace using velocity-triangle closure are always within 10° of the mapped trends, which strongly supports the triple junction hypothesis.

TECTONIC EVOLUTION OF THE TONGAREVA TRIPLE JUNCTION

Manihiki Plateau Rifting

The transtensional nature of the Manihiki scarp suggested to Stock et al. (1998) that part of an originally larger Manihiki Plateau was rifted from there and rafted away. Our mapping supports that suggestion. The lack of any significant volcaniclastic sediments imaged by our 3.5 kHz sonar in the Penrhyn Basin suggests that the basin formed after the rifting and removal of the plateau fragments. The ~120° intersection of the Manihiki scarp and the Galapagos Fracture Zone suggests part of a three-armed rift system similar to the Red Sea–Gulf of Aden–East Africa rift system. Like that modern system, rifting was very oblique on at least one of three arms, in this case on the Manihiki scarp. This implies an original Manihiki Plateau about twice its present volume, and that it subsequently rifted into three fragments (Fig. 3). Two have been rafted away on the Farallon and Phoenix plates.

New Triple Junction System

To reconstruct the Tongareva tectonic system, we calculated the velocity triangles that describe sequential plate motions near the triple

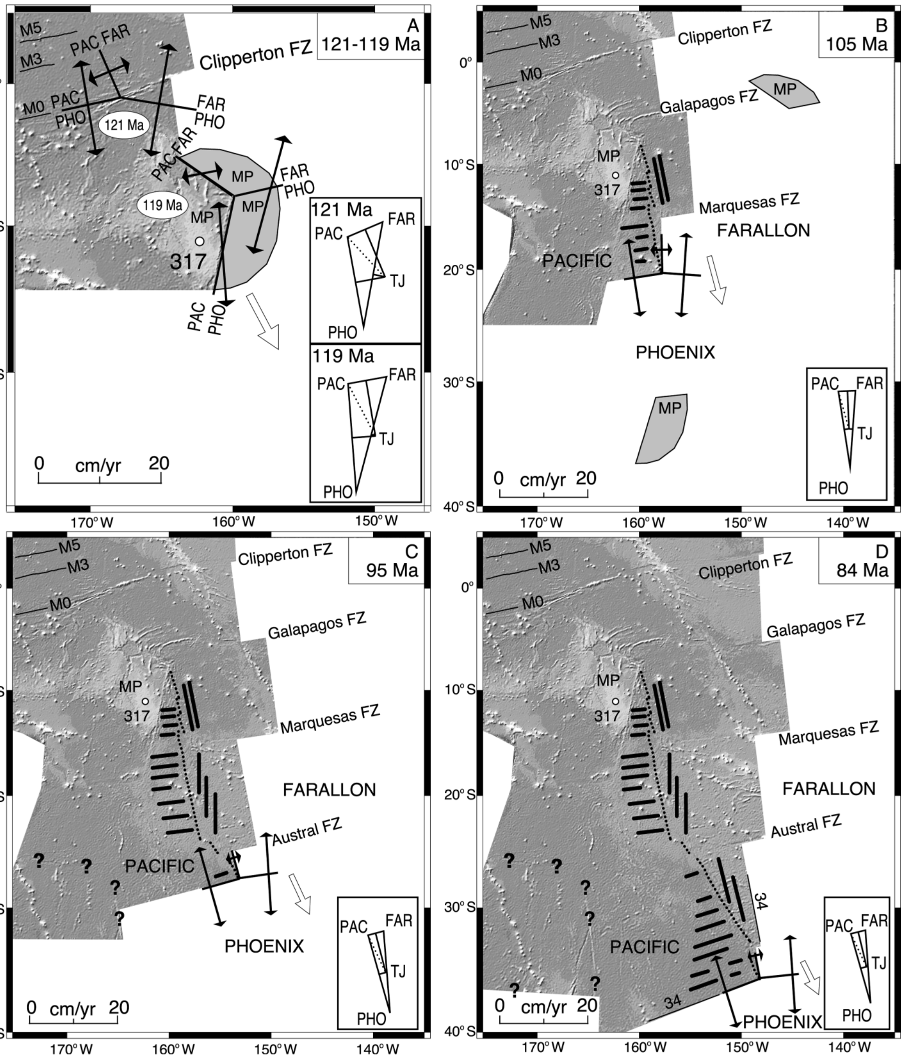

Figure 3. Plate boundary reconstructions of the Pacific (PAC), Farallon (FAR), and Phoenix (PHO) plates from beginning to end of Cretaceous magnetic superchron (121–84 Ma). Panel A is expanded relative to other panels. Plate boundaries (solid lines) are plotted on predicted topography of Pacific plate. Double-headed black arrows are whole spreading vectors. White arrows are calculated vectors for triple junction trace, for comparison with its mapped trend within each fracture zone compartment. Triangles in insets show relative plate and triple junction (TJ) velocities. Proposed Manihiki Plateau fragments (MP) shown at 105 Ma dispersed from their original locations at 119 Ma. Magnetic lineations, mean abyssal hill trends, and Deep Sea Drilling Project Site 317 are shown as in Figure 1. FZ is fracture zone.

junction (Fig. 3). We assume that the spreading directions on the Pacific-Phoenix and Pacific-Farallon Ridges were normal to the mean trends of the abyssal hills, spreading was symmetric, and the plates were rigid. All referenced spreading rates are whole rates.

To estimate mid-Cretaceous rates for the Pacific-Farallon Ridge in this area, we measured the spreading rates between anomalies M0 to 34 in the North Pacific between the Mendocino, Murray, and Molokai Fracture Zones, which average 12.4 cm/yr. We used that rate and the Pacific-Farallon Euler pole location at 34.6°S, 150.5°W (Joseph et al., 1993) to calculate rates along this plate boundary within our survey area. To estimate the mid-Cretaceous spreading rate for the Pacific-Phoenix Ridge, we first determined the initiation time of the new spreading system. This cannot be older than 121 Ma and must be younger than the breakup of the Manihiki Plateau. We assume that it is coincident with the end of volcaniclastic sedimentation and the onset of carbonate sedimentation on the Manihiki Plateau.

Sliter (1992) identified foraminiferal zone KS7 (the *Leupoldina cabri* zone) in core 33-317A-12 underlying a continuous sequence of monotonically younger foraminiferal zones. Core 33-317A-13, 140–142 cm, contains common nannofossils and *Eprolithus floralis* is abundant. The carbonate and volcaniclastic sediments are intercalated in core 33-317A-13, so we assume no time gap between the end of volcaniclastic and the beginning of carbonate sedimentation. The first occurrence of *E. floralis* marks the base of nannofossil zone NC7 (the *Rhagodiscus angustus* zone). Larson and Erba (1999) showed that the upper part of zone KS7 overlaps the lower part of zone NC7 ca. 119.5–118.5 Ma.

Thus, carbonate sedimentation on Manihiki Plateau began ca. 119 Ma, which dates the initiation of the Tongareva triple junction system. If Pacific-Phoenix spreading was constant from 119 Ma until anomaly 34 time, then oceanic crust was generated at 18 cm/yr for the next 35 m.y. at that ridge.

Tectonic Reconstructions

The sequential reconstructions of the Pacific-Farallon-Phoenix system (Fig. 3) are shown using the same chart projection as Figure 1. Because the ridge configurations and spreading rates before and after the tectonic reorganization were very similar, we retain the Phoenix plate as the name of the southernmost, now-subducted plate throughout the mid-Cretaceous. We see no evidence for the existence of a Moa plate in the vicinity of the Tongareva triple junction as suggested by Sutherland and Hollis (2001). However, the Moa plate could have influenced the area to the west.

Spreading vectors for the Pacific-Phoenix and Pacific-Farallon plates at 121 Ma are based on measurements on M7–M0 (127–121 Ma). As in subsequent reconstructions, the Farallon-Phoenix plate vector is based on closure of the Pacific-Farallon-Phoenix velocity triangle. The Manihiki Plateau would have just formed by 121 Ma, on the basis of the 123.7 $\pm$ 1.5 Ma date on the basalts in Hole 317A. At 121–119 Ma, the previous triple junction system ceased, leaving the Nova-

Canton Trough to mark its demise, and was replaced by rifting of the Manihiki Plateau. This tectonic discontinuity may have resulted from thinning of the lithosphere during formation of the Manihiki Plateau. The nature of initial motions on the plate boundaries at 119 Ma is unclear; however, we speculate that they were partially tensional, in accord with other three-armed rift systems. Two of the boundaries eventually evolved into the transform boundaries of the Galapagos Fracture Zone and the Manihiki scarp. By 119 Ma, rifting was completed and the Tongareva triple junction system initiated. The mapped strikes of the three en echelon segments within the Penrhyn Basin trend $\sim 10°$ more southward than the computed triple junction vector relative to the Pacific plate, perhaps due to some nonrigid plate behavior near the Pacific-Farallon Ridge.

At 105 Ma the triple junction had migrated to the south-southeast and the Marquesas Fracture Zone had formed. The mapped and calculated vectors for the triple junction trace were almost exactly aligned, indicating rigid behavior of all three plates near the triple junction. A western extension of the Pacific-Phoenix Ridge died ca. 105 Ma as it neared the subduction zone north of New Zealand, resulting in a change from compression to extension in the tectonic regimes of New Zealand and parts of West Antarctica (Bradshaw, 1989; Luyendyk, 1995). At 95 Ma the triple junction had migrated farther southeast and the Austral Fracture Zone had formed. The mapped and calculated vectors for the triple junction trace remained aligned, although both had rotated slightly to the east. The Manihiki Plateau fragments had been rafted off the chart area. At 84 Ma the triple junction had migrated southeastward to the anomaly 34 bight. The spreading rate on the Pacific-Phoenix Ridge was about to slow from ~ 18 to ~ 13 cm/yr as measured between anomalies 34 and 33. New Zealand began to rift away from Gondwana as a successor to the Pacific-Phoenix Ridge ca. 84 Ma (Watts et al., 1988; Luyendyk, 1995), and the Tongareva triple junction continued to evolve to the southeast.

CONCLUSIONS

We have mapped the Pacific-Farallon-Phoenix triple junction trace as a nearly continuous structure between magnetic anomaly 34 and the northeastern corner of the Manihiki Plateau. This disproves the hypothesis of Winterer et al. (1974) and Joseph et al. (1993), who suggested that the triple junction originated well south of the Manihiki Plateau. Instead, at 121–119 Ma, the triple junction at the Nova-Canton Trough jumped to its new location beneath the newly formed Manihiki Plateau, which then was about twice its present size. The plateau was rifted into three fragments and two of them were rafted away to surrounding continental margins. The subsequent spreading rates on the Pacific-Phoenix and Farallon-Phoenix Ridges averaged 18–20 cm/yr from 119 to 84 Ma, essentially the same rates as those calculated by Larson (1991a). Thus, at least in the vicinity of the Tongreva triple junction, fast spreading dominated the system and contributed to elevated eustatic sea level and higher paleotemperatures, which are defining features of the mid-Cretaceous greenhouse (Larson, 1991b).

ACKNOWLEDGMENTS

We thank the personnel on Expeditions Cook-4 and Kiwi-12 for professional support at sea and J. Mammerickx for helpful discussions. R. Sutherland and S. Gulick provided comprehensive and useful reviews. This research is sponsored by National Science Foundation grant OCE-9818776 to the University of Rhode Island, and by funding from the University of California and the California Institute of Technology.

REFERENCES CITED

Bradshaw, J.D., 1989, Cretaceous geotectonic patterns in the New Zealand region: Tectonics, v. 8, p. 803–820.

Cande, S.C., LaBrecque, J.L., Larson, R.L., Pitman, W.C., III, Golovchenko, X., and Haxby, W.F., 1989, Magnetic lineations of the world's oceans: Tulsa, Oklahoma, American Association of Petroleum Geologists, one chart.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., and Huang, Z., 1994, A Mesozoic time scale: Journal of Geophysical Research, v. 99, p. 24 051–24 074.

Joseph, D., Taylor, B., Shor, A.N., and Yamazaki, T., 1993, The Nova-Canton Trough and Late Cretaceous evolution of the Central Pacific, *in* Pringle, M.S., et al., eds., The Mesozoic Pacific: Geology, tectonics, and volcanism: American Geophysical Union Geophysical Monograph 77, p. 171–185.

Larson, R.L., 1991a, Latest pulse of Earth: Evidence for a mid-Cretaceous superplume: Geology, v. 19, p. 547–550.

Larson, R.L., 1991b, Geological consequences of superplumes: Geology, v. 19, p. 963–966.

Larson, R.L., 1997, Superplumes and ridge interactions between Ontong Java and Manihiki Plateaus and the Nova-Canton Trough: Geology, v. 25, p. 779–782.

Larson, R.L., and Chase, C.G., 1972, Late Mesozoic evolution of the western Pacific Ocean: Geological Society of America Bulletin, v. 83, p. 3627–3644.

Larson, R.L., and Erba, E., 1999, Onset of the mid-Cretaceous greenhouse in the Barremian-Aptian: Igneous events and the biological, sedimentary, and geochemical responses: Paleoceanography, v. 14, p. 663–678.

Larson, R.L., and Pockalny, R.A., 1997, Changing triple junctions in the mid-Cretaceous: From the Nova-Canton Trough to Tongareva Atoll [abs.]: Eos (Transactions, American Geophysical Union), v. 78, p. F721.

Lonsdale, P.F., 1973, Cruise report CATO Leg 3: La Jolla, Scripps Institution of Oceanography, University of California, Reference 73-19, 29 p.

Luyendyk, B.P., 1995, Hypothesis for Cretaceous rifting of east Gondwana caused by subducted slab capture: Geology, v. 23, p. 373–376.

Mahoney, J.J., Storey, M., Duncan, R.A., Spencer, K.J., and Pringle, M., 1993, Geochemistry and age of the Ontong Java Plateau, *in* Pringle, M.S., et al., eds., The Mesozoic Pacific: Geology, tectonics, and volcanism: American Geophysical Union Geophysical Monograph 77, p. 233–261.

Menard, H.W., and Atwater, T., 1968, Changes in the direction of sea floor spreading: Nature, v. 219, p. 463–467.

Nakanishi, M., and Winterer, E.L., 1998, Tectonic history of the Pacific-Farallon-Phoenix triple junction from Late Jurassic to Early Cretaceous: An abandoned Mesozoic spreading system in the central Pacific Basin: Journal of Geophysical Research, v. 103, p. 12 453–12 468.

Sandwell, D.T., Smith, W.H.F., and Small, C., 1997, Global topography: http://www.ldeo.columbia.edu/~small/GDEM.html.

Sliter, W.V., 1992, Cretaceous planktonic foraminiferal biostratigraphy and paleoceanographic events in the Pacific Ocean with emphasis on indurated sediment, *in* Ishizaki, K., and Saito, T., eds., Centenary of Japanese micropaleontology: Tokyo, Terra, p. 281–299.

Stock, J.M., Luyendyk, B.P., Clayton, R.W., and Shipboard Scientific Party, 1998, Tectonics and structure of the Manihiki Plateau, western Pacific Ocean [abs.]: Eos (Transactions, American Geophysical Union), v. 79, p. F870.

Sutherland, R., and Hollis, C., 2001, Cretaceous demise of the Moa plate and strike-slip motion at the Gondwana margin: Geology, v. 29, p. 279–282.

Watts, A.B., Weissel, J.K., Duncan, R.A., and Larson, R.L., 1988, Origin of the Louisville Ridge and its relationship to the Eltanin Fracture Zone system: Journal of Geophysical Research, v. 93, p. 3051–3077.

Winterer, E.L., Lonsdale, P.F., Matthews, J.L., and Rosendahl, B.R., 1974, Structure and acoustic stratigraphy of the Manihiki Plateau: Deep-Sea Research, v. 21, p. 793–814.

Manuscript received June 1, 2001
Revised manuscript received September 20, 2001
Manuscript accepted October 1, 2001

Printed in USA