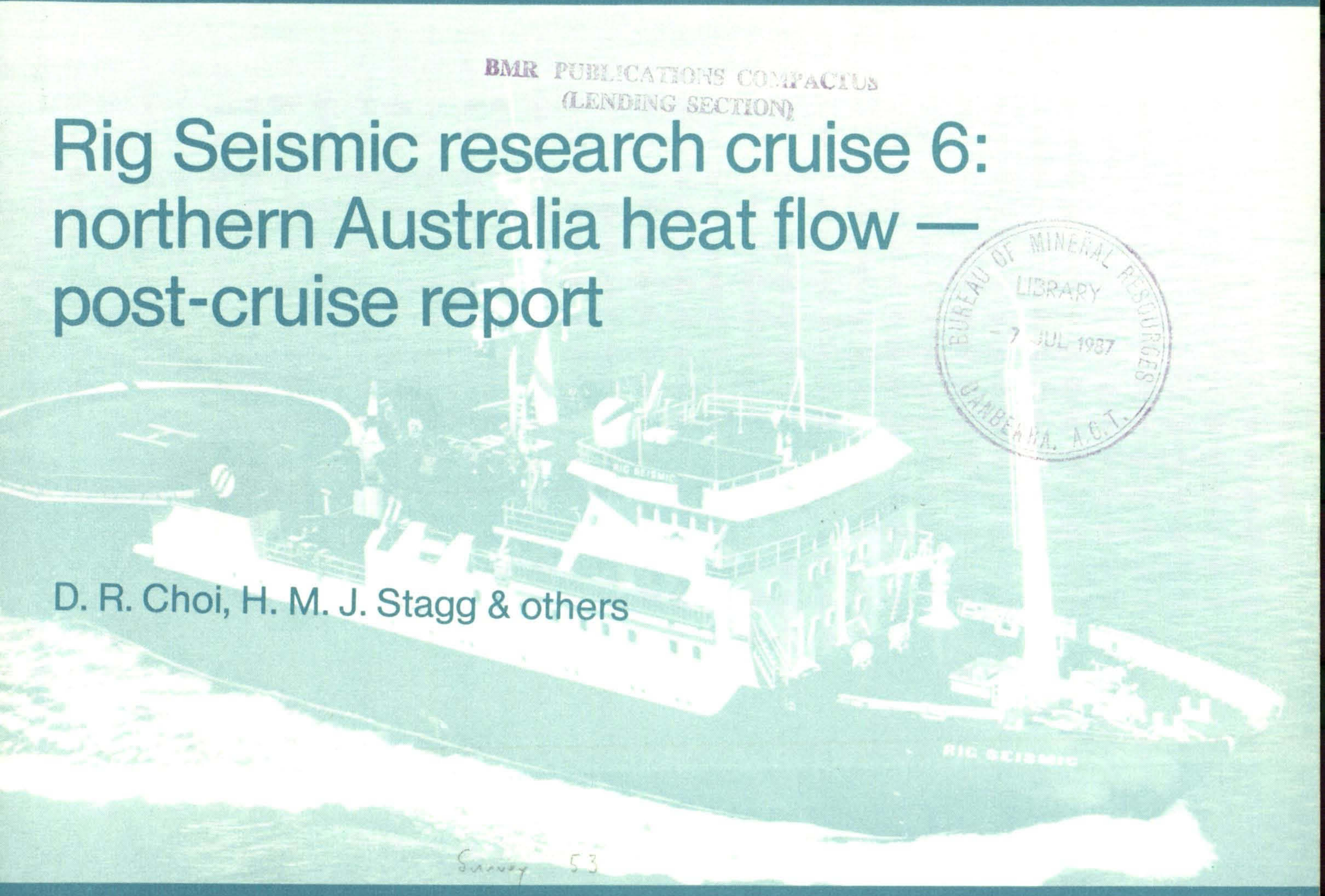
AUSTRALIA

Report 274

Rig Seismic research cruise 6: northern Australia heat flow — post-cruise report



D. R. Choi, H. M. J. Stagg & others

Bureau of Mineral Resources, Geology & Geophysics

Department of Resources & Energy

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

REPORT 274

RIG SEISMIC RESEARCH CRUISE 6:

NORTHERN AUSTRALIA HEAT FLOW - POST-CRUISE REPORT

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CONTENTS

ABSTRACT

Heat-flow data from Australian waters have, until now, been sparse and only rarely recorded from the continental margins. Historically, marine heat-flow studies have concentrated on deep-water oceanic sites. Cruise 6 of the R/V *Rig Seismic* (BMR Survey 53) is the first cruise on which heat-flow data have been collected systematically on the Australian margin. A transect along the axis of the Queensland Trough and a dip line and a strike line over the Exmouth Plateau were recorded. Fifty-five new heat-flow values were determined in the two areas, representing an approximate 40% increase in the Australian marine heat-flow data base.

Ship-board examination of the data showed that the average heat-flow in both areas studied (-60 mW/m^2) is close to the world average. As expected, in the Queensland Trough the data show a general correlation with the sedimentary basin sediment thickness, the higher values being recorded over shallow basement; and lower values, at the depocentres. Data from the Exmouth Plateau show a greater range than the Queensland Trough data and a general correlation with the gross geological structure is implied. The heat flow along the dip line transect appears to vary from high in the Montebello Trough to low on the eastern side of the Exmouth Plateau Arch, before rising again towards the northwest margin. The strike line transect shows considerable variation: this is thought to be a structural effect.

INTRODUCTION

An important and straightforward extension of the seismic/sampling studies in any area is evaluation of the present and past heat-flow regimes, with the aim of assessing the thermal and burial history of sediments and elucidating the importance of different tectonic processes in the geological evolution of an area.

Heat-flow at the surface of the earth is considered to be a product of the decay of radioactive elements in the crust and conductive and convective heat-flow from within the cooling core and mantle. When interpreted in conjunction with other geological and geophysical information, the surface heat flow becomes an important constraint for most theories regarding the constitution and history of the earth, and for assessing the maturity of sediments for the production of hydrocarbons.

The regional variation of heat flow is generally correlated with major geological structures. For instance, areas of uniformly high heat flow may be associated with a shallow Moho (as often observed beneath marginal seas), oceanic rises, areas of active volcanism, major deep-seated fault systems, or young sedimentary basins. In contrast, low heat-flow anomalies are typically associated with ancient continental shields and their thick crust. These general trends may be modified by local environments (eg., sea floor topography or irregular distribution of sediments and rocks), variations in the heat transfer mechanism (localised conduction and convection anomalies), or time-dependent phenomena at the sea floor, such as sedimentation rates or bottom water temperature.

Localised heat-flow studies are necessary for the analysis of the thermal and burial history of sedimentary basins, a technique referred to as 'geohistory analysis' (Van Hinte, 1978). Falvey & Deighton (1982) further refined van Hinte's techniques and have advocated that geohistory analysis enables improved accuracy in assessing the favourableness or otherwise of thermal history and the timing of structure (relative to migration), and, to a lesser extent, the existence of effective traps and seals and the potential for protection of reservoirs from flushing.

In Australia, a considerable quantity of terrestrial heat-flow data has been accumulated from bore-hole loggings since the early work by Newstead & Beck (1953) in Tasmania. These data were critically analysed by Cull & Denham (1979), Cull (1982), and Cull & Conley (1983). An attempt to use present and past geothermal regimes for analysis of hydrocarbon potential was made by Burne & Kantsler (1977) in the Canning Basin, Western Australia.

However, very few studies have been made of the heat-flow regime in Australian waters by Australian scientists, except for sporadic thermal-gradient measurements in offshore exploration wells. Most marine heat-flow measurements in the Australian region have been made by foreign institutes as part of their Pacific or Indian Ocean studies; consequently, the Australian marine heat-flow regime has generally received only cursory attention.

In 1985, a small multidisciplinary study team was formed in BMR to set up an Australian marine heat-flow capability. This involved the purchase of a digital heat-flow probe and assembly of thermal-conductivity measuring

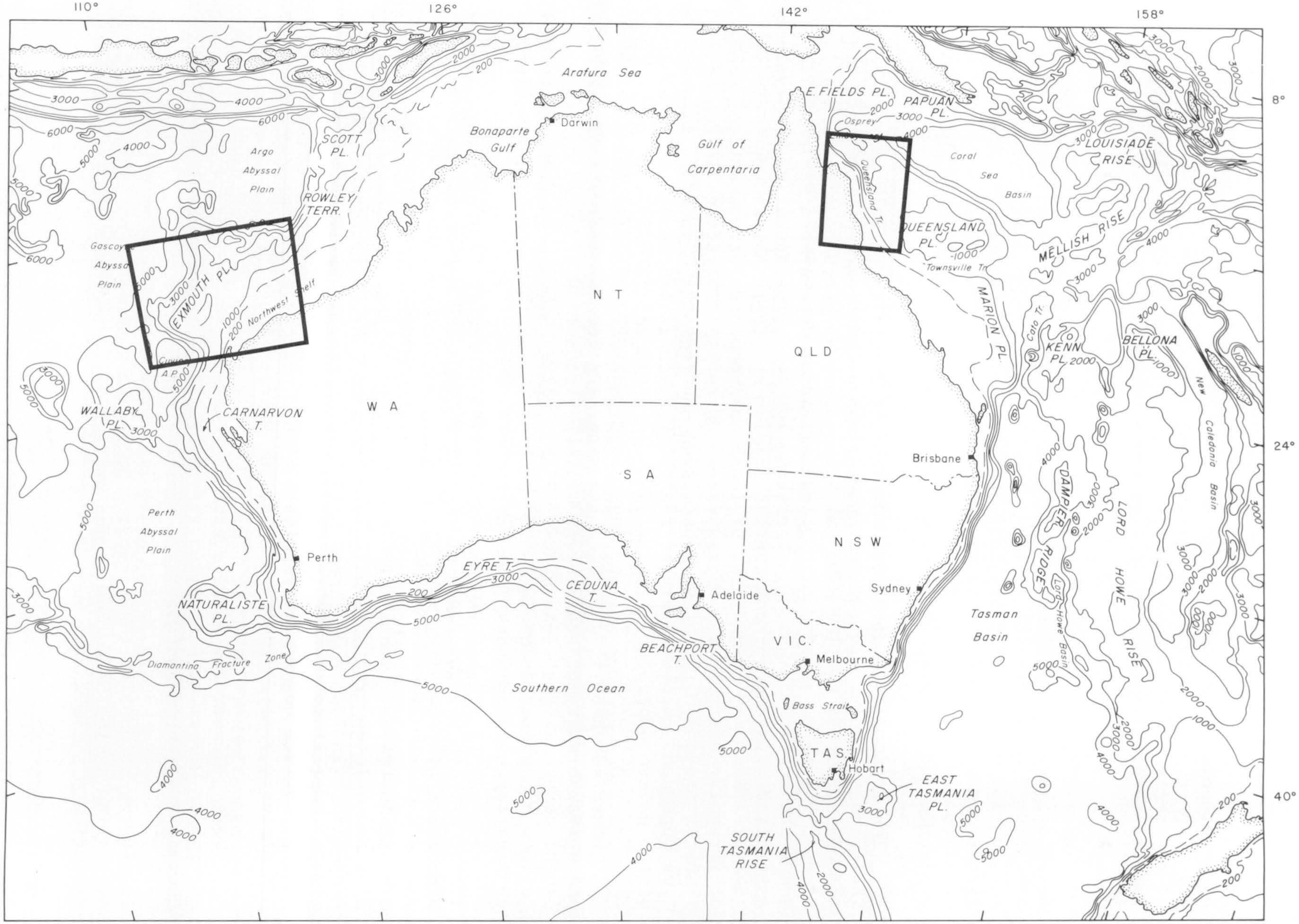

Figure 1. Locality map showing location of western Coral Sea and Exmouth Plateau study areas (adapted from Willcox, 1981).

equipment, and the selection of high-priority study areas. The areas selected for this study (Fig. 1) - the western Coral Sea and the Exmouth Plateau - satisfy the criterion of having been extensively studied and, with ample high-quality reflection seismic data being available, are appropriate areas to assess the value of heat-flow studies to the analysis of tectonic history and the applicability and value of geohistory analysis, respectively.

The intention of this report is three-fold. Firstly, we will comment on the performance of the Nichiyu Giken NTS-11AU heat-flow probe purchased for this project, and the associated thermal-conductivity measuring equipment, paying particular attention to the sources of error and calibration techniques. Secondly, we will make some preliminary comments on the significance of the heat-flow data acquired from the western Coral Sea and over the Exmouth Plateau. Thirdly, we will briefly report on the progress of ancillary programs conducted during the cruise.

The amount and quality of the data collected attest to the success of the cruise. Although only 12 days were available for operations that had to include the shakedown of unfamilar equipment and the refinement of new operational techniques, 55 new heat-flow values were determined, of which 70% are considered good quality; this represents an immediate 42% increase in the Australian marine heat-flow data set.

Whilst all staff provided input to all parts of this cruise report, the specific areas of reponsibility were divided as follows:

Equipment and techniques - B. Liu, M. Swift, and H. Stagg; Coral Sea - D. Choi; Exmouth Plateau - H. Stagg and M. Swift; Side-scan sonar - P. Harris.

Acknowledgements

The continuing enthusiasm, skill, and cooperation of the Master and crew of the R/V *Rig Seismic* are gratefully acknowledged; they have made their usual major contribution to the success of the cruise. We also wish to express our gratitude to the following: Dr D.A. Falvey and other officers in BMR for their support in getting an Australian marine heat-flow program underway; Dr E. Honza of the Geological Survey of Japan, for his invaluable suggestions on technical aspects of heat-flow survey and coring system; to the staff of Nichiyu Giken Kogyo Pty Ltd of Japan, who, in addition to supplying the basic equipment for the cruise, also provided invaluable advice in the early stages of operations; in particular, Nobo Kasanuke who joined the first part of the cruise; and to staff of the Engineering Services Unit, BMR, for their major contribution in setting up the equipment for this project.

HEAT-FLOW DATA IN AUSTRALIA

The acquisition of heat-flow data in Australian waters has been quite erratic in the past. A total of seven research cruises by foreign institutes obtained heat-flow values around the Australian margin between 1965 and 1973, while other values have been obtained from Deep Sea Drilling Project (DSDP) holes and oil-exploration wells. The locations of the approximately 130 marine heat-flow values to which we have access are shown in Figure 2; this data set represents only 10% of the available Australian heat-flow data base.

Most of the heat-flow data were originally compiled by Jessop and others (1976); and Tuezov & others (1984); these data were subsequently appraised by Cull (1982), who attempted to interpolate between marine and land stations, and whose work represents the most recent and and detailed evaluation of the Australian heat-flow regime. Cull & Conley's (1983) contours of geothermal gradient and heat-flow are shown in Figures 3-5. These maps do not clarify the transition of heat-flow patterns at the continental margins, primarily because of the paucity of marine data. However, the data do suggest that the Exmouth Plateau region is an area of average heat flow, 40-60 mW/m^2, whereas the Coral Sea Basin/Queensland Trough is an area of high heat flow, with values as high as 100 mW/m^2 being recorded (Langseth & Taylor, 1967). All available marine heat-flow data in the Coral Sea, Timor Sea, and the northeast Indian Ocean are listed in Table 1. Those values in the western Coral Sea and on the Exmouth Plateau are plotted on Figures 16 and 20.

Western Coral Sea

There have only been three heat-flow surveys on the northeast Australian margin (Langseth & others, 1971; Halunen & von Herzen, 1973). The first (Langseth & others, 1971) obtained 25 values in the area of the Queensland Trough. The widely spaced measurements show a mean heat flux of 70mW/m with a low standard deviation and standard error of 14mW/m^2 and 3mW/m^2, respectively. The geothermal gradients for this area are typically about 75 $^{o}C/km$ and the thermal conductivity for a 5x5 degree grid average for the western Coral Sea is of the order of 1.05 W/m/K.

Exmouth Plateau

Prior to Survey 53*, only one heat-flow value had been determined on the Exmouth Plateau - 61 mW/m^2 at a water depth of about 1800 m on the northwest margin of the plateau. Using the criterion of environment type, Anderson & others (1977) produced a thermal conductivity map for the plateau and forecast values of about 100 mW/m^2. Von Herzen & Langseth (1965) and Langseth & Taylor (1967) have studied the area north of the plateau, producing a number of deep-water heat-flow values.

Burne & Kantsler (1977) produced a detailed geothermal study of the Canning Basin, which indicated temperature gradients of approximately 30$^{o}C/km$ on the shelf. Nicholas & others (1980) compiled uncorrected geothermal gradients for the North West Shelf, using oil-exploration well data. Cull (1982), in evaluating the heat flow from a number of these wells in the offshore Carnarvon Basin, found that values from the shelf were typically in the range 75-119 mW/m^2: these have been incorporated in the BMR heat-flow data base. Barber (1982) reported geothermal gradients of 23$^{o}C/km$ for two of the deep-water exploration wells (Jupiter and Mercury) on the plateau, and a value of 34$^{o}C/km$ for Saturn No 1 in the Montebello Trough; these compare with the average of 35$^{o}C/km$ for the adjacent shelfal Rankin Trend.

While the lack of data from the Exmouth Plateau proper makes prediction of the heat-flow regime difficult, the data in the adjacent provinces suggest that the heat flow on the plateau is relatively low, around 50 mW/m^2.

* In BMR Marine Division's nomenclature, Rig Seismic cruise 6 corresponds to BMR survey 53.

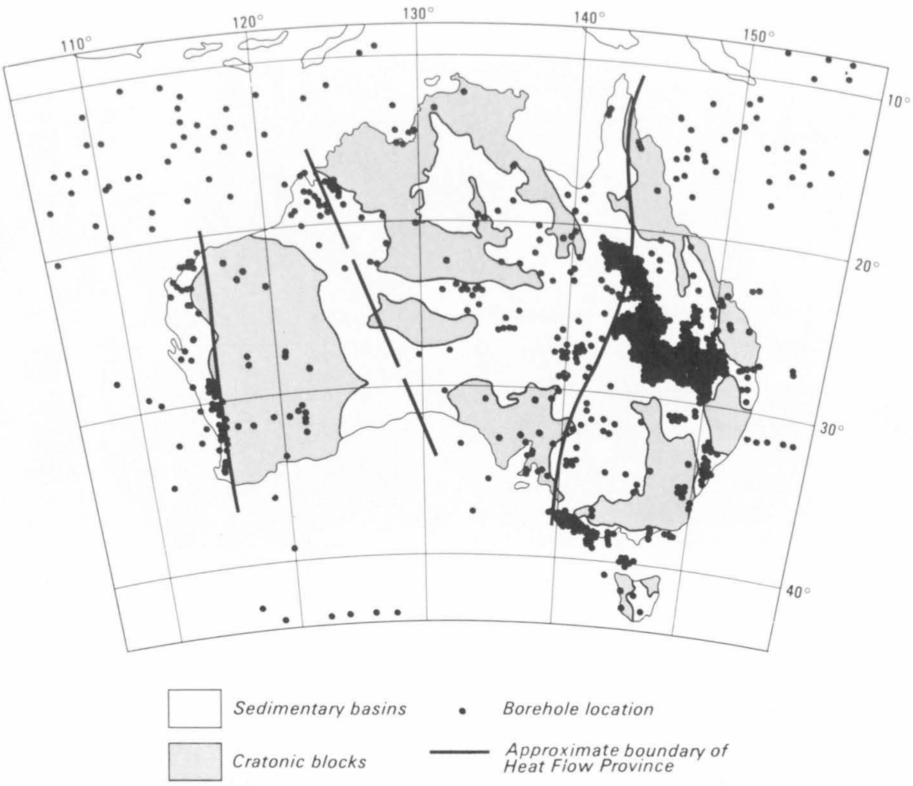

Figure 2. Locations of stations providing data for the Australian heat-flow data base (after Cull & Conley, 1983).

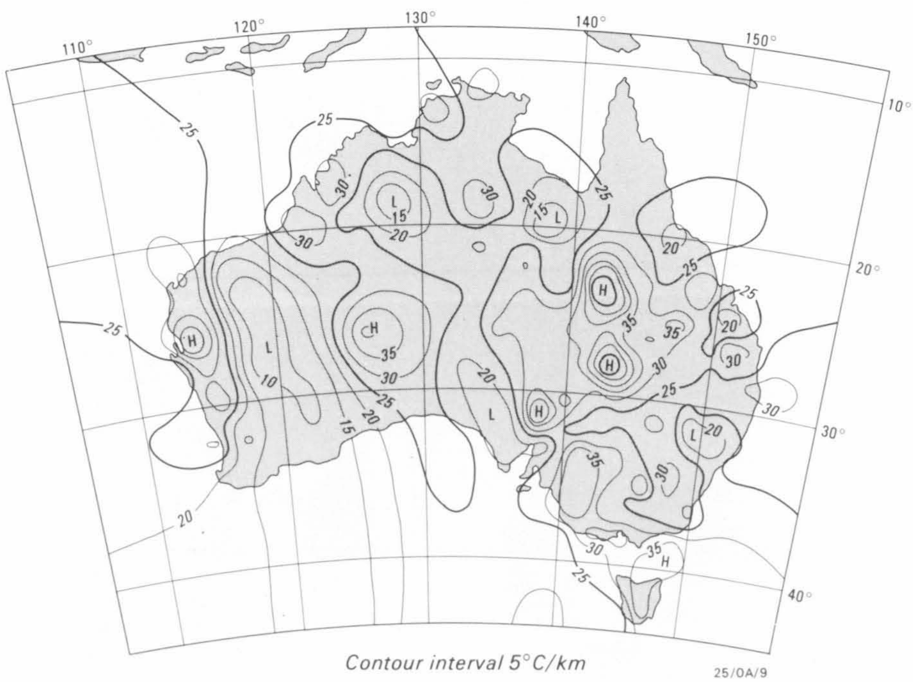

Figure 3. Variations in the geothermal gradient, based on averages over a 1 degree grid (after Cull & Conley, 1983).

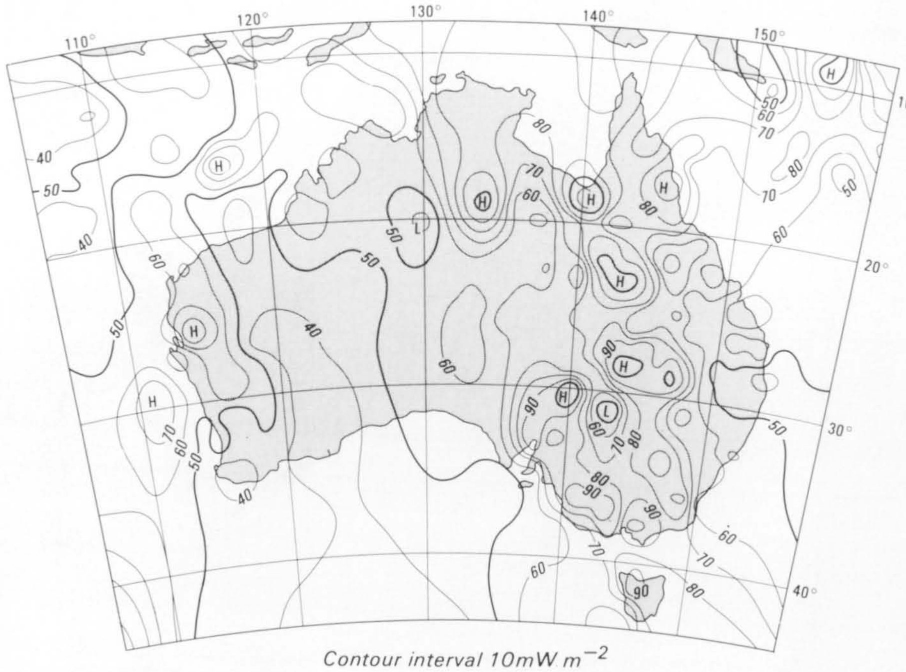

Figure 4. Estimated heat-flow, based on transformation of the geothermal gradients in Figure 3 (after Cull & Conley, 1983).

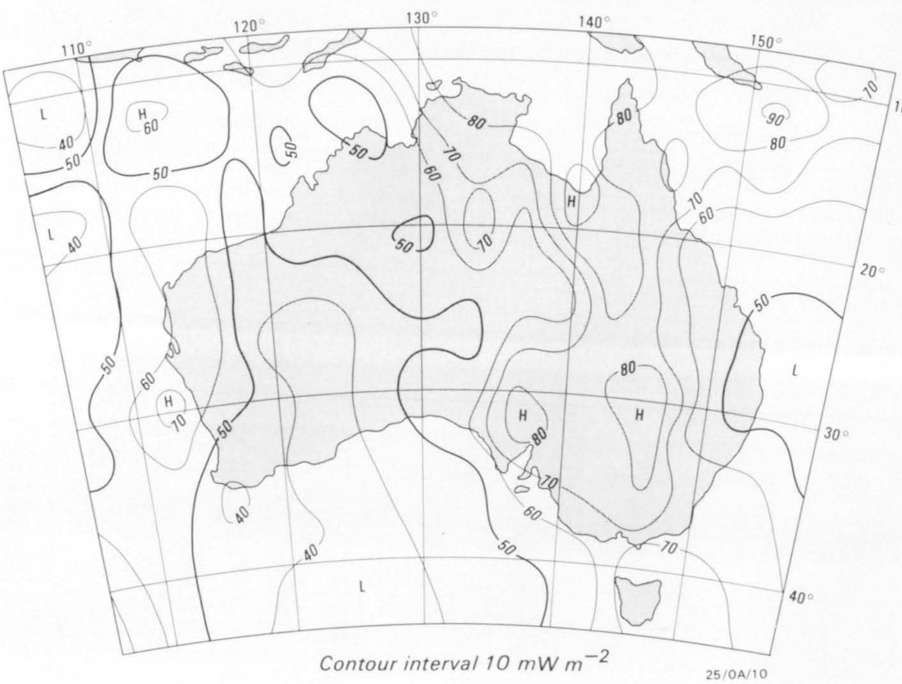

Figure 5. Heat-flow contours based on averages over a 3 degree grid (after Cull & Conley, 1983).

Table 1: Heat-flow data - offshore northern Australia

LOCATION NAME	LATITUDE	LONGITUDE	DEPTH (m)	PEN. (m)	TEMP. N.	GRAD.	CONDUC. N.	CONDUC.	BOTTOM WATER TEMP.	HEAT FLOW	REF.	YR.
CORAL SEA												
V24 124	12-03.0 S	151-14.0 E	4236	9			4	.938			4	1971
V24 125	12-52.0 S	150-12.0 E	4562	11	2	66	5	.980	2.10	64.8	4	1971
V24 126	13-49.0 S	149-04.0 E	4519	14	2	74	5	1.02	1.91	75.4	4	1971
V24 127	14-57.0 S	147-55.0 E	1214	10	2	66	4	1.01	3.42	66.6	4	1971
V24 128	15-15.0 S	146-51.0 E	1756	8	2	95	3	1.05	2.61	99.7	4	1971
V24 129	16-33.0 S	146-24.0 E	1405	10	3	89	4	1.04	3.34	93.0	4	1971
V24 130	18-07.0 S	147-36.0 E	1010	5			3	1.06			4	1971
V24 131	17-22.0 S	152-33.0 E	1326	10	3	55	5	1.13	3.33	62.0	4	1971
V24 132	15-27.0 S	153-34.0 E	4660	13	3	82	5	.967	2.10	79.1	4	1971
V24 133	13-52.0 S	153-58.0 E	4513	12	3	81	6	.888	2.08	72.0	4	1971
V24 134	16-31.0 S	150-47.0 E	817	7			3	.988			4	1971
V24 135	15-17.0 S	148-03.0 E	1182	14	4	70	5	.950	3.57	66.6	4	1971
V24 136	16-20.0 S	146-52.0 E	1783	11	3	55	4	1.02	2.54	56.1	4	1971
V24 137	13-31.0 S	146-53.0 E	2239	13	3	75	5	.988	2.36	74.1	4	1971
V24 138	14-41.0 S	146-49.0 E	1720	9	4	78	3	.984	2.44	76.6	4	1971
V24 139	11-46.0 S	148-06.0 E	3363	12	3	74	5	.863	2.01	63.6	4	1971
V24 140	11-07.0 S	150-52.0 E	993	7	3	38	5	.925		35.2	4	1971
V24 141	11-25.0 S	150-18.0 E	2635	11	2	74	5	.842	2.17	52.3	4	1971
V24 142	12-14.0 S	150-49.0 E	4420	8	2	66	6	.921	2.06	60.7	4	1971
V24 143	13-12.0 S	149-40.0 E	4515	12	3	71	7	1.06	2.07	75.4	4	1971
V24 144	14-06.0 S	148-50.0 E	4008	5			3	.858	2.02		4	1971
V24 145	15-49.0 S	148-49.0 E	1053	13	3	69	4	.980	3.79	67.8	4	1971
V24 146	17-31.0 S	147-30.0 E	1368	7	2	67	5	.955	3.22	64.1	4	1971
V24 147	15-20.0 S	146-15.0 E	2206	10	3	94	4	.946	2.28	88.8	4	1971
V24 148	12-52.0 S	146-12.0 E	3001	13	3	66	5	1.00	2.09	66.2	4	1971
NOVA A25	14-42.0 S	154-08.0 E	4630	2.5	3	76		.754		57.4	7	1972
NOVA A26	21-23.0 S	164-03.0 E	3561	2.5	3	57		.745		42.7	7	1972
CH100 3	14-16.6 S	163-54.1 E	3850			29		.771		22.6	6	1973
CH100 4	14-04.8 S	164-30.0 E	3905			110		.759		63.7	6	1973
CH100 5	14-52.0 S	165-15.0 E	3905			62		.771		47.7	6	1973
CH100 6	18-28.5 S	166-04.8 E	4440			158		.734		116.0	6	1973
CH100 7	18-13.5 S	166-41.7 E	4420			17		.742		13.0	6	1973
CH100 11	18-32.0 S	167-16.0 E	4665			212		.750		159.0	6	1973
CH100 12	18-03.0 S	167-11.0 E	4135			86		.855		73.2	6	1973
CH100 15	16-16.0 S	166-12.0 E	4550			79		.750		59.0	6	1973
CH100 19	13-33.9 S	166-16.5 E	5950			111		.830		92.5	6	1973
PROA 21	11-38.0 S	164-40.0 E	4500					.733		56.5	1	1973
PROA 22	12-49.0 S	163-53.0 E	4115					.762		79.1	1	1973
PROA 23	12-13.0 S	165-46.0 E	8960					.804		29.7	1	1973
PROA 24	20-18.0 S	166-51.0 E	3360					.846		84.6	1	1973
PROA 25	21-58.0 S	167-53.0 E	2020					.846		53.2	1	1973
PROA 26	20-35.0 S	167-34.0 E	3920					.775		79.6	1	1973
PROA 27	20-34.0 S	167-33.0 E	3800					.775		193.0	1	1973
MAHI 58	10-06.0 S	163-46.0 E	3032					.850		57.8	1	1973
MAHI 60	13-15.0 S	160-27.0 E	3473					.883		63.6	1	1973

Table 1 (continued)

LOCATION NAME	LATITUDE	LONGITUDE	DEPTH (m)	PEN. (m)	TEMP. N.	GRAD.	CONDUC. N.		BOTTOM WATER TEMP.	HEAT FLOW	REF.	YR.
CORAL SEA												
MAHI 61	12-13.0 S	158-56.0 E	3374					.825		55.3	1	1973
MSN 10	12-34.0 S	164-22.0 E	4260					.766		75.8	1	1973
LSDH 50	13-58.0 S	151-47.0 E	4655					.791		68.2	1	1973
LSDH 51	15-43.0 S	154-44.0 E	4160					.875		62.8	1	1973
LSDH 52	14-47.0 S	155-57.0 E	2985					.900		43.5	1	1973
LSDH 53	11-19.0 S	158-03.0 E	3025					.850		56.1	1	1973
DSDP 209	15-56.2 S	152-11.3 E	1428	54	3	73	6	1.13		82.1	2	1973
DSDP 210	13-46.0 S	152-53.8 E	4640	54	2	96	6	.992		95.0	2	1973
TIMOR SEA												
V24 149	09-38.0 S	126-35.0 E	2708	12	3	80	6	.854	2.78	68.2	4	1971
V24 150	10-53.0 S	122-06.0 E	1284	3			3	1.03	3.62		4	1971
NORTHWESTERN AUSTRALIAN SEA												
MSN-12	9-14.0 S	127-30.0 E	3300		2	81		.875		70.8	3	1965
MSN-15	7-46.0 S	121-14.0 E	4840		2	84		.846		71.2	3	1965
MSN-16	11-58.0 S	115-26.0 E	5010		2	63		.741		46.9	3	1965
MSN-17	12-48.0 S	115-24.0 E	5400		2	64		.691		44.0	3	1965
MSN-18	10-11.0 S	115-19.0 E	4330		2	24		.682		16.3	3	1965
MSN-20	13-19.0 S	109-34.0 E	4630		2	80		.775		62.0	3	1965
MSN-21	11-39.0 S	109-35.0 E	4605		2	100		.783		78.3	3	1965
MSN-23	8-49.0 S	109-36.0 E	3300		2	26		.787		20.1	3	1965
MSN-24	12-21.0 S	101-25.0 E	4745		2	78		.833		65.3	3	1965
LSDA-37	14-56.0 S	108-09.0 E	5580		2	68		.712		48.2	3	1965
LSDA-38	13-46.0 S	115-32.0 E	5680		2	69		.691		47.7	3	1965
LSDH-43	14-06.0 S	101-22.0 E	5110		2	111		.682		75.8	3	1965
LSDH-44	14-56.0 S	107-16.0 E	5805		2	79		.729		57.4	3	1965
LSDH-45	14-58.0 S	109-12.0 E	5630		2	65		.729		47.3	3	1965
LSDH-46	14-13.0 S	114-54.0 E	5670		2	63		.678		42.7	3	1965
LSDH-47	13-09.0 S	116-29.0 E	5670		2	69		.670		46.5	3	1965
LSDH-48	13-41.0 S	117-23.0 E	5715		2	58		.678		39.4	3	1965
V18-72	25-41.0 S	101-56.0 E	4720		1	85		.762		64.5	3	1965
V18-73	27-59.0 S	108-40.0 E	5148		2	63		.837		52.8	3	1965
V19-57	14-31.0 S	101-21.0 E	5363		3	71		.708		50.2	3	1965
V19-58	16-20.0 S	100-33.0 E	5906		2	60		.779		46.9	3	1965
V20-143	11-44.0 S	120-10.0 E	4210			56		.917		51.5	5	1967
V20-145	14-36.0 S	116-19.0 E	5680			52		.749		38.9	5	1967
V20-146	15-06.0 S	114-23.0 E	5660			46		.749		34.8	5	1967
V20-147	16-11.0 S	110-17.0 E	5670			61		.749		45.6	5	1967
V20-148	17-06.0 S	106-32.0 E	5620			46		.737		33.9	5	1967

Table 1 (continued)

LOCATION NAME	LATITUDE	LONGITUDE	DEPTH (m)	PEN. (m)	TEMP. N.	GRAD.	CONDUC. N.		BOTTOM WATER TEMP.	HEAT FLOW	REF.	YR.
NORTHWESTERN AUSTRALIAN SEA												
V24 151	11-43.0 S	120-12.0 E	4312	6	2	65	3	1.02	1.35	66.6	4	1971
V24 152	11-18.0 S	115-40.0 E	6949	8	3	41	4	.837	1.67	34.3	4	1971
V24 153	10-15.0 S	113-56.0 E	3623	13	2	21	4	.733	1.40	15.9	4	1971
V24 154	10-28.0 S	112-08.0 E	4060	10	4	47	4	.775	1.39	36.4	4	1971
V24 155	13-29.0 S	110-26.0 E	5354	7	3	67	4	.762	1.39	51.1	4	1971
V24 156	16-02.0 S	108-08.0 E	5376	6	1	63	5	.829	1.40	52.3	4	1971
V24 157	14-07.0 S	106-32.0 E	4609	5			3	.749	1.35		4	1971
V24 158	11-09.0 S	104-21.0 E	5262	7			4	.812	1.43		4	1971
V24 159	09-38.0 S	102-34.0 E	5495	12	4	78	5	.729	1.44	56.9	4	1971
V24 160	09-11.0 S	102.00.0 E	5440	8			4	.707	1.45		4	1971
	17-37 S	115-12 E								45.2	8	
	15-46 S	114-43 E								54.8	8	
	16-06 S	110-28 E								54.8	8	
	18-18 S	109-15 E								38.5	8	
	19-04 S	112-45 E								61.1	8	
	19-10 S	110-00 E								50.2	8	
	18-04 S	112-55 E								72.0	8	
	16-30 S	116-45 E								96.3	8	
	15-43 S	112-24 E								41.5	8	
	21-40 S	115-05 E								121.1	8	
	21-43 S	114-45 E								118.3	8	
	21-39 S	114-21 E								112.8	8	
	22-27 S	113-35 E								81.4	8	
	21-36 S	114-30 E								77.2	8	
	20-49 S	115-20 E								72.6	8	
	20-49 S	115-22 E								69.0	8	
	23-17 S	113-20 E								65.1	8	
	21-50 S	115-04 E								63.5	8	
	21-43 S	114-32 E								56.5	8	
	21-35 S	114-13 E								77.2	8	
	21-32 S	114-42 E								74.0	8	

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HEAT-FLOW INSTRUMENTATION AND TECHNIQUES

Heat flow at the surface of the earth is the product of the thermal gradient ($^{o}C/m$) and the thermal conductivity of the sediments (W/m/K) gradient. While the thermal gradient must neceessarily be measured in situ, the thermal conductivity normally is measured on a sediment core on board ship; this approach was adopted for this cruise.

The ship-board heat-flow instrumentation comprised a thermal-gradient probe, thermal-conductivity measuring equipment, and a computer system for heat-flow data retrieval and data processing. A modified 12 KHz pinger was also deployed with the gradient probe to provide an elementary telemetry monitoring unit.

As Survey 53 was the first BMR heat-flow cruise, we present here a brief description of the major components of the system and an evaluation of their performance.

Thermal gradient probe

Thermal-gradient measurements were made with a Nichiyu Giken Kogyo NTS-11AU heat-flow probe (Fig. 6). This is a hybrid probe, using thermistors mounted on outriggers, as does a Ewing-type (corer-mounted) probe, but using a lance, as does a Bullard probe. Two different lances were used: a 4 m lance with 8 thermistors at 450 mm intervals, and a 2 m lance with 5 thermistors at the same spacing. The thermistors are arranged spirally around the lance so as to avoid them all travelling through the same vertical column of sediment and hence generating excessive frictional heat, and to ensure that each thermistor comes to rest in undisturbed sediment. The basic probe (electronics package, head frame, and lance) weighs about 90 kg; up to ten 13 kg weights are added to the head frame to aid penetration. There are two advantages to this kind of probe as opposed to the corer-mounted Ewing probe: firstly, the probe is lighter than a corer and therefore easier to handle, and secondly, it can, theoretically, be used for multiple re-entries without the need for retrieval after each penetration. The principal disadvantage, however, is the additional need to take cores for measurement of the thermal conductivity of the sediments.

While most other heat-flow probes have recording systems that use digital cassettes or strip printers for data storage, the NTS-11 contains 64 Kb of RAM (solid state memory). At a 30 second sample rate and with 8 channels being recorded, this memory is sufficient for about 13 hours of continuous operation. The obvious advantage of a fully solid-state memory is that, as it has no mechanical moving parts, it is unlikely to be affected by jarring when the probe is handled on deck or when it penetrates the seabed. As there is no need to change cassettes or recording paper, there is normally no need to open the pressure casing during a survey, except to make an occasional check for water leakage. In practice, the down-loading of data and battery charging are done through two external connectors on the electronics package and there is no need to remove the probe from its launching cradle.

The underwater data acquisition system (UDAS) within the NTS-11 is based on an Intel low-power 80C85 microprocessor. The sampling frequency, number of data channels, and required temperature range are selected via an internal switch. As well as recording the thermistor voltages, the DAS also records time elapsed since system initialisation, data from an X-Y tilt sensor, and three precision reference resistors, corresponding to low, medium, and high temperature ranges. The sampling interval can be set at 30, 60, 90, or 120 seconds. Two separate A-to-D converters are used for data digitisation: a 12-bit A/D for the tilt sensors, and a high-resolution 4.5 digit A/D for the reference resistors and thermistors. To maximise the temperature resolution, temperature measurements are made in one of two ranges: -2 ^{o}C to 20 ^{o}C and 10^{o}C to 32 ^{o}C. Thus, for the 22^{o}C temperature span, the 4.5 digit A/D gives 1 mC temperature resolution.

During preparation for deployment, the NTS-11 has to be initialised by the computer playback system. The initialisation consists of clearing the DAS memory and setting the delay time before the start of recording. A separate magnetically actuated switch is also provided for use in conjunction with a piston corer.

Deployment

The dimensions and weight (220 kg maximum) of the NTS-11AU probe make it a simple matter for three people to deploy, using its custom-built deployment frame. After deployment, the probe is lowered to within 200 m of the sea floor and held at that depth for 10 minutes to allow temperature stabilisation and thermistor calibration. The probe is then dropped into the sea floor, with penetration being confirmed by a variable output pinger attached to the wire above the probe. After about 10 minutes in the sea floor, the probe is slowly withdrawn and then retrieved. Although the probe design is such that multiple re-entry is possible on the one deployment from the surface, in practice it was found that the lance was almost invariably bent at every station, necessitating its complete retrieval for repairs.

Extensive tests were performed to determine the best weight/drop-rate ratio for full penetration for each lance. It was found that excessive weight on the head frame caused the lance to bend on penetration of the sediments or if penetration was incomplete. Dropping the probe too rapidly into the sediment appeared to de-stablise it, causing it to enter the sediments other than vertically and, in extreme cases, to fall over.

The distance the probe is allowed to drop before penetration also appears critical. On this cruise, estimates of the distance of the probe from the sea floor were only good to within 50 m. Consequently, on a number of stations the probe was too close to the sea floor when the final drop was made, invariably with deleterious effects. Experience shows that it rarely requires more than a 1 tonne pull to withdraw the probe from the sediments.

Figure 7 shows a typical temperature/time plot from a thermistor at the lower end of the lance during a deployment and retrieval. Each phase of the penetration and retrieval is reflected as a distinct event in the plot. Region A shows the steady temperature decrease as the probe descends. Region B is the period of temperature stabilisation and calibration with the probe held about 100 m above the sea floor. Region C is the drop into the sediments. Note that there is a sharp drop in temperature as the probe falls at a rate of about 45 m/min towards the sea floor. The probe took about one minute to reach

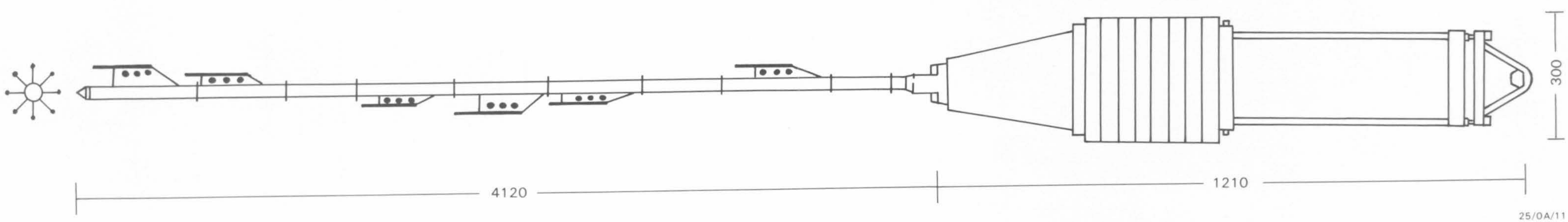

Figure 6. Nichiyu Giken Kogyo NTS-11AU heat-flow probe.

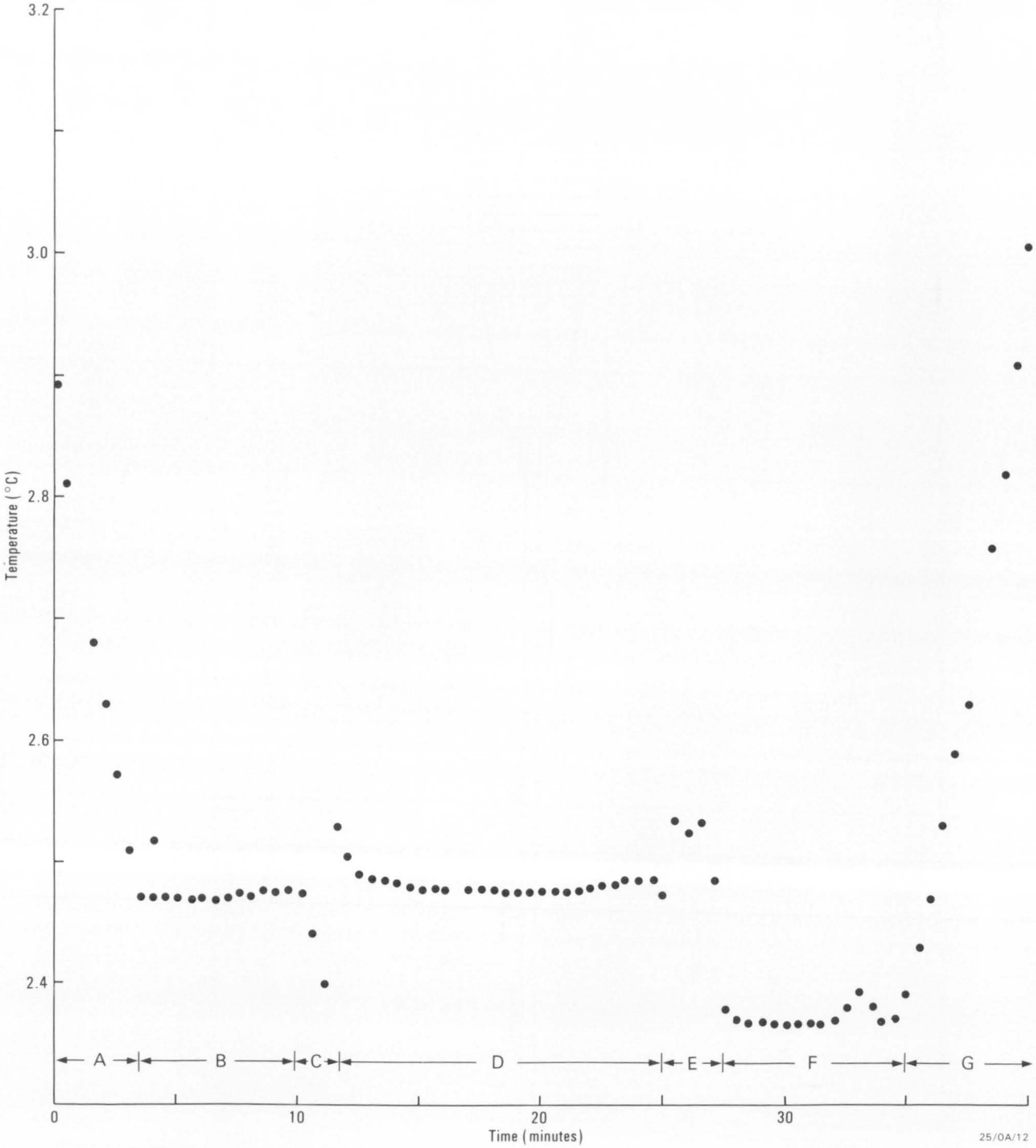

Figure 7. Temperature/time plot from a thermistor at the lower end of a heat-flow probe, showing the main thermal events during a typical deployment.

the sea floor in the example shown. Region D covers the time that the probe is in the sediments. Note the rapid rise in temperature due to the frictional heat generated on entry, after which the temperature decays to a steady value over a period of about 4 minutes. The frictional heat-generated temperature rise is far greater for the thermistors at the base of the probe, as these thermistors have travelled a greater distance through the sediment before coming to rest. It follows from this, that given the fairly brief time that this frictional heat takes to dissipate and the coarse sampling rate of 30 seconds, it can be difficult to determine how far the lance penetrated merely by looking at the temperature rise on penetration. Confirmation of the length of penetration can only come when the data have calibration factors applied; at this point it becomes obvious which thermistors were in the water column and which were in the sediment. Region E is the time of pull-out; the rise in temperature is again due to frictional heat. Region F is a period when the probe is dragged along the sea floor while the excess coring cable is wound in. Finally, Region G shows a steady rise in temperature as the probe ascends to the surface.

Also contained in the electronics package is a two-axis tilt sensor. While this sensor is rather coarse (accurate to about $\pm$ 3°C) and has a constant offset, the information (which is sampled at the same rate as the thermistor data) is useful in that it gives some indication of the angle of repose of the probe. Unfortunately, however, if the probe bends shortly after penetration, the tilt sensors will only record the tilt of the electronics package, and not the tilt of the probe. The sensors also appear to jam occasionally at the maximum 45° setting, owing to jarring of the probe on penetration.

DAS initialisation and data processing

The heat-flow probe processor hardware is shown as a block diagram in Figure 8. The three major parts of the system are the microprocessor underwater data acquisition system (UDAS), a Fujitsu FM-16π personal computer, and twin Fujitsu floppy disc drives. This part of the system has three functions, which may be described as follows:

System initialisation. Before the heat-flow probe can be deployed, the UDAS must be initialised. This involves clearing the RAM data storage area within the UDAS and starting the acquisition (with or without a recording delay time). During this phase, the FM-16π computer merely acts as if it were a terminal and all dialogue is initiated by the UDAS. Care must be taken in logging the starting time of acquisition, as the UDAS internal clock records elapsed time and not absolute time.

Data Retrieval. Immediately on retrieval of the heat-flow probe, the FM-16π computer is reconnected to the UDAS; again, the computer is configured as if it were a terminal only. After data acquisition has been halted, the data in the UDAS are downloaded, 8 Kb at a time, into the RAM 'disc' area on the FM-16π. When all data have been downloaded, processing control is returned to the FM-16π and the data are transferred to the hardware floppy discs for permanent storage.

Data Processing. A suite of three programs has been developed for processing the thermal-gradient data, which, at the end of stage 2 above, are still stored in the form of digitised voltages. The three programs perform the following functions:

(i) AUST5 - Converts the raw digitised voltages into raw uncalibrated temperatures. Each sample for each thermistor is listed on a printer for basic assessment. From this listing, the specific events in the deployment (stabilisation above the sea bed, penetration, withdrawal) can be identified for the next processing stage.

(ii) CAL2 - From the listing generated by AUST5, the thermistor calibration interval is selected. This interval is that part of the stabilisation time above the sea bed when temperatures are most constant, and is typically about five minutes. CAL2 then computes the calibration factor for each thermistor in the string relative to a specified reference thermistor. The calibration factors and standard deviations are then listed.

(iii) STAT - In the final processing stage, the calibration factors computed by CAL2 are applied. The calibrated temperatures are then computed and listed. It is only at this stage that a first estimate of the thermal gradient can be made and the number of thermistors that penetrated sediment can be assessed.

Heat-flow probe performance

Calibration tests were performed on a string of six thermistors. The test involved taping the thermistors together in a bundle to eliminate any temperature gradient effects between them, and lowering them about 2000 m. The temperature variation with time for each thermistor is shown in Figure 9. The variation of about 0.12°C during the test is probably due to currents causing some movement of the thermistor package within the water column. It is important to note that, although the thermistors record different absolute temperatures, the differences between them remain almost constant. The differences relative to thermistor 320C are given in Table 2. This table then gives the correction or calibration factor that needs to be applied to the raw data at that station in order to get correct temperature differences.

Table 2: Analysis of calibration factors relative to thermistor 310C.

Thermistor Number	Calibration Factor	Standard Deviation	Standard Error
310C	0.0000	0.0000	0.0000
265C	-0.0885	0.0007	0.0001
220C	-0.1058	0.0011	0.0002
175C	-0.0859	0.0008	0.0002
130C	-0.0144	0.0011	0.0002
85C	-0.0771	0.0041	0.0008

From Table 2 it can be seen that the relative calibration of the thermistors is within 0.05°C. If we ignore thermistor 85 C, the error after the calibration factor is applied is of the order of 0.003°C. The error in the thermal gradient is calculated from this temperature precision and the maximum distance between thermistors. In the case of a 2 m lance achieving full penetration, the gradient can be calculated to within 1.66°C/km, or 0.95°C/km in the case of the 4 m lance. The smallest thermal gradient that can be determined for the

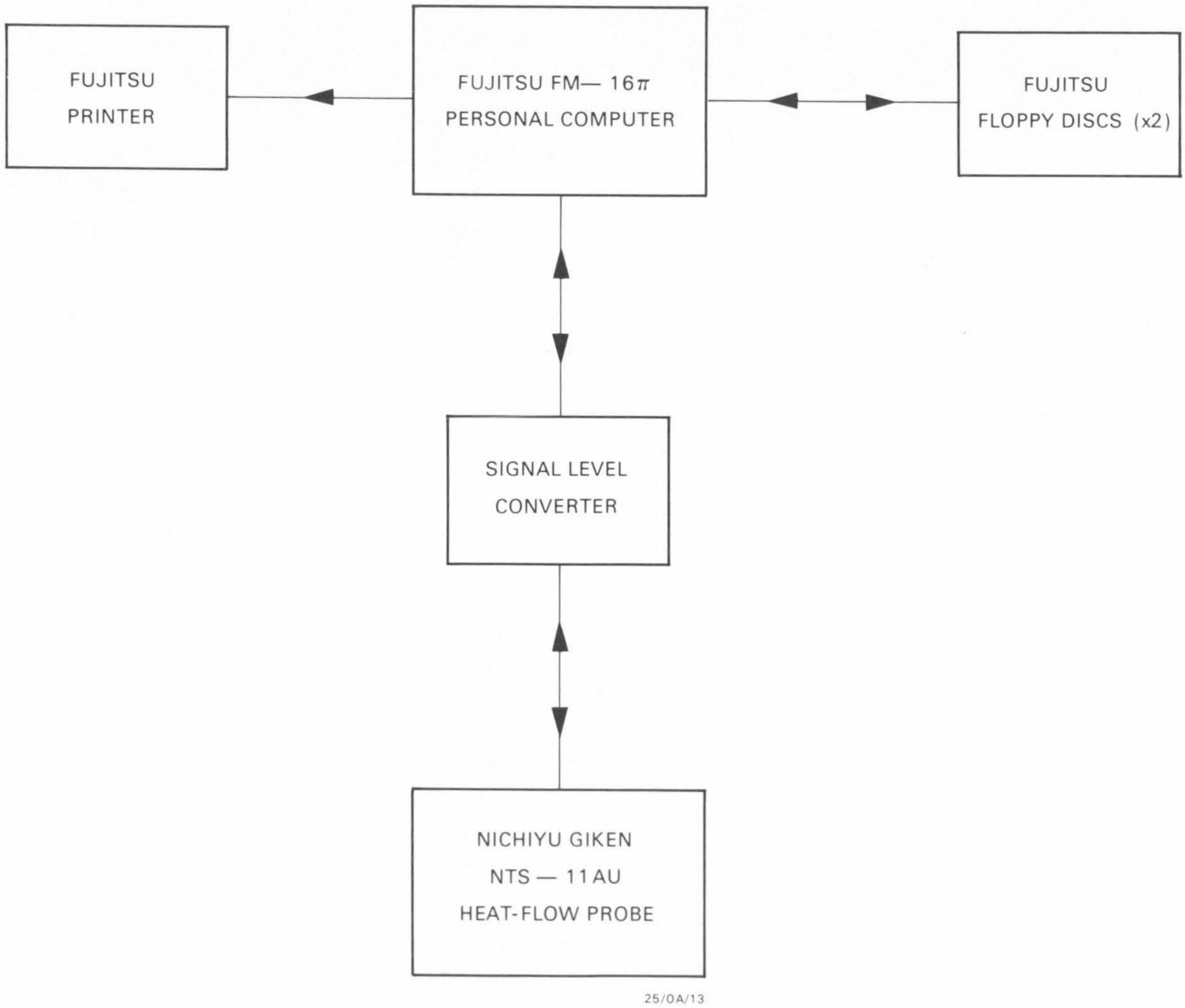

Figure 8. Block diagram of heat-flow probe and processing hardware.

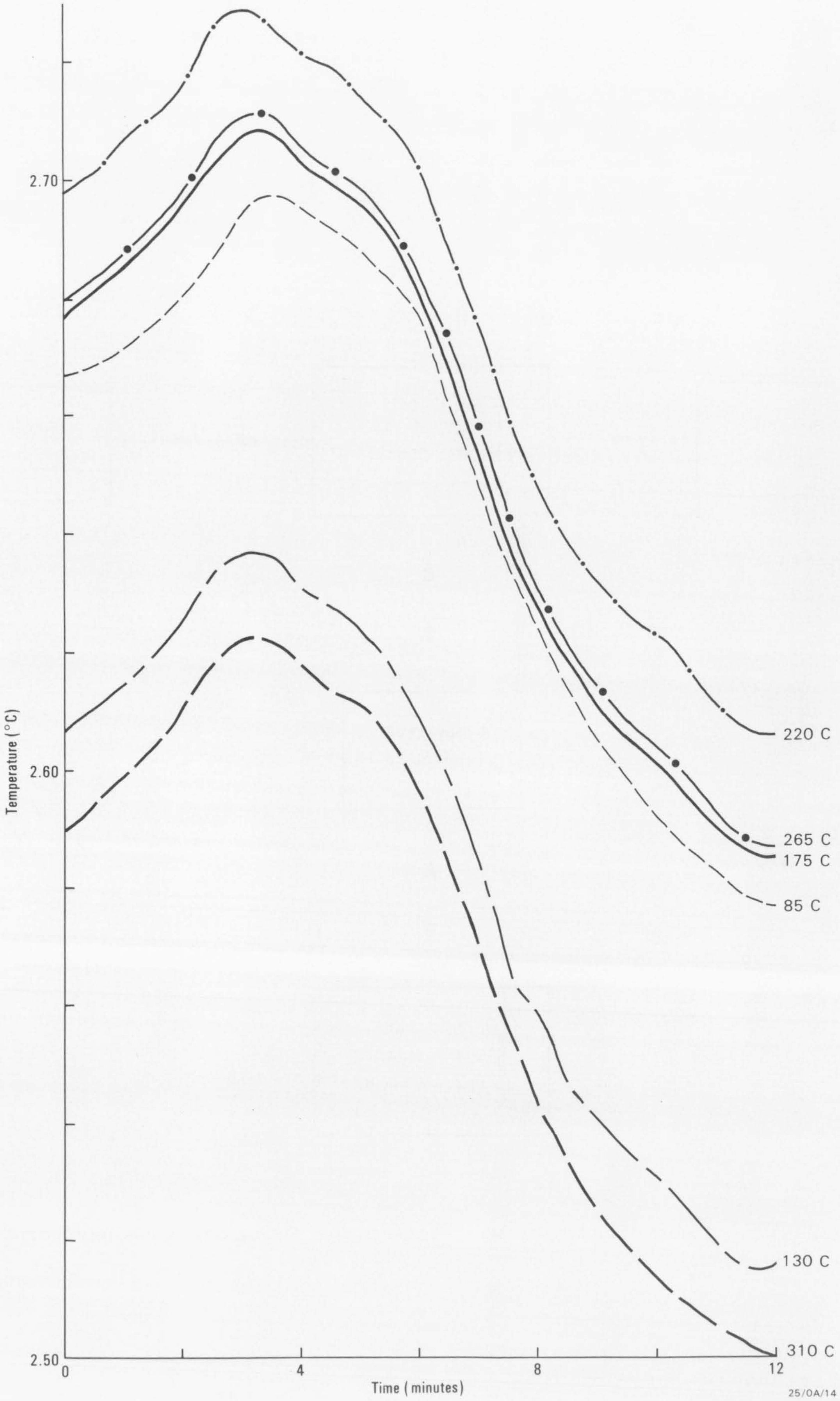

Figure 9. Temperature variation with time for a thermistor calibration with all thermistors taped together.

2 m probe is $3^{o}C/km$.

Figure 10 shows the calibration factors at each heat-flow station in the Coral Sea. Under normal conditions, the calibration is done with the thermistors assembled on the lance. The calibration factors obtained by this method remain relatively constant and compare well with the calibration test described above. Note that the calibration factors track each other well up to station HF-14, indicating that it is possible to derive calibration factors when the thermistors are on the lance. Station HF-15 was a test to see if calibration could be achieved from temperature data acquired while the probe was descending (i.e. dispensing with the 10-minute 'hold' period above the sea floor). The results indicate that this is not possible and that the 10-minute hold period is therefore essential. After station HF-15, thermistors 130C and 200C began to drift. There are indications that the drift rate was small compared to the time lag between calibration and data acquisition (about 15 minutes). Nevertheless, good results were obtained by using large calibration factors. After station HF-23, the C-series thermistor string was replaced, as the calibration factors were becoming too erratic and large.

Thermal-conductivity measurements

Thermal conductivity was measured on the sediment cores (Fig. 11) with a BMR-constructed needle probe, based on the thermal-transient technique pioneered by von Herzen (1959). The needle probe is 5 cm long, the same as the core diameter. The external diameter of the needle is 1 mm, giving a diameter:length ratio of 1:50. A Fenwal bead thermistor, type GL32L10, is fitted inside the needle, together with the heating wire (Fig. 12).

A BMR-constructed thermal-conductivity bridge was used in conjunction with the needle probe. It provides a constant current to drive the needle-heating element, and a precision Wheatstone Bridge to measure the voltage change of the thermistor sensor. The heater element produces 2.6 W/m. It was found necessary to have a low heater input to minimise the effect of convection heating. The heater turned on for 100 seconds, during which time the temperature is sampled once per second. Data logging is handled by a Hewlett-Packard 3456 DVM controlled by an HP 9825 desk-top computer. A strip printer and X-Y plotter are used for recording and graphic display.

The X-Y plotter plots temperature against logarithmic time increment (Fig. 13); in theory, this should be a straight line, the slope (determined by least-squares fit) determining the thermal conductivity. The small ripple towards the end of the linear part of the curve is due to the effect of convection heating, as there may be up to 60% water content in the cores.

In order to measure the conductivity of the cores a number of holes are drilled along the core liner at 200 mm intervals. The needle probe is then inserted through the hole perpendicular to the long axis of the core and therefore in the plane of the sediment layering. The initial ambient temperature of the core is measured with a digital thermometer. Aside from local variations due to varying sediment type, conductivity generally increased with depth, confirming the assumption that conductivity increases as the water content decreases with depth. On a number of cores, the conductivity dropped markedly at the very top of the core; this was found to be due to the sediment not completely filling the core liner.

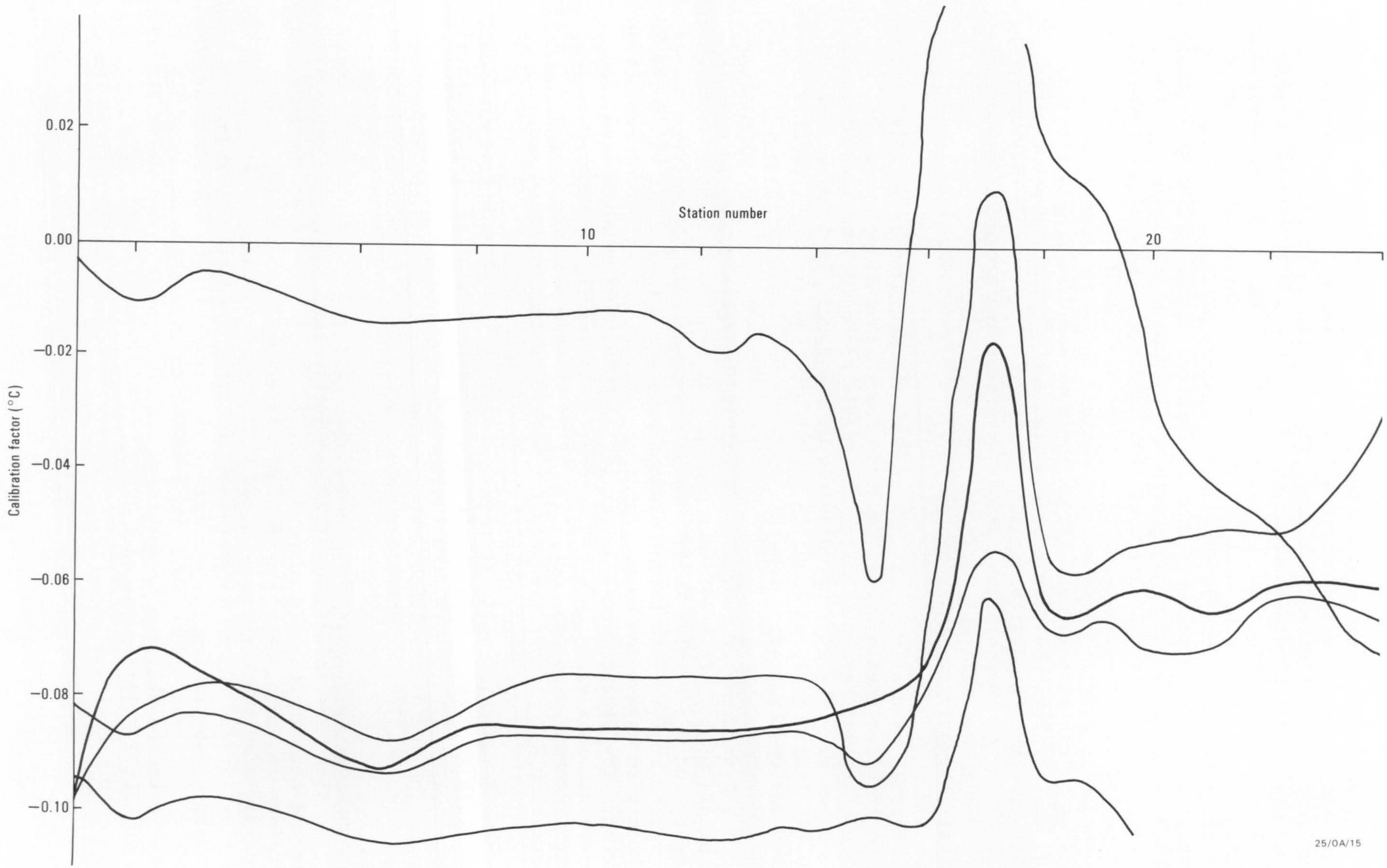

Figure 10. Variation of calibration factors for one thermistor string during the Coral Sea leg of Survey 53.

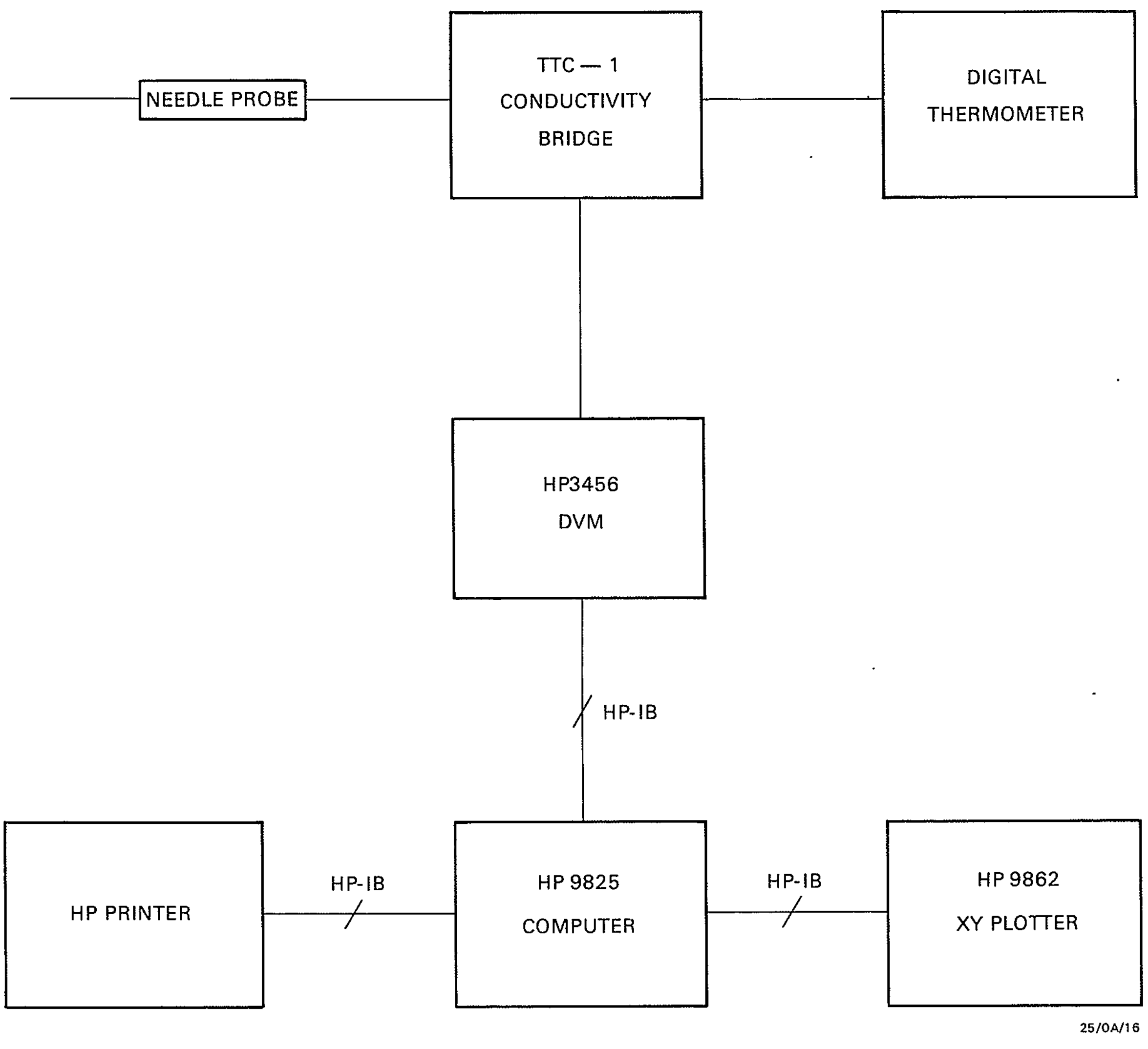

Figure 11. Block diagram of thermal-conductivity measuring equipment.

Acoustic telemetry system

For an underwater telemetry system, we used a 12 KHz pinger modified to give a different pulse rate during deceleration and when the pinger was not approximately vertical. The pinger was originally intended to be mounted on the probe head frame. However, in this position it was prone to become entangled with the coring winch wire on retrieval, and was subsequently removed and attached to the coring wire about 25 m above the probe. During rough sea conditions, in particular, the pinger was very useful for providing information on the probe relative to the sea bed. In the long term, it is intended to provide a real-time telemetry system to send temperature and tilt information back to the surface while the probe is deployed.

Equipment evaluation

During this first BMR heat-flow cruise, 25 heat-flow stations were occupied in the western Coral Sea, and a further 39 on the Exmouth Plateau, over a period of four weeks. The ambient operating temperature varied from about 35^{o}C on the deck to about 2^{o}C near the ocean floor. Both the electronics hardware and the pressure housing of the DAS worked reliably during the cruise, although the DAS was inoperative for about 3 hours for minor repairs during the survey.

The most disappointing parts of the heat-flow probe were the lances and the lance mounting stud at the base of the head frame. Both the 4 m and the 2 m lance were very prone to bending, even when the ship was using the Global Positioning System of navigation; this made multiple probe entries on one deployment totally impracticable. A replacement mounting stud had to be made on board when the original one became seriously weakened by repeated bending at the first few stations. We are convinced that the probe is almost invariably bent when being withdrawn from the sediments. As the ship cannot be expected to be kept perfectly stationary, particularly when navigating on dead-reckoning, it is apparent that a more rugged probe, or a probe that is capable of flexing when under torque, is required.

Extreme care must be exercised in the handling of the underwater connectors. Any contamination or leakage may easily cause erratic temperature readings. Cleaning of contacts with a fluorocarbon cleaner and application of silicone grease to the rubber contact areas should avoid most problems. Of the original 24 thermistors delivered with the heat-flow probe, one was lost and a further three went out of their calibration range, probably owing to their exposure to extreme temperature cycling; we consider this to be an acceptable record.

While the DAS generally performed satisfactorily, we would prefer to be able to set the sample rate, channel selection, and temperature range from the playback computer, rather than having to reset internal mechanical switches. There is also a case to be made for a sampling rate faster than 30 seconds, if we are to more fully understand the performance of the probe on penetration and withdrawal from the sea bed.

The conductivity measuring equipment performed satisfactorily throughout the cruise. However, thermal conductivity should ideally be measured *in situ*, although by leaving the cores to stabilise at room temperature for 24 hours, we

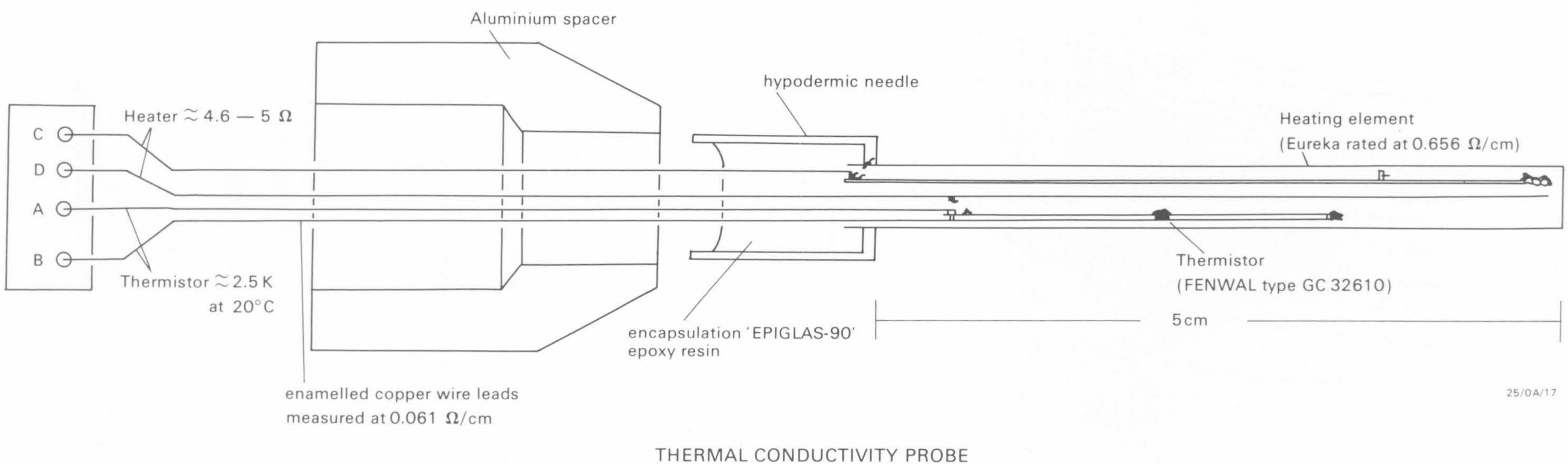

Figure 12. Construction of needle probe used in thermal-conductivity measuring equipment.

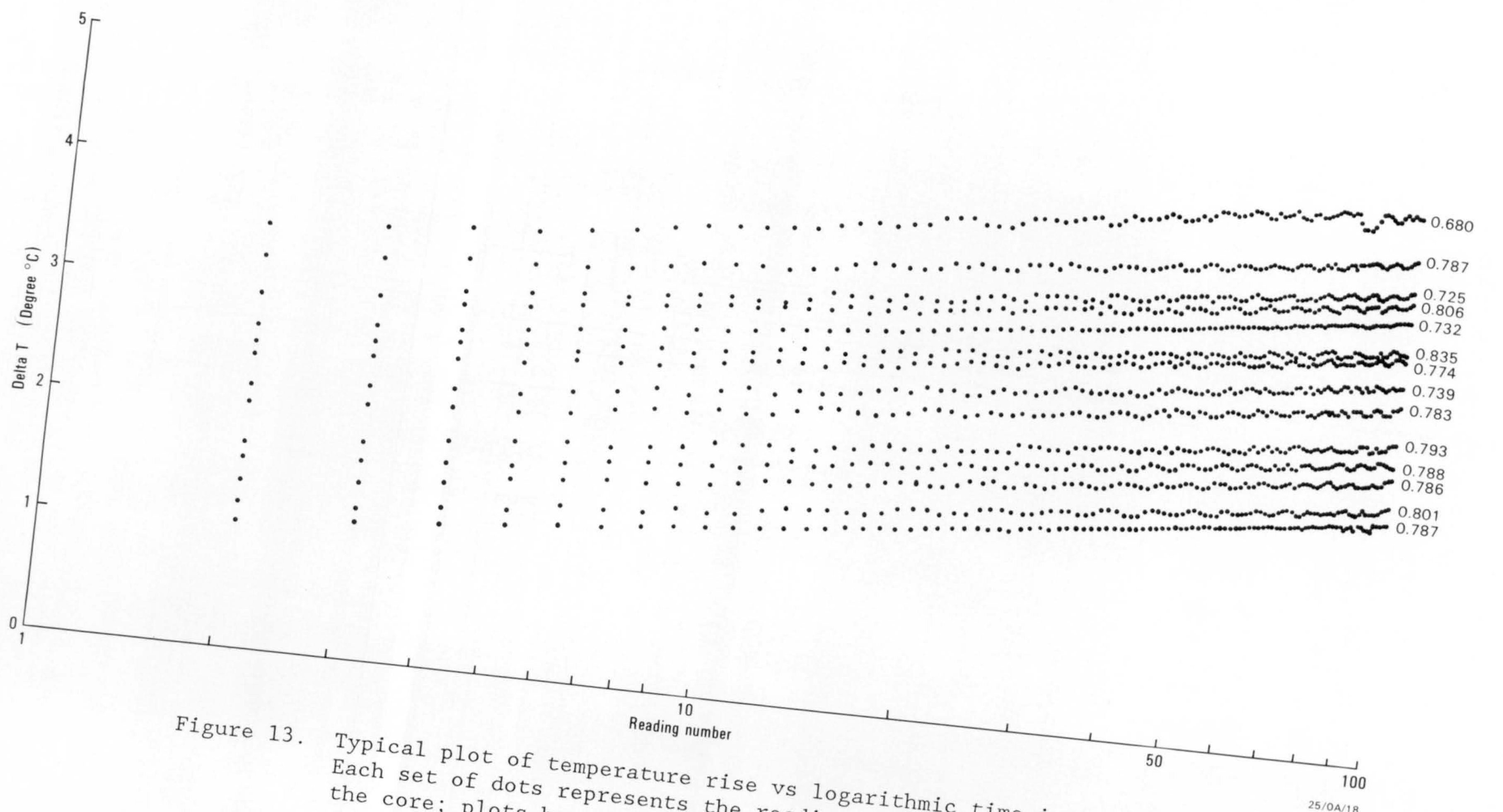

Figure 13. Typical plot of temperature rise vs logarithmic time increment. Each set of dots represents the readings for a single point in the core; plots have been intentionally offset from each other to avoid overprinting.

did manage to obtain consistent and repeatable recordings in most instances.

QUEENSLAND TROUGH (WESTERN CORAL SEA)

Summary of regional geology

The Queensland Trough is a morphological and geological depression between the continental shelf and the Queensland Plateau between 14° S and $17^{\circ}30$ S, adjacent to the Great Barrier Reef (Fig. 14). The western margin is much steeper than the eastern margin, with gradients of up to 1 in 3. The floor of the trough is flat and smooth and gently deepens northward from a depth of about 1100 m off Townsville to about 3000 m in the northern end of the trough, where it debouches into the Osprey Embayment.

The strike of the trough is the same as the dominant structural grain of the Tasman Fold Belt in northern Queensland (Hill & Denmead, 1960; Ewing & others, 1970). Mutter (1977) speculated that the Queensland Trough lies along a structural low of the Tasman Fold Belt. This idea was also followed by Falvey & Taylor (1974), and Taylor & Falvey (1977). However, Symonds & others (1984) suggested the possibility that the acoustic basement could indicate the top of the oceanic basement and thus the Queensland Trough could have been formed by opening or pulling apart of the Queensland Plateau from the Australian continent.

A generalised profile across the Queensland Trough is shown in Figure 15. This profile is based on all available seismic, dredging, and drilling information in the trough and its environs, including the Queensland Plateau and the Great Barrier Reef. The age of each stratigraphic unit is speculative and tentative. The sedimentary cover over the Paleozoic - Mesozoic basement shows, in general, a transgression upward from terrigenous (fluvial-deltaic) in the ?Cretaceous, to shallow marine in the Paleocene, to marine including carbonate buildups on basement highs on both the continental shelf and Queensland Plateau. Deep marine conditions may have prevailed from the Late Oligocene through to the Holocene. The stratigraphic units are separated by marked regional erosional unconformities.

The general structural framework of the Queensland Trough is shown in Figure 16. As clearly seen in the figure, the trough is a graben bordered by major structural highs on both sides. However, the over-all trend of the trough is slightly oblique to that of the basement structure, strongly suggesting that the trough was formed by a combination of Tasman orogeny and younger block movement tectonics.

In the central Queensland Trough, off Cairns, a distinctive east-northeast - west-southwest basement high is discernible. The sedimentary basins in the trough are divided by this ridge into southern and northern basins, with the southern basin being more restricted in environment. The eastern margins of the basins are bordered by major fault structures, and the basin centres are located on the synclinal axes.

Cores taken during this survey showed that copious quantities of sediment have been supplied from the continental shelf to the west by turbiditity currents or gravity slides. The core sections (2.5 to 3.8 m; Appendices 3,4) are characterised by deep-sea foraminiferal mud intercalated with sands and

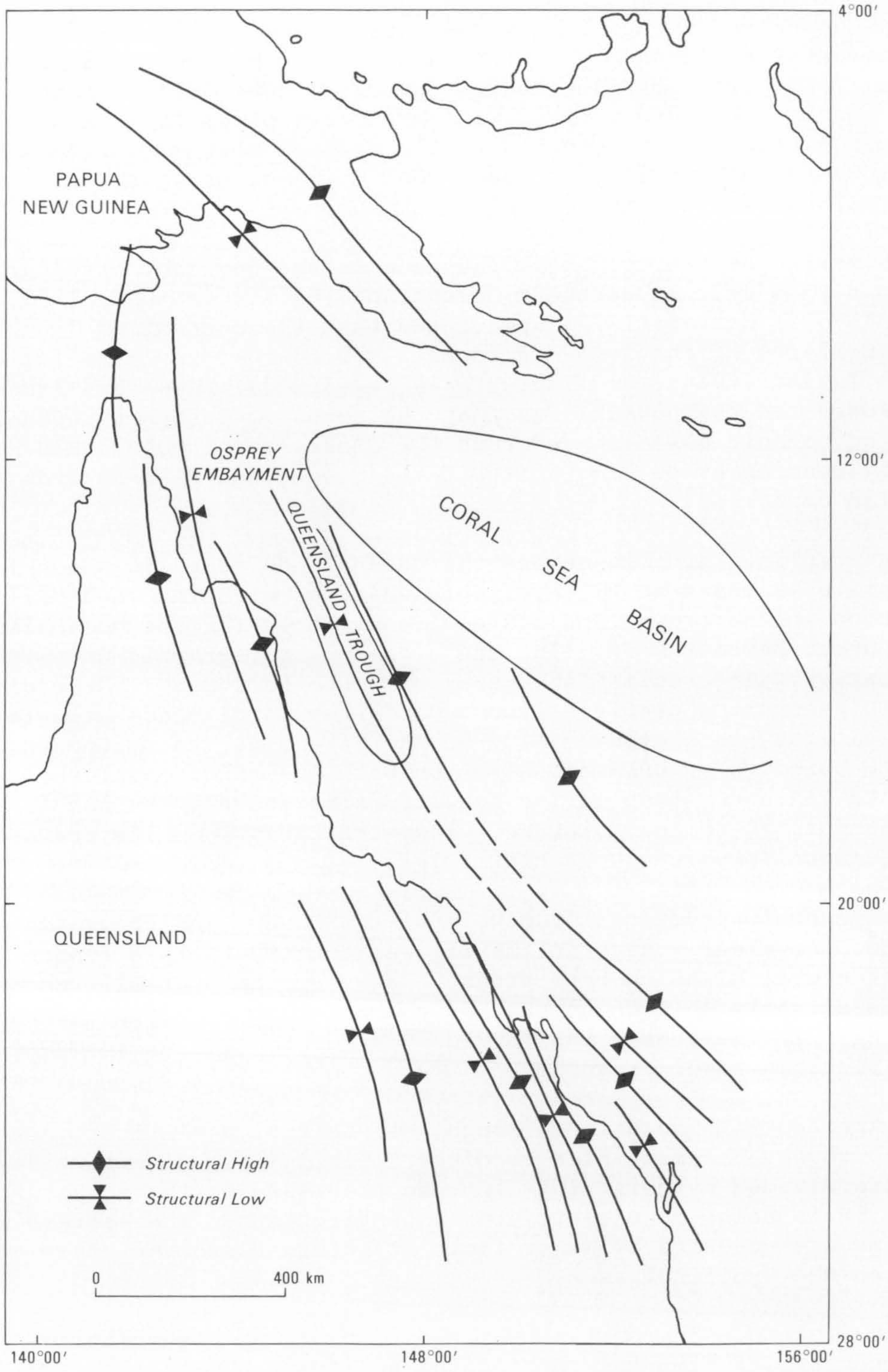

Figure 14. Tectonic framework of the Queensland Trough and the western Coral Sea.

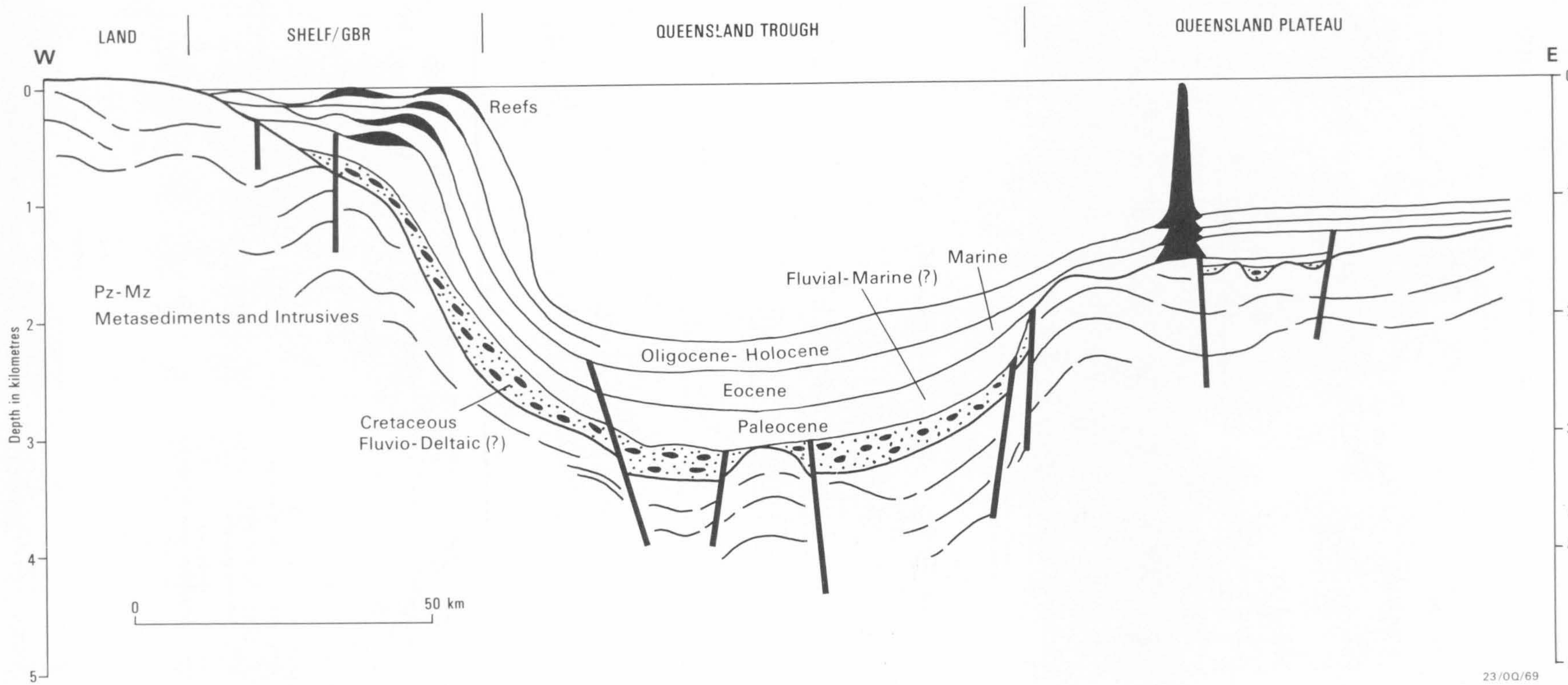

Figure 15. Generalised structural profile across the Queensland Trough.

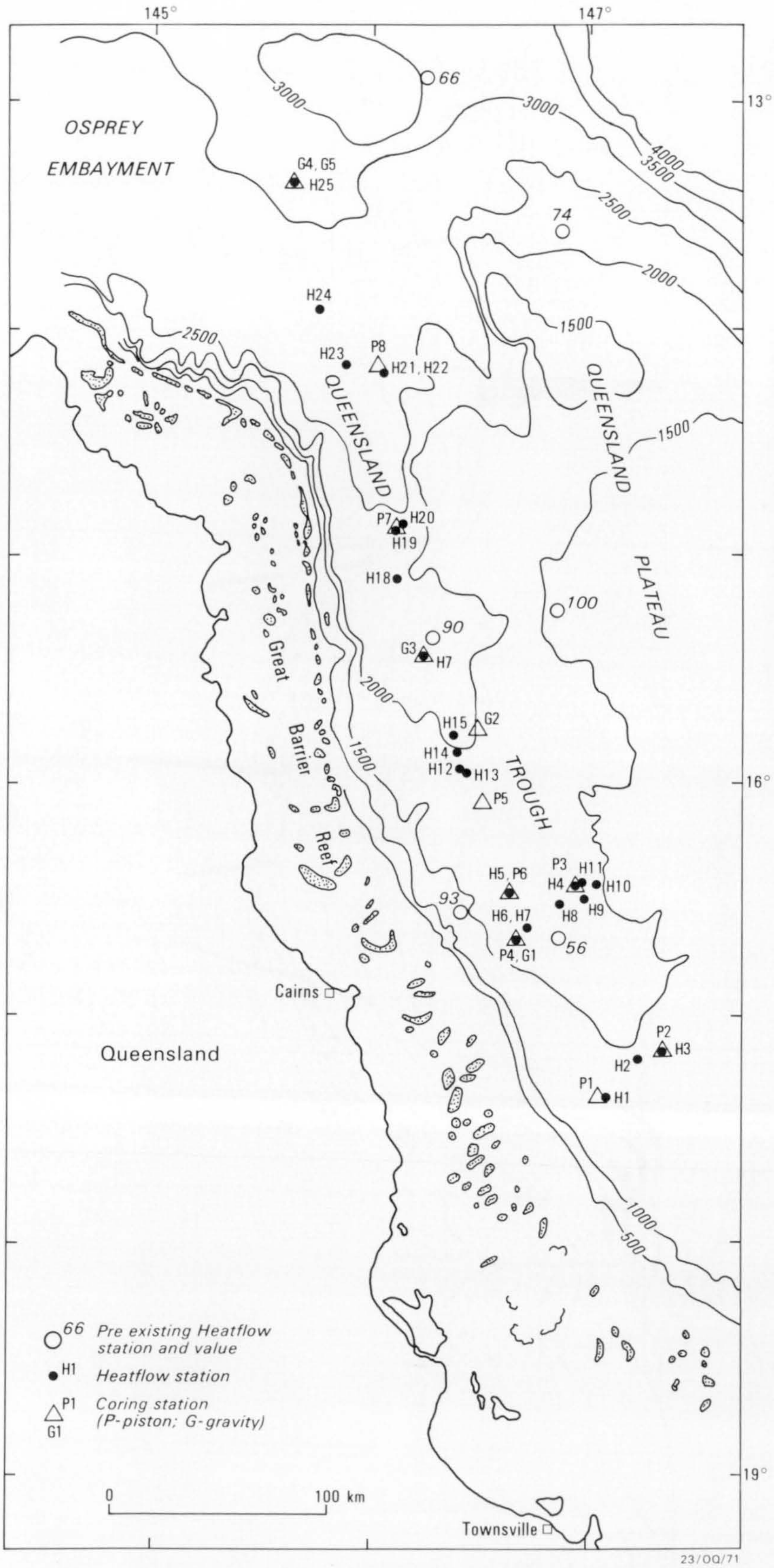

Figure 16. Morphology of the Queensland Trough and western Coral Sea. Pre-existing heat-flow station values are shown, together with the heat-flow and coring stations occupied on Survey 53. Survey 53 station locations and associated details are contained in Appendices 3 and 4.

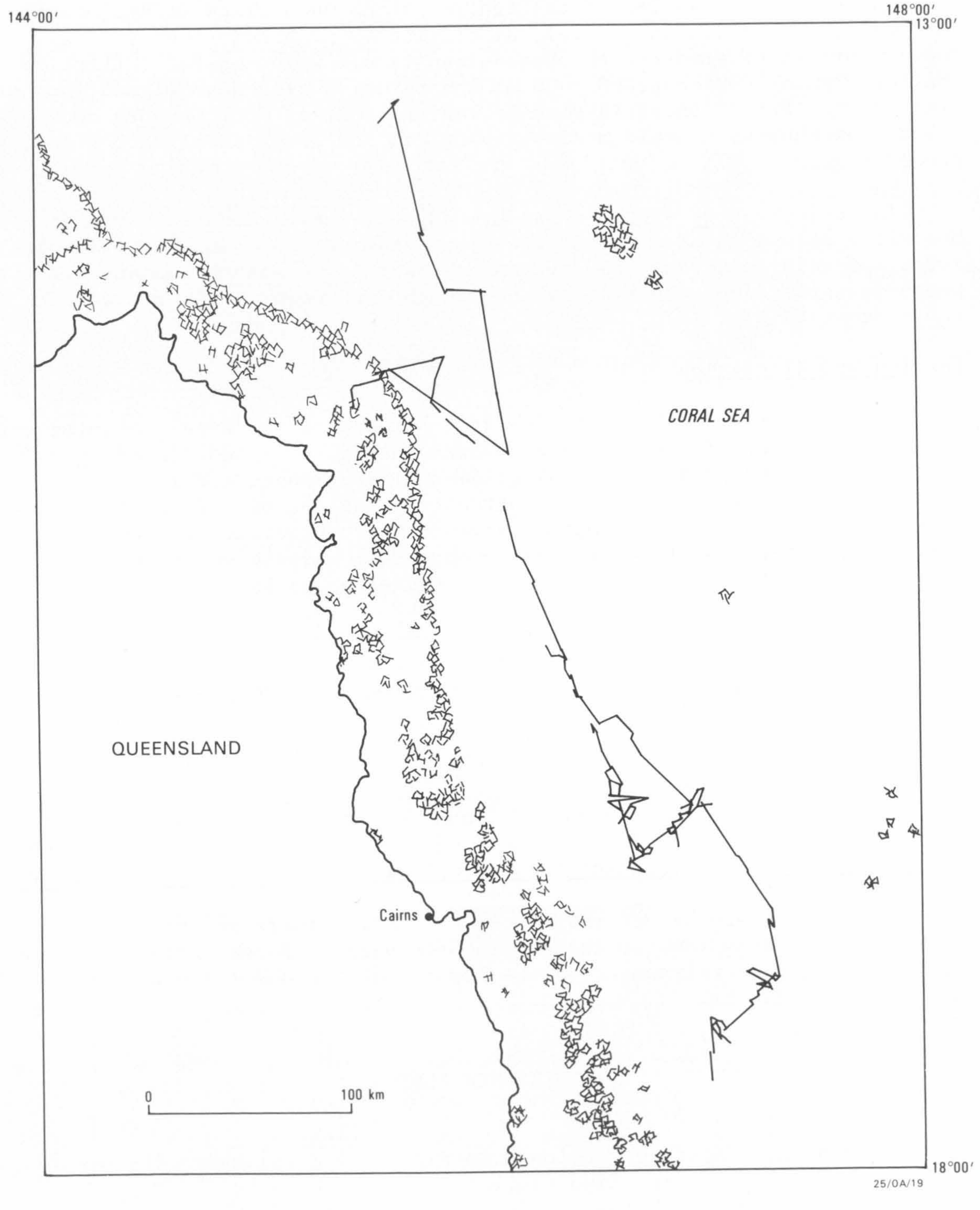

Figure 17. Survey 53 tracks in the western Coral Sea and Queensland Trough.

pebbles that have abundant shallow marine fauna and flora as well as abundant peat, and show a change from reducing to oxidising environments.

Aims of heat-flow study

Because of the cruise time constraints (7-8 days for operations) and our inability to carry out multiple entry with the heat-flow probe, it was decided to focus the Coral Sea leg of the cruise on the Queensland Trough, rather than the western Coral Sea in general, as originally proposed (Choi & Stagg, 1985). The advantages of studying the Queensland Trough were two-fold: firstly, the shallower water depths (1000-3000 m) and relative closeness of stations saved time and, secondly, there is good geological control from onshore and on the shelf, together with ample marine geological and geophysical data from the trough itself.

The selection of stations was aimed at clarifying the variation of heat-flow across major structural elements such as basement highs and fault zones, as well as across the sedimentary basins. A major transect was run south-to-north along the axis of the trough, and several minor transects were run east-west (Fig. 17).

Results and discussion

The locations of the heat-flow stations and coring sites occupied during the Coral Sea leg of the cruise are shown in Figure 17 and listed in Appendix 3. Twenty-three thermal-gradient measurements and 2 thermistor-calibration tests were attempted. Of the heat-flow stations, 15 gave good gradient measurements, 5 gave dubious measurements, 2 were unsuccessful because of inadequate penetration, and one was unsuccessful because of electronics problems in the underwater package.

Thermal gradients ranged from 37 to 107°C/km, with the average being 70°C/km. Thermal conductivity showed a good concentration in the range from 0.78 to 0.97 W/m/K. The heat-flow values calculated ranged from 33 to 86 mW/m^2, and averaged 60 mW/m^2.

In general, heat-flow values in the Queensland Trough are close to world average (Jessop & others, 1976). In the trough the preliminary average is 58 mW/m^2; extremes are 35 to 80 mW/m^2 and compatible with the earlier data of Langseth & Taylor (1967) in the same area. As expected, the new data show that there is a general correlation between basement structures and heat-flow values: where the basement is shallow and has thin sedimentary cover, the heat-flow values are higher than those areas with thick sediments. That is, heat-flow decreases towards the centre of a basin. A more detailed correlation must await further refinement of the structural map and the basic heat-flow data.

EXMOUTH PLATEAU

The regional geological setting of the Exmouth Plateau is shown in Figure 18; and the existing heat-flow stations, in Figure 21. Following the definition of Exon & Willcox (1980), the Exmouth Plateau is taken to be the region between the 800 m and 2000 m isobaths, giving it an area of 150 000 km^2, and making it Australia's second largest marginal plateau. The plateau is bound by the Argo

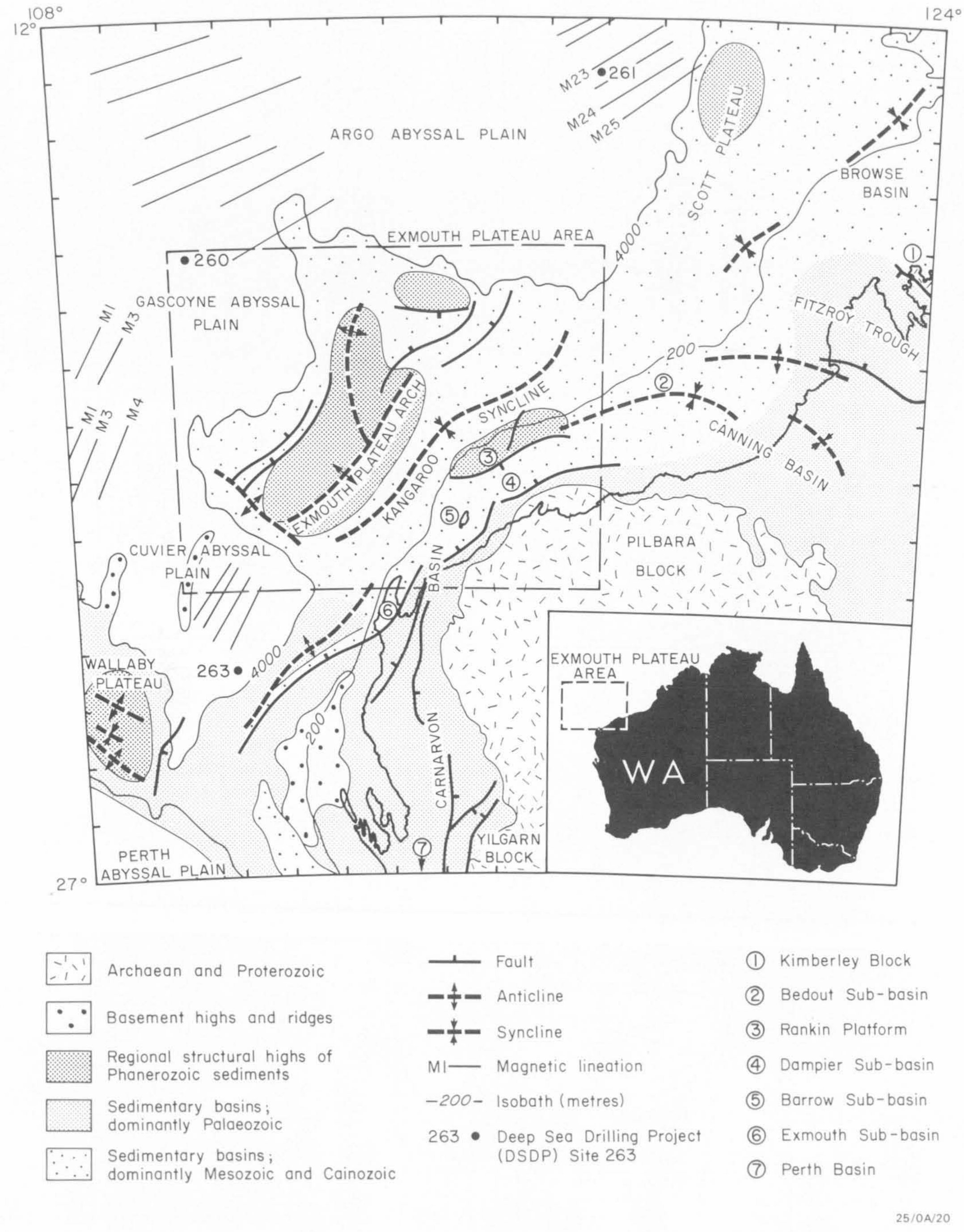

Figure 18. Regional geological setting of the Exmouth Plateau (after Exon & Willcox, 1978).

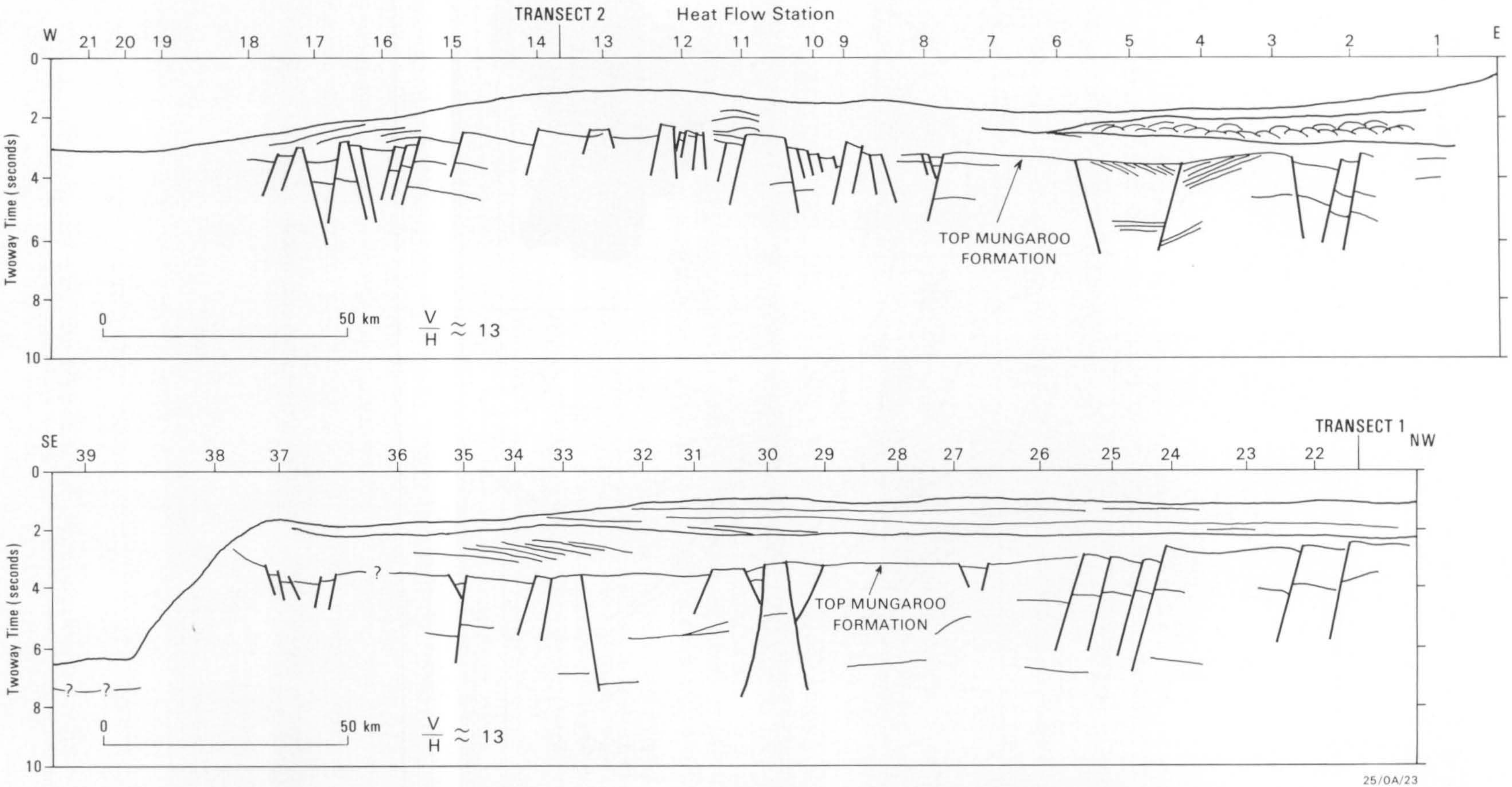

Figure 19. Line drawings of seismic sections along the two transects southeast-northwest and northeast-southwest across the Exmouth Plateau during survey 53. Locations of stations occupied during Survey 53 and of Jupiter No. 1, Mercury No. 1, and Saturn No. 1 exploration wells are shown.

Abyssal Plain in the north, the Montebello Trough in the southeast, the Cuvier Abyssal Plain in the southwest, and the Gascoyne Abyssal Plain in the northwest. The essential geology of the plateau consists of a Precambrian basement overlain by faulted and gently folded Permian to Cretaceous clastic and detrital sediments with a thin cover of Tertiary carbonates. The sedimentary column contains classical pre-rift, rift, and post-rift sequences, complicated by the two separate episodes of breakup along the margins.

Structural history

The structure and sediment distribution of the Exmouth Plateau is now well documented. The geological development of the plateau has been discussed in varying detail by Exon & others (1975, 1982), Exon & Willcox (1978, 1980), Falvey (1972b), Falvey & Veevers (1974), Falvey & Mutter (1981), von Stackelberg & others (1980), Larson & others (1979), Veevers & others (1974), Veevers & Cotterill (1978), Hogan & Jacobsen (1975), Powell (1976), Willcox & Exon (1976), Willcox (1981), Wright & Wheatley (1979), and Barber (1982).

The basic structure of what became the Exmouth Plateau was initiated by rifting during the Triassic and Jurassic, prior to separate seafloor spreading episodes in the Argo Abyssal Plain and the Gascoyne and Cuvier Abyssal Plains. The plateau did not subside substantially below sea level until well after the seafloor spreading had begun in the adjacent oceans (Falvey and Mutter, 1981). The northwestern margin has a normal rifted structure, and the southwestern margin is transform-faulted along the Cape Range Fracture Zone. The northern margin contains rifted and sheared segments, and may also contain at least one volcanic epilith (Platypus Spur; Veevers & Cotterill, 1978).

The earliest phase of continental margin formation was along the northern margin in the Callovian (~155 Ma), when seafloor spreading started in the Argo Abyssal Plain at about anomaly M-25 time. The northwest direction of spreading was initially recognised by Falvey (1972a); basin age was established by the Deep Sea Drilling Project Site 261 (Veevers, Heirtzler, & others, 1974), and spreading anomalies were identified by Larson (1975), and confirmed by Heirtzler & others (1978). An early phase of rifting on the northern margin of what is now the northern flank of the Wombat Plateau gave rise to Triassic-Jurassic trachytic and rhyolitic lavas (213-192 Ma), which overlie a thick Triassic paralic sequence. Steady subsidence north of an east-west hinge line allowed the accumulation of several thousand metres of Lower and Middle Jurassic carbonates and coal measures prior to breakup. During this period, the central part of the plateau was subjected to intermittent erosion. Breakup along the northern margin in the Callovian finally occurred along a series of rift and transform segments, with the geometry of the plateau being further complicated by northeast-trending Callovian horsts and grabens. Sedimentation during this time kept up with the slow rate of subsidence (about 20 m/Ma). The horsts were eroded during the Late Jurassic and Early Cretaceous, and the whole margin was then covered by a thin blanket of Upper Cretaceous and Tertiary pelagic carbonates as it began to subside rapidly to its present average depth of 2000-2500 m.

The northwestern margin formed during the Neocomian as 'Greater India' retreated to the northwest, causing a radical drop in sediment supply to the nascent Exmouth Plateau. At approximately 120 Ma in the Early Cretaceous, seafloor spreading started in the Cuvier and Perth Basins to the south of the plateau (anomaly M-3 to M-10; Markl, 1974; Larson, 1977; Larson & others, 1979). Normal faults parallel this margin of the plateau.

Magnetic anomalies in the Cuvier and Gascoyne Abyssal Plains suggest that the southwest margin formed by shearing in the Neocomian at the same time as the northwest margin. The margin is cut by northeast-trending Late Triassic to Callovian normal faults, and is parallelled by Neocomian and younger normal faults. Thermal uplift of more than 1000 m is interpreted to have taken place during the Neocomian shearing, and igneous intrusions subsequently buttressed the margin. Later, normal faulting caused the outer margin to subside, changing the uplift to a marginal northwest-trending anticline. This anticline had sunk below sea level by late in the Cretaceous, and, subsequently, a thin sequence of pelagic carbonates covered the margin which now lies at water depths of more than 1500 m (Exon & others, 1982).

Von Stackelberg & others (1980) have reported the results of dredging from the outer slopes of the plateau. The predominant sediments were deposited in shallow water during the Triassic and Jurassic, prior to breakup. Four dredges also contained intermediate to acid volcanics dated at about the time of rift onset, suggesting limited continental crustal anatexis very near to the incipient locus of breakup.

Stratigraphy

Stratigraphic studies based on dredging samples have been carried out by von Stackelberg & others (1980), Colwell & von Stackelberg (1981), and von Rad & Exon (1983). Seismic control was based on 12000 km of BMR seismic reflection, gravity, and magnetic data from the Continental Margin Survey, 9300 km of high-quality seismic data collected by GSI in 1976-77 (Wright & Wheatley, 1979), and subsequent petroleum industry seismic data. These studies showed the Exmouth Plateau to be relatively sediment-starved after the breakup of Western Australia-Antarctica and India. Consequently, seismic profiling, drilling, and dredging have been able to penetrate very old parts of the sedimentary column and hence resolve early stages of margin evolution (von Rad & Exon, 1982). Fourteen petroleum exploration wells have been drilled: although the basic data are all available, only the interpreted results of the Phillips Group wells Jupiter No. 1, Saturn No. 1, and Mercury No. 1 have been published (Barber, 1982).

Interpretation of the seismic and other geophysical data indicates that basement is overlain by up to 10 000 m of Palaeozoic to Cainozoic strata, of which about half has been deposited since the Late Palaeozoic. The sediments have been gently folded, and generally northeast-trending fault blocks affect the pre-Upper Jurassic section.

The Late Triassic to Middle Jurassic sediments beneath the Exmouth Plateau are considered to have been deposited in a part of the Carnarvon Basin that formed a north-facing embayment in Gondwanaland, receiving detrital sediment until the Early Cretaceous (Exon & Willcox, 1978). At least 3000 m of predominantly paralic and shallow-marine detrital sediment (Mungaroo Formation and its equivalents) was deposited between the first onset of rifting, in the Permian, and the Middle Jurassic, at which time the first margin breakup occurred in the north. Subsequent to this first phase of breakup, about 1000 m of shallow-marine and deltaic detrital sediment, derived from the south and east, covered the block-faulted surface during the Late Jurassic and Early Cretaceous. About 200 m of marine terrigenous sediment was deposited in the

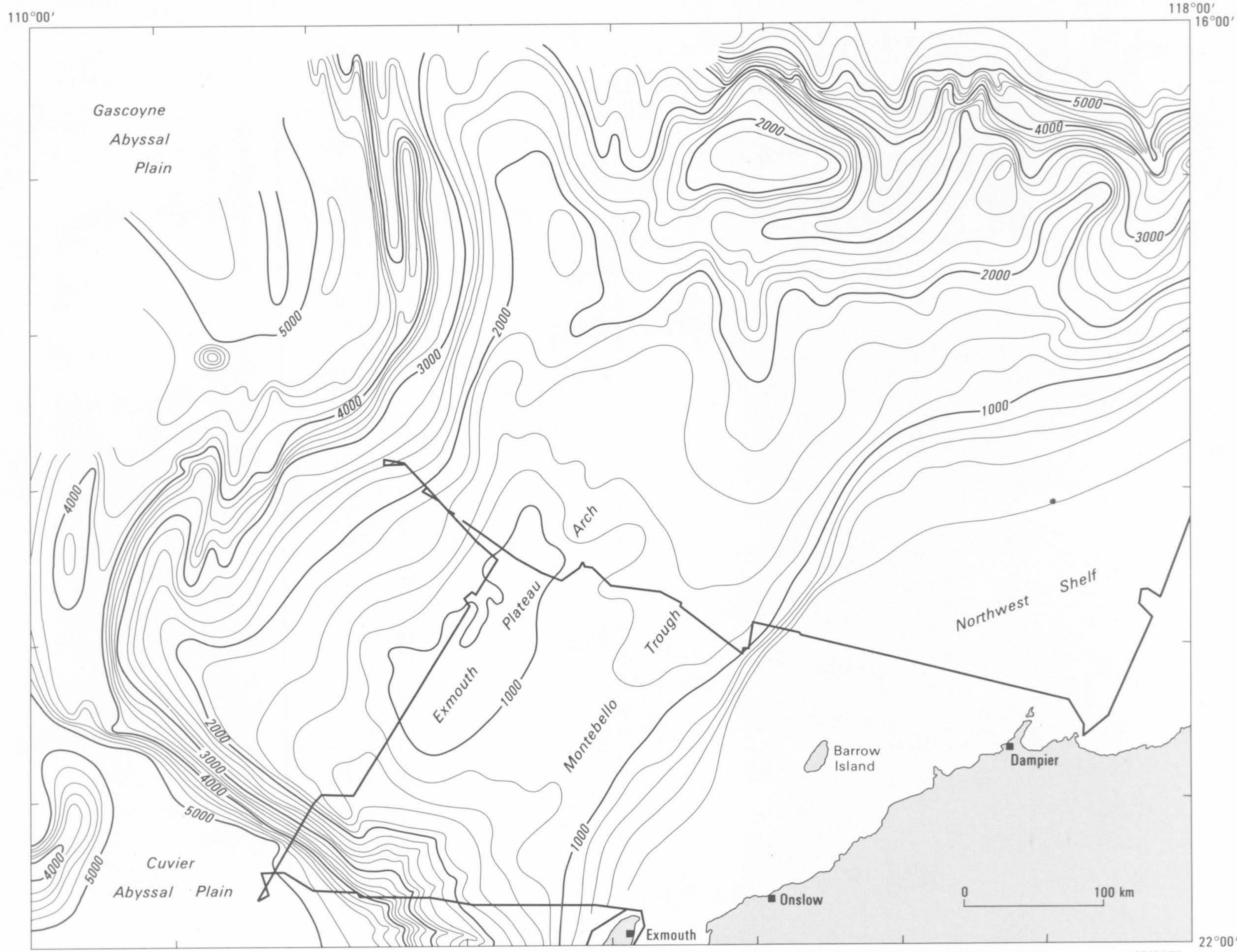

Figure 20. Tracks of Survey 53 on the Exmouth Plateau.

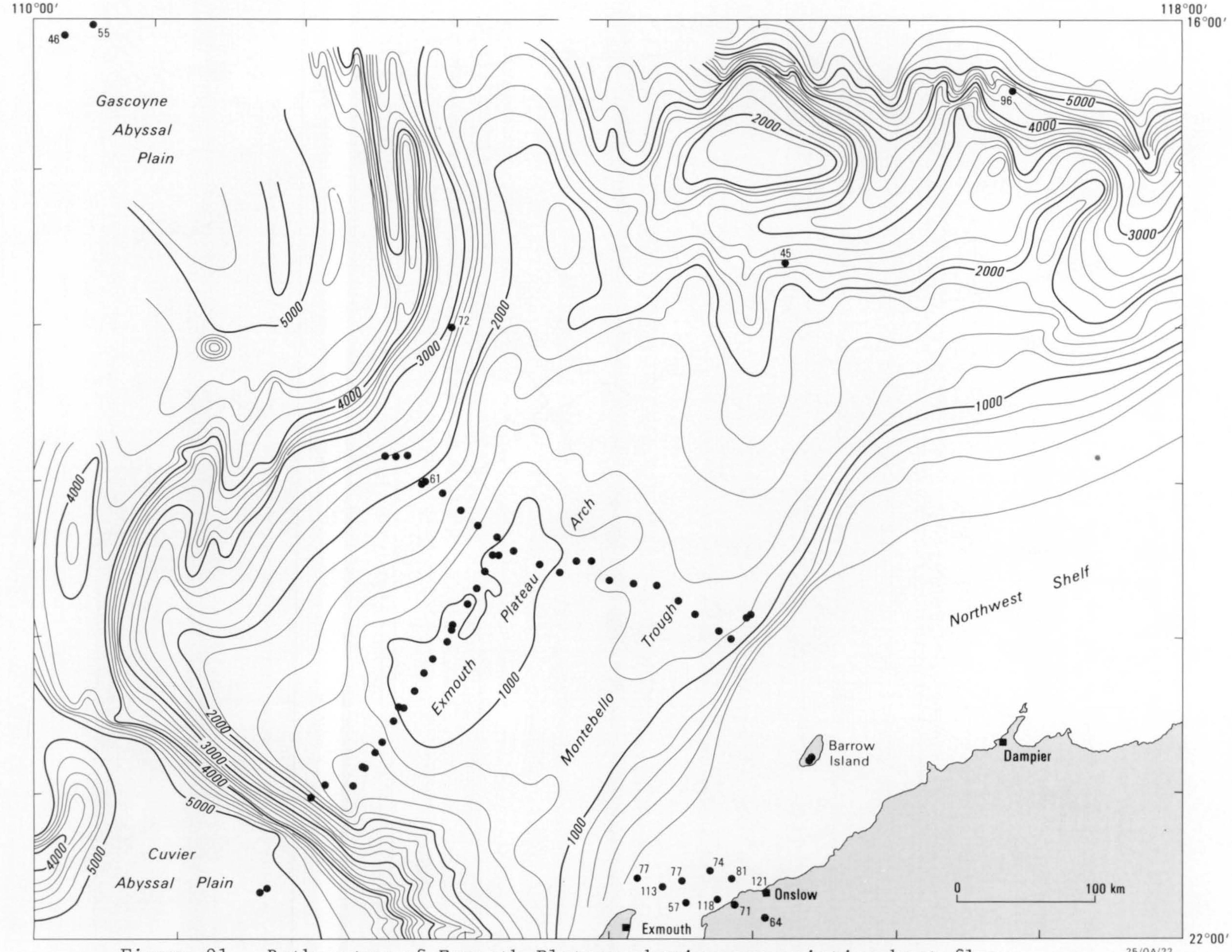

Figure 21. Bathymetry of Exmouth Plateau showing pre-existing heat-flow values and locations of stations occupied on Survey 53. Survey 53 station locations and associated details are contained in Appendices 3 and 4.

mid-Cretaceous, and 500-1000 m of carbonate sediment was deposited in the Late Cretaceous and Cainozoic. Since the Miocene, the rate of subsidence has exceeded the rate of sedimentation, and the Exmouth Plateau arch and Montebello Trough have taken their present form (Exon & Willcox, 1978, 1980).

Hydrocarbon prospectivity

The gross plateau structure consists of a major northeast-trending arch (the Exmouth Plateau arch) and a flanking northeast-trending syncline (the Kangaroo Syncline underlying the Montebello Trough). Willcox (1981) contended that the arch formed as early as the Late Cretaceous and so may have been available as a trap for hydrocarbon from that time onwards. The structure has a present-day closure of 300 m and a minimum areal closure of 7000 kmy. The most likely targets are draped fault blocks, usually sealed by Middle Cretaceous shales. Willcox (1981) pointed to another target being the thick Upper Jurassic-Lower Cretaceous delta under the southwest plateau as a possible source and reservoir. Wright & Wheatly (1979), on the basis of the regional GSI grid over the plateau, also pointed to the Triassic fault blocks as targets.

Despite water deeper than 800 m, the proximity of major hydrocarbon reserves on the adjacent Northwest Shelf and at Barrow Island gave rise to considerable optimism for the potential of the Exmouth Plateau. The main source of gas on the Rankin Platform is believed to be Upper Jurassic shales with a Triassic sandstone reservoir, with oil coming from Jurassic or Cretaceous shale (Thomas & Smith, 1974). The Barrow Sub-basin gas is produced from sources in Middle to Upper Jurassic shales, and oil seems to have been generated almost *in situ* within the Middle Cretaceous sequence (Powell & McKirdy, 1973).

Exploration permits covering the plateau were issued in 1977, and 14 exploration wells were subsequently drilled, including Jupiter No. 1, Saturn No. 1, and Mercury No. 1. Non-commercial gas shows were encountered in these three wells, as well as the Scarborough gas discovery, which has been retained by Esso. However, no heavier hydrocarbons were discovered. The average geothermal gradient on the Rankin Platform is 35°C/km, data from the Jupiter and Mercury wells indicate geothermal gradients on the Exmouth Plateau arch of about 23°C/km, and Saturn gave a gradient of 34°C/km for the Kangaroo Syncline (Barber, 1982).

The lack of liquid hydrocarbons is attributed to unfavourable source rocks, an inadequate burial history, and a historically low geothermal gradient. The low geothermal gradient means that the peak hydrocarbon generation today occurs in the mid-Triassic at a depth of 4 - 5 km below sea level. Gas from Jupiter No. 1 well was tested and found to be thermally over-mature. Despite drilling to almost 5000 m, Jupiter No. 1 did not penetrate the hydrocarbon generation window (Barber, 1982).

Cook & others (1985) have again examined the Upper Triassic Mungaroo Formation, previously assessed as a probable gaseous hydrocarbon generator, and have suggested that recent work elsewhere does not preclude the unit from producing liquid hydrocarbons. If correct, then this study considerably upgrades the hydrocarbon potential of the plateau from its current rather pessimistic level.

Aims of heat-flow study

The Exmouth Plateau is Australia's best-studied marginal plateau and has the most comprehensive data set - both seismic and drilling - for an Australian deep-water area. It is generally acknowledged as being an excellent choice for studying mechanisms of passive margin formation. The initial stages of passive margin rifting are thought to be due to thermal uplift, and yet few of the current models appear with accompanying thermal gradient or heat-flow profiles.

The two Exmouth Plateau heat-flow transects proposed by Choi & Stagg (1985) for this cruise were, respectively, perpendicular and parallel to the gross geological strike. Figure 19 shows the generalised structure along each transect. It is anticipated that the relatively simple horst and graben structure, with basement almost uniformly at great depth, should enable the data from the first heat-flow profile to be modelled to provide palaeoheat-flow. Being along strike, the second profile should show less variation in heatflow. Of particular interest on the second transect is the southwest sheared margin along which Exon & others (1982) postulated 1000 m of Neocomian uplift. The models proposed for this uplift include thermal uplift due to frictional heating along the shear zone, upwelling of hot asthenosphere along the shear zone, or heating caused by the passing of an oceanic spreading centre. Heat-flow data across this margin should enable these models to be tested.

Despite the disappointments of the first phase of Exmouth Plateau exploration and drilling, the plateau remains among the more prospective of Australia's deep-water areas. However, to date, a single heat-flow station and a handful of thermal-gradient measurements from exploration wells are our sum total of knowledge of the heat-flow field under the plateau, and knowledge of hydrocarbon generation depths remains speculative. The current study should throw some light on the subject of hydrocarbon generation under the plateau and perhaps suggest some new avenues of exploration.

The final aim of this part of the study is somewhat less eye-catching. Most heat-flow values taken to date have been on an erratic basis, usually as an adjunct to other studies. As heat-flow is known to vary with such factors as depth to basement, it is reasonable to assume that the 'spot' values taken in the past contain both regional and local components. If the local component (or anomaly) is a significant part of the total value, then, given the widely spaced samples, any interpretation of the existing data set must be at best hazardous. The data spacing along the Exmouth Plateau profiles (8-20 km) should enable us to clarify the variation of heat-flow across structures of limited extent.

Results and discussion

Thermal conductivity. A total of 11 gravity and 2 piston cores were deployed over the Exmouth Plateau and in the Cuvier Abyssal Plain (Figs. 19, 21; Appendices 3, 4): of these, only the piston core in the Cuvier Abyssal Plain failed. The successful cores had an average recovery of 4.03 m. Thermal conductivity was measured at 0.2-0.3 m intervals along each core (Fig. 2a).

Within the range of experimental error, thermal conductivity was reasonably constant over the Exmouth Plateau, averaging 0.85 W/m/K. This figure is 15% less than the value of 1.0 W/m/K obtained by Langseth & Taylor (1967) for the Exmouth Plateau; however, Langseth's figure was based on consideration of the environment type rather than actual measurements. The constancy of the measurements is a useful guide for future heat-flow work on the Exmouth Plateau - there will be no requirement to take as many cores as were taken on Cruise 53. Prior to the cruise, we had expected that piston cores would be essential to obtain reliable thermal conductivity data from an undisturbed section. It is worth noting that, at least on the Exmouth Plateau, gravity cores are just as acceptable for thermal conductivity.

Thermal gradients. Thirty-nine heat-flow probe stations were occupied on the Exmouth Plateau (Figs 19, 21, Appendices 3, 4). Three deployments failed due to total lack of probe penetration. A further 8 gradients are dubious. For the 28 successful stations, where at least 3 thermistors are known to have penetrated sediment, gradients are mostly linear and in the range 24-229°C/km.

The 8 stations designated as dubious appear to have suffered from a variety of ailments. Most of these are a result of only 2 thermistors penetrating sediment. An additional gradient was remarkably high (>200°C/km), while a further 2 gave large *negative* gradients; these last 3 gradients are not yet explicable.

Heat-flow. The average of the preliminary heat-flow values is 60 mW/m^2, while the extremes are 20 to 120 mW/m^2. If the average figure is correct, then the Exmouth Plateau is a region of average heat-flow.

The southeast-northwest dip line appears to be more consistent than the northeast-southwest strike line, although a direct relation between structure and variation in heat-flow is not readily apparent.

Three stations were at the sites of Jupiter, Mercury, and Saturn wells. Our gradients recorded there are up to three times those recorded to total depth in the wells. This is consistent with the figures given by Clark (1966) for the conductivity of sandstone and limestone at 50°C, which show the thermal conductivity of consolidated sediments to be around 3-4 times that which we obtained for unconsolidated sediment. The site of the only previous heat-flow station on the Exmouth Plateau was also tested. A 20% discrepancy in heatflow was observed: the reason for this is not yet clear.

SIDE-SCAN SONAR INVESTIGATIONS

Torres Strait

Side-scan sonar data were also acquired as part of this cruise. The purpose was twofold: to complete a scientific study commenced on the previous cruise; and to experiment with the acquisition of side-scan sonar data at transit speeds on the continental shelf.

The subaerial erosion and subsequent deposition of shelf-derived sediments onto submarine fans during periods of low sea level has been proposed for an area characterised by shelf-edge reefs along the northeast Australian margin (Symonds & others, 1983). The shelf area adjacent to Torres Strait is unique along this margin for several reasons. Firstly, the shelf-edge (barrier) reefs occur here as a continuous chain, broken only in a few places to form passages that channel shelf-derived sediments onto the submarine fans. Secondly, the area is influenced by the enormous sediment and freshwater input of the Fly River, which empties into the Gulf of Papua. Finally, the tidal currents of Torres Strait are of a magnitude far greater than those found in Great Barrier Reef waters to the south, and are known to act as an effective sediment dispersal mechanism on the Torres Shelf.

Although there is considerable evidence to suggest that sediment is transported west from Torres Strait, few data exist to confirm or disprove that eastward transport from the Strait has occurred. Such eastward transport of sediment would facilitate the growth of submarine fans adjacent to reef passes (Symonds & others, 1983) by forming deposits on the landward side of barrier reefs - which could then be eroded during low sea-level stands - or by directly transporting sediment through the reef passes onto the fan deposits. The object of this investigation was thus to examine the mechanisms of sediment dispersal presently active on the Torres Shelf and determine the extent of any easterly sediment transport.

Side-scan sonar data collected. A total of 400 km of side-scan sonar and high-resolution echo-sounder data was collected from Bramble Cay in the Great North East Channel to the Prince of Wales Channel west of Thursday Island (Fig. 22). The side-scan sonar data show the presence of sand waves and sand ribbons at locations between Sassie Island and Adolphus Channel, and confirm the location of sand waves in Adolphus Channel, as viewed in aerial photographs (see Figs. 23, 24, and 25).

Sand waves were observed along a 17.5 km length of track, in three groups separated by spaces of rocky seabed. From east to west the number in each group diminished from about 44 in the first to only 4 in the last. The sand waves are mostly asymmetrical in cross-section with their steeper faces oriented towards the west. A few in the first and second groups have their steeper sides facing east.

West of the sand wave field, the side-scan sonar data suggest that the sea bed is mostly scoured clear of surficial sediments. North of Adolphus Channel an area of sand ribbons (Fig. 22) testifies to the paucity of sand available for transport at this location. However, within Adolphus Channel, the presence of westward-oriented sand waves is confirmed by aerial photographs and the side-scan sonar data (Fig. 24).

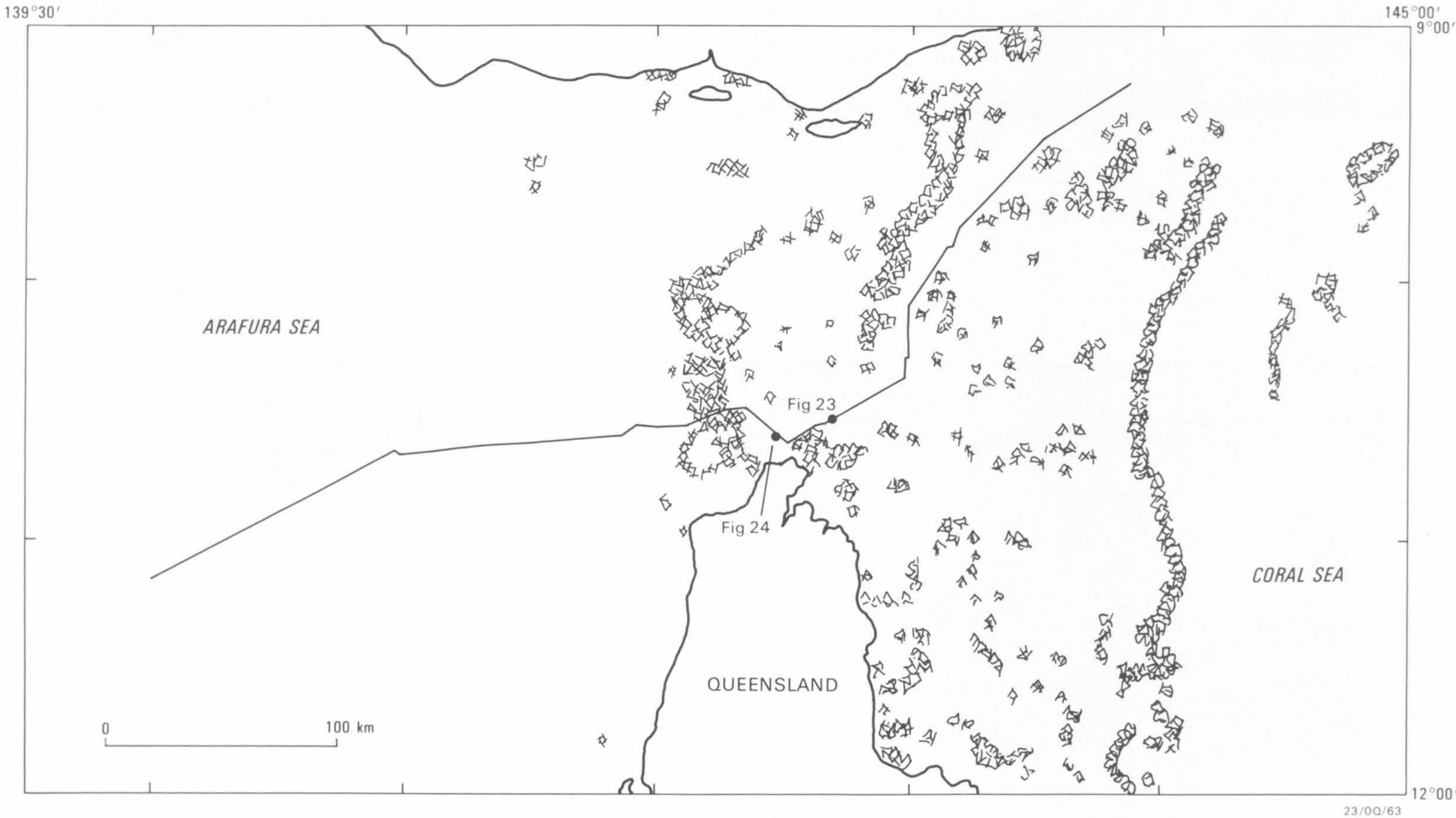

Figure 22. Location of side-scan sonar track line through Torres Strait. The segments of this line reproduced here as Figures 22, 23, and 24 are shown.

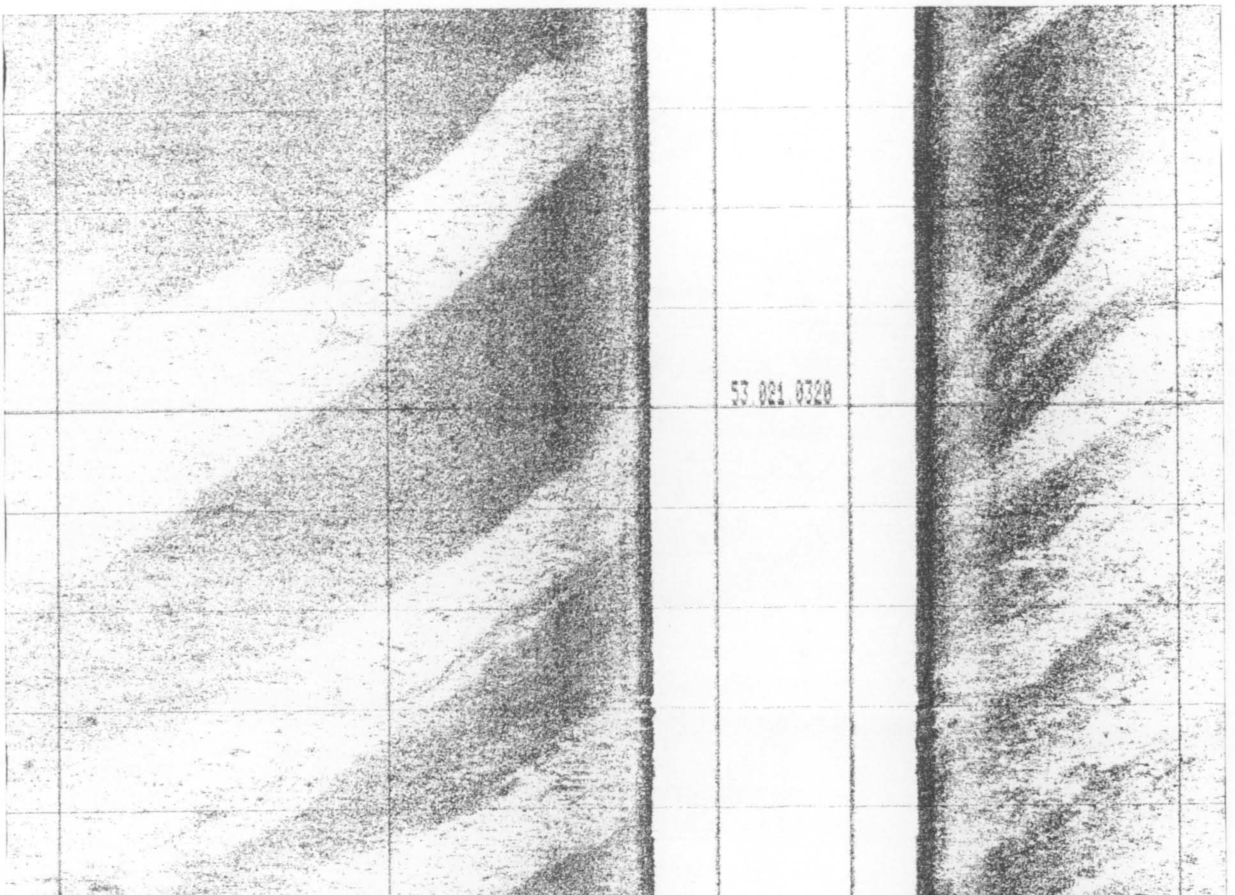

Figure 23. Side-scan sonar record, showing sand ribbons located to the north of Adolphus Channel. Sand ribbons are an indication of sediment deprivation from this area.

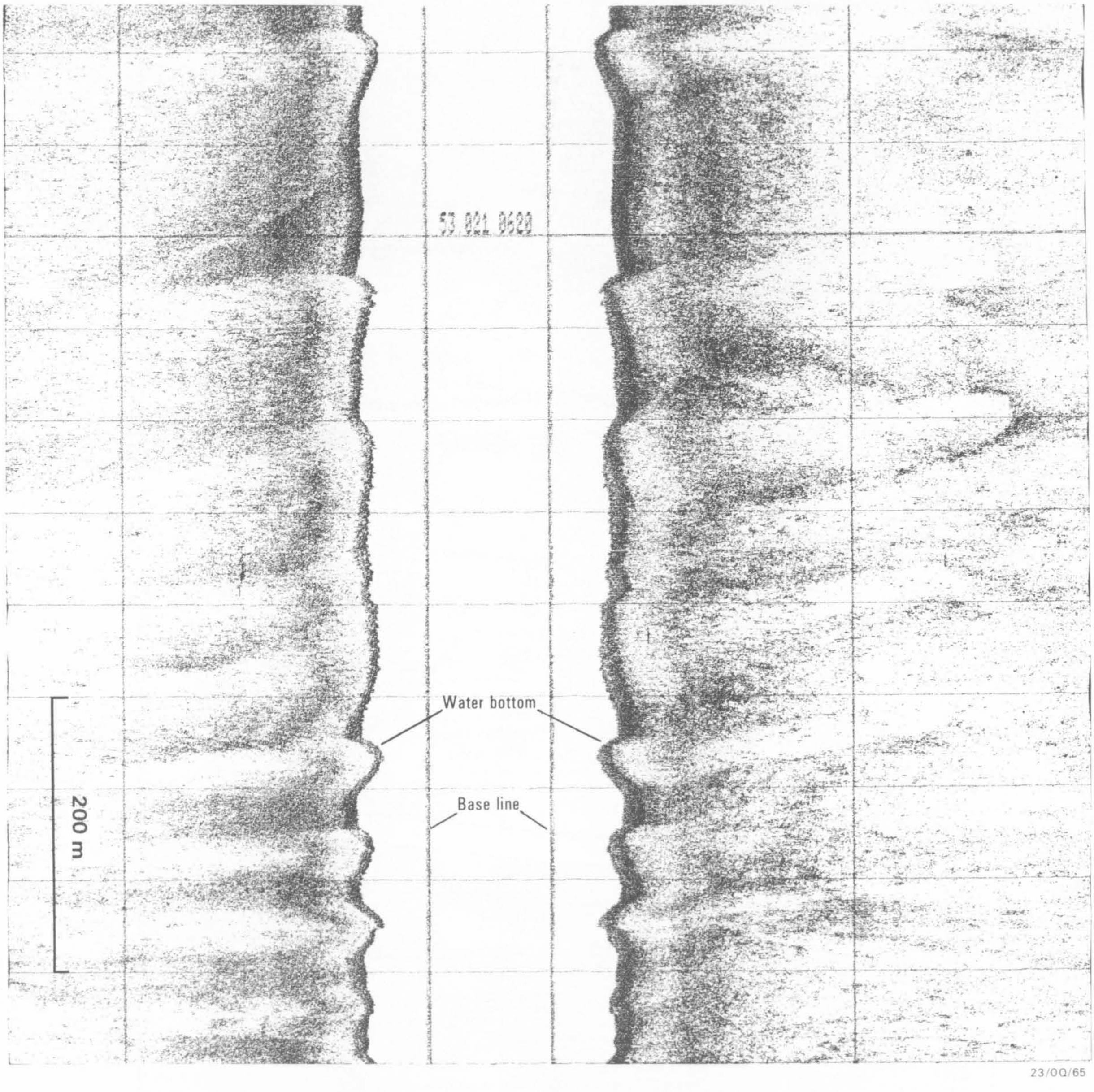

Figure 24. Side-scan sonar record, showing sand waves in the Adolphus Channel.

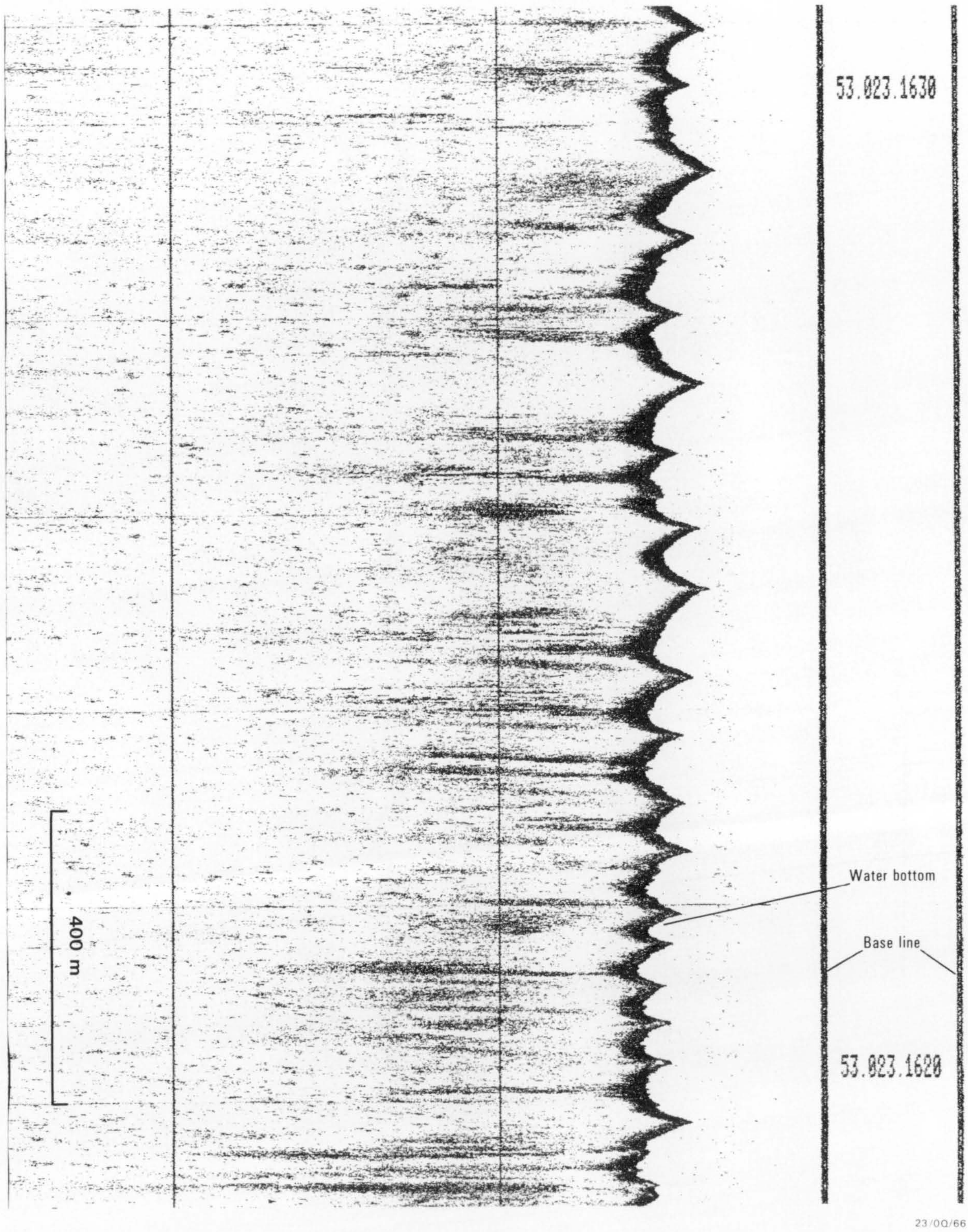

Figure 25. Side-scan sonar record, showing sand waves located in Dundas Strait (Van Diemen's Gulf). The low quality of the record was caused by the ship speed of about 10 knots.

In all other areas of Torres Strait and the Great North East Channel examined with side-scan sonar, bed forms are rare and most evidence is of scouring of the sea bed, with some localised evidence of erosion. Sand ribbons were observed in the western entrance to Prince of Wales Channel next to the shallow (<10m water depth) areas where sand waves are apparent on aerial photographs.

Conclusions and future investigations. Side-scan sonar data collected on the Torres Shelf have improved our present knowledge of this region's sedimentology by demonstrating:

(i) the effects of strong currents at the sea bed, as inferred from evidence of erosion; (ii) the presence of sand wave fields east of Torres Strait; and (iii) the correlation of a sea bed morphology sequence, indicative of decreasing rate of transport in a general east to west direction from Torres Strait, with models derived from other areas (Belderson & Stride, 1966).

It is intended that the side-scan data collected during Survey 53 be combined with other data available from the Torres Strait to generate a model for sediment dispersal mechanisms in the area. Other data available include surficial sediment samples, current-meter data, and aerial photographs.

Gulf of Carpentaria and Van Diemen's Gulf

On the transit from the Coral Sea to the Exmouth Plateau, an assessment was made of the feasibility of recording side-scan sonar data at transit speeds. The existing side-scan sonar data set is so restricted over much of the continental shelf that considerable time can be wasted in searching for suitable study areas. If such areas can be delimited (even by mediocre quality data) while *Rig Seismic* is on transit, then considerable ship time can be saved in future work.

A total of 530 km of data was recorded in moderate seas at speeds of 7.5-8.5 kn in the Gulf of Carpentaria and Arafura Sea and 180 km of data was recorded in low seas at speeds of 9.5-10.5 kn in Dundas Strait and Van Diemen's Gulf. Figure 25 is an example of the Van Diemen's Gulf data, and it can be seen that useful information can be acquired, even if data quality is low. We suggest that purchase of an inexpensive tow-fish for transit work on the shelf is well worth considering.

PERFORMANCE OF OTHER SYSTEMS

Although the principal cruise objectives were oriented to the acquisition of heat-flow data, the non-seismic data acquisition system (DAS) was operational at all times to provide navigation and bathymetric control and to record other geophysical data while on transit. For completeness, we will briefly summarise here the performance of that equipment.

Navigation

Navigation was provided by a plethora of systems (Appendix 6). The prime system was a Magnavox 1107 dual-channel Transit satellite navigation system with heading and velocity inputs from an Arma-Brown gyro-compass and a Magnavox 610D dual-axis sonar doppler. The backup system comprised a Magnavox 1142 satellite navigator with Robertson gyro-compass and Raytheon DSN-450 dual-axis sonar doppler. In addition to the satellite fixes and dead-reckoned (DR) data being recorded from each satnav, the DAS also records independently the course and velocity from all available gyros and speed logs.

A third, and independent, navigation system was also available for this cruise - a Magnavox T-set Global Positioning System (GPS). While GPS has the best potential of the non-radio-navigation positioning systems for good quality on-board position fixing, it is unfortunately still only partially operational. Coverage with three or more satellites was available for about 9 hours per day, while coverage with two satellites only was available for a further 4 hours. Unfortunately, the 2-satellite coverage was frequently degraded by the poor geometry of the satellites concerned.

Over-all, the navigation systems performed better than they have on previous surveys. In particular, both sonar dopplers appeared to work reasonably well much of the time when working on water track mode in deep water.

Magnetics & gravity

The Geometrics magnetometer was towed on all long transits when water depths were greater than 40 m. No major acquisition problems were encountered. Although the data will be of little value in isolation, they will provide useful ties for older surveys.

The Bodenseewerk KSS-31 gravity meter operated for the entire cruise. Gravity ties were made both at Townsville before the cruise and at Perth after the cruise. The gravity meter performed well except for a period of about 12 hours early in the cruise when it caged automatically on several occasions, probably owing to fluctuations in the 240V power supply.

Bathymetry

Both the 3.5 and 12 KHz echo-sounders performed adequately in the water depths encountered. However, neither system works as well as it should, and installation and electronics testing continued at appropriate times during the cruise.

Data acquisition system (DAS)

Continuing refinement of the DAS has led to considerable improvement in its usability and reliability. In particular, in the event of a software 'crash', it is now possible to have the DAS up and running again within the space of about 3-4 minutes.

CONCLUSIONS AND RECOMMENDATIONS

Heat-flow equipment & techniques

Perhaps more than any other marine geophysical technique, heat-flow measurements, because of the very small magnitude of the numbers involved, are potentially at the mercy of major unknown factors - particularly the effects of circulation near the sea bed and within the sediments. To obtain meaningful results, meticulous care must be taken in monitoring the thermistor performance and in keeping a constant check on thermistor calibration. Again, because of the unknown variables acting to modify the shallow-sediment temperature gradient, it is important that as many measurements as possible be taken to obtain a good estimate. If we are to successfully employ multiple re-entry with the heat-flow probe, then it may be that the most valuable application of the technique will be to take multiple readings in the one location, rather than a single reading before moving on to the next station.

From this cruise, it appears that the measurement of thermal conductivity will not be as susceptible to error as was first thought. Both in the Coral Sea and particularly on the Exmouth Plateau, thermal conductivity is quite consistent over large areas. While the hardware used for the conductivity measurements performed well, much of it is old and potentially unreliable in the marine environment. This equipment should be phased out in favour of equipment specifically purchased or built for the task.

While we now have a sound capability for measuring heat flow in deep water, a number of improvements to the system have been proposed that should make this capability more powerful. Two are the *in situ* measurement of thermal conductivity and the acoustic telemetry of raw data back to the ship while the probe is in the water. Both will speed up operations considerably as well as improving data quality. Other improvements (such as increasing the sample rate and interfacing the playback computer with the navigation DAS) are primarily software-related and will provide both a more flexible system and one which will allow more rigorous analysing of the results.

We propose that the first phase of future equipment development should be the acquisition of a second heat-flow probe, incorporating part or all of the features just outlined. Particular attention should be given to the design of a new lance, which should be either more rugged to resist bending or flexible enough to be immune to bending. Long term heat-flow data monitoring in shallow waters (several hundred to one thousand metres) would enable a better understanding of the effects of diurnal and annual temperature components on the heat-flow field. Such measurements are particularly important to some of the strategic areas of the northern and southern margins of Australia. We propose that consideration should be given to the development and construction of such a system, capable of measuring heat-flow data either once per day for twelve months, or once per hour for one month. Acoustic release or similar means would have to be used for the equipment recovery. Finally, it is desirable to acquire or develop a portable self-contained conductivity measuring set for both the laboratory and ship-board conductivity measurement.

<u>Coral Sea and Exmouth Plateau</u>

For both the Coral Sea and the Exmouth Plateau, it must be emphasised that the data require considerably more detailed examination before we can go beyond the generalisations outlined in the respective discussions. A number of stations that appeared initially on-board to have been failures later proved, after thermistor calibration, to have been at least partly successful. While the major improvements to the data have probably now been made, it is anticipated that there is still plenty of scope for further refinement. In particular, some of the more inexplicable stations on the Exmouth Plateau (the two negative gradients and the gradients in excess of 120°C/km) require close scrutiny.

From this cruise, it appears that the measurement of thermal conductivity will not be as open to error as was first thought. Both in the Coral Sea and particularly on the Exmouth Plateau, thermal conductivities were quite consistent over large areas.

It is most illuminating to compare the overall results of the two parts of the cruise. While the two areas are geologically very dissimilar, as well as being of greatly different ages, it is noteworthy that the average heat flow in each area is almost the same. The major difference between the two areas is in the range of values. It is perhaps surprising that the geologically older Exmouth Plateau shows a much higher variation in heat-flow than does the Queensland Trough. However, this may only be a function of the fact that the main Exmouth Plateau transect was perpendicular to the gross geological strike, whereas the Queensland Trough work was in a more restricted locality. The similarity of the average values in both areas suggests that for passive continental margins it is the *variation* in heat-flow that contains the important geological information, rather than the absolute values.

In both the Coral Sea and on the Exmouth Plateau much work remains to be done. In the Coral Sea, we were restricted to working only in the Queensland Trough by the early slow pace of operations. The pre-cruise proposal (Choi & Stagg, 1985) recommended a number of stations in the Osprey Embayment and on the Eastern Plateau; this recommendation still stands. On the Exmouth Plateau, the originally proposed program was cut by one-third because of the loss of time to other factors. There was insufficient time to extend the southeast-northwest transect into deep water, and the sheared southwest margin was inadequately covered after several heat-flow probes in that area failed. We believe there are three priorities for further work on the Exmouth Plateau. Firstly, a second southeast-northwest transect, parallel to the first and perhaps 40 km to the southwest, needs to be completed to confirm the validity or otherwise of our observations on this cruise. Secondly, another effort should be mounted to obtain data over the southwest margin, where the heat-flow is predicted to be higher than normal. Thirdly, the northeast half of the plateau is totally devoid of heat-flow data; this should be rectified with a transect either from the Montebello Trough or from the Exmouth Plateau Arch.

Because of the chronic difficulties encountered with the heat-flow probe bending, we generally used the 2 m probe on the Exmouth Plateau. However, core logging revealed that the top few metres of each core were always water-saturated, owing to the porous nature of the sediment. This is likely to expose the sediment to seasonal water temperature variations. It would be far more desirable to measure the thermal gradient on the Exmouth Plateau with a longer probe (at least 4 m) and this should be kept in mind when planning future cruises in this area.

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APPENDIX 1. Crew of R/V *Rig Seismic*

Ship Crew

Master	D. Harvey
Chief Officer	J. Alexander
2nd Officer	W. McKay
Chief Engineer	C. de Souza
2nd Engineer	S. Johnston
Electrical Officer	W. Hansen
ERA/AB	L. Clarke
Chief Steward	H. Dekker
Cook	G. Conley
Steward	J. Caminitti
2nd Steward	S. O'Rourke
AB	N. Luscombe
AB	P. Holdsworth
AB	B. Marsh

Scientific Crew

D.R. Choi	Geologist (Co-chief Investigator)
H.M.J. Stagg	Geophysicist (Co-chief Investigator)
T. Barton	Geophysicist
P. Crosthwaite	Geophysicist
P. Harris	Geologist (BMR Post-Doctoral Fellow)
C. Lawson	Technical Officer (Science)
Y.S.B. Liu	Engineer
L. Miller	Sen. Technical Officer (Electronics)
D. Simington	Technical Officer (Science)
J. Stratton	Technical Officer (Science)
M. Swift	Geophysicist
P. Walker	Technical Officer (Mechanical)

APPENDIX 2. Summaries of relevant cruise proposals

Heat-flow cruise (after Choi & Stagg, 1985)

In January 1986, the *Rig Seismic* must be re-positioned from Cairns following the second Coral Sea cruise to Fremantle in time for the first Exmouth Plateau cruise. The transit time of at least 10 days leaves no more than 18 days for scientific work, which is sufficient for a project of limited scope.

We propose here that the cruise be utilised exclusively for heat-flow measurements - a new field for Australian marine geoscience - in two priority areas of the Marine Division program. These areas are the western Coral Sea and the Exmouth Plateau (Figure 1), both of which have mature scientific or resource-oriented problems requiring solution.

In the western Coral Sea, the heat-flow study, together with all available geophysical and geological data, will focus on major deep-seated structures and crustal variations and their effect on the heat-flow field. Transects will be run from the northern end of the Queensland Trough through the Osprey Embayment to the Eastern Plateau, and east-west through the Osprey Embayment. On the Exmouth Plateau, the heat-flow study will be directed at obtaining a better understanding of the thermal/burial history of the plateau sediments, and hence giving an improved estimate of the hydrocarbon potential. Transects will be run from the Gascoyne Abyssal Plain southeastwards to the Phillips group exploration wells on the crest of the plateau and in the Kangaroo Syncline, thence southwestwards into the Cuvier Abyssal Plain.

Coral Sea cruise (after Davies & Symonds, 1985)

It is intended to utilise the R/V *Rig Seismic* off northeast Australia for two months from September-December 1985, beginning in Brisbane and ending in Townsville/Cairns. Cruise objectives are aimed at understanding the evolution and stratigraphic relations of the Townsville and Queensland Troughs, the western Queensland Plateau, the Osprey Embayment, The Torres Shelf, the Eastern Plateau, and the slope of the Great Barrier Reef. Objectives will be met by using several different methods of seismic profiling, and geological sampling techniques such as vibrocoring, piston and gravity coring, and dredging.

Exmouth Plateau cruise (after Williamson & others, 1985)

The Exmouth Plateau project is proposed for March-April, 1986. It will consist of a one month BMR leg and a one month cooperative BMR/Lamont-Doherty leg.

The BMR leg will address resource assessment and scientific problems. After a high level of hydrocarbon exploration on the plateau in the mid to late 1970s and the drilling of 14 wells, hydrocarbon exploration has virtually ceased on the plateau and only one permit, containing the Scarborough gas field is retained. The 3000 km of multichannel seismic data and geological samples from 12 dredge sites from the BMR leg will be augmented by 1500 km of multichannel seismic data from the combined BMR/Lamont leg. This will be assessed along with existing seismic and well data with the aim of establishing new hydrocarbon plays to encourage further exploration.

The BMR/Lamont cooperative leg will also address the nature of the continental and oceanic crustal interface. Data to be collected include 20 Expanded Spread Profiles (ESPs) in three transects to give deep crustal data. Suggested mechanisms of continental margin formation include lithospheric cooling, continental crustal stretching, deep crustal metamorphism, and supracrustal erosion. The resolution of the formation mechanism for the Exmouth Plateau margins may be possible from proposed and existing data sets and is of world-wide scientific importance.

APPENDIX 3. Station Summaries

The following summary of station locations and results is considered to be final. The position of each station is taken as the ship position at the time of bottom contact.

The following abbreviations have been used in the tables -

Station - HF - heat-flow
PC - piston core
GC - gravity core
DR - dredge

WD - water depth (metres)

K - thermal conductivity (W/m/K)
dT - thermal gradient (C/km)
N - number of thermistors that penetrated sediment
Q - heat-flow (mW/sq m)

CORING AND DREDGING STATIONS

Western Coral Sea

Station	Time	Lat	Long	WD	Result
53-CS-TEST1	010.2345	19 2.589	146 47.258	18	2.04 m recovery (GC)
53-CS-TEST2	011.0215	19 2.575	146 47.302	18	2.66 m recovery (PC)
53-CS-TEST3	011.0510	19 2.615	146 47.278	18	2.54 m recovery (PC)
53-CS-PC01	011.1850	17 21.598	147 2.899	1341	2.83 m recovery
53-CS-PC02	012.1229	17 10.637	147 20.548	1391	Failed to trigger
53-CS-PC03	012.2028	16 26.424	146 57.275	1744	3.02 m recovery
53-CS-PC04	013.0803	16 40.587	146 40.111	1550	1.88 m recovery
53-CS-GC01	013.1012	16 40.421	146 39.673	1534	3.3 m recovery
53-CS-PC05	013.1627	16 6.659	146 31.754	1800	Failed to trigger
53-CS-PC05a	013.1957	16 5.481	146 30.132	1797	3.16 m recovery
53-CS-PC06	014.0220	16 27.804	146 37.615	1675	3.68 m recovery
53-CS-GC02	015.1630	15 46.301	146 22.791	1995	2.67 m recovery
53-CS-GC03	016.0241	15 26.030	146 14.736	2084	3.10 m recovery
53-CS-PC07	017.1514	14 53.207	146 7.094	2508	2.85 m recovery
53-CS-PC08	018.0122	14 10.446	146 1.853	2818	1.52 m recovery
53-CS-GC04	018.2045	13 20.426	145 37.949	3019	0.28 m recovery
53-CS-GC05	018.2231	13 21.407	145 38.022	3044	3.8 m recovery
53-CS-unlab	022.0657	11 10.706	139 58.151	109	Failed (GC)
53-CS-unlab	022.0712	11 10.688	139 57.946	109	Failed (GC)
53-CS-GC06	022.0722	11 10.627	139 57.814	109	1 m recovery

Exmouth Plateau

53-EP-PC01	029.1246	19 53.594	114 58.227	1177	4.8 m recovery
53-EP-GC01	029.2148	19 53.595	114 35.400	1279	4.14 m recovery
53-EP-GC02	030.0352	19 42.669	114 20.106	1352	4.15 m recovery
53-EP-GC03	030.1249	19 32.124	113 52.975	1141	3.22 m recovery
53-EP-GC04	030.1828	19 35.109	113 32.052	956	4.12 m recovery

53-EP-GC05	031.0203	19 19.519	113 6.393	1279	3.27 m recovery
53-EP-GC06	031.1345	19 3.170	112 45.139	1979	4.93 m recovery
53-EP-GC07	031.1626	18 53.539	112 37.887	2256	5.0 m recovery
53-EP-GC08	032.0903	19 31.342	113 13.481	936	3.94 m recovery
53-EP-GC09	032.2047	20 .253	112 55.880	962	4.4 m recovery
53-EP-GC10	033.0809	20 29.899	112 35.154	947	3.98 m recovery
53-EP-GC11	033.1940	20 53.688	112 20.013	1432	3.7 m recovery
53-EP-PC02	034.1340	21 39.008	111 40.628	5050	Failed to trigger

Perth Basin

53-PB-GC12	037.0205	28 36.275	112 9.431	4557	2.3 m recovery
53-PB-DR01	038.0610	31 13.949	114 35.476	2520	40 kg recovery
53-PB-DR01	038.0654	31 13.887	114 36.391	1970	
53-PB-DR02	038.0853	31 13.868	114 39.569	1301	3 kg recovery
53-PB-DR02	038.0909	31 13.665	114 39.921	1275	

HEAT-FLOW STATIONS

Western Coral Sea

Station	Time	Lat	Long	WD	K	dT	N	Q
53-CS-HF01	012.0023	17 22.010	147 4.277	1355	.88	74	5	65
53-CS-HF02	012.0627	17 11.526	147 15.848	1463	.88	69	2	61
53-CS-HF03	012.0909	17 10.623	147 19.334	1441	.88	78	3	61
53-CS-HF04	013.0152	16 26.054	146 56.688	1758		Failed		
53-CS-HF05	014.0502	16 28.244	146 38.238	1665		Failed		
53-CS-HF06	014.0850	16 37.037	146 42.911	1628	.87	55	4	48
53-CS-HF07	014.1153	16 37.299	146 43.044	1623	.87	38	4	33
53-CS-HF08	014.1551	16 33.043	146 52.130	1694	.97	54	3	52
53-CS-HF09	014.1938	16 25.787	146 59.429	1737	.97	54	2	52
53-CS-HF10	014.2214	16 25.484	146 59.110	1734	.97	37	4	36
53-CS-HF11	015.0043	16 25.313	146 57.587	1747		Test		
53-CS-HF12	015.0656	15 55.604	146 25.854	1894	.83	58	3	48
53-CS-HF13	015.1044	15 56.548	146 27.431	1890	.83	74	4	61
53-CS-HF14	015.1426	15 51.670	146 24.141	1957	.81	50	4	41
53-CS-HF15	015.2041	15 46.866	146 22.919	1981	.81	98	4	79
53-CS-HF16	016.0616	15 26.195	146 14.150	2087		Test		
53-CS-HF17	016.0837	15 26.077	146 14.819	2089	.78	48	7	38
53-CS-HF18	016.1408	15 6.678	146 6.627	2093	.84	89	3	75
53-CS-HF19	017.1154	14 52.463	146 6.870	2509	.89	57	3	51
53-CS-HF20	017.1852	14 52.687	146 7.864	2511	.89	58	3	52
53-CS-HF21	018.0426	14 10.304	146 2.505	2816	.79	51	3	40
53-CS-HF22	018.0750	14 10.444	146 3.018	2815		Failed		
53-CS-HF23	018.1101	14 9.851	145 52.185	2823	.79	72	2	57
53-CS-HF24	018.1520	13 55.192	145 45.200	2880	.79	65	4	52
53-CS-HF25	019.0216	13 19.670	145 38.209	3060	.81	107	3	86

Exmouth Plateau

Station	Time	Lat	Long	WD	K	dT	N	Q
53-EP-HF01	029.1429	19 54.398	114 58.145	1162	.76	129	5	98
53-EP-HF02	029.1731	20 3.358	114 50.089	1149	.78	107	5	83

53-EP-HF03	029.1921	20	.387	114	45.612	1236	.78	93	7	73
53-EP-HF04	029.2322	19	53.240	114	34.208	1276	.86	88	5	76
53-EP-HF05	030.0131	19	48.483	114	28.950	1328	.85	111	5	94
53-EP-HF06	030.0526	19	42.757	114	19.582	1353	.85	90	4	77
53-EP-HF07	030.0724	19	41.348	114	10.794	1255	.85	71	5	60
53-EP-HF08	030.0924	19	40.933	114	.464	1251	.86	114	4	98
53-EP-HF09	030.1136	19	33.230	113	53.164	1139	.86	50	5	43
53-EP-HF10	030.1428	19	33.469	113	46.973	1175	.86	31	3	27
53-EP-HF11	030.1628	19	38.561	113	40.400	1098	.86	52	3	45
53-EP-HF12	030.2002	19	35.278	113	30.780	947	.86	-65	3	-60
53-EP-HF13	030.2208	19	29.894	113	21.288	922	.86	34	4	29
53-EP-HF14	031.0008	19	24.639	113	13.896	980	.84	24	5	20
53-EP-HF15	031.0343	19	19.908	113	6.443	1266	.84	72	4	60
53-EP-HF16	031.0707	19	14.518	112	59.207	1490	.87	79	3	69
53-EP-HF17	031.0953	19	7.716	112	51.266	1671	.87	66	4	57
53-EP-HF18	031.1211	19	4.013	112	44.443	2000	.87	56	3	49
53-EP-HF19	031.1857	18	53.330	112	37.557	2257	.86	44	3	38
53-EP-HF20	031.2113	18	53.148	112	32.043	2220	.86	42	2	36
53-EP-HF21	031.2311	18	52.573	112	27.902	2218	.86	44	2	38
53-EP-HF19B	032.0222	18	53.272	112	36.975	2223		Failed		
53-EP-HF22	032.1043	19	32.080	113	12.729	935	.88	37	4	33
53-EP-HF23	032.1249	19	38.015	113	9.298	940	.88	107	3	95
53-EP-HF24	032.1443	19	43.988	113	5.523	952	.88	44	2	39
53-EP-HF25	032.1647	19	49.974	113	2.074	947	.89	35	2	31
53-EP-HF26	032.1915	19	59.333	112	56.109	943	.89	138	5	123
53-EP-HF27	032.2317	20	5.648	112	52.082	909	.89	82	3	73
53-EP-HF28	033.0138	20	11.990	112	47.851	848	.89	229		204
53-EP-HF29	033.0400	20	17.380	112	44.152	852	.90	55	4	49
53-EP-HF30	033.0616	20	23.914	112	39.968	875		Failed		
53-EP-HF31	033.0925	20	29.887	112	34.647	953	.90	102	2	92
53-EP-HF32	033.1126	20	35.408	112	31.515	1103	.90	29	4	26
53-EP-HF33	033.1324	20	42.373	112	26.911	1264	.90	47	2	42
53-EP-HF34	033.1539	20	48.040	112	23.857	1426	.90	48	2	43
53-EP-HF35	033.1757	20	53.249	112	20.263	1427	.87	73	5	64
53-EP-HF36	033.2158	21	1.206	112	15.781	1541	.87	60	3	52
53-EP-HF37	034.0026	20	59.632	112	4.462	1270		Failed		
53-EP-HF38	034.0233	21	5.360	112	.486	1780		Failed		
53-EP-HF39	034.0923	21	40.247	111	38.711	5053	.87	68	5	60

Perth Basin

53-PB-HF01	038.0025	30	33.913	114	41.730	194		Test		

APPENDIX 4. Coring summary

An essential requirement in determining heat-flow is knowledge of the thermal conductivity of the sediments in which the gradient is measured. As a rule, conductivity measurements are made on piston or gravity cores obtained at the same location that the gradient is measured. All the cores obtained on this cruise were logged according to the format proposed by Swanson (1981), Two representative logs are shown in Figurees 26 and 27, and simplified lithologies of all cores are shown in Figures 28 and 29. The coring site details are tabulated in Appendix 3.

Coral Sea cores

Out of 13 cores attempted during the Coral Sea leg, 11 were successful; one piston core failed due to a malfunction of the trigger armer, and one gravity core failed because it was unstable as it entered the sediment. Three cores were obtained in shallow water near Magnetic Island during deployment tests at the start of the cruise near Townsville. The cores were taken in water depths varying from 1341 to 3058 m; the average length of recovery in a 5 m-long barrel was 2.9 m.

In general, all cores showed sections of deep-sea mud with abundant planktonic foraminifera and minor pteropod fragments. They were characterised by streaks of clean, porous, fine-grained foraminiferal and quartz sands, or sometimes by coarse-grained sands and pebbles (volcanic rock fragments, shells, corals, etc) with shallow-marine organic remains (benthonic foraminifera, corals, bryozoans, shells). These sands were presumably derived from the Great Barrier Reef and carried by turbidity currents and gravity slides. Abundant burrow networks, probably made by polychaete worms, are filled with hydrosulphide mud, and organic seams are commonly observed in all cores. Abundant wood remains were also noteworthy; some of these will be subjected to 14C dating after the survey.

The lower half of the cores is commonly dark grey in colour, and sometimes smells of hydrosulphide, both of which indicate a stagnant (reducing) environment. However, the middle sections of the cores are typically light grey with light brown bands, indicating an oxidising environment. The top 10-20 cm of each core consists of creamy-brown foraminiferal ooze or sand. Dating of planktonic foraminifera should clarify when the change from a reducing to an oxidising environment occurred.

Exmouth Plateau cores

Thirteen coring stations were occupied on the Exmouth Plateau and in the Cuvier Abyssal Plain. All except two of the stations were between 900 and 1400 m water depth and all except the deep-water site (5027 m) in the Cuvier Abyssal Plain were successful. In all cases, full penetration was achieved with a 5 m core barrel. Recovery ranged from 3.22 to 5.00 m, with the average being 4.14 m. The total length of the 12 cores was 49.65 m.

A representative core log from the Exmouth Plateau is shown in Figure 27. In general, the cores from the plateau show evidence of open oceanic circulation under an oxidising environment. Sediments are light grey with occasional greenish streaks, and are soft, porous, permeable, and sandy with a fine silty and muddy matrix. The top few metres of each core were, without

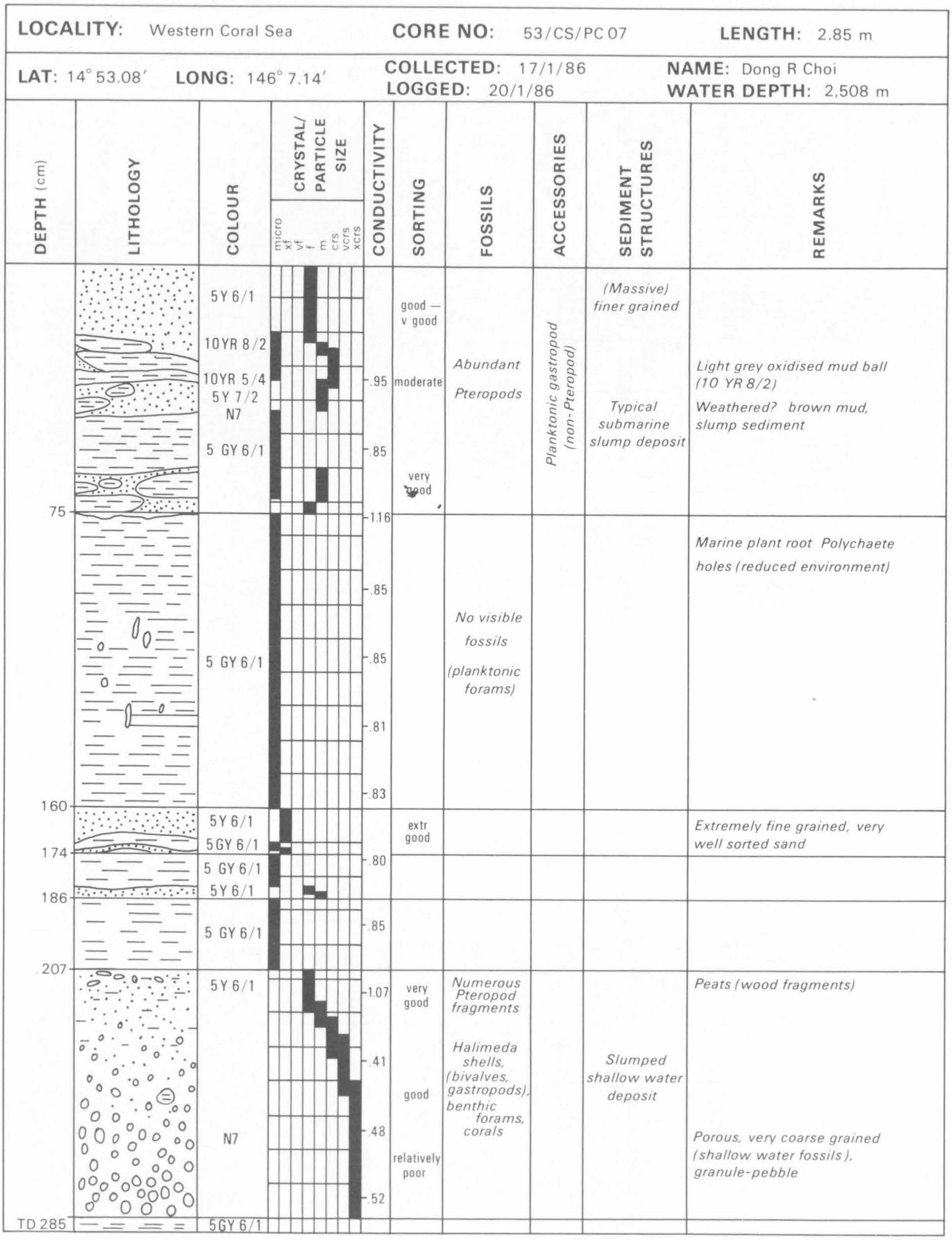

Figure 26. Sample coring summary from the Queensland Trough.

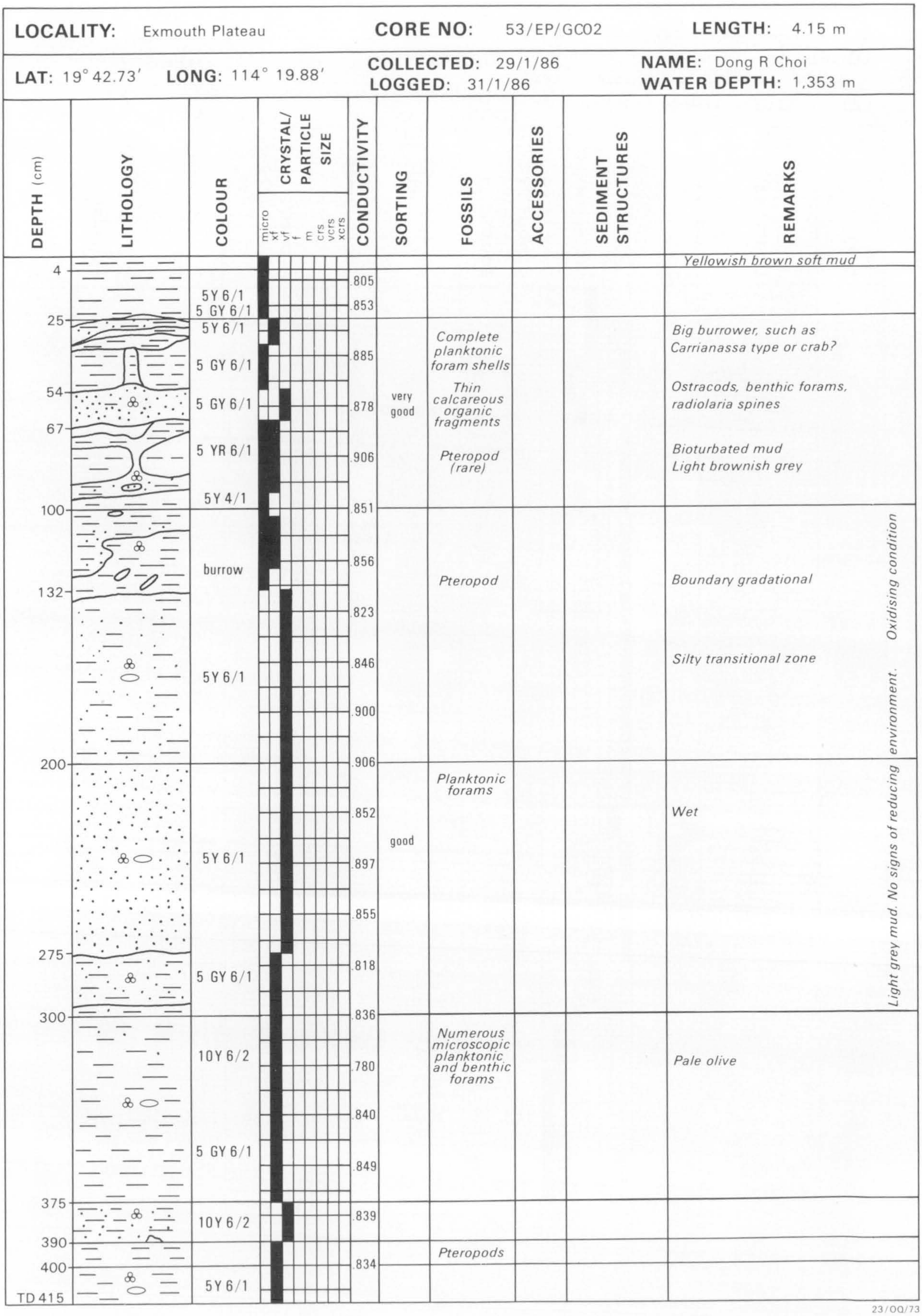

Figure 27. Sample coring summary from the Exmouth Plateau.

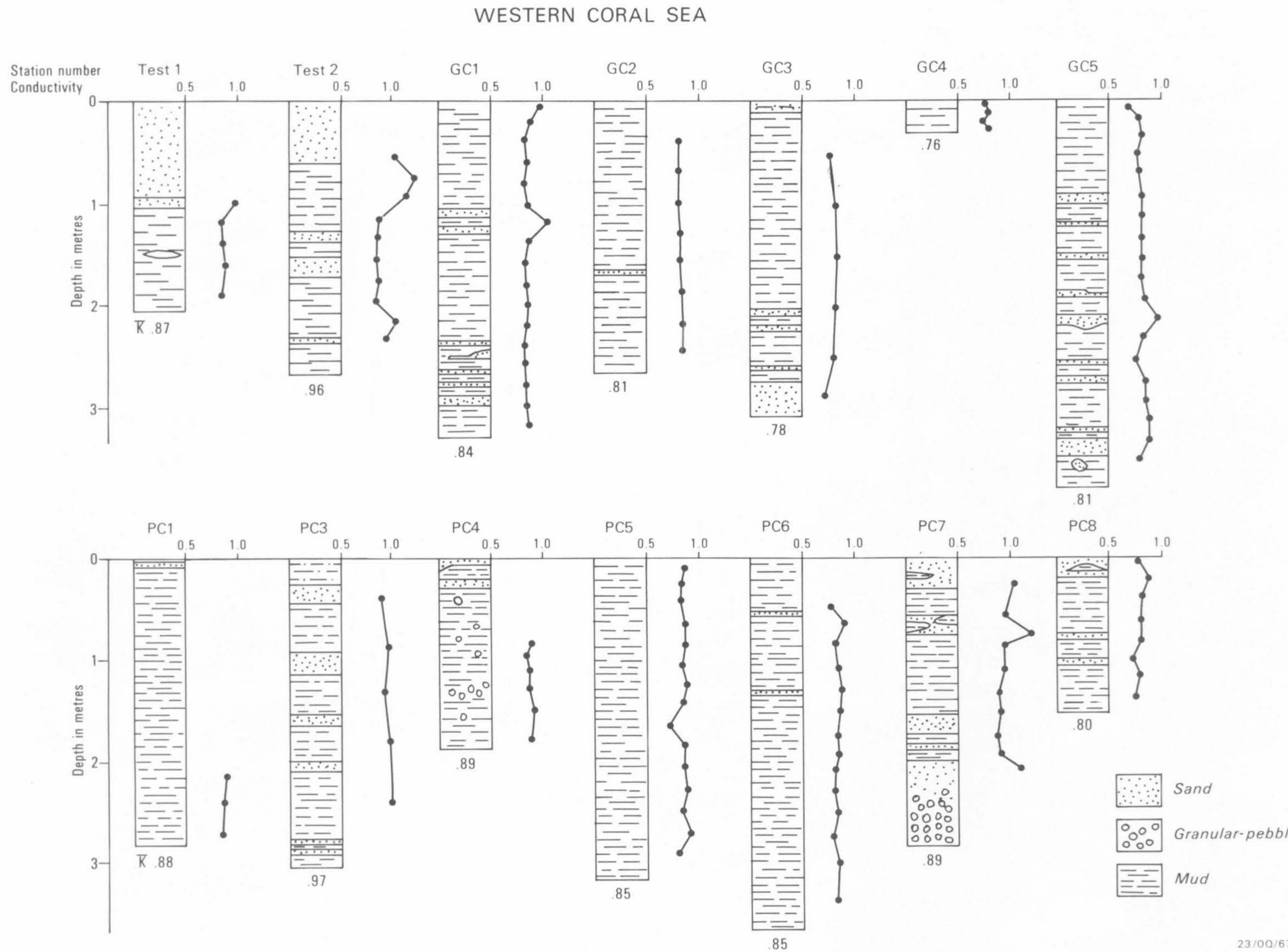

Figure 28. Core sections and conductivities - western Coral Sea.

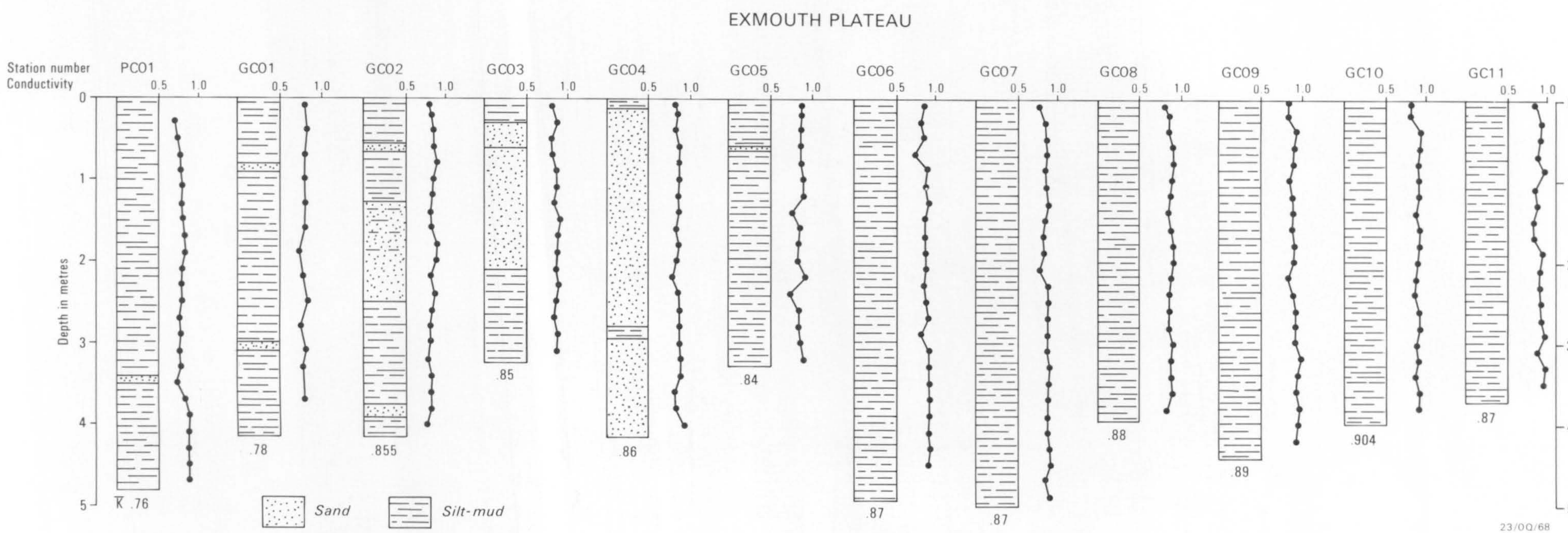

Figure 29. Core sections and conductivities - Exmouth Plateau.

exception, saturated with sea water. The sand grains are dominantly composed of planktonic foraminifera tests with minor amounts of benthonic foraminifera, radiolarians, and diatoms. Pteropod remains are rare in the cores, probably because the depth of the samples (900 m and greater) is below the carbonate compensation depth (Colwell & von Stackelberg, 1981). Terrigenous material was very rarely observed in the cores.

The Exmouth Plateau cores show extensive bioturbation by burrowers (such as polychaete and siphunculid worms, bivalve shells, and crustaceans) throughout their length. Although most of the burrows are now partly or completely filled with sediment, some of them are empty, allowing water to flow through the burrows. Taking this into consideration with the permeable porous sandy sediment, it is possible that the temperature gradient in the sediments may be affected to some extent by seasonal water temperature variations.

APPENDIX 5. Cruise diary and statistics

11 Jan	Depart Townsville; gravity and piston core testing near Magnetic Island.
12-17 Jan	Heat-flow probes, gravity and piston coring in southern and central Queensland Trough.
17 Jan	Call at Lizard Island to disembark J. Pittar and N. Kasanuki (Nichiyu Giken Kogyo Co. Ltd., Japan) and collect freight.
17-20 Jan	Heat-flow probes and coring in northern Queensland Trough.
20-22 Jan	Side-scan sonar in Torres Strait area from Bramble Cay to Carpentaria Light.
22-29 Jan	Transit from Gulf of Carpentaria to Exmouth Plateau. Magnetometer towed for most of transit; Side-scan sonar deployed in Arafura Sea and Dundas Strait. Brief port call at Pt Sampson on 28 Jan to collect ships stores.
29 Jan- 3 Feb	Heat-flow probes and coring on two transects across the Exmouth Plateau.
4 Feb	Port call at Exmouth to pick up BMR and Australian Winch and Haulage personnel.
4-7 Feb	Transit to Fremantle; equipment tests and winch commissioning.
8 Feb	Arrive Fremantle.

Cruise statistics

Heat-flow stations (occupied)	-	66
" " " (successful)	-	55
" " " (tests)	-	3
" " " (failed)	-	8
Gravity core stations (occupied)	-	21
" " " (successful)	-	19
Total length of gravity core	-	63.34 m
Piston core stations (occupied)	-	13
" " " (successful)	-	10
Total length of piston core	-	28.94 m
Total number of stations occupied	-	102
Side-scan sonar data acquired	-	930 km

APPENDIX 6. Equipment list

Heat-flow system

- Nichiyu Giken NTS-11AU lance-type, multiple re-entry, digital heat-flow recorder, including playback system.
- Needle-type thermal conductivity measuring equipment

Bathymetric systems

- Raytheon deep-sea echo sounder; 2 kW maximum output at 3.5 kHz.
- Raytheon deep-sea echo sounder; 2 kW maximum output at 12 kHz.

Magnetic system

- Geometrics G801/803 proton precession magnetometer.

Gravity meter system

- 1 Bodenseewerk Geosystem KSS-31 Marine Gravity Meter.

Navigation

Prime system

- Magnavox MX1107RS dual channel satellite receiver.
- Magnavox MX610D sonar doppler speed log.
- Arma-Brown SGB1000 gyro-compass.

Secondary system

- Magnavox MX1142 single channel satellite receiver.
- Raytheon DSN450 sonar doppler speed log.
- Robertson gyro-compass.

Computer Equipment

Non-seismic acquisition system (DAS)

- Hewlett-Packard 2113 E-Series 16-bit minicomputer with 512 kw of memory.
- 2 Hewlett-Packard 7905 15 Mb, moving-head disc and multi-access disc controller.
- 2 Hewlett-Packard 7970E 1600 bpi, 9-track magnetic tape drives.
- Hewlett-Packard 12979 I/O extender.
- Hewlett-Packard 2748A paper tape reader.
- BMR-designed and built 16-channel digital multiplexer (up to 3).
- BMR-designed and built 16-bit gyro/speed log interface.
- GED, NCE, or CHRONOLOG digital clocks (x2).
- KSR-43 teletypes, TELEVIDEO TVI-910 VDU's, and EPSON RX-80 line printers (various combinations).
- KAGA RGB colour monitors (up to 7) driven through RCA microcomputers.
- W & W 6-pen strip-chart recorders (x3).
- CALCOMP 1044 8-pen high-speed 36-inch drum plotter.

- ZETA 160 1-pen drum plotter.

Side-scan Sonar

- EG & G Side-scan sonar fish, cable, and on-board modem.
- Recording system, comprising Hewlett-Packard 2108 M-series minicomputer, Phoenix 6915 A-to-D multiplexer, Televideo TV-910 VDU, EPC graphics recorder, and Sansui D-770R analogue cassette deck.

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