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36. ARGO ABYSSAL PLAIN MAGNETIC LINEATIONS REVISITED: IMPLICATIONS FOR THE ONSET OF SEAFLOOR SPREADING AND TECTONIC EVOLUTION OF THE EASTERN INDIAN OCEAN[1]

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ABSTRACT

Linear magnetic anomalies in the Argo Abyssal Plain have been interpreted as having been recorded by seafloor spreading during Late Jurassic to Early Cretaceous Chrons M26 through M16. Ocean Drilling Program Leg 123 drilled at Site 765 in the southern Argo Abyssal Plain, near the base of the northwest Australia margin between anomalies thought to be M25A and M26. However, initial biostratigraphy of sediments overlying basement gave Early Cretaceous ages, ~20 m.y. younger than expected. With this discrepancy as impetus, we re-examined the magnetic lineations in the Argo Abyssal Plain and decided that the best model is still the sequence M26 through M16. In addition, we were also able to construct a model that accounts for most of the lineations with the reversal sequence M0 through M11, closer to the basement age predicted by initial biostratigraphic results from the deepest sediments at Site 765. This model proved unsatisfactory because it left a significant portion of the lineations unexplained, requires an unlikely sequence of tectonic events, and disagrees with a reliable Jurassic radiometric age that has been determined from Site 765 basement basalts. Later biostratigraphic studies caused the ages of the oldest sediments at Site 765 to be revised upward, but not enough to eliminate the discrepancy with the basement age inferred from the magnetic lineations. A 5–10 m.y. difference exists between oldest sediments and basement at Site 765, whereas the discrepancy at nearby Site 261 is 3–8 m.y. The probable explanation is that sedimentation on the Jurassic Argo Abyssal Plain was low because the northeast Australian margin was sediment-starved and rugged, allowing little sediment to reach the Argo basin. However, some of the discrepancy may arise from small inaccuracies in the Jurassic geomagnetic polarity reversal time scale or small ridge jumps in the young Argo Abyssal Plain. Our Argo magnetic lineation map implies a relatively simple tectonic history for the basin. Seafloor spreading began shortly before M26 time along the center of the northwest Australian margin and extended east and west through ridge propagation. An initially-segmented Argo spreading center coalesced into fewer, longer spreading segments until ~M21–M19 time when a global plate reorganization caused the ridge to resegment. Spreading began on the western margin of Australia at M10 time in the Early Cretaceous, but does not appear to have been contemporaneous with the observed period of spreading in the Argo basin.

INTRODUCTION

The Argo Abyssal Plain, a salient of Indian Ocean lithosphere wedged between Australia and the Java Trench, is one of several deep ocean basins that border northwest Australia (Fig. 1). Mesozoic magnetic lineations are found in these basins, indicating that they were formed by seafloor spreading. In the Gascoyne, Cuvier, and Perth abyssal plains, located to the west of the Exmouth Plateau and western Australia, these lineations generally have a trend of N30°E, but in the Argo Abyssal Plain, the trend is N70°E (Fig. 2). Moreover, the anomalies also indicate a difference in age. The Early Cretaceous sequence M0–M10 (118–132 Ma) is found in the Gascoyne, Cuvier, and Perth basins, but Late Jurassic anomalies M16–M26 (144–163 Ma) have been identified in the Argo Basin (e.g., Fullerton et al., 1989; ages from Harland et al., 1982). Thus, the Argo Abyssal Plain is one of the few remaining parcels of Jurassic-age seafloor in the oceans. Indeed, it is this antiquity that makes it of special interest to oceanographers and partially prompted drilling at Ocean Drilling Program (ODP) Site 765.

Before ODP Leg 123, the available drilling results from the abyssal plains off northwest Australia seemed in agreement with the ages of the anomalies found there (Table 1; Fig. 3). Leg 123 drilled at two sites, 765 and 766, on the southern edge of the Argo Abyssal Plain and southwest Exmouth Plateau, respectively (Fig. 2). Though the oldest sediments recovered at Site 766 were in accord with the age of the seafloor predicted by the magnetic anomalies, discordant results were obtained at Site 765 in the Argo Abyssal Plain, drilled between anomalies M25 and M26 near the base of the continental rise (Fig. 2). Over 935 m of sediments and 270 m of igneous rocks were recovered at the site, and the shipboard scientific party concluded that basement had been penetrated. Initial biostratigraphic studies of sediments recovered immediately above basement indicated late Berriasian to Valanginian stage, Early Cretaceous ages rather than an Oxfordian stage, Late Jurassic age as expected from the magnetic lineations (Ludden, Gradstein, et al., 1990).

This discrepancy seemed difficult to reconcile as it implied that no sediments accumulated in the Argo Abyssal Plain for ~20 m.y. after the beginning of seafloor spreading. Indeed, the shipboard scientific party of Leg 123 found this scenario unappealing and suggested that a reappraisal of the magnetic lineations and their tectonic implications was warranted (Ludden, Gradstein, et al., 1990). They proposed that previous assessments of the age of the central Argo Abyssal Plain lithosphere might be erroneous, perhaps as a result of incorrect interpretation of the lineation identities and trends. Indeed, the new inferred basement age for Site 765 implied that the Argo Abyssal Plain might have formed at the same time as the Gascoyne, Cuvier, and Perth abyssal plains rather than being much older as proposed by previous geophysical investigations (e.g., Fullerton et al., 1989). This situation

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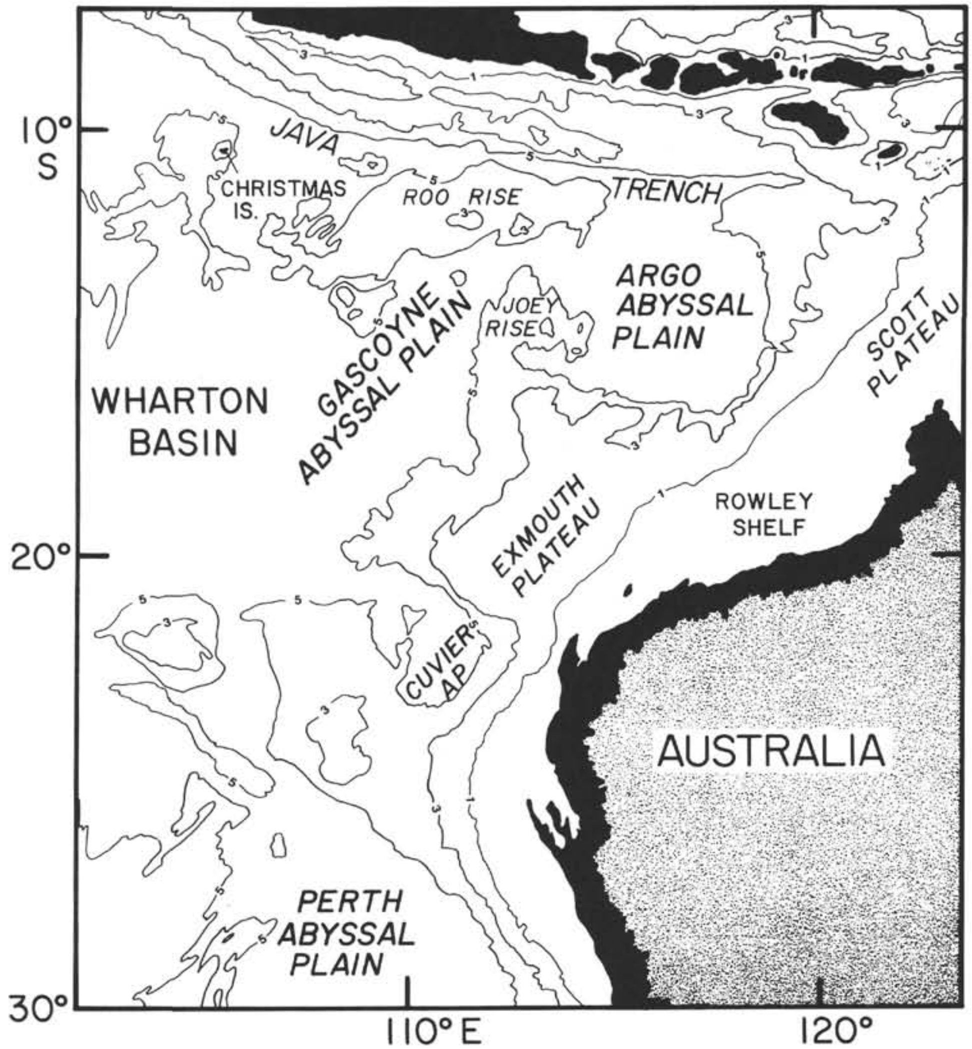

Figure 1. Generalized bathymetric map showing the study area and geographic features mentioned in text. 1, 3, and 5 km contours are shown (based on GEBCO charts 5-09 and 5-10).

prompted us to take a fresh look at the magnetic anomalies and to test the hypothesis that these anomalies correspond to magnetic reversals of the Early Cretaceous.

Though we were able to make a match of Early Cretaceous anomalies M0–M11 with some of the magnetic lineations, our study convinced us that the previous Jurassic model is best. While this article was in review, biostratigraphic ages for the oldest sediments at Sites 765 and 261 were revised (Table 1; Fig. 3). At Site 765, the age was revised upward, from late Berriasian-Valanginian to Tithonian (Dumoulin and Brown, this volume; Mutterlose, this volume), decreasing the discrepancy between the biostratigraphic and geomagnetic polarity time scale age estimates from about 20 to 10 m.y. However, the biostratigraphic ages for sediments overlying basement at Site 261, first thought to be late Oxfordian age (Veevers, Heirtzler, et al., 1974), were revised downward to Kimmeridgian–early Tithonian (Dumoulin and Brown, this volume; Mutterlose, this volume), creating a 3–8 m.y. discrepancy between the basement ages estimated by biostratigraphy and the magnetic polarity time scale (Fig. 3). Even more recently, an Ar^{40}–Ar^{39} radiometric age of 155±3 Ma was determined by R. Duncan using celadonite from Site 765 basement basalts (F. Gradstein and J. Ludden, pers. comm., 1991). This datum implies that the Jurassic magnetic lineation model for the Argo Abyssal Plain anomalies is probably correct. Rather than delete the Early Cretaceous lineation model entirely, it is left as an illustration of the process and pitfalls of reconciling the ages of magnetic lineations with overlying sediments.

Geologic Setting

The Argo Abyssal Plain is bounded on two sides, south and east, by the continental crust of Australia and to the north, by the Java Trench. The continental margin is an Atlantic-type rifted margin draped with only a thin blanket of sediments (Falvey and Veevers, 1974; Powell, 1976). Extension, uplift, and erosion occurred along this part of Australia during the Triassic, but breakup, subsidence, and crustal thinning began in earnest during the Middle Jurassic (Powell, 1976; Veevers and Cotterill, 1978). It is generally accepted that this rifting event carved a continental block from northwest Australia, although the present identity of this block is not certain (Larson, 1975). To the southwest of the Argo Abyssal Plain, the margin includes the stretched continental crust of the Exmouth Plateau and to the east, the Scott Plateau (Falvey and Veevers, 1974). Because sediments on the continental slope and rise are thin, the Continent-Ocean Boundary (COB)

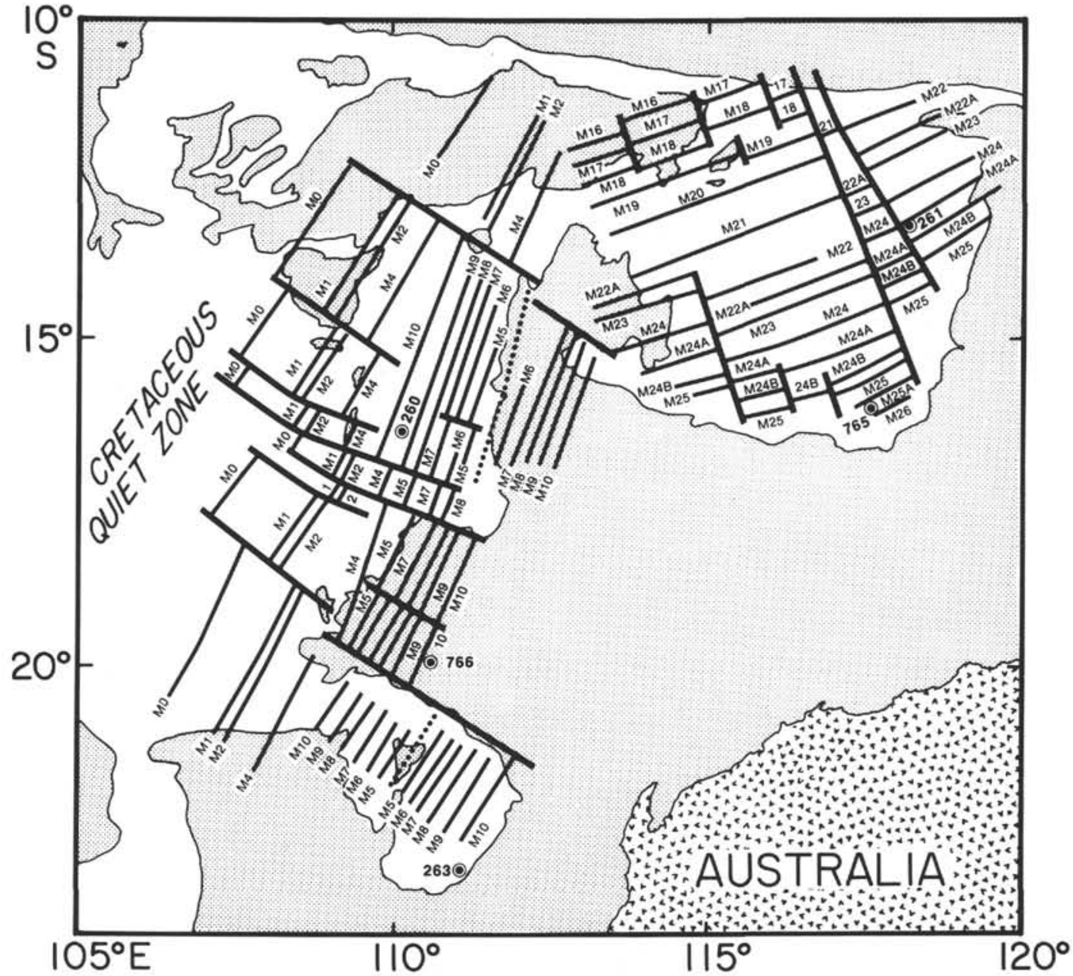

Figure 2. Magnetic lineations adjacent to the northwest Australian margin. (Stippled regions) bathymetry ≤5 km. (Heavy lines) fracture zones; (light lines) magnetic lineations; (dotted lines) abandoned spreading centers. (Large dots enclosed by circles) locations of DSDP and ODP sites (see Table 1). Figure modified from Fullerton et al. (1989).

Table 1. Magnetic lineation basement ages vs. oldest recovered sediments, DSDP and ODP drill sites located on oceanic crust northwest of Australia.

Site	Location (Latitude, Longitude)	Sediment thickness (mbsf)	Age comparison	
			Magnetic anomaly[a]	Oldest sediments
DSDP Leg 27				
260	16.15°S 110.30°E	331	M9–M10 (131 Ma Valanginian)	mid-Albian (basement not reached)[1]
261	12.95°S 117.89°E	580	M24 (159 Ma, Oxfordian)	late Oxfordian[1] Kimmeridgian–early Tithonian[2, 3]
263	23.32°S 110.98°E	746	M10 (131 Ma, Valanginian)	mid-Albian to Neocomian[1]
ODP Leg 123				
765	15.98°S 117.58°E	859	M25A (162 Ma, Oxfordian)	late Berriasian to Valanginian[4], Tithonian[2, 3]
766	19.93°S 110.45°E	458	M10 (131 Ma, Valanginian)	late Valanginian[2, 3, 4]

[a] Age of crust determined from closest magnetic lineation (see Fig. 2) using magnetic polarity reversal time scale of Harland et al. (1982).

[1] Veevers, Heirtzler, et al. (1974); [2] Mutterlose (this volume); [3] Dumoulin and Bown (this volume); [4] Ludden, Gradstein, et al., (1990)

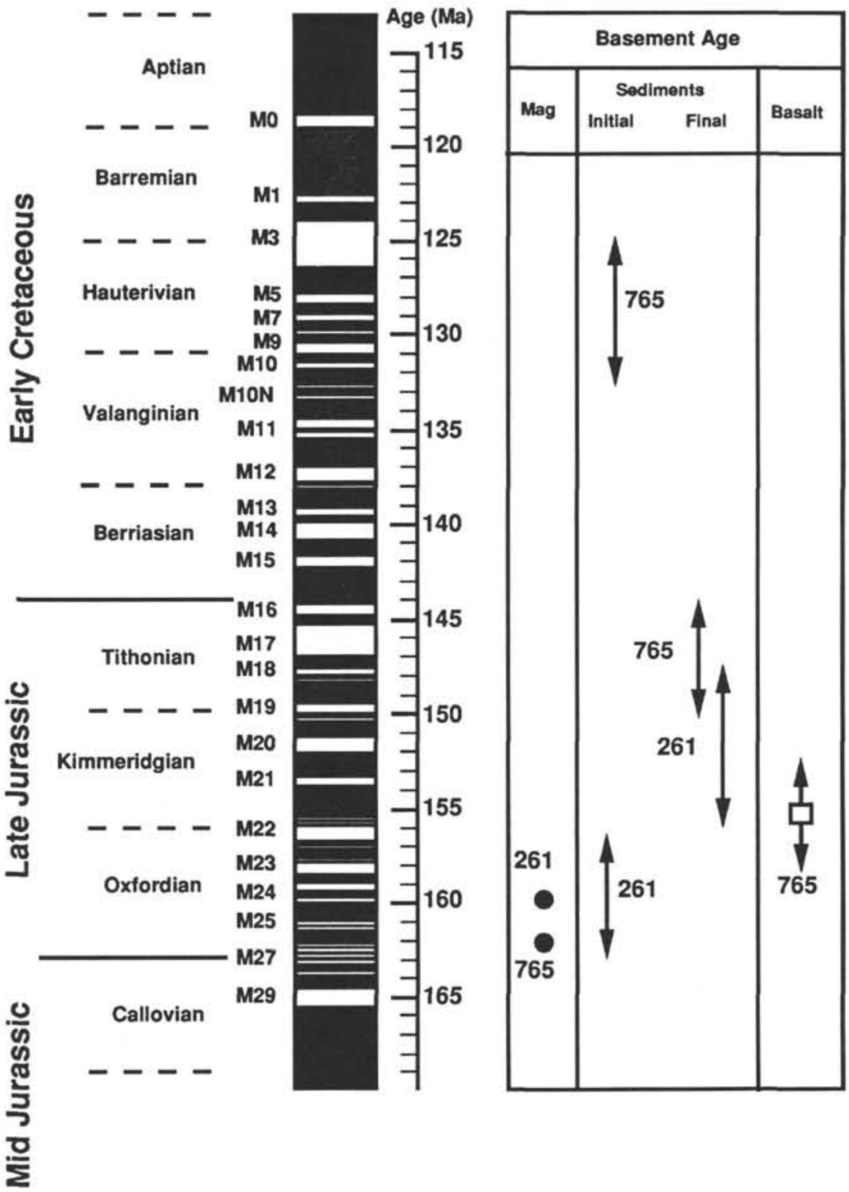

Figure 3. Geomagnetic polarity reversal time scale and comparison of basement ages inferred from magnetic anomalies and biostratigraphy. Time scale shown at left with periods of normal polarity in black (from Harland et al., 1982). Columns on right show ages of oceanic crust at Sites 261 and 765 inferred from magnetic lineations (model 1; Fig. 4), initial (Ludden, Gradstein, et al., 1990) and revised (Dumoulin and Brown, this volume; Mutterlose, this volume) biostratigraphic ages of basal sediments, and an Ar^{40}–Ar^{39} radiometric age (F. Gradstein and J. Ludden, pers. comm., 1991) (Table 3).

is usually found near the base of the slope, often buried by less than a kilometer of sediments (Fig. 1; Veevers et al., 1985a; 1985b).

To the east, trench meets continental crust, shutting off the basin. However, the western side of the Argo basin opens into the Indian Ocean. Partially blocking this opening are the continental Exmouth Plateau and two volcanic uplifts ≤3 km high, the Joey and Roo rises, which are thought to be oceanic in character (Powell, 1978; Johnson et al., 1980; Veevers, 1984). West from the Exmouth Plateau are the Gascoyne and Cuvier abyssal plains, formed by seafloor spreading as shown by correlatable magnetic lineations found in each (Fig. 2).

The Gascoyne and Cuvier abyssal plains contain a sequence of magnetic anomalies from M0 to M10 that trend ~30° east of north (Larson, 1977; Powell, 1978; Larson et al., 1979; Johnson et al., 1980; Powell and Luyendyk, 1982; Fullerton et al., 1989). These anomalies have been traced over the Joey and Roo rises as well as the northwest part of the Exmouth Plateau (Fig. 2), attesting to the oceanic nature of the crust in these areas. Anomaly M10 is found closest to the COB in this region, implying that seafloor spreading began on this margin of Australia during the Early Cretaceous. A similar set of magnetic lineations has been identified farther south in the Perth Abyssal Plain off western Australia (Markl, 1974; Larson et al., 1979). Together, these magnetic anomalies document the separation of Australia and India during the Early Cretaceous sundering of Gondwanaland.

Previous Work in the Argo Basin

Magnetic lineations trending N60°E within the Argo Abyssal Plain were first recognized by Falvey (1972), who identified them as Late Cretaceous to Cenozoic Chrons 22–32. This interpretation was shown to be incorrect by Deep Sea Drilling Project (DSDP) Leg 27, which drilled at Site 261 in the eastern part of the basin and recovered late Oxfordian sediments overlying basement (Table 1; Veevers, Heirtzler, et al., 1974). Soon thereafter, Larson (1975) modeled the anomalies along two ship tracks near the drill site as the Late Jurassic sequence M22–M25, with the oldest chron nearest Australia. With additional magnetic data, Heirtzler et al. (1978) carried these identifications westward across the basin to the Joey and Roo rises.

Several subsequent studies gathered additional magnetic data and refined the anomaly map of the Argo basin (Powell, 1978; Powell and Luyendyk, 1982; Veevers et al., 1985a; Fullerton et al., 1989). As a result, correlatable magnetic lineations are found over nearly the whole of the basin (Fig. 2). Most of these recent studies deduced similar anomaly patterns in the central, southern, and eastern parts of the basin. However, the region to the west and northwest, complicated by the bathymetry of the Joey and Roo rises, has yielded differing interpretations. Though most recent studies have agreed that the anomalies located on the south side of the Joey Rise are M22–M25, those over the northern Joey Rise and Roo Rise have been interpreted in several ways. Evidently Veevers et al. (1985a) found that they were confusing, for they did not speculate on their identity. On the other hand, Powell (1978) and Powell and Luyendyk (1982) postulated that these are M5–M14. Because these anomalies are contemporaneous with the Gascoyne Abyssal Plain anomalies, but have the same strike as the other Argo Abyssal Plain anomalies, they postulated that a southward ridge jump occurred during the Early Cretaceous, forming a triple junction off the northern Exmouth Plateau. Fullerton et al. (1989) rejected this hypothesis, preferring a simpler model in which these anomalies are identified as Chrons M16–M25 continued westward to meet the younger Gascoyne Abyssal Plain lineations over the middle of the Joey and Roo rises (Fig. 2).

DATA

The data set used in this study is virtually identical to that which we employed in our previous study (Fullerton et al., 1989). The one exception is the new geophysical data collected during Leg 123. Most of the data are magnetic anomaly readings collected by ships or airplanes. Bathymetry data were also used, where available, to identify anomalies caused by topographic features. These data are from various sources, listed in Table 2, and were obtained primarily from the National Geophysical Data Center (NGDC). In addition, U.S. Navy ship and aeromagnetic data were supplied by the Navy Ocean Research and Development Activity (NORDA; now NOARL, Navy Oceanographic and Atmospheric Research Laboratory).

All of the magnetic data are total field intensity values measured with proton-precession magnetometers and reduced to magnetic anomaly values using various versions of the International Geomagnetic Reference Field (IGRF). The ship data were collected at sea level, whereas the aeromagnetic data were measured at an altitude of 305 m. Four different types of navigation were used for positioning the magnetic readings. The ship data were navigated with celestial, Doppler satellite, and GPS satellite methods, and the aeromagnetic data were positioned with an inertial navigation system.

For a broad-scale study of magnetic lineations such as this, navigational errors of less than a few kilometers are insignificant. This level of accuracy is provided by the Doppler satellite, GPS, and inertial navigation systems. Celestial navigation is the least accurate and can be in error by tens of kilometers in the worst case. Fortunately, only seven of 32 ship tracks that we used to map the Argo Abyssal Plain anomalies were navigated in this manner, so the more accurately positioned tracks were used as the primary constraint of the lineation trends.

ANALYSIS

Magnetic lineations were mapped by plotting anomaly values perpendicular to ship and plane tracks and tracing them from line to line using their characteristic shapes and spacing. Bathymetry data also were plotted along track lines at the same scale as the magnetic data to facilitate comparison so that anomalies caused by topographic features would not be confused with those created by seafloor spreading.

A widely-used geomagnetic polarity reversal time scale (Harland et al., 1982) and a simple two-dimensional magnetic modeling routine (Talwani and Heirtzler, 1964) were used to generate synthetic magnetic anomaly profiles for identifying and modeling the magnetic lineations. Crustal magnetization parameters (Table 3) were chosen as appropriate to the location of the Argo Abyssal Plain during the Late Jurassic and Early Cretaceous, ~25° farther south than present and rotated ~20° clockwise (Scotese et al., 1988). Where it was necessary to associate biostratigraphic and absolute ages with the magnetic lineations, we used the Harland et al. (1982) magnetic polarity reversal time scale, chosen in part

Table 2. Argo Abyssal Plain geophysical cruise data.

Institution	Cruise ID	Ship/Plane	Data[a]	Navigation	Date	Lines[b]
Royal Australian Navy	M1972	HMAS *Moresby*	M	Celestial	1972	3,4
Deep Sea Drilling Project	DSDP22GC	D/V*Glomar Challenger*	MB	Satellite	1972	19,29
Lamont-Doherty Geological Observatory	V2819	R/V*Vema*	MB	Satellite	1971	20
NORDA (Naval Ocean Research	81IO1MAG	RP-3D Orion	M	Inertial	1981	2, 5, 6, 9, 10
and Development Activity)	81IO5MAG	RP-3D Orion	M	Inertial	1981	7, 8
Oceanographic Research Institute, Japan	UM63	R/V *Umitaka Maru*	MB	Celestial	1963	13
Ocean Drilling Program	ODP123JR	D/V*JOIDES Resolution*	MB	Satellite/GPS	1988	32
Scripps Institution of Oceanography	MONS02AR	R/V*Argo*	M	Celestial	1960	26
	LUSICAR	R/V*Argo*	MB	Celestial	1962	24,28
	LUSIDAR	R/V*Argo*	MB	Celestial	1962	21
U.S. Naval Oceanographic Office	WI343811	USNS*Bartlett*	MB	Satellite	1978	25, 27, 31
Woods Hole Oceanographic Institute	A093L14	R/V *Atlantis-II*	MB	Satellite	1976	1, 11, 12, 14, 15, 16, 17, 18 23, 30
	CH100L07	R/V*Chain*	MB	Satellite	1971	22

[a] M = magnetics; B = bathymetry

[b] Line numbers correspond to Figure 5.

Table 3. Argo Abyssal Plain magnetic lineation model parameters.

Earth's field		Crustal magnetization	
Inclination (°)	−46.0	Inclination (°)	−60.0
Declination (°)	1.0	Declination (°)	−20.0
Intensity (nT)	48,900	Crustal thickness (km)	0.5
		Depth to seafloor (km)	6.0
Magnetization intensity			
Model 1 (M15–M26)		Model 2 (M0–M11)	
144.0–153.3 Ma (M15–M21n)	15.0 A/m	117.0–128.8 Ma (M0–M7n)	7.5 A/m
153.3–162.0 Ma (M21–M25A)	12.0 A/m	128.8–130.4 Ma (M7–M9n)	13.0 A/m
162.0–163.0 Ma (M25A–M26)	4.0 A/m	130.4–136.0 Ma (M9n–M11)	4.0 A/m

for continuity with our previous study (Fullerton et al., 1989). In other Mesozoic geochronologies, the correlations of magnetic chrons to ages differs by only a few percent and stratigraphic stages are shifted slightly (e.g., Kent and Gradstein, 1985).

RESULTS

M-series chrons are mostly reversed in magnetization, and in the Argo Abyssal Plain they give rise to a negative anomaly slightly skewed toward the northern end of each reversed block (Fig. 4); thus, we based our correlations mostly on negative anomalies (Fig. 5). The anomalies are clearly linear, with an ENE trend, though the anomaly picks do display some deviations from linearity. We assumed that many of these small deviations were the result of navigational errors, so most lineations were interpreted as the best straight line fit to the picks.

Two particularly striking anomalies are those we have labeled M20 and M21 in the center of the basin (Fig. 5). Their shapes and amplitudes are consistent across 8–9 tracks. What is more, they show their shortest wavelength signals on tracks oriented NNW (e.g., track 12) and longer wavelengths on tracks trending nearly E–W (e.g., tracks 28 and 29). This pattern is repeated all across the central and eastern Argo Abyssal Plain, so there is little chance of mistaking the lineation trend. Thus, the suggestion that there might have been spreading in the Argo Abyssal Plain parallel to the Early Cretaceous Gascoyne Abyssal Plain lineations (Ludden, Gradstein, et al., 1990) should be discarded.

Late Jurassic Lineation Model

Although the Argo anomalies were first identified in the eastern part of the basin, we found that those in the center of the basin are the most diagnostic. In this region, relatively high-amplitude anomalies on the north side of the basin grade to low amplitude anomalies near the Australian margin (Figs. 4 and 5). In addition, this transition occurs abruptly to the south of the prominent magnetic anomaly we identified as M21. Furthermore, this anomaly stands out because the spacing between it and its neighbors is much larger than that of the other anomalies. All of these characteristics are typical of the Late Jurassic M-series lineations. Reversely polarized Chrons M20 and M21 are separated from one another and adjacent reversed chrons by normally polarized chrons of 1–2 m.y. duration, whereas the reversal rate is higher for anomalies M22 and older, as well as M15–M4 (Harland et al.,

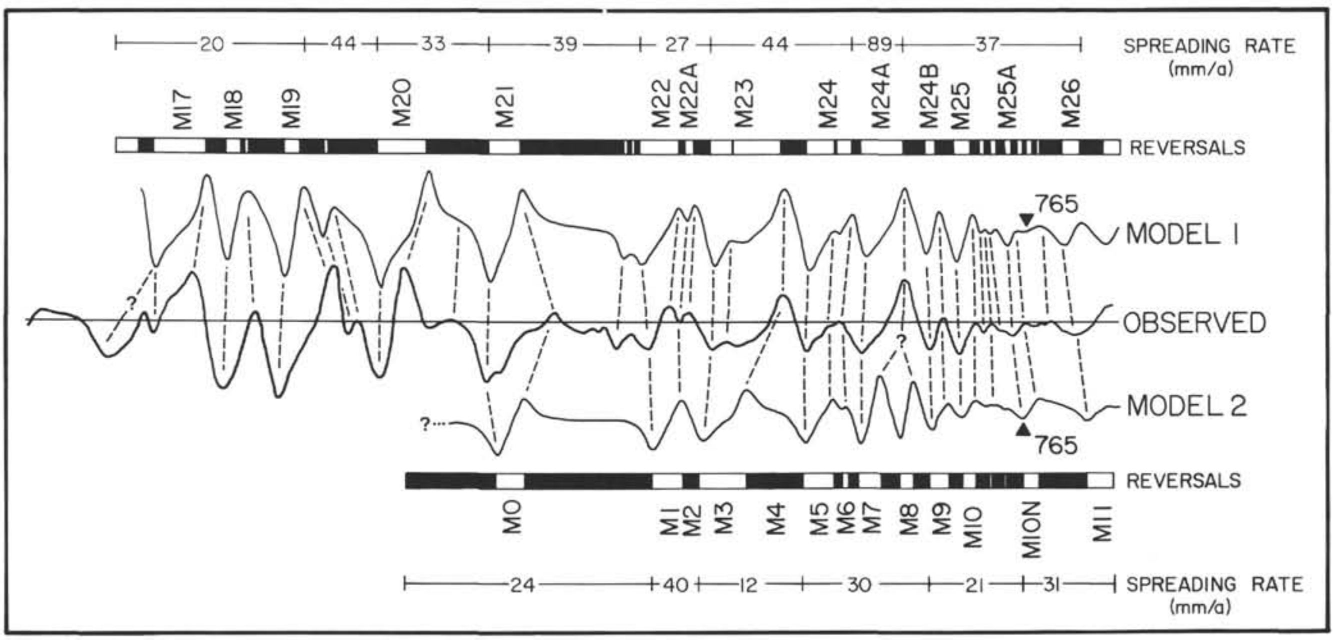

Figure 4. Models of magnetic anomalies observed along track 12 (Fig. 5). Observed anomaly at center. Above is calculated anomaly from model 1 using reversal sequence M26–M16. Bar with black and white sections represents the reversal sequence; black = normal polarity; white = reversed polarity. Anomalies labeled above bar. Spreading rates for model 1 (in mm a^{-1}) given at top. Alternative model 2 using reversal sequence M11–M0 shown below, with reversals and spreading rates shown as above. Model 2 does not account for magnetic lineations to the northwest (left) of M0. See Table 3 for model magnetization parameters. Solid triangles show location of Site 765.

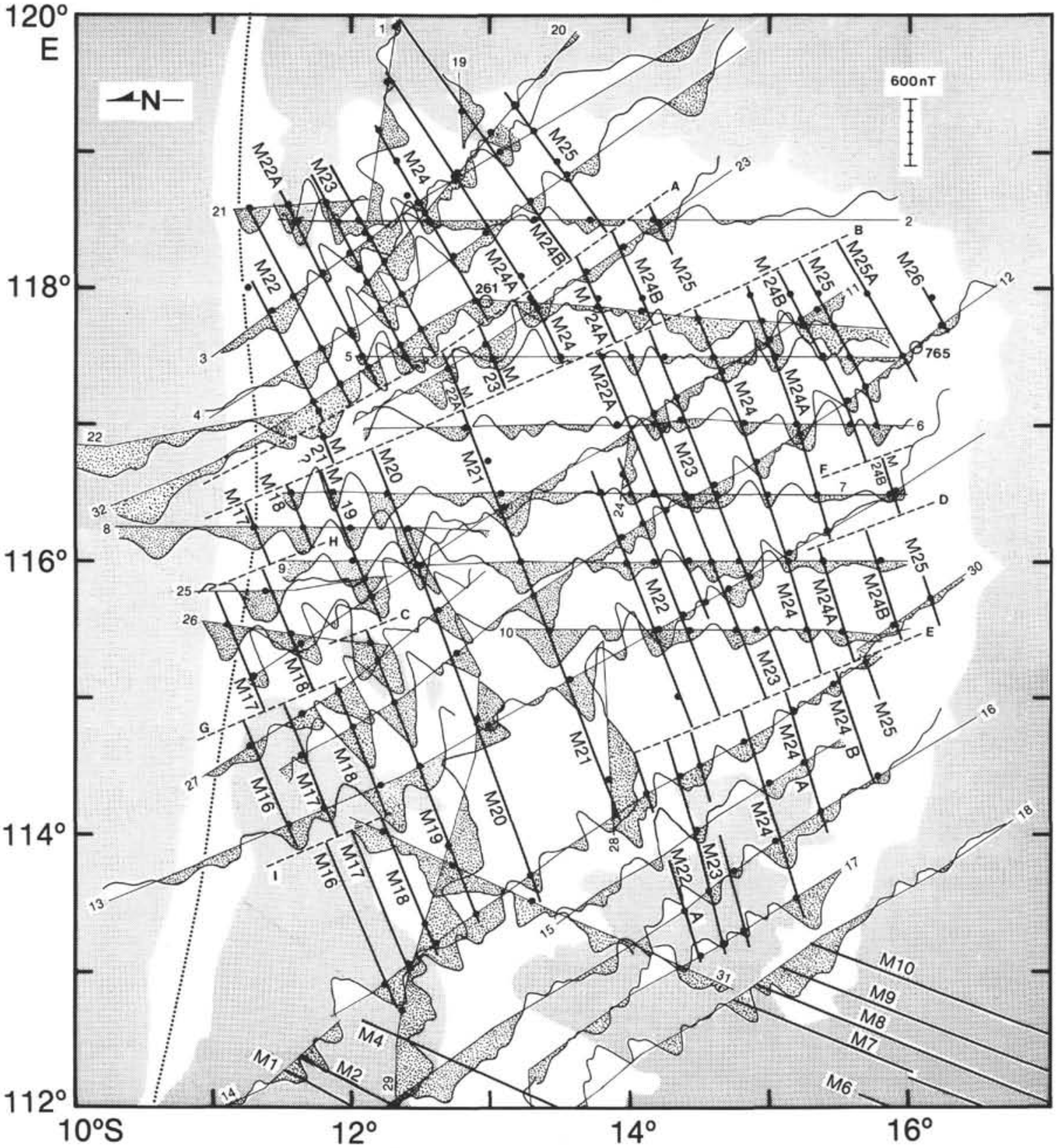

Figure 5. Magnetic anomaly correlations in the Argo Abyssal Plain. Magnetic anomalies are plotted perpendicular to ship tracks, which are represented by thin solid lines. Track numbers 1–32 refer to identifications in Table 2. Medium solid lines show anomalies. Negative anomalies are denoted by heavy stippled area. Large solid dots are anomaly picks, heavy lines show lineations. Dashed lines fracture zones, which are labeled A through I. Track identifiers 1–18 and fracture zone labels A–E are the same as those used by Fullerton et al. (1989). Open circles locations of DSDP Site 261 and ODP Site 765. Dotted line Java Trench axis. Light gray stippled area depths ≤5 km. Map has been turned on its side (with north to left) to highlight the lineation trends.

1982). Additionally, the transition from higher to lower anomaly intensities from ~M19–M22 has been noted in other oceans and attributed to either a reduced dipole field strength or an artifact of a shift from a high to a low reversal rate (Cande et al., 1978; Vogt and Einwich, 1979).

In Figure 4, the observed magnetic anomaly along track 12 is compared with a synthetic magnetic model constructed from the sequence M16 through M26. In this model, Site 765 is located between anomalies M25A and M26. The spreading rate was adjusted to stretch or compress the reversal sequence where necessary, but the averages from M26 to M22 and M21 to M16 are 29 mm a^{-1} and 48 mm a^{-1}, respectively, virtually identical to values reported earlier (Fullerton et al., 1989). We noted 37 points of correlation between the observed and calculated anomalies (Fig. 4). The best match was observed from M20 to M26. Within this sequence are several particularly diagnostic anomalies: large amplitude M21, double peaked M22–M22A, the broad, asymmetric minima of M22–M24, and the "tiny wiggles" of M24B through M25A. More difficult was the identification of anomalies M19–M16. Although the amplitudes of these anomalies are as expected, their observed spacing and shapes do not always fit the model well. Much of this problem may be an effect of the bathymetry of the eastern Roo Rise, over which these anomalies are found. An additional factor is that the anomalies in this area are correlatable only across 2–3 lines before being offset, implying that there are numerous fracture zones in the region that may adversely affect the anomaly signatures.

Alternative Early Cretaceous Lineation Model

Because of the initial biostratigraphic ages assigned to basal sediments at Site 765, we tried to find a series of Early Cretaceous anomalies that might also provide a plausible model of the observed lineations. The age given the oldest recovered sediments was late Berriasian to Valanginian, restricting the model to anomalies younger than ~M14–M16. It was also necessary to reproduce the shift from wider to narrower anomaly spacings around the anomaly previously identified as M21. Only the sequence from M0 to M3 shows such a shift (Fig. 4) as the sequence M4–M10N contains relatively rapid reversals. We were able to make a model of the southern two-thirds of track 12 using anomalies M0 through M11, with an average spreading rate of 23 mm a^{-1} (Fig. 4). In this model, Site 765 is located on anomaly M10N. The match of observed and modeled anomalies along this part of the track is surprisingly good, with 19 correlation points (Fig. 4).

However, there are some serious problems with this model. It cannot explain the correlatable anomalies north of M0 in what should be the Cretaceous Quiet Zone. Furthermore, we were forced to combine two anomalies, M7 and M8, into one; moreover, the variations in crustal magnetization (Table 3) necessary to reproduce the anomaly amplitudes, particularly those with small amplitudes, is unexpected and not observed in other oceans. Finally, basement age estimates have been revised upward by recent work. The basal sediment ages have been revised to Tithonian (Dumoulin and Brown, this volume; Mutterlose, this volume), implying that the oldest lineations should be ~M18–M20 age, rather than M14–M16 as previously thought. Additionally, the 155±3 Ma radiometric age for the basement is in accord with the Jurassic lineation model.

Lineation Interpretations

Satisfied that the Late Jurassic model was best for the anomalies in the central Argo Abyssal Plain, we extended the model to the rest of the basin. In the eastern part of the basin, in the area that Larson (1975) identified M22–M25, the line to line correlations are relatively obvious, and the anomalies have characteristics similar to those found in the south central part of the basin. Diagnostic features noted on several lines are the twin-peaked anomaly M22A and the broad minima of M22–M24 (Fig. 5). These lineations can be extended eastward to the edge of the Scott Plateau, and perhaps even into the northern part of the plateau on track 1 (Fig. 5).

The eastern and central Argo Abyssal Plain anomalies meet at fracture zones A and B (Fig. 5). Only one track (23) stays between the two fracture zones for a significant distance; thus, the anomalies in this area are not particularly well-defined. However, twin-peaked anomaly M22A was observed and serves as a guide to the identification of the other anomalies. Interestingly, there is a pronounced difference in lineation trend across fracture zone A. The anomalies between fracture zones A and B appear to have the same trend as those in the central part of the basin, about N70°E on average, whereas those to the east of fracture zone A have trends that differ by ~10°, N60°E on average.

The anomalies on the western side of the Argo Abyssal Plain, to the west of fracture zones E and I, are the most difficult to identify because their shapes on adjacent lines are variable. On the south side of the Joey Rise, a double-peaked M22A was observed on track 16, as were broad anomaly lows suggesting M23–M24 on tracks 14–16. The same interpretation has been made by several teams of investigators (Powell, 1978; Powell and Luyendyk, 1982; Veevers et al., 1985a; Fullerton et al., 1989).

To the north of the Joey Rise, the anomaly interpretations are varied. Veevers et al. (1985a) refrained from trying to identify these anomalies at all. Though Powell and Luyendyk (1982) and Fullerton et al. (1989) correlated the anomalies with the same trend as the rest of the Argo Basin lineations, the former thought they represented anomalies M5–M14, while the latter postulated that they were westward extensions of M16–M21. We decided to stick with our previous interpretation because we found three tracks (28, 29, 31) that can be used to trace anomalies M19 and M21 across the gap between tracks 13 and 14 (Fig. 5). This interpretation implies that fracture zones E and I are not connected, contrary to previous interpretations (Powell and Luyendyk 1982; Veevers et al., 1985a). Furthermore, it places anomaly M22A in close proximity to M21 on line 14, implying that a small, southward ridge jump occurred west of fracture zone E. Despite this last complication, this is a simpler model than that necessitated by interpreting the existence of simultaneous spreading in the Argo and Gascoyne basins (Powell and Luyendyk, 1982).

Fracture Zones

The Argo Abyssal Plain magnetic lineations appear to have been cut by at least nine fracture zones (Fig. 5). Only two of these features (A, B) appear to have been long-lived, extending across the entire observed suite of anomalies. Both have left-lateral displacements (A, 45 km; B, 120 km) and they combine to make the most significant offset of the lineation pattern, with the eastern Argo lineations shifted 165 km relative to the center of the basin. Offsets across the other fracture zones range from 15 to 65 km, but most are short, usually less than 100 km in length (Fig. 5). Of these, fracture zone E, offsetting anomalies M25–M22A on the west side of the basin, stands out as the longest (~240 km) with the largest displacement (65 km).

Most of the fracture zones were interpreted entirely by anomaly offsets, hence the accuracy of their placement depends on the density of ship tracks in the area and the accuracy of the anomaly interpretations. Fracture zones A and B are probably the most certain because they are bracketed by many tracks, their offset is large, and the anomalies are easily correlated and identified on either side. Moreover, seismic-reflection data from this area indicate that there are large buried linear basement highs with similar northwest trends lying between fracture zones A and B, which are interpreted to be a basement expression of these fracture zones. These highs can be observed on ODP seismic Line 1, shot during Leg 123 between Sites 261 and 765 (track 32 on Fig. 5), which is included on Plate 1 in Ludden, Gradstein, et al. (1990).

Some of our interpreted fracture zones have been recognized by previous investigators, some have not, and we have wholly or partially edited others. Fracture zones A and B were recognized by Heirtzler et al. (1978) and subsequent investigators. These we retained but, with our greater density of data, it appears that they are not parallel (Fullerton et al., 1989). Both Powell and Luyendyk (1982) and Veevers et al. (1985a) postulated one or two fracture zones cutting across the entire west side of the lineation set, one (FZGG) trending along the northern part of track 14 down to track 15, and the other (FZFF) along the trend of our fracture zones E and I. Our westward extension of anomalies M21–M16 alleviates the need for most of both fracture zones. All that remains are fracture zones E and I, the latter poorly constrained.

Previous investigators also included two fracture zones in the south central part of the Argo Basin (FZDD and FZEE of Veevers et al., 1985a), one between tracks 11 and 12 and the other between tracks 12 and 13. With our reinterpretation of the Argo anomaly trends in this area, the offsets mostly disappeared. Fracture zones D and F in this area are a result of difficulty in tracing anomalies M24A, M24B, and M25. Previously, we assumed that these lineations were curved (Fullerton et al., 1989), but our new interpretation may be a little more reasonable, considering that the Argo spreading center might have been more segmented immediately after seafloor spreading began in the basin.

Over the area of the eastern Roo Rise, we have hypothesized four short fracture zones (C, G, H, I), where we postulated only a single fracture zone (C) in our previous analysis (Fullerton et al., 1989). The extra fracture zones arise from slightly different anomaly identifications. Although the anomalies in this area are clearly correlatable (Fig. 5), it is difficult to follow a given anomaly across more than 2–3 tracks. Because of this problem, our identifications of anomalies M16–M18 and the fracture zones that cut them are tentative.

One other fracture zone postulated by prior investigators, bounding the Argo anomalies to the east, was not included in our tectonic map. Along the Scott Plateau a bathymetric notch and an offset of the COB have suggested a fracture zone bounding the east side of the magnetic lineations (Hinz, 1981; Stagg and Exon, 1981; FZAA of Veevers et al., 1985a). We did not include this feature in our interpretation because evidence for it was not compelling.

Additional evidence of fracture zone locations is provided by offsets of the continental margin. Fracture zones A, B, and F all project to notches or offsets of the margin bathymetry (Figs. 2 and 5) (Stagg and Exon, 1981) as well as offsets in the underlying basement structure (Ludden, Gradstein, et al., 1990). Indeed, much of the continental margin displays a northwest or southeast trending pattern of orthogonal bathymetric offsets. This pattern probably reflects fracture traces along the original rifted margin of northwest Australia. Many of these offsets later became the loci of submarine canyons that fed carbonate turbidites to the deep basin, mainly during the Cenozoic.

DISCUSSION

We have taken a critical look at the magnetic lineations created by seafloor spreading in the Argo Abyssal Plain, seeking evidence that they might have formed during the Early Cretaceous, as implied by the initial results of coring at Site 765 (Ludden, Gradstein, et al., 1990). We were able to construct a model of many of the lineations using Early Cretaceous Chrons M0–M11. Though this model partially solved the initial age discrepancy between the oldest sediments recovered at Site 765 and the crustal age inferred from the magnetic anomalies, it was ultimately unsatisfying because it created a number of awkward complications. The most severe difficulty with the M0–M11 model was that it could not easily explain the existence of magnetic lineations to the northwest of M0 in the area of the eastern Roo Rise. True, these anomalies were difficult to identify, but they are also clearly correlatable and should not exist in the area that would be the Cretaceous Quiet Zone in this model. To make this model work, it is necessary to postulate a large southward ridge jump sometime after the Cretaceous Quiet Period (~83 Ma, Harland et al., 1982). This new ridge would have to assume the same orientation as the Early Cretaceous anomalies and to have appeared fortuitously close to M0. Such an explanation seems too contrived. Furthermore, now that the age of the oldest Site 765 sediments has been revised upward and there is a Jurassic radiometric age determined for the basement basalts, this model predicts lithosphere ages that are too young.

The correct model appears to be one in which the anomalies are identified as Chrons M26 through M16, the oldest near the Australian continental margin and the youngest at the Java Trench. Though it is possible to quibble about the details of the anomaly correlations, this model gives a good fit to the observed anomalies. What is more, those lineations in the vicinity of Site 765 are the most diagnostic and most likely to have been identified correctly.

In accepting this model, we are again faced with the discrepancy between the ages of the oldest sediments at Site 765 and that of the underlying lithosphere. Though the discrepancy has been reduced, it implies that little or no sediment accumulated at this site for a period of ~5–10 m.y. Additionally, the oldest sediments at Site 261 may also be 3–8 m.y. younger than the age of the underlying crust. These age discrepancies probably result from extremely low Jurassic sedimentation rates in the Argo Abyssal Plain. However, it is also possible that there is a contribution from small errors in the geomagnetic polarity reversal time scale or that there were small ridge jumps during the initial seafloor spreading in the basin.

Sediment deposition on the northwest Australia margin has been slow throughout its history, as indicated by the thin drape of sediments that have accumulated since rifting began (Veevers and Cotterill, 1978). Also, the rifted margin formed a "highly irregular" surface (Powell, 1976), and rift valleys often separated offshore continental fragments from the main continental platform (Veevers and Cotterill, 1978; Falvey and Mutter, 1981). Moreover, a buried volcanic ridge separating Site 765 and the Argo Abyssal Plain from the Scott Plateau was mapped with seismic reflection data (Stagg and Exon, 1981). Likewise, large amplitude COB magnetic anomalies also suggest buried volcanic ridges (Veevers et al., 1985a). Such topography would be likely to trap most of the sediments eroded from the continent soon after rifting, so terrigenous deposition in the Argo basin may have been spotty. Moreover, it appears that the site was below the CCD, so that pelagic carbonate sediments could not accumulate (Ludden, Gradstein, et al., 1990). Indeed, isopach maps of Jurassic sediments on this margin show that they thin dramatically seaward, pinching out in many places (Stagg and Exon, 1981). Consequently, the Jurassic sedimentation at Site 765 may have been very low.

Another potential problem is the accuracy of the Late Jurassic geomagnetic polarity reversal time scale. Reliable calibration points for this part of the time scale are few. As a result, there exists a variation of several million years in the correlation of Early Cretaceous and Jurassic stratigraphic stages, magnetic anomalies, and absolute ages among different time scales.

Finally, though we are relatively confident of our magnetic anomaly identifications, those older than M23 have low amplitudes and are not as diagnostic as M21–M23. Many of these older anomalies are identified primarily by spacing, rather than shape, so it is possible that a small ridge jump might have incorporated a fragment of anomalously young lithosphere in the older section of the Argo Abyssal Plain. Noting the excellent match between the observed and modeled magnetic anomalies in Figure 4, we suggest that the probability that this occurred is remote.

Our map of magnetic lineations implies a relatively simple tectonic history for the Argo Abyssal Plain (Fig. 6). Seafloor spreading began slightly before anomaly M26 time (163 Ma). Reconstructed to their Late Jurassic orientation (e.g., Norton and Sclater, 1979), the Argo lineations are approximately parallel to other Jurassic lineations in the western Pacific Ocean (Larson and Chase, 1972) and western Indian Ocean (Rabinowitz et al., 1983), perhaps implying a genetic connection. The oldest lineations trend obliquely into the southern and eastern continental margin, implying that spreading may have begun in the center of the basin and propagated outward. Indeed, M26 was only identified between fracture zones B and F, suggesting that the spreading began there first.

The older lineations also appear to be cut by more fracture zones than younger lineations, indicating that the nascent Argo

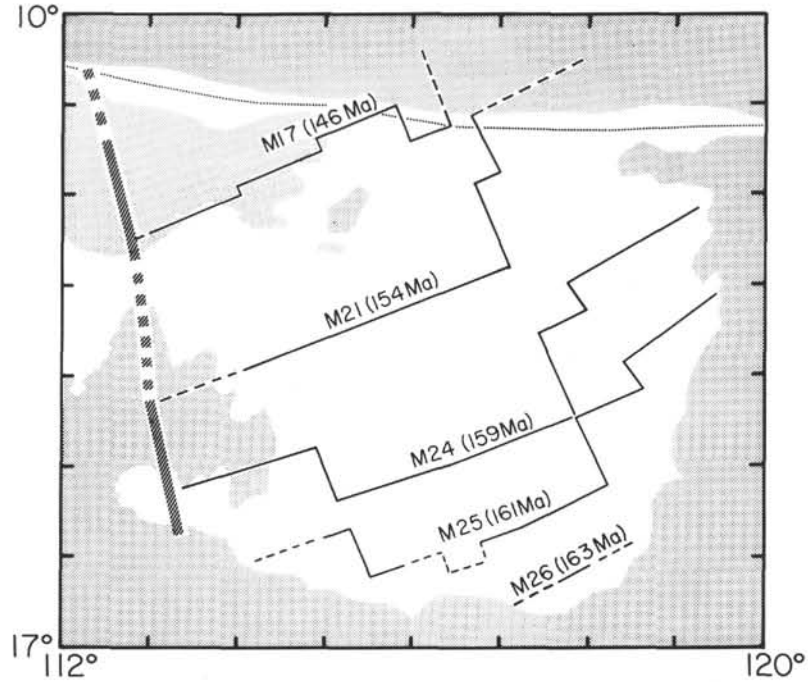

Figure 6. Tectonic evolution of the Argo Abyssal Plain. Heavy lines isochrons at the time of labeled anomaly. Ages (m.y.) from geomagnetic polarity reversal time scale of Harland et al. (1982) given in parentheses. Dashed lines inferred parts of isochrons. Dotted line location of Java Trench. Hachured line approximate location of age discontinuity between lithosphere created at Argo and Gascoyne spreading centers. Stippled areas shallower than 5 km.

spreading center was more segmented. As it evolved, the segments coalesced into a longer, straighter ridge system, an occurrence often noted in young ocean basins (Roots, 1976). The configuration of M21, M22A, and fracture zone E in the western part of the basin suggests that the ridge propagated westward across the fracture zone, slicing off a sliver of Australian plate and bringing M21 and M22A into close proximity.

Another interesting phenomenon of the young Argo spreading system is the 10° difference in trends across fracture zone A. It appears that the difference gradually disappeared as the eastern spreading segment rotated. During this reorientation, the spacing between fracture zones A and B decreased. By M22 time, the difference in trends was only a few degrees. The trend difference may indicate that spreading was slightly oblique on the eastern spreading segment, possibly related to the eastward propagation of the spreading center.

The Argo spreading center was straightest and simplest at ~M21–M20 time (Figs. 5 and 6). At about the same time, the spreading rate decreased from 48 mm a^{-1} to 29 mm a^{-1}, and by M19 time the ridge became more segmented, implying that a tectonic reorganization was underway. The Roo Rise is located where the anomalies appear to have been segmented, so it may also be related to this tectonic event. Interestingly, the timing of this event coincides with tectonic reorganizations at ~M21–M19 time in both the Pacific (Sager et al., 1988) and Atlantic (Klitgord and Schouten, 1986) oceans.

In our model, the youngest anomaly identified in the Argo Abyssal Plain is M16, so the records of spreading in the Argo and Gascoyne abyssal plains do not overlap. Sometime prior to M10 time in the Early Cretaceous, there was a profound tectonic reorganization in the eastern Indian Ocean, and spreading began to separate Australia and India along the present western margin of Australia (Markl, 1974; Larson, 1977; Norton and Sclater, 1979). What became of the Argo spreading center at this time is unknown, for the evidence has been consumed by the Java Trench. However, the oblique confluence of the Gascoyne and Argo lineations over the Joey and central Roo rises suggests that the Gascoyne spreading center propagated northward into older lithosphere previously formed at the Argo spreading center (Fullerton et al., 1989).

CONCLUSIONS

The best model for the Argo Abyssal Plain magnetic lineations is the Late Jurassic to Early Cretaceous reversal sequence M26–M16. Within the framework of this model, ODP Site 765 is located between anomalies M25A and M26, on oceanic crust of Oxfordian age. An alternative model of some lineations as M0–M11, was made to fit initial biostratigraphic estimates of the basal sediment ages at Site 765, but was dismissed as unsatisfactory because it left a large block of anomalies unexplained and required an unlikely sequence of tectonic events. Discrepancies in basement ages inferred from magnetic anomalies and fossils in the overlying sediments, ~5–10 m.y. at Site 765 and 3–8 m.y. at Site 261, probably result from extremely low Jurassic sedimentation rates. However, there may be undetected errors arising from inaccuracies in the geomagnetic polarity reversal time scale or from small ridge jumps in the early phase of seafloor spreading in the basin. We prefer the condensed section explanation because several lines of evidence suggest that the northwest Australia margin was rugged and may have trapped terrigenous sediments close to the continent. Moreover, Site 765 was beneath the CCD, so pelagic carbonate sediments should not have accumulated significantly.

In our preferred model, seafloor spreading in the Argo Abyssal Plain began immediately prior to M26 time. The Argo spreading center propagated outward from the center of the basin, consolidating smaller spreading segments into a longer, straighter ridge system. At ~M21–M19 time, a global plate reorganization caused the segmentation of the Argo spreading center and may have also played a role in the development of the Roo Rise. Seafloor spreading in the Argo Abyssal Plain and nearby Gascoyne, Cuvier, and Perth abyssal plains was not contemporaneous. The resultant age discontinuity is located over the Joey and central Roo rises.

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