Geological Society of America
Special Paper 388
2005

What built Shatsky Rise, a mantle plume or ridge tectonics?

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ABSTRACT

Shatsky Rise is an oceanic plateau that formed at the Pacific-Farallon-Izanagi triple junction during the Late Jurassic to Early Cretaceous. Its origin is unclear, but volcanism from a mantle plume or plume head is accepted as an explanation because many observations from the plateau are consistent with the plume head model. Initial eruptions were massive and rapid, with emplacement rates estimated at 1.2–4.6 km^3/yr, similar to continental flood basalts. The plateau exhibits an age progression, with igneous output waning over time, possibly representing the transition from plume head to plume tail. Shallow water fossils imply that the rise top was subaerial and that thermal and dynamic uplift was significant. Furthermore, the age progression and trends of Shatsky and Hess rises are mimicked by the Mid-Pacific Mountains, to be expected if these features formed by the drift of the plate over mantle plumes. In contrast, several observations do not fit the plume head model. The initial eruption was coincident with a reorientation of the Pacific-Izanagi ridge and an 800-km jump of the triple junction, a low probability occurrence if plume heads behave independently of plate motions. Moreover, this same type of event may have occurred repeatedly, as other western Pacific plateaus occur near the trace of this triple junction (Hess Rise) and the Pacific-Farallon-Phoenix triple junction (Magellan Rise, Manihiki Plateau, Mid-Pacific Mountains). If these other plateaus formed from plumes, either there were many plumes or the plumes defining the triple junction paths exhibited large relative motion. Moreover, rocks recovered from the main Shatsky Rise edifices have mid-ocean ridge basalt (MORB) geochemistry and isotopic signatures, whereas most plume head models imply that lower mantle material, with a different signature, will be carried to the surface. A simpler hypothesis is that Shatsky Rise and other near-triple-junction plateaus were formed as a result of ridge tectonics. One possibility is that decompression melting occurred near the triple junctions during the Mesozoic because the northwest Pacific was located over a region of anomalous asthenosphere that was susceptible to melting given only small perturbations in lithospheric stress. A pitfall for this argument is that changes in the thin, fast-spreading Pacific lithosphere must result in massive volcanism. Although both plume and ridge tectonics hypotheses explain some observations from Shatsky Rise, uncertainties make it premature to conclude which, if either, is correct. Resolution awaits future investigations, which must reveal missing pieces to this puzzle.

Keywords: oceanic plateau, triple junction, large igneous province, mantle plume, Pacific Ocean

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Sager, W.W., 2005, What built Shatsky Rise, a mantle plume or ridge tectonics?, *in* Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L., eds., Plates, plumes, and paradigms: Geological Society of America Special Paper 388, p. 721–733, doi: 10.1130/2005.2388(41). For permission to copy, contact editing@geosociety.org.

INTRODUCTION

How oceanic plateaus form is an outstanding question of modern geophysics. Not readily explained by plate tectonics, the origins of these anomalous basaltic mountains are enigmatic. Because of their igneous cores and sometimes immense size, plateaus are often attributed to mantle plume eruptions. One widely accepted hypothesis accounts for the largest plateaus as eruptions from a plume head, a bulbous mass of magma that rises owing to thermal buoyancy from the core-mantle boundary region to cause massive eruptions when it impinges upon the lithosphere (e.g., Richards et al., 1989; Coffin and Eldholm, 1994). In this view, oceanic plateaus are the submarine equivalent of continental flood basalts (Richards et al., 1989; Duncan and Richards, 1991) and are an anomalous phenomenon that is more-or-less independent of plate tectonics (Eldholm and Coffin, 2000). An alternative view is that plumes are not required to produce anomalous volcanism atop the plates. Instead, certain regions of mantle may be "fertile" by reason of composition or temperature and may react to changes in stress along plate boundaries with magmatic outpourings (e.g., Anderson et al., 1992; Anderson, 1995; Smith and Lewis, 1999; Hieronymous and Bercovici, 2000; Natland and Winterer, this volume). The resolution to this enigma is important because of the obvious implications for global tectonics, marine geology, and mantle geodynamics.

Shatsky Rise is a large oceanic plateau located 1500 km east of Japan, in the northwest Pacific Ocean (Fig. 1). With an area of ~4.8×10^5 km^2 (about the same as that of Japan or California) and estimated total volume (basaltic edifice plus root, excluding ocean crust) of ~4.3×10^6 km^3, this plateau is not only a prominent feature of Pacific bathymetry but also represents a significant large igneous province (LIP) (Sager et al., 1999). In addition, bathymetric ridges and geochemistry connect Shatsky with nearby Hess Rise, implying that the two plateaus arose from the same volcanic source (Bercovici and Mahoney, 1994) with nearly double the output.

Several factors combine to make the study of plateau formation at Shatsky Rise a potentially fruitful endeavor. The rise formed during the Late Jurassic and Early Cretaceous at the Pacific-Farallon-Izanagi triple junction (Larson and Chase, 1972), making it likely the oldest undisturbed ocean plateau, as well as one of the few that formed during a period of geomagnetic field reversals. The latter circumstance means that magnetic reversals recorded in plateau lavas help constrain its structure and tectonics (e.g., Sager and Han, 1993). In addition, the combination of morphology, apparent age progression of the rise, and surrounding magnetic lineations indicate that Shatsky Rise volcanism is spread out laterally, perhaps owing to rapid movement of the Pacific plate relative to the mantle (Nakanishi et al., 1999; Sager et al., 1999); therefore, the association of ridges and volcanism is more easily deciphered.

Recent publications have concluded that Shatsky Rise was constructed by a mantle plume, perhaps by a plume head (Sager et al., 1988, 1999; Nakanishi et al., 1989; 1999; Sager and Han, 1993). Given recent debate about the number, types, and even existence of mantle plumes (e.g., Anderson, 2000, 2001; Foulger, 2002; Courtillot et al., 2003; Sleep, 2003; Foulger and Natland, 2003; DePaolo and Manga, 2003; Anderson, this volume), it is an opportune time to assess existing data to see whether that conclusion remains valid. In this article, I review old and new geologic and geophysical data cogent to the formation of Shatsky

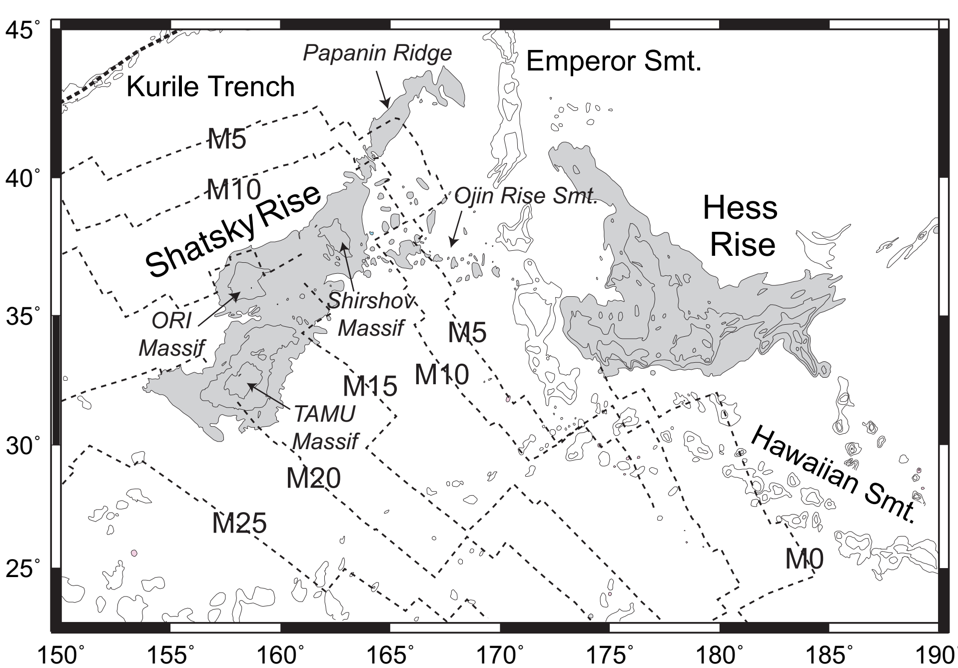

Figure 1. Location of Shatsky and Hess rises in the northwest Pacific Ocean. Selected bathymetry contours are shown at 1000-m intervals, with depths shallower than 5000 m on Shatsky and Hess rises shaded. Dashed lines are selected magnetic isochrons. Names of features mentioned in the text are labeled. Smt.—seamount.

Rise and compare them with model predictions. As the reader will see, there is as yet no "smoking gun" datum that unequivocally points to one mechanism. Although much geologic evidence is consistent with a plume head mechanism, other observations are difficult to reconcile with that explanation.

BACKGROUND

Plateau Formation Hypotheses

Ocean plateaus are usually remote and difficult to sample. The resulting geological ignorance has lead investigators to propose a variety of plateau formation mechanisms. One class of explanation calls upon anomalous behaviors of tectonic plates: leaky transform faults (Hilde et al., 1976), unusually active spreading ridges (Winterer et al., 1974; Winterer, 1976), and spreading ridge reorganizations (Anderson et al., 1992). Another class invokes a mantle plume, either as a steady-state magma source or an initial burst from an instability-derived head (Richards et al., 1989; Duncan and Richards, 1991; Coffin and Eldholm, 1994). A third type of mechanism is extraterrestrial, explaining plateau formation as a result of massive basaltic volcanism induced by a large meteorite impact (Rogers, 1982; Ingle and Coffin, 2004).

The mantle plume hypothesis has been most widely accepted, in part because of shortcomings or lack of development of the other hypotheses. The meteor impact hypothesis was proposed before evidence mounted to support the Chixulub impact explanation for the Cretaceous-Paleocene boundary (e.g., Hildebrand and Boynton, 1990) and many other impacts were documented. Combined with a lack of evidence linking plateaus and impacts, the idea lay fallow for many years. Interestingly, this hypothesis has been resurrected as a possible origin for Ontong Java Plateau (Ingle and Coffin, 2004; Tejada et al., 2004; see Jones et al., this volume) because evidence from the plateau does not neatly fit other hypotheses. Plate boundary mechanisms also gained limited support, perhaps because they appear ad hoc under the often-used assumption that the upper mantle is homogenous. Creating LIPs via cracks in a thin oceanic plate requires a seemingly small perturbation to unleash a massive volcanic eruption. Consequently, in such hypotheses, the mantle is often changed in some way, either by positing a mantle plume or fertile mantle, primed to undergo massive decompression melting (Anderson et al., 1992). A similar problem exists for the runaway-ridge hypothesis: An extraordinary change must occur for a normal spreading ridge to turn into a plateau-building monster.

Mantle plume explanations for plateaus have been fueled by a wide acceptance of the mantle plume hypothesis. The idea that thermal instabilities from the lower mantle rise to the surface, causing basaltic volcanic eruptions, probably became popular because it seemed a neat explanation for age-progressive volcanic chains (Wilson, 1963; Morgan, 1971, 1972). As more age-progressive seamount chains have been found, this explanation has been used repeatedly, one result being an implausibly large number of plumes being proposed. In part, this problem stems from the loose application of the plume definition. Recent re-examination of hotspot lists conclude that only a small number fit the original plume concept—that of a thermal diapir originating at or near the core-mantle boundary (Courtillot et al., 2003; Anderson, this volume). Instead, many hotspots likely have shallow sources that may or may not be related to significant thermal upwelling.

The plume head hypothesis arose as an extension of the traditional plume hypothesis. It was observed experimentally that perturbations in a gravitationally unstable layer form large, bulbous heads that rise through the overlying medium, and that the instabilities are followed by tails of rising, lower-layer material if the viscosity conditions are appropriate (Campbell and Griffiths, 1990; Griffiths and Campbell, 1990). Such models led to the idea that mantle plumes form in the core-mantle boundary layer and begin with massive thermal diapirs (plume heads) that rise quickly through the mantle, followed by a narrow cylindrical conduit of thermally buoyant material (plume tail) (Campbell and Griffiths, 1990; Griffiths and Campbell, 1990; Duncan and Richards, 1991). Other similar hypotheses start plumes from shallower levels, such as the 670-km discontinuity, either as the primary source region (White and McKenzie, 1989) or as the result of the arrest of a lower mantle plume that in turn creates an upper mantle plume head by heating the discontinuity (Tackley et al., 1993). All of these hypotheses are similar in that they require large thermal anomalies that arise deep in the mantle and advect large volumes of deep mantle material to the surface.

Impact of the plume head on the lithosphere is thought to result in rapid, voluminous basaltic eruptions, forming an oceanic plateau or continental flood basalt, depending on the type of lithosphere above the plume (Richards et al., 1989; Duncan and Richards, 1991). Wide acceptance of this hypothesis appears to have followed publication of radiometric dating studies that indicated massive, short-lived eruptions formed several LIPs (Coffin and Eldholm, 1994). Recently, however, dating results from Ocean Drilling Program coring of Kerguelen and Ontong Java plateaus may indicate longer, more complex eruption histories than previously thought (Coffin et al., 2002; Duncan, 2002; Frey and Weis, 2003; Pringle et al., 2003; Tejada et al., 2004). The effect of such complications on the acceptance or modification of the plume head hypothesis remains to be seen.

Prior Research on Shatsky Rise

Few geophysical mapping expeditions have spent significant time studying Shatsky Rise. Most ship tracks crossing the plateau are from cruises in transit (see Sager et al., 1999), and only a handful lingered to investigate rise features. By the late 1960s, it was known that Shatsky Rise is ancient because Early Cretaceous sediments were cored from its summit (Ewing et al., 1966). Seismic refraction experiments revealed an anomalously thick crust, with a similar velocity structure to ocean crust but

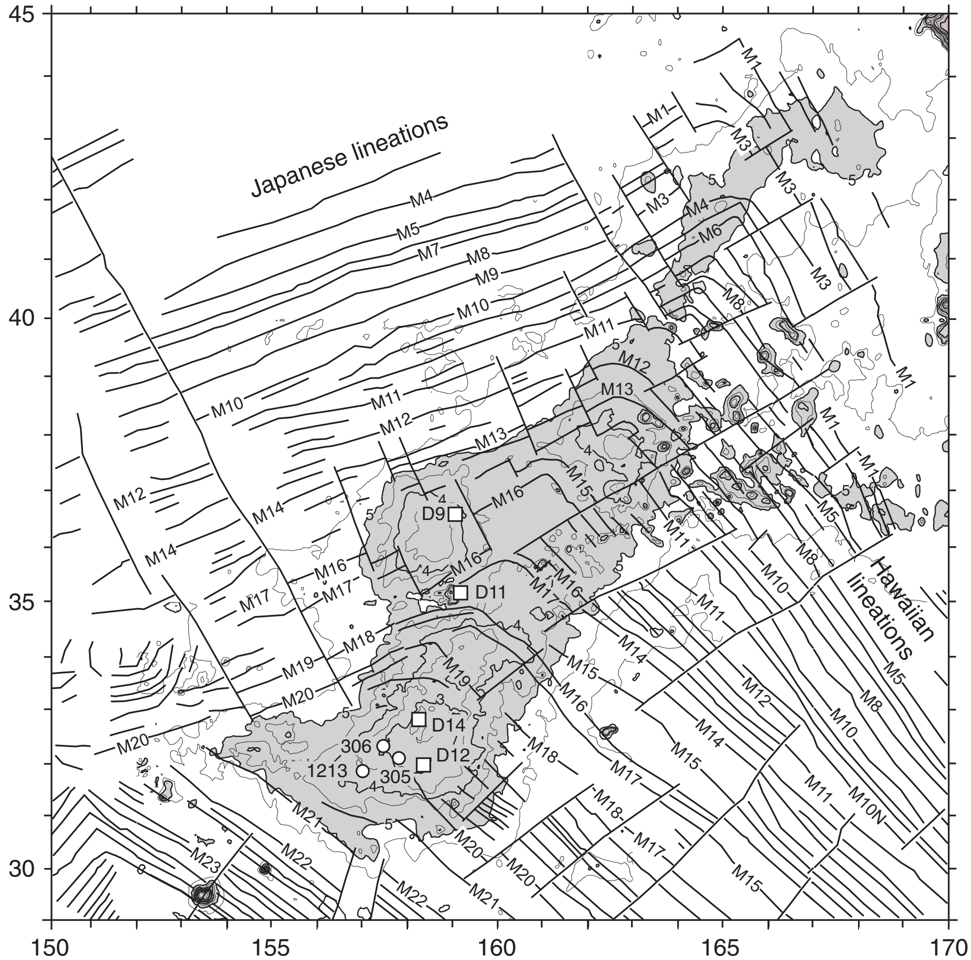

Figure 2. Magnetic lineations in the vicinity of Shatsky Rise. The 500-m bathymetry contours are shown on the rise. Deep Sea Drilling Project and Ocean Drilling Program sites on the southern rise, mentioned in the text, are shown as open circles. The open squares show the locations of dredges (D) mentioned in text (Sager et al., 1999). From Nakanishi et al. (1999).

several times thicker (Den et al., 1969; Gettrust et al., 1980). Furthermore, seismic profiling showed that the tops of the rise edifices hold thick piles of pelagic sediments (up to 1.2 km), whereas sediments on the rise flanks are thin or occasionally absent (Ewing et al., 1966; Ludwig and Houtz, 1979; Neprohnov et al., 1984; Sliter and Brown, 1993).

Several cruises of the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) cored Shatsky Rise over a span of 32 yr. In succession, DSDP Legs 7, 32, 86, and ODP Leg 132 cored atop the highest, southern mountain of the rise ("TAMU Massif" of Sager et al., 1999). None of the coring penetrated basaltic basement. DSDP Leg 32 probed farthest into Shatsky Rise history, recovering Berriasian age (earliest Cretaceous) sediments just above the expected level of basement at Site 306 (Fig. 2). This finding was significant because it implied that TAMU Massif formed during the latest Jurassic or earliest Cretaceous. Recently, ODP Leg 198 cored sediments from all three of the Shatsky Rise massifs (Bralower et al., 2002). Although cores confirmed the Mesozoic age of all massifs, a significant result was the coring of a 46-m section of basaltic sills at Site 1213 on the southwest flank of TAMU massif (Fig. 2). An apparently reliable radiometric date has been derived from these cores and is discussed below.

Magnetic lineations mapped in the northwest Pacific revealed that Shatsky Rise sits at the confluence of two lineation sets, the northeast-trending Japanese lineations and the northwest-trending Hawaiian lineations (Figs. 1 and 2) (Larson and Chase, 1972; Hilde et al., 1976). This circumstance indicates that the plateau formed at a triple junction separating the Pacific, Farallon, and Izanagi plates (Larson and Chase, 1972). Subsequent studies revealed that the triple junction jumped repeatedly during the time it occupied the location of the rise and that it must have been geometrically unstable to follow the path of the rise (Sager et al., 1988, 1999; Nakanishi et al., 1999). Furthermore, the few available age constraints (mainly Cretaceous dates of sediments), seismic stratigraphy, and isostatic compensation all indicate that the age of rise features is close to that of the seafloor (Sager et al., 1999). These observations imply that the triple junction and rise formation are closely linked. The prevailing hypothesis is that a plume is the link—a source of heat, uplift, and volcanism that both emplaced the rise and captured the triple junction (Sager et al., 1988, 1999).

Magnetic data were also instrumental in supporting the idea that Shatsky Rise formed from a plume head. Although other investigators had suggested that a mantle plume constructed the rise (Sager et al., 1988; Nakanishi et al., 1989), Sager and Han (1993) postulated that the rise formed rapidly, based on an analysis of the magnetic anomaly. They noted that the TAMU Massif magnetic anomaly implies a mainly reversed polarity, which they attributed to the edifice having formed mostly during a single reversed polarity time period. With simple calculations using the massif volume and assuming a conservative length for the single polarity period, the authors inferred that the rise formed with an eruption rate similar to those quoted for flood basalts (~1.8 km^3/yr).

DATA AND OBSERVATIONS

Tectonic History

Much of what is known about Shatsky Rise tectonic history is based on the magnetic lineations that surround the plateau and in some places transect it (Fig. 2) (Sager et al., 1988; Nakanishi et al., 1989, 1999). The lineations range from M21 (147 Ma; this and other polarity dates are from Gradstein et al., 1995), bordering the southwest edge of the plateau, to M1 (124 Ma) at the northern tip of Papanin ridge (Figs. 1 and 2). Magnetic lineations are mapped on the southeast flank of TAMU Massif and on flanks all around the ORI and Shirshov massifs (Figs. 1, 2). Magnetic lineations are also observed in the basins between massifs and all through Papanin ridge; indeed, little of Shatsky Rise is without magnetic lineations. This observation led to the conclusion that the rise consists of three large volcanic constructs (TAMU, ORI, and Shirshov massifs), surrounded by lithosphere that has not been pervasively modified by igneous activity (Nakanishi et al., 1999; Sager et al., 1999).

Magnetic lineations also give important clues to the links between triple junction evolution and the Shatsky Rise formation. The lineations show that a geometrically stable ridge-ridge-ridge or ridge-ridge-transform-fault triple junction was moving northwest (in a Pacific plate reference frame) prior to M22 (Fig. 3). At M21, the triple junction began to reorganize, with the Pacific-Izanagi isochrons showing a 30° rotation, leading to microplate formation and an eastward jump of the junction by 800 km, to the location of TAMU Massif, the oldest part of Shatsky Rise (Sager et al., 1988, 1999; Nakanishi et al., 1999). Afterwards, until M3 (126 Ma), Shatsky Rise formed along the trace of the triple junction. During this time the triple junction jumped repeatedly—at least nine times (Fig. 3) (Nakanishi et al., 1999). In addition, the three main volcanic massifs have sides parallel to spreading ridges and transform faults. Together, these observations imply that rise volcanism was episodic and tied to ridge jumps (Sager et al., 1999). Additional evidence for a connection between volcanism and ridge tectonics is the observation that many seamounts of the Ojin Rise group (Fig. 1), which intersect the eastern plateau at 37° N, are linear and parallel to magnetic isochrons (Fig. 2).

Shatsky Rise volcanism displays a progression in both age and volume along the trace of the triple junction. Rise volume decreases markedly with distance from TAMU Massif. This volcanic edifice has an estimated volume of 2.5×10^6 km^3, whereas ORI and Shirshov massifs both have volumes of 0.7×10^6 km^3. Papanin ridge, at the north end of the plateau, has a volume of 0.4×10^6 km^3, but the low ridge implies low volcanic flux over a long period (Sager et al., 1999).

Age also decreases with distance from TAMU Massif, and available data imply that the age of the volcanic edifices are close to that of the underlying lithosphere. Coring at Sites 306 and 1213 on TAMU Massif both bottomed in Berriasian sediments (Larson et al., 1975; Bralower et al., 2002), implying that the volcano is older. Furthermore, two radiometric dates averaging 144.6 ± 0.8 Ma (2σ error), have been derived from the basalt section drilled at Site 1213 (Mahoney et al., 2005). That the cored basalts are sills, which probably occurred during a late stage of edifice building, implies that this radiometric date is a minimum for the building of the main shield. In addition, the date corresponds to M19 in the geomagnetic polarity reversal time scale (Gradstein et al., 1995) and this isochron is the oldest recognized on the north side of TAMU Massif. Thus, the massif cannot be much older than this date (Fig. 4). ORI and Shirshov massifs must be younger than TAMU Massif because they reside on lithosphere that is younger than the radiometric date from TAMU. The youngest magnetic lineation beneath both ORI and Shirshof massifs is M14 (136 Ma), and Papanin ridge is underlain by anomalies M10–1 (131–124 Ma). Gravity anomalies indicate complete Airy isostatic compensation, which implies little difference in age between the rise and the underlying lithosphere (Sandwell and MacKenzie, 1989). This observation is consistent with a younging-northeastward trend, with rise volcanism following the triple junction path.

The radiometric date from TAMU Massif also places important constraints on the rate at which volcanism occurred during initial Shatsky Rise eruptions. To calculate this rate, estimates of volcanic duration and volume are needed. I calculated the volume of TAMU Massif between M21 and M19 (i.e., the part that appears to have been emplaced during the ridge jump) to get a total of 1.8×10^6 km^3. (Note that the volume used by Sager and Han, 1993, included all of TAMU Massif.) This value was determined from the volume of the volcanic high, minus 1 km of sediment at the top, plus the volume of a root calculated from Airy isostasy (using a density contrast of 400 kg/m^3 at the Moho). The volume calculation excluded oceanic crust, whose thickness was assumed to be 7 km (if this crust is included, the volume is 2.7×10^6 km^3). The duration of volcanism could vary by a factor of four, depending on assumptions made in the calculation. If I assume TAMU Massif volcanism filled all of the

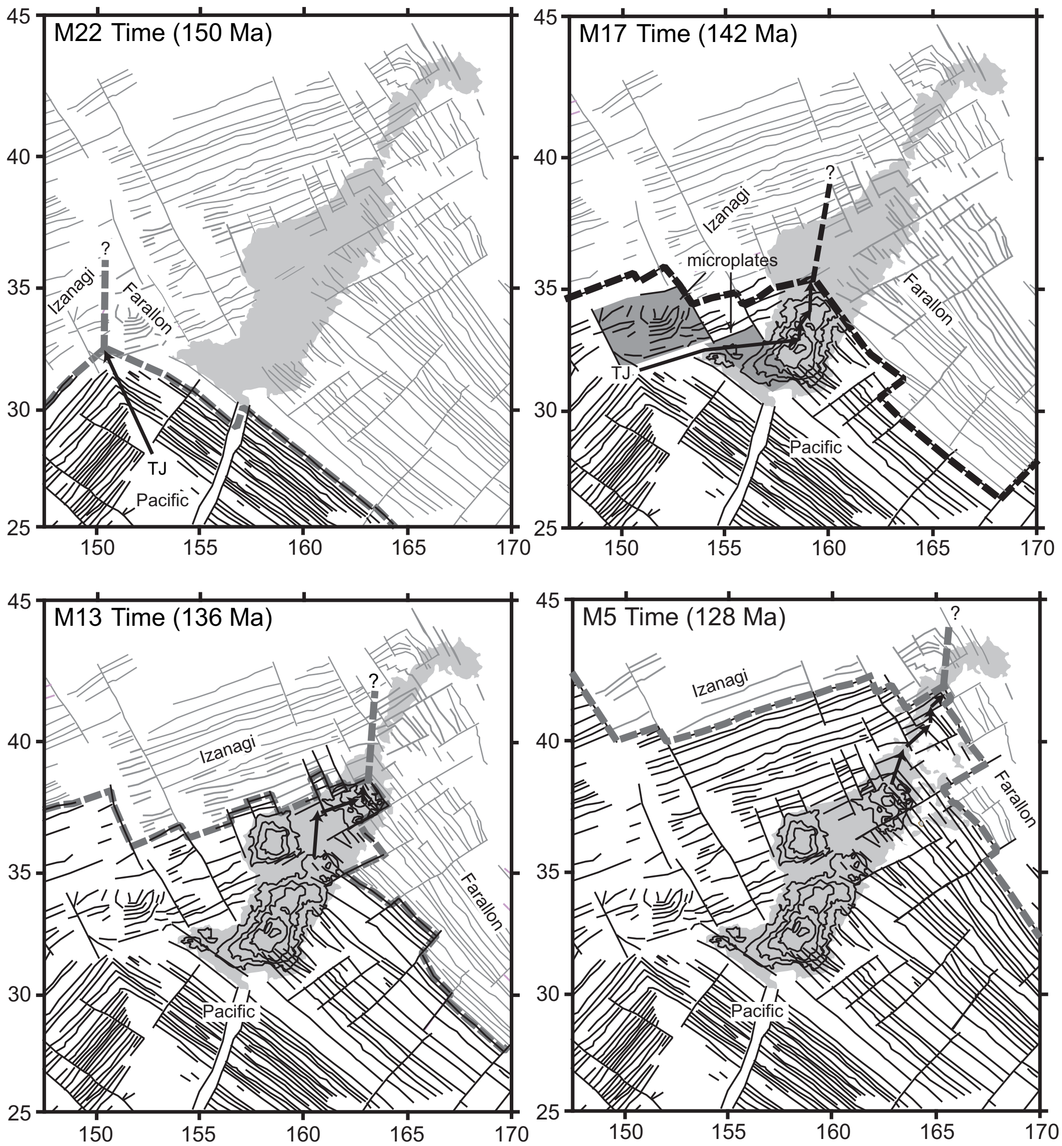

Figure 3. Tectonic history of Shatsky Rise, illustrating the migration of ridges and triple junction. Heavy dashed lines denote ridges. Dark magnetic lineations exist on the Pacific plate at the time given for each panel; light lineations show future isochrons for reference. Arrows show the path of the triple junction (TJ) and illustrate jumps and changes in direction. Question marks indicate uncertainties in TJ path. Modified from Nakanishi et al. (1999).

time between chrons M20 and M19 (the anomalies that bracket the ridge jump; see Fig. 2), then the duration is 1.5 m.y. Alternatively, if I use the interpretation of Sager and Han (1993) that TAMU Massif formed during a single reversed polarity chron, an interpretation bolstered by the interpreted reversed magnetic polarity of the Site 1213 sills (Tominaga et al., 2005), the duration is much less. For Chrons M19r and M20r, the durations are 0.40 m.y. and 0.75 m.y., respectively. The longer estimated duration yields an eruption rate of 1.2 km^3/yr, whereas the shorter, polarity-derived durations give 4.6 and 2.5 km^3/yr for M19r and M20r, respectively. All of these values are in the range of those reported for continental flood basalt eruptions (Richards et al., 1989; Johnston and Thorkelson, 2000).

Geochemical and Isotopic Data

Geochemical and isotopic data from rock samples are an important key to understanding the formation of ocean plateaus because such data may retain fingerprints of mantle magma reservoirs, temperature, and degree of partial melting. For Shatsky Rise, such data are few and somewhat contradictory. Only a few dredges have recovered basalt from the rise, and all such sam-

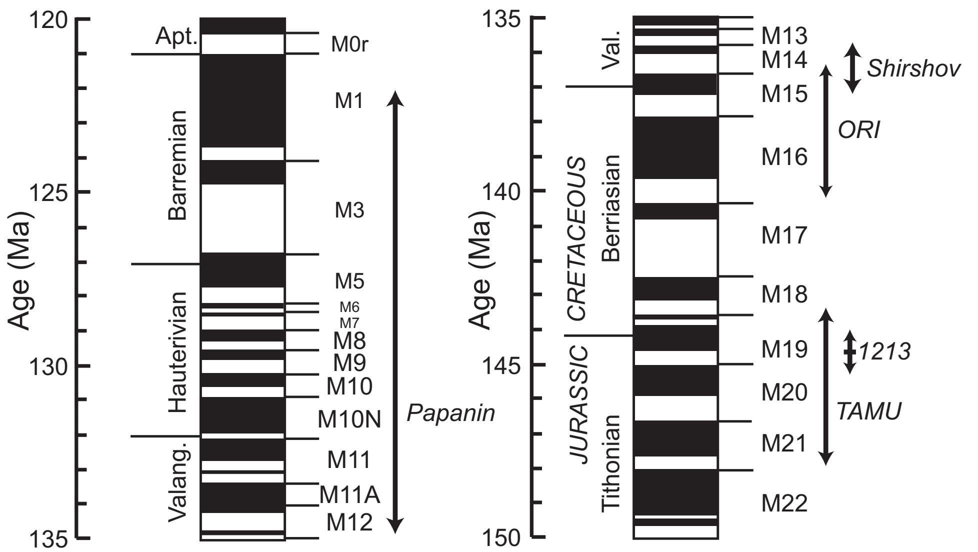

Figure 4. Shatsky Rise edifice ages, the geomagnetic polarity reversal time scale, and geologic time. Ages, geologic stages, and polarity sequence are from Gradstein et al. (1995). In the polarity columns, normal polarity is dark and reversed polarity, light. Double-headed arrows with edifice names show the range of magnetic isochons bordering or beneath that edifice. The arrow labeled "1213" shows the mean age and error bounds of the radiometric date from basalts cored on TAMU Massif at Site 1213 (Mahoney et al., 2005). TAMU Massif formed very close to the time of the Jurassic-Cretaceous boundary. Apt.—Aptian; Val., Valang.—Valanginian.

ples are highly altered, making the interpretation of isotopic and geochemical data difficult. Nevertheless, Tatsumi et al. (1998) analyzed dredge rock data using plots of Nb/Y versus Nb/Zr and concluded that samples from a seamount in the rise are similar to rocks from the south Pacific superswell region, a finding that was interpreted as evidence for a lower mantle source. Whether superswell magmas come from the lower mantle is a subject of some debate (e.g., Natland and Winterer, this volume). Furthermore, the sample in question comes from a seamount located in a basin between TAMU and ORI massifs (dredge D11 in Fig. 2), whose relationship to the larger plateau features is unclear.

Other geochemical and isotopic data, from TAMU and ORI massifs (dredges D9 and D14 and Site 1213 in Fig. 2) have MORB-like characteristics (Tejada et al., 1995; Mahoney et al., 2005). Age-corrected Nd and Pb isotope ratios from the Site 1213 samples are in the range of values for Pacific MORB, and the dredge samples have similar isotopic signatures. Furthermore, the Site 1213 basalts are tholeiites with compositions that fall within the global MORB array. Thus samples from the large basaltic edifices of Shatsky Rise have mid-ocean ridge characteristics, even though the dredge samples (D9 and D14) come from summit ridges and the drilled samples are from sills, all of which should be late-stage volcanic products. This finding does not fit the plume head hypothesis, which would predict the central plateau should contain rocks with lower mantle compositions and isotopic signatures (e.g., Fitton et al., 1997).

Sea Level Indicators

A strong plume should produce both thermal and dynamic uplift, implying that the top of a plume head volcano will be subaerial (e.g., Griffiths and Campbell, 1990, 1991). For most of Shatsky Rise, sea level evidence is lacking; however, a dredge from the upper flank (3000 m deep; D12 in Fig. 2) on TAMU Massif recovered shallow water fossils (rudist casts and corals; Sager et al., 1999). Because the TAMU Massif summit extends higher, the rise top must have been at or above sea level. Furthermore, a flat summit on Shirshov Massif (beneath the sediment cap) can be seen in seismic profiles (Sager et al., 1999) and may indicate sea level erosion on that part of the rise. Thus it appears that the volcanic conditions (i.e., temperature, magma flux, dynamic uplift) on Shatsky Rise were sufficient to raise the volcanism above sea level.

DISCUSSION

Shatsky Rise has been attributed to plume volcanism primarily because it is a large, somewhat linear, igneous construct (Sager et al., 1988; Nakanishi et al., 1989). Furthermore, circumstantial evidence of a rapid eruption rate has been the basis of proposing that the plateau formed from a plume head (Nakanishi et al., 1989; Sager and Han, 1993; Sager et al., 1999). At first blush, this explanation seems a good one to explain many of the characteristics of this large plateau. From a mantle plume, one would expect a trail of age-progressive basaltic volcanism tracking the motion of the plate over a source that is nearly fixed in the mantle (Morgan, 1971, 1972). Shatsky Rise seems to fit this criterion because existing age constraints imply that the rise becomes younger northeastward. Aseismic ridges connect Shatsky Rise with Hess Rise, apparently continuing the younging-eastward trend (Fig. 5). Moreover, a similarity of ages and trends between Shatsky and Hess rises and the Mid-Pacific Mountains even suggests that the volcanic tracks show the motion of the Pacific plate over nearly fixed mantle magma sources (Fig. 5).

The large thermal anomaly of a plume head should cause a high degree of partial melt; voluminous, high-rate igneous rock emplacement; and substantial uplift, similar to continental flood

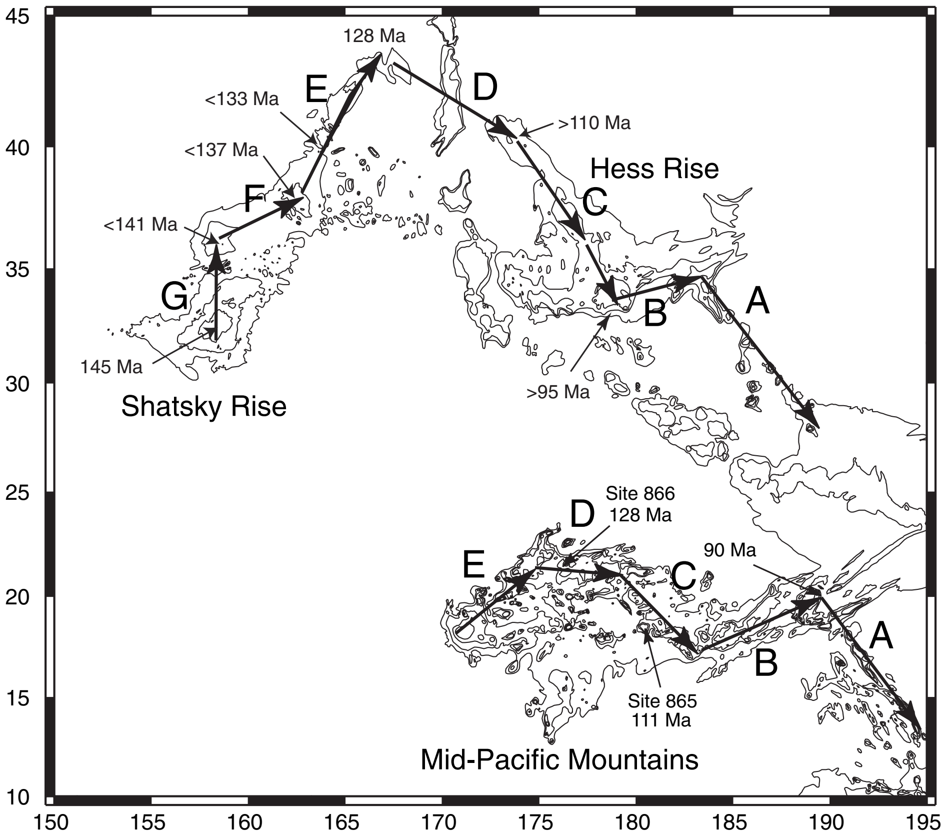

Figure 5. Similar volcanic and age trends in the Shatsky Rise–Hess Rise pair and the Mid-Pacific Mountains. Age estimates for Shatsky Rise come from Site 1213 and the magnetic lineation ages of parts farther north. Age estimates from Hess Rise are from Deep Sea Drilling Project cores dated by Pringle and Dalrymple (1993). Dates from the Mid-Pacific Mountains come from Ocean Drilling Program Leg 143 and dredge samples (reviewed by Winterer and Sager, 1995). Arrows show trends, with labels (e.g., A, B) to show correlation between the two lineaments, both showing a lopsided "M" shape with similar ages at analogous points. The 1000-m bathymetry contours are shown for reference.

basalt eruptions (e.g., White and McKenzie, 1989; Campbell and Griffiths, 1990; Duncan and Richards, 1991; Coffin and Eldholm, 1994). Although emplacement rates are not known for most of Shatsky Rise, the radiometric date from ODP Site 1213 constrains the formation of the oldest part of the plateau (TAMU Massif) to a short period (1.5 m.y. or less). If formed mostly during a single reversed polarity epoch, as proposed by Sager and Han (1993) the emplacement rate may have been prodigious. Moreover, the rise volume implies a substantial fraction of partial melting over a thick section of upper mantle. For example, if a 5–30% partial melt is assumed (e.g., Coffin and Eldholm, 1994), the 1.8×10^6 km^3 of igneous material initially emplaced in the rise implies the involvement of a sphere of mantle 224–408 km in diameter. The lower the degree of partial melting, the bigger the inferred volume. Evidence for uplift comes from shallow water fossils, recovered from the upper flanks of TAMU Massif, which imply that the top of the volcano was subaerial. An apparently contradictory conclusion was reached by Ito and Clift (1998), who used cores from DSDP Site 305 (see Fig. 2) to infer that the TAMU Massif summit was submarine. The two findings are not necessarily contradictory because the submarine interpretation was based on the recovery of pelagic sediments with large depth uncertainties. In addition, core recovery from Site 305 was low, meaning shallow water fossils may have gone unrecovered, and the age of the oldest sediments is 5–10 m.y. later than the radiometric date from Site 1213 sills, allowing time for subsidence.

The geometry of Shatsky Rise also appears to support the plume head hypothesis. Apparently the emplaced volume of igneous material waned with time, as shown by the decreasing volume northeastward, suggesting a transition from plume head to plume tail (Sager et al., 1999). The plume or plume head hypothesis is likewise an attractive explanation for the odd behavior of the Pacific-Farallon-Izanagi triple junction during the ca. 20 m.y. that the plateau formed. A plume head eruption, being a strong source of heat and uplift, is a potential reason for the initial 800-km jump of the triple junction. Continuing energy and flux from a plume might have pinned the triple junction, explaining the repeated triple junction jumps as well as the observation that the triple junction did not migrate away from the rise, as should have occurred, given the velocities of surrounding plates (Sager et al., 1988). In short, a plume head eruption appears a plausible explanation for many of the characteristics of Shatsky Rise.

This statement has been the stopping point for most analyses. Although the plume head hypothesis can potentially explain many aspects of Shatsky Rise, there are some observations that are not explained well without resorting to modifications of the plume hypothesis. One nagging point is the ridge reorganization that occurred near the time that Shatsky Rise formed. Between

M21 and M20, synchronous with the commencement of the Shatsky Rise eruptions, the Pacific-Izanagi ridge rotated 30° (Sager et al., 1988). Because it is generally accepted that plate motion is driven by subduction (e.g., Lithgow-Bertelloni and Richards, 1998), it is unclear how a plume head could cause plate velocity change by acting on the trailing boundary at the ridge. Although a plume may reorient ridges nearby, owing to uplift and heating, the ridge reorientation occurred >800 km from the alleged plume location. If plume activity and plate motions are independent or only loosely coupled (e.g., Eldholm and Coffin, 2000), then the temporal proximity of these two events must be a coincidence.

Another apparent coincidence is the proximity of the plume head and triple junction. How likely is a plume head eruption within 800 km of a triple junction? Assuming that a plume head erupts from a random point on the core-mantle boundary and could strike beneath the lithosphere with equal probability at any point on the globe, the probability of it striking within 800 km of a triple junction is simply the area of an 800-km circle divided by the area of the globe; that is, ~0.4%. If one wishes to postulate more plume heads erupting in a given period, the probability can be increased by a factor *N,* where *N* is the number of plumes. This simple-minded calculation ignores mantle convection or basal lithosphere topography that might steer the plume head to the ridge (e.g., Courtillot et al., 1999; Braun and Sohn, 2003; Jellinek et al., 2003). Although it is true that a ridge or triple junction in the vicinity of a plume will jump or reorganize to stay near the plume (e.g., Kleinrock and Morgan, 1988), this assumes that the ridges are already near the plume. Having a plume head find a triple junction as it rises from the deep mantle is a low-probability event unless there is some connection that steers the plume head impact point toward the triple junction.

Curiously, western Pacific bathymetry and magnetic lineations seem to imply that other, similar plume-ridge coincidences have occurred. It appears that other plateaus and microplates formed along or near the paths of the Pacific-Farallon-Izanagi triple junction as well as the Pacific-Farallon-Phoenix triple junction, located on the east end of the Pacific plate (Fig. 6). Moreover, many of these plateaus are located in the vicinity of proposed ridge reorganizations. The association of Shatsky Rise eruptions with the Pacific-Farallon-Izanagi triple junction prior to chron M1 was recounted above. After M1, the position of this

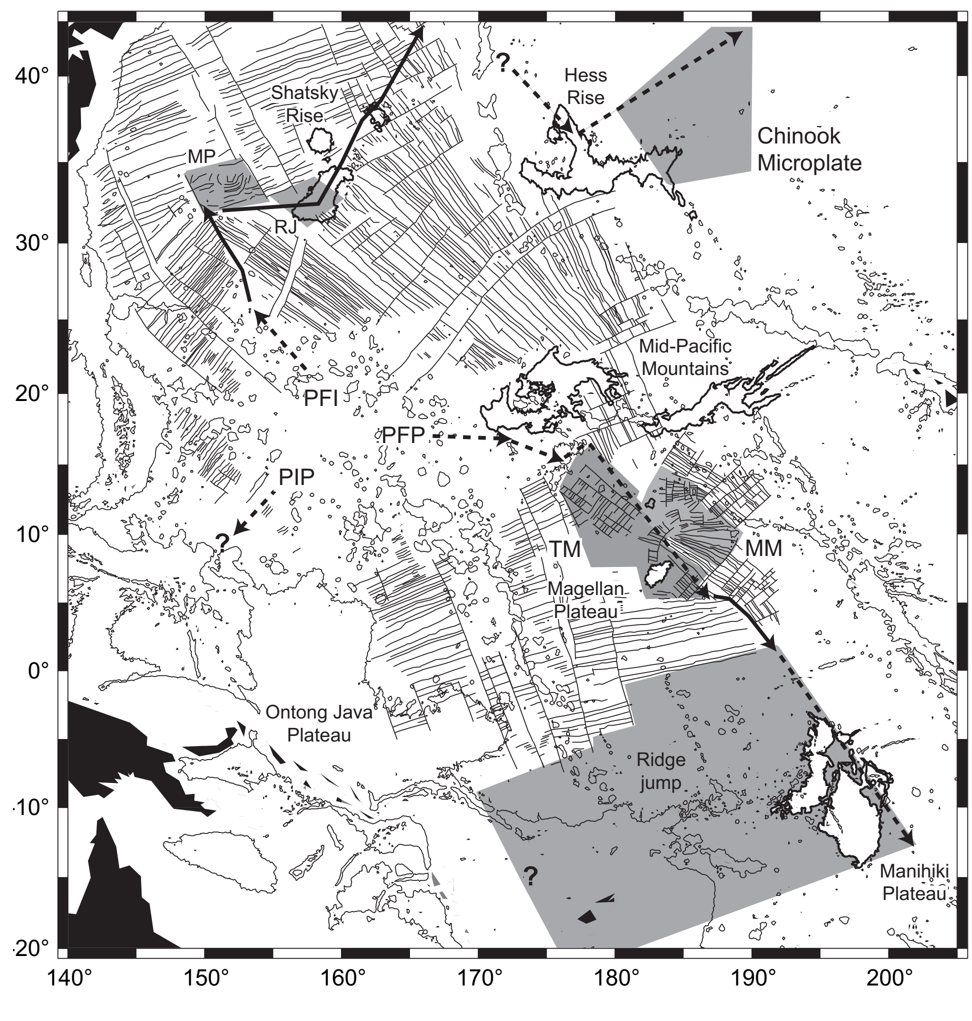

Figure 6. Mesozoic microplates and plateaus in the wake of two Pacific triple junctions. Thin solid lines are magnetic lineations. Heavy solid lines show the migration of triple junctions where clearly indicated by the lineations. Dashed heavy lines show inferred migration or jumps. Gray areas show microplates or lithosphere accreted by ridge jumps. Data from Tamaki and Larson (1988); Nakanishi et al., (1989, 1992, 1999); Nakanishi and Winterer (1998); Sager et al. (1999). MM—Magellan microplate; MP—unnamed microplate; P-F-I—Pacific-Farallon-Izanagi triple junction; P-F-P—Pacific-Farallon-Phoenix triple junction; P-I-P—Pacific-Izanagi-Phoenix triple junction; RJ—ridge jump; TM—Trinidad microplate.

triple junction is unclear, because of the lack of magnetic lineations in the Cretaceous Quiet Zone. Nevertheless, backtracking the junction from Late Cretaceous magnetic lineations in the northeast Pacific, together with fracture zone trends, implies that the triple junction was in the vicinity of Hess Rise ca. 100 Ma, that the triple junction jumped, and that a microplate (the Chinook microplate) formed nearby (Mammerickx and Sharman, 1988), similar to the situation with Shatsky Rise.

Likewise the Pacific-Farallon-Phoenix triple junction also seems to have left a trail of microplates and plateaus. The Trinidad microplate, Magellan Rise, and North Magellan Rise formed along its path from ca. M20 to M14 (Nakanishi and Winterer, 1998). Subsequently, the Magellan microplate evolved near the triple junction between ca. M14 and M11 (Tamaki and Larson, 1988). Furthermore, the wide Cretaceous Quiet Zone near Manihiki Plateau and the age of the plateau imply that a large ridge jump took place during the Cretaceous Quiet Period, moving the triple junction to the vicinity of Manihiki Plateau (Larson, 1997; Larson et al., 2002). Thus, like its northern counterpart, the Pacific-Farallon-Phoenix triple junction left a series of plateaus, microplates, and ridge jumps in its wake. Significantly, the path that this triple junction followed is decidedly different from that of the Pacific-Farallon-Izanagi triple junction, implying that if the two junctions followed mantle plumes, the plumes must have been moving rapidly relative to one another.

About half-way between the two triple junctions, another plateau-like feature, the Mid-Pacific Mountains, was forming at the same time. Unlike most simple seamount chains, this LIP has a low basaltic plateau beneath the seamounts (Winterer and Sager, 1995). Although only a few radiometric dates are available from the chain, existing dates indicate a younging-eastward trend, similar to Shatsky and Hess rises, with the age of the seamounts near that of the lithosphere beneath (see Fig. 5) (Winterer and Sager, 1995). Magnetic lineations in the vicinity of the Mid-Pacific Mountains (Nakanishi et al., 1992) imply that it formed along a transform fault (or its aseismic extension) on the Pacific-Farallon ridge. Furthermore, the location of the western end of the chain is close to the triple junction track and the western side of the Trinidad microplate, suggesting a link between triple junction tectonics and the initiation of volcanism.

Explaining all of these LIPs (Hess Rise, Magellan Rise, Manihiki Plateau, and the Mid-Pacific Mountains) by plumes or plume heads that are independent of ridge dynamics requires many recurrences of a low-probability correlation. Clearly this pronouncement suffers from the pitfall that the tectonic relationships of these plateaus and ridges are uncertain, as most are poorly surveyed and some formed during the Cretaceous Quiet Period. As a result, the exact location of the ridges when the plateaus formed is unclear. Nevertheless, many plateaus are clearly near the triple junction paths (Fig. 6). Another problem is the presumed independence of plume heads and ridges. Some modeling suggests that plumes can be drawn toward and subsumed into ridge upwellings (Jellinek et al., 2003), although this is supposed to occur for slow spreading (Pacific spreading was fast during the Jurassic and Cretaceous) and plumes with ordinary flux (not extraordinary flux plume heads). Clearly, it is possible to explain the LIPs near these two triple junction paths as plume volcanism if special conditions are assumed; yet pleading special cases is precisely the problem that often muddles discussions of the plume and plate models (Foulger and Natland, 2003; Anderson, this volume). A more straightforward explanation is that the LIP volcanism occurs where plate boundaries meet because the volcanism is related to plate boundary tectonics.

How could ridge tectonics lead to massive eruptions? Triple junctions could be the key. Perhaps massive volcanism broke out near triple junctions because when ridges meet at a triple junction, they are a focal point for strong upwelling (Georgen and Lin, 2002). What about the discrepancy between the volcanism along Jurassic to mid-Cretaceous Pacific triple junctions compared to the paucity of such activity during the Late Cretaceous through Cenozoic? One possibility is the fertile mantle hypothesis (e.g., Anderson et al., 1992; Anderson, 1995; Smith and Lewis, 1999; Smith, 2003), which states that the asthenosphere is not laterally homogenous and that certain portions, owing to past tectonic history, have lower melting points. In this scenario, a ridge reorganization may fracture the lithosphere, causing decompression melting in a susceptible region. This mechanism seems somewhat implausible because the ridges in the Mesozoic western Pacific were fast spreading, so that the lithosphere must have been thin, and the resulting pressure drop from fracturing would have been be small. Perhaps the reason for the unusual behavior is that the Pacific plate was atop an anomalous mantle zone.

What little Jurassic and Early Cretaceous lithosphere that remains intact can be found bordering the north Atlantic continents and in the Argo Abyssal Plain off northwest Australia (Klitgord and Schouten, 1986; Sager et al., 1992). In these regions, the abundance of LIPs is not as great as that of the northwest Pacific. This observation is consistent with the idea that the asthenosphere beneath the Pacific plate was different from that under the north Atlantic. Paleomagnetism shows that the Pacific plate was 20°–30° farther south during the Late Jurassic and Early Cretaceous and probably a similar distance to the east (e.g., Larson et al., 1992), placing the present-day north Pacific LIPs near the volcano-rich area called the *South Pacific superswell* (e.g., McNutt and Fisher, 1987). Although the nature of the superswell is debated (e.g., Stein and Abbott, 1991), it is widely thought that the asthenosphere beneath the region is anomalously warm and a source of magma for many small seamount chains (e.g., Courtillot et al., 2003). Shatsky Rise, other plateaus, and even many seamount chains in the northwest Pacific may be Jurassic and Early Cretaceous products of this anomalous region (McNutt et al., 1990; Tatsumi et al., 1998; Koppers et al., 2003). It is thought that the superswell has waned since the Mesozoic (McNutt et al., 1990); indeed, Larson (1991) concluded that the superswell was once a superplume that caused widespread mid-Cretaceous volcanism, creating Ontong Java Plateau and a plethora of seamounts and intrusions in the surrounding region.

The formation of Shatsky Rise preceded the mid-Creteacous volcanism, but may represent an early outpouring from the asthenosphere in that region.

In summary, Shatsky Rise clearly formed in association with plate velocity, ridge, and triple junction reorganizations during a time (Jurassic to Early Cretaceous) when anomalous volcanic constructs formed near ridges in general and triple junctions in particular. Although the plume head hypothesis can explain many features of Shatsky Rise, it must be modified from its simplest form (i.e., a thermal diapir that rises through the mantle independently of mantle circulation) to fit this specific case. Alternatively, the rise can also be explained by anomalous volcanism induced by changes in plate boundaries and lithospheric stress (e.g., the perisphere or plate model of Anderson, 1995, this volume). Such a model requires no coincidence of triple junction location and plume impact site and explains the apparent dearth of lower-mantle rocks from Shatsky Rise. However, it also relies on unusual circumstances because of the dichotomy of Pacific plateau formation during the Jurassic and Early Cretaceous compared to the paucity of such features since. At the present, data for and against each hypothesis is incomplete and largely circumstantial. As a result, the mystery of how Shatsky Rise formed is still an open question.

CONCLUSIONS

Geological and geophysical observations can be interpreted to support the idea that Shatsky Rise formed from a plume head. There were massive, rapid initial eruptions followed by a transition to lower output (i.e., plume head to plume tail). The rise appears to contain an age progression, as would be expected from drift of the Pacific plate over the mantle. Furthermore, this age progression seems to continue in Hess Rise and has similarities to the Mid-Pacific Mountains. In addition, rise eruptions seem to have captured a nearby triple junction, pinned it in a location that does not fit kinematic stability, and caused repeated ridge jumps. Shatsky samples indicate that the rise top was subaerial, perhaps caused by thermal uplift. Arguing against the plume hypothesis are missing geochemical and isotopic evidence for lower-mantle rocks and many coincidences that must have occurred if the rise was built by plume volcanism. Initial Shatsky Rise eruptions appear to have occurred simultaneously with a reorganization of spreading directions, a remarkable coincidence if plume eruptions are unrelated to ridge tectonics. Furthermore, the eruption of a plume head within 800 km of a triple junction is a low-probability occurrence. This coincidence is compounded by the existence of other northwest Pacific plateaus (Hess Rise, Magellan Rise, Manihiki Plateau, and Mid-Pacific Mountains) that also appear to have formed at or near triple junctions. Another problem is the large apparent drift implied between plumes, if the two triple junction paths are interpreted as plume induced. A simpler explanation for these coincidences is that ridge tectonics over anomalous mantle resulted in decompression melting during changes in plate boundaries. The uniqueness of western Pacific LIP volcanism may be a result of the present-day northwest Pacific having been atop the south Pacific superswell, a region of warm mantle thought to have produced many hotspots during the Late Jurassic and Early Cretaceous.

ACKNOWLEDGMENTS

I thank Bob Duncan and John Mahoney for sharing unpublished data and observations. Reviews by Gill Foulger, Stephanie Ingle, John Mahoney, and an anonymous reviewer were very helpful in keeping the interpretations grounded. Funding for my Shatsky Rise studies has been provided by the National Science Foundation (OCE93-14229) and Joint Oceanographic Institutions/U.S. Science Support Program. This research used samples and data provided by the Ocean Drilling Program (ODP). ODP is sponsored by the U.S. National Science Foundation and participating countries under the management of JOI.

REFERENCES CITED

Anderson, D.L., 1995, Lithosphere, asthenosphere, and perisphere: Reviews of Geophysics, v. 33, p. 125–149, doi: 10.1029/94RG02785.

Anderson, D.L., 2000, The thermal state of the upper mantle; no role for mantle plumes: Geophysical Research Letters, v. 27, p. 3623–3626, doi: 10.1029/2000GL011533.

Anderson, D.L., 2001, Top-down tectonics: Science, v. 293, p. 2016–2018, doi: 10.1126/science.1065448.

Anderson, D.L., Tanimoto, T., and Zhang, Y.-S., 1992, Plate tectonics and hotspots: The third dimension: Science, v. 256, p. 1645–1651.

Bercovici, D., and Mahoney, J., 1994, Double flood basalts and plume head separation at the 660-kilometer discontinuity: Science, v. 266, p. 1367–1369.

Bralower, T. J., Premoli-Silva, I., Malone, M. J., and Shipboard Scientific Party, 2002, Proceedings of the Ocean Drilling Program, initial reports: College Station, Texas, Ocean Drilling Program, 1–148 p.

Braun, M.G., and Sohn, R.A., 2003, Melt migration in plume-ridge systems: Earth and Planetary Science Letters, v. 213, p. 417–430, doi: 10.1016/S0012-821X(03)00279-6.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the origin of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79–93, doi: 10.1016/0012-821X(90)90072-6.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: Crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1–26, doi: 10.1029/93RG02508.

Coffin, M.F., Pringle, M.S., Duncan, R.A., Gladczenko, T.P., Storey, M., Müller, R.D., and Gahagan, L.A., 2002, Kerguelen hotspot magma output since 130 Ma: Journal of Petrology, v. 43, p. 1121–1139, doi: 10.1093/petrology/43.7.1121.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponier, P., and Besse, J., 1999, On causal links between flood basalts and continental breakup: Earth and Planetary Science Letters, v. 166, p. 177–195, doi: 10.1016/S0012-821X(98)00282-9.

Courtillot, V., Davaille, A., Besse, J., and Stock, J., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295–308, doi: 10.1016/S0012-821X(02)01048-8.

Den, N., Ludwig, W.J., Murauchi, A., Ewing, J.I., Hotta, H., Edgar, N.T., Yoshii, T., Asanuma, T., Hagiwara, K., Sato, T., and Ando, A., 1969, Seismic-refraction measurements in the northwest Pacific Basin: Journal of Geophysical Research, v. 74, p. 1421–1434.

DePaolo, D.J., and Manga, M., 2003, Deep origin of hotspots—The mantle plume model: Science, v. 300, p. 920–921, doi: 10.1126/science.1083623.

Duncan, R.A., 2002, A time frame for construction of the Kerguelen Plateau and Broken ridge: Journal of Petrology, v. 43, p. 1109–1119, doi: 10.1093/petrology/43.7.1109.

Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts, and true polar wander: Reviews of Geophysics, v. 29, p. 31–50.

Eldholm, O., and Coffin, M.F., 2000, Large igneous provinces and plate tectonics, *in* Gordon, R.G, and van der Hilst, R.D., eds., The history and dynamics of global plate motions: Washington, D.C., American Geophysical Union Geophysical Monograph 121, p. 309–326.

Ewing, M., Saito, T., Ewing, J.I., and Burkle, L.H., 1966, Lower Cretaceous sediments from the northwest Pacific: Science, v. 152, p. 751–755.

Fitton, J.G., Saunders, A.D., Norry, M.J., Hardarson, B.S., and Taylor, R.N., 1997, Thermal and chemical structure of the Iceland plume: Earth and Planetary Science Letters, v. 153, p. 197–208, doi: 10.1016/S0012-821X(97)00170-2.

Foulger, G.R., 2002, Plumes, or plate tectonic processes?: Astronomy and Geophysics, v. 43, p. 6.19–6.23.

Foulger, G.R., and Natland, J.H., 2003, Is "hotspot" volcanism a consequence of plate tectonics?: Science, v. 300, p. 921–922, doi: 10.1126/science.1083376.

Frey, F.A., and Weis, D., 2003, The Kerguelen plume: What have we learned from ~120 Myr of volcanism?: Penrose Conference, Plume IV: Beyond the plume hypothesis, 25–29 August 2003, Hveragerdi, Iceland, Abstracts.

Georgen, J.E., and Lin, J., 2002, Three-dimensional passive flow and temperature structure beneath oceanic ridge-ridge-ridge triple junctions: Earth and Planetary Science Letters, v. 204, p. 115–132.

Gettrust, J.F., Furukawa, K., and Kroenke, L.W., 1980, Crustal structure of the Shatsky Rise from seismic refraction measurements: Journal of Geophysical Research, v. 85, p. 5411–5415.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., and Huang, Z., 1995, A Triassic, Jurassic and Cretaceous time scale, *in* Berggren, W.A., et al., eds., Geochronology, time scales, and global stratigraphic correlation: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 54, p. 95–126.

Griffiths, R.W., and Campbell, I.H., 1990, Stirring and structure in mantle starting plumes: Earth and Planetary Science Letters, v. 99, p. 66–78, doi: 10.1016/0012-821X(90)90071-5.

Griffiths, R.W., and Campbell, I.H., 1991, Interaction of mantle plume heads with the Earth's surface and onset of small-scale convection: Journal of Geophysical Research, v. 96, p. 18,295–18,310.

Hieronymous, C.F., and Bercovici, D., 2000, Non-hotspot formation of volcanic chains: Control of tectonic and flexural stresses on magma transport: Earth and Planetary Science Letters, v. 181, p. 539–554, doi: 10.1016/S0012-821X(00)00227-2.

Hilde, T.W.C., Isezaki, N., and Wageman, J.M., 1976, Mesozoic seafloor spreading in the north central Pacific, *in* Sutton, G.H., et al., eds., The geophysics of the Pacific Ocean basin and its margin: Washington, D.C., American Geophysical Union Geophysical Monograph 19, p. 205–226.

Hildebrand, A.R., and Boynton, W.V., 1990, Proximal Cretaceous-Tertiary boundary impact deposits in the Caribbean: Science, v. 248, p. 843–847.

Ingle, S., and Coffin, M.F., 2004, Impact origin for the Ontong Java Plateau?: Earth and Planetary Science Letters, v. 218, p. 123–134, doi: 10.1016/S0012-821X(03)00629-0.

Ito, G., and Clift, P., 1998, Subsidence and growth of Cretaceous Pacific plateaus: Earth and Planetary Science Letters, v. 161, p. 85–100, doi: 10.1016/S0012-821X(98)00139-3.

Jellinek, A.M., Gonnermann, H.M., and Richards, M.A., 2003, Plume capture by divergent plate motions: Implications for the distribution of hotspots, geochemistry of mid-ocean ridge basalts, and estimates of the heat flux at the core mantle boundary: Earth and Planetary Science Letters, v. 205, p. 361–378, doi: 10.1016/S0012-821X(02)01070-1.

Johnston, S.T., and Thorkelson, D.J., 2000, Continental flood basalts: Episodic magmatism above long-lived hotspots: Earth and Planetary Science Letters, v. 175, p. 247–256 , doi: 10.1016/S0012-821X(99)00293-9.

Kleinrock, M.C., and Phipps Morgan, J., 1988, Triple junction reorganization: Journal of Geophysical Research, v. 93, p. 2981–2996.

Klitgord, K.D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, *in* Vogt, P.R., and Tucholke, B.E., eds., The western north Atlantic region: Decade of North American geology, vol. M: Boulder, Colorado, Geological Society of America, p. 351–378.

Koppers, A.A.P., Staudigel, H., Pringle, M.S., and Wijbrans, J.R., 2003, Short-lived and discontinuous intraplate volcanism in the South Pacific: Hot spots or extensional volcanism?: Geochemistry, Geophysics, and Geosystems, v. 4, 1089, doi: 101029/2003GC000533.

Larson, R.L., 1991, Latest pulse of the Earth: Evidence for a Mid-Cretaceous superplume: Geology, v. 19, p. 547–550, doi: 10.1130/0091-7613(1991)019<0547:LPOEEF>2.3.CO;2.

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, doi: 10.1130/0091-7613(1997)025<0779:SARIBO>2.3.CO;2.

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., Moberly, R., and Shipboard Scientific Party, 1975, Initial Reports of the Deep Sea Drilling Project, v. 32: Washington, D.C., U.S. Government Printing Office.

Larson, R.L., Steiner, M.B., Erba, E., and Lancelot, Y., 1992, Paleolatitudes and tectonic reconstructions of the oldest portion of the Pacific plate: A comparative study, *in* Proceedings of the Ocean Drilling Program, scientific results, v. 129: College Station, Texas, Ocean Drilling Program, p. 615–631.

Larson, R.L., Pockalny, R.A., Viso, R.F., Erba, E., Abrams, L.J., Luyendyk, B.P., Stock, J.M., and Clayton, R.W., 2002, Mid-Cretaceous tectonic evolution of the Tongareva triple-junction in the southwestern Pacific basin: Geology, v. 30, p. 67–70, doi: 10.1130/0091-7613(2002)030<0067:MCTOET>2.0.CO;2.

Lithgow-Bertelloni, C., and Richards, M.A., 1998, The dynamics of Cenozoic and Mesozoic plate motions: Reviews of Geophysics, v. 36, p. 27–78, doi: 10.1029/97RG02282.

Ludwig, W.J., and Houtz, R.E., 1979, Isopach map of sediments in the Pacific Ocean basin and marginal sea basins: Tulsa, Oklahoma, American Association of Petroleum Geologists, 2 sheets, scale 1:13,999,369.

Mahoney, J.J., Duncan, R.A., Tejada, M.L.G., and Sager, W.W., 2005, Jurassic-Cretaceous boundary age and mid-ocean-ridge type mantle source for Shatsky Rise: Geology, v. 33, p. 185–188, doi: 10.1130/G21378.1.

Mammerickx, J., and Sharman, G.F., 1988, Tectonic evolution of the north Pacific during the Cretaceous Quiet Period: Journal of Geophysical Research, v. 93, p. 3009–3024.

McNutt, M.K., and Fisher, K.M., 1987, The South Pacific superswell, *in* Keating, B.H., et al., eds., Seamounts, islands, and atolls: Washington, D.C., American Geophysical Union Geophysical Monograph 43, p. 25–34.

McNutt, M.K., Winterer, E.L., Sager, W.W., Natland, J.H., and Ito, G., 1990, The Darwin Rise: A Cretaceous superswell?: Geophysical Research Letters, v. 17, p. 1101–1104.

Morgan, W.J., 1971, Deep mantle convection plumes in the lower mantle: Nature, v. 230, p. 42–43.

Morgan, W.J., 1972, Deep mantle convection plumes and plate motions: American Association of Petroleum Geologists Bulletin, v. 56, p. 42–43.

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, doi: 10.1029/98JB00754.

Nakanishi, M., Tamaki, K., and Kobayashi, K., 1989, Mesozoic magnetic anomaly lineations and seafloor spreading history of the northwestern Pacific: Journal of Geophysical Research, v. 94, p. 15,437–15,462.

Nakanishi, M., Tamaki, K., and Kobayashi, K., 1992, Magnetic anomaly lineations from late Jurassic to Early Cretaceous in the west-central Pacific ocean: Geophysical Journal International, v. 109, p. 701–719.

Nakanishi, M., Sager, W.W., and Klaus, A., 1999, Magnetic lineations within

Shatsky Rise, northwest Pacific Ocean: Implications for hot spot–triple junction interaction and oceanic plateau formation: v. 104, p. 7539–7556.

Neprohnov, Y.P., Merklin, L.R., and Khankishiyeva, L.M., 1984, Map of distribution of sedimentary cover on the Shatsky Rise: Doklady Akademik Nauk SSSR [English Translation], v. 277, p. 119–122.

Pringle, M., Chambers, L., and Ogg, J., 2003, Synchronicity of volcanism on Ontong Java and Manihiki plateaux with global oceanographic events?: EGS-AGU-EUG Joint Assembly, 6–11 April 2003, Nice, France, EGS-AGU Spring Meeting Abstracts, EAE03-A-13768.

Pringle, M.S., and Dalrymple, G.B., 1993, Geochronological constraints on possible hotspot origin for Hess Rise and the Wentworth seamount chain, *in* Pringle, M.S., et al., eds., The Mesozoic Pacific: Geology, tectonics, and volcanism: Washington, D.C., American Geophysical Union Geophysical Monograph 77, p. 263–277.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot-spot tracks: Plume heads and tails: Science, v. 246, p. 103–107.

Rogers, G.C., 1982, Oceanic plateaus as meteorite impact signatures: Nature, v. 299, p. 341–342, doi: 10.1038/299341a0.

Sager, W.W., and Han, H.-C., 1993, Rapid formation of Shatsky Rise oceanic plateau inferred from its magnetic anomaly: Nature, v. 364, p. 610–613, doi: 10.1038/364610a0.

Sager, W.W., Handschumacher, D.W., Hilde, T.W.C., and Bracey, D.R., 1988, Tectonic evolution of the northern Pacific plate and Pacific-Farallon-Izanagi triple junction in the Late Jurassic and Early Cretaceous (M21–M10): Tectonophysics, v. 155, p. 345–364, doi: 10.1016/0040-1951(88)90274-0.

Sager, W.W., Fullerton, L.G., Buffler, R.T., and Handschumacher, D.W., 1992, Argo abyssal plain magnetic lineations revisited: Implications for the onset of seafloor spreading and tectonic history of the eastern Indian Ocean: Proceedings of the Ocean Drilling Program, scientific results, v. 123: College Station, Texas, Ocean Drilling Program, p. 659–669.

Sager, W.W., Kim, J., Klaus, A., Nakanishi, M., and Khankishieva, L.M., 1999, Bathymetry of Shatsky Rise, northwest Pacific Ocean: Implications for ocean plateau development at a triple junction: Journal of Geophysical Research, v. 104, p. 7557–7576, doi: 10.1029/1998JB900009.

Sandwell, D.T., and MacKenzie, K.R., 1989, Geoid height versus topography for oceanic plateaus and swells: Journal of Geophysical Research, v. 94, p. 7403–7418.

Sleep, N.H., 2003, Mantle plumes?: Astronomy and Geophysics, v. 44, p. 1.11–1.13.

Sliter, W.V., and Brown, G.R., 1993, Shatsky Rise: Seismic stratigraphy and sedimentary record of Pacific paleoceanography since the Early Cretaceous: Proceedings of the Ocean Drilling Program, scientific results, v. 132: College Station, Texas, Ocean Drilling Program, p. 3–13.

Smith, A.D., 2003, The regular distribution of intraplate volcanism in the Pacific basin: Penrose Conference, Plume IV: Beyond the plume hypothesis, 25–29 August 2003, Hveragerdi, Iceland, Abstracts.

Smith, A.D., and Lewis, C., 1999, The planet beyond the plume hypothesis: Earth Science Reviews, v. 48, p. 135–182, doi: 10.1016/S0012-8252(99)00049-5.

Stein, C.A., and Abbott, D., 1991, Heat flow constraints on the South Pacific superswell: Journal of Geophysical Research, v. 96, p. 16,083–16,100.

Tackley, P.J., Stevenson, D.J., Glatzmaier, G.A., and Schubert, G., 1993, Effects of an endothermic phase transition at 670 km depth in a spherical model of convection in the Earth's mantle: Nature, v. 361, p. 699–704, doi: 10.1038/361699a0.

Tamaki, K., and Larson, R.L., 1988, The Mesozoic tectonic history of the Magellan microplate in the western central Pacific: Journal of Geophysical Research, v. 93, p. 2857–2874.

Tatsumi, Y., Shinjoe, H., Ishizuka, H., Sager, W.W., and Klaus, A., 1998, Geochemical evidence for a mid-Cretaceous superplume: Geology, v. 26, p. 151–154, doi: 10.1130/0091-7613(1998)0262.3.CO;2.

Tejada, M., Mahoney, J.J., Sager, W.W., and Shipboard Scientific Party, 1995, Isotopic study of basement rocks from Shatsky Rise, northwestern Pacific Ocean [abstract]: Eos (Transactions, American Geophysical Union), v. 76, p. F699.

Tejada, M.L.G., Mahoney, J.J., Castillo, P.R., Ingle, S., Sheth, H.C., and Weis, D., 2004, Pin-pricking the elephant: Evidence on the origin of Ontong Java Plateau from Pb-Sr-Hr-Nd isotopic characteristics of ODP Leg 192 basalts, *in* Fitton, J.G., et al., eds., Origin and evolution of the Ontong Java Plateau: London, Geological Society of London Special Publication 229, p. 133–150.

Tominaga, M., Sager, W.W., and Channell, J.E.T., 2005, Paleomagnetism of the igneous section, Hole 1213B, Shatsky Rise: Proceedings of the Ocean Drilling Program, scientific results, v. 198: College Station, Texas, Ocean Drilling Program, in press, http://www-odp.tamu.edu/publications/198_SR/113/113.htm.

White, R.S., and McKenzie, D.P., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.

Wilson, J.T., 1963, A possible origin of the Hawaiian Islands: Canadian Journal of Physics, v. 41, p. 863–870.

Winterer, E.L., 1976, Anomalies in the tectonic evolution of the Pacific, *in* Sutton, G.H., et al., eds., The geophysics of the Pacific Ocean basin and its margin: Washington, D.C., American Geophysical Union Geophysical Monograph 19, p. 269–282.

Winterer, E.L., and Sager, W.W., 1995, Synthesis of drilling results from the Mid-Pacific Mountains: Regional context and implications: Proceedings of the Ocean Drilling Program, scientific results, v. 143: College Station, Texas, Ocean Drilling Program, p. 497–535.

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 Accepted by the Society January 3, 2005