Paleoceanography of the eastern Indian Ocean from ODP Leg 121 drilling on Broken Ridge

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ABSTRACT

Broken Ridge, in the eastern Indian Ocean, is overlain by about 1,600 m of middle Cretaceous to Pleistocene tuffaceous and carbonate sediments that record the oceanographic history of southern hemisphere midto high-latitude regions. Prior to about 42 Ma, Broken Ridge formed the northern part of the broad Kerguelen-Broken Ridge Plateau. During the middle Eocene, this feature was split by the newly forming Southeast Indian Ocean Ridge; since then, Broken Ridge has drifted north from about 55° to 31°S.

The lower part of the sedimentary section is characterized by Turonian to Santonian tuffs that contain abundant glauconite and some carbonate. The tuffs record a large but apparently local volcanic input that characterized the central part of Broken Ridge into the early Tertiary. Maestrichtian shallow-water (several hundred to 1,000 m depth) limestones and cherts accumulated at some of the highest rates ever documented from the open ocean, 4 to 5 g (cm²·10³ yr)⁻¹. A complete (with all biostratigraphic zones) Cretaceous-Tertiary boundary section was recovered from site 752. The first 1.5 m.y. of the Tertiary is characterized by an order-of-magnitude reduction in the flux of biogenic sediments, indicating a period of sharply reduced biological productivity at 55°S, following which the carbonate and silica sedimentation rates almost reach the previous high values of the latest Cretaceous. We recovered a complete section through the Paleocene that contains all major fossil groups and is more than 300 m thick, perhaps the best pelagic Paleocene section encountered in ocean drilling. About 42 Ma, Broken Ridge was uplifted 2,500 m in response to the intra-plateau rising event; subsequent erosion and deposition has resulted in a prominent Eocene angular unconformity atop the ridge. An Oligocene disconformity characterized by a widespread pebble layer probably represents the 30 Ma sea-level fall. The Neogene pelagic ooze on Broken Ridge has been winnowed, and thus its grain size provides a direct physical record of the energy of the southern hemisphere drift current in the Indian Ocean for the past 30 m.y.

INTRODUCTION

Broken Ridge is an elongate plateau-like feature that rises 3,500 m above the surrounding sea floor in the southeastern Indian Ocean (Figs. 1 and 2). More than 1,500 m of post-middle Cretaceous, fairly shallow water (less than 1,500 m) sediments has accumulated on Broken Ridge, and these sediments record both the geologic history of this feature and the oceanographic history of the mid-latitude Indian Ocean. Herein, we examine this sedimentary record and present the major events in the evolution of Broken Ridge and the southeastern Indian Ocean.

Tectonic History

Broken Ridge originated as the northern flank of the broad Kerguelen-Broken Ridge Plateau and was detached from the main part of that feature during the Eocene. Various indications, including the dating of dredged basalts (R. Schlich, 1988, personal commun.) and the results of Legs 119 and 120 (Leg 119 Scientific Drilling Party, 1988; Leg 120 Scientific Drilling Party, 1988), suggest that the main constructional phase of the Kerguelen–Broken Ridge Plateau occurred during the Albian. The middle Cretaceous is an important time for constructional volcanism through most of the world's ocean basins; other important rises, Ontong Java, Manihiki, and Hess, are of similar basement age (Rea and Vallier, 1983). Greater

Figure 1. Map of the eastern Indian Ocean, showing the operational area of Leg 121 and DSDP and ODP drill sites.
Kerguelen apparently formed at or near the ridge crest in the then restricted seaway between Antarctica, recently separated India, and Australia.

About 60 m.y. after it was formed, Broken Ridge was uplifted by flexure that occurred in response to intra-plateau rifting. Following the rifting, sea-floor spreading began between the two parts of the old plateau at the Southeast Indian Ocean Ridge at anomaly 18 time, about 42 Ma (Houtz and others, 1977; Mutter and Cande, 1983). An important result of the Leg 121 drilling on Broken Ridge was to demonstrate that the Eocene rifting was not a thermal event, as there was no pre-rift arching or shoaling as would be expected in such circumstances. Furthermore, present heat-flow values are low, implying little additional heating associated with the rifting (Weissel and others, 1988). The rifting and uplift event is now seen as the pronounced angular unconformity that crosses the ridge crest (Fig. 3). Since the time of rifting, Broken Ridge has drifted north from its original position at about 55°S to its present location at 31°S.

**Stratigraphy and Sediment Accumulation Rates**

The biostratigraphy utilized in this report is based on the nannofossil stratigraphy as determined on board ship and as slightly revised at the Leg 121 post-cruise meeting in January of 1989 (Pierce, Weissel, and others, 1989). For Cenozoic materials, we use the zonations of Okada and Bukry (1980) as tied to the time scale of Berggren and others (1985). Mesozoic stratigraphy is based on the zonation of Sissingh (1977) as tied to the magnetic reversal time scale of Harland and others (1982) using the revisions proposed by Kent and Gradstein (1985).

Combining the shipboard biostratigraphic, lithologic, and physical-properties data permits
Figure 4. Lithologic columns from the four drill sites on Broken Ridge; from north to south, they are 753, 752, 754, and 755.
the calculation of rates of sediment deposition. The traditional value for deposition rate is the linear sedimentation rate (LSR), commonly measured in meters per million years (m/10^6 yr) or centimeters per thousand years (cm/10^3 yr). A more useful value to describe sediment deposition is the mass accumulation rate (MAR). MAR is a quantification of the true mass flux of sedimentary material to the sea floor and is the product of LSR and the dry bulk density (DBD):

\[
\text{MAR} \, [\text{g} \, (\text{cm}^2 \, \text{I}0^3 \, \text{yr})^{-1}] = \text{LSR} \, (\text{cm}/10^3 \, \text{yr}) \times \text{DBD} \, (\text{g/cm}^3).
\]

This value inherently accounts for the variable amounts of pore space in sediments, thus for compaction. When the total MAR values are multiplied by the weight percent of any sedimentary component, the flux of that component is also quantified, and so the pitfalls of interpreting relative-abundance data can be avoided.

LSR values are based on the nannofossil biostratigraphy; bulk density measurements were determined in the sediment laboratory of the Resolution. Because of the limitations of the sedimentation rate data, which are determinable for every zone, interpretations of the resulting data are useful for deciphering phenomena that occur on longer, tectonic time scales. We estimate the accuracy of these data to be ±20%; minor changes may not be significant.

Paleoceanographic Setting and Objectives

The elucidation of the paleoceanographic and paleoclimatic history of the southeastern Indian Ocean was one of the major objectives of the Leg 121 drilling. Broken Ridge has always been above the calcium carbonate compensation depth, thus permitting deposition of a fossiliferous calcareous sedimentary section. The angular unconformity (Fig. 3) associated with the Eocene rifting separates underlying, northerly dipping Cretaceous and lower Paleogene tuffs, limestones, and chalks from the overlying upper Paleogene and Neogene calcareous oozes.

Four drill sites (752-755, Table 1) are located along a 21.2-km north-south profile extending across the shallow, about 1,100 m depth, platform of Broken Ridge (Figs. 2 and 3). The sedimentary record of these sites (Fig. 4) contains evidence for locally important volcanic activity, high Cretaceous and Paleocene biological productivity, events of the Cretaceous-Tertiary boundary at high southern latitudes, Eocene uplift and erosion, Oligocene sea-level changes, and Neogene current winnowing.

THE SEDIMENTARY SECTION ON BROKEN RIDGE

The Pelagic Cap

The shallow plateau region of Broken Ridge is immediately underlain by a nannofossil ooze with foraminifers. The ooze reaches a maximum thickness of about 120 m at site 754 and thins to the north and south (Figs. 3 and 4). A layer of sand with limestone and chert pebbles (Fig. 5) divides the ooze section into upper and lower parts. The upper ooze unit is Pleistocene to Oligocene in age, 0 to 30 m.y. old.

The lower part of the ooze sequence is darker brown and contains numerous large foraminifers; 1% or 2% sand-sized, iron-stained quartz grains; and abundant fossil material reworked from the underlying Paleogene and Cretaceous sediments. This interval of ooze is of latest Eocene age, roughly 38 to 40 m.y. old.

The pelagic cap of Broken Ridge apparently has been winnowed (Davies, Luyendyk, and others, 1974), perhaps by the southern hemisphere drift currents. To determine the extent of the winnowing, we conducted on-board grain size analyses of the bulk sediment of this unit at quasi-regular intervals from sites 752, 753, and 754. Grain size of purely pelagic sediment has been shown elsewhere to afford paleocurrent and sedimentary process information (van Andel, 1973; Ledbetter, 1979; Rea and Janecek, 1986). Results show large changes in the grain size of the bulk sediment, from 5.4Φ (24µm) to 3.3Φ (100 µm), which are systematic and coherent among the three drill sites studied (Fig. 6).

**Table 1. DSDP and ODP Drill Sites on Broken Ridge**

<table>
<thead>
<tr>
<th>Site</th>
<th>S. lat.</th>
<th>E. long.</th>
<th>Water depth</th>
<th>Penetration</th>
<th>Oldest seds.</th>
</tr>
</thead>
<tbody>
<tr>
<td>255</td>
<td>31.131°</td>
<td>93.729°</td>
<td>1.144 m</td>
<td>108.5 m</td>
<td>Santonian</td>
</tr>
<tr>
<td>752</td>
<td>36.891°</td>
<td>93.578°</td>
<td>1.086 m</td>
<td>45.6 m</td>
<td>M. Eocene</td>
</tr>
<tr>
<td>753</td>
<td>36.839°</td>
<td>93.590°</td>
<td>1.176 m</td>
<td>62.8 m</td>
<td>M. Eocene</td>
</tr>
<tr>
<td>754</td>
<td>36.941°</td>
<td>93.567°</td>
<td>1.065 m</td>
<td>54.2 m</td>
<td>L. Maastrichtian</td>
</tr>
<tr>
<td>755</td>
<td>31.030°</td>
<td>93.548°</td>
<td>1.057 m</td>
<td>208.4 m</td>
<td>Turonian</td>
</tr>
</tbody>
</table>

Figure 5. Limestone pebbles in ooze, recovered from the Oligocene disconformity at Hole 752A, core 10H, section 7.
Poorly recovered nearshore deposits lie beneath the ooze unit on the upper Eocene erosion surface. This layer consists of quartz sand, dark chert and greenish-gray limestone pebbles, and shell hash mixed with Cretaceous through Eocene reworked carbonate material (Fig. 7). The Eocene and Oligocene pebble layers coalesce at either edge of the crest of Broken Ridge (Fig. 4). At the southern site, 755, the material lying on the Eocene-Oligocene erosion surface is a lower Miocene foraminifer sandstone, and the underlying Santonian limestones have been oxidized to a depth of 1.5 m (Fig. 8). Well logs suggest that this lower sand and gravel horizon may reach a thickness of 25 m at Site 754.

**Lower Paleogene and Upper Cretaceous Carbonates and Cherts**

Below the angular unconformity is nearly 1,200 m of sediment dominated by chalks and limestones and ranging in age from middle Eocene (45 m.y. old) at Site 753 to early Maestrichtian (75 m.y. old) at Site 754 (Fig. 4; Table 2). Opal and black chert are important components in the Paleocene chalks and Campanian limestones, respectively. The chalks are light colored to white in the upper part and darken to grayish green as ash content increases down section. Millimeter-scale green laminae that occur in bundles a centimeter or two thick are characteristic. These bundles in many cases exhibit scoured basal contacts, cross-laminae, and gradational coloration suggestive of graded bedding. Ash layers become common in the Maestrichtian carbonates. Microfaults, pyrite blebs, wavy laminae, and millimeter-sized dolomite rhombs, all indicative of increasing overburden and early diagenesis, occur in the lower part of carbonate series (Peirce, Weissel, and others, 1989).

The Cretaceous/Tertiary boundary occurs within the lower indurated chalk unit of Hole 752B at about 358 m below the sea floor. The boundary lies within a 60-cm-long ash-chert-chalk sequence (Fig. 9) that directly underlies a 5.5- to 6.5-m-thick ash layer. Details of the magnetic susceptibility data for this sequence suggest that the thick ash may be the result of multiple lesser ashfalls rather than one large one.

**Santonian to Turonian Tuff**

The lowest part of the Broken Ridge sedimentary section, recovered at Hole 755A, is 143 m of dark greenish-gray to black ash with limestone and glauconite of roughly late Santonian to early Turonian age, 83 to 90 m.y. Glauconite occurs throughout, in a more disseminated form in the upper parts of the hole, and in fining-upward units with sharp lower contacts in the lower few cores (Fig. 10). Numerous minor
components occur: porcellanite, shell fragments, pyrite, in some cases associated with the calcite veinlets, apatite and rare gypsum crystals found in vugs. The entire section displays mottles and burrow structures.

**COMPARISON WITH THE SECTION RECOVERED FROM KERGUELEN PLATEAU**

The composite section recovered from the central and northern parts of Kerguelen Plateau (Leg 119 Scientific Drilling Party, 1988; Leg 120 Scientific Drilling Party, 1988), those locations that might reasonably be expected to represent the same general sedimentary environment as do the Broken Ridge drill sites, is similar to the Broken Ridge composite section. Regional geologic units on Kerguelen Plateau include:

1. Quaternary to upper Miocene diatom oozes that include small percentages of foraminifera and nannofossils. Ice-rafted debris occurs in sediments younger than middle Pliocene.

2. Middle Miocene to Paleocene nannofossil ooze, in many cases with foraminifera. This unit is stark white in the younger parts but takes on more color, generally light greenish gray, with depth. Faint greenish laminae occur, as do minor intervals of chalk, chert, and porcellanite. A middle Eocene hiatus occurs within this unit.

3. Maestrichtian to Campanian chalk with black chert and green laminae. Glaucophane (5% to 58% of the sediment) and glauconite sandstones occur lower in this unit. Indications of shallow-water deposition occur, including 40-m-thick Maestrichtian series of gravels and breccias derived from volcanic basement that interrupts the pelagic limestones.

4. Santonian through Turonian pelagic limestone and chalk with clayey interlayers, shelly layers, layers with sharp lower contacts, and abundant glauconite.

5. Basalt. Silica-saturated transitional tholeites (T-MORB) underlie middle Turonian and perhaps Cenomanian(?)) limestones.

This composite section with its upper ooze, chalks with green laminae and black chert, and glauconitic limestones is similar to the Broken Ridge section. Three significant differences occur. The first is the vast quantities of ash recovered in the Broken Ridge sections, roughly two orders of magnitude more ash than occurs in the Kerguelen sections. This aspect of the Leg 121 recovery requires a large, local source of basaltic debris. Second, there is a greater extent of lithification or early diagenesis at the Broken Ridge sites than in the Kerguelen sediments, apparently the result of greater overburden in the more northerly locations. Finally, the Neogene sequence on Kerguelen records the great increase in silica productivity that occurred in the Antarctic Circumpolar Ocean during the late Cenozoic, a paleoceanographic event that occurred well to the south of the late Neogene paleoposition of Broken Ridge.

**RATES OF SEDIMENT ACCUMULATION**

The nannofossil ooze that forms the pelagic cap of Broken Ridge accumulated at 0.35 to 0.5 g (cm² · 10³ yr)⁻¹ (Table 2), values normal for oligotrophic mid-gyre shallow-water carbonate fluxes (Rea and Thiede, 1981; Thiede and Rea, 1981; Rea and Leinen, 1986a). The youngest chalks recovered below the angular unconformity at Site 753, of middle Eocene age, accumulated at rates of about 1.2 g (cm² · 10³ yr)⁻¹, rates slightly higher than normal for a low-
productivity carbonate depositional environment. Rates increase down section. Lower Paleocene and upper Maestrichtian chalks have MAR values that average about 3.4 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) through this interval with relatively low rates of 1.4 to 1.6 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) at and just above the Cretaceous-Tertiary boundary and a higher rate of 4.9 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) in the zone just below it (Table 2).

Biosedimentary zonations are less detailed in the Maestrichtian chalk-limestone-chert sequence. Those data indicate a MAR of 7.6 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$). The underlying Santonian to Turonian ash, glauconite, and limestone unit has MAR's of 1.4 to 9.6 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) (Table 2); these values are not so well constrained as those for the Maestrichtian limestones above.

The total flux of sediments can be proportioned among the various sedimentary components (Table 3; Fig. 11). The flux of calcium carbonate increases downcore from 0.4 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) in the pelagic cap to 1.0 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) in the middle Eocene chalks, 2.9 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) in the Paleocene to upper Maestrichtian chalks, and 4.7 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) in the Maestrichtian limestones. The lowermost unit dominated by the Santonian to Turonian ash has a CaCO$_3$ flux of 0.7 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$).

The ash flux also increases downcore (Table 3; Fig. 11). Ash entered the pelagic sediments of the upper unit in trace amounts only. Ash MAR in the middle Eocene chalks of Site 753 is 0.1 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$); in the Paleocene to upper Maestrichtian section, the ash flux is 0.6 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$); in the lower Maestrichtian limestones, the ash flux is 2.5 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$); and in the lowest, ash-rich rocks, the flux of volcanic material is 1.1 to 6.5 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$). These accumulation rate values for volcanic ash are among the largest ever recorded from within (not immediately overlying basement) oceanic sedimentary sections (Rea and Thiede, 1981) and denote important volcanic activity on the northeastern part of the Kerguelen-Broken Ridge Plateau.

Opal is an important sedimentary component in the Paleocene section, where siliceous materials accumulated at rates of 0.2 to 1.0 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) (Table 3). Glaucophane is an important component of the Santonian to Turonian ash-dominated unit and accumulated at about 1.9 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$) (Table 3).

THE PALEOCEANOGRAPHIC RECORD OF BROKEN RIDGE

Turonian to Santonian Volcanism

The ash-rich sediments of the Late Cretaceous indicate a somewhat unusual depositional environment on Broken Ridge. The volcanic component that dominates these sediments requires a large and local source of basaltic material. None of the surrounding drill sites, specifically Site 255 (20.7 km east-southeast of Site 755) but with very poor recovery; Sites 256, 257, and 258 (1,000 to 1,800 km to the north and east) (Davies, Luyendyk, and others, 1974); or any of the Leg 119-120 sites on Kerguelen, exhibit more than the normal trace amounts of Cretaceous ash. Very high fluxes of volcanogenic material combined with a truly local distribution of the deposit suggest that the Broken Ridge transect was within several tens of kilometers of the volcanic source. The ash was erupted subaerially, and so, if one assumes that the plateau lay beneath prevailing westerlies during the Cretaceous, the volcano lay to the west. Because information concerning the older geologic record is not available, it is not clear whether the volcanism is part of the waning phase, perhaps recently subaerial, of plateau construction or a distinctly separate and younger event.

Glaucophane is an important component of these sediments and was incorporated into the ash material at rates of as much as 1.9 g (cm$^2$ \cdot 10$^3$ yr$^{-1}$). This component has a wide regional distribution, occurring in all the Kerguelen cores of equivalent age (Bitschene and others, 1989) and at Site 258 on the Naturaliste Plateau 1,800 km to the east (Davies, Luyendyk, and others, 1974). The normal environment of formation of glauconite is a shallow-water, outer-shelf, low-to very low-sedimentation-rate locale. Overlying waters are oxidizing, but the sediments themselves may be reducing; micro-reducing environments, such as within fecal pellets, may be
important in the formation of glauconite (Reading, 1978). The co-existence of significant amounts of glauconite, denoting a slow sedimentation rate, and the ash, being deposited at very high rates, is paradoxical.

One possible scenario that would account for these observations is as follows. The part of the sea floor that is now the crest of Broken Ridge must have been situated at the shelf-slope break on the northeastern margin of Kerguelen-Broken Ridge Plateau (Weissel and others, 1988). Glauconite formed in suitable locations all across the plateau in low-sedimentation-rate, low-productivity but carbonate-rich settings. This environment, recorded at several Kerguelen drill sites, was subjected to a large but local influx of volcanic debris. Much of this material found its way to the north slope of the Kerguelen-Broken Ridge Plateau. Presumably, episodes of greater current activity brought glauconite over the edge of the plateau, where it was disseminated with the hemipelagic ash and/or formed discrete downslope density flows, resulting in the glauconite turbidites of Site 755 (Fig. 10).

Maestrichtian Carbonate Platform

Volcanic ash continued as an important component of the Upper Cretaceous sediments. Fifteen million years after it was first recorded, ash fluxes were about 2.5 g (cm² · 10³ yr⁻¹) (Fig. 11), roughly half the average Turonian to Santonian flux. The source of this activity remained close at hand to the west; nearby drill sites do not contain any record of this ongoing Broken Ridge eruption.

Carbonate deposition increased markedly during this time span. Limestones and chalks accumulated at about 4.7 g (cm² · 10³ yr⁻¹) during the early Maestrichtian compared to 0.4 g (cm² · 10³ yr⁻¹) in the underlying ash-rich material (Table 3; Fig. 11). By comparison, carbonates on the Ontong-Java Plateau, Shatsky Rise, Manihiki Plateau, and the Magellan Rise accumulated through the later Cretaceous at rates of 1 to 2 g (cm² · 10³ yr⁻¹). Only Hess Rise, which was beneath the equatorial high-productivity zone at this time, has similar carbonate mass accumulation rates, 3.8 g (cm² · 10³ yr⁻¹) in the Campanian and Maestrichtian and 7.6 g (cm² · 10³ yr⁻¹) during the early Cenomanian and late Albainian (Thiede and Rea, 1981; Vallier and others, 1983).

These high carbonate flux rates for the northeastern edge of Kerguelen-Broken Ridge Plateau require a setting of high biological productivity and most likely deposition above the paleolysocline. Chert, the alteration product of biogenic silica, is also an indicator of high biological productivity. The sediments are completely bioturbated, an indication of oxygenated, open-water environments.

The important question posed by these deposits concerns the nature of the source of nutrients necessary to sustain millions of years of apparently high biological productivity. Whatever the source, it became effective some time during the 8 m.y. represented in the Leg 121 cores, between about 83 and 75 Ma. The time of 80 to 85 Ma is important around the world as a time of plate boundary rearrangement, changes in the rates and directions of plate motion, and the opening of oceanic gateways (Berggren and Hollister, 1977). Oceanic circulation between Antarctica and Australia may have started or become more pronounced at this time (Cande and Mutter, 1982; Mutter and others, 1985; Fig. 12). Furthermore, the northward motion of India, which became much more rapid than previously, also may have allowed true oceanic circulation in the proto-Indian Ocean south of the subcontinent (Fig. 12). Whatever the cause, some important change in oceanic circulation across Kerguelen-Broken Ridge Plateau is implicated in the large flux increase of biogenic sediments. Northward motion of the plateau was minimal during the Latest Cretaceous, and so any new circulation patterns would have influenced regions at fairly high latitudes in the southern proto-Indian Ocean.

The great oceanic rises, when they project up into the realm of the ocean surface circulation,
cause bathymetrically induced upwelling as those currents are forced upslope. This process occurs now over the Galapagos platform and happened during the Cretaceous over Hess Rise (Valiier and others, 1983). Nutrients are thereby brought into the photic zone, and productivity is enhanced. In the case of the Kerguelen-Broken Ridge Plateau, this scenario would further imply the development of a drift current in the southern proto-Indian Ocean about 80 to 85 m.y. ago since the plateau was already there. The increase in carbonate and silica productivity apparently records the evolution of the environment of Kerguelen-Broken Ridge Plateau from a restricted sea, shielded by India and Australia, to that of an open ocean, complete with drift currents.

Depositional Environments at the Cretaceous-Tertiary Boundary

The rock record of the Cretaceous-Tertiary boundary, recovered at Hole 752B, must be interpreted with some caution. The recovered materials occur as "drilling biscuits," 4- to 10-cm-long cylinders of rock that twist off during coring and are captured by the core barrel. There is no way of knowing how much material is missing between biscuits. The Cretaceous-

Tertiary boundary occurs in section 3 of core 121-752B-11R (the ODP code is Leg-Hole-core-core type; R is for rotary drilled; Fig. 9). That section contains 10 biscuits, including chert biscuits in the middle of the 23-cm-long transition zone between sub-boundary Cretaceous foraminifera at 95 cm and supra-boundary Tertiary nannofossils at 72 cm. In general, most recovery loss is associated with cherts, and so there may be important components of the Cretaceous-Tertiary boundary section missing from core 121-752B-11R, section 3. The depositional environment is one of moderate energy, as indicated by horizontal laminations in the ash layers and soft-sediment deformation features; oxygenated bottom waters, as indicated by burrows and mottles; and continuing ash influx.

Immediately overlying this boundary section is an ash layer that may exceed 6 m in thickness. Magnetic susceptibility data suggest that this thick unit is a compound ash layer, composed of several individual ash fall events. This unusual deposit may represent either a sudden, great influx of volcanic debris or a representation of the normal, ongoing ash flux in the absence of any carbonate input; the flux data permit differentiation between these possibilities (Table 3; Fig. 11). Volcanic ash MAR increases from 0.7 g (cm$^2$ · 10$^3$ yr)$^{-1}$ in the uppermost Maestrichtian zone to 0.9 g (cm$^2$ · 10$^3$ yr)$^{-1}$ in the lowest Paleocene zone, an increase barely larger than the estimated errors of calculation. At the same time, the mass accumulation rate of calcium carbonate falls by an order of magnitude, from 3.9 to 0.4 g (cm$^2$ · 10$^3$ yr)$^{-1}$ just above the boundary, almost an order-of-magnitude reduction of flux. Opal fluxes are also reduced across this boundary (Table 3). The important change in sedimentation at the Cretaceous-Tertiary boundary, then, is in the rate of deposition of the biogenic component; ash flux may increase only slightly.

The significant implication of this scenario is that the carbonate flux at Kerguelen-Broken Ridge Plateau was greatly reduced through the initial two zones of the Tertiary, a period of about 1.5 m.y. The nannofossils preserved in the thick ash unit constitute an assemblage of opportunistic "survivor species" that bloomed when previously dominant groups were no longer competitive or were absent (Pospichal and others, 1989; Peirce, Weissel, and others, 1989). The record is of an oceanic ecosystem lasting more than a million years where the combination of nutrient supply and the ambient carbonate-secreting organisms was suddenly insufficient to precipitate previously normal amounts of calcite (Smit, 1982; Hsü and McKenzie, 1985; Zachos and Arthur, 1986). Normal productivity resumed between 63.8 and 64.8 Ma (Table 3; Fig. 11).

Figure 12. Backtrack-paleoposition diagrams of Ninetyeast Ridge, Broken Ridge, and Kerguelen Plateau. ODP Leg 121 drill sites shown as large dots. Reconstructions are taken from Royer and Sandwell (1989); note that subsidence is not accounted for in these figures.
Paleoenvironments of the Early Paleogene

The Paleocene and Eocene chalks record ongoing open-ocean, high-latitude deposition on the gradually subsiding northern margin of the Kerguelen-Broken Ridge Plateau. Sediment mass accumulation rates remain high. Biogenic components accumulated at rates of about 2.4 to 4.2 g (cm$^2$ · 10$^3$ yr)$^{-1}$; volcanic ash accumulated at rates as high as 1.0 g (cm$^2$ · 10$^3$ yr)$^{-1}$, still a large input value and one that records the waning eruptive cycle that began in the Miocene. Rates decline in the Eocene (Table 3; Fig. 11). Sediments of middle to late Paleocene age are enriched in diatoms and radiolarians. Biogenic silica exceeds 30% of the sediment, and opal fluxes were as much as 1.0 g (cm$^2$ · 10$^3$ yr)$^{-1}$ (Table 3), a high rate for open-ocean silica productivity; the flux of opal in the modern eastern equatorial Pacific is 0.1 to 0.2 g (cm$^2$ · 10$^3$ yr)$^{-1}$ (Lyle and others, 1988).

Information from foraminifers, both the benthic assemblages and the planktico-benthic ratios, suggests that the lower Paleocene material accumulated in rather shallow water depths probably somewhere on the upper slope (Peirce, Weisell, and others, 1989). Paleodepths determined from these sorts of considerations gradually increase throughout the Paleocene and into the Eocene, reaching 1,000 to 1,500 m. The sedimentary structures in the lower and middle Paleogene materials, horizontal laminae with scoured lower contacts, cross-bedding, and graded bedding, are a direct indication of current velocities above the threshold of motion of silt, approximately 20 cm/s (Miller and others, 1977).

Sediments in the short middle Eocene section encountered at Site 753 exhibit ash MAR's of 0.1 g (cm$^2$ · 10$^3$ yr)$^{-1}$ or less, a more normal value for Eocene sediments; the long eruptive history of the nearby volcanic center was over. The flux of carbonates has dropped to about 1.0 g (cm$^2$ · 10$^3$ yr)$^{-1}$, low by Kerguelen-Broken Ridge standards, but normal for oceanic plateaus. The reduction in flux of biogenic material may connote ongoing subsidence, lowering the platform such that bathymetrically induced upwelling no longer occurred; reduced intensity of oceanic surface circulation; or migration of the sub-polar convergence away from the site.

Lacunae and Hiatuses

Two distinct limestone and chert pebble layers were encountered at Sites 255 (Davies, Luyendyk, and others, 1974), 752, and 754, each representing an important unconformity (Figs. 4, 5, 7, and 8). The older layer denotes the major angular unconformity atop Broken Ridge (Fig. 3) and, at Site 752, separates underlying lower Eocene chalk from overlying upper Eocene ooze. The age of the oldest material above this unconformity is about 38 m.y., and the youngest material below, recovered at Site 753, is about 45 m.y., and so the timing of this event that denotes the uplift of Broken Ridge at the time of rifting is well constrained and matches the estimated rifting age of 42 m.y. based on geophysics (Mutter and Cande, 1983). Calculations of basement subsidence, using the square root of age relationship and considering the effects of sediment loading (Davis and Lister, 1974; Detrick and others, 1977; Rea and Leinen, 1986b), added to the amount of material eroded from the ridge following uplift, indicate that the total uplift of Broken Ridge was about 2,500 m. This uplift must have happened in the course of, at most, 2 or 3 m.y., and possibly much more rapidly.

Exposed Cretaceous limestone and chert sequences were subjected to subaerial erosion (Fig. 8) and shed clastics down the north-facing dip slope, where they occur in the Eocene pebble and sand layer. Ensuing subsidence occasioned the resumption of open-water carbonate deposition, although in very shallow conditions as depicted by both the benthic foraminifers, some of which have suffered mechanical abrasion, and the large rounded quartz grains in the upper Eocene ooze (Peirce, Weisell, and others, 1989).

The younger pebble and sand layer (Fig. 5) marks a disconformity that separates upper Eocene ooze from upper Oligocene ooze. The oldest age of the underlying sediment is about 30 m.y., and the youngest age of the underlying material is about 38 m.y. Early to late Oligocene microfossils are mixed in with this pebble layer. The Oligocene hiatus on Broken Ridge could result from either a relative fall in sea level or an intensification of ocean circulation. Kennett (1977), noting the occurrence of lower Oligocene hiatuses, has suggested that ocean circulation in the southern hemisphere became more intense at the time of the ice volume increase at the Eocene-Oligocene boundary, presumably in response to heightened pole-to-equator temperature gradients.

The presence of the widespread pebble and sand layer with clasts as much as 5 to 6 cm in diameter (Fig. 5) implicates a change in relative sea level as the cause of this event, as the other alternative, an increase in oceanic current velocity, would neither expose the rocks of Broken Ridge to further erosion nor occasion the transport of large pebbles. Because details of the post-rifting subsidence history of Broken Ridge are not yet clear, there can be no well-constrained estimate of the magnitude of the mid-Oligocene sea-level fall at this mid-ocean location.

Neogene Paleocurrents

Above the Oligocene disconformity lies an apparently complete Neogene section of foraminiferal and nanofossil ooze. This section accumulated at average rates of 0.35 to 0.5 g (cm$^2$ · 10$^3$ yr)$^{-1}$ (Table 2; Fig. 11), a much lower rate than in the Paleogene section below. The combination of shallow depths, high percentage of foraminifers, and lower carbonate MAR are all consistent with the interpretation of the DSDP Leg 26 scientists that this unit is a winnowed foraminifer nanofossil silt and sand layer (Davies, Luyendyk, and others, 1974). If this interpretation is correct, then the bulk grain size of these sediments should provide an indication of current velocity across Broken Ridge.

Broken Ridge has subsided by about 1,100 m since the post-rifting resumption of sedimentation about 38 m.y. ago. If the only process affecting the winnowing energy across the crest of Broken Ridge were subsidence, then the grain size of those sediments would be expected to display a smooth, upward-fining sequence. Any additional character in the grain size curve represents additional processes. Two such processes are especially likely: changes in relative sea level and fluctuations in the velocity of ocean currents. Rise in relative sea level would result in a lower-energy sea floor and deposition of smaller grains, whereas a coarsening-upward sequence might reflect a fall in sea level. Similarly, stronger ocean currents would be expected to remove finer grains, leaving a lag deposit of coarser sediment. The downcore grain size determinations of sediments from Sites 752, 753, and 754 conducted on board the Resolution show fluctuations that are temporally coherent from site to site (Fig. 6).

The size of the winnowed grains decreased during the late Oligocene and earliest Miocene from 30 to 20 Ma, increased during the late early Miocene from 20 to about 16 Ma, decreased from 16 to 13 Ma, increased through the middle and late Miocene from 13 to about 6 Ma, decreased into the early Pliocene to a low at about 2.5 or 3 Ma, and may have increased during the Pleistocene (Fig. 6). Of these several transitions, the one most likely to be related to a change in relative sea level is the lowermost, the upward-fining sequence of the upper Oligocene and lowermost Miocene. This change, which begins with the middle Oligocene pebble layer, apparently reflects increasing water depths on Broken Ridge as subsidence continued rela-
tively rapidly and eustatic sea level rose, follows-
ning the 30 Ma lowstand, to a relative high at 21
Ma (Haq and others, 1987). Although we can-
not completely discount the effects of ensuing
lesser eustatic sea-level changes, the remaining
changes in grain size are interpreted to reflect
changes in the circulation intensity of the wind-
driven geostrophic drift current on the southern
side of the southern hemisphere subtropical
gyre. There is no correlation between the grain
size variations shown in Figure 6 and the occur-
cence of hiatuses in other deep-sea sections
(Keller and Barron, 1987). Since 30 m.y. ago, the
Broken Ridge platform has moved north
through about 15° of latitude, starting from
about 46°S.

The grain size data suggest that the intensity
of ocean circulation increased three times during
the Neogene, 20–16, 13–6, and since 2.5 Ma,
and decreased 16–13 and 6–2.5 Ma (Fig. 6).
Important paleoclimatic changes occurred in the
Miocene, changes that are usually linked with
episodes of ice volume growth on Antarctica.
Paleoclimatologists have generally assumed that
increased ice volume can be equated with colder
polar temperatures, steeper pole-to-equator
temperature gradients, and thus more vigorous
atmospheric and oceanic circulation. The weak
link in this presumptive chain is the intuitive
coupling of ice volume and temperature at the
poles; the other assumptions are better
demonstrated from observation.

The events of 16 to 13 Ma are a particularly
good example of this. This was the time of an
important ice volume increase on Antarctica
(Woodruff and others, 1981; Vincent and oth-
ers, 1985; Miller and others, 1987; Prentice and
Matthews, 1988), enough to cause a 1 permil
enrichment of oceanic δ18O values for benthic
foraminifera. This event would also have caused
a eustatic sea-level fall and, presumably, signif-
icantly intensified atmospheric and oceanic circu-
lation. Both of these consequences would tend
to result in coarser grain size of winnowed
deposits; yet, this was most clearly a time of increas-
ing finer grains in all three Broken Ridge sections
(Fig. 6). The middle to late Miocene is thought
to be a time of steady or perhaps decreasing ice
volume (Miller and others, 1987), and yet there
was a constant coarsening of the winnowed
grains from 12 to 6 Ma. These observations sug-
gest that the circulation intensity of the ocean
(Woodruff and Savin, 1989) is not directly
linked to polar ice volume. Other information
suggests that the intensity of southern hemo-
sphere atmospheric circulation appears to have
increased at this later time, between 11 and 9
Ma, rather than earlier during the ice volume
increase (Rea and Bloomstine, 1986; Woodruff
and Savin, 1989). The latest Miocene southern
hemisphere ice buildup event at about 5 Ma
(Hodell and Kennett, 1986) also corresponds to
a time of decreasing grain size on Broken Ridge,
and so the Miocene pattern is consistent.

The implications are that a moisture supply
threshold (Ruddiman and McIntyre, 1984) may
be more important for significant ice buildup,
rather than any further reduction in the tempera-
ture of polar regions. Southern hemisphere
temperature reductions may follow ice buildup
by a few million years, as snow-covered and
high-albedo regions slowly increase in altitude
or in area. The northern and southern hemi-
pheres may behave differently in this respect, as
Antarctic high-albedo regions are effectively
limited by the ocean, whereas the continents of
the northern hemisphere permit the rapid expan-
sion of snow-covered high-albedo regions.

The younger part of the grain size record, the
early Pliocene minima, corresponds with the
known last time of equitable climates before the
onset of northern hemisphere glaciation at 2.4 or
2.5 Ma.

SUMMARY

Kerguelen–Broken Ridge Plateau was formed
by constructional volcanism during middle Cret-
aceous, presumably Albainum, time. This broad
depositional platform has remained within 1 or
2 km of sea level throughout its history and has
accumulated a predominantly biogenic sedimen-
tary section of limestones, chalks, and cherts. At
the very northern edge of this broad submarine
bank, a strong but local volcanic center provided
significant ash deposits for more than 30 m.y.,
from 90 to 60 Ma.

In Turonian through Santonian time, most of
the Kerguelen–Broken Ridge Plateau was a shall-
low open-ocean carbonate bank, receiving a low
to moderate flux of calcium carbonate, perhaps
0.7 g (cm² · 10³ yr)⁻¹, and was the site of
extensive glauconite formation. From approxi-
mately 80 to 85 m.y. ago, the biological produc-
tivity of the overlying waters was greatly
increased; the flux of carbonate increased to
about 4.7 g (cm² · 10³ yr)⁻¹ (Fig. 11). These Late
Cretaceous carbonate fluxes are among the
highest ever recorded on oceanic plateaus and
require an environment of ongoing high biologi-
cal productivity. They denote a combination
of increased oceanic circulation, perhaps the result
of widening of the Australo-Antarctic and pro-
to-Indian Oceans (Fig. 12), and of bathymetri-
ically induced upwelling of the surface waters.
The Broken Ridge volcanic center continued to
be a source of important amounts of ash during
the latest Cretaceous (Fig. 11).

The Cretaceous-Tertiary boundary was re-
covered in Hole 752B. These sediments consist
of the typical chalk-tert-ash layer sequence that
had preceded that time for 8 m.y. or so. The
mass accumulation rate of calcium carbonate
dropped by an order of magnitude at the bound-
ary and remained low for the first 1.5 m.y. of the
Tertiary, indicating a significant and continuing
reduction in the overall rate of biological pro-
ductivity. At the same time, the input of volcanic
ash rose slightly (Fig. 11).

Carbonate and opal deposition rates recovered
from the low values that persisted immedi-
antly following the Cretaceous-Tertiary bound-
ary and continued high through the Paleocene,
providing an expanded and fossiliferous high-
latitude section. Carbonate accumulated at 2.1
to 3.2 g (cm² · 10³ yr)⁻¹, and the volcanic input
was reduced to 0.5 g (cm² · 10³ yr)⁻¹, indicat-
ing the waning of the long period of volcanic
activity on the northern part of the Kerguelen-
Broken Ridge Plateau. By middle Eocene time,
these fluxes had been reduced to about 1.0 g
(cm² · 10³ yr)⁻¹ for carbonate and 0.1 g (cm² ·
10³ yr)⁻¹ for volcanic material, both normal
values for oceanic shallow-water depositional
settings. The Late Cretaceous through middle
Eocene record is one of decreasing ash input,
availing biological productivity from very high
to normal values, and gentle subsidence
(Fig. 11).

An episode of uplift and erosion occurred in
the middle Eocene. The sedimentary units were
tilted gently northward and eroded, producing
the striking angular unconformity seen in the
seismic profiles (Fig. 3). Clastics, mostly pebbles
of limestone and chert mixed with sand from the
uplifted sediments, were shed northward along
the exposed surface of the ridge and reworked
into sand and gravel layers as it subsided
through sea level. The total amount of vertical
uplift at the south edge of Broken Ridge was about
2,500 m.

The Oligocene to Pleistocene history of
Broken Ridge is one of post-eruptive subsidence
and northward drift (Fig. 12) to its present loca-
tion near 31°S. A middle Oligocene unconform-
bity, denoted by a pebble and sand layer, occurs
within the pelagic unit atop the ridge and
probably records the 30 Ma fall in eustatic sea
level.

Upper Oligocene through Pleistocene car-
bonate oozes were deposited on this shallow
platform at oligotrophic flux rates, about 0.35 to
0.5 g (cm² · 10³ yr)⁻¹, and have been subjected
to winnowing during the past 30 m.y. The win-
nowing record suggests, among other things, re-
duced ocean circulation intensity during times of
southern hemisphere ice volume increase in the
Miocene, an observation that contradicts the general assumption of significant polar cooling caused by enhanced circulatory vigor at times of ice volume increase.

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