

Tectonic and sedimentary history of the Argo Abyssal Plain, eastern Indian Ocean

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Bathymetric and seismic reflection profiles totalling about 2800 km, and covering about 110 000 km² of the Argo Abyssal Plain, have been analysed. The early emplacement of oceanic crust and volcanic edifices (Late Jurassic and Early Cretaceous) was followed by cooling, and marked subsidence until the Miocene. The principal structural features have been identified as the right-laterally sheared Wombat Graben in the south, the N-S trending Joey Rise in the west, the parallel sediment-filled Joey Graben to its east, a NW-trending eastward tilted and subsided volcanic massif to its east, a NW-trending linear volcanic massif on the old oceanic plate farther east, the deformed and uplifted sediments and basement in the north, and the central basin with 1.2 km thick sediments. The Joey, Wombat and Kivi Grabens are newly identified.

The N-S trending Joey Graben is 400-450 km long, parallel to and east of the Joey Rise, and it is filled with up to 1 km of sediment. Beneath it, the mantle has been identified at depths of 12-15 km and deepening westward. The other two grabens form moats hundreds of metres deep, at the foot of the Australian margin in the south. The right-lateral displacements in the axis of the Wombat Graben reflect the initial shearing and rifting of

the thinned crust. The widespread faulting in the basement, and the persistence of some faults upward into sediments as young as early Miocene, indicate that tectonism was marked until then. The eastern and northern parts of the abyssal plain have been uplifted as they came within the peripheral fore-bulge south of the Sunda Trench.

Five sequences (A-E) overlie the oceanic crust and they have been correlated with the lithology of ODP Site 765 and DSDP Site 261. They probably represent Plio-Pleistocene, upper Miocene-lower Pliocene, middle Miocene, upper Oligocene-lower Miocene and uppermost Jurassic to Lower Cretaceous strata, respectively. The depositional trends in the Mesozoic and Miocene sediments are controlled by basement structure. Isopach maps of the Mesozoic and Cainozoic sediments reveal that their maximum thicknesses are about 0.6-0.8 km and 0.2-0.4 km, respectively, with the bulk of the sediments (calcareous turbidites and claystone) laid down in the Early Cretaceous and the middle Miocene to Pliocene. During the Oligocene to early Miocene period (37-16 Ma), a remarkable geologic event led to non-deposition or erosion of sediments.

Introduction

The Argo Abyssal Plain in the northeastern Indian Ocean is bounded by the Australian continental marginal plateaus (Exmouth/Wombat and Scott) in the south and east, the eastern Sunda Arc-Trench in the north and the Joey and Roo Rises in the west (Fig. 1). The plain's oceanic crust is the oldest, 108-156 Ma, in the Indian Ocean. Volcanic rises separate the Argo Abyssal Plain from the Gascoyne Abyssal Plain to the west. The plain is a quadrangle with water depths generally exceeding 5000 m, and is a depositional plain with a regional inclination down to the southwest. Important papers dealing with the plain include Cook et al. (1978), Heitzler et al. (1978), Hinz et al. (1978), Powell & Luyendyk (1982), Veevers et al. (1985), Powell et al. (1988), Fullerton et al. (1989), Pillipenko & Sivuka (1990), Exon et al. (1982), and Gradstein & von Rad (1991). Other important papers are included in the DSDP and ODP volumes of Veevers et al. (1974); von Rad et al. (1992), and Gradstein et al. (1990, 1992).

Mesozoic M10-M25 magnetic anomalies are aligned N 70°E, and offset by northwest-trending fracture zones (Powell & Luyendyk, 1982; Fullerton et al., 1989). The crust was drilled at Deep Sea Drilling Project (DSDP) Site 261 and Ocean Drilling Program (ODP) Site 765 (Figs 2 and 5), and the site investigations revealed the litho-, bio- and magneto-stratigraphy of the sediments, and the magneto-stratigraphy of the igneous basement. In the south, ODP Site 765 identified 155 Ma oceanic basement, as compared to the older age (160 Ma, pre-Oxfordian) of the basal sediments in the north, identified at DSDP Site 261. Thus, both site investigations confirm the Jurassic opening of the Indian Ocean, but some

uncertainty about the exact age of initial opening of the plain remains. The present geomorphological and seismic investigations were done to map structural elements, the nature and temporal distribution of sediments, and the tectonics of the Argo Abyssal Plain region. Study of the sediments helps decipher the ongoing tectonic processes at the time of their deposition.

The study area of about 110 000 km² covers the Argo Abyssal Plain and lies in water depths exceeding 5000 m (Fig. 1). The various morphological units of the plain and the bordering continental margin (plateaus, rises and ridges) were identified from the bathymetric and seismic reflection studies. The data used in this study are six north-south and nine east-west profiles, totalling about 2800 line km (both multichannel and single-channel seismic) within the Argo Abyssal Plain, and carried out by the Soviet Research Vessels "Issledovatel", "Yuzhmoregeologiya", and "17 Syezd Profsoyuzov" during 1986-1988 under the auspices of the Trans Indian Ocean Geotraverse (Fig. 2). Seismic sequences were identified using the reflection patterns on seismic records (Figs 3 and 4), and correlated with the sequences in ODP Site 765. The chronostratigraphy of the sequences is interpreted by correlation with the DSDP and ODP results. Isopach and structure contour maps were prepared from the interpreted seismic profiles.

Regional distribution of seismic sequences in the Argo Abyssal Plain

Five seismic sequences have been recognised (A-E, Figs 3 and 4 A-D). Ages and average thickness are shown in Table 1. This study is complementary to that of Buffler (1994 - see this issue), who has correlated ODP Site 765 and DSDP Site 261 in the eastern Argo Abyssal Plain with key horizons and sequences on a seismic line that connects the sites. A correlation of Buffler's seismic sequences with ours is shown in Figure 5.

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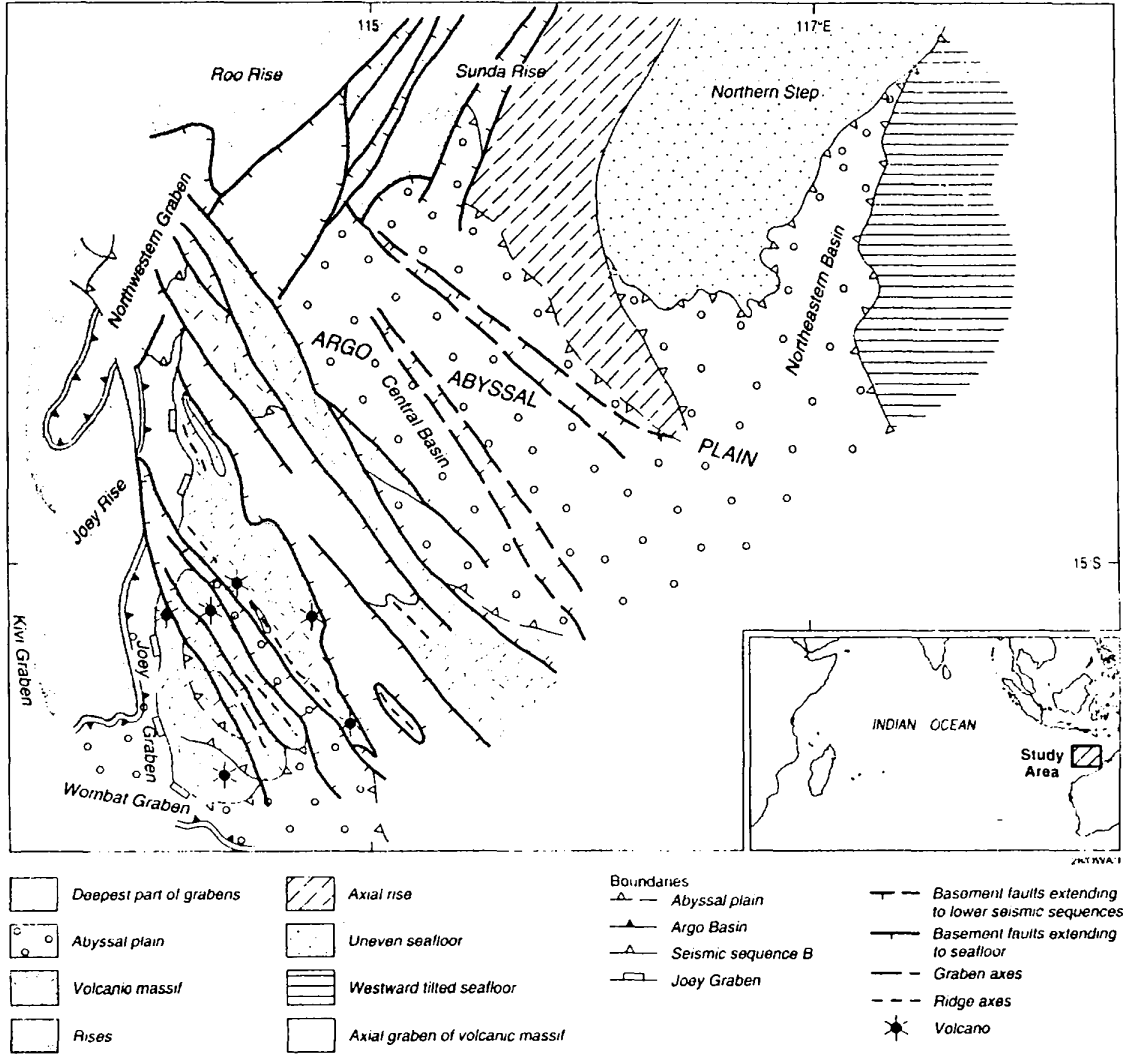


Figure 1. Geomorphology of the Argo Abyssal Plain.

Table 1. Seismic sequences.

Letter	Biostratigraphic age	Average thickness in depocentres (m)	Seismic character
A	L Pliocene — Recent	150	Well-stratified
B	l Miocene —E Pliocene	150	Well-stratified, semi-transparent
C	M Miocene	300	Well-stratified, semi-transparent
D	Oligocene —E Miocene	150	Well-stratified
E1	Palaeogene	200	Well-stratified, semi-transparent
E2	L Jurassic —Cretaceous	200	H u m m o c k y clinofoms

The reflectors of the seismic sequences A to D are parallel laminated; the lower sequence E is subdivisible into a lower discontinuous sequence E2 which has hummocky clinofoms, and an upper ubiquitous sequence E1 which

is continuously stratified and acoustically semi-transparent. Several broad submarine depressions, filled with Late Miocene and Quaternary sediments (sequences A and B) were reported by Cook et al. (1978). The present study, of the morphology of basement (Fig. 6) and the surface of the plain (Fig. 1), delineates the major structural elements (Fig. 7): Wombat Graben, Joey Graben, northern and eastern steps; central basin; volcanic massif and Sunda Rise. The thickness of the various sequences in the different structural elements is summarised in Table 2.

The total sediment thickness within the plain is generally 1.0–1.2s two-way time (TWT) (Fig. 8). The Mesozoic and Cainozoic sediments are about 0.8s and 0.4s in maximum thickness (Figs 8 and 9). The major morphological units on the plain are described below.

The Wombat Graben

The newly defined sediment-filled Wombat Graben, at the northern foot of the Wombat Plateau of the north-western Australian shelf base, is about 35 km long, 20 km

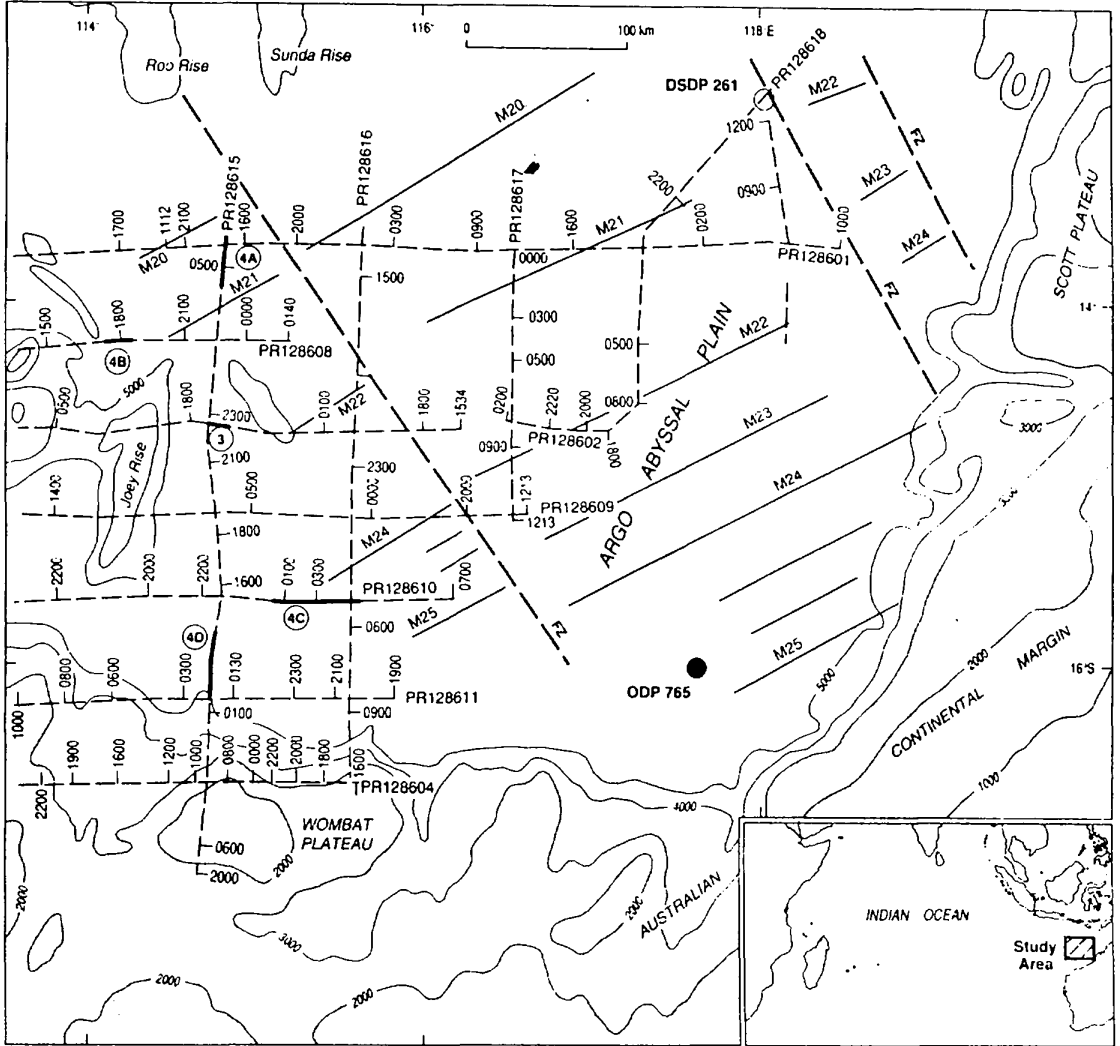


Figure 2. Generalised bathymetry (in metres) of the Argo Abyssal Plain area and index map of the study area. Tracks of seismic reflection and bathymetric investigations (dashed lines). Very thick lines refer to parts of seismic profiles shown in Figures 3 and 4. Thick dashed and continuous lines represent fracture zones and magnetic chrons respectively (after Powell & Luyendyk, 1982). Open and closed circles represent DSDP and ODP drill sites, respectively. Stippled areas mark the identified continental crust (after Veevers et al., 1985).

Table 2: Sediment thickness of Argo Abyssal Plain structures.

Structure	Thickness of seismic sequences (in m)					Total sediment thickness (m)
	[A]	[B]	[C]	[D]	[E]	
Wombat Graben	30-130	70-110	60-210	100-300	750-850	1200
Joey Graben	130-160	60-200	0	140-190	230-250	750-900
The western and eastern parts of volcanic massif	100-160	70-200	0-150	0-290	0-300	170-950
Axial graben	170-200	140-200	160-220	150-210	140-460	1140-1180
Central basin	120-240	220-270	170-270	150-200	120-500	1160-1200
Axial graben in central basin	100-160	210-220	150-160	120-220	0-250	610-650
Northern step	70	100	0	0	250	420
Eastern step	170-190	100	100-160	0-120	120-300	500-600
Average thickness in the grabens and depressions	140	130	220	145	376	921
On basement highs	116	145	130	110	125	626

Note: Thickness in metres estimated using average velocity of 2.2 km/s in sediments (after Bulmer et al., 1992).

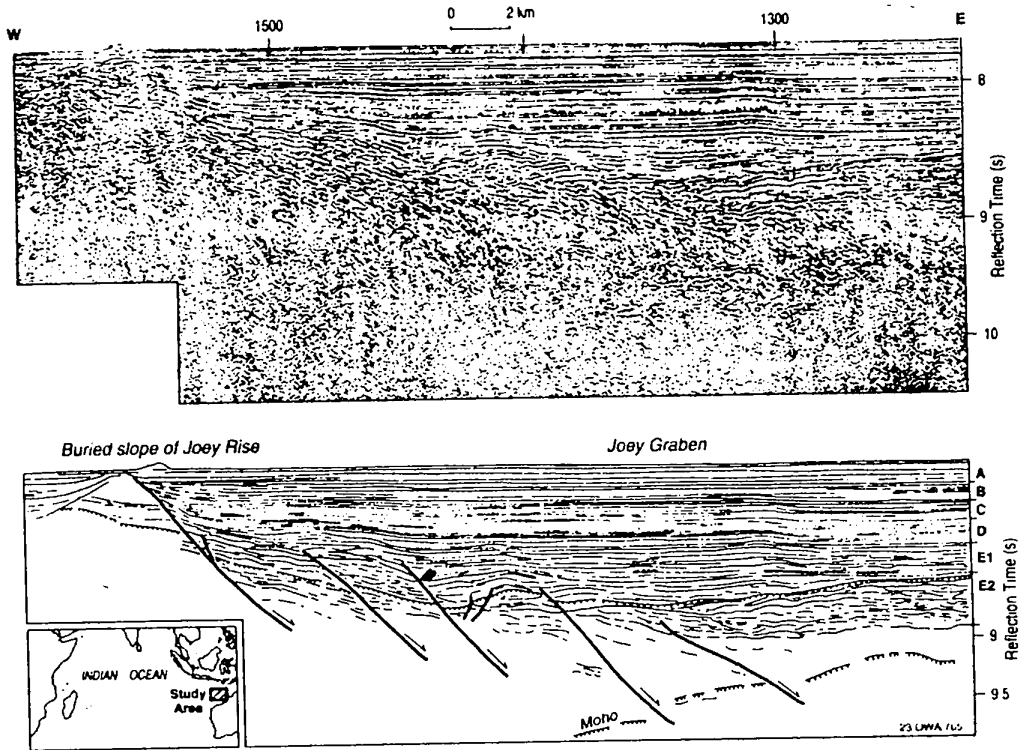


Figure 3. Multichannel reflection seismic profile 128602, east-west across the Joey Graben, and interpreted line drawing. Shows seismic sequences A, B, C, D, E₁, E₂; and the interpreted Mohorovicic discontinuity dipping westward toward the Joey Rise. Location in Figure 2.

wide and several hundred metres deep (Figs 4 and 9 D). It trends almost WNW close to the edge of the Argo Abyssal Plain, and is bounded by the Wombat Plateau in the south and a basement high in the north. There are several elongated, 10–12 km long, basement depressions reaching depths of 6800–7000 m, within the central graben and bounded by basement faults. These trend northwesterly, oblique to the graben edge, and are right-laterally displaced (Fig. 6). Gradual deepening and thickening of seismic sequence E occurs towards the north (Fig. 4D); its reflectors are nearly parallel and acoustically semi-transparent. Sequence D is absent in the axial graben, and reflectors in sequences C to A overlap underlying sequences and basement. The older sequence E gradually thins southward up the plateau slope (Fig. 4D). In the graben, axis sediments are up to 1.2s thick. The NNE-trending Kivi Graben (Figs 6 and 7), separated from the Wombat Graben by the Joey Rise, is also a newly defined similar feature that lies NW of the Wombat Graben, north of the Australian margin and between the Joey Rise and a basement high farther west.

The Joey Graben

The newly defined Joey Graben is a north-south trending, 400–450 km long and 20–25 km wide feature, in 5400–5800 m water depths, with a smooth seafloor (Figs 3 and 4 B). It parallels and lies east of the Joey Rise and is oblique to the Mesozoic oceanic fracture zones (Figs 6 and 7). Multichannel seismic reflection profiles covering the eastern Joey Rise and part of the graben reveal intense reflectors dipping towards the Joey Rise at 9.0 to 10.5s (ca. 12–15 km) depth. The graben extends northward beyond the Joey Rise to terminate against the Roo Rise

(Fig. 4B). It consists of local subgrabens trending west-northwest to north-south (Fig. 6), which have faulted basement blocks bounded by normal faults (Figs 3 and 4 B). The maximum sediment thickness within the graben is about 1.0s (TWT), and a maximum of about 0.6s of Mesozoic sediments is confined to the central graben close to the eastern slope of the Joey Rise. Miocene and Plio-Pleistocene sediments are about 0.2s thick in the graben and they thicken to the east.

The southern, north-trending, subgraben is about 150 km long and contains up to 1.0s of sediments. The northern, WNW-trending, subgraben is 100 km long and has sediments about 0.6s thick. Basement is generally about 6400 m deep (Fig. 6). In the northwest of the northern subgraben, upper Miocene (Sequence B) sediments are covered by Pliocene–Pleistocene (Sequence A) mass-wasting deposits from the Joey Rise (Fig. 4 B). Sequence C sediments are absent in the central Joey Graben. Numerous basement faults extend through the older sediments (Sequences D and E) and displace them. Sequences A, B, and C thicken eastward, while sequence D thins and dips eastward. The variable disposition of the depocentres implies changes in the tectonic regime with time.

Step-like structures

In the northeast of the plain, two steps within the basement are separated by a northeast-trending basin (Figs 7 and 8). Within the northeastern basin, small linear grabens separate the northern and eastern steps (Fig. 6). The northern step is broad and dips gently to the southeast and east (Figs 4 A and 6). It is down-faulted southward by up to 400 m, forming local horsts (around 6000 m

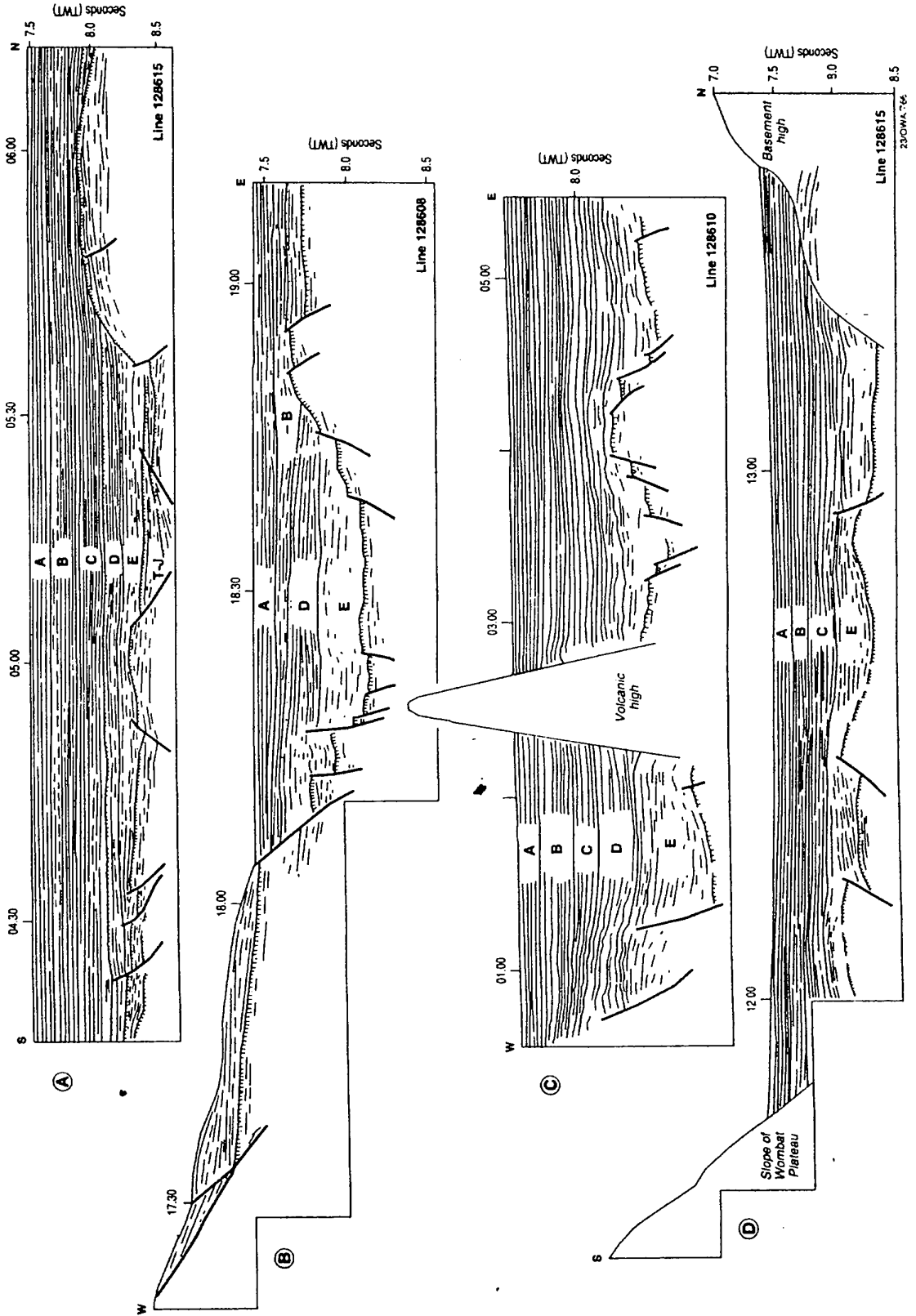


Figure 4. Line drawings of analogue seismic reflection records (TWT in seconds): A, B, C, D, and E are identified seismic sequences. A: Profile across the central basin and northern step; B: Profile across the Joey Graben; C: Profile across the Wombat massifs; D: Profile across the Wombat Graben; note distinct block-faulted style of the basement on either side of the massifs. E: Profile across the Joey Graben.

ODP SITE 765

SYSTEM	SERIES	STAGE	UNIT	THICKNESS (m)		OUR SEISMIC SEQUENCE	ODP SEISMIC SEQUENCE	ODP LITHOLOGIES
QUATERNARY	PLEISTOCENE							
NEOGENE	PLIOCENE		1	189.1		A	1	Carbonate turbidites and debris flows
						B2	2	Carbonate turbidites
	MIOCENE		2	265		B1	3	Carbonate turbidites
						C	4	Carbonate turbidites and claystone
						D	5	Carbonate turbidites, debris flows and claystone
PALEOGENE	OLIGOCENE		3	117.6		E1	6	Carbonate turbidites and claystone
	PALEOCENE - EOCENE							
CRETACEOUS	Upper		4	132.4		E2	7	Carbonate turbidites, claystone, bentonite
		Albian						
	Lower	Aptian	5	135.1				
		Neocomian	6	33.7				
		Tithonian ?	7	29.7				
JURASSIC	Upper			265.8			Oceanic pillow basalt	

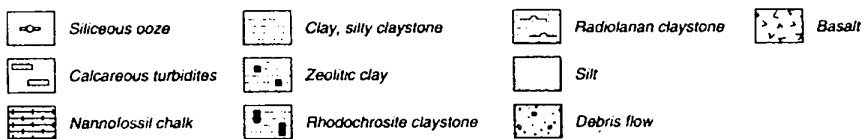


Figure 5. Lithological log of ODP Site 765 and correlation with our seismic sequences. ODP seismic sequences and lithological descriptions from Gradstein et al. (1990).

deep) and grabens (around 6400 m deep) about 5 to 6 km wide. The seismic sequences in the area can be grouped into two units. The lower sequences (C, D and E) fill the axial graben and are up to 0.7–0.8s thick. Sequence E sediments are up to 0.2s thick within the deepest parts of local grabens. The top of seismic sequence D is an unconformity which dips southward, with the lower reflectors of Sequence C overlapping it. All seismic sequences thin to the north toward the Sunda Rise (Fig. 4 A). Sequences E and D are dislocated by basement faults, resulting in local anticline-like structures. The sediments are between 0.25–0.8s thick on the northern step, and 0.45–0.85s on the eastern step. Up to 1.0s of sediment occurs at the intersection of the northern and eastern steps, where the basement is broken by numerous fractures (Fig. 6). Seismic sequence E is absent in the north (Fig. 4

A). Flexural deformation decreases upward. Local folds, in both acoustic basement and sediments, form a chain of subsurface hills in the northeast (Fig. 6).

Central basin

The central basin covers a large area of the plain (Figs 4A and 7). Sediment thickness varies from 1.0s to 1.2s (Fig. 8), and the thickest sediments are in the southeast where Mesozoic sediments of Sequence E are present. Sequence E is nearly twice as thick in the axial parts of the grabens within the basin as it is on basement rises. The entire central basin is covered with Cainozoic sediments 0.5–1.0s thick. Isopachs of the Plio-Pleistocene reveal a dominant northeast–southwest trend (Fig. 9 D), concurrent with the Mesozoic crustal features, but unlike

the intervening sequences.

Flexural deformation of sequences E, D and C occurs above most of the fracture zones. Acoustically transparent zones, within parallel and horizontal seismic sequences, are widespread through sequences C, D and E and above local basement rises. Cook et al. (1978) identified them as mud diapirs, but the present multichannel seismic records show that the "diapirs" are faulted folds, and seismic reflectors continue across them. Seismic sequences A, B and C onlap onto them.

The graben northeast of the volcanic massif (Figs 4 C and 7) is 12–20 km wide and contains 1.0 to 1.2s of sediments, and basement there is 6850–7000 m deep. The lower sequences and basement are severely faulted against the eastern slope of the volcanic massif, and sequences D and E thin up its slope.

Volcanic massif

Southwest of the central basin are two lengthy NW-trending-ing features: an oceanic basement rise and a volcanic massif farther west (Figs 4 C and 7). The volcanic massif itself consists of three linear basement ridges separated by two linear depressions or grabens. At a number of places basement ridges reach the sea floor (Fig. 8). Several local grabens, and submarine seamounts with complex structure, occur along the western part of the massif. Sediment thickness varies from zero on some of the volcanic seamounts to 1.0s in the grabens. In this area, the basement subsides in steps (Fig. 4A). West of the massif, the down-faulted basement consists of blocks 2–8 km wide, which are displaced 100–150 m by faults. A seismic section across the axial graben of the volcanic massif reveals downfaulted basement blocks, 70–80 km wide, at 6400–6000 m depth.

Thus, the eastern part of the volcanic massif (Fig. 4C)

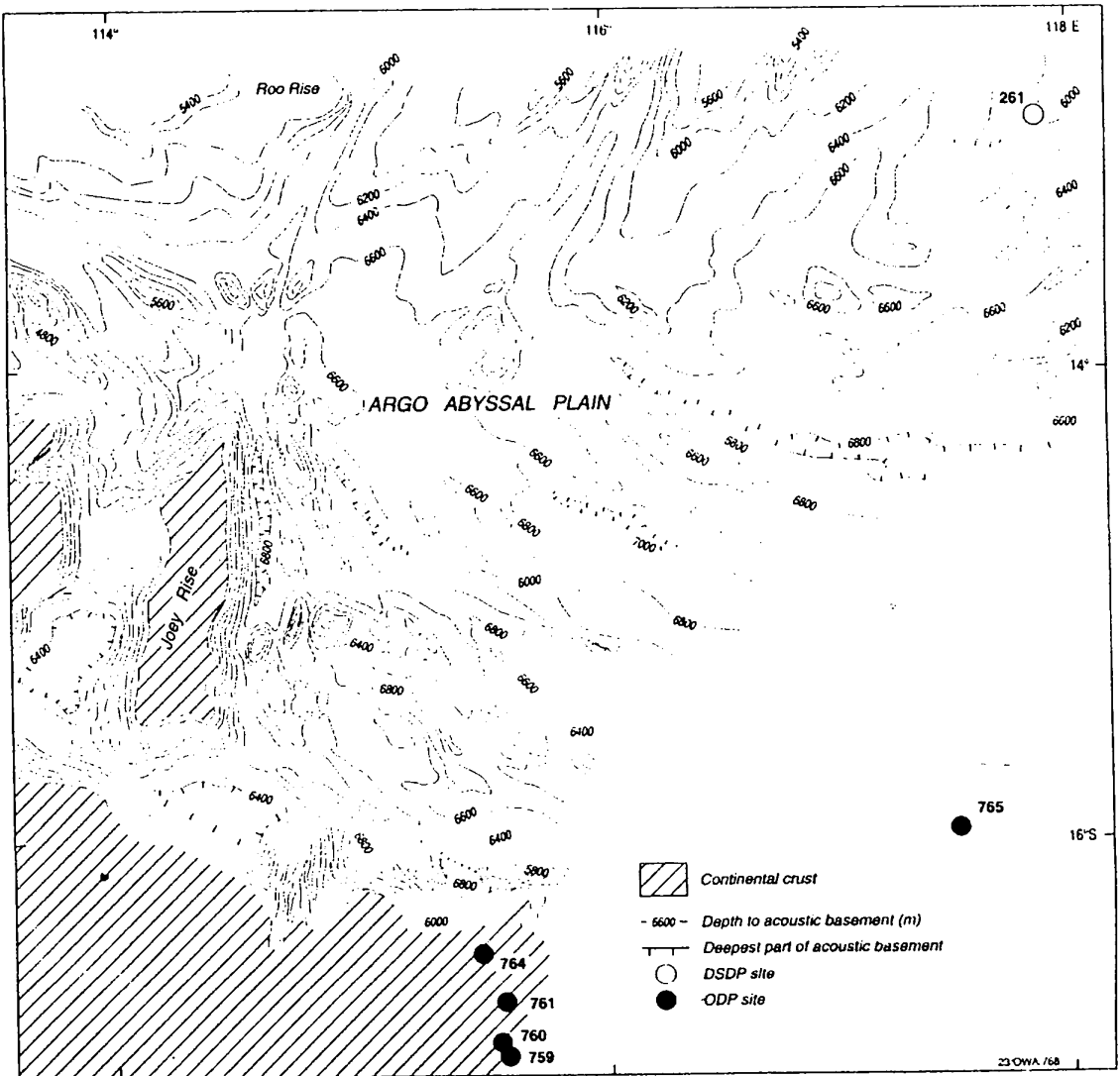


Figure 6. Map of depth to acoustic basement (depth in metres). Open and closed circles represent the DSDP and ODP drill well locations, respectively.

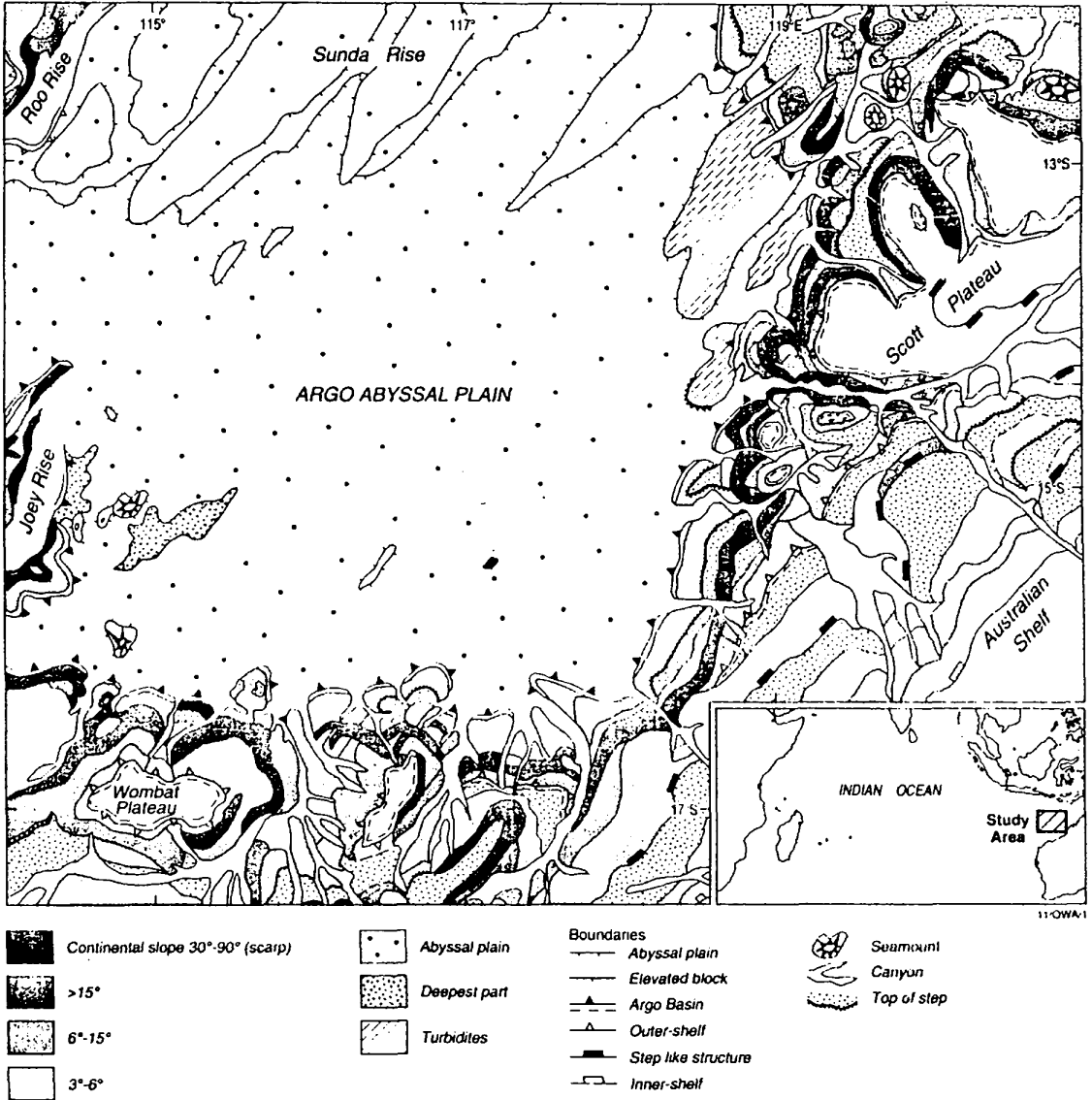


Figure 7. Map of the identified structural elements of the Argo Abyssal Plain. Index map on the right lower corner shows the study area.

is characterised by a less-rugged basement than the western part. Sequence E is thicker above deeper basement: 0.05–0.15s above the uplifted blocks, and 0.2–0.3s in depressions. It is everywhere overlain by about 0.1–0.2s of sequence D, and about 0.2s of sequence C. The C and B sequences unconformably overlie the older sequences on the eastern volcanic massif. Sequence B is 0.1 to 0.2s thick.

Crustal structure, sequences and tectonic evolution

Seismic sequences

The seismic sequences A, B, C, D and E are generally present throughout the Argo Abyssal Plain, excepting sequence C in the Joey Graben and sequence D in the

Wombat Graben.

In large areas of the Argo Abyssal Plain, the Mesozoic (sequence E) and Early Cainozoic (sequence D) sediments occur in palaeo-deeps, in areas of downfaulted basement. DSDP site 261 revealed Cretaceous pelagic clays with glauconite in the northeastern plain (Veevers et al., 1974), while ODP Site 765 revealed hemipelagic clays and claystones overlain by calcareous turbidites in the south-east (Gradstein et al., 1990). This points to thick infill of pelagic sediments and turbidites in the grabens close to the continental margin, and pelagic sedimentation on the northeastern plain. Further, downfaulted basement, and faulting of the overlying Mesozoic to early Miocene (E and D) sediments in the central basin, the grabens of the volcanic massif, and the step-like structures, clearly indicate relatively intense tectonism till the end of the

early Miocene. The confinement of the oldest sediments to the axial graben denotes early faulting, and its control of sedimentation. The regional tilt of the abyssal plain, with the basement deeper in the south and southwest, and higher in the west and in the north in the tectonic bulge south of the Sunda Arc, may have developed early, on the evidence of the thicker older sequences there.

The low frequency and high amplitude reflections of seismic sequence D mark near-bottom, high-energy sedimentation. DSDP site 261 revealed a sharp reduction of the sedimentation rate in the early Palaeogene, and palaeogeographic changes. A notable change in near-bottom sedimentation at the end of the early Miocene (sequence C) is inferred. Sequence D dips eastwards in the Joey Graben (Fig. 4 B) and across the adjacent volcanic massif, due to tectonism during the Oligocene/Miocene period. This may have caused erosion or non-deposition, as suggested by the absence of sequence C.

Gradstein & von Rad (1991) interpreted structural tilt northward of the Wombat Plateau into the Argo Abyssal Plain as having been caused by isostatic rebound due to subsidence of the Wombat half-graben (south of the plateau) along normal faults unloading it in the latest Jurassic, just before breakup. The faulted basement and the overlying Mesozoic sediments also suggest early tectonic activity of the area.

Increase in areal extent with time, and the thickness of sequences C to A, point to gradual migration of depocentres to the east, and increase in extent of sedimentation with time. The ubiquitous Plio-Pleistocene sediments of sequence A gradually thicken eastward. However, there are notable changes in sedimentation during the Oligocene-Miocene period (37-16 Ma) as shown by the absence of middle Miocene sediments (sequence C) in the Joey Graben; the presence of upper Oligocene-lower Miocene (sequence D) sediments northwest of the Wombat Graben;

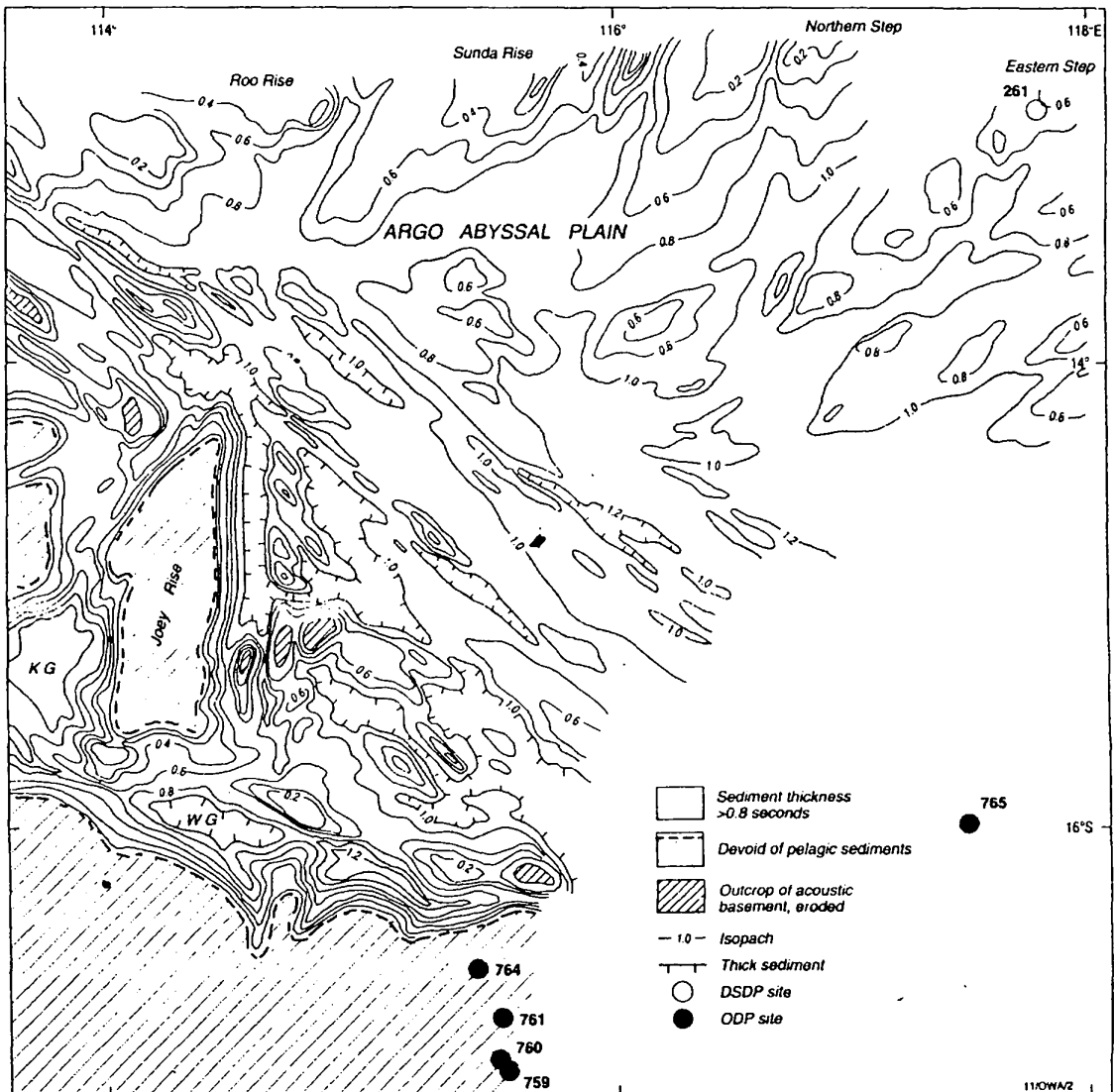
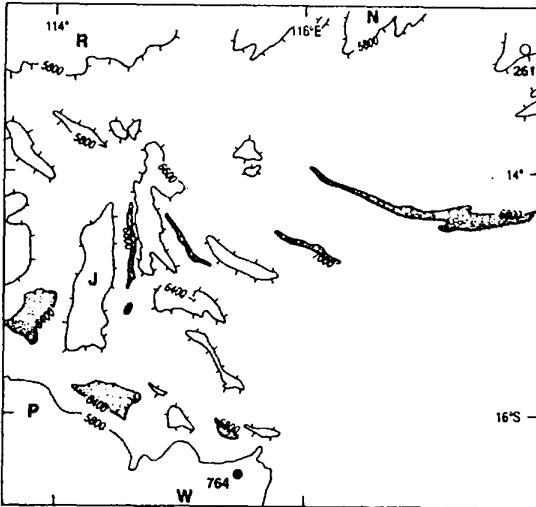
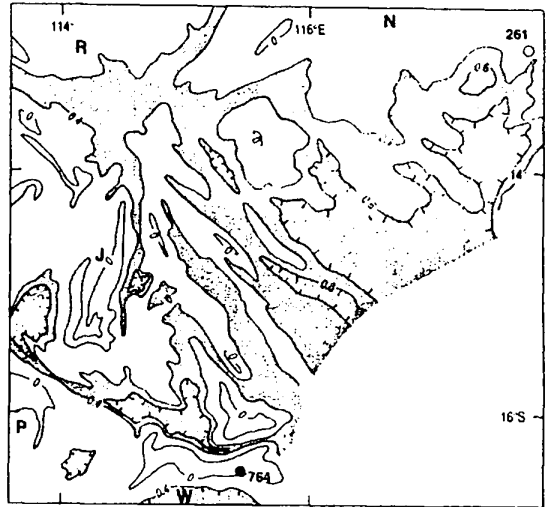


Figure 8. Isopach map of total sediments. Thickness values are in seconds (TWT). Open and closed circles are DSDP and ODP drill well locations, respectively. KG = Kivi Graben; WG = Wombat Graben.

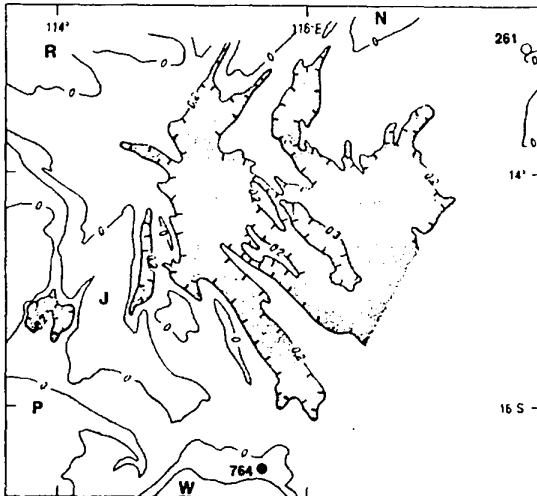
(A) Basement Features



(B) Mesozoic isopach



(C) Upper-Middle Miocene isopach



(D) Plio-Pleistocene isopach

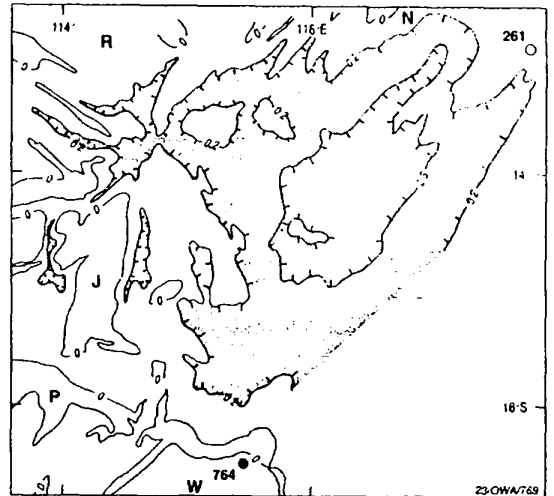


Figure 9. Maps of the Argo Abyssal Plain in seconds (TWT). A = basement features, B = Mesozoic isopach, C = upper to middle Miocene isopach, D = Plio-Pleistocene isopach. N = northern step, J = Joey Rise, P = Platypus Spur, W = Wombat Plateau, 261 = DSDP Site 261, 764 = ODP Site 764.

and the identification of the top of sequence D as an unconformity south of the step-like structures in the northern Argo Abyssal Plain. Bottom currents probably resulted in erosion or non-deposition.

Tectonics

The widespread fault-controlled deformation of earlier sediments, and the less-widespread deformation of younger sediments, suggest continued compressional stress, which is more pronounced in the northeast than the south. The basement in the northeast is broken into numerous local blocks 50–70 km across with vertical displacements of 250–300 m. Deformation continued until the early Miocene in the north, much later than in the south. Furthermore, there are altogether different structural and tectonic fabrics on either side of the volcanic massif (Figs 6 and 7). The presence of Upper Jurassic–Cretaceous and upper Oligocene–lower Miocene sediments along the slopes of the extinct volcano on the massif suggests that it originated

in the Upper Jurassic. Downbending and increasing thickness of seismic sequences E and D toward the volcanic massif, with flat-lying sequences above them, mark its subsidence till the late Miocene (about 14 Ma). The increase of basement depth and earliest sediment thickness north of the Wombat Graben, and the right-lateral shift of the axial parts of the graben (Fig. 6) appear to be a manifestation of the initial shearing and rifting of the crust. Thick Mesozoic and Cainozoic deep-sea basin sediments surrounding the Australian continental margin in the Indian Ocean were also reported by Pillipenko & Sivukha (1990), who believed that they originated during an early stage of graben/basin evolution.

In the deep grabens, the basement contour map (Fig. 6) shows about 7000 m depth to acoustic basement, and the total sediment isopach map (Fig. 8) shows about 1200 m thickness of sediments. The individual isopachs of Mesozoic to upper Miocene sediments are closely controlled by the northwest structural trend of the Mesozoic ocean floor.

A comparison of the isopachs of the Mesozoic, upper to middle Miocene, and Plio-Pleistocene, with maps of basement features (Figs 6, 7 and 9), shows how sediment distribution has changed with time. The Mesozoic isopach (Fig. 9 B) represents the sediments that infilled the Late Jurassic to Early Cretaceous volcanic surface, and shows obvious control by the basement features. In the various areas, different basement features exert control: in the far north, NE trends; in the east, centre and northwest, NW trends; in the south the WNW-trending Australian continental margin, and in the west the north-trending Joey Rise. The sequence is absent only on local highs, and most of the plain is covered by more than 0.4s of section. There are local depocentres along the Australian margin where sediment was derived as turbidites from Australia (as first mapped off the Swan Canyon by Cook et al. 1978). There was little deposition between the Early Cretaceous and the Miocene.

The Miocene isopach (Fig. 9 C) shows that the area sedimented was smaller than in the Mesozoic, with little deposition near the Australian margin, and the depocentre was in the middle of the abyssal plain. NW-trends predominate in the central basin and NE trends in the north. The Plio-Pleistocene isopach (Fig. 9 D) is similar to the Miocene isopach, but NE-trends are prominent farther south, perhaps because of cracking of the oceanic crust in that direction, as it climbed the peripheral fore-bulge of the Sunda Trench. The tilt down to the south, and the deposition of unstable volcanic ash from the Indonesian Arc, caused the flow of sediment to the south.

Seafloor spreading started with early Mesozoic anomaly M26 (ca. 156 Ma). Spreading ridges trend NE and there are complementary NW-trending fracture zones. The trends of the major grabens like the Joey Graben (Fig. 7), oblique to the fracture/transform trends in the plain, point to further shearing and rifting of the crust in NNE to northerly directions. Seismic reflectors at 9.0–10.5s (12–15 km) depth near the Joey Rise are most likely from the upper mantle. The shallow mantle in the Joey Graben, and the right-laterally displaced axial parts of the Wombat Graben, suggest the presence of thin sheared and rifted crust in the grabens. In the southwest, too, the volcanic massif subsided till the Oligocene–Miocene, and there is early block-faulting of basement on either side of it. The regional tilt and increasing areal extent of the sediments on the accumulative plain to the south, and the shearing, rifting, subsidence and faulting of basement until the Miocene period, have been the keys to the present structural configuration of the Argo Abyssal Plain.

Conclusions

The Argo Abyssal Plain is limited by the Sunda Trench to the north, the Joey and Roo Rises to the west, the Scott Plateau and Rowley Terrace to the east, and the Exmouth Plateau to the south (Fig. 1). It started to form in the Late Jurassic as Gondwana broke up, and the Late Jurassic and Early Cretaceous oceanic crust should, according to magnetic mapping (e.g. Fullerton et al., 1989), be structured by fracture zones trending NNW and spreading ridges trending ENE. However, the basement structure of the western two-thirds of the plain mapped here does not show these trends at all (Fig. 6): the dominant trend is west to west-northwest in much of the area, northeasterly trends predominate in the north, and northerly and northwesterly trends in the north. This

discrepancy could be the result of limitations in the mapping of the magnetic trends by various workers, or of the seismic mapping reported here, together with a complex tectonic history. In both cases, the line-spacing is open at 50 km or more, and perhaps we must await the release of GEOSAT images to be sure of the fabric. The volcanic edifices of the Joey and Roo Rises were built soon after the ocean floor formed.

The isopach maps show the broad changes in sediment pattern with time (Figs 8 and 9) and these can be related to the depositional pattern in ODP Site 765 (Fig. 5). The Mesozoic saw widespread sedimentation, about 400–600 m thick, of bentonite and clays, and carbonate and other types of turbidites (Fig. 5), derived largely from erosion of the Australian margin. Fan-like depocentres were present along the Australian margin, both in the area of the Wombat Plateau mapped here (Fig. 9 C), and in the area farther east off the Swan Canyon mapped by Cook et al. (1978). The trends in the isopachs mimic the basement trends in many areas, but northwesterly trends are more common in the isopach map than the basement map (Fig. 6), for unknown reasons.

The next major sequence is the Miocene (Figs 5 and 9 C), consisting of carbonate turbidites, debris flows and clay deposits. It is thinner than the Mesozoic, averaging 300 m thick, and is not as widespread around the margins of the abyssal plain. Trends in the isopachs are not dissimilar to those in the Mesozoic, with northeasterly trends prominent in the north, and northwesterly trends in the centre of the plain. The Plio-Pleistocene isopach (Fig. 9 D) shows a similar distribution and thickness to the Miocene isopach, but the northwesterly trends have largely been eliminated by sedimentation. This sequence consists of carbonate turbidites and debris-flow accumulations, much like the earlier ones (Fig. 5).

The structural and isopach maps, and the seismic sections, suggest that on-going movement on basement faults affected sedimentation through into the Miocene, but in the Plio-Pleistocene the only tectonism has been the uplift of the Sunda Trench peripheral fore-bulge as the plain moved north, and associated jostling of the northeasterly trending faults. The basement and the abyssal plain tilts southwestward down from the fore-bulge, and some seismic evidence suggests that turbidites are flowing in that direction. However, that tilt does not apply in the southwest, with its rugged basement relief.

The map of crustal structural elements (Fig. 7) summarises the tectonic situation. It shows the importance of northeast to north-northeast-trending structures in the north and west: Roo Rise, northwest graben, Sunda Rise, northern step, and northeastern basin. Northwesterly and northerly trends predominate in the southwest, with a series of NW-trending volcanic massifs and troughs, and the Joey Graben stretching about 400 km to the north, from east of Joey Rise to join the northwest graben. Along the WNW-trending Australian margin in the southwest (Fig. 6), the subsidence of the Australian margin has developed a moat up to 50 km wide, which extends eastward from the Kivi Graben of Figure 6. Figure 7, although a sketch, does indicate that the interplay of seafloor spreading, later volcanism, continental subsidence, and movement northward into the peripheral fore-bulge, has probably involved strike-slip as well as normal faulting. The seismic evidence of shallow mantle (12–15 km) below the Joey Graben suggests thinned crust

that may have been readily sheared.

Acknowledgements

We thank coordinators of this project of the Trans Indian Ocean Geotraverse, Dr B.I. Emerkov (Head of the Department of the Problems of the World Oceans, erstwhile USSR State Committee for Science and Technology, Moscow), and Dr B.N. Desai (Director, National Institute of Oceanography, Dona Paula, Goa, India), for agreeing to the carrying out of this study. The study comes under the auspices of Indo-USSR collaboration in oceanography.

This paper was refereed by Barry Willcox of the Australian Geological Survey Organisation (AGSO) and John Veevers of Macquarie University (Sydney), and modified in the light of their comments. The figures were finalised at AGSO's Cartographic Services Unit.

References

- Bolmer, S.T., Buffler, R.T., Hoskins, H., Stephen, R.A. & Swift, S.A., 1992. Vertical seismic profile at Site 765 and seismic reflectors in the Argo Abyssal Plain. *Proceedings ODP, Science Results*, 123, 583-600.
- Buffler, R.T., 1994. Geologic history of the eastern Argo Abyssal Plain based on ODP drilling and seismic data. *AGSO Journal of Australian Geology & Geophysics*, 15(1), 157-164.
- Cook, P.J., Veevers, J.J., Heirtzler, J.R. & Cameron, P.J., 1978. The sediments of the Argo Abyssal plain and adjacent areas, northeast Indian Ocean. *BMR Journal of Australian Geology & Geophysics*, 3, 113-124.
- Exon, N.F., von Rad, U. & von Stackelberg, U., 1982. The geological evolution of the passive margins of the Exmouth Plateau off northwest Australia. *Marine Geology*, 47, 131-152.
- Fullerton, L.G., Sager, W.W. & Handschumacher P.W., 1989. Late Jurassic-Early Cretaceous evolution of the eastern Indian Ocean adjacent to northwest Australia. *Journal Geophysical Research*, 94, 1937-2953.
- Gradstein, F.M. & von Rad, U., 1991. Stratigraphic evolution of Mesozoic continental margin and oceanic sequences: Northwest Australia and northern Himalayas. *Marine Geology*, 102, 131-174.
- Gradstein, F.M., Ludden, J.N. et al., 1990. *Proceedings ODP, Initial Reports*, 123. College Station, Texas, 716 p.
- Gradstein, F.M., Ludden, J.N. et al., 1992. *Proceedings ODP, Science Results*, 123. College Station, Texas, 846 p.
- Heirtzler, J.R., Cameron, P., Cook, P.J., Powell, T., Roeser, H.A., Sukardi, S. & Veevers, J.J. 1978. The Argo Abyssal plain. *Earth and Planetary Science Letters*, 41, 21-31.
- Hinz, K., Beierdorf, H., Exon, N.F., Roeser, H.A., Stagg, H.M.J. & von Stackelberg, U., 1978. Geoscientific investigations from the Scott Plateau off northwest Australia to the Java Trench. *BMR Journal of Australian Geology & Geophysics*, 3, 319-340.
- Pillipenko A.I. & Sivukha, N.M., 1990. Tectonics of northern part of Exmouth Plateau and adjacent deep basin Indian Ocean. *Geotectonic*, 2, 112-121. (In Russian.)
- Powell, C.M., Roots, S.R. & Veevers, J.J., 1988. Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean. *Tectonophysics*, 155, 261-283.
- Powell, T.S. & Luyendyk, B.P. 1982. The seafloor spreading history of the eastern Indian Ocean. *Marine Geophysical Research*, 5, 225-247.
- Veevers, J.J., Tayton, J.W. & Johnson, B.D., 1985. Prominent magnetic anomaly along the continent-ocean boundary between the northwestern margin of Australia (Exmouth and Scott plateaus) and the Argo Abyssal plain. *Earth & Planetary Science Letters*, 72, 415-426.
- Veevers, J.J., Heirtzler, J.R. et al. 1974. *Initial Reports of the Deep Sea Drilling Project, XXVII*. National Science Foundation, Washington, 1060 p.
- von Rad, U., Haq, B. et al., 1992. *Proceedings ODP, Science Results*, 122. College Station, Texas, 934 p.