1. REGIONAL TECTONIC SETTING OF THE SOUTHWESTERN ATLANTIC[1]

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ABSTRACT

This paper, an introduction to the tectonic aspects of Leg 72, begins with an explanation for the presence of a tectonic element within a paleoenvironmental drilling program, in terms of the importance of the Rio Grande Rise as an influence on and sampler of deep and intermediate circulation and sedimentation. The state of knowledge of the origin and history of this part of the South Atlantic before Leg 72 drilling (including that of the Rio Grande Rise-Walvis Ridge system of seamounts and ridges) is then reviewed, and the main body of the Rio Grande Rise is considered in detail. Finally, with benefit of hindsight, we examine how Leg 72 drilling could most effectively help our understanding of the evolution of the Rise and increase the precision with which a subsidence history may be computed.

INTRODUCTION

DSDP Legs 71 to 75 in the South Atlantic were designed to study the circulation and climatic consequences of the growth of a long meridional ocean. With only limited drilling time available, the drilling program had to concentrate on a few, crucial parts of this development. One factor in the choice of objectives was the availability of the hydraulic piston corer (HPC), which permitted the study of less-consolidated sediments on a fine scale. Among the more important topics were:

1) early restricted circulation in small isolated basins;

2) development of an asymmetric circulation between eastern and western basins as the ocean widened;

3) interaction with steepening zonal climatic gradients through the Late Cretaceous and Cenozoic; evolution of the present intermediate and deep water mass structure.

The importance of the anomalously elevated parts of the South Atlantic was recognized at an early stage; and the Falkland Plateau, Rio Grande Rise, and Walvis Ridge attracted a high proportion of the sites. These elevations have played crucial roles in controlling circulation, particularly during the early phase of opening when their bulk was proportionally more effective. Also, they provide sampling opportunities from beneath to well above the calcite compensation depth (CCD) within the range of deep and intermediate water masses. Compared with the continental margins, biogenic sediments there are less diluted by terrigenous debris, so that older horizons are more accessible and preservation is better; slope instability on the elevations is much less common, and it is more likely that the water masses at the seabed there were at representative oceanic depths.

Because of a lack of knowledge of the tectonic evolution of these elevations and because of the potential paleoenvironmental value of such knowledge, the investigation of their origins and history became recognized as a legitimate concern of the drilling program; on Leg 72, although time was short, we wanted to extend at least one hole on the Rio Grande Rise to basement. This goal was achieved at Site 516 on the northern flank of the Rise, and the results from that site occupy much of this volume. To introduce those results and to complement the more extensive description of regional oceanographic setting that follows (Johnson, this volume), this paper gives a brief summary of the state of knowledge of Rio Grande Rise evolution at the start of South Atlantic drilling.

SOUTH ATLANTIC OPENING

Our understanding of the growth of the South Atlantic has developed rapidly over the past 15 years as a result of magnetic anomaly interpretation (largely by Lamont-Doherty workers, from Dickson and others, 1968 through to Rabinowitz and LaBrecque, 1979), calibrated by Deep Sea Drilling activity (Leg 3, for example: Maxwell, Von Herzen, et al., 1970). The anomalies are now reasonably well mapped, from the margins to the ridge crest, although in many areas, because of data gaps or imperfectly formed anomalies associated with slow spreading, only the major anomalies have been identified. Ladd (1974) and Rabinowitz and LaBrecque (1979), using the reversal time scales of Larson and Hilde (1975) and LaBrecque and others (1977), have computed a set of interval poles and rates of South Atlantic opening, some of which are reproduced here in Table 1. Despite the detail of these data, it is not claimed that they provide an exact indication of when and how changes in the speed and direction of opening took place. In particular, there is a striking increase in spreading rate apparently contained mostly within the long Cretaceous normal polarity interval, in fact between Anomaly 31 (67.57 Ma: LaBrecque et al., 1977) and Anomaly MO (108.19 Ma: Larson and Hilde, 1975). Despite widespread concern about the near-exact coin-

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Table 1. Poles and rates of rotation of Africa with respect to South America, from Rabinowitz and LaBrecque (1979) and Ladd (1974).

Rotation limits (anomalies)	Time period (Ma)	Latitude	Longitude	Rotation angle (degrees)	Rate (°/Ma)
Boundary to MO	130–107	2.5°S	45.0°W	11.1	0.48
MO to 34	107–80	41.3°N	43.8°W	18.0	0.69
34 to 31	80–68	63.0°N	36.0°W	8.0	0.67
31 to 0	68–0	63.0°N	36.0°W	25.8	0.38

cidence of a dramatic increase in spreading rate with the start of the Cretaceous normal polarity interval, independent evidence sufficiently precise to refine the spreading history is lacking. Also, of course, alternative ages for these anomalies are emerging (see, for example, Ness et al., 1980; Lowrie and Alvarez, 1981), which would change the parameters in Table 1 without necessarily changing their possibly approximate nature. The Cretaceous normal polarity interval is of particular concern because the main parts of the Rio Grande Rise and Walvis Ridge lie directly "outside" (west and east, respectively) Anomaly 34 (79.65 Ma) and thus could well have been formed initially within this interval. Uncertainty about the age of formation of the Rio Grande Rise has been an important barrier to understanding its tectonic evolution and computing a subsidence history. It is compounded by the possibility of jumps of the ridge crest having taken place during the early stages of opening. Mascle and Phillips (1972) and Sclater and McKenzie (1973) noted that the present ridge crest lies asymmetrically within the South Atlantic basin in the latitude of the Rio Grande Rise and farther north, and Ladd (1974) concluded that any ridge jumps, which may have produced such asymmetry, had to have taken place before Anomaly 34 time.

THE RIO GRANDE RISE–WALVIS RIDGE SYSTEM

The symmetric position of the Walvis Ridge and Rio Grande Rise about the mid-oceanic ridge has long been considered a clue to their origin. The original conception of such oceanic island chains as a product of plate motion over a sublithospheric magmatic source, a hot spot in the mantle (Wilson, 1965), has survived remarkably well, although the notion that hot spots supply a significant part of the driving force for plate motions, as Morgan (1971) supposed, now has little support. More recent use of these features in a "mean hot spot reference frame" to estimate "absolute" plate motions (e.g., Minster et al., 1974; Minster and Jordan, 1978; Chase, 1978) demonstrates that relative motion between hot spots has been much slower than plate motions, so that they *can* be regarded as fixed in a globally static mantle beneath the plates. Further, the "absolute" motions of the South American and African plates so computed (e.g., Chase, 1978), if extrapolated back in time, reproduce the gross northwestern and northeastern orientations of the chains of diverse submarine elevations that form the Rio Grande Rise and Walvis Ridge (although the uncertainties of the computed vectors are large).

When these chains are examined in detail, it is not at all clear that they represent as coherent and progressive a process as formed, for example, the Hawaiian-Emperor seamount chain (Clague and Jarrard, 1973), with which implicitly they are being compared. In general, however, the elevations do become younger southward and towards the ridge crest. On the African plate the younger, southwestern seamount province of the Walvis Ridge (Connary, 1972) is characterized by off-axis alkalic volcanism. Tristan da Cunha was recently active and lies about 400 km from the ridge crest, on ocean floor about 20 Ma old (Ladd, 1974). At DSDP Site 359 subaerial trachytic tuff, which yielded a K-Ar age of 40 Ma (Fodor, Keil, et al., 1977), was drilled from the top of a seamount that was about 1000 km from the ridge crest and lay on ocean floor of Anomaly 25 age, about 59 Ma old (Neprochnov et al., 1977, p. 1009). Northeastward, the topographic expression of the Walvis Ridge changes, becoming more massive and linear, reflecting the influence of ridge crest and fracture zone trends in the ocean floor. Dredge hauls from this northeastern province contain a mixture of rocks with both alkalic and tholeiitic affinities (Hekinian, 1972). No ages are available for the dredged rocks, but rocks from nearby DSDP Site 363 (Bolli, Ryan, et al., 1978) show that the Frio Ridge, which abuts the continental margin (Fig. 1) is at least as old as early Aptian. The adjacent onshore Kaoko lavas of Namibia (South-West Africa) range in age from 128 to 93 Ma (Siedner and Miller, 1968; Gidskehaug et al., 1975). Thus the older, northeastern Walvis Ridge appears to possess both "off-axis" *and* "ridge-crest" characteristics.

The character of the Rio Grande Rise is different in some respects from that of the Walvis Ridge. The equivalent of the younger seamount province of the Walvis Ridge is hardly present. The Rio Grande Rise is prominently developed only on older ocean floor, as a series of massive bodies with orientations again clearly influenced by the ridge crest–fracture zone fabric. We are concerned in this volume only with the broad, east-west elongated main body of the Rio Grande Rise centered on 31°S, 35°W (Figs. 1–2), but it is important to recognize that the Rise, as broadly understood, has other components. An east-west ridge extends eastward from the northern limit of the main body, connecting with a north-south ridge along 29°W, which forms the eastern limit of elevated topography on the South American plate. The east-west section lies along the Rio Grande Fracture Zone, which forms the northern boundary of the Rise and the southern boundary (as the São Paulo Ridge) of the São Paulo Plateau (Lonardi and Ewing, 1971; Kumar et al., 1977; Gamboa and Rabinowitz, 1981). Basalt recovered from a Cretaceous conglomerate at Site 356 on the São Paulo Ridge is probably alkalic (Fodor, Husler, and Keil, 1977). The Rio Grande Fracture Zone lies approximately along the same small circle of the early pole of South Atlantic opening as does the Frio Ridge (Kumar, 1979). Thus, the São Paulo Ridge may be seen

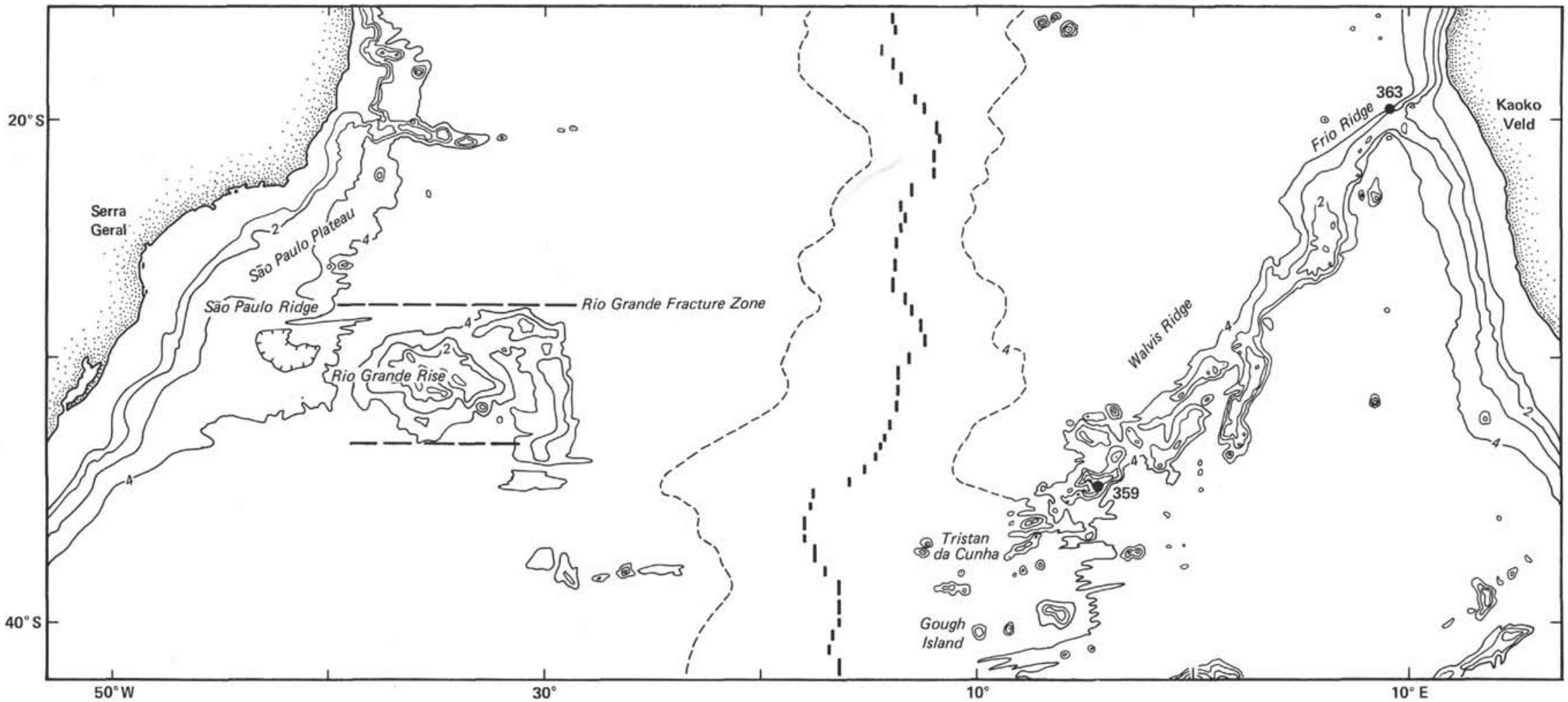

Figure 1. South Atlantic bathymetry, contoured at 1-km intervals, 4 km and above (after Uchupi, 1979). Mid-ocean ridge 4-km contour (dashed) is smoothed. Note greater area inside 4-km contour indicating Tristan da Cunha hot-spot swell.

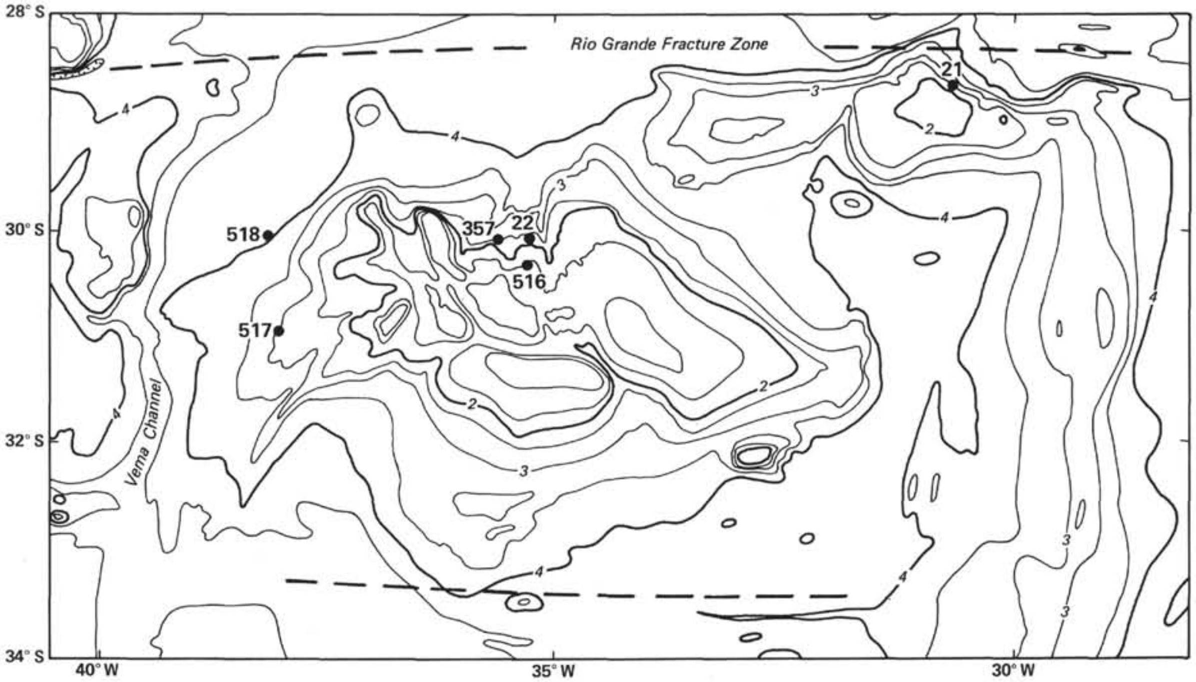

Figure 2. Rio Grande Rise bathymetry, 0.5-km contour intervals showing Leg 72 and existing DSDP sites. From Barker and others (this volume).

as an additional component of the Rio Grande Rise–Walvis Ridge system, but its prominence is masked by the sediment fill of the basin underlying the São Paulo Plateau to the north. Restricted circulation within that basin, because of the barrier presented by the São Paulo (and Frio) Ridge, is considered to have been responsible for evaporite deposition until the end of Aptian time (Leyden et al., 1976; Ponte and Asmus, 1976; Kumar and Gamboa, 1979). South of the São Paulo plateau and west of the Rio Grande Rise, oceanic basement is also shoaler than normal ocean floor of its (presumed mid-Cretaceous) age, though much less prominent than the Rise itself (Kumar, 1979). The path of the Vema Channel is partly controlled by this elevated basement topography.

No radiometric dates have been published hitherto for any dredged or cored rocks from the Rio Grande Rise or São Paulo Ridge, but the onshore Serra Geral province of Brazil, also a mixture of alkalic and tholeiitic rocks, has yielded a most interesting bimodal distribution of radiometric ages, grouped around 140–110 Ma and 80–50 Ma (Campos et al., 1974). The older grouping spans the onset of South Atlantic spreading and may thus be seen in combination with the synchronous African Kaoko volcanism as the earliest signs of activity of the Tristan hot spot. The distinct second phase of activity, however, some 60 Ma younger but in the same place, place, is incompatible with the simple notion of steady migration of the South American plate away from that same static hot spot.

At this stage, before looking in detail at the main Rio Grande Rise itself, we may summarize what is known of the regional tectonics. Both Rio Grande Rise and Walvis Ridge show a broad, gross orientation that forms a V, with the apex close to the Mid-Atlantic Ridge near the recently active Tristan Da Cunha and Gough Island groups, and has been characterized as a hot-spot trace. There are clear limits, however, to the extent to which Rio Grande Rise–Walvis Ridge volcanism may be compared to the systematic and well-defined activity of the Hawaiian-Emperor seamount chain. For instance, although mixed alkalic and tholeiitic volcanism on both continental margins preceded South Atlantic opening and continued for a short while after spreading had started, the South American margin also saw a later, distinctly separate volcanic episode of a similar nature. Offshore also, volcanism appears sporadic and scattered, and its character has changed with time. Younger volcanism is alkalic, off axis, and largely confined to the African plate; it has produced clusters of separate seamounts. Older volcanism occurred on both plates, had a mixed alkalic and tholeiitic nature, and produced more massive linear bodies, which were oriented along the oceanic ridge crest–fracture zone fabric and which were thus possibly produced at least partly at the ridge crest and along active transform faults. Alkalic volcanism may characterize activity at leaky transform faults as well as midplate hot spot–related activity (Thompson and Melsom, 1972; Barberi et al., 1974). Also, anomalously elevated ocean floor is often produced at the destinations of spreading center jumps in oceanic lithosphere (Barker, 1979; LaBrecque and Hayes, 1979); Kumar (1979) has speculated that the main body of the Rio Grande Rise was produced at or very near the mid-oceanic ridge crest, after an eastward jump to the vicinity of the Vema Channel about 100 Ma. Thus, regarding the regional tectonic environment of the main Rio

Grande Rise, several options remain (off-axis or ridge crest, hot spot–related or not, ridge jump or not), which might be resolved by Leg 72 drilling.

RIO GRANDE RISE

The main body of the Rio Grande Rise is roughly oval, measuring 650 km east-west by 400 km north-south at the 3500 m contour (Fig. 2 and Fig. 2 of Johnson, this volume). It is capped by a number of guyots, whose flat tops lie at depths of 560–900 m below sea level. The guyots lie roughly in two lines, separated by a narrow trough oriented WNW-ESE. One other guyot rises to the same general depth but is distinct from the main Rise at the 3000 m contour. The main body is separated from the continental margin in the west by deep water, including the Vema Channel, and joined in the northeast to the other two, more linear segments of the Rise. Close to the Rise, the Rio Grande Fracture Zone runs east-west at about 28.5°S (Gamboa and Rabinowitz, 1981), and the other fracture zone considered by Kumar (1979) to form its southern boundary probably lies along 33.5°S. It displaces the magnetic anomalies (Cande and Rabinowitz, 1979), but its topographic expression is very small.

Before Leg 72, most of the information about the tectonic evolution of the Rio Grande Rise came from DSDP Sites 21 and 22 (Maxwell, Von Herzen, et al., 1970) and 357 (Supko, Perch-Nielsen, et al., 1977). These sites are located in Figure 2, and Figure 3 contains comparative stratigraphic columns. Supplementary data have come from two adjacent Lamont-Doherty dredge sites on the northern wall of the central trough (Fodor, Husler, and Kumar, 1977) and from three *Jean Charcot* dredge hauls from the flanks of other, more westerly guyots (Thiede, 1977). Sites 22 and 357 are located on the northern shoulder of the main body of the Rise and Site 21 on the northern flank of the adjoining east-west ridge (Fig. 2). None sampled igneous basement. At Site 357, drilling was terminated at 797 m sub-bottom in fine-grained marly chalks and limestones of early Santonian age, containing *Inoceramus* fragments. These latter were considered *in situ* and used to infer a 300–500 m paleodepth of deposition (Thiede and Dinkelman, 1977). Their disappearance upsection and the parallel decrease

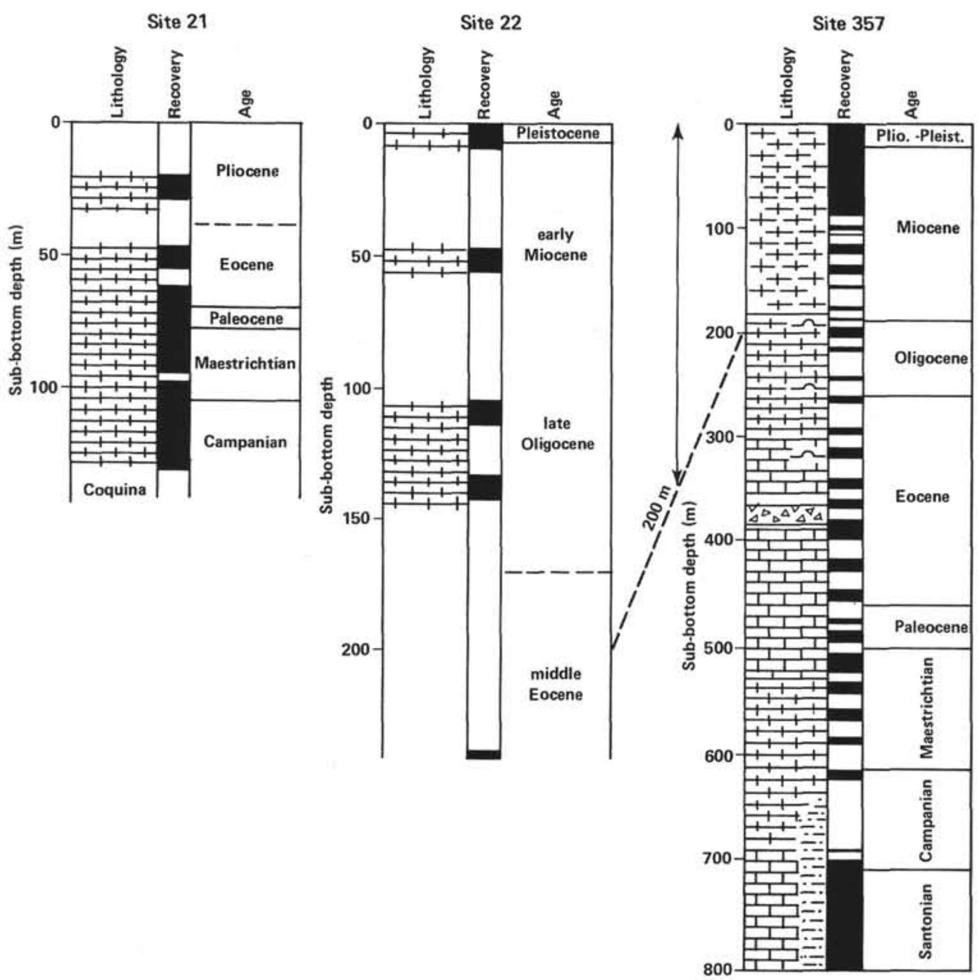

Figure 3. Comparative sediment columns, DSDP Sites 21, 22 (Maxwell, Von Herzen, et al., 1970), and 357 (Supko, Perch-Nielsen, et al., 1977). Water depths are as follows: Site 21, 2113 m; Site 22, 2134 m; Site 357, 2086 m. See Figure 2 for site locations. See Explanatory Notes (Coulbourn, this volume) for lithology symbols.

in the terrigenous sediment component were taken to reflect subsidence at the Site and of the Rise as a whole, including a decreasing subaerial portion. Before drilling, the basal limestones had been misidentified on the single-channel seismic profiles as igneous basement, so the actual depth to basement beneath Site 357 and basement age remained uncertain. The decision to abandon Site 357 before reaching 'oceanic' basement may have been influenced by the results of two sonobuoy seismic refraction stations on the Rise, reported by McDowell and others (1977). An enigmatic 3.6-km/s layer, 850 and 900 m thick on the two lines, is overlain by 900 and 550 m of presumed 2.3-km/s sediments and underlain by a 4.3–4.7-km/s layer. Such an intermediate-velocity layer had been found also on other aseismic ridges. The rationale for abandoning the hole may have been that this layer would be a mixed off-axis volcanic and sedimentary sequence providing no significant regional tectonic information, with true oceanic basement lying up to 1 km deeper.

The other significant feature of the Site 357 section was a mid-Eocene volcanic breccia within an otherwise pelagic carbonate succession. The clasts included subangular basaltic fragments, bivalve and gastropod shell fragments, bryozoans, and red algae. Fresh pyroxenes from within the breccia were alkalic. The overall texture of the breccia resembled a hyaloclastite (Fodor and Thiede, 1977), and the entire sequence was size graded, implying a single depositional event, essentially a slide from shallow water. No older sediments were entrained, but it was considered that the lavas could have been erupted at any time from the formation of the Rise to the middle Eocene.

Data from the nearby DSDP Site 22 contributes nothing to this discussion, because of limited penetration and infrequent coring, but the data do reinforce the conclusion that the history of sedimentation on the Rise has been mainly one of pelagic biogenic deposition. Site 21, on the separate east-west ridge component of the Rise (Fig. 2), again yielded an almost entirely calcareous pelagic biogenic section. At its base was a white coquina of Campanian or older age, containing bivalves, echinoderms, red algae, and probable glauconite. The coquina has been assumed by later workers to have been an essentially autochthonous shallow-water deposit because of the relatively shallow (300—500 m) paleodepth of the overlying *Inoceramus*-bearing Campanian nannofossil chalk.

Of the dredge stations on the main body of the Rio Grande Rise, the two Lamont-Doherty hauls (McDowell et al., 1977; Fodor, Husler, and Kumar, 1977) recovered alkalic basalt, trachybasalt, and trachyandesite from the northern scarp wall of the trough dividing the crest of the Rise, about 80 km southwest of Site 357. The rocks were similar to those of Tristan da Cunha and very similar to the volcanic component of the middle Eocene breccia sampled at Site 357 (and thus a possible source). The three *Jean Charcot* dredge hauls (Thiede, 1977) included shallow water limestones of Oligocene, Eocene, and possible Late Cretaceous age, but the geometry of the dredge tracks, up steep scarps over several hundred meters, prevented the attribution of a precise present-day *in situ* depth to these samples.

TECTONIC EVOLUTION AND SUBSIDENCE HISTORY

Before DSDP Leg 72, the available evidence was not sufficient to support a precise, unambiguous model of the tectonic evolution and subsidence history of the Rio Grande Rise. Nevertheless, after DSDP Leg 39 (Supko, Perch-Nielsen, et al., 1977) there was considerable interest in the Rise, both as an example of an aseismic ridge (e.g., Detrick et al., 1977; Kumar, 1979) and as an influence on and monitor of South Atlantic circulation and sedimentation (e.g., Sclater et al., 1977; Thiede and van Andel, 1977; van Andel et al., 1977; Kumar and Gamboa, 1979). The degree of unanimity among these authors, in assumptions made and subsidence model adopted, is the result of the seminal influence of the detailed analysis by Thiede (1977) of data from the Rio Grande Rise itself. Thiede's model had the great advantage of being simple; under certain assumptions it was compatible with all of the relevant drilling and dredge data from the Rise. In reviewing it here, I do not seek to detract from what was clearly a perceptive and attractive analysis, merely to show how Leg 72 could hope to test its assumptions and increase the precision and discriminatory power of the data set. Thiede's main conclusions were that:

1) The Rio Grande Rise formed at or near the mid-oceanic ridge crest in the Late Cretaceous (95–97 Ma), as an oceanic island or island group reaching 2000 m or more above sea level.

2) It then subsided as a single unit, without tectonic disturbance, exactly as normal oceanic lithosphere would.

The data used, and their treatment and contributions, are summarized in Figures 4 and 5 (from Supko, Perch-Nielsen, et al., 1977; after Thiede, 1977). Thiede selected four data points on the Rise for which paleodepth, present depth, and age were known and, by correcting each for paleodepth and for the isostatic effect of sediment load, obtained four estimates of paleo-sea level (Fig. 4). Then, a standard oceanic subsidence curve (after Sclater et al., 1971) was fitted to these four points, to obtain a starting age and height. The computed age (95–97 Ma) was close to that (~ 90 Ma) obtained by McDowell and others (1977) for the ridge crest near Site 357, using the time scale and South Atlantic history of Larson and Pitman (1972) and Larson and Ladd (1973), but the computation assumed the existence of a thick, compressible sedimentary section below the base of the hole at the site. That this result is less consistent with an estimate (85 Ma for Site 357) based on the more recent data of Cande and Rabinowitz (1979) and Rabinowitz and LaBrecque (1979 and Table 1) is therefore cause for concern. The younger age leaves much less time for such thick sediments to accumulate and reduces the likelihood that the 3.6-km/s layer, if it exists everywhere on the Rise, is a thick off-axis volcanic pile barring access to a much older oceanic basement. Thus, to reach and date igneous basement on the Rise (provided that it did

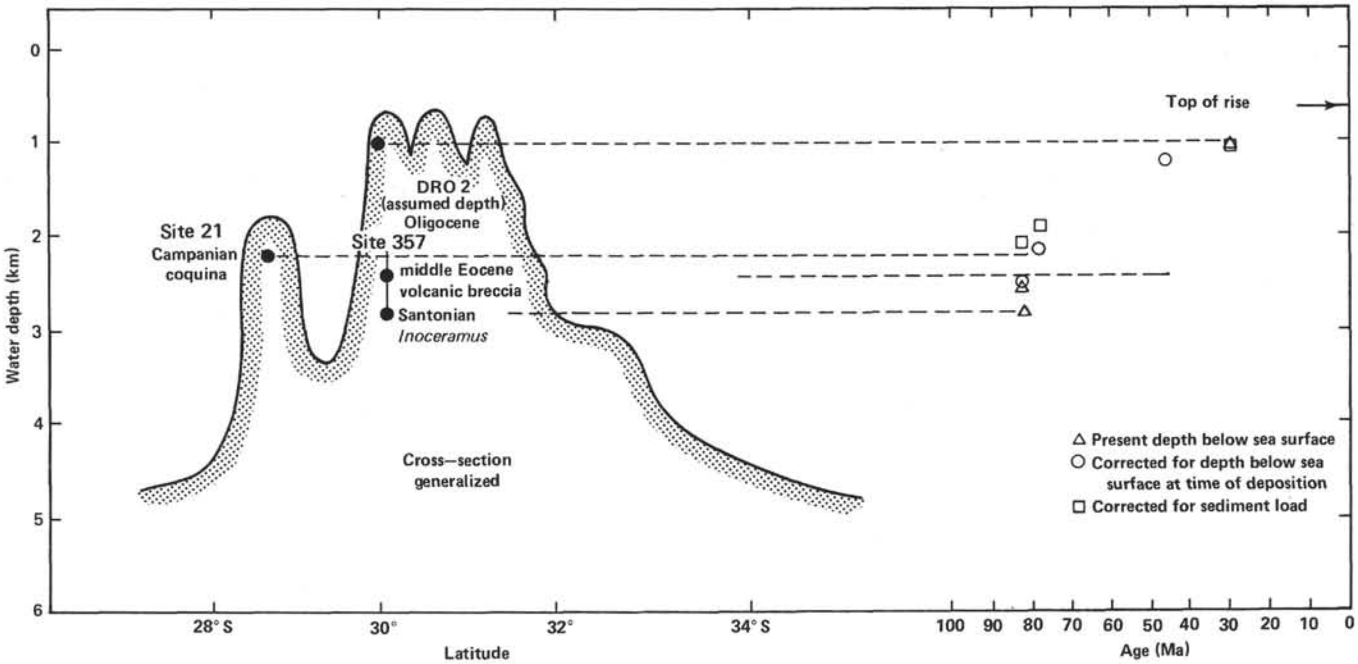

Figure 4. Distribution and treatment of paleodepth data for Rio Grande Rise subsidence computation (Supko, Perch-Nielsen, et al., 1977, p. 1126; after Thiede, 1977). Corrected data were fitted to oceanic age-depth curve (Sclater et al., 1971), as illustrated in Figure 5. DRO 2 is dredge station datum.

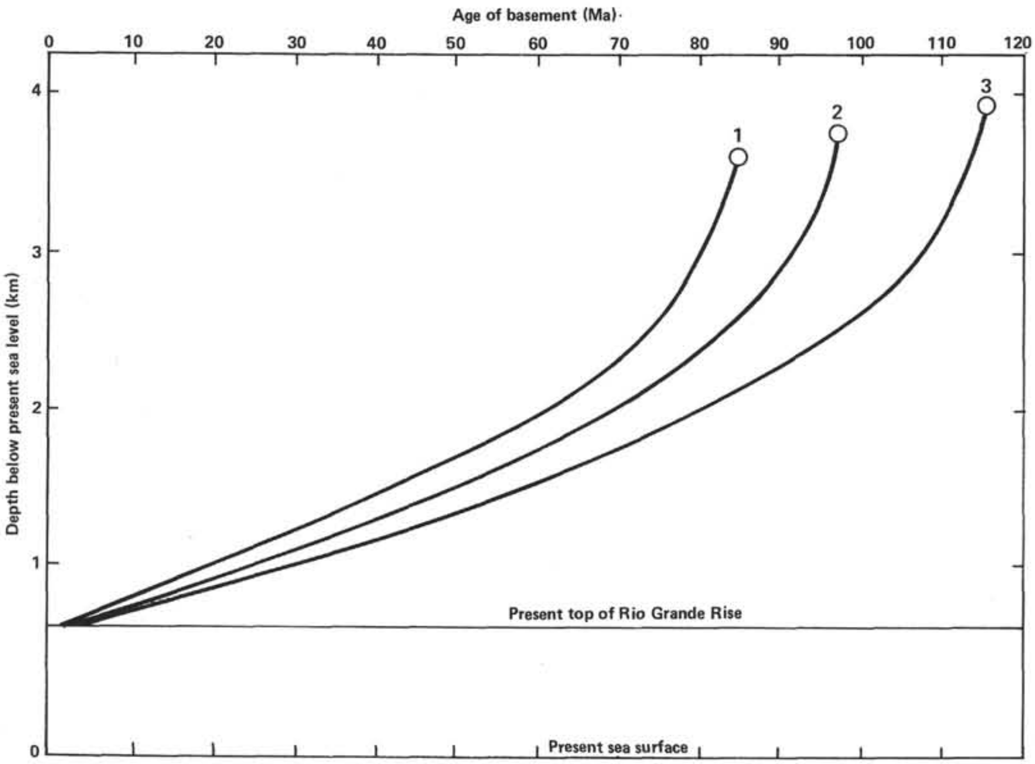

Figure 5. Computed subsidence curves for Rio Grande Rise (Supko, Perch-Nielsen, et al., 1977, p. 258; after Thiede, 1977), using data shown in Figure 4. Curve 2, preferred by Leg 39 scientists, implies a basement age of 95–97 Ma and the presence of 800 m of sediment between the base of Hole 357 and basement.

not represent off-axis activity) in order to resolve this ambiguity was a high priority for Leg 72.

A repetition of Thiede's analysis now would include an assessment of sediment compaction and a correction for eustatic sea level change, and could not justify the assumption that submarine erosion, unlike sedimentation, would not attract isostatic compensation (although the effects of some of these changes could be small). There would be some doubt, also, about the validity of assuming a common tectonic evolution for the main body of the Rise and the ridge where Site 21 is located. Probably more important however, is Thiede's assumption that the middle Eocene volcanic breccia, completely anomalous within the otherwise pelagic biogenic section at Site 357, was an essentially random depositional event in the steady, tectonically undisturbed subsidence of a large oceanic island group. In support of his assumption is the existence of active spreading centers where alkalic and tholeiitic volcanic activity coexist, such as the Azores-Gibraltar Ridge (Ridley et al., 1974; Searle, 1980). Equally, however, the renewed alkalic volcanism at the Brazilian margin 80–50 Ma (Campos et al., 1974) and the off-axis activity at Tristan da Cunha (Baker, 1973) and Site 359 (Supko, Perch-Nielsen, et al., 1977) demonstrate that not all of the magmatism in the province occurs at the ridge crest. If the middle Eocene breccia at Site 357 were associated with such an off-axis event, its uniqueness within the depositional record would be more acceptable, but off-axis magmatism would necessarily involve a perturbation of Thiede's simple thermal subsidence curve.

Because this introductory review has the benefit of hindsight, it will be obvious that Leg 72 drilling was able to make some contribution to the two main topics identified here, those of the age and nature of igneous basement on the Rise and the origin and significance of the middle Eocene breccia sampled at Site 357. Apart from the Site 516 chapter, this volume contains relevant chapters on basement chemistry and age (Thompson et al., Weaver et al., Mussett and Barker, Hart and Staudigel), paleodepth indicators (Milliman, Dailey, Tjalsma), middle Eocene sediments (Bryan and Duncan), and seismic stratigraphy (Barker et al.). The combined contribution of these studies is assessed and a revised subsidence curve computed in a final synthesis chapter (Barker), to which this paper is an introduction.

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