BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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PRELIMINARY POST CRUISE REPORT

RIG SEISMIC RESEARCH CRUISES 7 & 8

DEEP SEISMIC STRUCTURE OF THE EXMOUTH PLATEAU

Principal Investigators

P.E. Williamson and D.A. Falvey

Department of Primary Industry & Energy
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INTRODUCTION

This report describes the second data collection phase of a three phase, Exmouth Plateau research program, undertaken by B.M.R.'s Division of Marine Geosciences and Petroleum Geology (B.M.R. Marine) during 1986. This phase consisted of a one month, two-ship seismic reflection and refraction study to define the deep basinal and crustal structure of the Exmouth Plateau. The objectives of this research program are a better understanding of passive continental margin subsidence and tectonic evolution and a redefinition of the regional petroleum potential of the plateau.

The Exmouth Plateau is a submarine marginal plateau with an area of about 150,000 sq. km. situated off the N.W. Australian continental margin (Fig. 1). The plateau consists of deeply rifted and subsided continental crust. It is separated from the N.W. Shelf by the Kangaroo Syncline and is bounded to the north, south and west by oceanic crust. At its crest, the plateau is 800 m below sealevel and sedimentary thicknesses, consisting of pre-breakup Paleozoic to early Mesozoic sediments, and post-breakup Mesozoic and Tertiary sediments, are up to 10 km.

The large areal closures in the post-breakup section, which drape the underlying fault controlled rift structures, encouraged petroleum exploration in the late 1970's and early 1980's. This led to the collection of more than 20,000 km of multichannel seismic data over the central plateau and the drilling of 14 exploration wells on five exploration permits. Exploration showed the plateau to be mainly immature in the post-breakup section and predominantly terrigenous, gas prone and partly overmature in the prebreakup section with a possible increase in marine influence and possible oil sourcing potential to the west. The perceived gas prone nature of the area and the deep water over the plateau has resulted in permit relinquishments through the early 1980's, with the exception of the area surrounding the Esso Scarborough gas discovery. Hydrocarbon exploration has ceased in recent years.

B.M.R. Marine Division planned this three phase research program to re-stimulate petroleum exploration over the plateau. The first phase was a 6 day, heatflow program on the plateau during January, 1986. This was designed to examine present day source rock maturation levels and is reported in B.M.R. Report 274. The second phase, conducted in March through May, 1986, and reported here, involved a cooperative two-ship study in conjunction with Lamont-Doherty Geological Observatory, New York (LDGO). Broad structural analyses of the plateau, its normal and transform faulted margins and adjacent oceanic features were carried out using multichannel seismic data both from two-ship Expanded Spread Profiles (ESP) and Wide Aperture C.D.P. (WACDP) seismic profiles. Data were collected from 18 ESP's arranged along three transects, with the centres of the individual ESP's tied with WACDP seismic reflection profiles shot along the transects.

The study also addressed the nature of the continental to oceanic crustal transition. Suggested mechanisms for continental margin formation include lithospheric cooling, continental crustal streching, deep crustal metamorphism, subcrustal erosion. This work provided a sound crustal data base on the different styles of ocean/continent boundaries associated with the Exmouth Plateau as evidenced by transform faulting in the south, rifting in the west and rifting and intrusion in the north. Thus, the Exmouth Plateau is an ideal location to study the transition from continental to oceanic crust. A full understanding of the formation of the Exmouth Plateau may be possible from this and other existing data sets. The project is therefore of worldwide scientific importance, as well as providing important insights into the origin and history of the plateau, which might re-stimulate further petroleum exploration.

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The enthusiasm, skill, and cooperation of the master and crew of *R/V Rig Seismic* is gratefully acknowledged. They have made a major contribution to the success of both the cruise and the research program.

The contribution of NATMAP personnel in setting up and manning the onshore HIFIX radio navigation stations for the study is also gratefully acknowledged. This arduous effort in remote areas has resulted in effectively doubling the percentage of crucial high accuracy navigation during the study.

B.M.R.'s Exmouth Plateau program consists of three distinct research cruise projects. The broad objectives of this program are: to determine the history of basin subsidence; to define regional basin thermal history; to determine the structural and stratigraphic framework of the entire Exmouth sedimentary basin, as well as the structure of the deep crust underlying the basin; to relate the evolution of the crust and basin to the formation of the surrounding oceanic crust of the Argo, Gascoyne and Cuvier abyssal plains; and finally, to relate all these factors to the parameters governing regional petroleum potential.

This Report covers the second research phase, whose principal objective was the determination of deep sedimentary basin, basement and lower crustal structure by two-ship seismic reflection and refraction methods. The project was conducted in conjuction with R/V *Robert D. Conrad*, of Lamont-Doherty Geological Observatory, Columbia University, New York. In particular, the two ship seismic project was designed to address questions related to the nature of the continental crust underlying the Exmouth Plateau, the nature of the continent-ocean crustal transition, the mechanisms of deep crustal modifications associated with rifting and breakup, the relationships between these various mechanisms and the thermal history of the overlying sedimentary basin, as well as its structural fabric.

A great deal is already known about the Mesozoic-Tertiary sedimentary basin which underlies the southern, central and eastern Exmouth Plateau. This knowledge is derived from the large amount of good quality seismic data now on open file from industry sources, as well as some published results from exploration drilling. Little was known of the pre-Mesozoic sedimentary basin or the underlying crust. Gravity and magnetic data interpreted by Exon and Willcox (1980) suggest that basement is about 8-10 km below seabed over much of the plateau and that igneous bodies and crystalline basement are at shallow depths at its seaward margin. Regional crustal thickness was thought to be about 20 km.

The crustal structure of a rifted continental margin should be clearly related to the mechanism of basement subsidence: models for this mechanism include lithospheric cooling and contraction; continental stretching and crustal extension; deep crustal metamorphism; supra-crustal erosion; igneous injection and sub-crustal erosion . The determination of which mechanism applies, or the relative contributions of various mechanisms, can then be related to models which can be used to predict paleoheatflow and thus petroleum source rock maturation history. Understanding of the mechanisms also provides a means of predicting and modelling basin subsidence patterns.

A clearly long-term objective of deep crustal studies at passive continental margins is the development of a general model of the processes involved in continental margin formation in particular, and the processes involved in basin formation on continental crust in general.

Two-ship multichannel seismic data were collected during parts of two one-month BMR cruises, with BMR *Rig Seismic* as principally the receiving ship and LDGO *Robert D. Conrad* as principally the shooting ship. The data were collected on 18 ESP's in three transects, together with WACDP and other multichannel seismic data (Fig. 2). The basic technique for such ESP operations is for two ships to steam towards each other through and past a common midpoint, one ship firing an airgun array at a 60 second repetition rate, the other recording arrivals on a multichannel streamer (Fig. 3). The shooting ship may also collect vertical incidence multichannel seismic data at the same time on it's own streamer, thus obtaining structural information which is subsequently used in ESP data reduction. After a group of ESP's has been shot, the two ships then form up in-line and shoot a WACDP seismic profile through the midpoints of all ESP locations, as described by Buhl and others (1982). ESP's can also be collected by the two ships steaming apart from a common midpoint. In this instance it is necessary for the shooting ship to rerun the ESP track to obtain the vertical incidence seismic data. At the end of the run the ships proceed to the midpoints of the next ESP line. The centres of these ESP's, shot from midpoint outwards, must also be subsequently tied by a regular reflection or wide aperture profile. The former method was normally used during the co-operative BMR/LDGO survey program. A full description of both the ESP and WACDP methods and operations is contained in Chapter 5.

The ESP's were collected with a maximum offset of 100 km. Conrad had at that time the greater airgun capacity (6000 cu in at 2000 psi on a 60 sec repetition rate) and consequently was the shooting ship, with Rig Seismic being the receiving ship. Explosives were employed at longer ranges where seismic signal strength from the airguns was insufficient. LDGO is experienced in this technique and have acquired and processed around 100 ESP's to date: off the Voring Plateau, the East Greenland Margin, in the North Atlantic, on the East Pacific Rise, around the Hawaiian Swell and on the China Margin of the South China Sea.

The three transects collected during the Exmouth Plateau project are referred to as the *Exmouth*, *Cape Range* and *Cuvier* Transects and relate to the centre/western and southern margins of the plateau, and the normal margin south of the plateau. Each ESP took around 12 hours and the 18 ESP's and 3 WACDP profiles were collected in approximately 25 days of on-station time.

ESP data will be processed using the methods of Detrick and others, (1982); Mutter and others (1983); Diebold and Stoffa, (1981); and Wenzel and others (1982). This involves binning of the seismic data and analysis in the X-T and t-p domains to generate velocity/time information relating to the ESP midpoints (Fig 4). These data can then be converted to velocity/depth profiles by inversion.

The regional geological setting of the Exmouth Plateau is shown in Figs 1&4. The plateau is a continental block bounded on the north, west and south by oceanic crust forming the Argo, Gascoyne and Cuvier Abyssal Plains respectively. The Canning and Carnarvon Basin sediments which cover the plateau extend to the east and abut the Pilbara Precambrian block. Prebreakup, rift phase deposition has been identified on the plateau and beneath the shelf to the east (Fig. 5). The stratigraphic sequences in the region are shown in profile in Fig. 5a and b. These consist of Tertiary limestones overlying Cretaceous to Permian clastics overlying Precambrian basement. A more detailed description of the regional structural history and stratigraphy focusing on the Exmouth Plateau is given below.

Tectonic Framework

The geological development of the Exmouth Plateau has been discussed in some detail by Falvey (1972b), Falvey and Veevers (1974), Veevers and others (1974), Exon and others (1975, 1982), Hogan and Jacobson (1975), Veevers and Cotterill (1976), Powell (1976), Willcox and Exon (1976), Exon and Willcox (1978, 1980), Wright and Wheatly (1979), Larson and others (1979), von Stackelberg and others (1980), Falvey and Mutter (1981) and Willcox (1981).

The present structural configuration of the Exmouth Plateau region was initiated by rifting in Triassic to middle Jurassic prior to seafloor spreading. The western margin reflects a normal rifted structure and the southern margin reflects a transform dominated structure. The northern rifted margin is obliquely rifted with associated igneous activity.

The northern margin of the plateau formed in the Callovian (approx. 150m.y. ago), when seafloor spreading commenced in the Argo Abyssal Plain (anomaly M-25 time). The northeast-trending seafloor spreading anomaly pattern was initially described by Falvey (1972a) and basin age was established by DSDP drilling (Veevers, Heirtzler and others, 1978). Throughout the Jurassic, prebreakup rift graben tectonics affected the entire western margin (Falvey and Mutter, 1981) (Figs 7 and 8). The initiation of rifting may be associated with the occurence of Triassic-Jurassic intermediate and acid volcanics (213-192 m.y. ago), which overlie a thick Triassic paralic sequence. Steady subsidence along the incipient northern margin, north of an east-west hinge line allowed several thousand metres of Lower and Middle Jurassic carbonates and coal measures to accumalate before breakup. Breakup occurred along a series of rifted and sheared margin segments, the tectonic setting being further complicated by northwest trending Callovian horsts and grabens. The horsts were planed off in late Jurassic and early Cretaceous times, and the whole northern margin was covered by a few hundred metres of Upper Cretaceous and Cainozoic pelagic carbonates as it subsided steadily to its present average depth of 2000-5000 m.

The northeast-trending western margin of the plateau formed by breakup in the Neocomian as "Greater India" moved off to the northwest. At approximately 120 m.y. b.p. (early Cretaceous), seafloor spreading began in the Cuvier and Perth Basins (anomaly M-3 to M-10 time). Portions of the northeast trending seafloor spreading magnetic anomally pattern were initially described by Markl (1974) and Larson (1977), and have been integrated by Larson and others (1979). At a regional scale however, details of the spreading pattern around the southwest corner of Australia may be complex (Markl, 1978) and are yet to be fully described. Through the earliest Cretaceous, late stage rift graben tectonics affected the Australian southwest margin where it bordered India and Antarctica. Early Cretaceous rifting also affected Eastern Australia, the Gippsland Basin, Lord Howe Rise, and Queensland Plateau. The earliest phase of rifting also began on the southern margin adjacent to Antarctica (Falvey and Mutter, 1981). On the Western margin of the Exmouth Plateau, Callovian normal faults parallel the margin. A thick Triassic paralic sequence is unconformably overlain by a thin, post-breakup Upper Jurassic and later marine sequence indicating that the area was high in the early and middle Jurassic. Thin Upper Cretaceous and Cainozoic pelagic carbonates cover the western margin, which now lies more than 2000 m below sealevel.

The northwest trending southern margin of the plateau formed along an incipient transform in the Neocomian, at the same time as the western margin. It is cut by northeast trending normal faults, which formed in the late Triassic and Callovian, and is paralleled by Neocomian and later normal faults. A thick Jurassic paralic sequence is unconformably overlain by a thick Upper Jurassic and Neocomian delta. This suggests that the area was high in the early and middle Jurassic, but a depocentre before and afterwards. There was thermal uplift of more than 1000 m during the Neocomian. Igneous intrusions butress the margin. Later normal faulting lowered the outermost margin, and turned the uplift into a marginal anticline trending northwest. The anticline had sunk beneath the sea by late in the Cretaceous, and thereafter this margin was covered by a thin sequence of pelacic carbonates, which now lie at a water depth of 1500 m (Exon and others, 1982).

Von Stackelberg and others (1980) have reported 30 dredge hauls from the outer slopes of the Exmouth Plateau. More than half contained Jurassic and Triassic prebreakup shallow water sediments. Four dredges also contained intermediate to acid volcanics dated at about the time of rift onset. This suggests limited continental crustal anatexis very near to the incipient continent-ocean boundary. These data also indicate that it is not valid to interpret the occurrence of volcanics on a marginal plateau slope as definitive evidence of non-continental crustal structure, either in whole or in part (Falvey and Mutter, 1981).

Stratigraphy

The paleogeographic evolution of the Exmouth Plateau is sketched in Fig. 9 and the stratigraphy is outlined in Figs. 10a and b. Sediment starvation has led to a greatly reduced post breakup sequence on the continental margin. Thus, seismic profiling and drilling have been able to penetrate well into the prebreakup sequence and resolve early stages of margin evolution (von Rad and Exon, 1982). Fourteen petroleum wells have been drilled and results from Phillips Jupiter No. 1, Saturn No. 1 and Mercury No. 1 have been published (Fig. 11, Barber, 1982). Stratigraphic studies have been carried out by von Stackelberg and others (1980), Colwell and von Stackelberg (1981), and von Rad and Exon (1982). The extensive seismic control consists of 12,000 km of BMR seismic reflection, magnetic and gravity data from the 1972 BMR continental margin survey, 9300 km of GSI seismic data collected in 1976 and 1977 (Wright and Wheatley, 1979) and subsequent petroleum industry seismic data.

Interpretation of seismic profiles indicates that up to 5000 m of Paleozoic strata and up to 5000 m of younger strata overlie basement. The sediments have been gently folded, and the prebreakup section is affected by northeast trending faults.

The sediments beneath Exmouth Plateau are considered to have been deposited in an extension of the Carnarvon Basin. This formed a north-facing Tethyan embayment in Gondwanaland and received detrital sediments from the south until early Cretaceous time. In the central plateau region, at least 3000 m of mainly paralic and shallow marine detrital sediments were deposited from Permian to middle Jurassic times. After the late Triassic rifting, about 1000 m of shallow marine and deltaic detrital sediments derived from the south and east, covered the block faulted surface in late Jurassic and early Cretaceous times. About 200 m of marine terrigenous sediment was deposited in the middle Cretaceous, and 500 to 1000 m of carbonate sediment in the late Cretaceous and Cenozoic. In the Miocene, the rate of subsidence exceeded the rate of sedimentation and thereafter, the Exmouth Plateau arch and Kangaroo Syncline took their present form (Exon and Willcox, 1978 and 1980).

Petroleum Exploration

In the mid 1970's the Exmouth Plateau was regarded as the possible location of major petroleum reserves. Reconnaissance surveys shot in the mid-1970's (Fig. 12) revealed the presence of large fault bounded structures (Exon and Willcox, 1978; Wright and Wheatley, 1979) and, in spite of water depths greater than 800 m, the close proximity of major hydrocarbon accumulations on the NW Shelf and at Barrow Island in the Carnarvon Basin encouraged optimism. Five exploration permits divided up the plateau in 1977 and 14 exploration wells were drilled (Fig. 13). These included three wells by the Phillips Group (British Petroleum, Gulf, Mount Isa Mines, Mobil and Phillips) in Permit WA-84-P on the central Exmouth Plateau, which have been published (Barber, 1982). Several non-commercial gas shows were encountered as well as the Scarborough gas discovery that has been retained by Esso. However, no heavier hydrocarbons where encountered.

Early exploration concepts involved generation of oil from

Upper Jurassic and Neocomian shales in the Kangaroo Syncline and subsequent migration into the Jurassic and Triassic tilted fault blocks on the Exmouh Plateau High. The lack of liquid hydrocarbons was attributed to unfavourable source rocks, unsuitable burial history and a low paleo-thermal gradient. For the three wells published (Phillips Saturn No. 1 , Jupiter No. 1 and Mercury No. 1) Upper Triasssic, Jurassic and Cretaceous sections were found to be immature and incapable of generating hydrocarbons. Most hydrocarbons so far encountered on the Exmouth Plateau are thought to have originated from deep (5 km or more) overmature gas source rocks, probably Lower Triassic and Permian shales, by deep tapping of source beds along faults bounding the tilted block structures, enabling the gas to migrate upwards (Barber, 1982).

The lack of success in finding oil in the major Exmouth Plateau structures has resulted in dropping in all except part of one permit and cessation of petroleum exploration on the plateau. The re-stimulation of further petroleum exploration interest would appear to depend on demonstrating a marine oil prone source at mature depths, either in Jurassic graben fill in the Kangaroo Syncline, in local grabens, or in Triassic and Permian prerift sediments on the western margin of the plateau , along with suitably located trapping structures.

Evolution of the Continental Margins

The geological and structural evolution of a continental margin is a complex and protracted process. While this has been recognised to a greater or lesser extent ever since the concepts of continental drift were first enunciated, the majority of evolutionary schemes proposed have been largely qualitative and generally have not been based on studies of continental margins themselves (examples are Wagener,1929; Du Toit, 1937; Heezen, 1960; Dewey and Bird, 1970).

Falvey (1974) envisaged an evolutionary scheme for the Southern Australian margin which involved three distinct phases:

1. Initially, intracratonic basins and then rift basins developed as regions of major basement subsidence, generally in the vicinity of an incipient breakup axis. The rifting occurred some 50 m.y. before the initiation of a divergent plate boundary (the "rift valley" phase). Subsidence and deposition rates generally decreased towards breakup time.

2. During a 5-10 m. y. period near the time of breakup, the intensity of relative uplift and then subsidence increased (the breakup phase).

3. After seafloor spreading had been active for a few million years, subsidence and deposition rates again generally decreased with sedimentation showing a marked decrease in marine influences (the post breakup phase).

These evolutionary phases appear to provide a generally satisfactory description of the development of most parts of

Australia's rifted margins.

The mechanism of continental margin formation has been described in terms of models which usually relate cycles of uplift and subsidence to the thermal evolution of continental and oceanic lithosphere (Dewey and Bird, 1970; Sleep, 1971; Falvey, 1974; Mutter, 1978). However, such tectonic models differ markedly, and appear strongly dependent on the type of continental margin chosen by a particular author for analysis. Thus, the emergence of a general continental margin model has been hindered by apparent geological and structural complexity, and also by limited depth of penetration and resolution of relevant marine geophysical methods.

There are major advantages to the Exmouth Plateau as a study area for continental margin problems:

1. The progressive dispersal of Gondwanaland from around continental Australia has provided two parts of the western margin with different breakup times:
   a. Northwest- Late Jurassic (155 m.y. b.p.)
   b. Southwest- Early Cretaceous (120 m.y. b.p.)

2. The kinamatic evolution of the ocean basins adjacent to these margins is fairly well understood (Figs 7 and 8).

3. For various climatological and oceanographic reasons, post breakup deposition on these continental margins consists dominantly of thin carbonates. This alleviates many problems involving seismic resolution and depth of penetration.

4. Fairly extensive oil search coupled with government policy on open file and public release of information already provides a substantial set of shallow data on these margins.

Expanded Spread Profiles

An ESP is a highly specific two-ship seismic reflection/ refraction experiment, that achieves a large spatial offset and a very high spatial density in a common reflection mid point geometry by use of a multichannel receiving array and repetitively fired high energy sound sources, as shown in Fig. 3 (Stoffa and Buhl, 1979).

An ESP involves collection of a set of source-receiver pairs, with one ship providing the source (airguns and/or explosives) and the other ship, the receiver (towed multichannel seismic streamer). Source-receiver separation was up to 100 km on the Exmouth Plateau. The receiving system, provided by *Rig Seismic*, consisted of a 2.4 km, 48 channel Teledyne seismic streamer. The sources used during each ESP and shot from the *Conrad*, were of two types:

1. A dual source, consisting of 10 airguns in a 96 litre tunned array shot on one side of the ESP mid point; with explosive charges of 20 kg shot on the other side. This combination of sources was used when deeper continental crust was anticipated.
2. The airgun array source alone was used on both sides of the ESP in regions of thinner continental, transitional or oceanic crust.

The shot repetition rate for the gun array was 60 second, which at 5 kts represented a shot interval of 150 m or a shot-receiver separation of 300 m. This gives an 8-fold stack of traces from the 48 channels when summed in 50 m bins. The shot repetition rate for the explosive sources was 7 minutes. This gives an effective single fold stack.

The shooting and receiving ships each sailed inwards from opposite ends of the selected ESP line (Fig. 14). A line was defined by its end points, which in turn defined a mid point. To maintain correct geometry the source ship began shooting at it's end of the line, underway at 5 kts with the centre of the source array over it's end point at the start time. The receiving ship sailed into it's end of the line at 5 kts with the centre of the receiving array over it's end point at the start time. With both ships maintaining a "collision" course at constant speed, the centre of the receiving array would then cross the centre of the source array at the mid point. The profile was then extended, as the source and receiving ships continued on course and passed out of opposite ends of the ESP profile simultaneously. Thus, two nominally identical ESP's were recorded during each full run. For a 100 km line, this took 11 hours at 5 kts. In the case of ESP lines shot using only airguns as source, the source ship also towed its own streamer, thus obtaining a vertical incidence 8-fold CDP seismic profile. That profile is required for structural control during subsequent ESP processing. In the case of ESP lines shot with both airgun and explosive sources, the profile was begun with airguns and finished with explosives. At the end of an ESP, the two ships would then proceed along parallel tracks to the next ESP line (Fig. 15a).

The ESP shooting method described above results, as stated, in two ESP's: one on the inward track; and one on the outward track. A simpler method can be used which collects only a single ESP, as shown in Fig. 15b. Both ships turn, say to port, just after the mid point; one looping to avoid entangling streamers. The poceedure is reversed at the start of the next ESP. This method was used only once during the Exmouth Plateau project.

Clearly, an avoidance manouevre was required at the mid point (Fig. 14b). This was generally carried out by the source ship taking avoidance action. The side chosen was that opposite to the direction in which the streamer was feathering astern of the receiving ship; eg. if the streamer feathered to starboard, the ships passed port-to-port. Avoidance action commenced 2 km ahead and concluded up to 4 km astern of the receiving ship (ie. 20 minutes either side of the ESP line mid point). During Exmouth Plateau operations, *Rig Seismic* and *Conrad* passed between 200 and 1250 m abeam, depending upon weather and the feathering angle of streamers on one or both ships.

Corrections were often required to account for different convergence rates. These were most easily and frequently carried out by the source ship through direct bridge-to-bridge communication. Unless the convergence rates remained constant, the mid point would shift towards the slower ship, disrupting the common mid point geometry.

These geometrical mid course corrections were based on precise navigational data. Waypoints were set in each ship's navigational computer corresponding to the ESP mid point and each ship's corresponding starting point. Each ship's bridge watch was responsible for minimizing computed cross course errors and differences in down line distance to and from the ESP mid point. Both ships were equiped with satellite navigation and Global Positioning System (GPS). The latter was available for only 10 to 11 hours each day during this survey, due to the small number of satellites in the constellation at present. Full coverage will not be available until 1989. During most of the survey, *Rig Seismic* used HIFIX, provided by NATMAP, as backup to GPS.

Precise processing requires knowledge of the relatively separation of source and receiver to an even greater precision. This was provided at short range by *miniranger* (less than 30 km) and at longer ranges by RAYDIST. The actual lane number provided by RAYDIST was not necessarily reliable at the start of an ESP line. It was calibrated from *miniranger* later in the line and previous ships' separation recomputed. When taken in conjuction with the absolute HIFIX position for *Rig Seismic*, the relative range data also helped minimize errors in dead reckoning on *Conrad*.

The geometry on passing is also required to process the near range ESP data. Since neither *miniranger* nor RAYDIST provides information on bearing, these were provided from the bridge of each ship, at each shot instant, by optical or radar sights.

Finally, the shot instant had to be available to the receiving ship to an accuracy of about 1 millisecond. The recording cycle on the receiving ship was initiated by a master clock which also transmitted a calibration tone, at short ship-to-ship distances, to a slave clock on the source ship. The gun array was fired on the minute, and explosives timed for every 7 minutes.

ESP lines involving both airguns and explosives were shot as outlined above. The switch from airguns to explosives always took place after the source ship had passed the mid point and cleared the receiving ship's tail bouy (Fig. 14c). This would result in an approximately 30 to 50 minute, or 4 to 8 km gap, 2 km beyond the mid point while *Conrad* retrieved her gun array. This gap is covered by records made on converging ranges. Clearly, *Conrad* could not also tow a streamer during explosive lines and consequently, no vertical incidence CDP profile could be collected. Thus a separate multichannel seismic profile had to be subsequently collected by one or other ship, or the ESP laid out on a pre-existing seismic line. All mid course corrections were undertaken by the source ship, since she had no streamer astern.

ESP lines on the Exmouth Plateau were laid out in three transects: an *Exmouth Transect*, running WNW across the plateau from the shelf north of Barrow Island to the Gascoyne Abyssal Plain, consisting of 9 ESP's; a *Cape Range Transect*, running SW from the centre of the plateau to the Cuvier Abyssal Plain, consisting of 4 ESP's; and a *Cuvier Transect*, running ESE from the Cuvier Abyssal Plain to the shelf south of NW Cape, consisting of 5 ESP's. All 18 ESP's were laid out to avoid known structural complexity or along-line variation, to be representative of known structural or physiographic provinces, and to simplify operations and minimize transits. Where possible, ESP's on the *Exmouth Transect* were laid out along segments of the GSI 1976 "group shoot" multichannel seismic grid, as well as other commercial and B.M.R. data.

Exmouth Plateau Transect

An example ESP (E-7) from the Exmouth Transect is shown as Fig. 16, and two examples of velocity versus depth profiles (from E-5 & E-7) as Fig. 17. There are qualifications, however, concerning some results which must be emphasised:

1. Shelf ESP's E-1 and E-2 will be strongly affected by blind zones and velocity inversions. Velocity data from West Tryal Rocks No. 1 indicates an inversion of velocity below the 3.2 km/sec. layer.

2. Outer slope ESP E-7 may be strongly affected by steep dips and unseen structure.

3. Rise ESP's E-8 and E-9A may be strongly affected by navigation errors and seabed topography. Indeed, E-9 was reshot as E-9A because of a seamount.

The interpretation of the velocity layering has been aided by knowledge of the stratigraphy and upper velocity structure in NW Shelf and plateau exploration wells, the interpretation of the WACDP profile through all ESP's on the transect and general knowledge of the significance of various crustal velocities. An immediately obvious conclusion is that the principal depocentre of the basin complex, consisting of the Exmouth Plateau, the NW Shelf continental margin and the northern Carnarvon Basin - prebreakup as well as post breakup elements - lies in the vicinity of the Kangaroo Syncline. The total sediment thickness above basement is about 13 kms.

1. Layers with velocities less than 2.6 km/sec. on the plateau, its lower slope and rise can be associated with sediments of post Triassic rift onset unconformity age.

2. Layers with velocities in the range 2.8 to 5.0 km/sec. are be associated with Triassic and probably Permian sediments. The structural relief of the

3. Normal mid continental crustal velocities in the range 6.0 to 6.4 km/sec. are observed beneath the continental shelf, the plateau and the rise, and are interpreted to represent Palaeozoic metasediments as well as lower crustal lithologies.

4. Deep crustal velocities in the range 7.0 to (?)7.3 km./sec., typical of continental margins (Falvey and Middleton, 1981) occur beneath the outer rise and beneath the plateau itself. In this respect, the structure of the Exmouth Plateau and the Queensland Plateau are quite similar. These velocities have interpreted for the Exmouth Plateau, as underplating (Mutter et al., in press).

Cuvier Transect

A number of qualifications must be made concerning some results:

1. Water bottom topography on ESP C-2 was irregular due to the presence of canyons not charted on bathymetry compilations. This resulted in scollopping of the ESP surface and may affect the velocity interpretation.

2. The presence of strong multiple energy in shelf ESP C-5 may also affect the deeper crustal interpretation.

The interpretation of velocity layering has been aided by knowledge of the stratigraphy and upper crustal velocity structure in the Pendock No.1 well near the location of shelf ESP C-5. The initial conclusions are of progressive downfaulting of the continental margin from the continental shelf to the Cuvier Abyssal Plain, accompanied by thickening of the upper crustal layer westward.

1. Velocities of 3.0 km/sec. and less on the transect are associated with post Palaeozoic sediments. No pre-Cretaceous sediments were encountered in the Pendock No.1 well but they may be preserved in half grabens in the Palaeozoic surface west of the well location.

2. Velocities of 3.2 to 4.7 km/sec. are interpreted as Carboniferous and Devonian sediments as were encountered in the Pendock No.1 well, the low velocities on the shelf reflecting shallow depth of burial. These sediments are truncated on the continental slope between ESP C-3 and ESP C-2. A series of layered horizons with a velocity of 4.1 km/sec. in ESP C-2 may represent layered lava flows.

3. A basement layer with velocities ranging from 4.9 to 6.0 km/sec. ties to Silurian strata in the Pendock No.1 well and can be tied seaward along the profile.

4. A lower crustal layer with velocities ranging from 5.8 to 6.7 km/sec. is interpreted. The shallow depth of this layer on the shelf may be associated with emergence of the Pilbara Precambrian Shield Block to the east. High velocities (>8.0 km/sec) are interpreted as Moho.

Cape Range Transect

Only shipboard results for this transect are now available and at this preliminary stage one qualification concerning results must be emphasised:

1. Structural effects may be present in plateau ESP CR-3, so that accuracy of refractor velocity data must be qualified.

The interpretation of velocity has been aided by knowledge of the stratigraphy and upper velocity structure in the plateau exploration wells, and general knowledge of various crustal velocities. The initial conclusions are of a progressive deepening of crustal layers southwest away from the crest of the plateau, followed by an ancient and persistent uplift near to and possibly determining the southern plateau margin and plateau margin high.

1. Velocities of 3.0 km/sec. or less, on the transect are associated with post Triassic sediments. An exception to this is the 2.9 km/sec. velocity associated with the less deeply buried Triassic at the southern margin of the plateau.

2. An interval with velocities ranging from 2.9 to 4.3 km/sec. represents the Triassic/Permian section. A consistent refractor with velocities ranging from 4.1 to 4.3 km/sec. occurs in the top third of the interval and defines the top of a layer which accompanied most of the thickening of sedimentary section between the plateau crest and the plateau margin high. The implication is that the structural configuration which determined the presence of the plateau margin horst existed in the Palaeozoic and lower crust. That is, the southern plateau transform margin rifted preferentially on the downthrown side of an already uplifted basement block.

3. An upper crustal layer with velocities ranging from 5.3 to 5.9 km/sec. is interpreted to represent Lower Palaeozoic sediments and metasediments. The corresponding layer on the close-in Cuvier Abyssal Plain has a velocity at the top of the range. An elevated velocity is typical of quiet zone crust (Talwani et al., 1979).

4. Lower crustal velocities of 6.5 to 7.5 km/sec. were tentatively identified. High deep crustal velocities (>7.0 km/sec.) were also encountered on the Exmouth Transect and are reported previously for continental margins by Falvey and Middleton (1981).

5. A base crustal refractor (8.1 km/sec.) is tentatively interpreted for the Cuvier Abyssal Plain site. The resulting crustal thickness of 13 km (total depth 18 km) is more typical of quiet zone and may indicate thicker than normal oceanic crust. Oceanic seafloor spreading magnetic anomalies are interpreted in the Cuvier Abyssal Plain to the south of the CR-4 site.

Wide Aperture CDP Profiles (WACDP)

A WACDP achieves the equivalent of a conventional multichannel seismic profile with an extra long receiving array. It is constructed from the streamers of two ships towed separately in line, each ship firing its own airgun array alternately into both streamers, as shown in Fig. 18 (Buhl et al, 1981). The benefit derived from use of a wide aperture, or long receiving array is that it provides a combined high CDP fold (48) with sufficient source-receiver offset that travel time separation of primary and multiple reflections can be achieved in relatively deep water. This is sufficient to enhance very deep reflection events and provide greater velocity discrimination at greater depths (Fig. 19). It is therefore ideally suited to deep crustal studies, in particular, in tying individual ESP lines together at their mid points. Centres of all the ESP's in the *Exmouth*, *Cape Range* and *Cuvier Transects* were tied with WACDP profiles.

In all three WACDP profiles, *Rig Seismic* was the lead ship and *Conrad* was the tail. Both ships towed a nominal 2400 m, 48 channel streamer. A 2450 m gap (48 plus 1 channels) was left between the last channel on the lead streamer and the first channel on the trailing streamer. *Rig Seismic* fired its airgun pair on the minute and *Conrad* fired its airgun array on the half minute, both shots being recorded in both streamers, on both ships.

Timing of the shot cycle to 1 millisecond was achieved by using the same synchronized clocks on both ships, as used during ESP operations. Ship separation was maintained at better than 10 m, or less than a quarter of a group, by using *miniranger*. Thus a streamer of apparent nominal length 7200 m was synthesized. In practice the much smaller airgun pair on *Rig Seismic* meant that the arrivals on the streamer from 4800 to 7200 m were relatively weaker than those from 0 to 4800 m and may therefore not always be useful.

Exmouth Plateau Transect

The Exmouth Plateau WACDP transect ties the midpoints of ESP's E1 through E9. Four of the range data sets were collected by the cable of the *Rig Seismic* and the remaining two by the cable of the *Conrad*. The *Rig Seismic* was the lead ship and thus recorded the 0 to 2400 m and the 2400 to 4800 m ranges. The WACDP profile displays the rift structure and defines the main tectonic features investigated by the transect (Fig. 20).

The eastern end of the transect crosses the Rankin Trend, the location of current major gas production at North Rankin "A". The

Rankin Trend diplays a dominantly horst and graben structure formed by normal rift faulting. Downfaulting west of the Rankin Trend forms the Kangaroo Syncline.

Further west of the Kangaroo Syncline, the reflector corresponding to the Triassic rift onset unconformity is progressively elevated along normal rift faults to form the Exmouth Plateau Central Dome and further west, downthrown to form the continental slope and rise of the Exmouth Plateau. The character of the seismic reflections below the rift onset unconformity surface over the plateau and to the east is sedimentary. On the deep western margin of the plateau the character of events below the rift onset unconformity suggests that volcanic flows have outpoured onto the rift surface, although these are not as extensive as the outpourings on the Voring Plateau (Mutter et al., 1983).

The affects of the second rift stage on the Exmouth Plateau (Fig. 21) can be best seen within the Triassic and probable Permian sediments. Similar extension within the lower crust is implied but not well imaged in the WACDP data. Fault blocks associated within the Triassic/Permian sediments tilt seaward and are bounded by landward dipping rift faults towards the landward margin of the Exmouth Plateau. The extension levels are low and the extensional faults appear to sole into decolements in the lower layers of the sedimentary setion. High seismic amplitudes are associated with the zones of decolement on the inner plateau possibly relating to mylonitisation of those zones (Mutter et al., in press). On the central Exmouth Plateau the direction of tilting of the fault blocks changes to landward and the rift faults change to dipping seaward. The region of reversal of fault direction over the central plateau coincides with an absence of the zone of strong amplitude reflections within the lower sediments overlying basement and may coincide with a less developed decolement zone in the lower sediments above basement in that location.

Towards the seaward margin of the Exmouth Plateau tilt blocks dip landward and extensional faults dip seawards and a deep high amplitude decolement zone is again in evidence above basement. On the seaward edge of the plateau extensional faults are observed to detach within basement and lower crust indicating a more ductile basement and lower crust close to the ultimate junction with the Cretaceous oceanic crust (Mutter et al., in press).

Data relating to the first rifting stage which mainly accomplished the Exmouth Plateau's basement and lower crustal configuration, are also contained within the WACDP and ESP data sets. The Moho interpreted from the ESP data set appears to correspond to the base the zone of corresponding to underplating velocities above 7.0 km/sec. ESP's E4 and E5 both have truncated basement and lower crustal sections associated with a major low angle landward dipping detachment zone interpreted from the WACDP data between CDP's 7000 and 12000. Landward of that location between CDP's 2000 and 7000, a seaward dipping detachment zone is developed. Another seaward dipping detachment appears to be present towards the landward edge of the WACDP profile. A free air gravity high on the central Rankin trend appears to represent relatively shallower lower crustal material associated with movement along the latter seaward dipping detachments. Fault zones within the basement and lower crust on the plateau may be imaged by some tentatively identified seismic events. Such zones would be expected to be present, since the second stage extension in the lower crust would be expected to approximately equal that in the sedimentary section. Detachment of second stage rifting within the sedimentary section over the plateau proper is above basement implying extension of basement and lower crust from that in the sedimentary section during the second stage of rifting. The onset of oceanic crust appears from seismic and magnetic data to coincide approximately with the foot of the western scarp of the Exmouth Plateau.

Cuvier Transect

The Cuvier WACDP profile (Fig. 22) is 250 km in length and ties the centres of ESP's C-1 to C-5 from the Carnarvon Terrace to the Cuvier Abyssal Plain, south of and parallel to the southern margin of the Exmouth Plateau.

The eastern end of the WACDP profile ties the Pendock No.1 well on the continental shelf and the general arrea of DSDP Site 263 in the Cuvier Abyssal Plain. The Pendock No.1 well encountered Pleistocene Exmouth Limestone at the seafloor (W.D. 131 m) overlying Miocene limestone and calcarenite at 198 m, Eocene calcarenite at 411 m and Palaeocene basal Cardabia Group at 585 m. These strata disconformably overly Upper Cretaceous Koronjon Calcarenite at 749 m. At 817 m these in turn disconformably overly Lower Cretaceous strata consisting of Gearle Siltstone, Windalia Radiolarite, Muderong Shale and Birdrong Formation. An unconformity at 1019 m, occurs at the top of the Carboniferous interval, which unconformably overlies Devonian sediments at 1094 m and Silurian at 1840 m.

The WACDP profile shows a progressive downrifting of the continental margin producing horst/graben topography on the continentl shelf, slope and rise. On the continental slope a number of half grabens are formed by down to the ocean westward dipping normal faults and are infilled by strata unrepresented at the Pendock No.1 location.

The Cuvier transect is characterised by shallow basement. Consequently, no well developed separate second rifting stage structures analogous to that on the Exmouth Plateau, are present within the sedimentary section. Secondary rifting prior to seafloor spreading would, in this instance correspond to faults largely within basement and lower crust, which are not well imaged in the present data set. The Exmouth half-grabens feature on the continental slope of the Cuvier transect and a number of other fault zones could reflect either second stage faulting or lesser faulting within the first rifting stage.

The continent/ocean boundry (COB) is interpreted at the location of coincident positive gravity anomaly expressed as an inflection of the regional and magnetic anomaly high. The mounded feature probably representing the COB occurs oceanward of a series of volcanic flows discussed by Mutter (1988). The effect of these flows is to broaden the observed magnetic anomaly to incorporate both the anomalies associated with the lava flows and the COB (Fig. 22).

The crustal thinning and extension during the primary rift phase is suggested by the interpretation of velocities from the ESP data sets. A pick of base crust for the three seaward most ESP's C1, C2 and C3 and extrapolation of a weak WACDP pick landwards suggests a thinning of the basement and lower crust from around 10 km in the region of the continent- ocean boundary to approximately 25 km on the continental shelf in the region of the Pendock 1 well.

Cape Range Transect

The Cape Range WACDP transect ties the midpoints of CR1 through CR4. The Cape Range transect is 300 km long and runs in a south westerly direction from the southern Exmouth Plateau to the Gascoyne Abyssal Plain (Fig. 2). The line ties the Vinck No. 1 well and the GSI data on the southern Exmouth Plateau.

Triassic blocks rise toward the southern plateau margin and the sedimentary character of prerift strata persists to the continental slope. This is in contrast to the western margin of the Exmouth Plateau where the prerift seismic character is suggestive of basement or igneous lithologies. On the plateau near the southern margin, the strata under the rift unconformity typically tilt away from the plateau margin and are cut by normal faults downthrown to the plateau margin. Normal faults dipping away from the margin are less common close to the margin but occur south of the Vinck No. 1 well and are associated with a reversal of structural dip at that location. Deeper intra Triassic or base Triassic rflectors are observed towards the plateau margin.

Prograding of the Barrow deltas from the south is observed in the shallow section near the plateau margin reflecting a provenance from the south in prebreakup time. Onlap and pinchputs of the Muderong Shale between the base Gearle and Top Barrow reflectors occurs just south of the structural rollover on which the Vinck No. 1 well was drilled.

The southern plateau scarp is formed by progressive down-faulting where ponding of sediments over oceanic crust is observed. Two prominent unconformities occur in the shallow sedimentary section on the abyssal plain. Sediments below the lower unconformity are similar in character to the Barrow Group sediments on the plateau but are flat lying suggesting they are composed largely of erosional products of Barrow Group sediments.

Model for the Formation of the Exmouth Plateau

The first stage of rifting in the Exmouth Plateau region, which established the basic basement and lower crustal configuration, appears to be Permian in age and to be associated with onshore half graben development. The Exmouth Plateau margin clearly does not fit a simple upper plate/ lower plate model such as is discussed by Wernicke (1985) of Lister et al., in press. Two models appear possible for the early development of the plateau region. The first suggests that the plateau is formed by subsequent extension along the major seaward dipping detachment, of a conventional lower plate margin. The problems of this interpretation are two-fold. Firstly, an initial lower plate/ upper plate pair 500 km in width is required. Secondly, the top basement/ lower crustal velocities from the ESP data are 6.0-6.4 km/sec and would not seem to represent the lower regions of the prerift lower crust, even for a low velocity Archean type crust which could occur in the region, as a lower plate origin would suggest.

The preferred model (Fig.23) utilises a major landward dipping detachment at the eastern margin of the plateau to allow separation of the basement/lower-crustal segment which ultimately formed the Exmouth Plateau. The basement and lower crust of the plateau can thus be thought of as the top of a now departed conjugate lower plate margin removed along a deep detachment now retained above the top of the underplating zone beneath the Exmouth Plateau. It can equally be thought of as the base of the upper plate margin now retained landward of the Exmouth Plateau removed along the shallower major detachment mentioned previously. This model has two advantages. Firstly, it does not require an upper plate/lower plate pair each 500 km in length. Secondly, it is more consistent with the landward increase in top basement velocities on the plateau from 6.0-6.4 km/sec (Fig. 24) since a progressively deeper section of prerift crust would be predicted to occur in a landward direction. The model also produces a lateral variation in thermal properties of basement which is sufficiently large to sustain the thermal convection cell indicated in heat flow studies of the plateau. Supporting heatflow results are discussed below.

In the above model the plateau basement and lower crust represent an 'intermediate' plate segment from the primary crust. The Cuvier margin can readily be classified on seismic velocities and morphological grounds as of probable upper plate origins using the models of Wernicke (1985) of Lister et al. (in press). The upper plate model is consistent with the rapid continental crustal thinning from approximately 25 km to 10 km, over 100 km horizontal distance for the Cuvier margin. The major detachment along which the conjugate lower plate margin separated from the Cuvier upper plate would now correspond to the crust/mantle interface of the Cuvier margin. The Cuvier margin, in fact, corresponds closely in terms of the rate of basement and lower crustal thinning, to the Exmouth margin east of the Kangaroo syncline.

The second stage rift imaged within the Triassic and Permian section on the Exmouth Plateau is occurring within what were originally continental sag phase sediments laid down subsequent to the the primary rift phase which produced the fundermental basement and lower crustal architecture. The second stage of rifting preceeded but was probably associated with the onset of seafloor spreading.

Heatflow Data

The thermal structure of the West Australian Shield is modelled by Sclater and Francheteau (1970) as composed of two heat generating zones. The top layer of the crust is 8 km thick and has as heat generation factor of 1.25 uW/m**2. The lower layer of the crust has an internal heat generating factor of 0.25 uW/m**3. . The combination of mantle heatflow and internal heat generation within the crust produces a surface heatflow of 42 mW/m**2.

The heatflow pattern for the Exmouth Plateau transect (Swift et al., in press) is relatively simple. A heatflow high of 100 mW/m**2 occurs in the east and a low of 17 mW/m**2 occurs in the centre of the plateau. The West Australian Shield parameters when combined with the structuring of the preferred model define heat production zones. To the east the basement's thermal structure is predicted to be like that of the West Australian Shield, whereas the Exmouth Plateau arch is predicted to be a pod of low heat production.

The conductive heatflow model alone (Fig.25) does not fully explain the measured heatflow highs and lows even though the average of each curve is 56 mW/m**2. The major feature of the surface conductive model is the heatflow low in the centre of the plateau. This low is due to the pod of initial lower crust which has a low heat production rate. This low is seen on the curve representing conductive heatflow on top of basement (Fig. 25). That curve shows good agreement with the WA Shield average in all regions except in the centre of the plateau and towards the plateau margin in the west where the crust has been thinned.

Unlike the WA Shield there has been up to 12 km of sedimentation on top of basement in this region. The average surface heatflow is 56 mW/m**2 not 42 mW/m**2 as is found on the WA shield. The difference corresponds to a reasonable heat production rate of 1.4 uW/m**2 for the sedimentary section.

The heatflow low cannot be modelled by conductive heatflow alone, and a major convection cell within the sedimentary section is required to explain the measured surface heatflow (Swift et al., in press). There is a correspondence, however, of the conductive heatflow low and high at the top of basement and the measured conductive/convective surface heatflow. The differing thermal properties of the basement result in one region of the plateau being heated more than another. The fluid is then not in equilibrium so convection will occur. Convection occurs because the higher temperature on the hot side leads to density differences and hence buoyancy forces in relation to the cooler side,resulting in the hotter fluid rising while the cooler fluid sinks. The heatflow in the rising column should be higher. Consequently, a lateral variation in heatflow at the basement level will be accentuated at the surface because of convection.

In the case of the Exmouth Plateau, the average fluid velocity is 3/10**9 cm/sec which implies a horizontal temperature gradient of 0.08 degrees C/km or more is required to have convection. When considering the whole thermal structure the horizontal gradient is, in fact, of the order of 0.2 C/km. That is, the thermal structure within basement favours convection within the overlying sediments. There is no direct relationship, however, between surface heatflow and baseement structure. This is because of the convection of pore fluids above basement. The thermal structure at the top of basement is, however, consistent with production of a convection cell within the sediments.

Magnetics

Magnetics were recorded during ESP's and WACDP profiling and in transit using 2 Gradiometrics G801/803 proton procession magnetometers. Where Gradiometer data were not collected due to equipment servicing or complexity of manouevres, single channel magnetometer data were recorded. Diurnal effects during the study were monitored by an onshore magnetic station maintained by NATMAP personnel. Details of magnetic data collected are given in Appendix A and are plotted along with line drawings Figs 20 and 22.

Total field magnetic anomalies recorded over the plateau are of long wavelength and low amplitude reflecting a substantial thickness of non-magnetic sediments. Towards the plateau edge and on the slope and rise the shallower basement and the presence of igneous rocktypes at the rift unconformity produces higher amplitude shorter wavelength anomalies. Seafloor spreading anomalies over oceanic crust on the abyssal plains adjacent to the plateau.

Gravity

Gravity data were recorded during ESP's and WACDP profiling and in transit using a Bodenseewerk Geosystem KSS-31 Marine Gravity Meter. Locations of traverses are given in Appendix A and gravity data corrected for Etvos effects but not latitude are displayed along with line drawings on Figs 20 and 22.

The raw gravity data largely reflect changes in water depth. However, regional variations are observed which are due to local changes in crustal rocktypes and densities. Processing of the gravity data and modelling in conjunction with the results of the ESP, WACDP and multichannel seismic reflection results will allow a more refined definition of the structure and crustal composition of the plateau.

SYSTEMS RESULTS

Data Acquisition System

Navigation

The Exmouth Plateau cruise presented a considerable challenge in providing high accuracy navigation in deep water. This was needed to adequately control the ESP and WACDP profiles. A major effort has been mounted by the Division of National Mapping (NATMAP) to provide a HIFIX radio navigation system in a difficult and remote environment.

Positioning of the ship is derived from a heirachy of three largely independent systems. Considerable skill is required to choose the best system as each exhibits limitations from time to time.

Global Positioning System

A Magnavox T-Set gives continuous absolute positioning within about 20 metres r.m.s. under optimum conditions. However the system is in the experimental stage with only 7 of the proposed 24 satellites in orbit. Positioning is possible for some 8 hours a day but this can be extended to 12 hours in the two-satellite mode by using an atomic frequency standard. Success depends entirely upon an acceptable frequency bias between the satellite transmissions and the standard being determined during the previous period of three to four satellite visibility.

The period from 2000 through to 0300 GMT generally gave consistently good results with three or more satellites above the horizon for about five hours. A further period from 1100 to 1900 GMT could also be used for navigation but for roughly half the time there were only two satellites visible. Effective use of periods of only two satellites was found to have considerable uncertainty. With the incomplete satellite constellation, the quality of fixes as the third satellite disappeared from view was often poor, and the resultant frequency bias inaccurate. Positions in error by as much as two or three miles were found to occur, so continued monitoring of the bias values and exclusion of unacceptable periods was necessary.

Navigation System

The HIFIX system is typically used for position fixing over distances of 100-200 kms where shore transmitters can be located to provide acceptable accuracy in hyperbolic range mode. The Exmouth Plateau exercise required operation in the range 300-500 kms while the the shape of the coastline meant a restrictive shore station geometry. As a result, only two transmitters were likely to be received at any one time.

From previous experiments on the Queensland Plateau, we had shown that HIFIX data could be satisfactorily received over ranges in excess of 500 kms, though noise levels were in excess of 20 centi-lanes (about 30 metres) at night. If the geometry problem could be solved along with operation using only two transmitters, we had a viable navigation system.

The requirement has been met by installing an atomic standard at the master station onshore to stabilise all shore transmissions. In addition another atomic standard was used on the ship to provide pseudo-range observations, obtained by comparing the observed signal with the standard rather than another of the channels as in hyperbolic mode. In theory the only error is the drift between the two standards.

Shore stations have been set up at Karratha, Onslow, Exmouth and later at Ningaloo and Gnaraloo. Only three transmissions can be received at any one time. The prime transmitter was at Onslow for the northern chain and Ningaloo for the southern chain, with Exmouth as a common slave station.

HIFIX reception on the ship has proven successful most of the time despite the long range. Onslow and Exmouth have been picked up 24 hours per day with a tendency to lose lane lock between dusk and midnight local time when over the western side of the Plateau. Less success has been obtained with Karratha and similarly with Ningaloo when night time reception was almost nonexistent.

Despite these problems, adequate real-time navigation (25-50 metres) has been achieved over much of the plateau for some 18 hours a day. There are times when the velocity control can be most inadequate, though positional control can still be acceptable. Post-processing allowed recovery of accurate positions for upwards of 20 hours a day.

Dead Reckoning System

Two independent systems incorporating gyro compass, dual-axis sonar doppler log and satnav receiver provide basic dead reckoning for periods where the other systems prove inadequate. Such a system was the main method for positioning a research ship until the advent of GPS, or the rare occasions when a high resolution system such as HIFIX was available.

The primary dead reckoning system of Arma-Brown gyro, Magnavox MX610D sonar doppler and MX1107RS satnav receiver provides the best available positioning of this type. A lower grade system of Robertson gyro, Raytheon DSN450 sonar doppler and MX1142 satnav receiver is the backup.

Ship-to-Ship Ranging and Synchronisation

Determining the relative positions of the *Conrad* and *Rig Seismic* was achieved using radar observations and two independent electronic distance measuring systems, the Miniranger III and the Raydist. The prime station for both EDM systems was on the *Conrad*, and no information could be obtained or recorded from the transponders on the *Rig Seismic*.

Direct observation of range and bearing were made out to around 5 kms as the two ships passed, using radar and gyro compass. These best define the common centre of the the ESP lines.

At medium range, the Miniranger was used to give accurate distances directly in metres. Two transponders were needed on the *Rig Seismic*, one looking forward and one looking aft to give all round coverage out to about 20 kms. However, no bearings could be obtained and these must be derived from best fit of the observations to ships' position. The Mini-Ranger was also used to maintain vessel separation during WACDP work, and is similar to HIFIX giving only a relative distance.

For ranges up to 100 kms the Raydist was used. This is a phase comparison device and phase must be calibrated against the Mini-Ranger to give distance. Again information on bearings is not available.

A VHF radio was installed in the instrument room for communication between the *Rig Seismic* and *Conrad* laboratories. Range was about 40 km. Clock synchronisation was checked by transmitting an alarm signal which was sounded on the minute by the gun firing system on the *Rig Seismic*, via the VHF radio to the *Conrad*.

Bathymetry

Development of both the 3.5 kHz and 12 kHz echo sounder system is continuing. The 3.5 kHz system has been separated into two groups of transducers, one in a special coffer dam and the other in Centre Tank 6 to allow evaluation.

Another step forward has been to develop slave recorders that are intended for both the bridge and winch labs, with automated time marks and labelling. These are driven by an M-series computer which provides independent asynchronous operation. Evaluation is continuing. Eventually, these will operate with the 12 kHz echo sounder to give more reliable depth information around the ship, when coring or in restricted waters.

The 12 kHz system has been converted to operate with the CESP-I signal correlator. This provides an improvement in signal-to-noise ratio of 20 dB which should allow effective operation at abyssal plain depths and on the steep slopes of the continental margin.

Magnetics

A gradiometer with two sensors 200 metres apart was used for most of the survey because of the considerable distance from shore. Synchronisation of the two standard magnetometers used has proved difficult to achieve because of a drift in the timing cycle triggering polarisation and measurement. Considering the depth of water and wavelength of the magnetic anomalies, the noise levels are quite acceptable though further improvement is necessary to detect the nuances at the surface caused by faulted basement under great thicknesses of sediment found over the Exmouth Plateau.

Gravity

Essentially no problems were experienced with the Bodenseewerke KSS-31 marine gravity meter. During heavy rolling seas, the ship's heading varied by up to 10 degrees which in turn produced increased noise levels in the gravity data, at times reaching around 5 mgals. Post-processing allowed reduction of this to a more acceptable level.

Seismic Acquisition Systems

The differing operational techniques used in CDP, ESP and WACDP, have necessitated the software generation of two new Seismic Acquisition Operating Systems. Basic differences exist in record length and shot firing control. The two operating systems have grown as hybrids of the BMR CDP system.

ESP Data Acquisition

The ESP operating system is similar to that used for the CDP profiles except that the shot rate is constant and cannot be altered. To assist in the synchronizing of firing upon *Conrad* and acquisition of seismic data upon *Rig Seismic*, the shot was fired on the minute, using transit satellite time. System clocks upon the two ships were checked regularly; *Rig Seismic's* Seismic Acquisition System transmitted a tone over a VHF radio to *Conrad* at *Rig Seismic's* one minute mark.

Instead of the shot interval being converted into a counter and incremented as it is in the CDP operating system, the system clock is read on the 0.1 sec interrupt to determine when there is a new minute. If it is a new minute, acquisition will be scheduled but no guns fired as the firing lines are not connected.

A record length of 32,000 milliseconds was chosen to make full use of the Hewlett Packard computer's 16 bit logic and enable observation of later seismic returns.

Due to the slow sampling rate and the lack of visible information, the displays upon the ship-board monitors have been spread out and a raster limit set to better emphasize the seismic return. Two of the monitors were preset so that one displays the record length 0 - 12 secs + delay and the other 12 - 24 secs + delay.

As it was not possible to see most of the raw data, it was decided to use the following rules to decide on the acquisition delay.

Distance from Centre of ESP Line (n.miles)			Delay (secs)
0	-	10	0
10	-	16	5
16	-	20	8
	> 20		10

WACDP Data Acquisition

The WAPCDP operating system is the most diverse from the standard CDP in its concept of alternate shot firing. Similar to the ESP operating system, the system clock is checked to determine whether acquisition should occur. If it is a new minute then control is set, a pulse sent to the firing box and acquisition occurs after the specified delay has elapsed. On the half minute, acquisition is restarted but no control is set to fire the guns, thus producing a non-shot acquisition cycle.

The acquisition which occured when there was no shot fired by *Rig Seismic's* Seismic Acquisition System, was that for the shot fired on-board *Conrad*, where firing occurred on the half minute.

Using the shot instant time which is recorded in the SEG-Y header to determine which shot has just been fired, the on-board seismic monitors were modified so that the Cycling, Slow and Fast monitors displayed the seismic returns from Rig Seismic's shots and the Special monitor became a Fast monitor displaying Conrad's shots. Data enhancement techniques used in the ESP operating system have been incorporated in this system. Special attention was required to ensure correct annotation on all outputs. During the WPCDP profiles, acquisition delays were determined by the observed seismic returns from *Rig Seismic's* shots.

Airguns

A 6000 cu in airgun array was operated by *Conrad* as primary shooting ship. Two 500 cu in Bolt airguns were operated by *Rig Seismic* throughout the cruise, with no difficulty encountered in maintaining operation during lines when *Rig Seismic* was shooting as well as receiving.

CONCLUSIONS

The results of phase two of the Exmouth Plateau research program indicate that the ESP, WACDP and multichannel seismic reflection data collected can help define the crustal structure and stratigraphy of the Exmouth Plateau region, as well as its mode of formation. This will enable particularly a reassessment of the possible distribution of potentially oil-prone Lower Triassic and Permian source rocks beneath the plateau by calibrating seismic reflection data with ESP velocity results which identify gross stratigraphy and structure.

Nineteen ESP's were collected, nine on the Exmouth Plateau transect and four on the Cape Range transect, and five on the Cuvier Transect. Nine of the ESP's were collected with explosives and airguns, and nine with airguns alone. The WACDP tie to the Exmouth transect collected 700 km. of two-ship multichannel seismic reflection data and gravity and magnetics data. The remainder of the 18 ESP's added an additional 1100 km. of multichannel seismic reflection data.

The principal conclusion from the ESP and WACDP Transect of the Exmouth Plateau is that the northern Carnarvon Basin and the continental margin basins beneath the NW Shelf and the Exmouth Plateau form a single, continuous Permian to Recent sedimentary basin, up to 800 kms. wide and 13 kms. thick, as illustrated in Fig. 20. This extensive basin was formed prior to the rifting which preceeded breakup and seafloor spreading, firstly along the boundary of the Argo Abyssal Plain and the along the boundaries of the Gascoyne and Cuvier Abyssal Plains. Rift faulting and formation of horsts and grabens occurred at the end of the Triassic. One of the sites of deepest rifting and post Triassic subsicence was along the axis of the Kangaroo Syncline. Post breakup thermal subsidence commenced on the western, central and southern plateau about 120 m.y. ago.

A model for the formation of the Exmouth Plateau has been devised which is consistent with seismic and heatflow data sets. The model involves Permian emergence of the Exmouth Plateau basement and lower crust along a major detachment interpreted from the reflection and refraction data sets on the Exmouth Transect. The model explains the increase in velocity at top basement, landwards towards the Kangaroo Syncline, on the plateau, by relating it to a progressively deeper level of primary crust. The modelled exposure at top basement of deeper levels of primary crust with differing thermal properties is also consistent with the size and polarity of the thermal convective cell indicated by heatflow data from the plateau.

Consequently, the basement and lower crust of the Exmouth Plateau is modelled as a segment of 'intermediate crust' from a primary basement and lower crust which has been separated along two major landward-dipping detachments. The Exmouth Plateau basement And lower crust was, according to this model, originally beneath the upper plate segment retained landward of the Kangaroo Syncline, and above the conjugate lower plate which moved away due to seafloor spreading. This primary rift stage which established the basic basement and lower crustal configuration of the Exmouth Plateau region is probably of Permian age and assocaited with onshore Permian half graben development. Triassic and probable Permian sag phase sediments on the plateau were subsequently rifted prior to seafloor spreading. This second phase rifting within the sedimentary section is associated with decolements near top basement. The basement and lower crust appear to have extended separately from the sediments during second stage rifting, except near the plateau's western margin, where detachment of second phase faults occurs within basement and lower crust, suggesting a more ductile extension in that region prior to seafloor spreading.

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APPENDIX A: GEOPHYSICAL DATA SET

LINE	TIME START GMT	TIME FINISH GMT		WAY-POINT LATITUDE DEG S	WAY-POINT LONGITUDE DEG E	TAPES	LINE LENGTH	DATA COLLECTED
1	System/cable tests					55/001-012		
12	84.1926	85.0708	SOL	19 05.00	113 32.20	55/322-338	109	EX5 G M N B
			MP	19 30.75	113 20.20			
14	85.1846	86.0623	SOL	19 49.00	113 47.20	55/339-356	107	EX4 G M N B
			MP	19 23.25	114 00.40			
16	86.1155	86.2248	SOL	19 09.80	114 31.80	55/357-373	102	EX3 G M N B
			MP	19 36.65	114 34.80			
18	ABORTED					55/374-379		
18	88.0540	88.1632	SOL	20 03.20	115 12.00	55/380-395	101	E2 G M N B
			MP	19 47.60	115 33.65			
20	89.0050	89.1202	SOL	19 40.00	116 31.00	55/396-412	105	E1 G M N B
			MP	19 55.00	116 07.50			
21	90.0306	92.0234	SOL	19 19.50	113 56.00	55/413-495	239	W1 G M N B
22	92.0247	93.0132		19 43.00	112 41.00	55/497-535	203	
			EOL	18 10.00	110 52.50			
24	93.1038	93.1528	SOL	18 39.10	110 51.00	55/536-543	45	E9 G M N B
			MP	18 21.35	111 05.00			
26	93.1755	93.2358	SOL	18 28.00	111 13.00	55/544-552	56	E9A G M N B
			MP	18 10.00	111 27.00			
28	94.0541	94.1509	SOL	18 30.30	111 51.80	55/553-566	88	E8 G M N B
			MP	18 47.90	111 35.80			
30	94.2309	94.1014	SOL	19 31.10	111 44.00	55/567-583	103	EX7 G M N B
			MP	19 11.70	112 03.50			
32	95.1634	96.0338	SOL	19 10.00	112 39.40	55/584-600	103	EX6 G M N B
			MP	19 32.20	112 31.60			
34	96.1735	97.0536	SOL	20 27.50	112 26.00	55/601-618	112	CX3 G M N B
			MP	20 47.50	111 47.00			
36	97.1035	97.2150	SOL	21 05.00	112 14.00	55/619-635	105	C2A G M N B
			MP	20 40.50	112 02.50			
38	98.0227	98.1350	SOL	21 01.00	112 21.00	55/636-652	106	C2 G M N B
			MP	20 33.50	112 17.00			
40	98.1950	99.0434	SOL	20 45.40	112 50.60	55/653-665		C1 G M N B
			MP	20 20.20	112 40.05			
3*	101:0927	101:2239	SOL	20 19.00	112 51.00	56/001-023	126	W2 G M N B
4*	101:2240	102:0909		20 48.50	111 45.00	56/024-042	100	W2 G M N B
			EOL	21 26.00	111:0600			
5*	102:1548	102:1659		ABORTED		56/043-044		
5*	103:1957	104:0445	SOL	21 30.00	111 35.00	56/045-058	84	CR4 GM N B
			EOL	21 15.50	111 18.25			
6*	104:1018	104:2008	SOL	21 26.00	111 06.00	56/059-075	86	W3 G M N B
			EOL	22 13.00	111 30.00			
7*	104:2009	105:2205	SOL	22 13.00	111 30.00	56/076-120	242	W4 G M N B
			EOL	23 16.00	113 33.00			
8*	105:2331	106:0510	SOL	23 14.50	113 28.50	56/121-129	53	C5 G M N B
			MP	23 39.00	113 16.00			
9*	106:1249	106:2345	SOL	23 21.00	112 41.00	56/130-146	102	C4X G M N B
			MP	22 59.00	112 56.50			
10*	107:0211	107:1303	SOL	22 34.00	113 06.00	56/147-164	101	C3X G M N B
			MP	22 53.25	112 46.00			
11*	107:2004	108:0705	SOL	22 17.00	112 37.00	56/165-182	103	C2X G M N B

			MP	22 57.00	111 58.00			
12*	108:1042	108:1730	SOL	22 09.00	112 20.00	56/183-193	64	C1 G M N B
			MP	22 29.75	112 02.00			

En ESP expanded spread profile using airguns
EXn ESP expanded spread profile using airguns to the midpoint and explosives for the remainder of the line.
CRn CR Cape Range ESP
CRXn CR Cape Range as for EXn
Cn Canarvon Terrace ESP
CXn Carnarvon Terrace ESP as for EXn
Wn WACDP wide aperture constant depth profile
n n is the line number; Cruise 7
n* n* is the line number; Cruise 8
SOL start of line
MP midpoint of line
WP way point on line, line number unchanged
EOL end of line
G gravity data
M magnetic data
N navigation data
B bathymetry

APPENDIX B: EQUIPMENT LIST

Geophysical

Primary Seismic Systems

-2400 m Teledyne hydrophone streamer cable; minimum group length of 12.5 m; maximum 96 channels.
-Syntron RCL -2 idividually addressable cable levelers.
-3 BOLT 1500C airguns, each of 500 cu in (8.2 l) capacity, with wave-shape kits; one or two guns, fired simultaneously, would normally be used.
-Teledyne gun signature phones and gundepth sensors, and Input/Ouput SS-8 shot-instant transducers (1 each per gun).
-3 Price A -300 compressors, 300 scfm each; output pressure 2000 psi.
-1 Price AGM W2 compressor, 200 scfm; output pressure 2000 psi.

Secondary Seismic Systems

-2 Teledyne 28420 single-channel hydrophone streamers.
-1 BOLT 1500C airgun of 100 cu in (1.6 l) capacity, with wave-shape kit.
-Reftek 6 sonobuoy receiver.
-Teledyne 28990 acoustic beacon cable location system.

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

-2 Geometrics G801/803 proton precession magnetometers; may be used as standard single -sensor cable or in horizontal gradiometer configuration.

Gravity meter System

-1 Bodenseewerk Geosystem KSS-31 Marine Gravity Meter.

Navigation

Prime Systems

-(1). Magnavox G.P.S. T-Set
-(2). Decca Hi-Fix
-(3). Magnavox MX1107RS dual channel satellite receiver.
  -Magnavox MX610D sonar doppler speed log.
  -Arma-Browm 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 F-Series 16-bit minicomputer with 512 kw of

memory.
-2 x Hewlett-Packard 7905 15 Mb, moving-head disc and multi-access disc controller.
-2 x Hewlett-Packard 7970E 1600 bpi, 9-track magnetic tape drives.
-Facit cassette recorder.
-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.
-Phoenix 6915 15-bit analogue-to-digital multiplexer.
-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.

Seismic Acquisition System (MUSIC)

-Hewlett-Packard 2113 E-Series 16-bit minicomputer with 1 Mega word of memory (acquisition system).
-Hewlett-Packard 2117 F-Series 16-bit minicomputer with 256 kw of memory (development system).
-Hewlett-Packard 7905 15 Mb moving -head disc drive and multi-access disc/cpu controller.
-3 x Hewlett-Packard 7970E 1600 bpi, 9-track magnetic tape drives.
-Phoenix 691515 -bit analogue-to-digital multiplexer.
-BMR-designed 48-channel SMF-1 computer-controlled preamp/filters.
-KSR-43 teletype and TELEVIDEO TVI 910 VDU.
-EPSON MX-100 dot-matrix line printers (x4).
-EPSON MX-100 shot logger.
-Tektronix 611 X-Y storage CRO.
-BWD 804 single-channel CRO.
-BWD 845 dual-channel storage CRO.
-CHRONOLOG digital clock.
-BMR-designed and built NTM-1 marine timing unit.

Hi-Fix Acquisition System (Hi-Fix)

-Hewlett-Packard 2108 M-Series 16-bit minicomputer
-BMR-designed and built 16-channel digital multiplexer
-TELEVIDEO TVI-910 VDU

Raydist/Miniranger Acquisition System

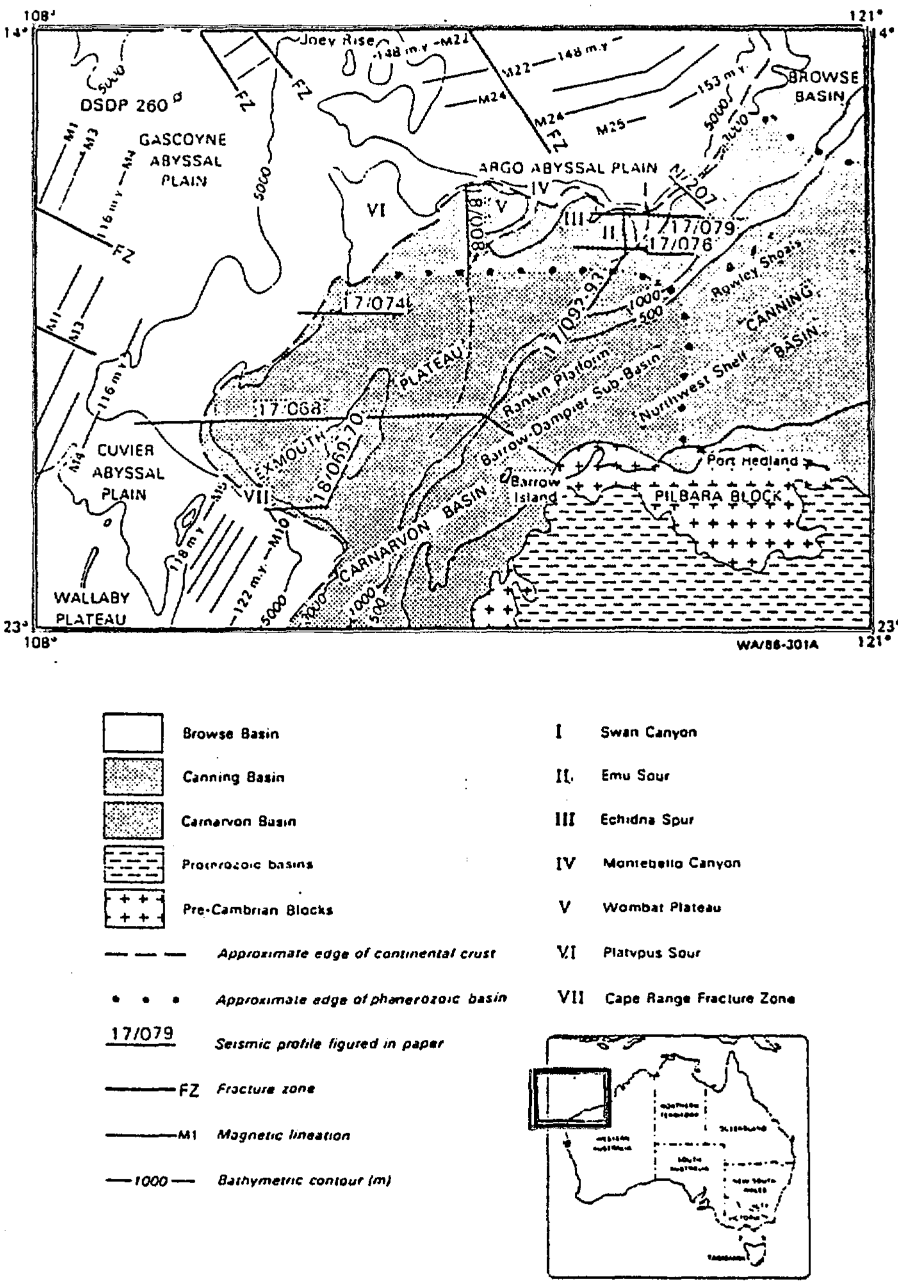
-Forward looking Miniranger III transponder
-Backward looking Miniranger III transponder
-Raydist transponder
-VHF radio

Sub-bottom Profiler Acquisition System

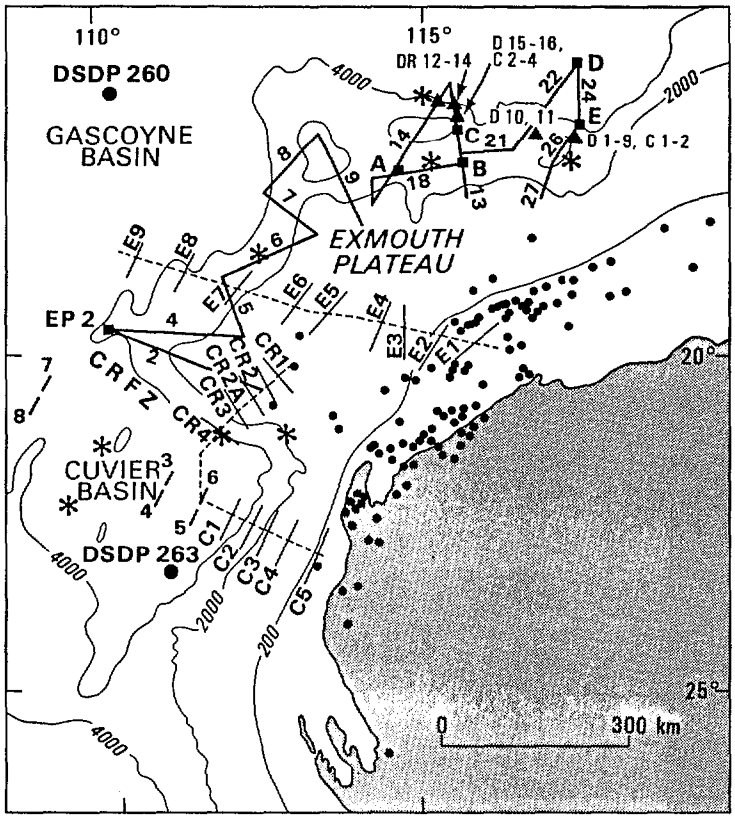
-Hewlett-Packard 2108 M-Series 16-bit minicomputer.
-Facit Cassette recorder.
-Phoenix 691515 -bit analogue to digital multiplexer.
-TELEVIDEO TVI-910 VDU
-EPC Graphic Recorders (up to 4)

APPENDIX C: CO-ORDINATES OF HIFIX TRANSPONDERS

STATION	LATITUDE		LONGITUDE	
Withnell Bay	20	34.939	116	48.440
Onslow	21	38.119	115	6.654
Vlaming Head	21	48.363	114	6.314
Ningaloo	22	40.090	131	41.183



1. Regional and tectonic setting of the Exmouth Plateau.



23/OWA/60

Data generated in 1986

——— *BMR multichannel seismic*

——— *ESP location*

------- *WACDP*

■ *Site survey (ODP and/or geology)*

▲ *Dredge/core site*

Previous data

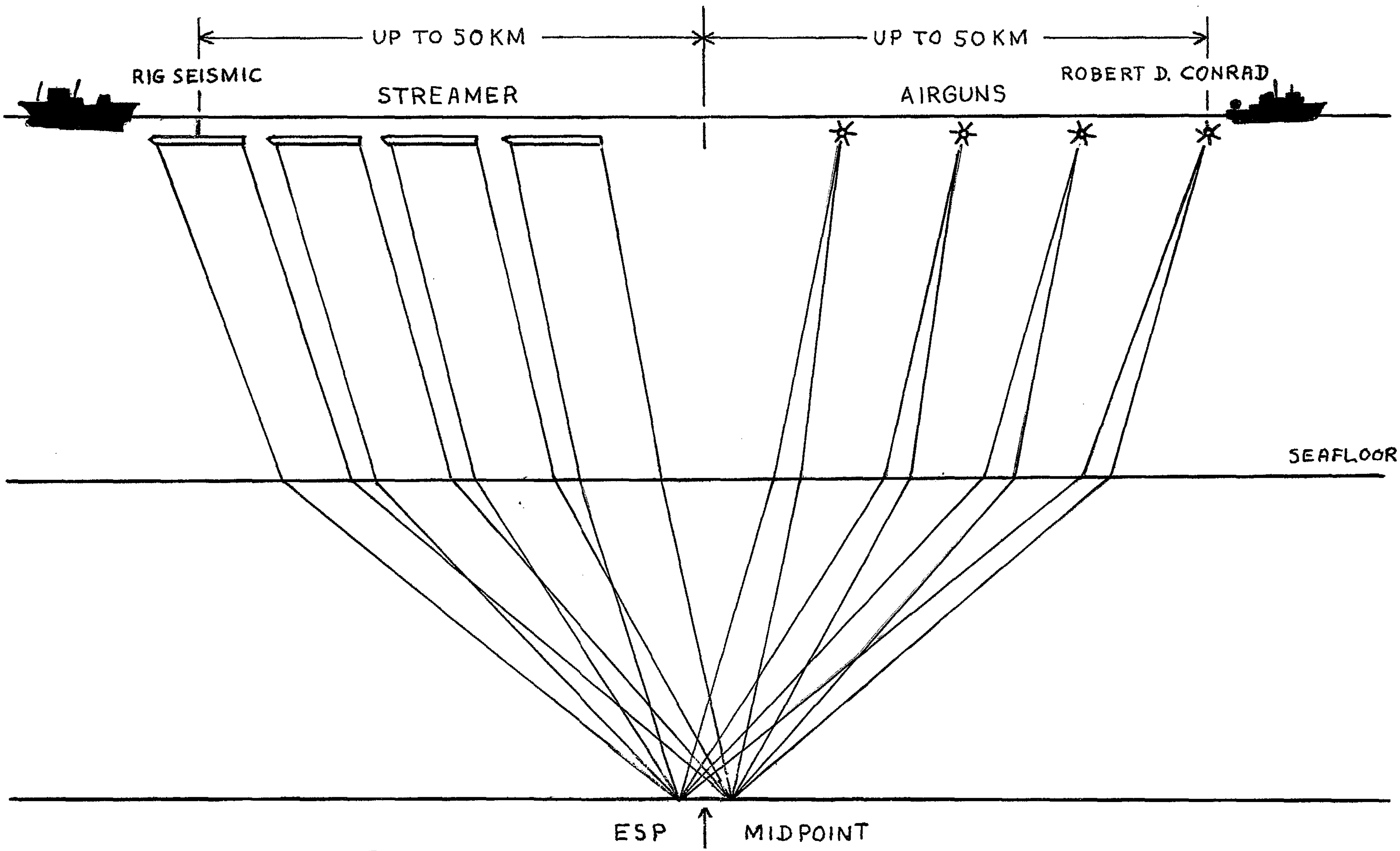
— — *Refraction profiles from Larson & others (1979)*

• *Exploration well*

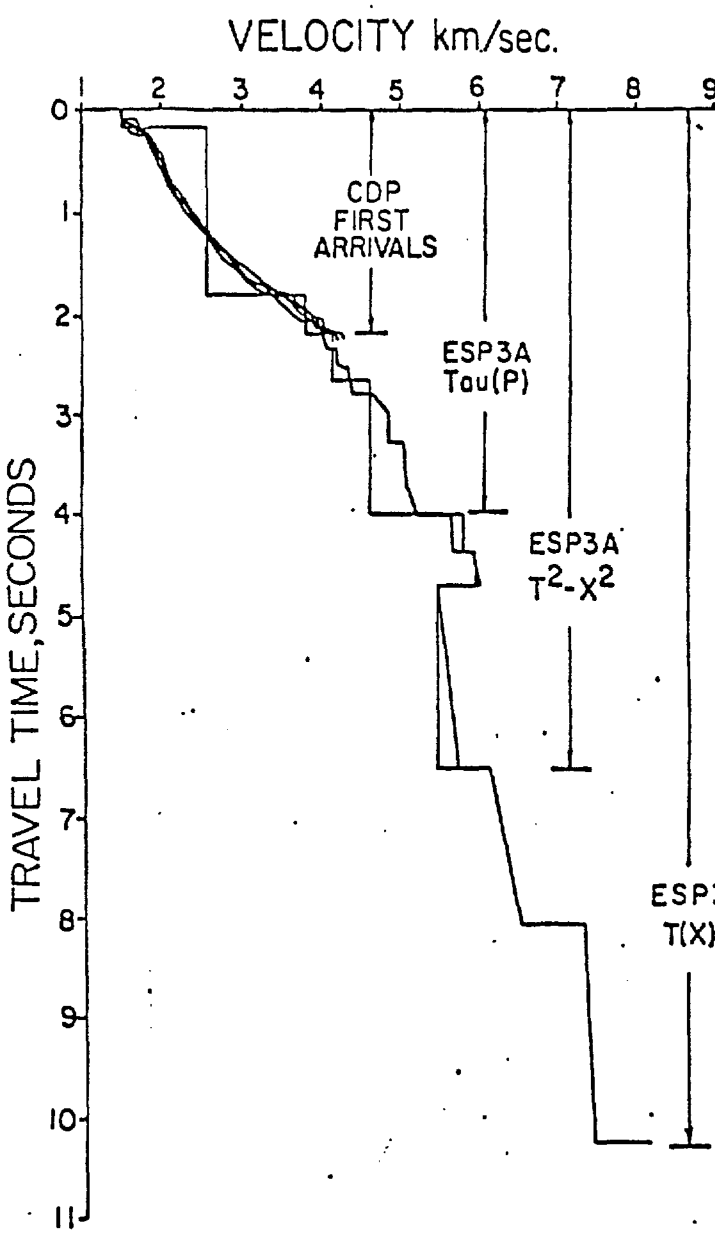
✻ *Dredge location*

2. Location of data from BMR Cruises 7&8 including ESP's and WACDP's.

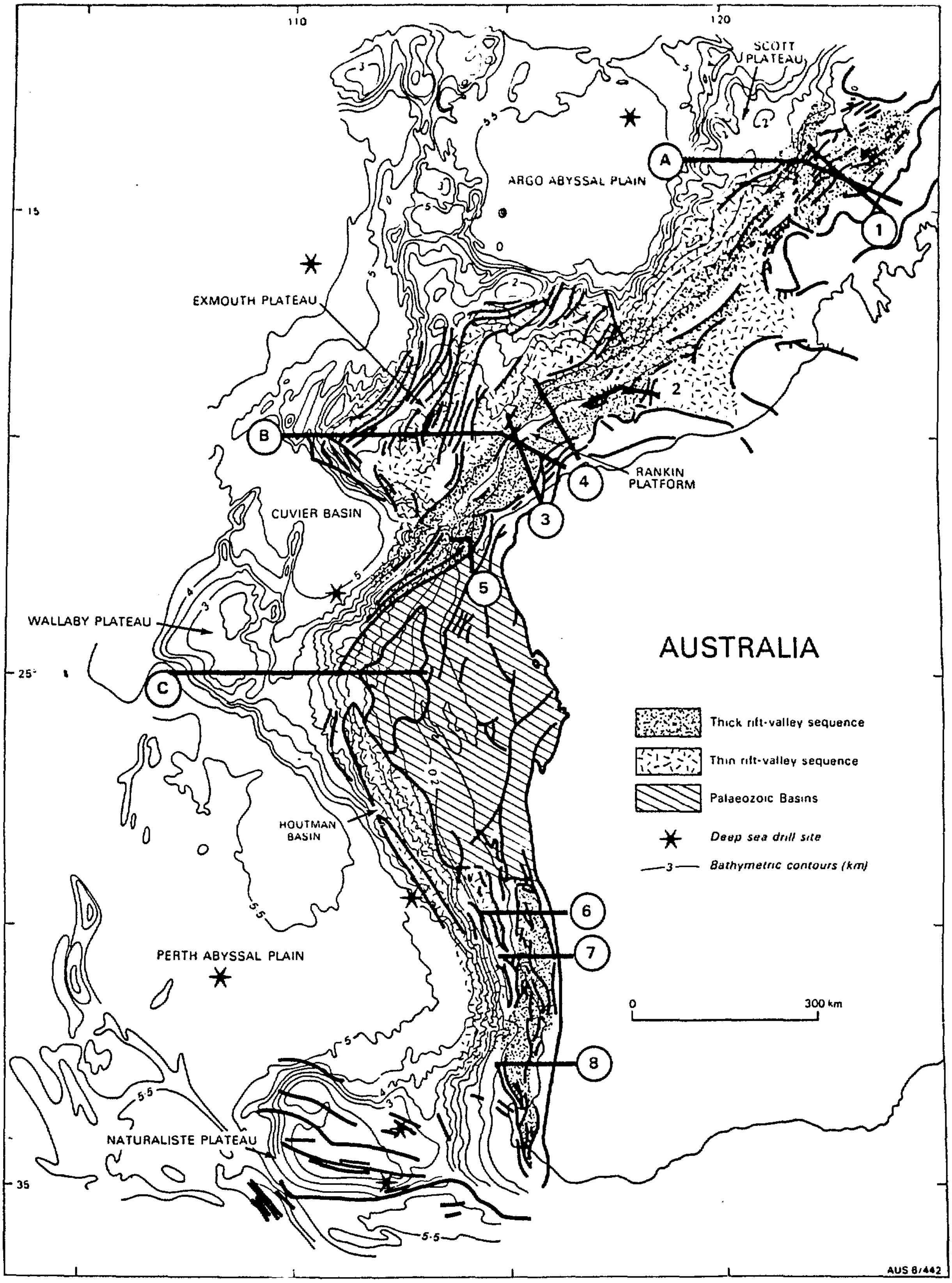
EXPANDED SPREAD PROFILING



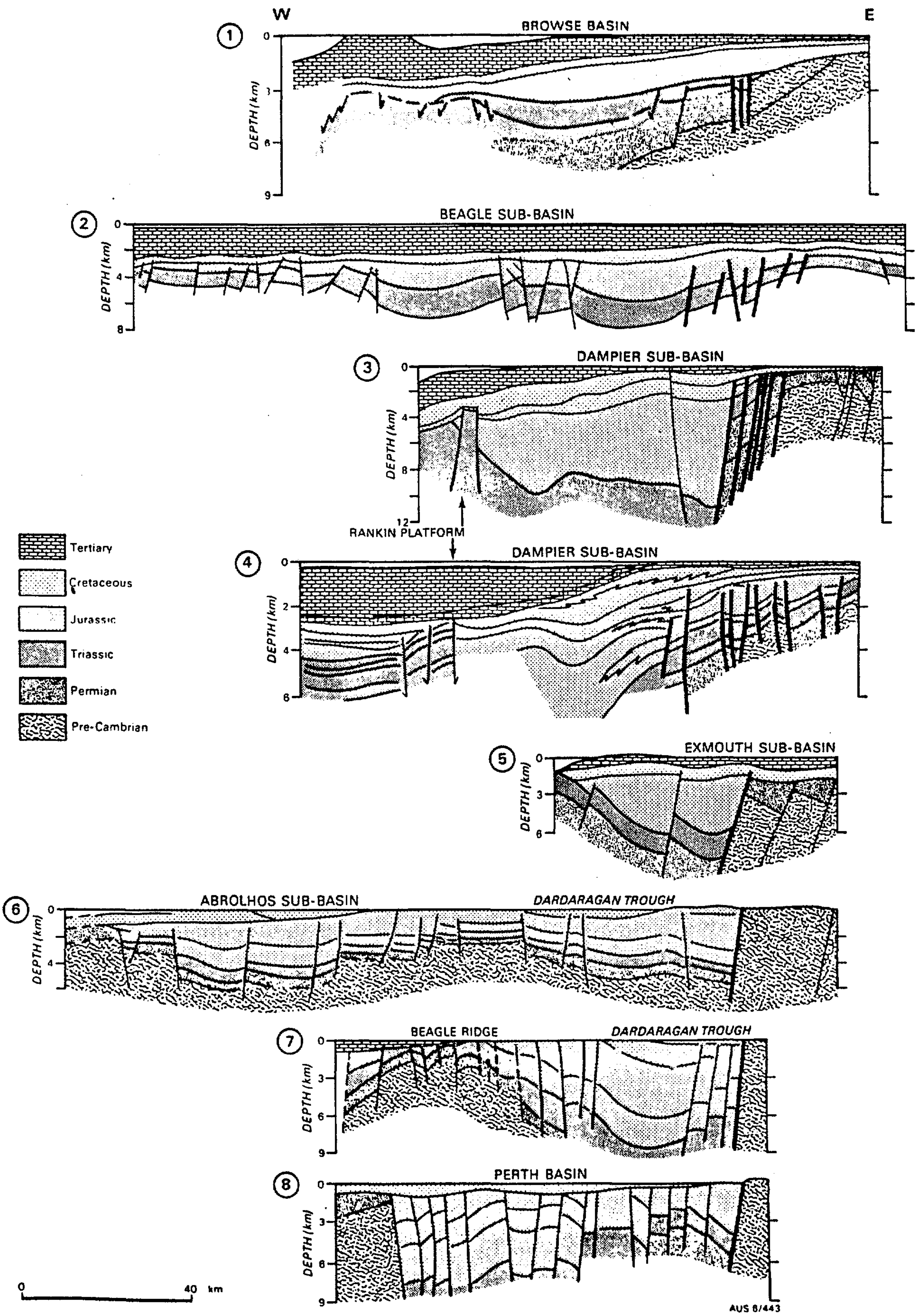
3. Schematic of an Expanded Spread Profile (ESP).



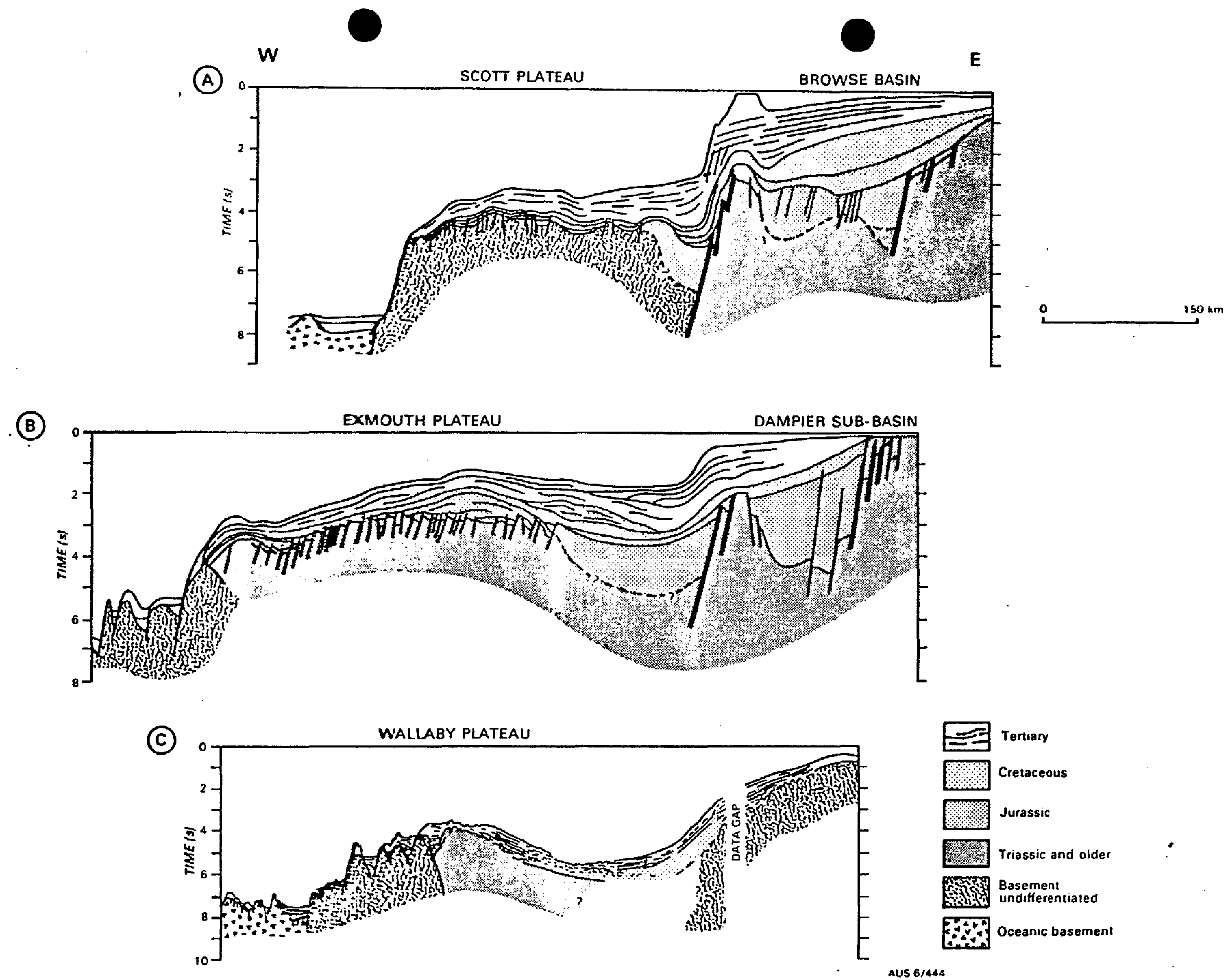
4. Example of an ESP velocity-time inversion.



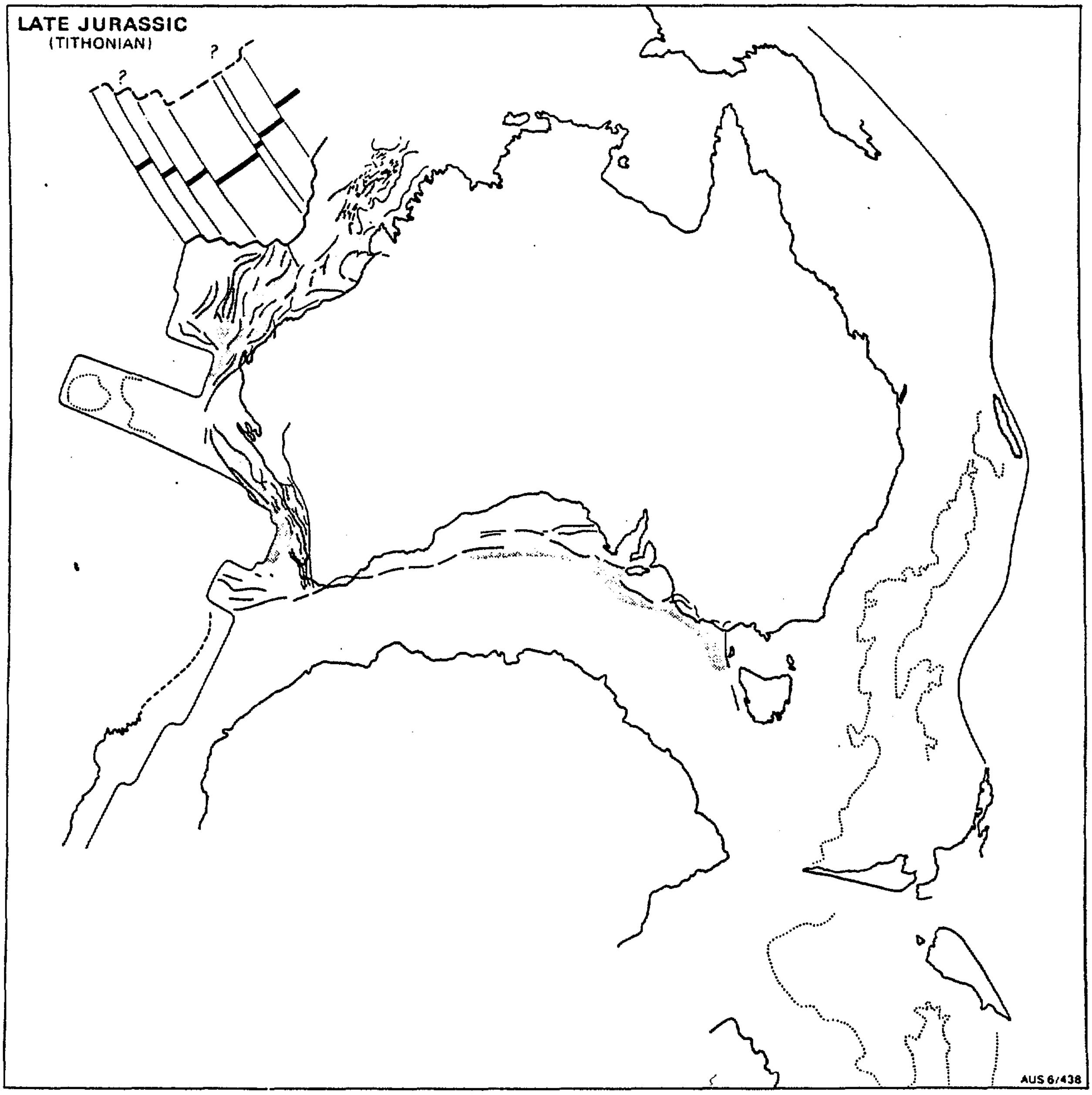
5. Major structural trends on the Western Australian continental margin.



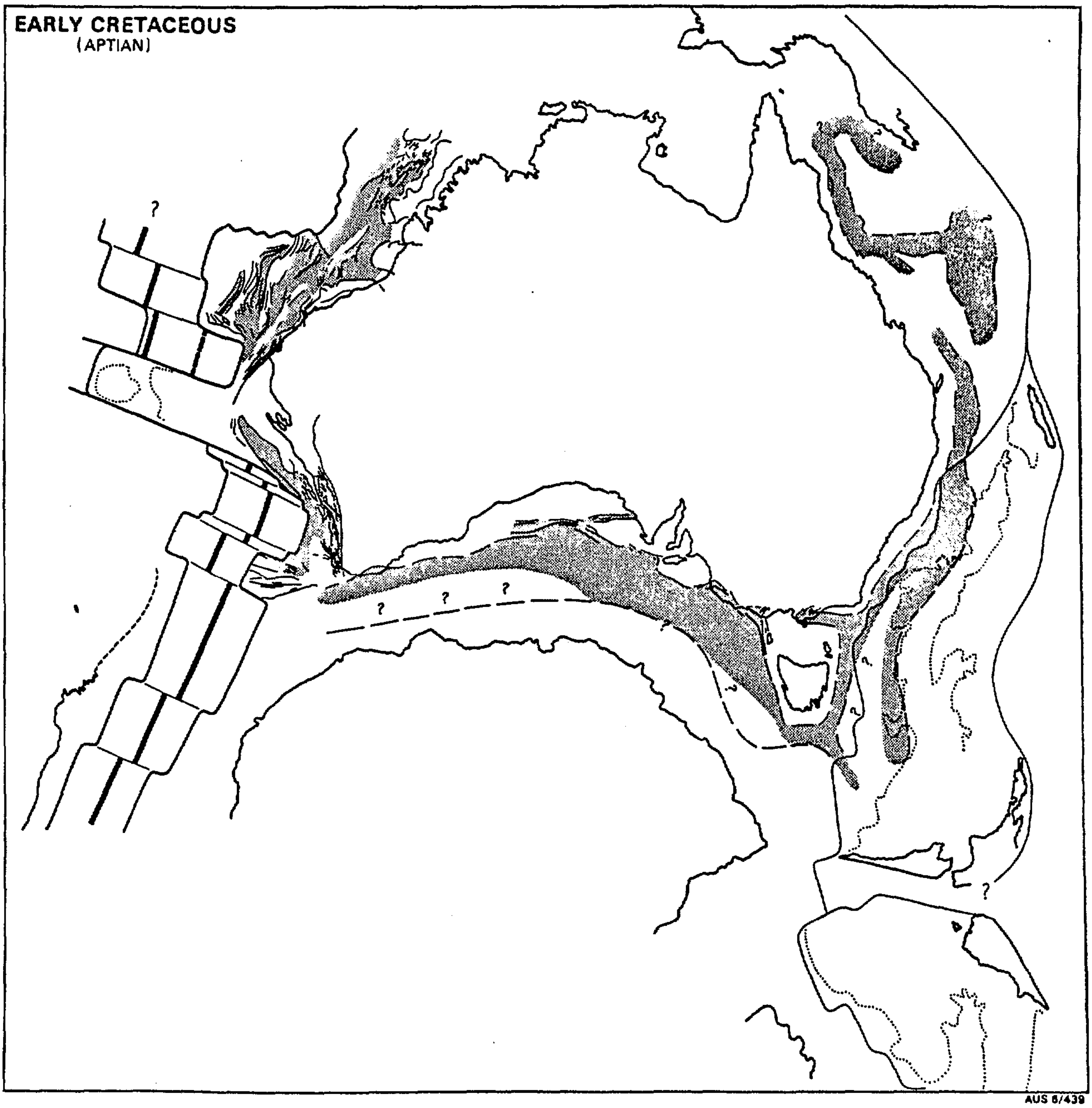
6. (a) Structural and stratigraphic cross sections 1-8, Fig. 5.



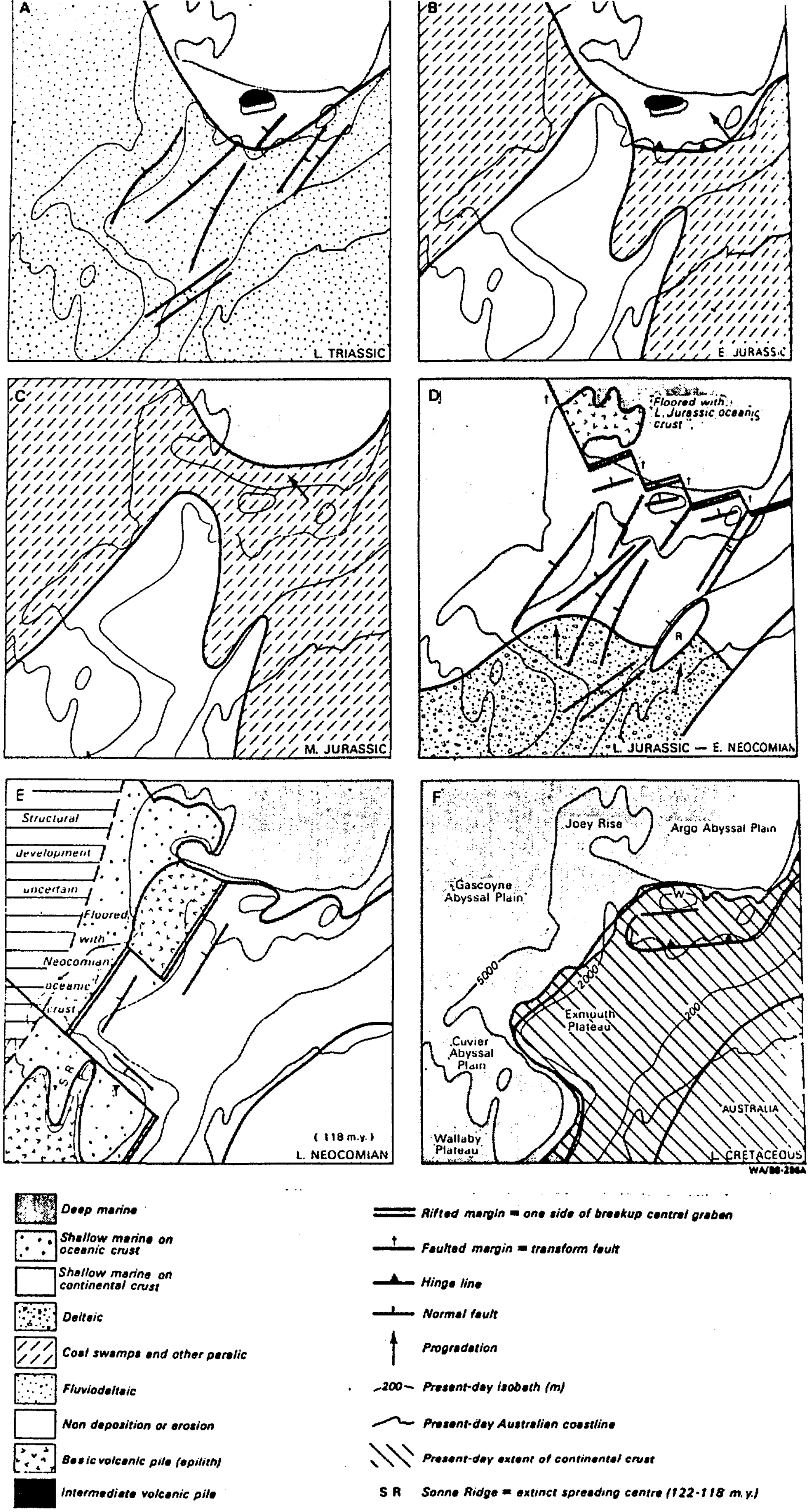
(b) Structural and stratigraphic cross sections A-C, Fig. 5.



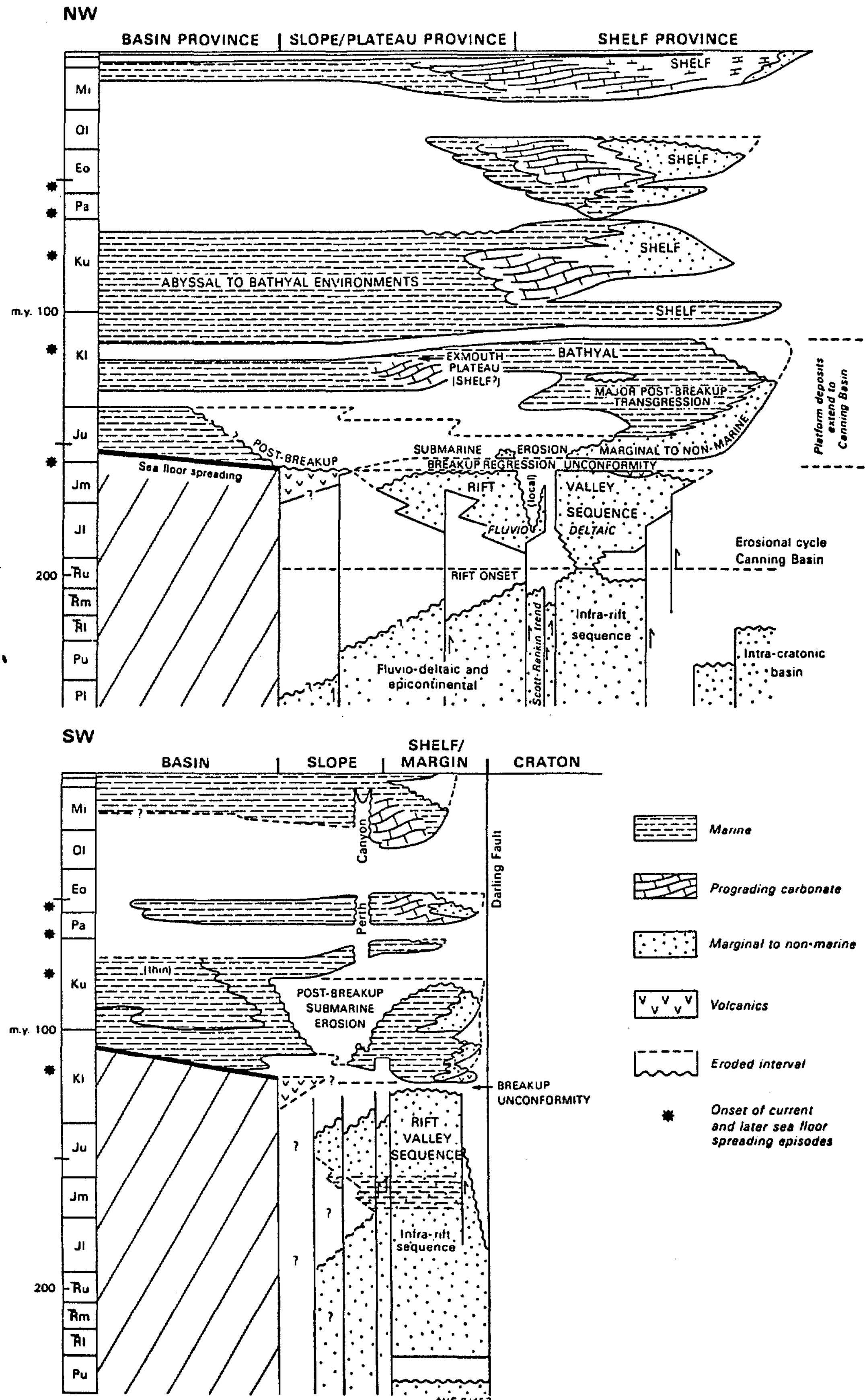
7. Late Jurassic reconstruction of Australia, India and Antarctica.



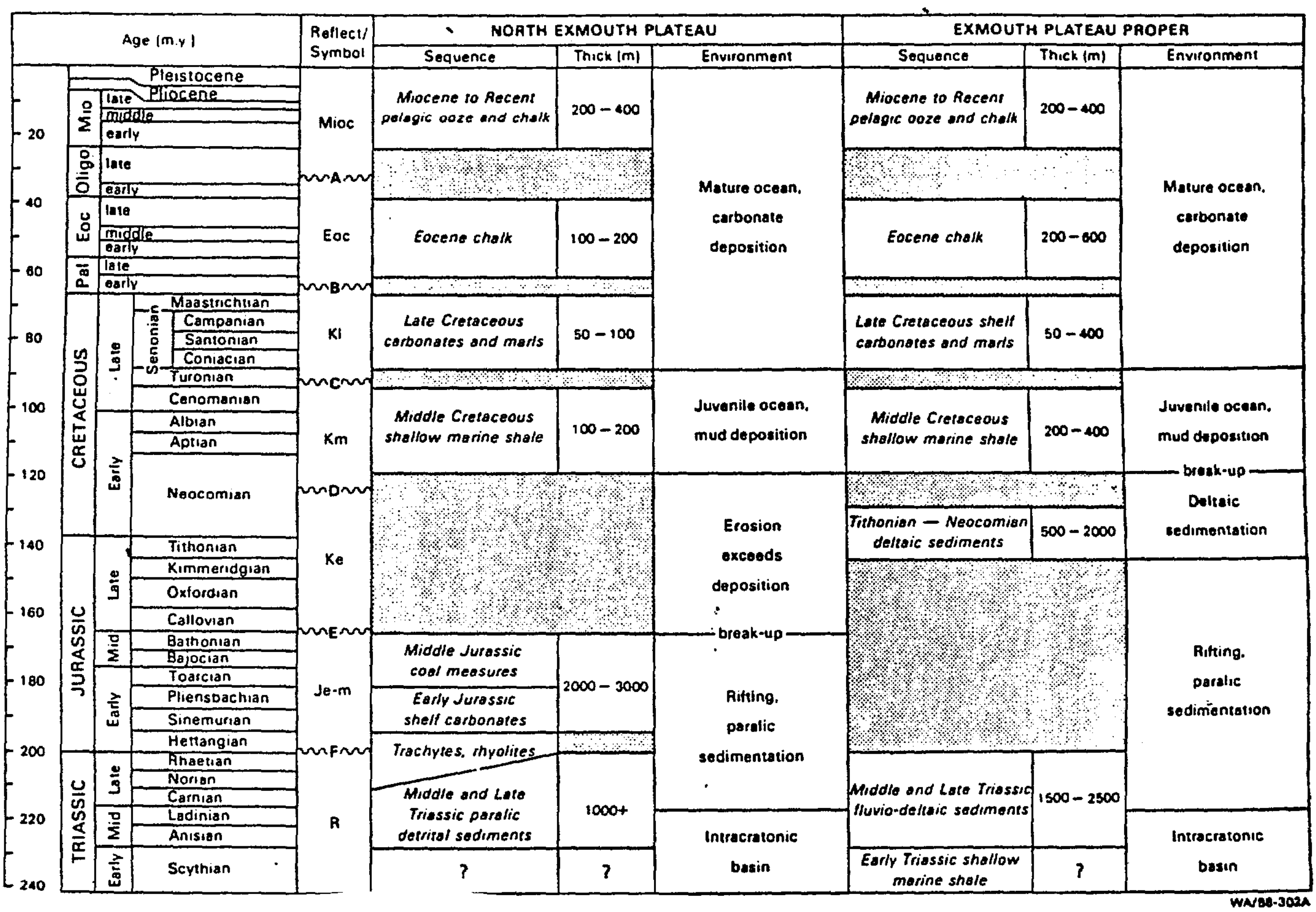
8. Early Cretaceous reconstruction and seafloor spreading.



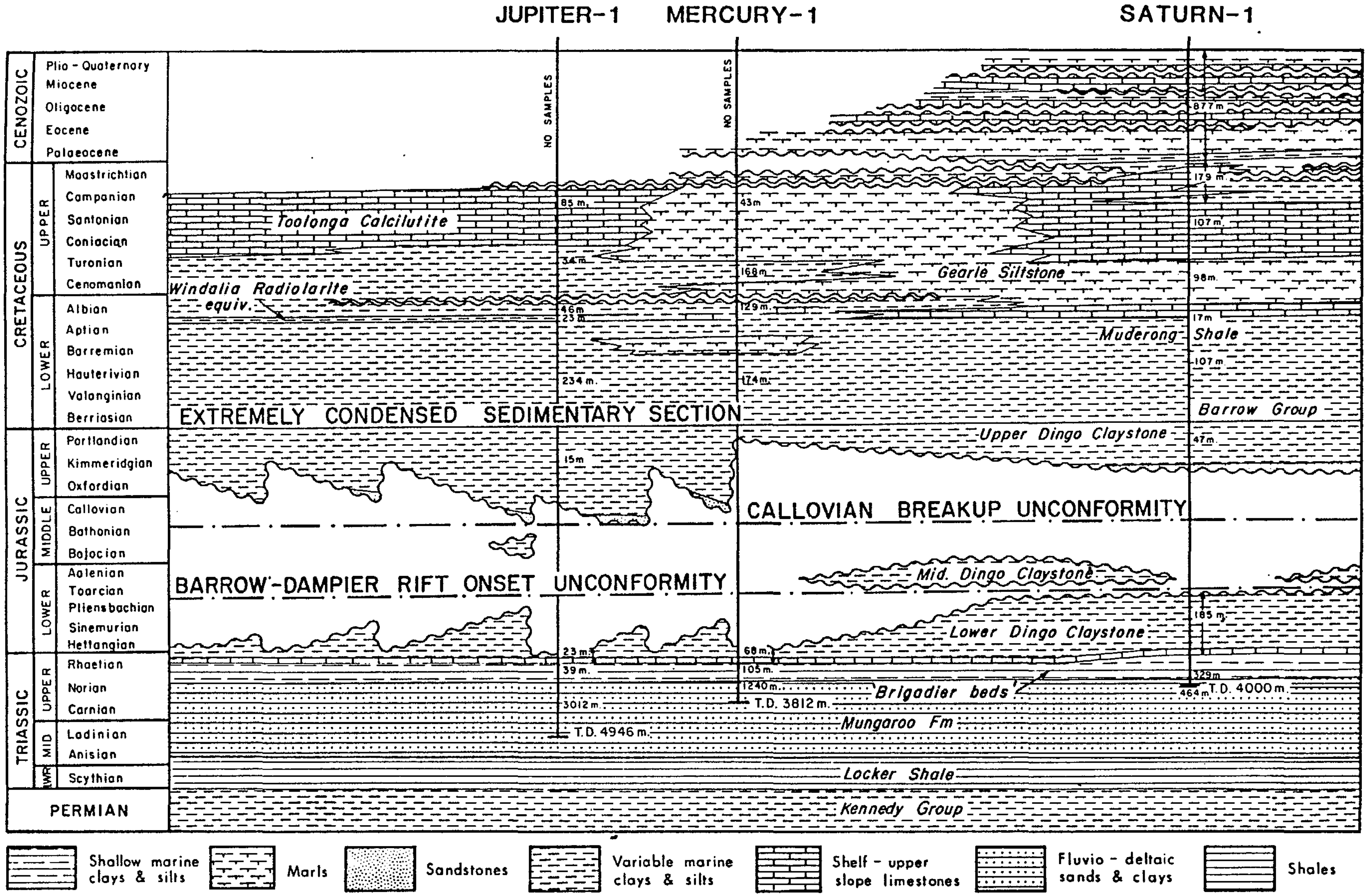
9. Paleogeography of the Exmouth Plateau region.



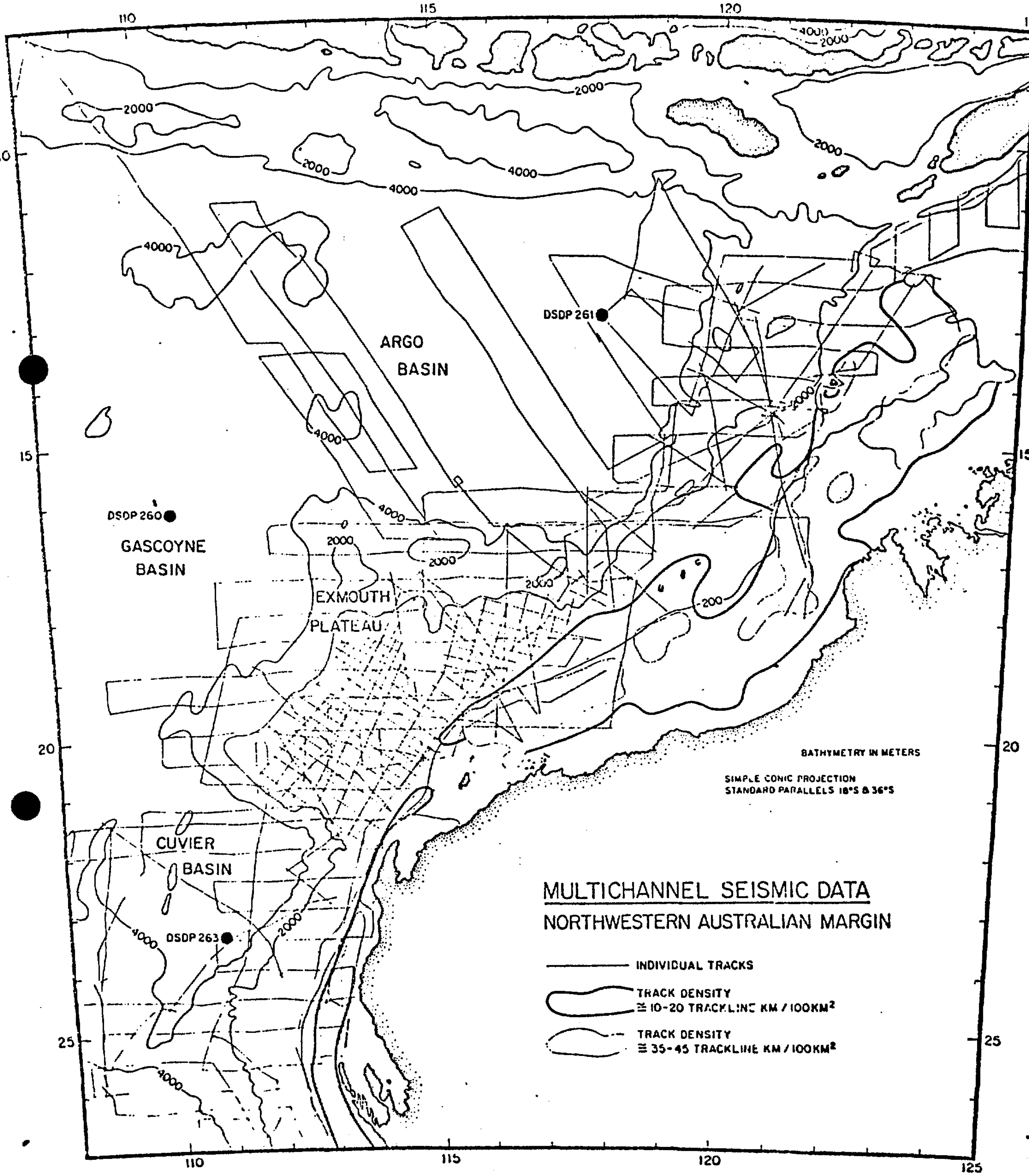
10. (a) Generalized time stratigraphy: Western Australian margin.



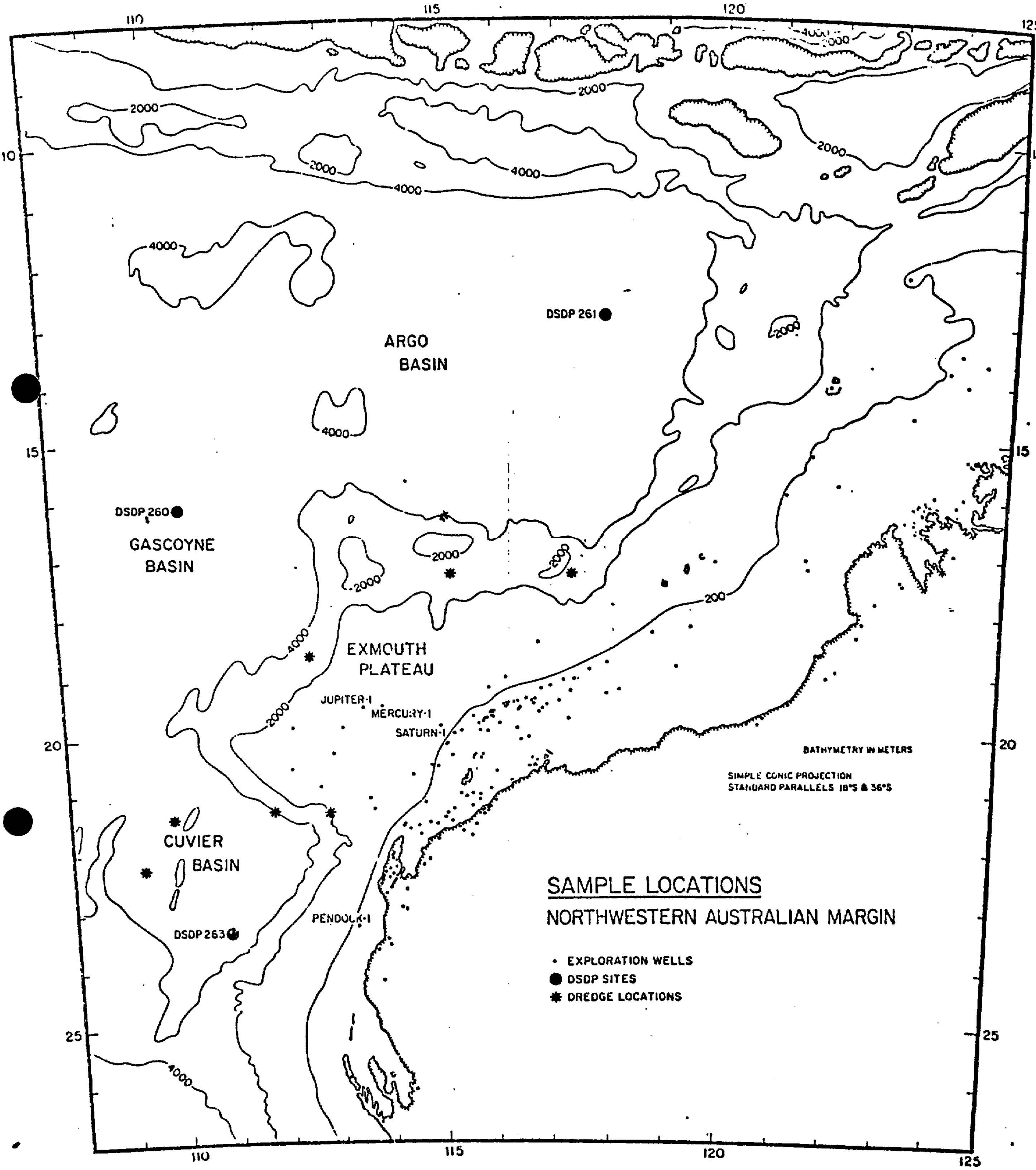
(b) Simplified stratigraphy of the Exmouth Plateau region.



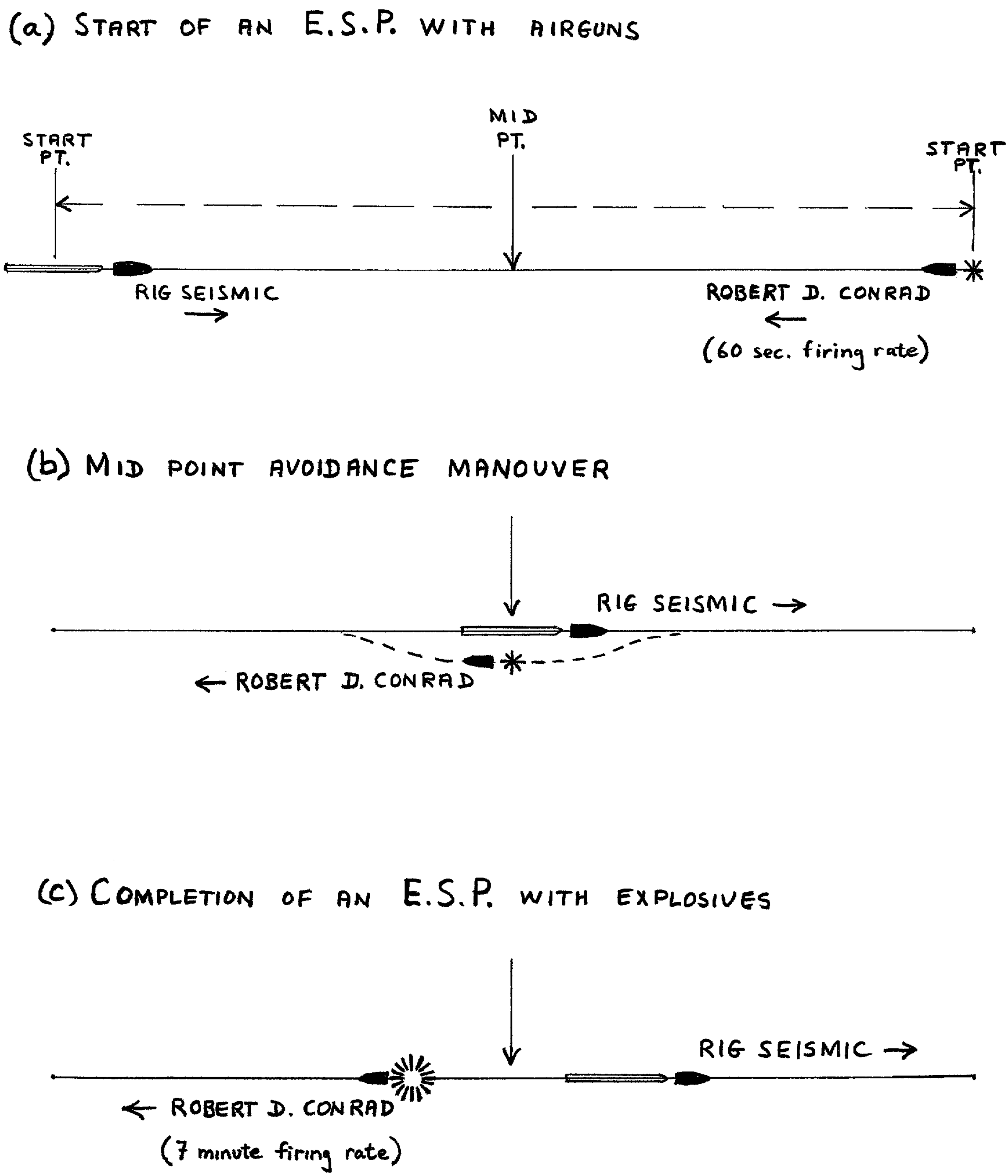
11. Detailed time stratigraphy of the Exmouth Plateau.



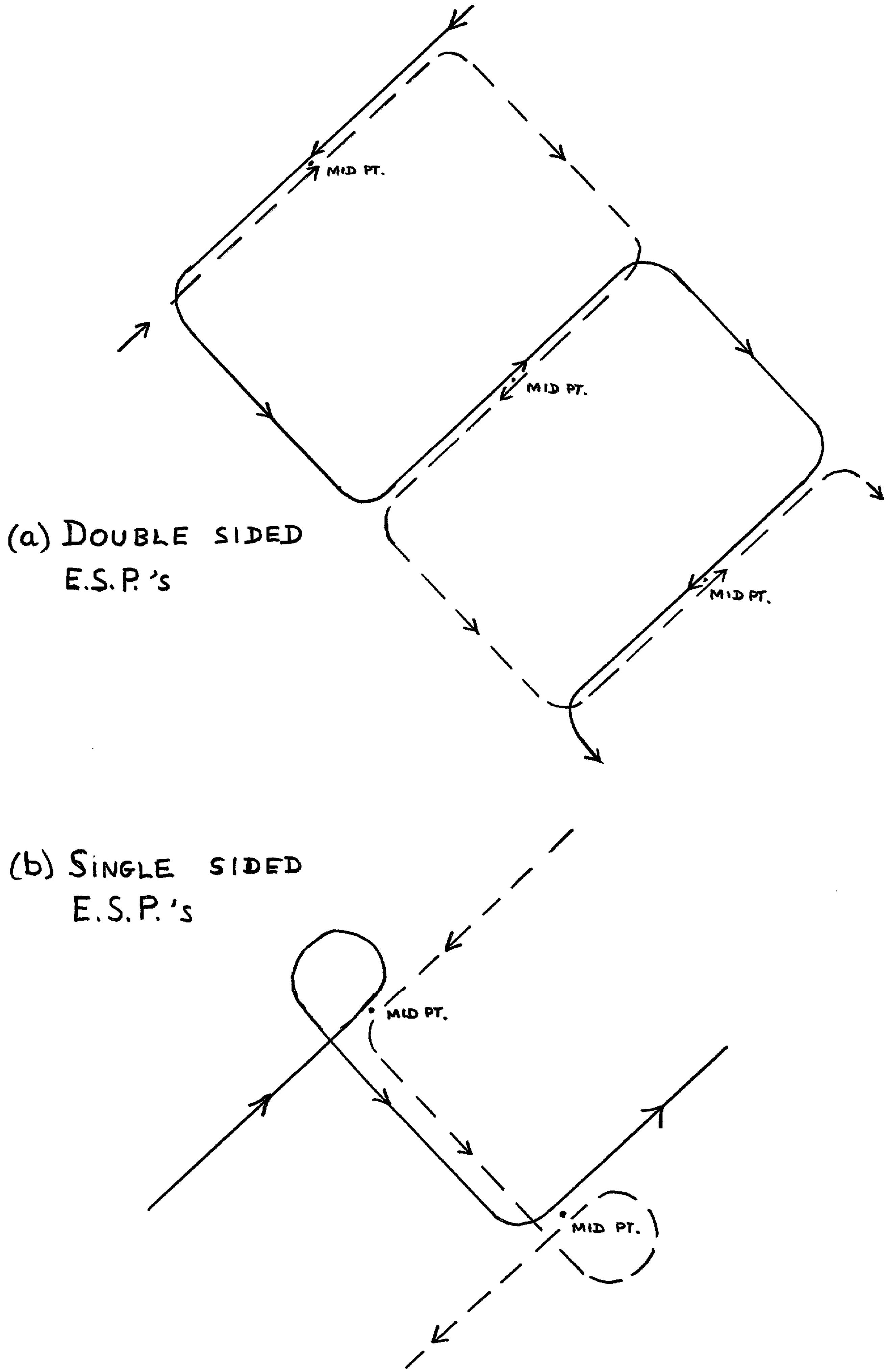
12. Multichannel seismic coverage the Exmouth Plateau region.



13. Exploration well and dredge locations - Exmouth Plateau and NW Shelf.

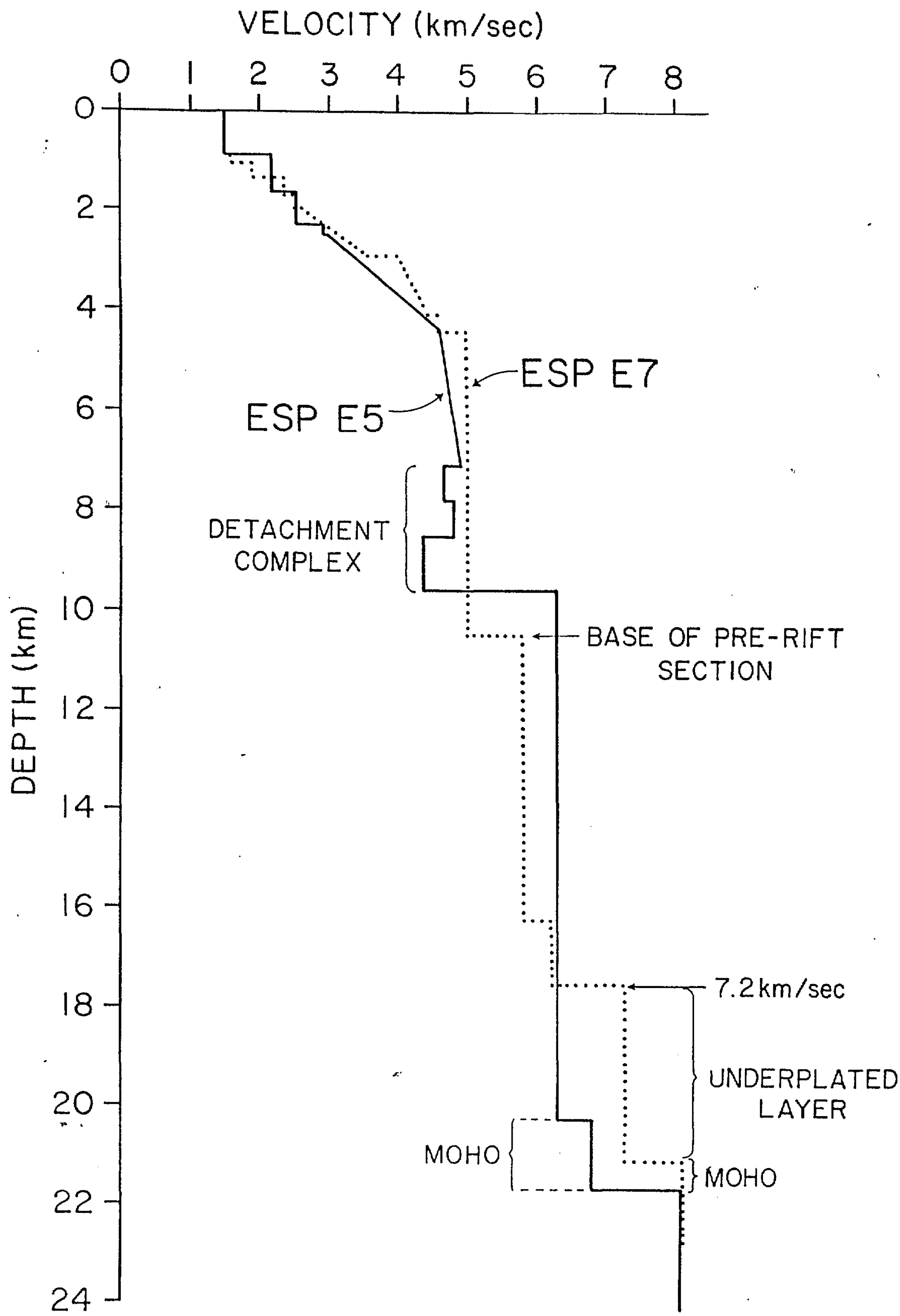


14. Ship manoeuvres for an ESP.



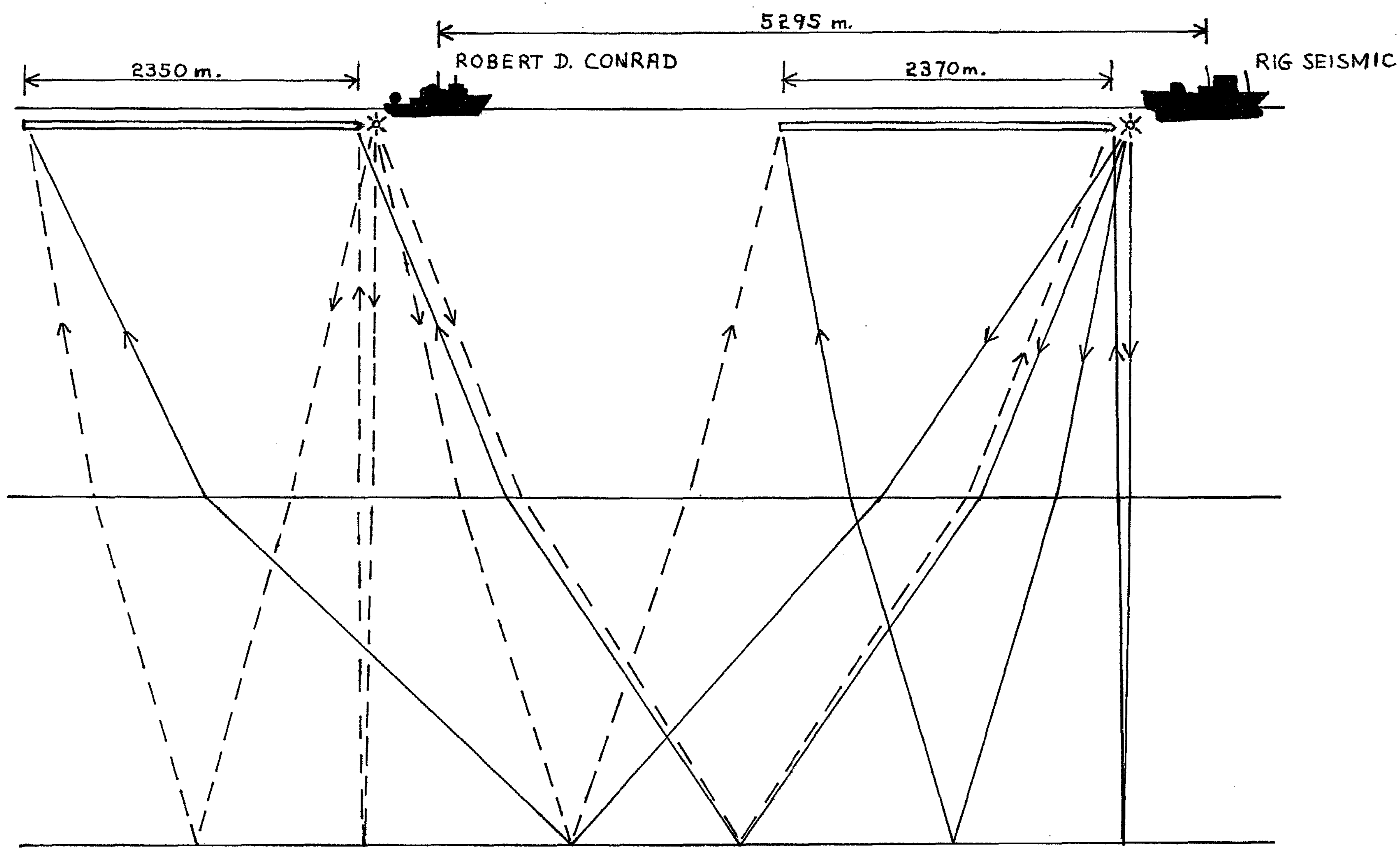
15. Ship manoeuvres for multiple ESP's.

16. Display of ESP E-7 showing airgun phase (left) and explosive phase (right) reduced at 7 km/sec.

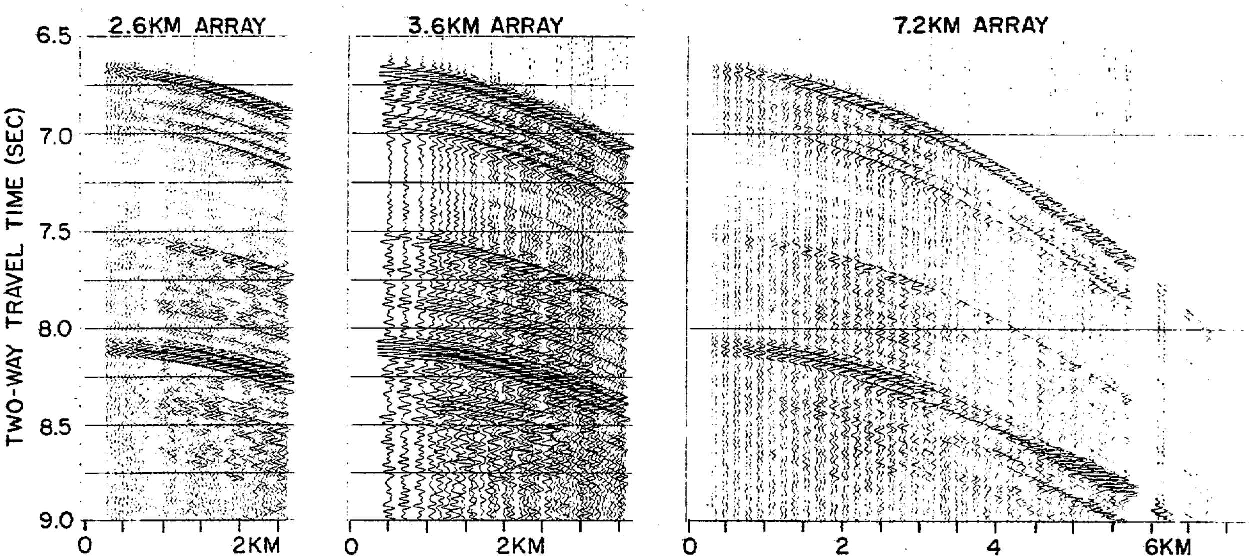


17. velocity versus depth plots from ESP's E-5 & E-7 (Mutter et al., in press).

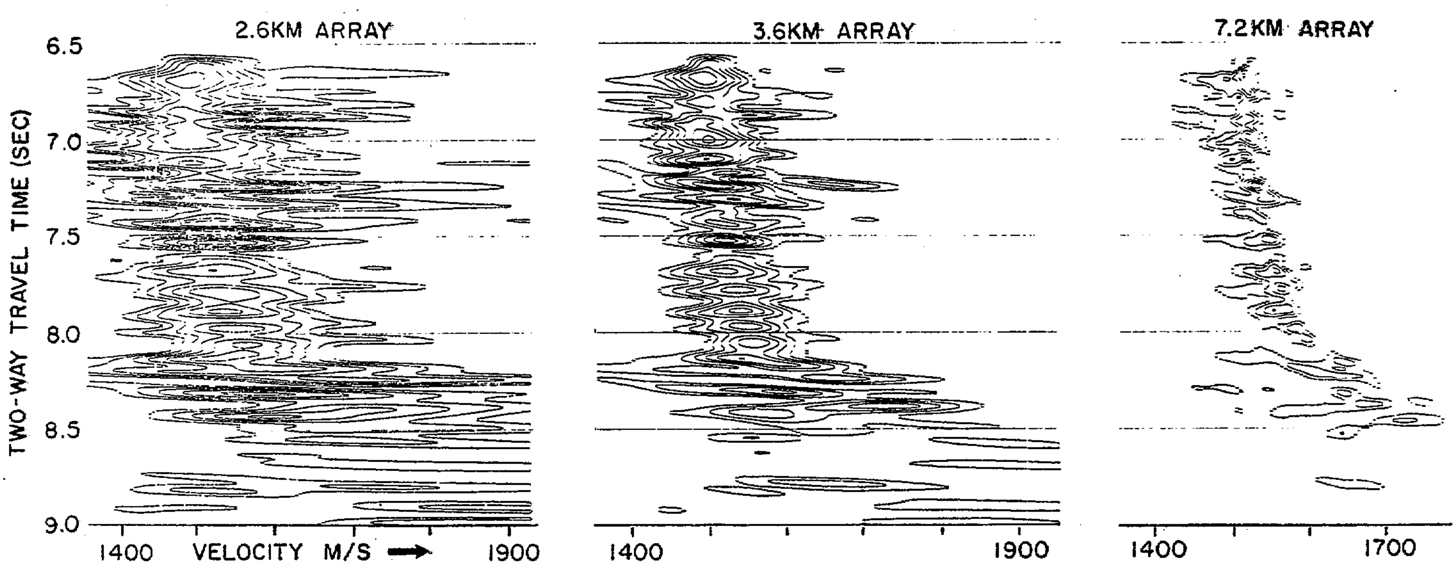
WIDE APERTURE C.D.P. PROFILING



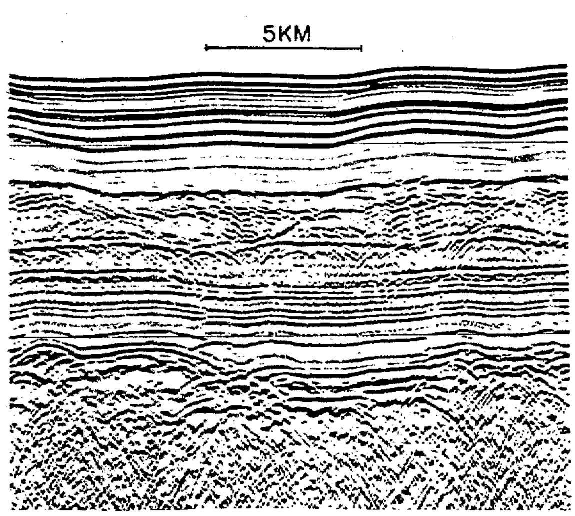
18. Schematic of a Wide Aperture CDP profile (WACDP).



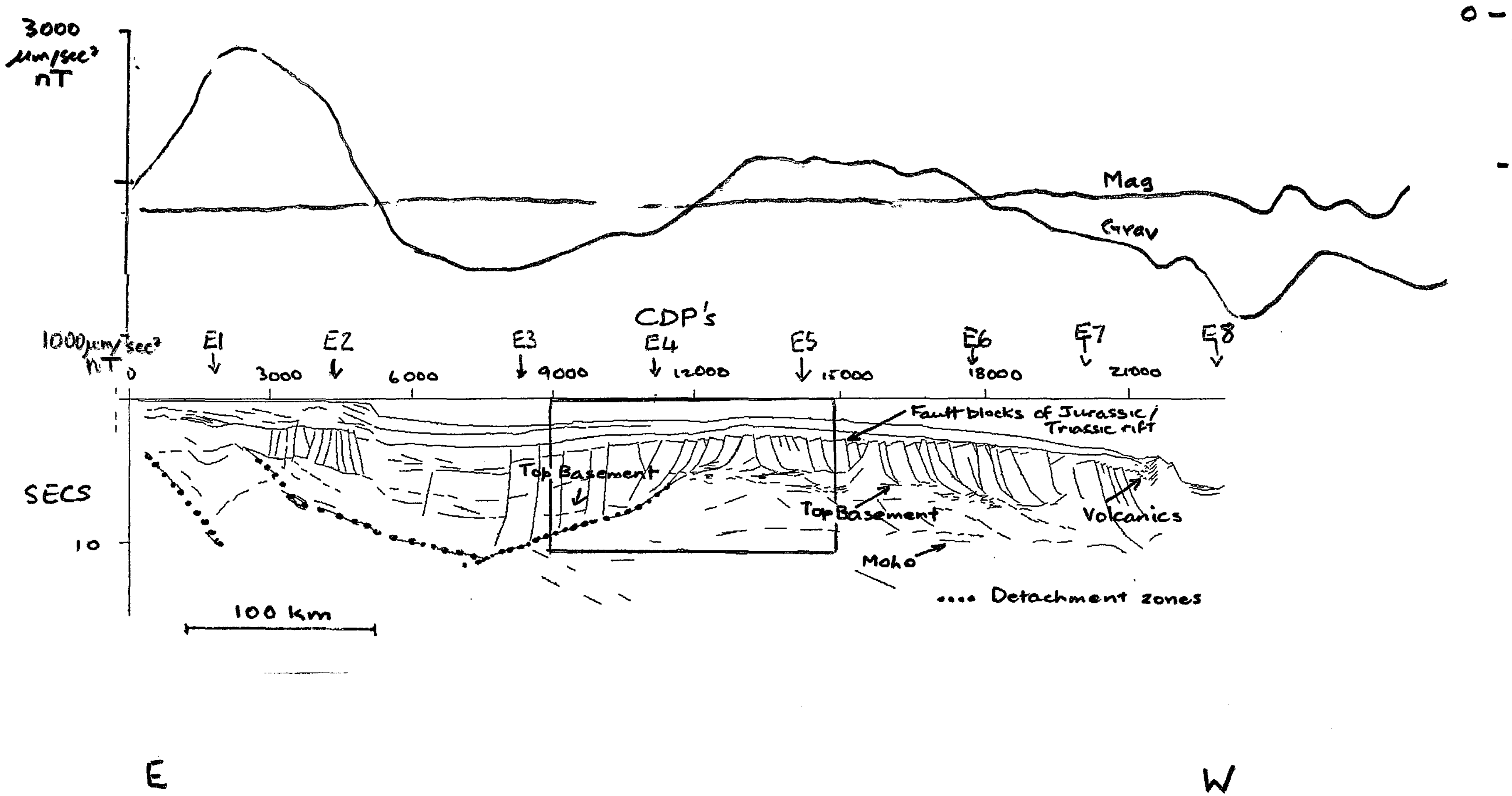
CDP velocity analysis: *CDP record, and a corresponding set of gathers from arrays of three different lengths. As the array length increases there will be information from a greater portion of the time-distance curves of reflections from various geologic horizons. As the amount of the time-distance curve available for analysis is increased, it is possible to determine the velocity of sound in the geology above a horizon with ever greater accuracy.*



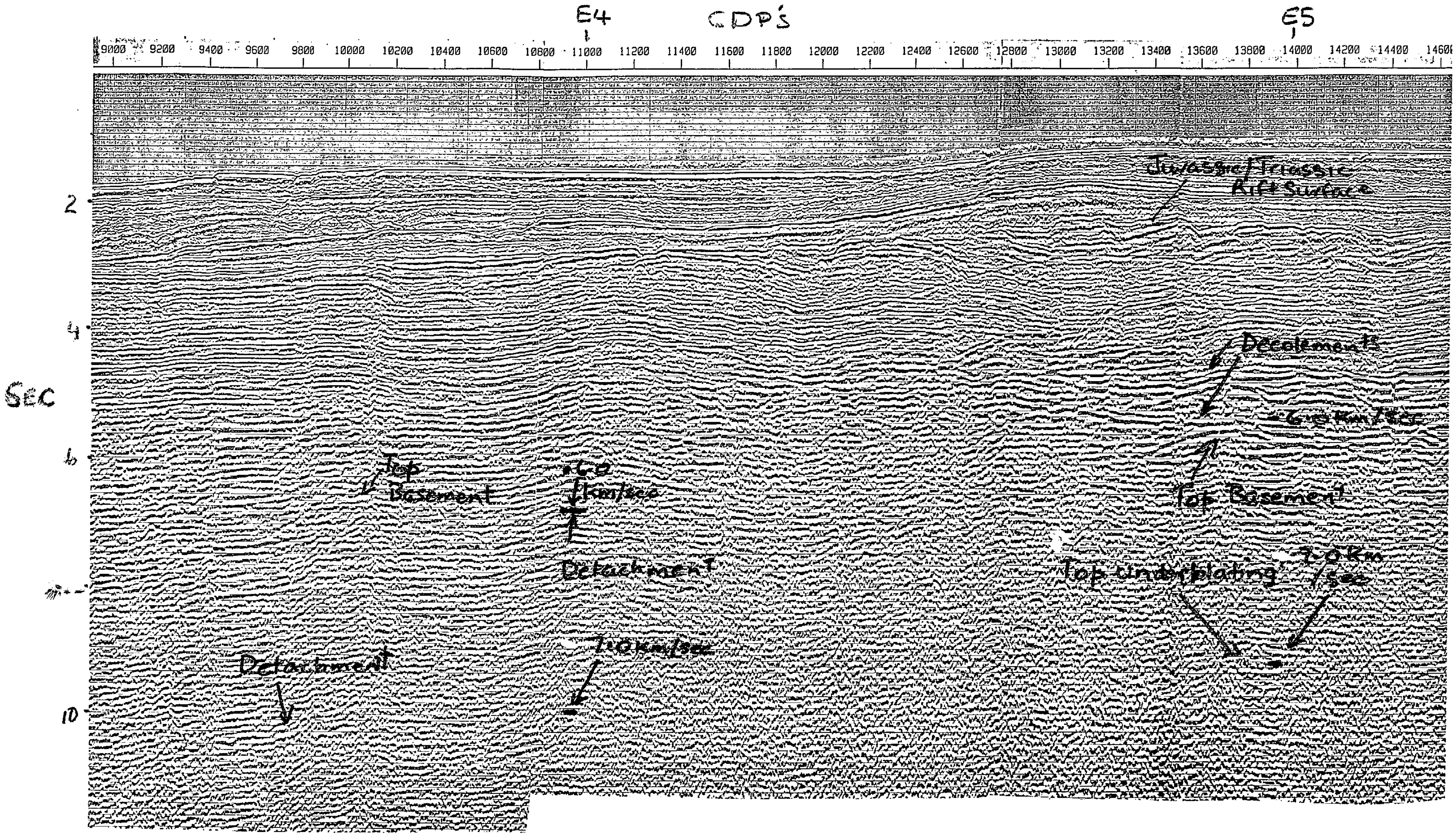
Semblance velocity calculation: *An example of hyperbolic semblance velocity calculations for the data displayed in the CDP gathers above. The center of the contoured bullseye indicates the best stacking velocity for the data at the two-way traveltime of the bullseye center. The width of the contours around the bullseye is related to the precision of the velocity estimate. With longer array length, tighter contours are obtained around the center of the bullseye.*



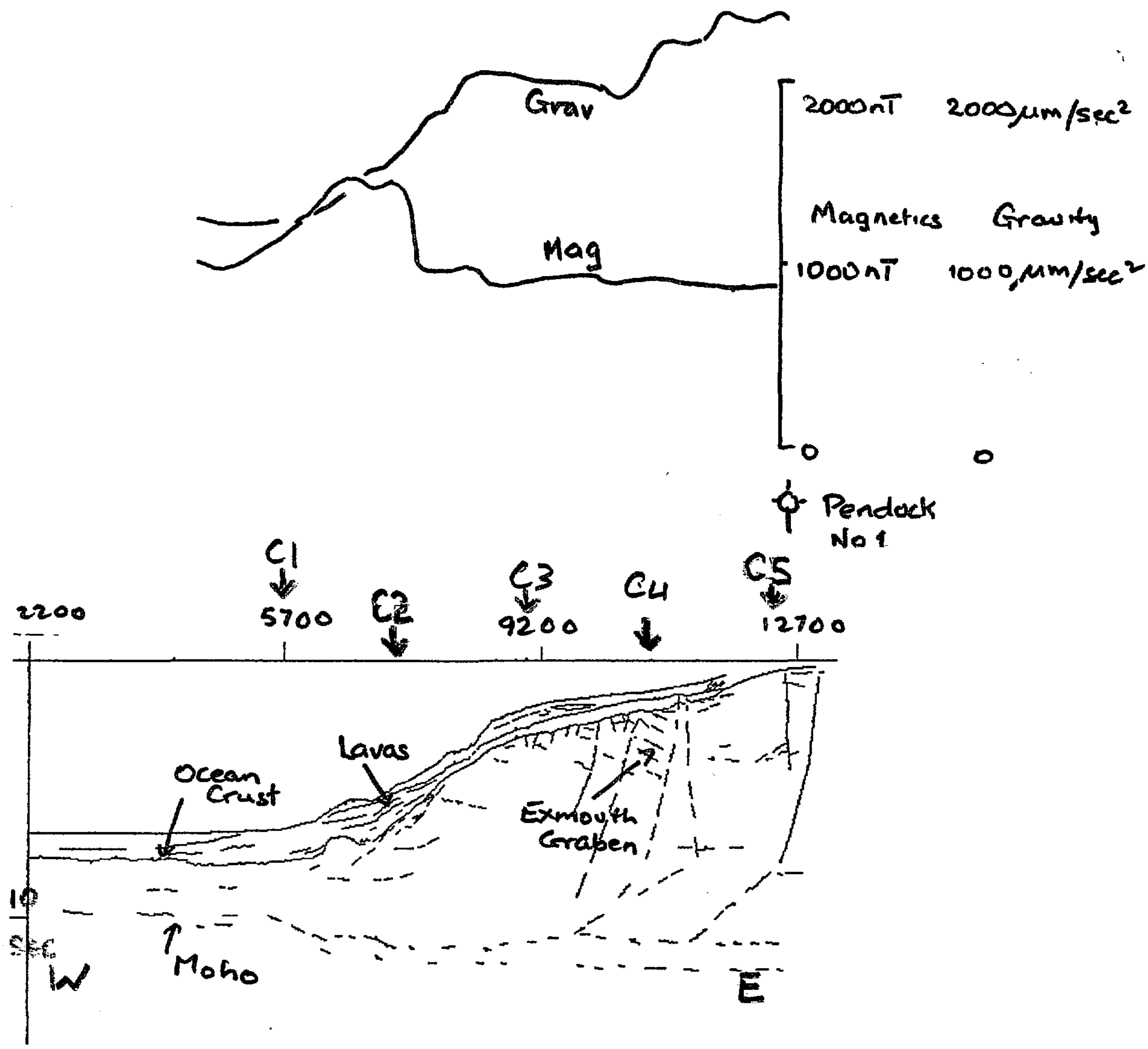
19. Example of improved velocity dicrimination obtained from long array lengths.



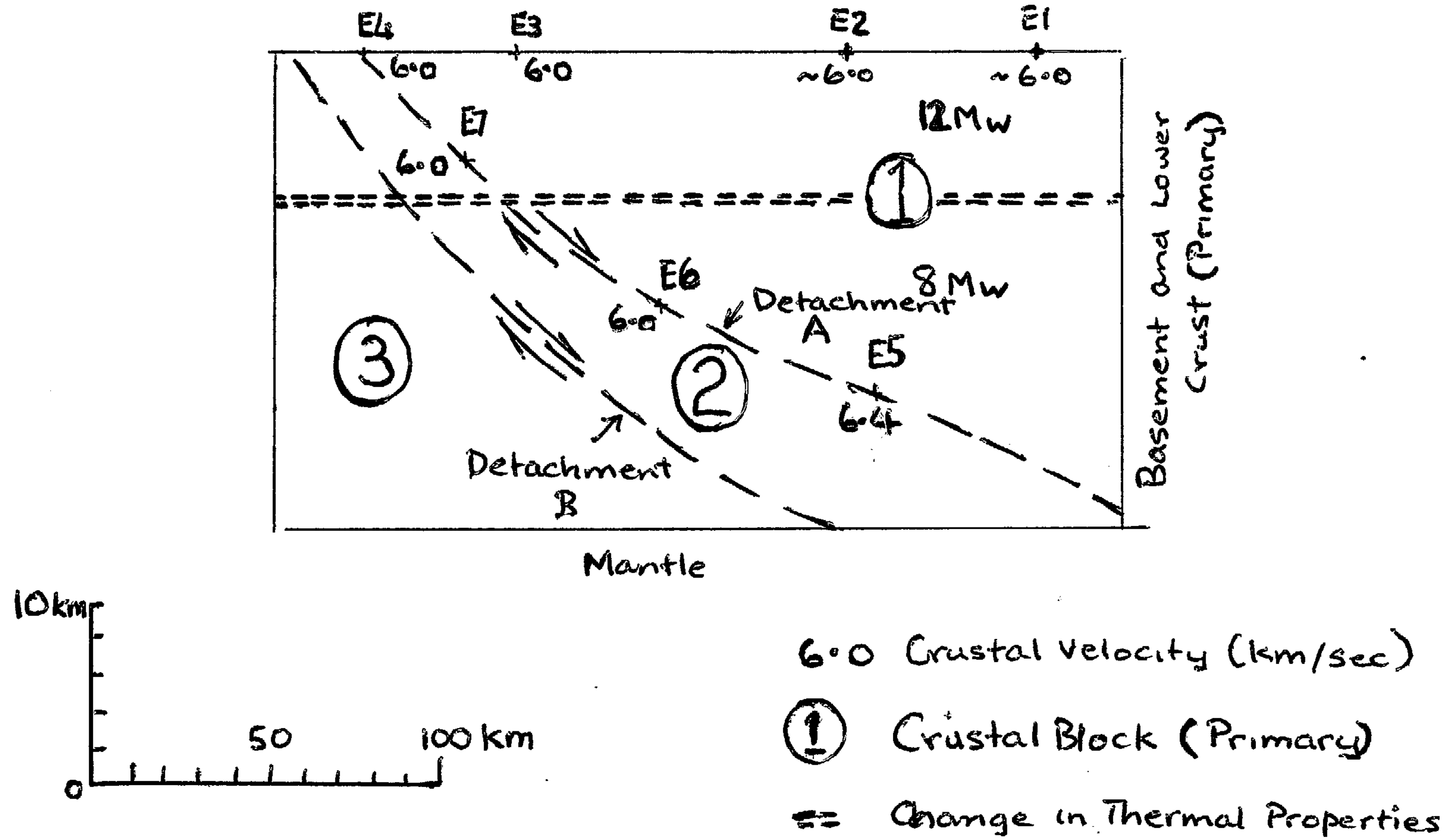
20. Line drawing of Exmouth Plateau WACDP profile.



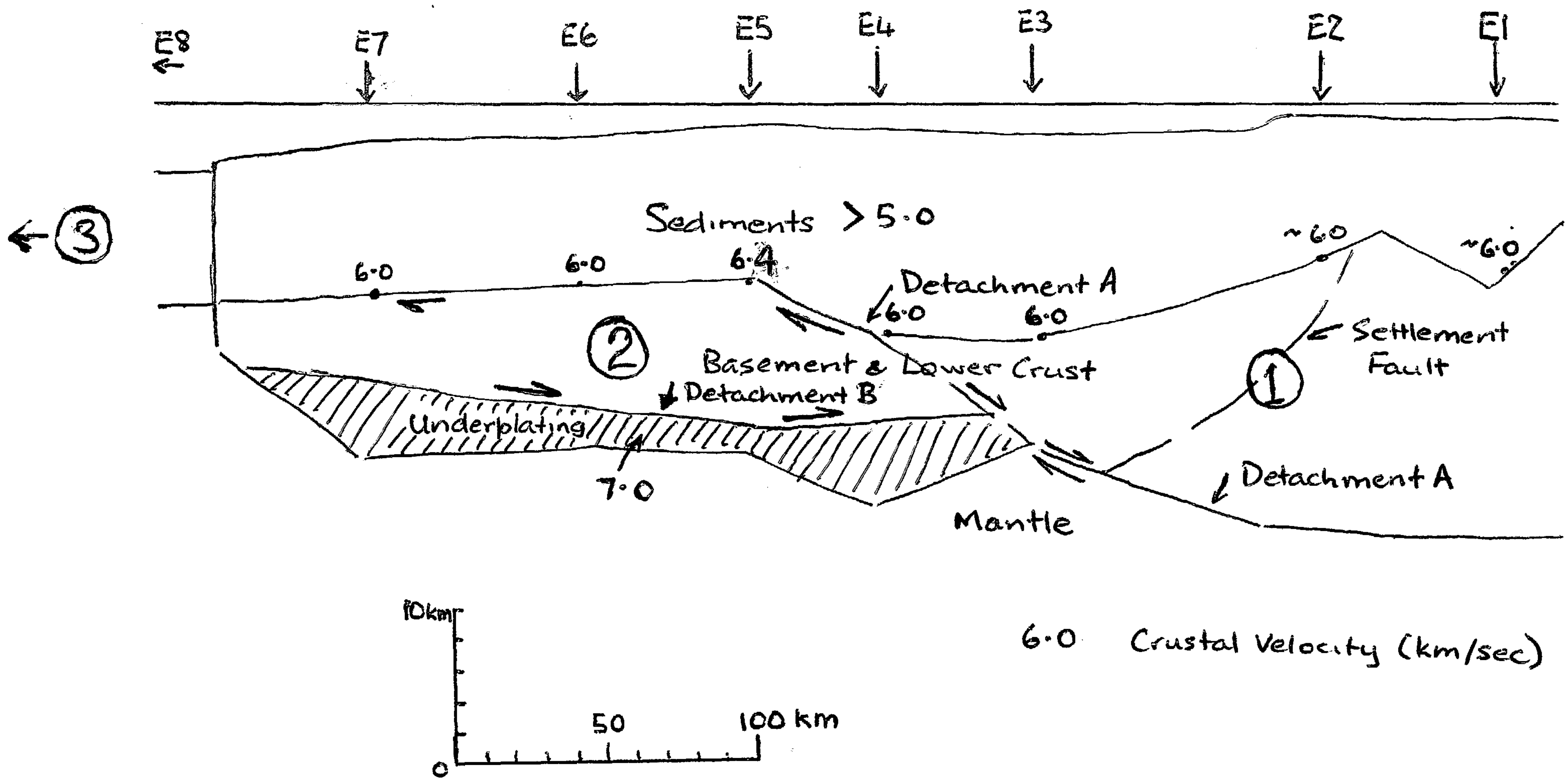
21. Seismic data from Exmouth WACDP profile. Location is shown in Figure 20.



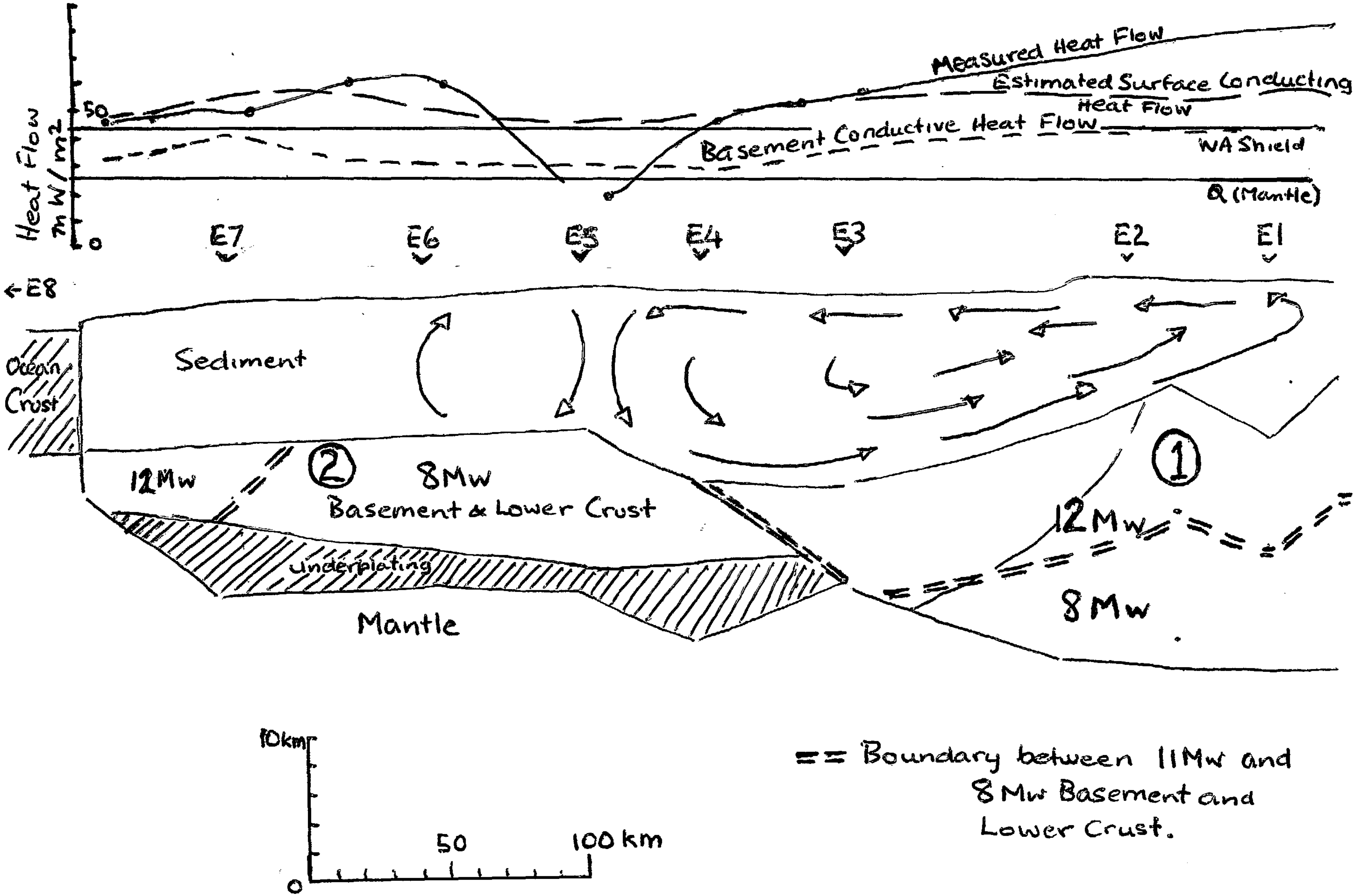
22. Line drawing of Cuvier WACDP profile.



23. Preferred model for Permian formation of Exmouth Plateau basement and lower crustal structure.



24. Exmouth Plateau depth cross section showing main elements of first stage Permian rift.



25. Heatflow data and interpretation for Exmouth Plateau.