Reports

Rapid Formation of Ontong Java Plateau by Aptian Mantle Plume Volcanism

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The timing of flood basalt volcanism associated with formation of the Ontong Java Plateau (OJP) is estimated from paleomagnetic and paleontologic data. Much of OJP formed rapidly in less than 3 million years during the early Aptian, at the beginning of the Cretaceous Normal Polarity Superchron. Crustal emplacement rates are inferred to have been several times those of the Deccan Traps. These estimates are consistent with an origin of the OJP by impingement at the base of the oceanic lithosphere by the head of a large mantle plume. Formation of the OJP may have led to a rise in sea level that induced global oceanic anoxia. Carbon dioxide emissions likely contributed to the mid-Cretaceous greenhouse climate but did not provoke major biologic extinctions.

MASSIVE OUTPOURINGS OF LAVA known as continental flood basalts have been linked to phenomena as varied as continental breakup, climatic change, and global extinctions. Certain flood basalt provinces, such as the Deccan Traps of India, may be sites where large heads of mantle plumes penetrated the continental lithosphere (*1, 2*). This model relies on two key observations. First, many continental flood basalts record the earliest volcanism of hot-spot tracks, which are believed to mark out on moving lithospheric plates the trace of plumes fixed deeper in the mantle. Second, flood-basalt volcanism is geologically brief (<1 million years) in duration; thus, eruption rates must be much greater than those occurring at present-day hot spots (*3*). If this model is correct, hot-spot initiation should also leave distinctive features on the oceanic lithosphere. Some oceanic plateaus backtrack to active hot spots through plate reconstructions; thus, they are prime candidates for initiation sites (*3*), but the timing of volcanism that formed most oceanic plateaus is largely unknown. In this report, we describe paleomagnetic and paleontologic data from new drill sites on the largest oceanic plateau, the Ontong Java Plateau (OJP), acquired during Leg 130 of the Ocean Drilling Program. These data are combined with data from sites elsewhere in the Pacific basin to estimate the time of initiation and the duration of OJP volcanism.

Earlier, in Leg 30 of the Deep Sea Drilling Project (DSDP) two sequences were drilled that bear on the origin of the OJP. At DSDP Site 288, on the southern part of the plateau (Fig. 1), although basement was not reached, limestone of late Aptian to Coniacian age was recovered (*4*). The oldest samples belong to the *Ticinella bejaouaensis* foraminiferal Zone (*5*). At DSDP Site 289, on the northern plateau, approximately 9 m of basaltic basement was penetrated (Fig. 2). Recent Pb, Nd, and Sr isotopic data for this basalt are consistent with a hot-spot type source (*6*) and show no evidence for the presence of continental crust under the plateau, as postulated on the basis of earlier seismic refraction studies (*7*). Paleomagnetic measurements indicate that the basalt was erupted during an episode of constant normal polarity (*8*), most likely the Cretaceous Normal Polarity Superchron (K-N). The Cretaceous sedimentary sequence above basement contains late Aptian limestone, which overlies and is interbedded with altered tuff (*4*), an overlying 80-cm interval of reddish-brown zeolitic claystone, and at the top a Maastrichtian-Campanian limestone. The oldest fossils in the sequence fall within the *Globigerinelloides ferreolensis* foraminiferal Zone (*5, 9*).

Two additional basement sites, Sites 803 and 807, were recently drilled during ODP Leg 130 on the northern part of the plateau (*10*) (Fig. 1). In a single 10-m core from Site 803, carbonate with nannofossils characteristic of those near the Cretaceous-Tertiary (K-T) boundary grade downward into claystone devoid of calcareous microfossils. Several intervals within the claystone contain radiolarians of the upper *Acaeniotyle umbilicata* to lower *Abesacapula sophedia* zones, indicating a late Albian to early Cenomanian age (*11*). Because late Albian to Paleocene ages are represented by less than 10 m of section, extremely slow sedimentation rates or major hiatuses are indicated. The lowermost datable radiolaria are located 0.6 m above the first basalt. The radiolarian age thus may substantially underestimate the age of basaltic basement. Beneath the claystone, 26 m of altered tholeiitic pillow basalt was penetrated. The basalt is capped by a 2-cm-thick layered deposit, likely of hydrothermal origin. Paleomagnetic analyses of the basalt flows indicate that they are of constant normal polarity, as at Site 289 (*10*).

Site 807, located in a small (3 km by 1.5 km) graben in the top of basement, provides the clearest picture of the timing of the cessation of volcanism responsible for OJP formation (Fig. 2). The sedimentary sequence recovered at Site 807 is remarkably

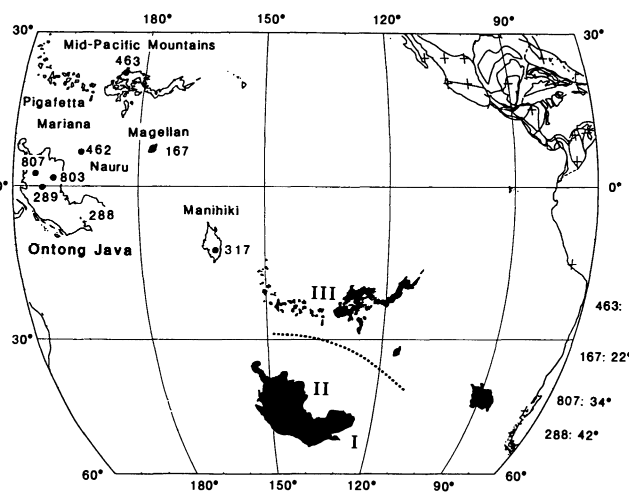

Fig. 1. Present-day locations of the Ontong Java Plateau, Mid-Pacific Mountains, Manihiki Plateau, and Magellan Rise (4000 m contour) and reconstructed positions at 120 Ma (shaded) using a fixed hot-spot rotation frame (*40*). Paleolatitude values for selected sites (on right) are derived from the apparent polar wander path for the Pacific Plate (spin axis) (*42*) and differ from the hot-spot reference frame (mantle) illustrating true polar wander.

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like that of Site 289 but greatly expanded. Maastrichtian-Campanian limestone overlies 18 m of reddish-brown claystone, which overlies approximately 10 m of limestone, which directly overlies basement. As at Site 803, the claystone is barren of calcareous microfossils but yields a similar radiolarian fauna indicative of a late Albian to early Cenomanian age (*11*). If conditions had not favored the preservation of carbonate above basement at Site 807, the paleontologically determined minimum age would be identical to that of Site 803. Foraminifera are preserved directly above basement (sample 807C-74R-1-24), however, and the taxa are of the *Globigerinelloides blowi* Zone, indicating an early Aptian age, some 15 million years older than the overlying radiolarians.

In all, 148.7 m of fresh, tholeiitic basalt consisting of both pillow and massive flows was penetrated. The massive flows are mostly less than 3 m thick but one is 28 m thick, comparable in thickness to flows in continental flood basalt provinces. Resistivity data from logging suggest that the hole was terminated at the top of another thick massive flow. The basement sequence can be divided into five volcanic subunits and two sedimentary subunits represented by thin layers (0.07 to 0.50 m) of vitric tuff and limestone (*12*). The thickness of the limestone interbeds suggests that the waning stages of volcanism recorded at Site 807 likely spanned a period of at least thousands of years. The presence of tuff associated with basement here as well as at Site 289, suggests that a shallow-water source was present on the plateau.

Many cores recovered at Site 807 consisted of long (>0.5 m), continuous basalt segments, and it was thus possible to measure the natural remanent magnetizations (NRM) of 1.5-m-long sections on ship. All measurements yielded negative inclinations (*10*). If the NRM is dominated by a primary remanence, in accord with the unaltered nature of the flows, then the entire sequence is of normal polarity because the OJP was in the Southern Hemisphere during Cretaceous times (*8*). Detailed thermal and alternating-field demagnetization of 55 specimens performed on shore confirmed this inference, which is consistent with magnetization within the K-N Superchron.

Unless cores of reversed polarity chron M0 have been omitted from collection by chance, the available data suggest that much of the plateau formed during a relatively brief part of the early Aptian. A limitation of the deep sea drilling data, however, is our knowledge of a true cross section of the OJP; if the plateau is composed of flood basalts several kilometers thick (*13*), then some age progression may be hidden in the largely unsampled mass of the plateau. The effects of an early Aptian plume large enough to account for the great area of the OJP ($>1.5 \times 10^6$ km^2) (*13*) would likely be recorded widely in the contemporaneous Pacific basin. Therefore, to test this hypothesis we examined deep sea drilling sites that were proximal to and distant from the OJP in the early Aptian.

Several attempts have been made to recover Jurassic sediments and crust from the Nauru and Marianas basins, which are proximal to the OJP. Site 462 (DSDP Leg 61) in the Nauru basin (Fig. 1) is on crust that formed in Oxfordian times [magnetic anomaly M-26 (reversed)] (*14*). Instead of Jurassic sediments, an extensive intrusive and extrusive sequence of basalt, at least 500 m thick (Fig. 2) was encountered. Both the sills and flows were of normal polarity (*15*). The hole was deepened during Leg 89, and an additional 140 m of basalt was penetrated, all of normal polarity (*16*). Radiolarians

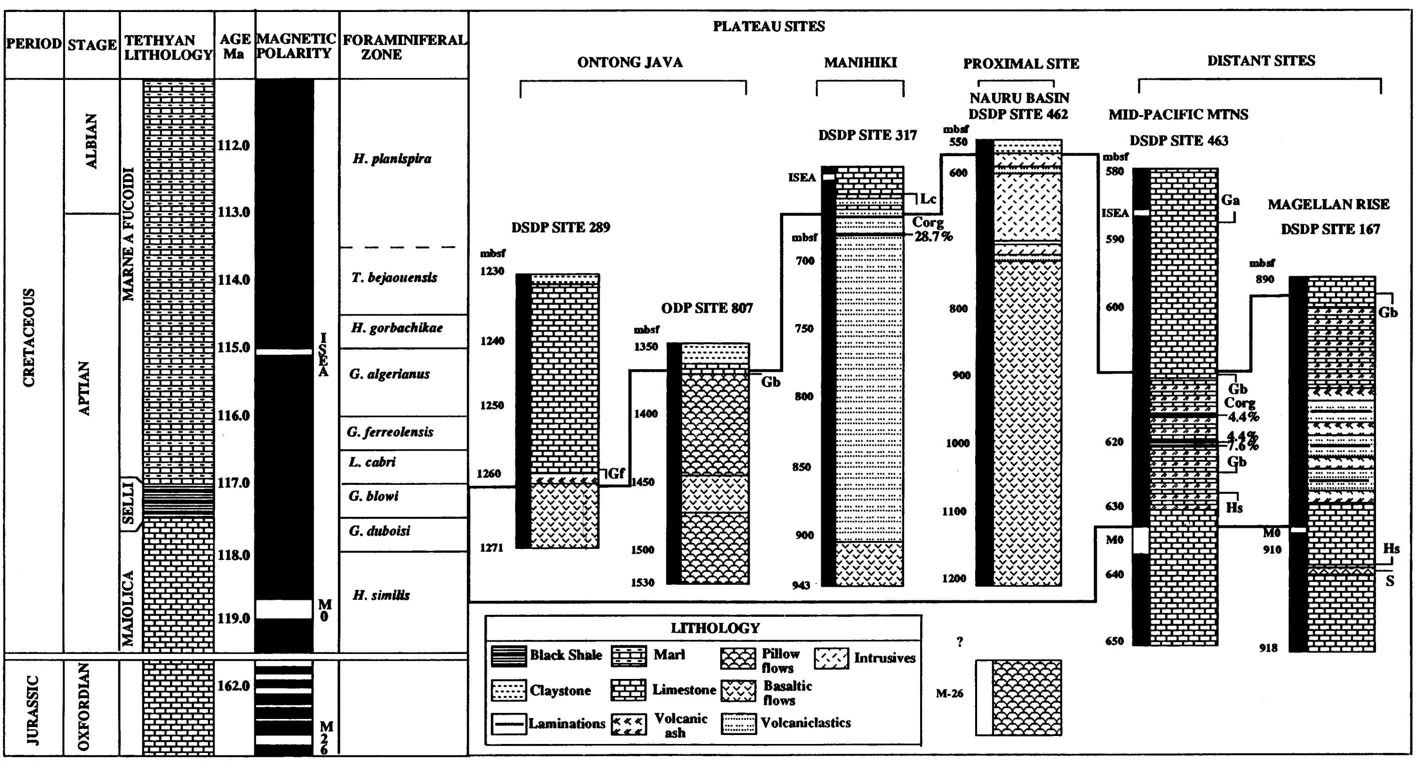

Fig. 2. Major lithology, paleomagnetic polarity, and foraminiferal age for representative Pacific Plate deep sea drilling sites. Paleomagnetic and paleontologic data from OJP Site 807 constrain volcanism at that site to a brief portion of the early Aptian postdating reversed polarity chron M0 and predating the *L. cabri* foraminiferal zone. This interval (shaded) correlates with basement formation of the Manihiki Plateau (Site 317), early Aptian volcanism overlying Jurassic crust in the Nauru basin (Site 462) and volcanic ash in the sedimentary columns of the Mid-Pacific Mountains (Site 463) and Magellan Rise (Site 167). Data sources as follows: magnetostratigraphy, Sites 317, 463, and 167 (*22, 23, 53*); Site 462 (15, 16); Site 289 (*8*); biostratigraphy, Sites 463 and 167 (*22*); Sites 317 and 289 (*5, 46*). Site 462 is not constrained in age by foraminifera; however, radiolaria suggest an early Aptian age (*17*). Abbreviations: Corg, intervals of unusually high preservation of organic carbon shown as weight percent; Gf, *G. ferreolensis* Zone; Gb, *G. blowi* Zone; Lc, *L. cabri* Zone; Hs, *H. similis* Zone; upward arrow, first occurrence; downward arrow, last occurrence; straight line, within zone; S, sedimentary slide boundary (*22*).

recovered in thin sedimentary interbeds of both legs are of early Aptian age (*17*). The Sr, Nd, and Pb isotopic compositions of the Nauru Basin basalts overlap with those from the OJP; thus, these basalts may have related mantle sources (*6*).

Three sites were drilled in the Pigafetta and East Marianas Basins on Leg 129 (*18*) (Fig. 1). At Site 802 in the East Marianas Basin, the lowermost sediments recovered were brown pelagic clay and claystone of Albian-Aptian age. These sediments overlie volcaniclastic rocks, which in turn overlie basaltic flows of normal magnetic polarity (*18*). The isotopic compositions of these basalts are also similar to those from the OJP (*19*). Whole-rock $^{40}Ar/^{39}Ar$ incremental-heating analyses of the basalts from Site 802 yielded a date of 117 ± 2 Ma, consistent with an early Aptian age (*19*).

At Site 800 in the Pigafetta Basin, Jurassic crust also was not reached. Instead, a lower Cretaceous (Berriasian) claystone was recovered overlying a dolerite sill. Above the basal claystone and below pelagic deposits (Albian and younger chert and limestone) a thick sequence of volcaniclastic turbidites was recovered, of early Aptian age. These deposits mark the erosion of a volcanic source. At Site 801 in the Pigafetta basin Jurassic crust was finally penetrated below (as at Site 800) a sequence of volcaniclastic turbidites of Albian-Aptian(?) age packaged between nonvolcanically derived pelagic deposits.

The various drilling expeditions to the basins north of the OJP indicate that these areas were affected by a massive Early Cretaceous volcanic episode (*20*). Even though the lack of calcareous fossils in these deep basin sites precludes the identification of foraminiferal stage, the available paleomagnetic, paleontologic, and sedimentologic data are consistent with an early Aptian age for this episode, coeval with OJP volcanism. The extensive intrusive and extrusive sequences, younger than basement, may represent the effects of plume initiation centered at or close to the OJP.

The most precise recorders of a broad plume source far from its center would be volcanic ash intercalated in carbonate sedimentary rocks deposited on bathymetric highs, because such sediments can be dated accurately by calcareous microfossils. Two DSDP sites in the southwestern central Pacific may meet these criteria: Site 167 on Magellan Rise and Site 463 in the western Mid-Pacific Mountains (Fig. 1).

At Site 167, 345 m of Tithonian-Berriasian through Turonian sediments was penetrated above basaltic basement (*21*). The sediments are mainly limestones, with one important exception; within the Aptian carbonates is an interval several meters thick of volcaniclastic rock including both altered and fairly fresh volcanic glass, possibly of pyroclastic origin (Fig. 2). Little or no volcanic material occurs in younger or older sediments. Although dating is hampered by sedimentary sliding, foraminifera bracketing the interval suggest that the age is within the lower Aptian *G. blowi* Zone (*22*), the same zone found in the oldest sediments overlying the OJP.

Both reversed polarity chron M0 and the ISEA reversed polarity chron (*23*) have been identified in the Aptian carbonate sequence recovered at Site 463 (Fig. 2). Between the two reversed polarity intervals is a distinct interval of ashy limestone (*24*); little or no ash occurs below and above. In addition, three horizons with abundant organic carbon occur within the same interval of limestone. As at Site 167, the limestone with volcanic debris falls within the *G. blowi* Zone. Thus, at both distant Pacific reference sites a voluminous volcanic contribution is recorded in an interval coinciding precisely with the best paleontologic and paleomagnetic age estimates for the OJP volcanism, and there is little of such material in the rest of the sedimentary section.

In summary, the available age data from sites on the plateau, proximal basin sites, and distant reference sites suggest that much of the OJP formed in a relatively short period during the early Aptian, between reversed polarity chron M0 and the top of the *G. blowi* foraminiferal Zone. Harland *et al.* (*25*) estimated that the top of *G. blowi* Zone is at approximately 117.7 Ma and that reversed polarity chron M0 is at 118.2 Ma; for these estimates, the duration of OJP volcanism is less than 1 million years. A recent revision of the time scale (*26*) suggests that the Aptian Stage was over twice as long (12.5 million years) as the original estimate. The revised time scale places the top of the *G. blowi* Zone at 121 Ma and the top of reversed polarity chron M0 at 124 Ma; in this case OJP volcanism would have occurred over 3 million years. Although we have reservations about the details of the revised absolute ages (*26*), we will apply these because they suggest a longer, and hence more conservative estimate of the duration of OJP volcanism.

We propose that the OJP formed from a broad plume source that is recorded in three zones surrounding the plume center (Fig. 1). Closest to the plume head center, the OJP formed (interval I). Farther away, fissures formed (*27*) in areas of lithospheric weakness (perhaps fracture zones), and the oceanic crust was capped by volcanic flows and intruded with sills (interval II). Because the magmatic episode was brief, during an interval of constant magnetic polarity, the marine magnetic anomaly structure of the preexisting oceanic basement was preserved. Beyond this zone, seamount volcanism was still induced (interval III), and volcanigenic debris was derived from the seamounts and perhaps even exceptional eruption of ash on the OJP. Although OJP emplacement is used, in part, to define the "superplume" of Larson (*28*), the superplume is represented by increased volcanic activity over 41 million years. In contrast, our model is for volcanism on a much shorter time scale, which we here term the "Ontong Java event."

Using global elevation data and an assumption of Airy isostasy (constrained by seismic refraction data), Schubert and Sandwell (*29*) estimated the volume of the OJP as 51×10^6 km^3. This volume estimate is for a base depth (seafloor) of 4.65 km and implies that lithosphere surrounding the plateau has been thermally rejuvenated, because the OJP is substantially shallower than predicted by sediment loading and subsidence due to cooling (*30*). If the crust has followed a normal subsidence curve but is anomalously shallow because of thickening caused by Aptian volcanism, as observed in the Nauru Basin, a greater base depth would be more appropriate. For a base depth of 6.0 km to account for the outlying volcanic rocks, the total volume is 91×10^6 km^3. To obtain the crustal volume related to the formation of the plateau, we must subtract the volume of preexisting crust (*31*). If the plateau formed entirely on preexisting crust (a conservative estimate), volumes of 24×10^6 and 65×10^6 km^3 result, corresponding to the base depths of 4.65 and 6.0 km, respectively.

Magma emplacement rates required to produce such a volume in the 3 million years range from 8 to 22 km^3/year. Because we link volcanism in the Nauru basin to the Ontong Java event, our preferred estimate is the larger of these numbers. This rate is more than several times greater than rates calculated for continental flood basalts such as the Deccan Traps (*3*), even if underplating is included in the latter (Fig. 3). Uncertainties in the emplacement rate for OJP include contributions due to subsequent minor volcanic episodes (plume tail) (*32*), the possibility that large volumes have been subducted, and time-scale errors. If our bounds on volume and the duration of volcanism are accurate, however, the Ontong Java event may be the largest volcanic event of the past 200 million years.

Because cooling in the mantle is a control on the thermal structure of the core (*33*), the chronology of geomagnetic field reversals may provide a proxy measure of long-term conditions at the core-mantle boundary useful for understanding the initiation of the mantle plume postulated to form the OJP.

The reversal chronology (Fig. 3) likely reflects temperature at the core-mantle boundary and hence may be a measure of mantle convection (*34*). Minima in reversal frequency are represented by the K-N Superchron and the Kiaman Reversed Polarity Superchron (*35*); OJP volcanism coincides with the beginning of the K-N Superchron.

The thickness and temperature of D″, the seismically determined layer thought to mark a thermal boundary layer at the base of the mantle, have been suggested to reach a maximum during the K-N Superchron (*35–37*). Courtillot and Besse (*36*) suggested that D″ became unstable then and that mantle plumes were formed. These plumes were inferred to have resulted in an increase in mantle convection, reversal frequency, and true polar wander, and to have formed the Deccan flood basalts. The volume and emplacement rate of the OJP eclipse those of the younger Deccan Traps and this plume activity may have been greatest at the beginning of the K-N Superchron. No single plume would be able to break up completely D″ and initiate reversals; for reasonable ascent rates (*36, 38*), reversal rate does not increase after formation of even a large OJP plume. Rather mantle convection must transfer heat from the core-mantle boundary to create a temperature gradient favorable for vigorous outer-core convection, as is consistent with the long normal period.

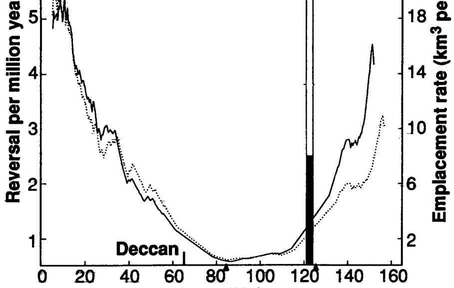

Fig. 3. Geomagnetic reversal rate per million years versus age for two recent time scales with the addition of a short reversed polarity event in the late Aptian (*23*). Reversal frequency calculated by a sliding window of 25 polarity intervals shifted by one reversal for each estimate, modified from (*34*). Solid line, Harland *et al.*, 1989 (*26*); dotted line, Harland *et al.*, 1982 (*25*). Solid triangles mark location of the Cretaceous Normal Polarity Superchron using the Harland *et al.*, 1989 time scale. Also shown versus the Harland *et al.*, 1989 time scale are estimated emplacement rates for the Deccan Traps (*3*) and Ontong Java Plateau (OJP). Emplacement rate for the Deccan Traps is a minimum due to the unknown amount of underplating. Emplacement rates for OJP range from 8 km^3/year (solid rectangle) to 22 km^3/year (open rectangle and preferred estimate) based on bounds on OJP volume.

The OJP has been backtracked to the Louisville hot spot (*39, 40*), currently located at ~51°S (*41*). Data from the Pacific apparent polar wander path (*42*) suggest that the OJP was between 34°S and 42°S during the Early Cretaceous (Sites 807 and 288, respectively) (Fig. 1). Southward motion of the hot spot is indicated since its formation, in the same sense but of a larger extent than that calculated from Suiko seamount (paleolatitude 27°N) (*43*), a seamount that backtracks to the active Hawaiian hot spot (latitude 19.5°N). Such motion is consistent with increased true polar wander due to OJP formation.

If the OJP formed rapidly as suggested, it might have had other global consequences. In Cretaceous pelagic rocks exposed in the Umbrian Apennines of northern Italy (*44*) a distinct horizon of organic carbon is preserved in a 1- to 3-m interval of the lower Aptian *G. blowi* Zone (*45*). This interval, called the Selli level, has recently been shown to be of global extent (*22, 46, 47*) and apparently records a short-term rise of eustatic sea level of some 75 m (*48*).

Several authors have proposed that a broad period of increased volcanism produced a change in sea level that resulted in oceanic anoxia and preservation of organic carbon (*49*). The relation of the Selli level to OJP volcanism is illustrated at Site 463 (Fig. 2) where limestone of the *G. blowi* Zone contains ash (*24*) and three intervals with high organic carbon contents representing the Selli Level (*22, 46*).

By itself, even the addition of the great volume of the OJP may not account for such a large change in sea level (*50*), but two other great oceanic plateaus may be coeval with the OJP. At DSDP Site 317 on the Manihiki Plateau, Aptian limestone and volcanigenic sandstone and siltstone overlie basaltic basement (*51*). Isotopic analyses of basalts have been interpreted as strong evidence for a hot-spot source (*6*). The oldest planktonic foraminifera are of the lower Aptian *Leupoldina cabri* Zone and are separated from basement by nearly 250 m of volcaniclastic rocks. In neither the sediments nor in the ten flows penetrated by drilling has reversed polarity chron M0 been identified (*23, 52–53*). A thin layer rich in organic carbon in the volcaniclastic rocks has been tentatively correlated with the Selli level (*46*) (Fig. 2). These data suggest that basement at Site 317 formed during a brief part of the early Aptian. If Site 317 is representative of the Manihiki Plateau as a whole, an oceanic crustal volume of some 13 × 10^6 km^3 may have been created in a time period nearly identical to that of the OJP (*54*). The southern parts of the Kerguelen Plateau of the Indian Ocean also may have been formed in early Aptian time, by initiation of the Kerguelen hot spot (*55, 56*).

The effect of volatiles associated with OJP plume volcanism on ocean chemistry is unclear. For example, CO_2 additions may have resulted in increased dissolution of carbonate, and this contributed to the condensed nature of lower Aptian deposits. The extra input of CO_2 was probably a factor in driving Cretaceous greenhouse conditions, which are thought to have reached a maximum from the late Aptian through late Albian (*57*), following the OJP event. Although perhaps responsible for a sea level rise and widespread ash, OJP volcanism does not coincide with a major extinction event. Instead, some microfauna, such as planktonic foraminifera, show a radiation after the *G. blowi* Zone (*58*), like the response after extinctions at later carbon-rich horizons and the K-T boundary. But clearly the differences in the biotic responses to OJP volcanism as compared to events such as at the terminal K-T boundary are much greater than their similarities. Extraordinary periods of volcanism—possibly the largest event of the last 200 million years—can apparently occur without a major breakdown of the global marine ecosystem when large mantle plumes penetrate the oceanic lithosphere.

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16 May 1991; accepted 29 July 1991

Oxygen Isotope Zoning in Garnet

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Oxygen isotope zoning was examined within garnet with the use of the stable isotope laser probe. Four metamorphic garnets from the regional metamorphic terrane in Vermont and the skarn deposit at Carr Fork, Utah, were examined and were found to be concentrically zoned in $\delta^{18}O$ values. The largest variations in $\delta^{18}O$ values were observed in the regional metamorphic garnets, where $\delta^{18}O$ values change by 3 per mil from core to rim. These oxygen isotope zoning profiles reflect the changes in the $\delta^{18}O$ values of the rocks during garnet growth, which are caused by infiltration of fluids and by dehydration reactions during metamorphism.

Until recently, analysis of the oxygen isotopic composition of rocks has been restricted to the study of whole rock powders and mineral separates. However, the advent of the stable isotope laser probe (*1*) and the ion microprobe makes it possible to examine both oxygen isotope zoning within minerals (*2*) and the oxygen isotope composition of minerals in situ within a rock (*1*). These technological breakthroughs are leading to significant advances in the understanding of fluid-rock interactions, the scale of isotopic equilibrium (*2*), and kinetic isotopic effects (*3*). Because $\delta^{18}O$ variations reflect the nature of fluid-rock interactions, $\delta^{18}O$ zoning within minerals provides important information about the temporal nature of fluid migration during mineral growth. Such information is of fundamental importance in understanding the geochemical processes that occur in igneous and metamorphic rocks. We have used the stable isotope laser probe to study oxygen isotope zoning in metamorphic garnets from both regional and contact metamorphic terranes.

Many garnets are zoned in cations (Fe, Mg, Mn, and Ca) (*4*), trace elements (*5*), and radiogenic isotopes (*6, 7*). Zonation profiles of these elements have been used to determine variations in pressure (*P*), temperature (*T*), and time (*t*) during garnet growth (*6–9*). Studies of $\delta^{18}O$ zoning in garnets, coupled with this *P-T-t* information, have the potential to provide a monitor

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