The sediments of the Argo Abyssal Plain and adjacent areas, northeast Indian Ocean

P. J. Cook[1], *J. J. Veevers*[2], *J. R. Hiertzler*[3], *and P. J. Cameron*

A series of geophysical traverses by the Atlantis II across the Argo Abyssal Plain, together with coring at a number of selected localities has provided new information on sedimentary and tectonic processes in this region of the northeast Indian Ocean. Isopach maps prepared from the seismic profiles show that sediment thicknesses crudely parallel the bathymetry. The presence of some diapirs in the Argo Abyssal Plain was indicated. It was not possible to say from the present program whether the probable diapirs are salt or mud-cored. A diverse group of cores were obtained from a variety of sites including siliceous clays from below the CCD, calcareous oozes from above the CCD, calcareous clays (showing evidence of abundant sulphate reduction) from a fore-arc basin site, and manganese nodules from an abyssal site. In addition, hyaloclastites from the Joey Rise area (north of the Exmouth Plateau), suggest that the Joey Rise, and possibly also the Roo Rise, are underlain by basaltic material. A sample of basalt was also recovered from the outer part of the Exmouth Plateau.

Introduction

The purpose of this paper is to report on some of the sedimentary results of the cruise by the RV Atlantis II of the Woods Hole Oceanographic Institution in the northeast Indian Ocean. The cruise took place from 29 October to 26 November 1976, commencing at Darwin and finishing at Singapore (Fig. 1). During the course of the cruise bathymetric, seismic (reflection and refraction), gravity, and magnetic surveying was undertaken. In addition, 9 core and 2 dredge sites were attempted. Using this range of techniques it was possible to add significantly to the amount of geophysical and geological information available on this region.

The aims of the cruise were as follows:

(i) To define the magnetic anomaly field in the Argo Abyssal Plain. Results from the Deep Sea Drilling Program had already shown this area to be underlain by upper Jurassic basement.

(ii) To determine whether domal structures underlying the Argo Abyssal Plain are true diapiric structures and, if so, whether they were likely to be salt or mud domes.

(iii) To clarify the early spreading history of the northeastern Indian Ocean.

The area studied included five physiographic regions (Fig. 2):

(i) the Australian Margin; (ii) the Argo Abyssal Plain; (iii) an oceanic rise off the northwest Exmouth Plateau (the name Joey Rise is proposed by Heirtzler and others (in press) for this feature; (iv) the Roo Rise; (v) the western sill of the Argo Abyssal Plain, south of Roo Rise, and a northern sill which is the lip of the Java Trench.

Of these, only the Australian margin had previously been surveyed in detail.

Preliminary results have already been summarised by Heirtzler and others (1977), and detailed discussion of the bathymetric and geophysical results is provided by Heirtzler and others (in press). This publication deals with the sedimentary (seismic and coring) results and some of the implications arising from those results.

1. Research School of Earth Sciences, The Australian National University, P.O. Box 4, Canberra 2600, Australia.
2. School of Earth Sciences, Macquarie University. North Ryde, New South Wales 2113, Australia.
3. Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, U.S.A. (Cruise Leader.)

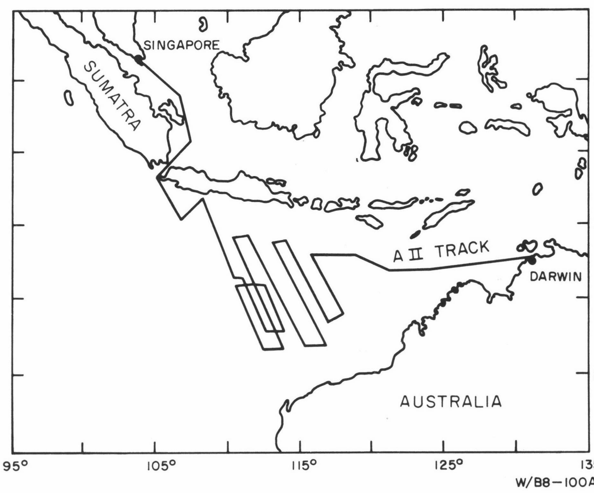

Figure 1. General location.

Methods

Seismic profiling

Continuous seismic reflection measurements were made at an underway speed of approximately 8 kn. An 80 and a 40 cubic-inch airgun were fired simultaneously as an energy source. The outputs of two trailing hydrophone strings were summed for the acoustic signal recorded. Two records were made: one with a 2.5 sec. sweep and the other with 5.0 sec. sweep. The delay before the sweep was separately variable on each of the recorders. Twenty geophysical lines were made, with seismic, magnetic, and gravity measurements on each (Fig. 1).

Sediment sampling

Conventional coring and dredging techniques were used. Coring was by means of a piston corer with a barrel up to 10 m long. For dredging operations, a steel-mesh dredge was used. Difficulties in obtaining samples were experienced at several sites, possibly owing to a lack of soft sediment. No dredge samples were obtained. Smear mounts were prepared for shipboard petrology. It was not possible to split cores longitudinally on

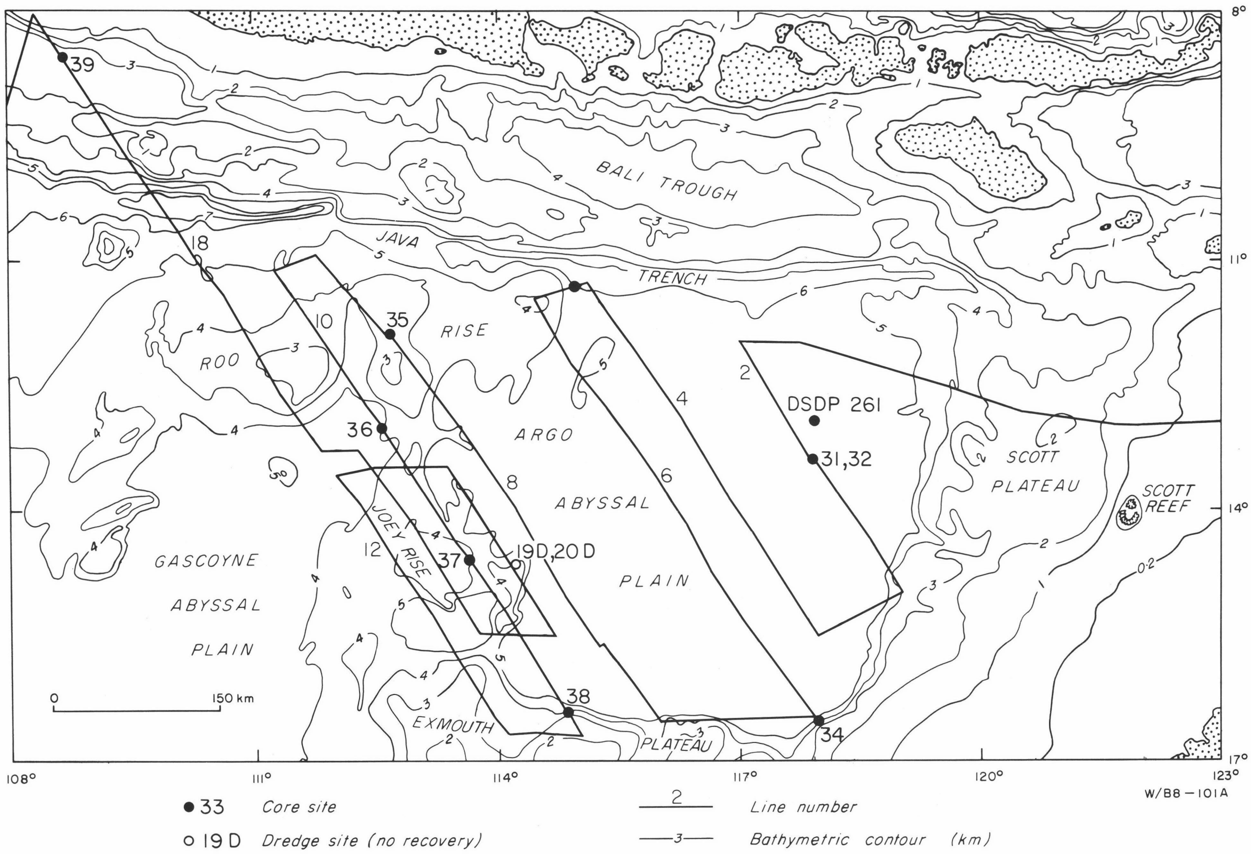

Figure 2. Location of coring sites in the Argo Abyssal Plain and adjacent areas.

board, and consequently only point sampling could be undertaken.

Shipboard geochemistry

The shipboard (geochemical) program was concerned solely with interstitial water geochemistry. Pore waters were extracted from the sediments through a stainless-steel filter press using nitrogen at a pressure of 3500 kPa, and filtered through a millipore filter system. Pore-water salinity was determined by means of a previously-calibrated Goldberg Refractometer. The pH was determined on the water and also in the sediment by means of a Metrohm pH meter. Alkalinity was obtained by the potentiometric titration technique of Gran (1952), modified by Geiskes & Rogers (1973).

Shorebased geochemistry

All shorebased analytical work was undertaken at the Research School of Earth Sciences, Australian National University. Most chemical analyses were by atomic absorption spectrophotometry (using a Varian Techtron AA6), or colorimetry; a Leco analyser was used for C and S (Mr. E. Kiss). Rb, Sr, U, and Th were determined by V-ray fluorescence (Mr P. Beasley). A number of microprobe analyses were also undertaken (Mr. N. Ware). X-ray diffraction analysis of whole-sediment powder and minus-two-micron fractions were carried out on most sediment samples (Mr H. Cutten).

Results

Seismic profiles

Seismic profiles of the area have been described previously by Veevers and other (1974), Veevers (1974), and Veevers & Heirtzler (1974), and have been related to the drilling at DSDP site 261 in the Argo Abyssal Plain (Veevers, Heirtzler, and others, 1974). In the Argo Abyssal Plain, a generally hummocky basement reflector (M), and an intermediate reflector (L), were drilled at site 261, and were found to be basalt (M) and the surface of a layer of late Jurassic and Cretaceous, pelagic clay and claystone (L) respectively. In previous records obtained using lower power seismic sources, the sequence below reflector L was essentially acoustically transparent, but this distinction is much less evident in the Atlantis II records (Heirtzler and others, in press). The entire record above the clay and claystone is overlain by a layer of calcareous ooze which was probably deposited by turbidity currents. Reflector L may be equivalent to a regional reflector found along the western margin of Australia and on the adjacent ocean floor (Reflector R_4 of Veevers & Cotterill (1978)) (Fig. 3).

An additional important feature (discussed later) is the vertical tube or sheet-like structures (? diapirs) which interrupt parts of the sedimentary sequence of the Argo Abyssal Plain, sometimes showing as clear areas on the seismic records (Fig. 4). These structures are particularly well developed along seismic line 2. They range in width from about 200 m to 1 km or more, and in vertical extent from about 200 m to 700 m. They occur in water depths of 4400-5800 m over a wide region of the Argo Abyssal Plain and adjacent areas. There are three main types of structures (Fig. 4).

(1) Those showing a decreased seismic reflectivity of the record, associated localised arching of overlying and flanking sediments, and a sea bottom topographic expression. This type is found only in the eastern part of the abyssal plain and is rare. It includes the largest of the structures.

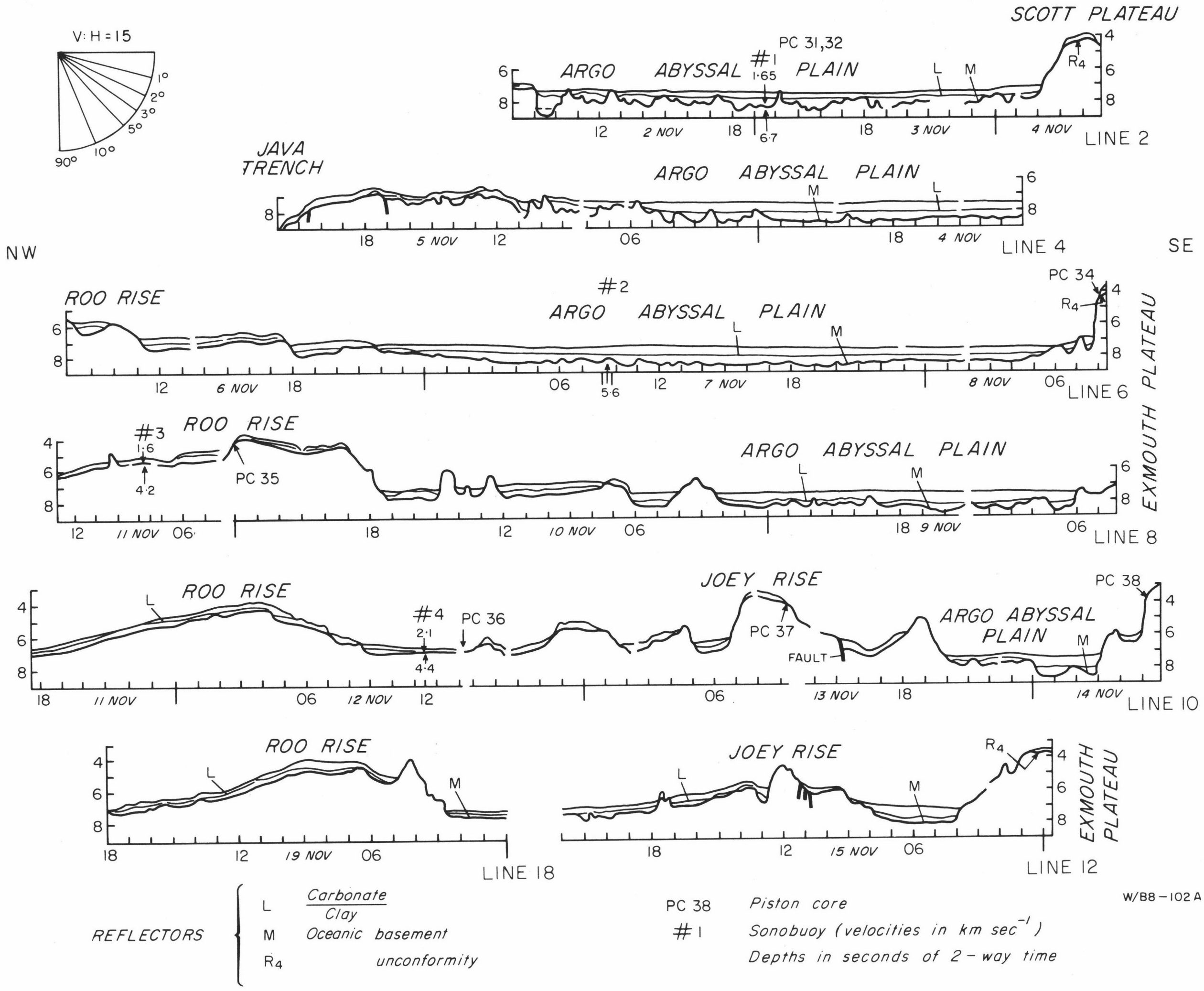

Figure 3. Generalised seismic profiles for the Argo Abyssal Plain and adjacent areas. Ship's speed was about 8 knots. Coring sites are indicated.

(2) Those showing decreased seismic reflectivity and localised arching, but no topographic expression. This type is more common than (1). It is restricted to the central part of the abyssal plain, where it forms an approximately ENE oval-shaped trend.

(3) Those which show only the columns of decreased seismic reflectivity. These are the most widespread, but the smallest, of the three types.

The isopachs of total sediment thickness (Fig. 5A) crudely parallel the bathymetry with the thickest sediments ($>$1.0s equivalent to 900 m) in the centre of the Argo Abyssal Plain, slightly offset from the area of deepest basement (i.e., deepest with respect to sea level). Figures 5B, C, D show that this correspondence between thickness and structure is due to: (i) the thick accumulation (0.4s or 400 m) of Late Jurassic and Cretaceous claystone in the central depressed part of the Argo Abyssal Plain, and the thin accumulation ($<$0.2 s) in the southwest part (Fig. 5B). As a consequence, the structure contours on L (Fig. 5C) are almost flat over the Argo Abyssal Plain, except for a slight depression in the southwest corner; and (ii) a compensating extension of the thickest calcareous ooze (Fig. 5D) southwestward from the central area into the L-reflector depression, to produce the flat surface of the present-day plain.

The southeast ends of lines 2, 6, 8, 10 and 12 cross the lower continental slope to reach the edge of the marginal plateaus of the Australian margin. On each of these lines, the breakup unconformity (reflector F of Willcox & Exon, 1976, reflector R_4 of Veevers & Cotterill, 1978) was found (Fig. 3).

Coring

Lithology

Sites at which sampling was successfully carried out are shown in Figures 2 and 3. Results are summarised in Table 1. Sites are referred to by the core number rather than the station number. Dredging was unsuccessfully attempted at two sites on the Joey Rise (Table 1). Aspects of sediment chemistry are given in Tables 2 and 3. Basalt chemistry is given in Table 4.

Sites 31 and 32. These adjacent sites in the Argo Abyssal Plain were cored in an attempt to determine the characteristics of sediments overlying possible diapiric structures (Fig. 3, Profile 2). At both sites the sediments are typical abyssal siliceous clays with abundant whole or fragmentary siliceous organisms including radiolarians, diatoms, and (?) silicoflagellates. Possible fish fragments are present. No calcareous fragments are evident, yet the acid (HCL) soluble fraction ranges from about 17 to 27 percent, suggesting that very fine $CaCO_3$ may be present in greater than normal amounts

Stn no.	*Core no.*	*Dredge no.*	*Begin depth (m)*	*End depth (m)*	*Begin latitude*	*Begin longitude*	*End latitude*	*End longitude*	*Physiographic province*	*Piston core sample (cm)*	*Pilot core sample (cm)*	*Dredge sample*
49	31 PC	—	5698	5698	13°23.12′S	117°54.50′E	13°22.44′S	117°54.12′E	Abyssal plain Wharton Basin	575	141	—
50	32 PC	—	5698	5694	13°22.35′S	117°53.08′E	13°22.18′S	117°53.24′E	Abyssal plain Wharton Basin	896	135	—
51	33 PC	—	6121	6014	11°19.20′S	114°57.27′E	11°19.08′S	114°57.30′E	Axis, Java Trench	710	37	—
54	34 PC	—	3235	3218	16°33.06′S	117°59.33′E	16°31.47′S	117°59.21′E	N edge of Exmouth Plateau	160	16	—
55	35 PC	—	3436	3501	11°54.01′S	112°40.32′E	11°54.10′S	112°40.14′E	Roo Rise	659	88	—
58	36 PC	—	5217	5225	13°01.13′S	112°34.15′E	13°00.34′S	112°34.21′E	Base of Roo Rise (South flank)	312	16	—
59	37 PC	—	3067	3052	14°36.14′S	113°38.47′E	14°36.09′S	113°38.35′E	Joey Rise (SW side)	229	0	—
60	38 PC	—	2636	2824	16°25.44′S	114°51.31′E	16°25.22′S	114°51.51′E	Exmouth Plateau (N flank)	fragments		—
61		19 D	3494	3892	14°39.09′S	114°11.33′E	14°38.44′S	114°10.10′E	Joey Rise	—	—	0 kg
62		20 D	3276	3182	14°40.55′S	114°12.28′E	14°39.26′S	114°13.15′E	Joey Rise	—	—	0 kg
63	39 PC	—	3563	3563	08°31.59′S	108°39.58′E	08°31.37′S	108°40.02′E	Western extension of the Bali Trough	820	111	—

Table 1. Coring and dredging sites in the Eastern Indian Ocean.

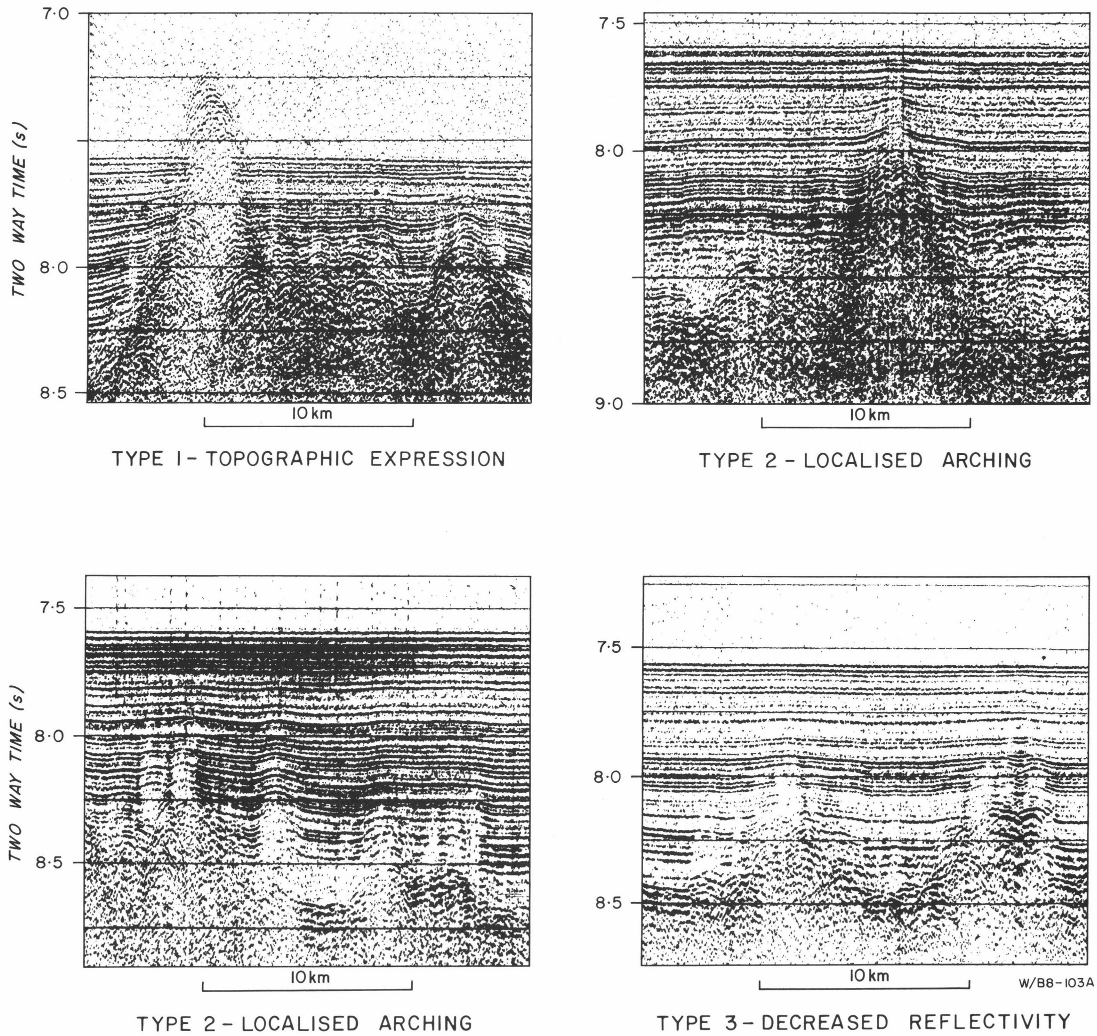

Figure 4. Photographs of seismic records showing possible diapiric structures in the Argo Abyssal Plain area.

for abyssal clays from below the CCD, indicating some input from turbidity currents. The clay component of these sediments is dominantly kaolinite and montmorillorite, with minor illite and traces of chlorite.

Site 33. This site, which was located below the CCD near the axis of the Java Trench, also yielded a siliceous clay with abundant siliceous organisms. The terrigenous sediment is composed mainly of clays, with abundant montmorillonite and kaolinite, intermediate quantities of illite, and minor amounts of chlorite. Unlike the sediment from Sites 31 and 32, there is a minor amount of sub-angular silt-size detrital material (quartz, plagioclase, feldspar, heavy minerals, and probably rock fragments). Pyrite, some of it framboidal, infilling and partly replacing organisms, is fairly common. This is probably a reflection of the higher level of sulphate reduction at this Trench location than is to be found at the abyssal plain sites.

Site 34. Unlike the previous three sites, this site, on the flanks of the Exmouth Plateau (Fig. 3, Profile 6), is well above the CCD. The sediment is a white calcareous ooze composed predominantly of nannofossil remains, with minor foraminifera (5%), small amounts of terrigenous clay (2%), and trace quantities of very fine silt-size quartz grains, possibly of aeolian origin, and rare crystals of heulandite. Coring at this site was attempted in order to obtain a sample from near the break-up unconformity (reflector F of Wilcox & Exon, 1976, and reflector R_4 of Veevers & Cotterill, 1978). The core has been found to contain Early or Mid Oligocene, and Late Paleocene faunas (P. G. Quilty and B. V. Haq, pers. comm.), and is assumed to be from above the breakup unconformity.

Site 35. This site is on the south flank of the Roo Rise (Fig. 3, Profile 8). It is also above the CCD; however, it is darker in colour, richer in organic carbon, and slightly less calcareous than the sediment from Site 34. Nannofossils are dominant (80%), but foraminifera are common (15%), and miscellaneous siliceous organisms are present in trace amounts. The upper part of the core contains abundant faecal pellets, suggesting extensive bioturbation. The foraminifera indicate an Early Pleistocene age at a depth of 439-643 cm within the core. The non-biogenic component forms no more than 5 percent of the total sediment, with quartz and feldspar predominant. Volcanic glass shards form a variable, but significant, proportion of the sediment.

Sites 36, 37, 38. Coring at these sites was to sample prominent seismic reflectors. At all three sites volcanoclastic or volcanic material was obtained.

Site 36, located at the foot of the Roo Rise at a depth of 5200 m (Fig. 3, Profile 10) was originally sampled on the assumption that the flat, acoustically strongly reflective surface probably indicated a manganese

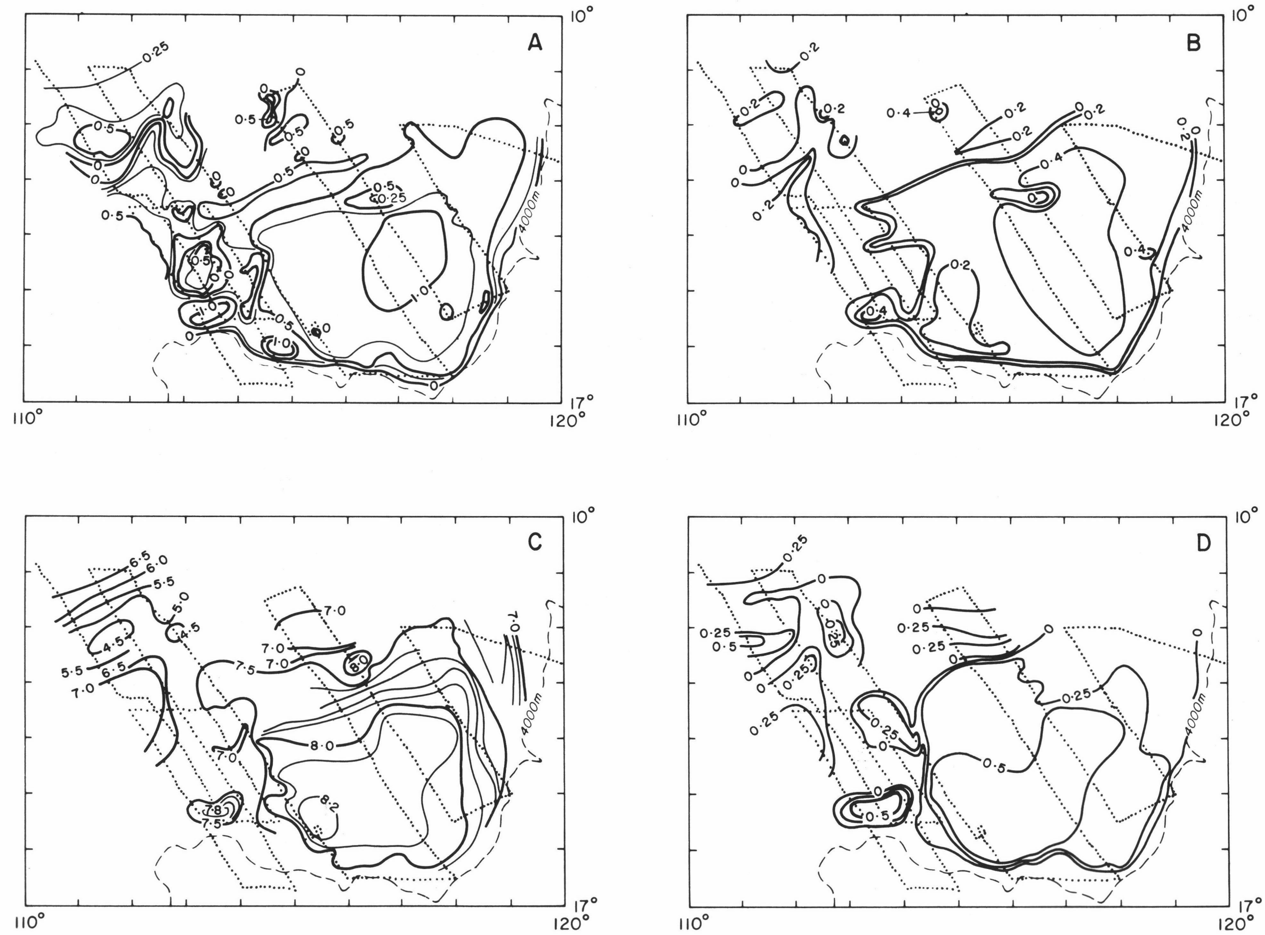

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Figure 5. A—Isopach (in seconds of 2-way time) of oceanic sediments. Contour interval 0.5 seconds 2-way time (heavier line), intermediate contours at 0.25 second intervals (lighter line).
B—Isopachs (in seconds of 2-way time) of the sediments between basement (reflector M) and reflector L. Contour interval 0.2 second in the Argo Abyssal Plain region.
C—Structure contours (in seconds of 2-way time) on reflector L. Contour interval 0.5 second, with intermediate contours at 0.2 second interval.
D—Isopach (in seconds of 2-way time) of sediments between reflector L and the seafloor. Contour interval 0.25 second.

nodule pavement. The core does contain a 12 cm layer at the top with abundant small nodules (up to 5 cm in diameter) and manganese-coated material. This is underlain by 10-20 cm of manganiferous sediment. However, most of the core is composed of angular to subrounded glassy particles and rock fragments, ranging in size from fine sand to fine gravel (?hyaloclastite), commonly with a manganiferous rind. The matrix, comprising no more than 5-10 percent of the sample, is typical abyssal brown clay containing abundant whole or fragmentary siliceous organisms. The sand and grit-size clasts are of mixed volcanic origin, comprising vesicular (palagonitised sideromelane) (Fig. 6). Phenocrysts and microphenocrysts of plagioclase feldspar are common. Zeolite crystals are present in minor amounts throughout the sediment. Material showing textures and compositions of this type may be present as the variolitic material marginal to basaltic pillows (Furnes, 1973); however, the thickness of this unit (more than 3m were penetrated) suggests that the material is a basaltic hyaloclastite, similar to that described from the St Paul's Rocks region of the Atlantic Ocean (Melson & Thompson, 1973).

Site 37 was located on the flanks of the Joey Rise at a water depth of about 3000 m. Coring was to sample a prominent reflector (Fig. 3, Profile 10). Despite the bathymetric differences between this site and the previous site, the sediments are very similar (Fig. 7), and those at Site 37 are also interpreted as hyaloclastites. The only major difference in the sediment from these two sites is in the matrix, which at Site 37 (located well above the CCD) is predominantly calcareous with abundant foraminifera and minor clay (dominantly montmorillonite). Quilty (pers. comm.) determined the foraminifera as dominantly Early Pleistocene, and suggests that evidence of dissolution may possibly indicate a history below the CCD at some stage.

Site 38, on the northern margin of the Exmouth Plateau in about 2600 m of water (Fig. 3, Profile 10), yielded fragments of bedrock of basaltic composition and a few grams of calcareous ooze. The texture of the basalt, particularly the abundant phenocrysts and microphenocrysts of plagioclase (Fig. 8), is identical to that of many of the sand and grit-size clasts of Sites 36 and 37. However the sample was an angular fragment which clearly had been broken off a larger mass of material. Consequently it seems unlikely that it is a clast from within a hyaloclastite sequence, though it may possibly be parent material of some of the hyaloclastitic material. The calcareous ooze from Site 38 is composed

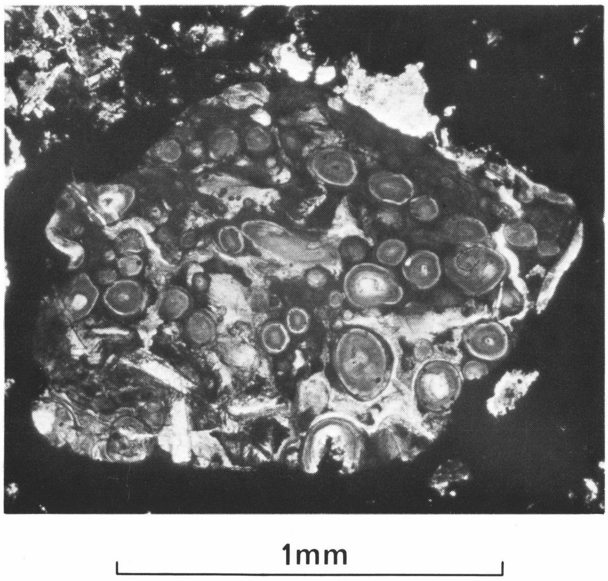

Figure 6. Hyaloclastite from core 36, with a sub-angular fragment of vesicular basalt.

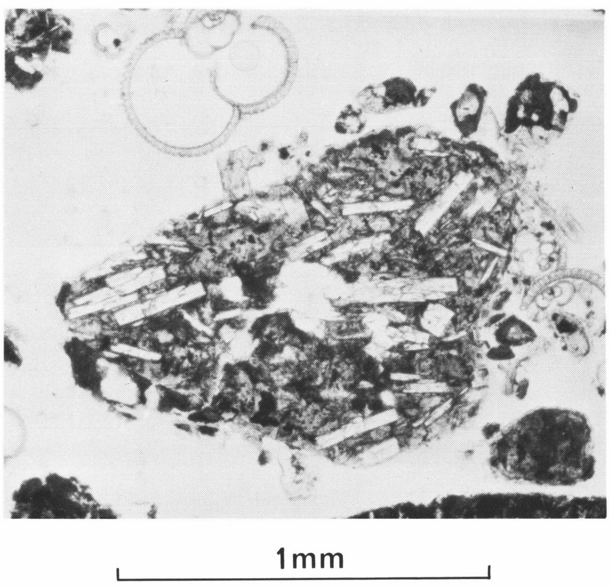

Figure 7. Hyaloclastite from core 37, with a sub-rounded clast of basalt containing microphenocrysts of plagioclase feldspar.

predominantly of nannofossil remains with a few foraminiferans. A small fragment of botryoidal manganese, probably part of a manganiferous encrustation, was also recovered from this site. The ooze from this site is dated by Quilty (pers. comm.) at Late Miocene or younger. It would appear that material from below (basalt) and above (the calcareous ooze) the unconformity were obtained from this site.

Site 39. This site, located on the axis of the north-westerly extension of the Bali Trough (a fore-arc basin) at a water depth of about 3600 m, was sampled primarily to obtain a core of trough sediments from above the CCD for ongoing geochemical studies. The sediments are olive-grey nannofossil, foraminiferal, diatomaceous, radiolarian-bearing clays and silty clays, in which montmorillonite is the dominant clay mineral, with illite and kaolinite somewhat less abundant. Pollen and wood fragments are fairly common. Quilty (pers. comm.) reports Holocene faunas in the core

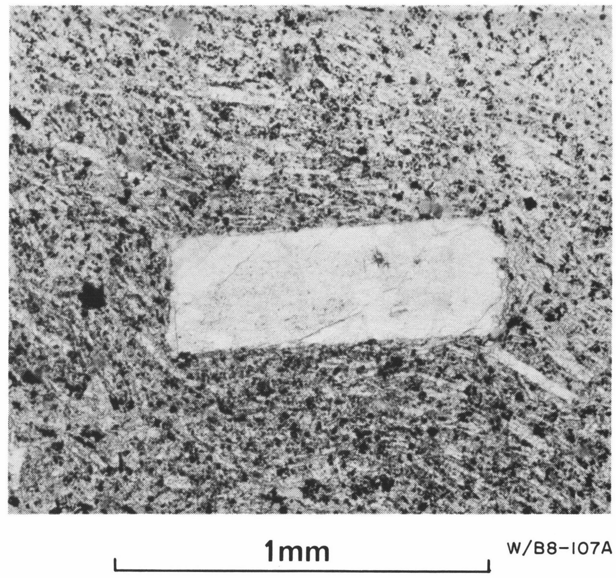

Figure 8. Basalt from core 38 with a large plagioclase feldspar phenocryst.

down to at least 520 cm, which indicates a very rapid rate of sedimentation; however, the next fossiliferous sample, at 820 cm, has a very mixed fauna, with elements of Paleocene, Eocene, and perhaps Early Oligocene age, suggesting extensive reworking of sediments. Pyrite, replacing and infilling wood fragments and siliceous and calcareous organisms, is particularly common. The high alkalinity recorded (up to 24 meq/L) together with the abundance of methane in the core, suggest very active sulphate reduction within these sediments.

Geochemistry

Sediments

Shore-based chemical work is incomplete at the time of writing; consequently, this is a preliminary account of the geochemistry of the sediments and associated volcanic material. Results to date are summarised in Table 2, which gives minor and trace element analyses for the total sediment, and Table 3, which gives minor and trace element contents of the acid (1N HCL) soluble fraction only. Table 2 shows that the sediments are a diverse group, with wide variations shown by almost all components. However, four main groupings are apparent. The siliceous oozes (analyses 31 and 32) are characterised by generally high metal contents (except for Sr and U), possibly concentrated by siliceous organisms as part of their metabolism. Whether these metals are in the siliceous tests or in the associated organic matter as organo-metallic complexes is unknown. Other features of the siliceous sediments include high organic carbon, moderately high sulphur, yet relatively low P_2O_5. The trench and trough clays (analyses 33 and 39) are generally characterised by moderately high metal contents, except for Sr which is fairly low. P_2O_5 remains low, whereas S and C are particularly high. By contrast, the calcareous oozes (analyses 34 and 35), are low in all metals with the exception of Sr and U, which probably substitute for Ca in the $CaCO_3$ lattice. Both the C and S contents are low, suggesting that there is little or no sulphate reduction within these calcareous sediments. The fourth group of sediments (analyses 36 and 37) is characterised by the highest metal contents. Some, perhaps most, of the

Cores	31	32	33	34	35	36	37	39
No of analyses	9 ppm	7 ppm	7 ppm	2 ppm	6 ppm	4 ppm	2 ppm	7 ppm
Cu	173	190	134	38	58	496	50	34
Pb	26	24	18	1	9	72		8
Zn	168	168	145	48	145	223	221	101
Mn	2181	2293	801	150	615	13341	459	633
Fe	44184	42213	41847	11335	25450	71470	86151	48727
Co	26	26	16	3	11	93	19	16
Ni	139	137	67	16	37	560	53	29
Cr	71	65	43	28	20	58	11	46
V	100	126	121	29	62	86	126	117
Rb	79	84	62	18	27	53	60	44
Sr	133	124	188	1026	750	232	223	262
U	0.5	0.5	1.1	1.4	1.0	0.6	1.1	0.5
Th	13	19	13	5	4	28	9	16
P_2O_5	335	319	262	660	377	1848	2145	312
S	839	1066	3160	260	910	330	150	7789
C	10876	6629	5310	449	4137	690	231	12402

Table 2. Average metal, P, S, and organic carbon contents of miscellaneous sediments from the Atlantis II cruise, Eastern Indian Ocean.

Cores	31	32	33	34	35	36	37	39
No. of analyses	9 ppm	7 ppm	7 ppm	2 ppm	6 ppm	4 ppm	2 ppm	7 ppm
Cu	118	139	88	14	31	276	29	15
Pb	27	24	22	4	12	57	5	11
Zn	106	105	91	25	108	124	78	62
Mn	2010	2233	560	140	403	1963	222	538
Fe	17042	13697	11067	2209	8922	10991	11629	15341
Ba	523	342	605	622	736	425	406	321
Sr	74	62	87	1225	784	84	174	199
P_2O_5	234	239	139	507	250	492	457	225
ASF*	22.2%	23.8%	23.2%	78.1%	54.3%	21.1%	30.2%	23.5%

Concentrations in parts per million except where indicated.
* Acid-soluble fraction.

Table 3. Average metal (and P_2O_5) contents of the acid (1N HCl) soluble fraction of miscellaneous sediments from the Atlantis II cruise, Eastern Indian Ocean.

high metal contents may result from the presence of manganese nodules and encrustations in these sediments. It is apparent that the hyaloclastite containing the higher Mn content and the greater abundance of siliceous organisms (analysis 36) also has the higher metal contents of the two. The C and S contents are particularly low in these sediments but, in contrast, the P_2O_5 content is high. This may reflect slow deposition (this is unlikely for hyaloclastites) or a volcanic source rich in phosphorus. Another possibility is that the present sediment-water interface may represent a major hiatus, thus providing ample opportunity for post-depositional phosphatisation. This third possibility is supported by the presence of manganese nodules, which are also generally more abundant in areas with either a slow rate of terrigenous or biogenic sedimentation, or a prolonged hiatus.

It had been assumed that the composition of the acid-soluble fraction (Table 3) would be more uniform than the acid-insoluble fraction (Table 2), reflecting primarily the minor and trace element geochemistry of the carbonate fraction. In fact, the acid-soluble compositions are almost as heterogeneous as the composition of the total sediment. With the exception of the P_2O_5 values, which are much more homogeneous than the values in Table 2, the four main groups are again apparent from the elemental compositions of their acid-soluble fractions. This may be a consequence of the carbonate fraction reflecting the elemental composition of the total sediment fairly closely, and even elements known for their high geochemical affinity for Ca (such as Sr) not being as clearly partitioned in the carbonate and non-carbonate fractions as is generally assumed. Parekh and others (1977) found this situation in Jurassic limestones.

Bedrock

Major element analyses on some of the small chips of basaltic bedrock from Site 38 were obtained by electron microprobe, after first preparing glass beads by the method of Nicholls (1974). These results (Table 4) show that the Site 38 basalt is more alkalic than most of the oceanic basalts from the northeast Indian Ocean. This difference between Site 38 basalt and other Indian Ocean basalts is also illustrated in the $(Na_2O + K_2O)/SiO_2$ plot (Fig. 9), with the core Site 38 basalts apparently falling into the alkalic basalt field of Macdonald & Katsura (1964) (although they do not in fact extend the field beyond 5 percent $N_2O + K_2O$). However the low K/Na ratio, and the low CaO and high Al_2O_3 values, suggest that there has been some alteration of the original basaltic composition; the apparently alkalic nature of the basalt must be regarded as questionable.

Interstitial waters

Interstitial waters were extracted from a number of the cores for shipboard and subsequent geochemistry. Results of the shipboard work are summarised in Table 5. In general, values fall into the range normally encountered in deep-sea sediments. A particular object of the pore-water program was to establish whether

	A	*B*	*C*	*D*	*E*	*F*	*G*
SiO_2	53.0	51.1	50.3	49.9	50.0	52.1	51.2
TiO_2	2.2	1.4	2.2	2.3	1.4	0.8	1.1
Al_2O_3	19.4	14.9	16.0	14.8	16.1	16.1	16.5
FeO (Total Fe)	11.5	10.8	10.3	11.2	9.4	9.6	8.5
MgO	5.8	7.4	7.4	7.7	8.7	6.8	9.1
CaO	1.5	11.9	9.8	10.7	11.3	11.8	9.6
Na_2O	5.7	2.2	3.1	2.4	2.8	2.4	2.9
K_2O	0.9	0.3	0.8	1.0	0.3	0.4	1.1
	100	100	100	100	100	100	100
	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Rb	29	—	—	30	1	5	10
Sr	206	—	—	465	123	200	330

A Dredge sample from site 38, this cruise (mean value based on six electron microprobe analyses by N. Ware, RSES). Volatiles not determined.
B Sill at DSDP site 261 (after Robinson & Whitford, 1974).
C Ocean basalt from DSDP site 261 (after Robinson and Whitford, 1974).
D Average basalt (after Turekian & Wedepohl, 1961).
E Average oceanic tholeiite (after Melson & Thompson, 1971).
F Average island-arc tholeiite (after Jakes & White, 1971).
G Average calc-alkaline basalt (after Jakes & White, 1971).

Table 4. Recalculated basalt compositions (%) from the Indian Ocean compared with average basalts.

there was an increase in interstitial salinities in the vicinity of diapiric structures, which would indicate a salt core. It is evident from the results for Sites 31 and 32 that overall there is no such increase when compared with other core sites. However, if the vertical salinity profiles are examined (Fig. 10), there does appear to be downward increase in salinity at core Site 32, but the increase is fairly small and cannot readily be taken as strong evidence of nearby salt.

The alkalinity values provide a good indication of the level of sulphate reduction occurring within the sediments. From this it is clear that a very high level of sulphate reduction is occurring in the sediments of core 39 from the extension of the Bali Trough. This is supported by ongoing work which shows a depletion of sulphate in these pore waters.

Discussion

The Atlantis II cruise was primarily to obtain geophysical data. Coring and dredging was undertaken for the most part on an opportunity basis; consequently, it is not possible to reach major conclusions from the sedimentological part of the program. There are, nevertheless, a number of discoveries which are of significance to an overall understanding of the processes of sedimentation and tectonic activity in the northeast Indian Ocean.

The origin of the Joey Rise

Many of the rises and marginal plateaus of the northeast Indian Ocean are of uncertain origin. Some, such as the inner part of the Exmouth Plateau, are clearly underlain by continental crust, but for others the evidence is equivocal. Geophysical results in the vicinity of the Joey Rise are discussed by Heirtzler and others (in press); however, some of the samples obtained by coring also provide information which is relevant to our understanding of its origin. The well-defined reflector between the Roo and Joey Rise cored at Site 36, and also the prominent seismic reflector cored at Site 37 on the flanks of the Joey Rise, are both hyaloclastites with a basaltic composition. The reflector

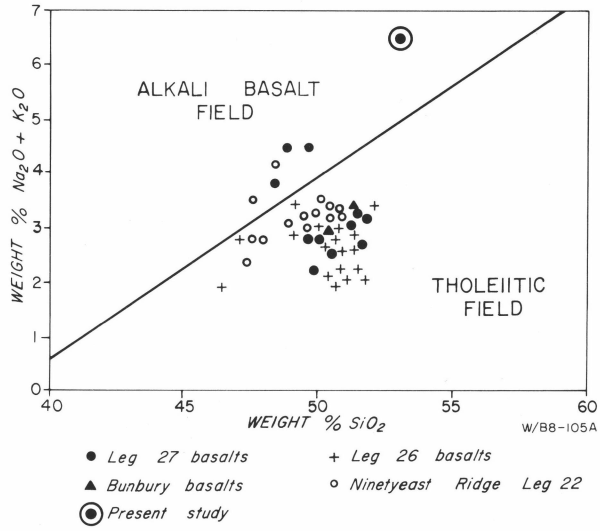

Figure 9. ($Na_2O + K_2O$)/SiO_2 plot of the composition of Indian Ocean basalts, after Robinson & Whitford (1974), and core site 38, this study. The alkali basalt/tholeiite fields are after MacDonald & Katsura (1964), with an extrapolated boundary about 5% $Na_2O + K_2O$.

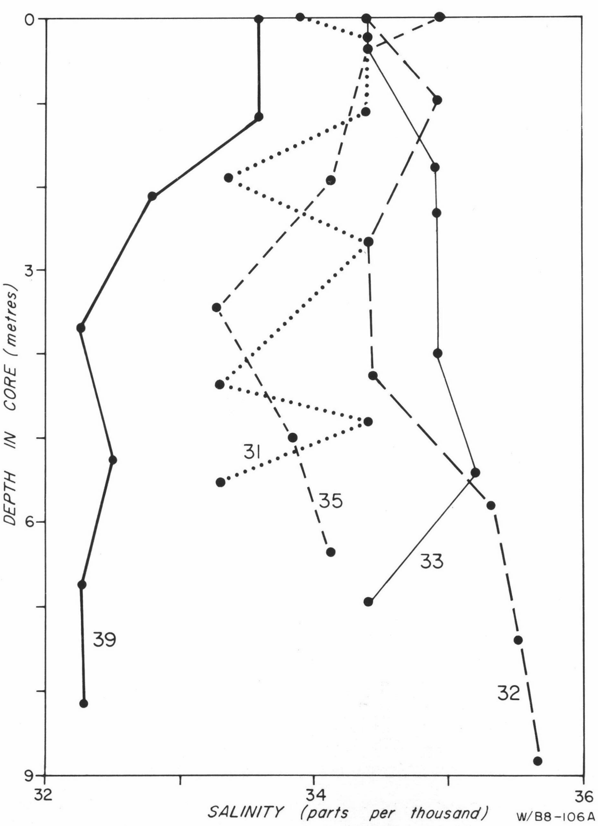

Figure 10. Vertical salinity profiles for interstitial waters from various cores.

cored at Site 38 on the flanks of the Exmouth Plateau (at what is generally taken to be the break-up unconformity) is similarly a basalt. If these basalts are alkalic then such basalts are commonly associated with intraplate volcanism of the type which may result in the formation of seamounts like those of the East Pacific (Batiza, 1977), or the New England Seamounts (Heirtzler and others, 1977). Many such seamounts form along linear structural features, possibly in

Core site	31 (8)	32 (7)	33 (6)	34 (2)	35 (6)	36 (3)	39 (7)	SSW	DSDP 262 (24)
Salinity (ppt)	33.9	34.9	34.7	34.1	34.1	34.7	32.8	35.0	36.3
pH	7.6	7.6	7.6	7.9	7.6	7.5	7.8	7.7	7.7
Alkalinity (meq/L)	3.2	3.5	3.3	i.s.*	3.0	2.5	22.0	1.8	58.3

Numbers in brackets indicate the number of analyses.
* Insufficient sample available for the analysis.

Table 5. Average shipboard geochemical results for salinity, pH, and alkalinity compared with results for standard seawater (SSW) and pore waters from the upper half of DSDP Site 262.

response to the migration of crust over a hotspot, or volcanism along an ancient fracture zone. In this case, linearity is not clear, though a poorly defined north-northwest trend may be present. This trend is approximately at right angles to the anomaly pattern, i.e. consistent with the hot-spot or fracture hypothesis. However, as pointed out earlier, the alkalic composition is questionable, and all that can be said at this time from the coring results is that the Joey Rise and probably also the Roo Rise are underlain by basaltic material and therefore are unlikely to be continental fragments. The fact that the sea-floor spreading magnetic anomalies of the Argo Abyssal Plain extend westward without change into the Joey and Roo Rises (Heirtzler and others in press), suggest that these features are underlain by oceanic basalt. On the basis of earlier seismic and magnetic evidence Veevers & Cotterill (1978) also suggest that the outer part of the Exmouth Plateau may be underlain by oceanic crust; in opposition to the views of Willcox and Exon (1976).

The age of the volcanic activity which resulted in the formation of the Joey Rise is uncertain. The presence of a manganese pavement 12 cm thick, overlying the hyaloclastite at Site 36, suggests the volcanism is at least several million years old. Associated overlying sediments at Site 37 have an Early Pleistocene age; however, this only provides a minimum age for the volcanic activity. The acoustically layered sediment (probably calcareous ooze) which overlies the presumed volcanic material on the crest of the Joey Rise is up to half a second thick. At pelagic rates of sedimentation above the CCD this thickness of sediment could take anywhere from 10 to 50 million years to accumulate, suggesting that the volcanism could be Early Cenozoic or older. The anomaly pattern indicates a Mesozoic age. However, as it is unlikely that normal oceanic basalts would underlie positive topographic features (except at an active spreading ridge), there must have been subsequent uplift associated with for instance a hot spot, or with faulting, to maintain it as a large positive topographic feature.

Sedimentary processes

The types of sediments obtained are those normally found on abyssal plains (siliceous clays), or on topographic highs above the CCD (calcareous ooze). The volcanic glass in the oozes of the Roo Rise was more abundant than in many other calcareous oozes. Whether this reflects volcanic activity on the Roo Rise or on the nearby Indonesian archipelago is not certain, though the latter explanation is more likely. The hyaloclastites were unexpected; this type of volcanogenic sediment had not previously been documented from this part of the Indian Ocean.

An understanding of sulphate reduction is important to our understanding of pyrite in ancient sediments. The current coring program provided evidence of sulphate reduction in the trough site and, to a lesser extent, in the deeper trench site. Minor sulphate reduction may also be taking place in the moderately organic-rich sediments of the sub-equatorial abyssal zone. At the other core sites there is little or no evidence of it. The site in the extension of the Bali Trough is a particularly interesting site because of its very high alkalinity (and presumably a very high rate of sulphate reduction). In this respect it shows similarities to the Timor Trough sediments at DSDP Site 262 (Cook, 1974; Veevers, Heirtzler, and others, 1974). However, the interstitial waters in the Bali Trough sediments show salinities below those of the overlying water column, whereas those in the Timor Trough are much higher. This suggests that there may be some reflux of fresher continental waters under the Bali Trough, producing a decrease in interstitial salinities.

Manganiferous sediment was found at both rise and abyssal locations. The occurrences on rises were probably encrustations. The nodules obtained from Site 36 were smaller than those reported from the Pacific, but this is likely to be a function of the smaller diameter of the corer. Only total sediment analyses are available at present. The most manganiferous sediment (3% Mn) contains 0.06% Cu, and 0.1% Ni. It is reasonable to expect the individual nodules to have metal contents significantly above these concentrations in the total sediment (including matrix). The extent of the manganese nodule pavement is unknown, as it was only traversed on one line. Such a location, at the foot of the Roo and Joey Rises, might be expected to be a site of major calcareous input by turbidity flows, but there is no evidence of this; Site 36 is situated on the sill between the two rises, and is likely to be one of the few places through which bottom waters can enter or leave the Argo Abyssal Plain. Consequently, the location is probably swept by strong bottom currents which will remove any allochthonous calcareous sediment, giving an overall low rate of terrigenous deposition and an enhanced relative development of manganese nodules. This area should be sampled by a comprehensive dredging program to provide a better evaluation of its economic potential.

Diapiric structures

It is uncertain whether all the columnar seismic structures are really true diapirs and the gravity and magnetic data appear at this stage to be of little assistance in resolving this question. The ill-defined type (iii) structures in particular are at times less-than-convincing as diapirs. In some cases, the 'diapirs' may in fact be acoustic artifacts resulting, for instance, from the type of wave diffraction effects (perhaps off a point reflector at the top of a basement high) discussed by Ball (1969), or following differential compaction (Collette & Rutten, 1970), or of side reflection from a nearby basement high. However, from the seismic profiles some of the structures do have the appearance of piercement (diapiric) structures.

Deep-sea diapirs are known from many parts of the world (Schneider & Johnson, 1970). In areas such as the Mississippi delta, or the Magdalena delta off Colombia, the diapirs are giant mudlumps or mud volcanoes (Shepard and others, 1968). Mud diapirism is a possible explanation for the Indian Ocean structures. Drilling at DSDP Site 261 (Veevers, Heirtzler, and others, 1974) showed that the acoustically transparent layer (which appears to be the diapiric unit) is a Late Jurassic-Cretaceous nannofossil and radiolarian-bearing clay. Shear strengths of these clays at DSDP Site 261 indicate that they would flow relatively easily. The shear strengths also suggest that the overlying calcareous unit is weak, and would be susceptible to piercement by the underlying Mesozoic clays. Montmorillonite is the dominant clay mineral in the lower clays. Kerr and others (1970), who found that montmorillonite is characteristically the preponderant clay in many mud volcanoes, suggest that the mobile, thixotrophic nature of these clays is responsible for their ability to form diapiric structures. As the 'diapiric unit' at Site 261 has an average bulk density of about 1.69 (using the values of Rocher, 1974), compared with a density of about 1.56 for the overlying layered unit, the underlying unit will not rise in response to buoyancy. A more probable cause is tectonism, perhaps associated with the northward movement of the Australian plate and subduction along the Java Trench. Such a cause is supported by an approximately east-west elongation of the diapiric zone roughly parallel to the Java Trench. Alternatively, some diapirism may have been triggered by differential loading of the sediment column. Such a mechanism is possible because most of the upper layered unit was probably deposited as turbidites (Robinson and others, 1974).

So far, it has been assumed that the diapirs have mud cores, but, in fact, many deep-sea diapirs are thought to have salt cores. Pautot and others (1970), Schneider and Johnson (1970), and Kinsman (1975), have pointed out that young rift oceans are commonly the site of large-scale evaporite deposition at low altitudes. Using the polar-wander paths of Schmidt (1976), and the method of Haile (1975) for determining palaeolatitudes, the mid-point of the Argo Abyssal Plain at 155 m.y.—the date of initial rifting in the northeast Indian Ocean (Heirtzler and others, 1973) was at latitude 13°S. A restricted ocean at such a latitude would potentially be a site for salt deposition. The Argo Abyssal Plain area is the only part of the Eastern Indian Ocean where there may be diapiric structures. The Jurassic palaeolatitude for this area and its possible location near a spillway from the open Tethys to the north (analogous to the Atlantic spillways used by Burke (1975) to explain the distribution of Atlantic salt), would have potentially made this area a favoured site for the formation of evaporites.

Palaeozoic salt is known on the West Australian margin (Johnstone and others, 1968); Pliocene (or possibly Miocene) salt is inferred to be present in the Timor Trough area (Veevers, Heirtzler, and others, 1974). However, there is no clear indication of Jurassic-Cretaceous salt in this area. Drilling in the Wharton Basin did not reveal any salt. Generally, the pore-water salinities decrease with depth—except at Site 261, where there is a slight increase in salinity in the seismically transparent Jurassic-Cretaceous sediments.

If the columnar seismic structures are salt domes, then it is possible that this would be reflected in an envelope of elevated salinities in the pore waters. Attempts were made to test this by determining salinity profiles in gravity cores at Sites 31 and 32. Neither core was sufficiently long to be expected to provide a large increase in salinity. At core Site 32 an increase in pore water salinity was noted (from 34.4 p.p.t. at the top of the core to 35.6 p.p.t. at the bottom). No such increase was detected at Site 31 or at any of the gravity cores obtained at Sites 33-38 (Fig. 10). However, this evidence is too tenuous to conclude that the diapiric structures have salt cores.

Conclusions

The seismic profiling generally confirmed the conclusions reached from earlier cruises regarding the distribution and form of the main seismic reflectors. Incorporation of the Atlantis II data with earlier data makes it possible to draw up accurate sediment isopach maps for the Argo Abyssal Plain and adjacent areas. These show that the maximum sediment thicknesses for all seismic units are found in the central or southern part of the Abyssal Plain.

The presence of hyaloclastites at two core sites on or adjacent to the Joey Rise, suggest that these features and possibly also the Roo Rise are not continental fragments but volcanic excrescences. Basalt was recovered from the outer margin of the Exmouth Plateau, but the implications of this occurrence are presently equivocable.

A manganese nodule pavement of unknown extent occurs between the Joey and Roo Rises.

There is abundant evidence of a high level of sulphate reduction in the sediments of the northwestern extension of the Bali Trough.

The cruise confirmed the wide distribution of diapir-like piercement structures underlying the Argo Abyssal Plain, but it is not possible to say whether they are salt or mud-cored.

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