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# 3. SEISMIC STRATIGRAPHY AND PASSIVE MARGIN EVOLUTION OF THE SOUTHERN EXMOUTH PLATEAU[1]

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## ABSTRACT

Permian/Carboniferous to Neocomian rifting along northeast Gondwanaland transformed an intracratonic basin fronting the eastern Tethyan continental margin to a new passive margin along northwest Australia fronting the newly created Indian Ocean. Subsequent sedimentation has been relatively thin, resulting in a starved passive margin and an ideal opportunity to use high-quality shallow seismic data from industry together with ODP drilling methods to investigate the entire history of passive margin evolution and the resulting sedimentary successions. Since 1968, more than 40,000 km of seismic-reflection line data have been collected on the southern Exmouth Plateau. The combined results of Leg 122 Sites 762 and 763 and 11 exploration wells on the southern Exmouth Plateau enable precise dating and geological confirmation of the extensive seismic data base.

A wide range of seismic-reflection data sources was used to define eight seismic stratigraphic packages that overall contain three major clastic depositional wedges and a carbonate blanket deposit. The analysis of these eight packages has provided (1) an updated interpretation of the regional seismic stratigraphy in the light of new data, research results, and advances in interpretation methods; (2) a regional framework in which to place the multidisciplinary drilling results from Sites 762 and 763; and (3) a tectono-stratigraphic interpretation of passive margin evolution. This margin evolution documents a history of intracratonic sedimentation in the Norian-Rhaetian, rift onset and initial breakup from the Hettangian-Callovian, a second rift and final breakup between the Callovian and Hauterivian, and postbreakup and rift to drift transition from the Hauterivian-Cenomanian that ends with a mature ocean phase in transition to a collision margin from the Turonian-Holocene.

Further results derived from seismic stratigraphic analysis show the presence of both synrift and postrift sediments in the thin Jurassic sequences on the western Exmouth Plateau and a clear synrift, prebreakup source in the Gascoyne Sub-basin of five Tithonian-Valanginian depositional episodes on a northward-prograding coastal plain to basin depositional wedge. The age of breakup on the southern Exmouth Plateau is seen to be Hauterivian, which corresponds with a period of intense uplift of the Tithonian-Valanginian sediments and the progradation of a previously undescribed Hauterivian sediment wedge north from the Cape Range Fracture Zone. At about the Cenomanian/Turonian boundary the sediment supply on the southern Exmouth Plateau shifted from a northward-prograding clastic source to carbonate-dominated southward-onlapping blanket. Folding related to collision farther north increased slopes on the southern Exmouth Plateau beginning in the Eocene and produced widespread submarine erosion and resedimentation in saturated Cenozoic oozes.

## INTRODUCTION

### Tectonic and Stratigraphic Evolution of the Southern Exmouth Plateau

In the early Mesozoic, the present northwest Australian margin (Fig. 1) was part of a continental rift zone on northeast Gondwanaland that bordered the Tethys sea to the north (von Rad and Exon, 1983; Fullerton et al., 1989). Northwest Australia was involved in a major late Paleozoic (possibly Permian) rifting event that allowed the separation of a basement/lower crust segment and its westward translation to form the Exmouth Plateau (Williamson et al., in press; Williamson and Falvey, 1988). This was followed by subsidence and progradation of a thick Triassic depositional wedge along the western Australian margin (Boote and Kirk, 1989), which has been termed the Mungaroo Sand/Locker Shale Facies (see Fig. 2 for a stratigraphic summary of the regional geology) in the Barrow-Dampier Sub-basin (summarized in Hocking et al., 1988). The stratigraphic equivalent of this Triassic depositional wedge extends across the central Exmouth Plateau (Vos and McHattie, 1981), where it is more than 3000 m thick and reaches as far as the Wombat Plateau (Exon et al., 1982; von Rad et al., in press). This progradation was terminated by a regional transgression, which deposited the largely paralic Brigadier Formation and calcareous lower Dingo Claystone between the Norian and Pliensbachian (Crostella and Barter, 1980; Hocking et al., 1988) in the Barrow-Dampier Sub-basin, on the Rankin Trend, and over much of the Exmouth Plateau. Farther north on the Wombat Plateau an uppermost Triassic marginal carbonate facies with reef development occurred in the Rhaetian (Williamson et al., 1989).

A second extended phase of rifting began in the latest Triassic–Early Jurassic and continued until final breakup occurred in the Early Cretaceous (Audley-Charles, 1988; Boote and Kirk, 1989). Rifting began along the margin north from the Exmouth Plateau and resulted in the ?Callovian-Berriasian (see von Rad et al., 1989) breakup of a continental fragment in latest Jurassic–earliest Cretaceous times. Prior to and concurrent with this second rifting event, a thick Jurassic synrift sedimentary succession accumulated in restricted rift-graben locations in the Barrow-Dampier Sub-basin (Veenstra, 1985) and south into the Perth Basin (Boote and Kirk, 1989). Barber (1982) documented mid-Jurassic erosion over much of the central Exmouth Plateau in response to the rifting, and this region began to accumulate thin holomarine muds only after

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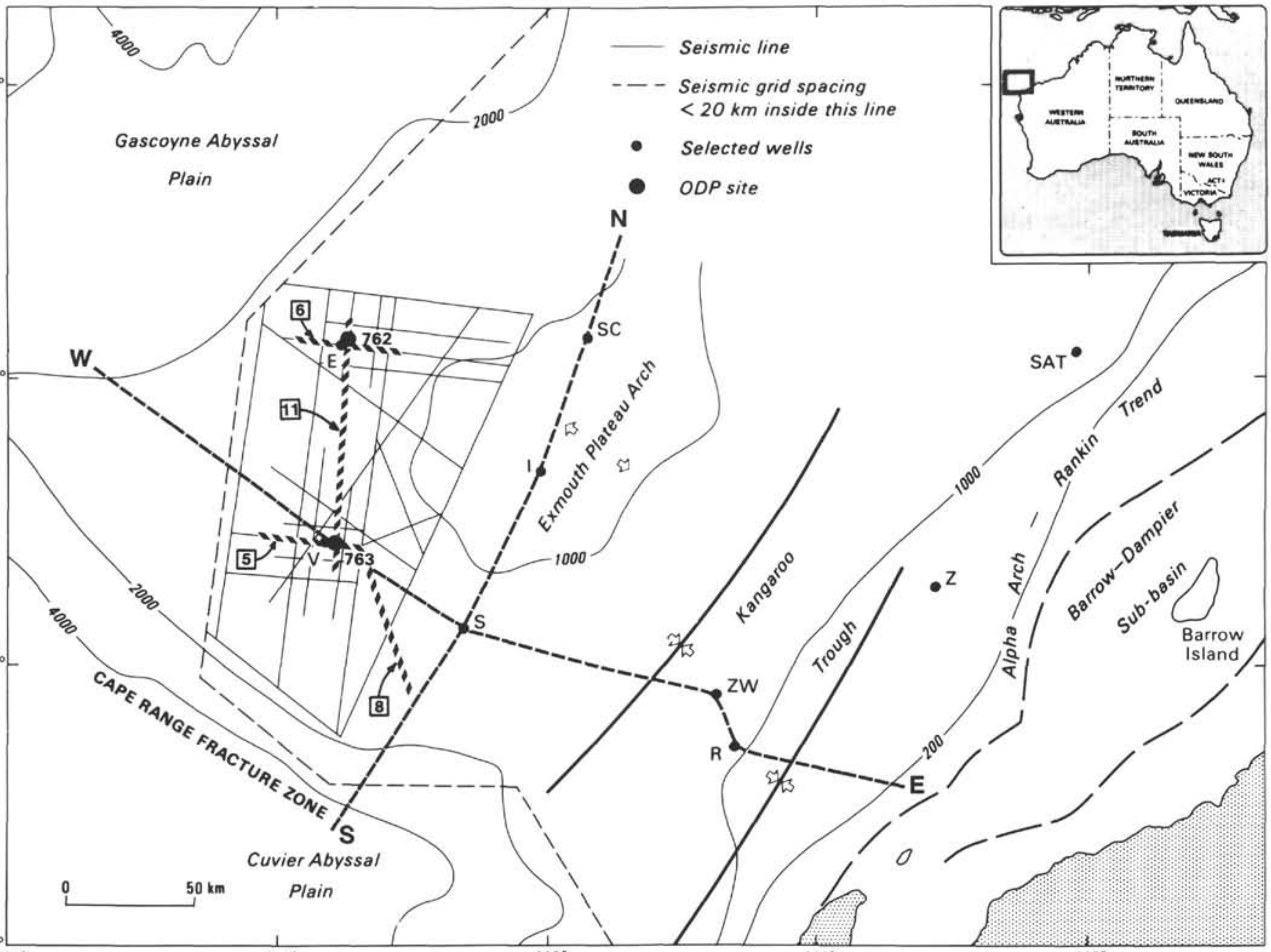


Figure 1. The study area is located on the southern Exmouth Plateau off northwest Australia. Seismic data were analyzed from all regions of the plateau west of the Alpha Arch–Rankin Trend. Intensive seismic correlation was conducted on the lines shown inside the boxed area. Bathymetric contours are in meters below sea level and letters refer to well locations used in the study as follows: SC = Scarborough, SAT = Saturn, Z = Zeepard, ZW = Zeewulf, R = Resolution, S = Sirius, I = Investigator, V = Vinck, E = Eendracht. The Cuvier Rift lies off the figure, to the south of the Kangaroo Trough. E-W shows the location of the cross section in Figure 3, N-S is the cross section in Figure 4. The numbered boxes are the locations of figures.

the Callovian breakup event. Wright and Wheatley (1979) interpreted the main angular unconformity seen on seismic records over much of the plateau to be mid-Jurassic in age. Subsequently, a thick mid-Callovian to Tithonian marine sequence filled the Barrow-Dampier rift and marine shales accumulated up to 2000 m thick in the southern Kangaroo Trough (Barber, 1988).

Subsidence continued accompanied by thin marine shale deposition into the Early Cretaceous, except in the southern region, where a major clastic source resulted in progradation of the Barrow Group sediments (Fig. 2) northward into the Barrow Sub-basin and across the southern Exmouth Plateau (Exon and Willcox, 1978; Wright and Wheatley, 1979). The source region for these sediments is interpreted to range from the length of the Cape Range Fracture Zone in response to uplift during transform motion (Veevers and Powell, 1979) to uplift in the southern Precambrian source region prior to rifting (Boote and Kirk, 1989). In the Barrow Sub-basin Barrow Group sedimentation occupied the time interval from Tithonian (Hocking et al., 1988) to Valanginian (Kopsen and McGann, 1985). On the Exmouth Plateau earlier studies suggested a Neocomian age for the Barrow Group equivalents, and Erskine and Vail (1988) considered the majority of the section near the point of maximum progradation to be Valanginian. Most studies suggest that the Barrow Group is deltaic in nature and seismically and lithologically consists of topset, foreset, and bottomset beds in both the Barrow Sub-basin and on the Exmouth Plateau (e.g., Campbell et al., 1984; Tait, 1985; Barber, 1982, 1988). It is also considered to owe its origin to tectonic uplift prior to (Boote and Kirk, 1989) or associated with (Veevers and Powell, 1979) the final (third) phase of continental breakup and the onset of seafloor spreading. A major sea-level fall is interpreted to have occurred in the middle Neocomian at the end of Barrow Group progradation and coeval with the deposition of thick submarine fan facies (Flag Sandstone, Boote and Kirk, 1989; correlative with the dating on the central Exmouth Plateau of a Valanginian lowstand fan by Erskine and Vail, 1988).

Paleomagnetic data from the Cuvier and Gascoyne abyssal plains (e.g., Fullerton et al., 1989) identify the first magnetic

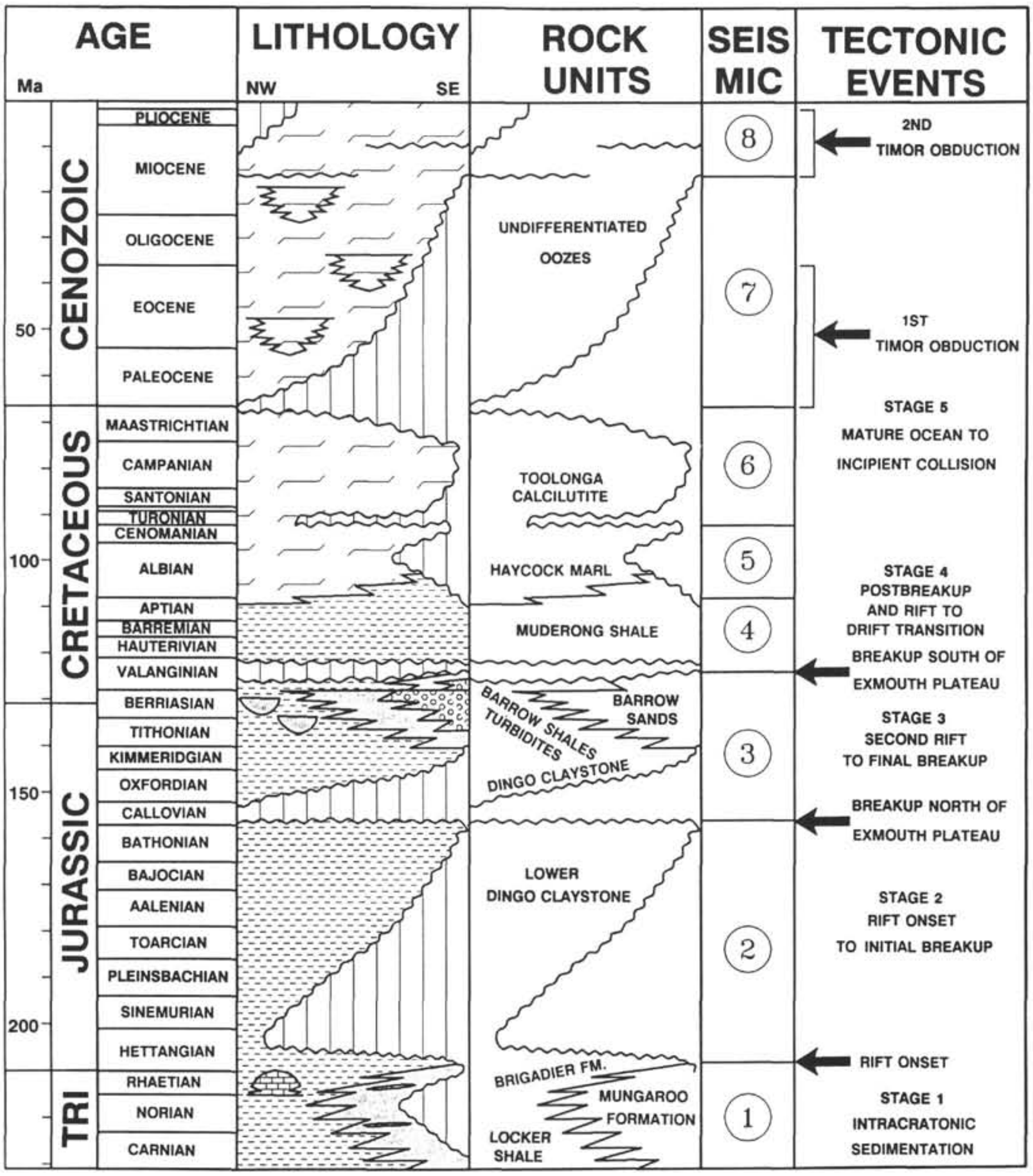


Figure 2. Stratigraphic summary of the southern Exmouth Plateau from Triassic to Holocene. The chronostratigraphy is from Haq et al. (1987). Lithologic patterns are as follows: dashes = mudstone; small and large dots = sandstone and conglomerate, respectively; wavy bars = marl and ooze; brick = limestone and marl. Vertical lines indicate hiatuses. The correlated seismic packages are discussed in the text. Corresponding seismic reflectors for each package lie between that package and the overlying package.

anomaly and hence the final breakup event in both areas to be M10, of early Hauterivian age (Haq et al., 1987). This is supported by the Valanginian age of rift valley sediments directly above basaltic intrusions at Site 766 on the Gascoyne Abyssal Plain (Leg 123 Shipboard Scientific Party, 1989). Subsidence following breakup enabled a regional transgression to occur along the northwest Australian margin, depositing the Winning Group in the Barrow Sub-basin (Hocking et al., 1988) and a widespread unit interpreted as an equivalent of the Muderong Shale (Fig. 2) on the Exmouth Plateau (Exon and Wilcox, 1978). Due to the lack of previous sampling within the Neocomian to Holocene over much of the Exmouth Plateau and the lack of any prospective reservoir units in this interval, little detailed information has previously been available for the area from this time interval (Barber, 1988).

Following breakup, the Exmouth Plateau was considered to have slowly subsided, while continuing to deposit a diminishing fine-grained clastic supply equivalent to the Muderong Shale into the middle Cretaceous (Barber, 1982), and experienced a Late Cretaceous erosional event (Wright and Wheatley, 1979) followed by a transformation to carbonate deposition with more than 500–1000 m deposited between Late Cretaceous and Cenozoic times (Exon and Willcox, 1978) chiefly as a result of progradation of the northwest Australian margin onto the eastern region of the plateau. With continuing subsidence, bathyal depths are considered to have been reached some time between the early Cenozoic (Barber, 1982) and the Pliocene-Pleistocene (Exon and Willcox, 1980). Structural reactivation and basin inversion occurred in the late Tertiary (Fig. 2) in response to obduction of the northern

Australian plate margin in the Java Trench (Kopsen and McGann, 1985; Howell, 1988) and with major structural growth occurring during the Miocene (Barber, 1988). Exon and Willcox (1978, 1980) identified three Cenozoic unconformities in the Paleocene, early Eocene, and Oligocene. They interpreted most of the Cenozoic sediments as bathyal oozes but recognized widespread Cenozoic erosion and interpreted some erosion as shallow water or possibly subaerial in nature.

### Previous Seismic Investigation

Seismic investigation began on the southern Exmouth Plateau in the 1960s, and a range of data was collected up to 1976 by the Australian Bureau of Mineral Resources (BMR), Esso Australia Ltd., Gulf Research and Development Company, and Shell Development (Australia) Pty. Ltd., as summarized in Exon and Willcox (1980). Major regional seismic surveys were conducted in 1976 by GSI International (summarized in Wright and Wheatley, 1979) and from 1978 through 1981 by Esso Australia Ltd. Surveys on the central Exmouth Plateau were conducted in the late 1970s by the Phillips Group. More recent seismic investigations undertaken by BMR and partners along the northern, western, and southern plateau margins have been documented in Williamson and Falvey (1988) and Exon and Williamson (1988). Some deep seismic results of these surveys were used by Mutter et al. (1989) and Williamson et al. (in press) to provide evidence for rifting deformation of the Exmouth Plateau. More than 40,000 km of reflection-seismic line data makes up the southern Exmouth Plateau data base (see Fig. 1).

Eleven exploration wells were drilled on the Exmouth Plateau between 1979 and 1981. Nearly all of these wells were terminated in Mesozoic sediments, commonly of Neocomian to Triassic age, and the results were discussed by Barber (1982, 1988).

Erskine and Vail (1988) used seismic sections from the southern Exmouth Plateau to discuss the sequence stratigraphy and global sea-level correlation of the Neocomian Barrow Group. In addition to these studies on the Exmouth Plateau, the large literature base accumulated on the seismically and stratigraphically similar sediments found in the adjacent Barrow-Dampier Sub-basin (e.g., Kirk, 1985; Veenstra, 1985) has been summarized in Purcell and Purcell (1988).

### Objectives

The objectives of this study are to provide an updated interpretation of the seismic stratigraphy of the southern Exmouth Plateau based upon new data and research that have accumulated since the latest regional studies a decade ago (Wright and Wheatley, 1979; Exon and Willcox, 1978, 1980) and to use more advanced interpretation methods (e.g., Vail et al., 1977; Vail, 1987). Our interpretation is also intended to provide a regional framework in which to place the multidisciplinary results from Sites 762 and 763 on the southern Exmouth Plateau. This resulting synthesis gives a better understanding of (1) the Triassic–Early Cretaceous prerift and synrift history and the rift to drift transition in a starved passive margin setting and (2) the Cretaceous to Cenozoic postbreakup development of sedimentation and paleoenvironment from the early juvenile to final mature ocean phases of evolution. Because many of the original drilling objectives of Ocean Drilling Program (ODP) Leg 122 were related to the Lower Cretaceous section, this interval is given a more detailed treatment here.

## METHODS

An examination of at least part of all original seismic data sources was conducted for this study. The primary data sources analyzed (see Fig. 1 for data coverage) were multichannel seismic-reflection lines from Exon and Willcox (1980), unpublished Esso 1978 and 1979 surveys, the unpublished GSI 1976 Group Shoot, ODP site-survey lines used to position Sites 762 and 763 and a tie line between the two sites (von Rad et al., 1989), and *Rig Seismic* and *Conrad* seismic lines shot during a joint experiment in 1986 (Williamson and Falvey, 1988; Exon and Williamson, 1988). Record length was at least 6 s and mostly unmigrated, with Esso data recorded 48-fold, BMR and GSI data 24-fold, and ODP data single-fold. All data are currently held at the BMR repository and were used under Australian access to information regulations. Data quality was generally good to very good, especially in the post-Triassic section (generally above 3 s).

Data analysis employed a seismic/sequence stratigraphy approach (e.g., Vail et al., 1977; Vail, 1987) tied to the Haq et al. (1987) time scale. Seismic sequences were defined after Vail et al. (1977) as stratigraphic units composed of a relatively conformable succession of genetically related strata bounded at top and bottom by unconformities or their correlative conformities and identified on seismic sections by reflection terminations. Because of the large number found on the Exmouth Plateau, sequences were grouped into eight seismic packages separated by major regional unconformities. These eight packages appear to form natural tectono-stratigraphic units and form the basis of our interpretation (e.g., Figs. 3 and 4).

## STRUCTURE

The major tectonic elements of the Exmouth Plateau (Figs. 1 and 3) are the western buttress of the Rankin Trend; the Kangaroo Trough, which widens to the north and separates the Rankin Trend from the bathymetrically subsided Exmouth submarine plateau; the Exmouth Plateau Arch; the rifted western plateau margin; and the southern faulted anticline margin (Fig. 4) of the Cape Range Fracture Zone (Exon and Willcox, 1978; Wright and Wheatley, 1979; Barber 1982, 1988). Many of these original Mesozoic features have undergone inversion and renewed growth associated with broad folding during the later Cenozoic.

High-angle normal faulting on this megacrustal block dominates the rift onset unconformity and the prerift and synrift sediments. Faults follow a broad northeast-southwest or north-south trend paralleling the major structural elements of the plateau (Exon and Wilcox, 1980) and reflecting the preexisting Precambrian structural trend of the adjacent West Australian cratonic blocks. In contrast, near the southern margin of the plateau, faults follow a northwest-southeast trend. Faults form an extensive network of horsts and grabens on the south-central Exmouth Plateau (e.g., Fig. 3). In this region the fault blocks have a relatively minor throw that averages less than 200 ms. The throw results from minor clockwise rotation on fault blocks, as seen from seismic lines trending northeast-southwest. These down-to-the-basin normal faults are complemented by a suite of antithetic normal faults with a comparable northeast-southwest trend. Closer to the plateau margins and to the Kangaroo Trough, faulting styles change and are characterized by greater throws and increased rotation. Throw on individual fault blocks is up to 400 ms. Mutter et al. (1989) recognized two mid-crustal reflectors that are not penetrated by normal faulting, occur at a depth of around 5 s, and are interpreted as detachment surfaces associated with Jurassic rifting. Along the southern plateau margin, the faults swing to a more northwest-southeast trend and exhibit a different style in which seismic packages are difficult to correlate between adjacent faulted blocks and fault surfaces are obscured by numerous diffrac-

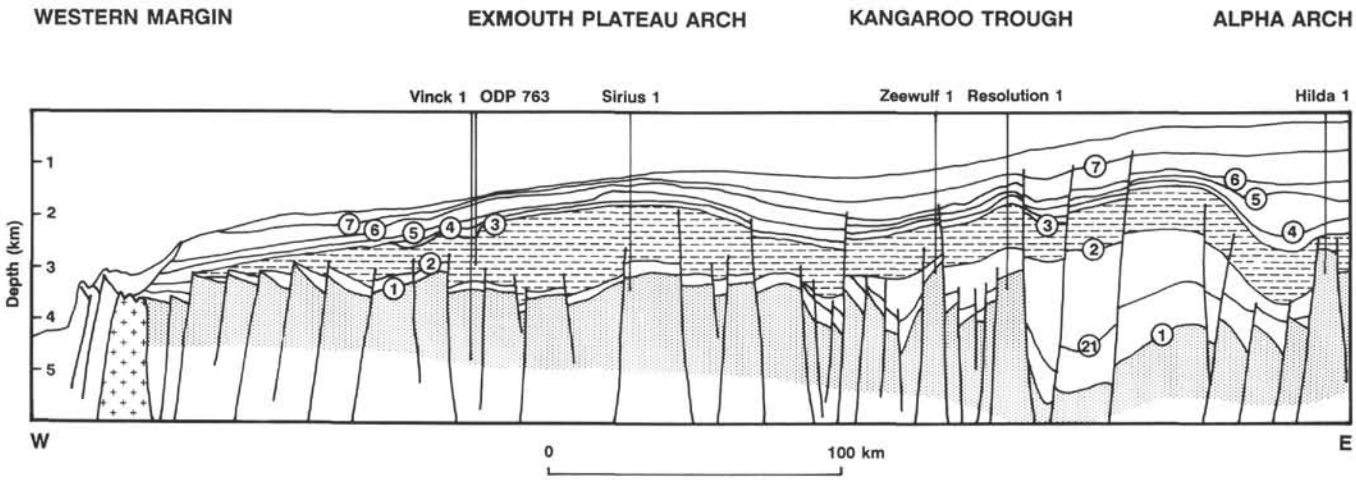


Figure 3. E-W cross section based on a synthesis of seismic results from this study and those from Barber (1982, 1988), Exon and Willcox (1980), and Mutter et al. (1989). The broad tectonic features of the Exmouth Plateau High, Kangaroo Trough, and Rankin Trend–Alpha Arch are clearly seen as well as the normal faulting style across the Exmouth Plateau megacrustal block. Note the thick Jurassic synrift sequence in the eastern Kangaroo Trough and its division into Late and Early Jurassic components separated by the Callovian breakup unconformity (number 21). The Barrow-Dampier Sub-basin lies east of the Alpha Arch. Seismic packages discussed in the text are separated by seismic reflectors 1–7. Each reflector occurs at the top of its respective package.

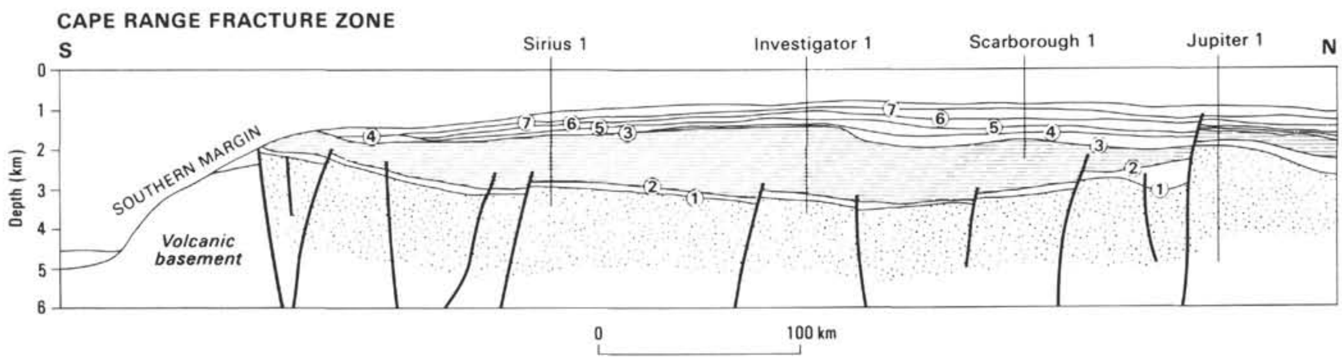


Figure 4. N-S cross section based on a synthesis of seismic results from this study and those from Barber (1982, 1988), Exon and Willcox (1980), and Erskine and Vail (1988). The cross section shows the progradation of package 3 away from the southern transform margin and the subsequent uplift and erosion during Hauterivian continental breakup. Packages 3–5 thin northward, reflecting diminishing clastic supply, whereas packages 6–8 thin and onlap southward, reflecting the shallower water depths that persisted along the southern margin into the Tertiary. Seismic reflectors are numbered as in Figure 2.

tions originating from beyond the plane of the section. The location near the Cape Range Fracture Zone and the faulting style suggest that these are transform faults.

## SEISMIC STRATIGRAPHY

Seismic reflections have been divided into sequences separated by unconformities and their correlative conformities. Several of these unconformities are regional events on the southern Exmouth Plateau and exhibit high amplitude and/or erosional truncation, commonly associated with significant tectonic events. The seismic sequences have been grouped into packages, separated by the regional unconformities. Packages and their intervening reflectors have been numbered 1 through 8, beginning at the base.

### Package 1

Package 1 lies below reflector 1 and consistently extends to the top of the major rifted fault blocks (Figs. 3 and 4). The base of the package is undefined and extends to the base of the records in most locations. Reflector 1 is commonly an erosional unconformity that truncates underlying reflections and occurs in close juxtaposition to reflector 2. Package 1 is overlain by either package 2 in graben settings or, across the top of elevated blocks, package 3. In rare instances such as the elevated Jurassic–Early Cretaceous Rankin Trend on the Alpha Arch (Fig. 3), package 1 is overlain by package 4. Along the southern and western plateau margins, package 1 is seen to outcrop at the seafloor. In these locations, package 1 is intruded by diapiric structures (e.g., western end of Fig. 3) generating high-amplitude diffractions. Where the sequence boundary at the top of package 1 can be clearly identified–for example, near the Investigator-1 well site–it is associated with a prominent negative amplitude anomaly that coincides with a source of numerous hyperbolic diffractions. At other locations, the upper surface of rotated fault blocks has been extensively eroded, giving reflector 1 variable amplitude and low continuity. Farther west on the plateau reflector 1 is more conformable with the overlying package 2 (e.g., Fig. 3).

The reflections within package 1 can be grouped into numerous individual seismic sequences. Reflections have highly variable amplitude and frequency together with moderate continuity. Where unobscured by faulting, the se-

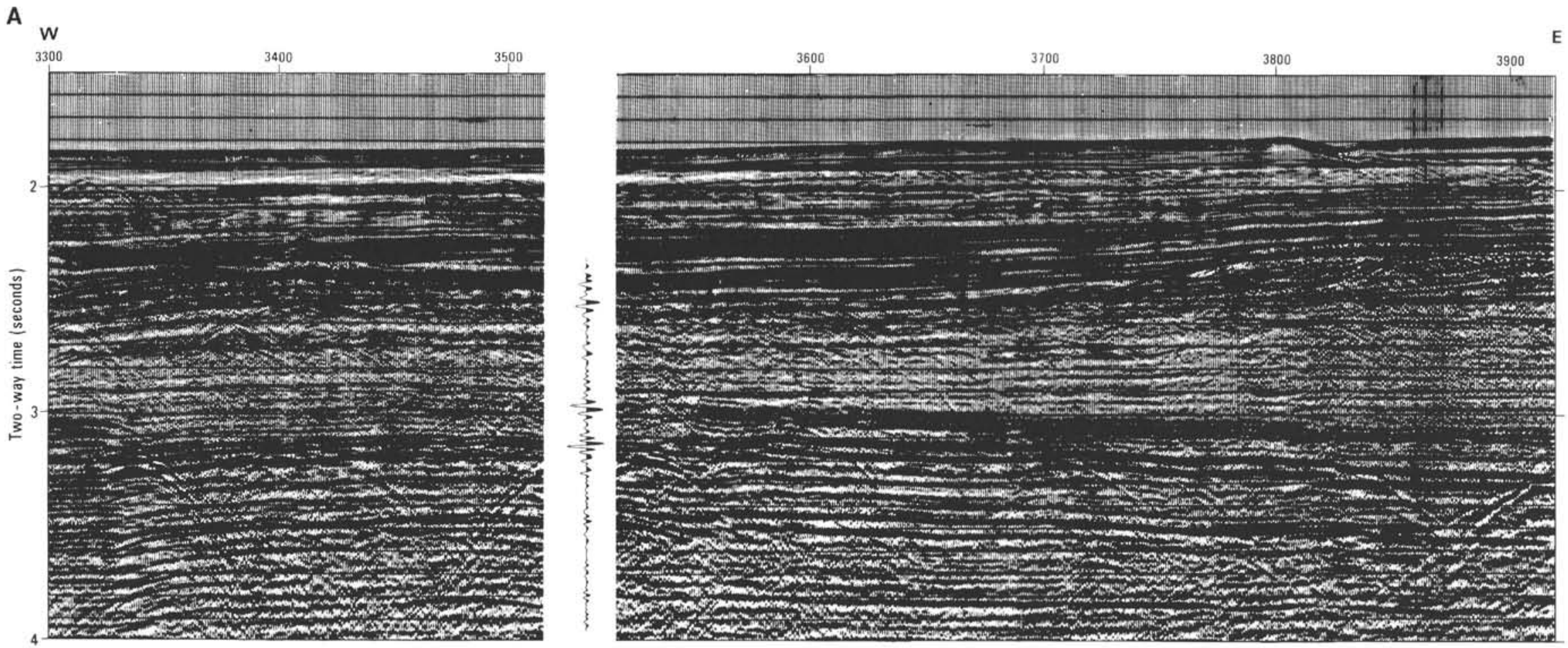


Figure 5. Seismic section through Site 763 and the Vinck-1 well (**A.** uninterpreted; **B.** interpreted). All eight seismic packages are present here and separated by reflectors 1–7. A simplified lithologic column from Site 763 and a synthetic seismogram from the Vinck-1 well site are also presented for comparison. Shown are the normal faulting of the rift-onset unconformity of reflector 1 (here Rhaetian in age) and thickening of package 2 into the resulting grabens (shotpoints 3500–3325). The Late Jurassic age here of package 2 postdates the Callovian breakup unconformity. The upper sequence of package 1 increases in thickness and contains more reflections toward the west. The final progradation of package 3 into this region terminates less than 10 km east of Site 763 (at shotpoint 3790). Packages 4–7 thin eastward onto this depositional platform. Note seabed erosion at shotpoint 3825 and similar subsurface features in packages 7 and 8 (e.g., at shotpoint 3310).

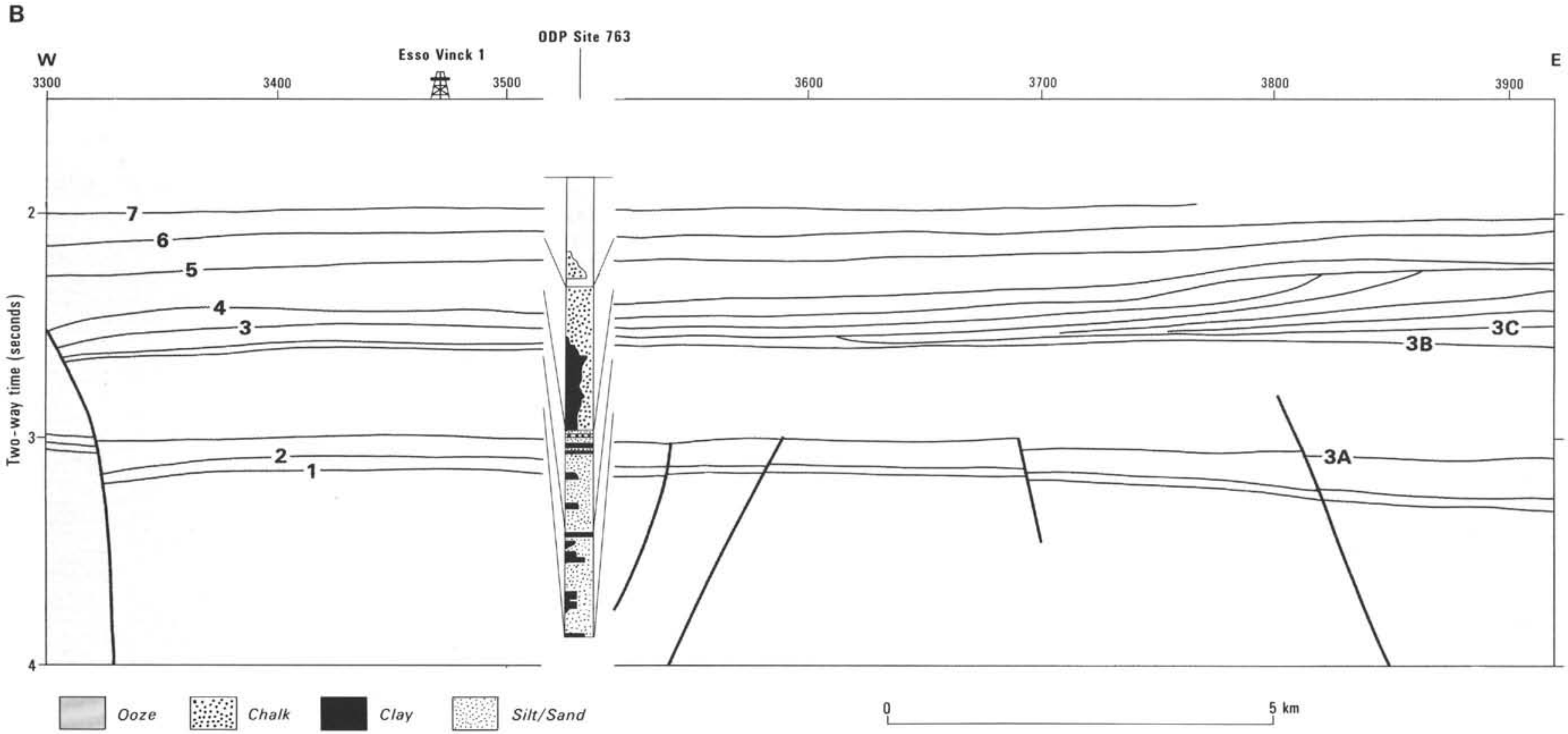


Figure 5 (continued).

quences in package 1 typically alternate between containing high-amplitude–low-frequency seismic facies and low-amplitude–high-frequency seismic facies (e.g., Figs. 5 and 6). Seismic configurations are commonly parallel or slightly divergent and sporadically show low-relief, shingled clinoforms. Sporadic reflections exhibit very high amplitudes. Other locations within package 1 exhibit chaotic, low-amplitude, low-continuity configurations of limited lateral extent. West from the Investigator-1 well and northwest from Site 763 toward Site 762, the uppermost units of package 1 undergo a change from alternating high-/low-amplitude events, shingled clinoforms, and chaotic channeled facies to a more uniform wedge-shaped, low-amplitude sequence. This sequence thickens to the north, where it contains sporadic high-continuity, high-amplitude reflections. It is the strong negative impedance at the top of this upper sequence that produces the characteristic negative amplitude anomaly at the upper sequence boundary of package 1.

### *Interpretation*

The parallel/divergent seismic-reflection configuration characterized by alternating high/low amplitudes, moderate to good continuity, and shingled clinoforms is characteristic of a coastal plain setting depositing deltaic sediments. The chaotic, low-amplitude facies are interpreted as fluvial channels (e.g., at a depth of 3.6 s between shotpoints 3700 and 3900 on Fig. 5). Particularly high-amplitude intervals are interpreted as coal seams, or at the 5 s two-way traveltime (TWT) as possible mylonite zones within the detachment surfaces of Mutter et al. (1989). The upper, northward-thickening transition from alternating high/low-amplitude events, shingled clinoforms, and chaotic channeled facies to a wedge-shaped, more uniform, low-amplitude sequence is interpreted to represent the transition from fluvial-deltaic to marine facies.

Package 1 was not penetrated at Sites 762 or 763, but it has been penetrated at nearly all other commercial wells on the Exmouth Plateau (Vos and McHattie, 1981; Barber, 1988), and it consistently corresponds to the Mungaroo Formation equivalents and Brigadier Formation (Fig. 2) of Scythian/Anisian (Crostella and Barter, 1980) to Rhaetian age (Hocking et al., 1988). Dip on shingled clinoforms indicates a southeast source from the Australian continent. The transition from fluvial-deltaic to marine facies between Sites 762 and 763 occurs at the maximum northwesterly advance of the Mungaroo progradational wedge. The uppermost part of the Mungaroo wedge is a transgressive unit correlative to the Brigadier Formation. The extension of this transgressive marine unit possibly also correlates to the marine and shelf edge reef development seen in Rhaetian age sediments drilled on the Wombat Plateau (Williamson et al., 1989; Haq, von Rad, O'Connell, et al., 1990).

## Package 2

Package 2 is thin over most of the southern plateau but thickens dramatically in the southeast corner (Fig. 3). Only one or two seismic sequences can normally be distinguished in package 2 except in the southeast, where multiple seismic sequences are developed. Reflector 2 (the upper boundary) and internal reflections of package 2 are commonly sequence boundary unconformities or interference composites and have a broad cycle breadth (e.g., Figs. 5 and 6), particularly in the lower resolution GSI 1976 data set. This, combined with the thinness of the package (commonly less than 100 ms), usually inhibits detailed seismic stratigraphic analysis of package 2. The lower sequence is widely distributed on the southern plateau and is commonly only 1 cycle thick, but west of Site 763 the transition in package 2 from a single cycle to multiple cycles can be seen. With this increase in thickness, the lower part of package 2 lies conformably on package 1 and is involved in the block-faulting event. The upper part of package 2 usually increases in thickness toward the downthrown side of half grabens and, although involved, appears to postdate the major block-faulting event. Internal reflections are rarely discernible in package 2, but where present appear to be discontinuous and of low amplitude. The upper sequence of package 2 thins out of the half grabens and in places onlaps the elevated fault blocks.

In the southeast corner of the Exmouth Plateau package 1 has undergone significant subsidence in the Kangaroo Trough (Barber, 1988) as a consequence of extensional fault movement (Fig. 3). In this area, reflector 1 is located at depths in excess of 4.5 s and occurs in a depositional trough more than 2 s thick and filled by several westerly prograded wedges in package 2. The sequences within these wedges are commonly characterized by thick seismic facies of low-amplitude reflections or variable amplitude low-continuity facies with a clinoform configuration. Sedimentation was confined by uplifted fault blocks on the west side of the Kangaroo Trough, and little of package 2 was able to prograde out of the trough and onto the central plateau.

### *Interpretation*

The thin but complex nature of package 2 suggests syndepositional tectonic activity. The lack of package 2 and erosion of package 1 over the Rankin Trend and fault block crests to the west of the Kangaroo Trough can be attributed to uplift associated with Early Jurassic rift shoulders (rift-onset unconformity in the sense of Falvey, 1974) and subsequent mid-Jurassic breakup (breakup unconformity or "main unconformity" of the Barrow-Dampier Sub-basin; Veenstra, 1985). In contrast, away from the tectonism on the southwest Exmouth Plateau in the Investigator–Sites 762 and 763 region, deposition was thin but continuous during much of the Jurassic (Esso Australia, unpublished well completion reports for Investigator-1, Vinck-1, and Eendracht-1), ranging in age from Rhaetian to Tithonian and time equivalent to the Dingo Claystone. This indicates that uplift associated with subsequent rifting on the western Exmouth Plateau margin had not yet begun by the Late Jurassic. The lower conformable part of package 2 is closely involved with block faulting and is probably pre-Callovian in age. The upper part of package 2 thickens into half grabens and onlaps emergent fault blocks, suggesting that it is Callovian to Tithonian in age.

Subsidence accompanying deposition of package 2 east of the uplifted Rankin Trend created a large depositional trough to trap Jurassic sediments from an Australian continent source to the east (Dingo Claystone equivalents). The eastern Jurassic shelf edge prograded westward, infilling the Kangaroo Trough with more than 800 m of Late Jurassic sediment above the Callovian breakup unconformity at the Resolution-1 well site.

## Package 3

### *Geometry*

The external geometry of package 3 is a broad tabular wedge (seen in Figs. 3 and 4). Analysis of progradation direction derived from measurements of the orientation of the shelf break (Fig. 7) identify a source region located to the southeast of the Exmouth Plateau, coinciding with the intersection of the Cape Range Fracture Zone trending northeast-southwest and Cuvier Rift trending northwest-southeast (located south of the Kangaroo Trough). Northwest progradation took place along a broad depositional front, extending the shelf break 150 km northward (Figs. 4 and 7), and transported sediments more than 250 km to marine onlap the uplifted western and northern margins of the present-day plateau and the Australian craton to the east. The maximum progradation of the depositional break (slope inflection between coastal plain and prodelta) varies with age and location across the plateau and adjacent basins. Successive sequences prograded northeast and northwest away from the sediment source, eventually reaching the Investigator well site and almost as far as Site 763. A younger, upper sequence was confined to the adjacent Barrow sub-basin (Tait, 1985) and to the southeast Exmouth Plateau (Fig. 7).

Package 3 is thickest in a 50- to 100-km-wide tongue trending northeast from the southern margin in the direction of the Investigator and Scarborough well sites (Fig. 7). The maximum thickness of 1.14 s TWT (or 1750 m) occurs near the Investigator well site. A depocenter containing more than 1.0 s TWT of sediment also occurs in the southeast Exmouth Plateau. Following deposition, uplift along the southern plateau margin resulted in increasing southward erosion (Fig. 7) of package 3 from the Airlie-1 well site in the Barrow Sub-basin (Boote and Kirk, 1989) to the western plateau (Exon and Willcox, 1980).

### *Structure*

Structure at the level of package 3 is relatively simple. A small number of the normal faults from package 1 continue through the top of package 3, where they usually have small offsets of less than 50 ms. The entire package is arched over an uplifted region at the southern and southeastern margin of the plateau, under the present shelf and slope, and was not deposited on the crest of the emergent Rankin Trend horsts (Barber, 1982). Package 3 is downwarped over the Kangaroo Trough, and from the shelf edge near the Investigator site it is tilted gently back to the south (Figs. 3 and 4). It has also been uplifted into a broad arch along the south-central plateau. Most of these northeast-southwest trends are of Jurassic-Cretaceous age and were reactivated by post-Oligocene basin inversion (Barber, 1988). Along the southwest margin, all of package 3 (like packages 1 and 2) is offset by transform faults and intruded by diapiric structures.

### *Seismic Facies*

The internal geometry of package 3 consists of at least five progradational episodes (in the sense of Frazier, 1974). Each one of these episodes is characterized by an oblique to sigmoidal offlap style with downlap onto the basal boundary and toplap on the upper boundary. Several of these progradational episodes contain basin-restricted onlapping wedges (as shown also in Mitchum, 1985; Erskine and Vail, 1988) and major incised channels landward. Onlapping wedges can be recognized along the length of the depositional break, in contrast to the observations of Erskine and Vail (1988). Several onlapping wedge tops are high-amplitude reflections of good lateral continuity basinward of the depositional shelf break (Fig. 8, back pocket) and commonly display a mounded geometry in both depositional strike and dip directions. Laterally adjacent shelf breaks commonly show erosional truncation and broad seismic cycle wavelength. The uppermost progradational episode is thickest in the southeast but occupies only a single cycle over much of the depositional platform. In the east, the depositional shelf break of this episode extends beyond the previous shelf break (Fig. 7) and is associated with a basinward onlapping wedge. A thick lens of low-amplitude, low-continuity, and chaotic seismic reflections extends westward from the wedge, parallel to the older shelf break.

### *Age*

Age determinations in package 3 are based on a dinoflagellate zonation (Helby et al., 1988). Reflector 2 is an unconformity over much of the Exmouth Plateau, separating Late Jurassic from Berriasian sediments. However, in the southeast corner the stratigraphic relationship may be conformable (Hocking et al., 1988) and the base of package 3 extends into the Tithonian (*Pseudoceratium iehiense* Zone of Helby et al., 1988). The basal hiatus increases in the direction of northwest progradation. The final progradational episode is Valanginian in age and ends in the *Systematophora areolata* Zone (Brenner, this volume, chapter 31; Kopsen and McGann, 1985).

### *Interpretation*

Package 3 is seismically (Kirk, 1985) and age equivalent to the Barrow Group (Hocking et al., 1988) of the Barrow Rift basins. On the Exmouth Plateau it is considered to represent the progradation of a number of linked depositional systems consisting of coastal plain, shoreline, continental shelf, continental slope, canyon, and submarine fan components. Rapid subsidence and abundant sediment supply resulted in an expanded section developing in package 3. During the Berriasian, thermal and tectonic subsidence and sediment loading (Swift et al., 1988) allowed more than 1700 m of sediment to accumulate in less than 6 m.y. Neglecting compaction effects, each progradational event was characterized by a relatively low depositional front with less than 300 m of relief, indicating an average subsidence rate of at least 300 m/m.y.–a very rapid rate compared with that of most basins (e.g., Galloway, 1989). Individual fans and canyons associated with the depositional front were of relatively small relief (100–300 m) compared with those present on Quaternary continental margins. Package 3 was deposited entirely on thinned continental crust, also unlike many modern slope/fan systems. Nevertheless, the package should be regarded as a thin but complex depositional wedge rather than as a simple "delta," which leads to the use of misleading concepts such as topset, foreset, and bottomset beds (e.g., see discussions in Hocking et al., 1988; Howell, 1988). The depositional wedge of package 3 contains all the major physiographic provinces of an Atlantic-style continental margin (in the sense of Kennett, 1982), including a coastal plain, continental shelf, slope, and rise consisting of coalesced submarine fans. In most locations the coastal plain passes directly onto a continental slope/prodelta without the development of an extensive continental shelf.

Thickness distribution is controlled mainly by paleotopography (Fig. 7). Package 3 is thinner over the old Jurassic rift flanks of the Kangaroo Trough, Barrow Dampier Sub-basin, and adjacent to the Rankin Platform. Package 3 also thins against the Neocomian rift flanks of the current plateau margins. Thick depocenters accumulated over the central southern plateau and in the axis of the Barrow Sub-basin west of Barrow Island. Deposition ended with the separation of the rifted margin south of the Exmouth Plateau. Injection of volcanics along this southern transform margin may have prevented subsidence to prebreakup levels and account for the continuing presence of a subsurface arch in this region. The volcanism intruded and therefore was contemporaneous with or postdated deposition of package 3. This, together with the involvement of all of the package 3 sediments in transform faulting on the Cape Range Fracture Zone, indicates that package 3 was deposited prior to continental breakup and seafloor spreading. Uplift and subsequent erosion of the southern margin as India slid past Australia during and after breakup, as suggested by Veevers and Powell (1979), was not the source of the majority of the package 3 sediments.

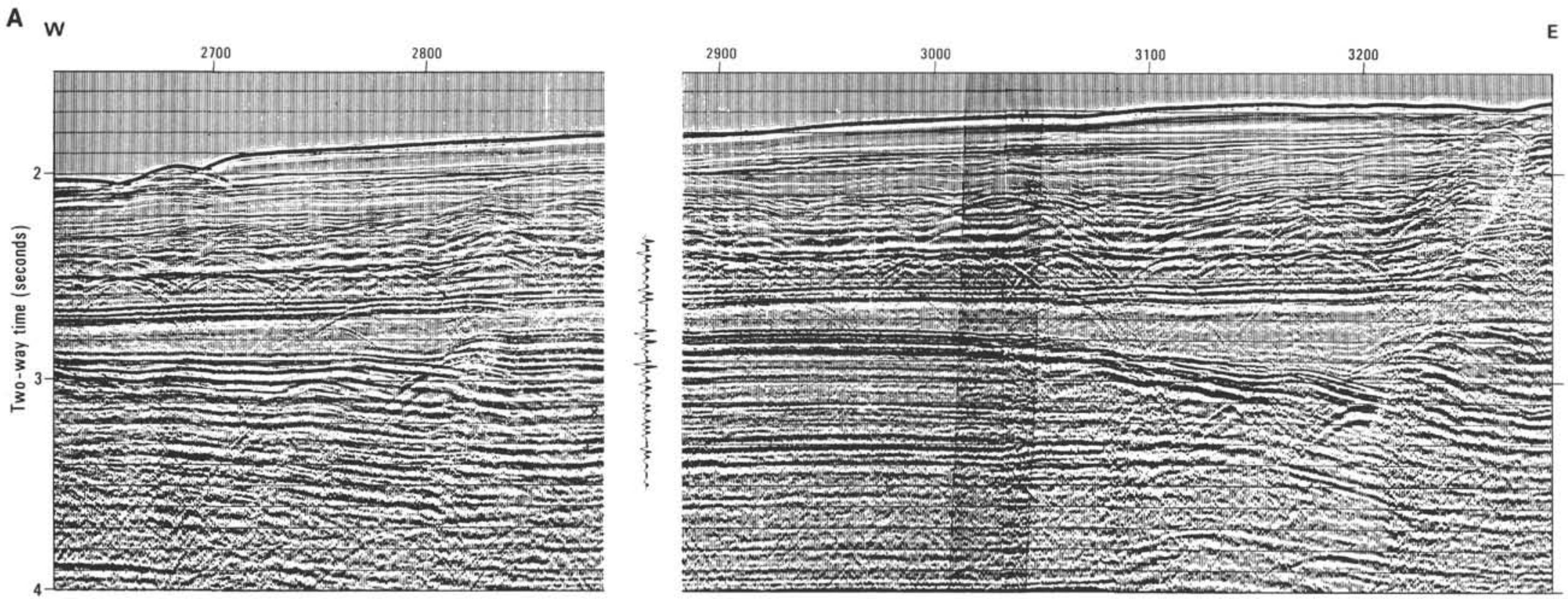


Figure 6. Seismic section through Site 762 and the Eendracht-1 well (**A.** uninterpreted; **B.** interpreted). All eight seismic packages are present here. A simplified lithologic column from Site 762 and a synthetic seismogram from the Eendracht-1 well site are presented for comparison. Compared with Site 763, throws on normal faults are much greater at Site 762 and extend into the Tertiary section (above reflector 6–Cretaceous/Tertiary boundary). Both the upper sequence of package 1 and all of package 2 are thicker here and contain more reflections than at Site 763. Packages 3–5 in this distal position are much thinner than at Site 763, whereas package 7 here is much thicker, reflecting higher rates of deep-water Tertiary carbonate accumulation. Reflector 7A is at the Paleocene/Eocene boundary and represents an upward transition to gravity-dominated resedimentation shown by the numerous channels in package 7 and the seafloor erosion in package 8.

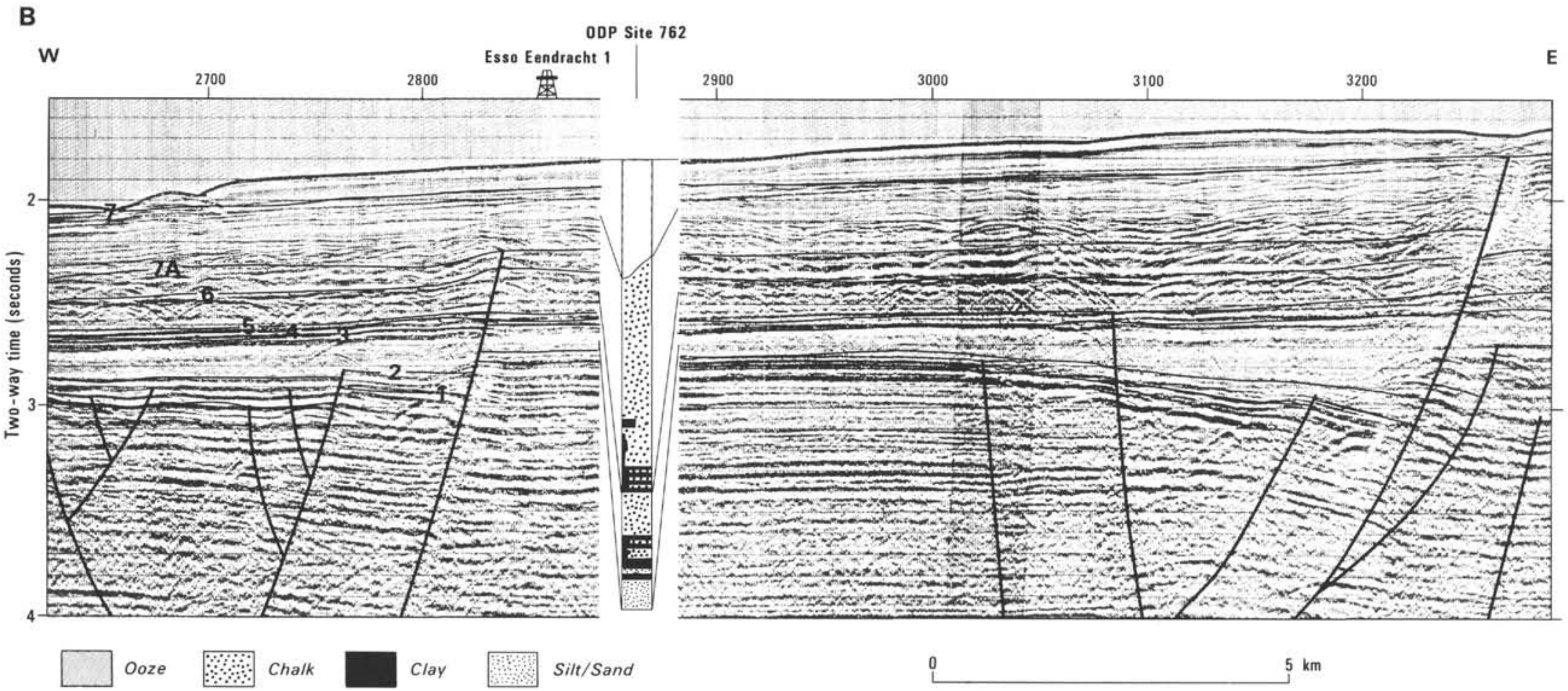


Figure 6 (continued).

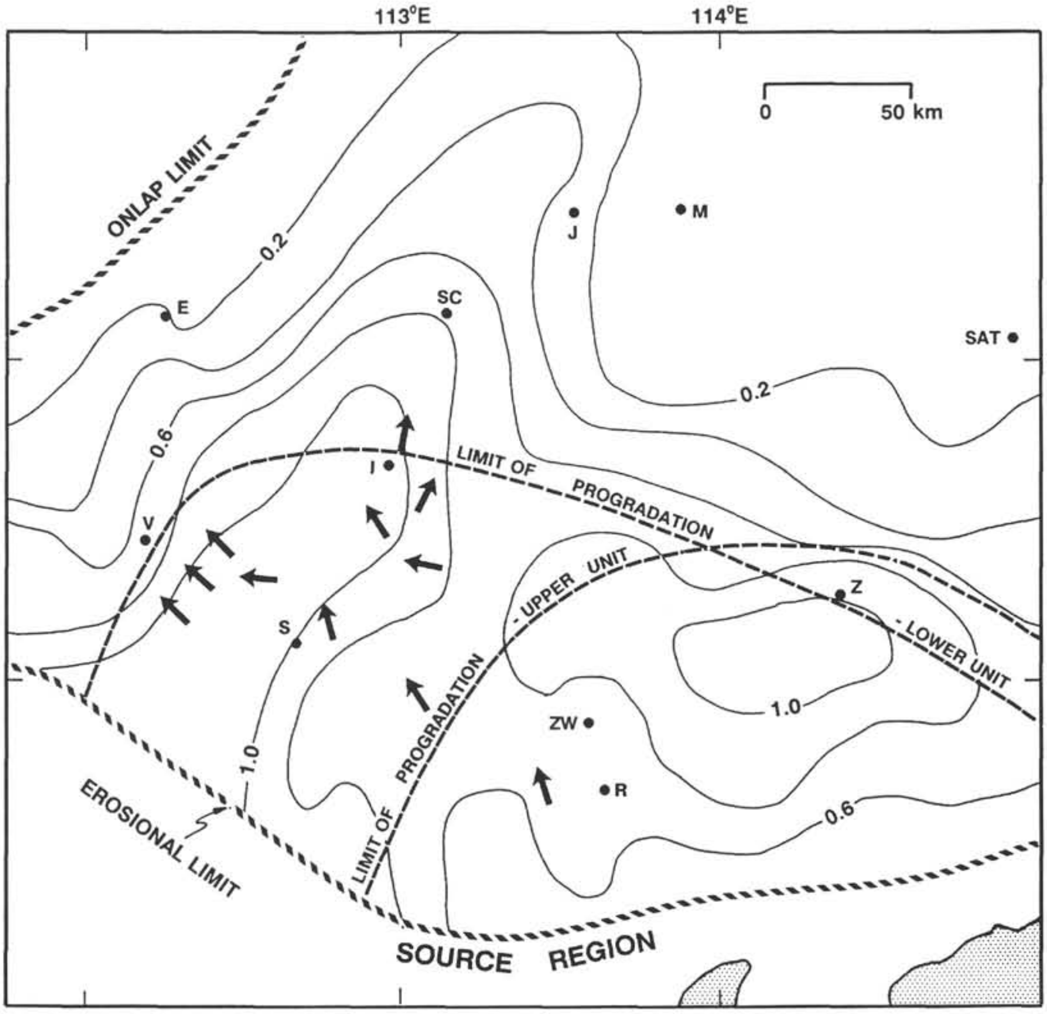


Figure 7. Isopach map of the package 3 Neocomian sediment wedge on the Exmouth Plateau shows sediment thicknesses of more than 1.2 s one-way traveltime (more than 1700 m) occur on the south central and southeast corner of the plateau. Arrows in the direction of progradation of the continental slope indicate a southern source region centered between the Australian continent and the Cape Range Fracture Zone (extending south into the Gascoyne Sub-basin) and not the southern transform margin as suggested by Veevers and Powell (1979) or the adjacent Australian continent as suggested by Boote and Kirk (1989). The Neocomian wedge laps out onto the western margin of the plateau and was eroded after deposition by uplift along the southern margin during the Hauterivian breakup event. Variations in sediment thickness result from preexisting topography derived from an earlier Callovian rifting event. The limits of shoreline progradation for the lower unit of package 3 (including episodes 1–4) and the upper unit (episode 5) are shown as dashed lines. Well locations are labeled as in Figure 1.

## Packages 4 and 5

Packages 4 and 5 are relatively similar in nature and distribution over the Exmouth Plateau and are discussed together. Separate discussions are presented for their difference in detail in the region of Sites 763 and 762. They have a broad blanket or sheet geometry 100–300 ms thick and are present over most of the southern Exmouth Plateau (Figs. 3 and 4). They are thickest in the east, where Package 5 expands to a thickness of more than 900 m near the Zeepard-1 well and occurs as a mounded wedge prograded northwestward from near Barrow Island. Internally this wedge contains large overlapping mounds with bases showing bidirectional downlap. The mounds extend laterally for at least 30 km and contain sediment thickness of more than 800 ms. Packages 4 and 5 onlap the southern and western margins of the plateau and are locally removed by slumping along the western margin. Both packages are thin over the depositional platform of package 3. In the Barrow-Dampier Sub-basin the basal part of package 4 displays an onlapping relationship to package 3 (Kopsen and McGann, 1985; Kirk, 1985) and this relationship is duplicated over much over the Exmouth Plateau.

Reflector 5 at the top of package 5 is an erosional unconformity sequence boundary of high amplitude and widespread occurrence over all of the southern Exmouth Plateau. It has a low-frequency, high-amplitude character, particularly on the outer plateau, where it is commonly the most prominent reflection on the postrift section. It commonly truncates underlying reflections, typically with 100–150 m of relief over a distance of 5–10 km–sufficient to have sporadically removed all sediment down to the top of package 3.

The internal reflection configurations of packages 4 and 5 vary widely. Where the sequences are thinner, the internal reflections are commonly of low frequency, high amplitude, and high continuity in a sheet geometry. Internal reflections in both packages are disrupted by numerous small-scale diffractions. Some channels are present in the distal mound of package 5, but reflections are typically low amplitude or alternating low/high amplitude, variable frequency, and low–medium continuity. In the proximal location internal reflections in the mounded accumulation of package 5 are persistent and of alternating high to low amplitude with little disruption.

***Interpretation***

Precise dating of packages 4 and 5 from Sites 762 and 763 (Haq, von Rad, O'Connell, et al., 1990) and correlation to other commercial wells indicate that they occupy the intervals from Hauterivian to Aptian and Albian to Cenomanian, respectively. Package 4 is thus equivalent to the Muderong Shale and package 5 is equivalent to the Haycock Marl lithologic units of the Carnarvon Basin (Hocking et al., 1988; Exon et al., this volume, chapter 12).

The distribution of packages 4 and 5 indicates a dominant eastern source during all of this interval except in the southwest, where in package 4 a small wedge prograded from the uplifted southern margin. This suggests a distinct reorientation of sediment source during and after breakup from the eastern end of the southern transform margin (package 3) back to the Australian craton by package 5. Deposition across the highs of the Rankin Trend indicates submergence by the mid-Cretaceous of all antecedent relief derived from the Jurassic rifting event. Onlap against the southern and western plateau margins indicates that these areas remained topographically elevated through the middle Cretaceous.

The parallel, continuous reflection configuration of alternating amplitude in packages 4 and 5 suggests deposition in a low-energy outer shelf setting over much of the plateau, which is confirmed by the identification of a Cenomanian shelf edge located along the southeast margin of the plateau 20 km west of the Zeepard-1 well and 25 km east of the Zeewulf-1 well site. Sediment deposition was thin and blanketlike in package 4 and was controlled by the uplifted western and southern plateau margins and the antecedent platform topography inherited from package 3. Package 5 is dominated by northeast progradation of a lobelike continental margin onto the east-central Exmouth Plateau along a corridor between the Zeewulf-1 and Saturn-1 sites and centered around the Zeepard-1 site (see Fig. 1 for well locations). This distribution is also controlled by the remaining positive relief of package 3 southwest from the Zeepard-1 site.

In such a distal setting it is difficult to interpret relative sea-level response, but deposition during the basal section of package 4 clearly occupies a rise in sea level indicated by coastal onlap and transgression over the entire Exmouth Plateau in late Valanginian to early to middle Hauterivian time. This seismic event correlates well with log interpretations at Sites 763 and 762 (see Boyd et al., this volume) and well correlations in the Barrow-Dampier Sub-basin (Kopsen and McGann, 1985).

The origin of reflector 5 and the associated major erosion event is not clear. Reflector 5 occurs at the Cenomanian/Turonian boundary and is marked by black shale deposition (Haq, von Rad, O'Connell, et al., 1990). Hence, it correlates with the worldwide Cenomanian/Turonian boundary event presumed to mark an oxygen minimum greater than 1000 m deep in the world oceans and related to increased surface productivity (Arthur et al., 1987). On the Australian Northwest Shelf the Cenomanian/Turonian event is also considered to represent a significant carbonate dissolution event during a relative rise rather than a lowstand of sea level (Apthorp, 1979). However, the removal of up to 150 m of section in many locations on the Exmouth Plateau and the presence within the black shale of reworked palynomorphs of various ages from Cenomanian to Albian (Brenner, this volume, chapter 31) indicate that a period of physical erosion related to enhanced current activity in deeper water accompanied the chemical event. The time represented by reflector 5 is coeval with separation of Antarctica from Australia, and the erosional unconformity may represent submarine erosion resulting from enhanced oceanic circulation at that time.

## Packages 6, 7, and 8

Like packages 4 and 5, packages 6, 7, and 8 are of a relatively similar nature and distribution over the Exmouth Plateau and are discussed here together. They can be accurately separated and correlated in the region of Sites 763 and 762 and are discussed individually for there. Packages 6–8 are found over virtually all of the Exmouth Plateau and usually display a conformable drape relationship with reflector 5 and with each other (Figs. 3 and 4). They are thickest along the eastern margin of the plateau in a belt that follows the trend of the Kangaroo Trough along the margin of the Northwest Shelf. Here these packages are more than 1.3 s thick and make up the majority of the section above package 1. Packages 6–8 thin in the central Exmouth Plateau over the arch of package 3 (Fig. 3) and the mound of package 5. They also thin on the margins of the plateau as a result of slumping and mass movement. Packages 6–8 show extensive slumping along the western plateau margin but locally overlie the faulted and intruded sediments of packages 1 and 2. However, on the plateau side of the southwest margin packages 6–8 onlap packages 1–5 and are not always present on the eroded topographic high along the margin crest. Slumping here is restricted to the abyssal plain side of the margin crest. Along the eastern plateau margin, packages 6–8 display a thick prograding-wedge geometry with sigmoid to oblique offlap and growth to within 200 m of present-day sea level. Downlapping clinoforms of package 6 occur on the eastern plateau across the older package 5 mound. Extensive channeling in package 7 occurred in topographic lows controlled by the persisting positive relief of package 5.

Package 6 is commonly composed of high-amplitude, continuous reflections with a parallel configuration. Package 7 is composed of alternating high/low-amplitude, high/low-frequency seismic facies that are commonly disrupted by high-amplitude reflections that truncate the underlying reflections of package 6. Truncation and erosion here is typically extensive and severe, extending as deep as reflector 5 and sporadically incising it. Channeling seems to be intense in specific zones such as at the base of the Northwest Shelf, where the channel fill is up to 1 s thick and individual channels are up to 200 ms deep. Channel orientation seems to parallel the present shelf edge and may connect to large submarine canyons such as Swan Canyon along the plateau margins. Package 8 is characterized by low-amplitude, high-frequency reflections that have variable continuity. Reflector 8 is a prominent reflector between packages 7 and 8, where it marks a change from erosion and channeling below to mostly parallel reflections above. Package 8 has fewer large channels but there is evidence of large-scale slumping, particularly along the plateau margins both within the package and on the present seafloor (see Fig. 5).

*Interpretation*

The low-amplitude, variable frequency/continuity of the reflections, their presence seaward of the shelf break, and the blanketlike geometry of packages 6 and 8 indicate a low-energy, deep-water depositional environment probably with a fine-grained lithology. Water depths during deposition were at least 300 m at the beginning of package 6 deposition and continued to deepen thereafter. The internal reflector character of packages 6 and 8 on the central plateau is very continuous and, apart from episodes of submarine channeling, reflects deposition by suspension fallout. Correlation of seismic reflectors to Sites 762 and 763 indicates that package 6 is Turonian to Maestrichtian in age, Package 7 is Paleocene to middle Miocene in age, and package 8 is Miocene to Holocene. Lithology in all these packages at the ODP sites is dominated by deep-water carbonate chalks and oozes (Haq, von Rad, O'Connell, et al., 1990). The cessation of significant terrigenous input to the Exmouth Plateau and the transformation to a deepening biogenic-dominated depositional environment occurs above the Cenomanian/Turonian erosional event at the boundary between packages 5 and 6, as documented elsewhere throughout the region at this time (e.g., Apthorp, 1979). The source of sediments deposited after this event was mainly from the eastern shelf edge, which continued to be located close to its position during package 5 deposition. A second source came from pelagic carbonates generated over the plateau itself. Reflector 6 corresponds to an erosional event around the Cretaceous/Tertiary boundary, and reflector 7 to another unconformity or hiatus of mid-Miocene age. Both these events have been previously recognized in the region (e.g., Apthorp, 1979, 1988; Quilty, 1980).

Several locations on the present seabed, particularly on the plateau margins, have experienced mid- to late Cenozoic erosion and mass movement. This pattern may reflect a trend of increasing submarine slopes in response to broad folding on the Exmouth Plateau Arch and associated post-Miocene movement. Gravity-controlled sedimentation seems to have occurred during the deposition of most of packages 6–8, as they are thinnest over the elevated central plateau arch and thickest at the base of the continental slope to the east. Much of the products of submarine erosion may have been transported off the plateau down major submarine canyons, such as Swan Canyon on the northern plateau margin. Seaward of this canyon at Site 765, turbidite deposition was encountered from the Eocene to Holocene. The onset of extensive submarine gullying since the mid-Tertiary either trends parallel to the adjacent northwest margin or is directed around the mound of package 5. This may imply that the easterly source that fed the package 5 mound continued to be active in supplying the submarine channel systems of package 7 and, in lesser amounts, packages 6–8. The topographic relief on package 5 and, hence, available accommodation indicate that water depths over most of the central Exmouth Plateau at the beginning of the Turonian were at least 300 m. The dunelike features along the eastern plateau margin in package 8 are therefore considered to be indicative of submarine erosion based on reflection truncation relationships and not of shallow-water or aeolian origin as suggested by Exon and Willcox (1980). Lap-out relationships of packages 6–8 on the Exmouth Plateau margins suggest that the western margin subsided during the Tertiary and was progressively covered by deep-water carbonates. In contrast, the southern margin remained high and slow subsidence, possibly as a result of volcanic buttressing, resulted in gradual onlap with thin deposition extending only to the margin crest after the Miocene.

## DETAILED SEISMIC STRATIGRAPHY OF SITES 762 AND 763

### Local Structure and Tectonics

In the region of both Sites 762 and 763 (Figs. 5 and 6), normal faulting occurs at the level of the Mesozoic rift surfaces and exhibits throws on the order of hundreds of meters. Reactivation of these rift faults offsets seismic horizons corresponding to strata within the Cretaceous section. The fault reactivation that occurred within the Cretaceous resulted in fault throws on the order of tens of meters. Reactivation of faulting decreased progressively into the Late Cretaceous and is rarely seen to displace the Cretaceous/Tertiary boundary horizon. Minor fault reactivation above that level in the region may be indicated by seismic diffractions (apparently associated with gas-saturated zones) that occur in some locations along the upward extension of the fault zones.

Site 763 is located in a region where the trends of the Triassic and Jurassic rift faults change from mainly north-south to mainly northwest-southeast (Exon and Willcox, 1978; Barber, 1982). At Site 762 the fault trends have further rotated to lie parallel to the north-northeast- to south-southwest-trending bathymetric contours and the adjacent western margin of the Exmouth Plateau. At both sites horst and graben structures are developed by faults that dip both landward and seaward. These faults are approximately normal at the Triassic and Jurassic level. The structure on which the Vinck-1 well and Site 763 are located (Fig. 5) is a faulted anticline. Fault throws generally average less than 200 ms and do not extend beyond the Neocomian section. The structure on which the Eendracht-1 well and Site 762 are located (Fig. 6) is a gently eastward-tilted horst block. Here fault throws are larger, ranging up to 400 ms and extending into the Tertiary section. South from Site 763 fault trends rotate to a more northwest-southeast trend, paralleling the southern margin of the Exmouth Plateau, and normal faulting is replaced by transform faults. Major offsets occur up to reflector 3, suggesting that transform motion was concentrated in the Neocomian. The lack of associated sedimentation indicates that the transform faults were transpressional rather than transtensional in the region south of Site 763.

### Distribution and Characteristics of Seismic Packages in the Region of the Drill Sites

*Packages 1 and 2*

The main differences of packages 1 and 2 in the vicinity of Sites 763 and 762 with their more regional character is their structure (discussed previously), the change in reflection character at the top of package 1, and the detailed distribution of package 2. From east to west across Site 763 (Fig. 5), the upper sequence of package 1 increases in thickness from less than 100 ms to more than 200 ms and changes character from two high-amplitude interference composites to five resolvable reflections, three of which are of high continuity and two highly variable. Sampling in Vinck-1 (Esso Australia unpublished well completion report) indicates that this upper unit is a transgressive Rhaetian-Norian marine mudstone, and seismic interpretation indicates westward grading into interbedded marine sandstones and mudstones. The underlying sequences are interpreted from well data as fluvial-deltaic in nature. Northward at the Eendracht-1 site, over 370 m of Norian-Rhaetian marine sediments accumulated in the upper section of package 1. From north to south, reflections at the top of package 1 lose amplitude and sequences become more uniform, suggesting a southern source prograding into a deepening marine basin. Package 2 at Site 763 onlaps fault-block highs, is missing from the crests of the highest blocks, and is less than 50 ms thick in the intervening grabens. Palynology from the Vinck-1 site in a small graben at the reflector 1 level indicates that package 2 is only of Late Jurassic (Tithonian) age and therefore the Site 763 area remained high throughout the Early to Middle Jurassic or that there was erosion associated with the Callovian tectonic event. At about 15 km south of Site 762 package 2 thickens to more than 150 ms and contains several seismic sequences. Drilling results at the Eendracht-1 well indicate a complete condensed Jurassic section may be present.

### *Package 3*

For safety reasons Sites 763 and 762 were located beyond the sand-prone depositional break of package 3. In the vicinity of Site 763, package 3 can be subdivided into five depositional episodes involving the clastic progradation of deltas, submarine fans, and a coastal plain. Of these five episodes, four progressively advanced toward Site 763 (Fig. 8, back pocket). Their respective shelf breaks terminated 36, 32, 20, and 7.5 km to the southeast. Site 762 remained in a distal basin location at all times with the closest approach of the episode 4 shelf break lying more than 50 km to the southeast. Both sites remained in a distal setting for the final episode 5, which is located more than 120 km from the shelf break. Site 762 lies within 20 km of the marine onlap edge of package 3 along exposed fault blocks of the rising western plateau margin (Fig. 7). Sediment progradation remained toward the northwest throughout package 3, indicating a constant source located in the Gascoyne Sub-basin, where Neocomian sediments are missing and an elevated block was present throughout the Jurassic (Symonds and Cameron, 1977; Hocking et al., 1988). Although numerous examples of reworked Jurassic and Triassic palynomorphs were found in package 3 sediments at both Sites 762 and 763 (Brenner, this volume, chapter 31) no reflectors interpreted as pre-Cretaceous were seen to outcrop on the Exmouth Plateau, implying a source for package 3 beyond the boundaries of the present Exmouth Plateau. The shoreline of the closest episode 4 trended 10°–20° east of north, which agrees with progradation directions derived from internal clinoforms (Fig. 7) and the lack of any progradation seen on north-south seismic lines west of Site 763. Taken together, these data indicate that the Cape Range Fracture Zone adjacent to Site 763 was not a topographic high during the progradation of package 3 and did not function as a southern source area during the Neocomian (although areas west of Site 763 may have acted as additional source areas).

Correlation of Site 763 geologic data (Fig. 9) to adjacent seismic lines (Fig. 5 and back-pocket Fig. 8) using a time-depth conversion based on velocity and check shot surveys (Esso Vinck-1 unpublished well completion report) and correlation to Site 763 physical-property data (Fig. 10) show that most of the sediment (Core 122-763C-11R to the base of the hole) accumulated at the site as a result of progradation during episodes 2 and 3, when many onlapping wedges accumulated sediment seaward of the depositional shelf break. Episode 1 exhibits only a thin basinal facies and was not penetrated at Site 763. Episode 4 also thins rapidly basinward toward Site 763 but provides the coarsest grained sediment, recovered in small amounts in Cores 122-763B-52X to 122-763B-54X and 122-763C-5R, from when the shoreline made its closest approach. This unit is seismically transparent and thins abruptly to the northwest suggesting chaotic downslope movement by slumping or turbidites but not canyon incision and discrete fan deposition. Most of the progradation in episodes 2–4 appears to occur along a broad depositional front, implying multiple local sediment sources rather than a trunk stream experiencing lobe switching. However, a northwest-prograding lobe was found some 25 km southwest of Site 763. The interpreted delta platform exhibited bidirectional dip of shingled clinoforms, was approximately 24 km wide, and prograded into water depths of approximately 150 m (neglecting compaction). Sedimentation in package 3 at distal Site 762 is difficult to correlate seismically because of the lack of reflections. Sediments seem to have accumulated during all of episodes 1–5, but thicker sections result from episodes 2 and 3, indicating the closer proximity of the shoreline at these times.

Transgression and onlap following episode 4 resulted in condensed sections accumulating during the latest Berriasian to mid-Valanginian that correspond to high-amplitude, broad-frequency seismic reflections derived from interference composites. These sections are characterized by claystones and limestones in Cores 122-763B-48X to 122-763B-51X and 122-762B-81X to 122-762B-83X. Further carbonate intervals at both sites may be related to condensed sections formed during minor halts in the progradation of episodes 2–4. For example, a seismic downlap surface at the base of episode 4 correlates to a carbonate interval in Core 122-763C-12R. Low-continuity chaotic seismic facies of post-episode 4 age form a lens up to 150 ms thick between Sites 763 and 762. They remain in a band parallel to the episode 4 paleoshoreline and do not reach either drill site in significant quantities. These sediments were derived from an eastward source, and from their distribution pattern are interpreted as basinal shales.

### *Package 4*

Package 4 at Sites 763 and 762 is Hauterivian-Aptian in age and equivalent to the Muderong Shale of the Northwest Shelf (Hocking et al., 1988). It consists of a thin sheetlike deposit near Site 762 with conformable, continuous high-amplitude reflections (Fig. 6). Farther south toward Site 763, package 4 thins onto the topographic high of package 3 and onlaps to the southeast, typically lapping out onto the package 3 depositional platform before reaching the southern margin (Fig. 4). Farther west, away from the package 3 depositional platform, package 4 forms a small but well-defined depositional wedge 150 ms thick and 15–20 km wide, with a flat top and internal clinoforms. This wedge prograded from the southern margin after uplift and truncation of package 3 and is considered coeval with the Hauterivian westward movement of Greater India along the Cape Range Fracture Zone. This confirms the prebreakup age of deposition for package 3, the synchronous occurrence of package 3 uplift and erosion with breakup, and the concurrent deposition of package 4.

### *Package 5*

Package 5 at Sites 762 and 763 is an Albian to Cenomanian chalk or calcareous claystone, equivalent to the Haycock Marl and perhaps also the Windalia Radiolarite of the Northwest Shelf (Hocking et al., 1988; Exon et al., this volume, chapter 12). As elsewhere on the Exmouth Plateau, reflector 5–the upper boundary of package 5 in the area of Sites 762 and 763–is marked by a high-amplitude erosional unconformity (Figs. 5, 6, and back-pocket Fig. 8) at the Cenomanian/Turonian boundary event. Package 5 onlaps the southern plateau margin (e.g., 10 km south of Site 763), thins or onlaps the package 3 or 4 platforms in the area of Site 763, thins and downlaps on package 3 and 4 to the north near Site 762 (Fig. 11), and onlaps the western plateau margin. This distribution pattern indicates that the southern and western margins of the plateau remained high during Albian-Cenomanian time. The southerly increase in clay content, sediment thickness, and northward downlap

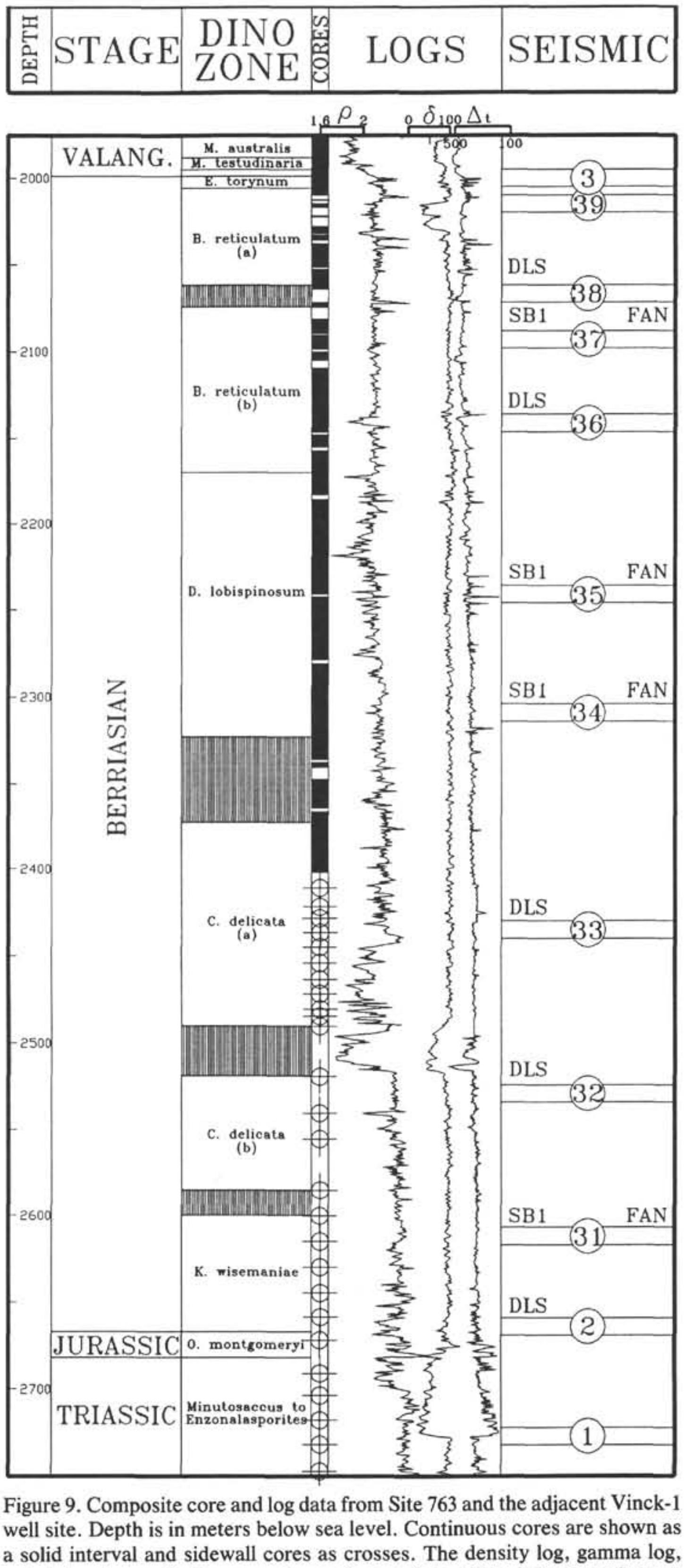


Figure 9. Composite core and log data from Site 763 and the adjacent Vinck-1 well site. Depth is in meters below sea level. Continuous cores are shown as a solid interval and sidewall cores as crosses. The density log, gamma log, and interval transit time are shown from left to right. Seismic reflectors correlate with those of Figure 8 (back pocket). This correlation together with Figure 10 and others from the adjacent Site 762 and Investigator-1 well enables accurate ground truthing of the seismic stratigraphy from lines such as shown in Figure 8 (back pocket) with borehole lithostratigraphy and chronostratigraphy.

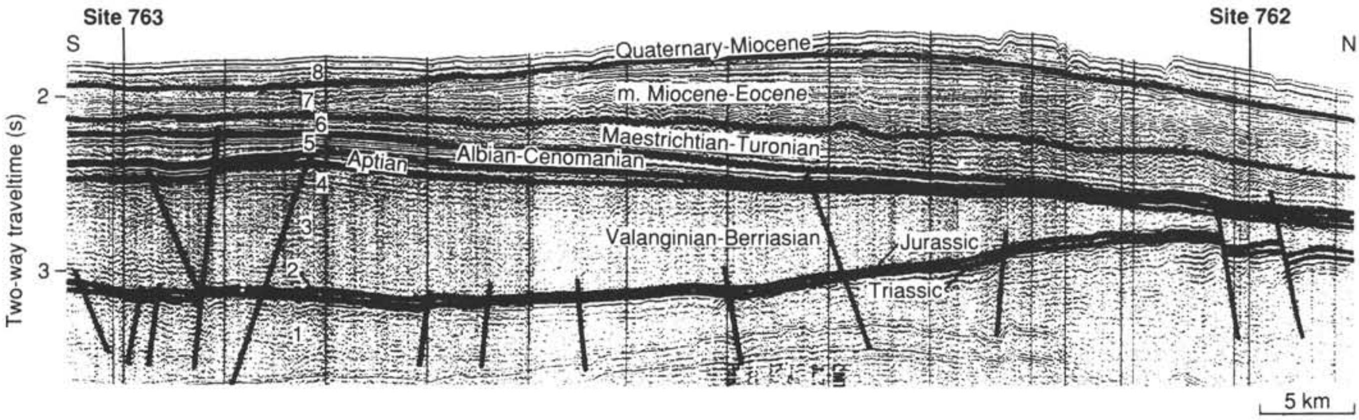


Figure 10. Seismic correlation between Sites 763 and 762 showing the northward thinning of mainly clastic sediments in packages 3–5 and the northward thickening of deep-water carbonate sediments in package 6–8. Southward onlap can be seen at the base of packages 6 and 7. Channeling is common above the base of package 7, and slumping at the seabed can be seen south from Site 762.

at the base of package 5 indicate a continuing minor clastic source from the south until the Turonian.

### *Package 6*

Package 6 consists of foraminifer-nannofossil chalks and claystones of Turonian to Maestrichtian age. Like package 5, it onlaps packages 3 and 4 along the southern margin but exhibits a conformable sheet geometry over the rest of the area. Minor erosion over the previously shallow-water areas toward the southeast removed some of the Maestrichtian near Site 763. The small diffractions that disrupt the otherwise continuous reflections in package 6 (Figs. 5 and 6) correlate with a zone of high gas concentration in cores at both drill sites, and the diffractions are considered to originate from gas-saturated sediments with a source via faults from the underlying section. This interpretation is supported by numerous direct hydrocarbon indicators, such as flat spots in packages 1 and 3, and by the presence of gas chimneys in the region (also reported in Wright and Wheatley, 1979).

### *Package 7*

Package 7 was found to consist of Paleocene to mid-Miocene foraminifer nannofossil ooze and chalk at Sites 762 and 763. The most prominent seismic features of package 7 are persistent onlap onto reflector 7 and ubiquitous submarine erosion (e.g., Figs. 6 and 11). Reflector 7 is markedly diachronous across the region and ranges from earliest Paleocene/Maestrichtian at Site 762 to middle Eocene/Campanian at Site 763. Sediments of Paleocene age onlap reflector 7 at about halfway between Sites 763 and 762 (Fig. 11), and sediments of early Eocene age onlap near Site 763. Submarine erosion during the Eocene was primarily by channel incision, with early Eocene channels in particular commonly up to 50 ms deep and incising each other. Channeling became more sporadic after the mid-Eocene, although a late Eocene regional erosion event removed up to 120 ms of section in the region between Sites 762 and 763. The southward sediment onlap in package 7 is in contrast to the blanketlike style of package 6 and the northward-downlapping style of packages 3 and 5 (Fig. 11). This change in reflection configuration signals a change from a northward-prograding clastic source to ongoing subsidence causing southward onlap of pelagic carbonates.

### *Package 8*

Package 8 is mid-Miocene–Holocene in age based on biostratigraphic dating at Sites 762 and 763 (Haq, von Rad, O'Connell, et al., 1990). It consists primarily of low-amplitude continuous reflections near these sites, disrupted by slumping events that have removed 50–100 ms of section at the present seafloor (e.g., Figs. 6 and 11). This unit is the only one to be deposited on the southwest margin crest and indications are that it did not sink to bathyal depths suitable for biogenous pelagic deposition until after the Miocene. Although not as common as in package 7, numerous submarine channels up to 150 ms deep incise package 8 and continue deeper into package 7. Evidently, submarine erosion and downslope resedimentation were continuous on the southwest Exmouth Plateau throughout the period from the early Eocene to Holocene, which correlates well with the progressive plate collision in the north and associated structural inversion over the Exmouth Plateau (Barber, 1982, 1988).

## DISCUSSION

The deposition of seismic packages 1–8 on the southern Exmouth Plateau of the passive northwest Australian margin records a tectonic history consisting of initial Triassic-Jurassic deposition and rifting, Early Cretaceous rifting and continental breakup, rift to drift transition, mature ocean phase sedimentation, and a final transition toward collision tectonics (Fig. 2). On the Exmouth Plateau, packages 1–8 consist of three major clastic depositional wedges and a carbonate blanket deposit. Analysis of the wealth of seismic detail in packages 1–8, constrained by the excellent chronology provided by continuous cores from the two ODP sites and a broader comparison with 11 industry wells, enables a useful model of passive margin evolution to be constructed for this region.

### Stage 1: Intracratonic Sedimentation

This model begins with eastern Gondwanaland providing a southerly source of sediments into the western Tethys at about a paleolatitude 45°–50° south (wedge number 1 of Boote and Kirk, 1989). Beginning prior to the Norian and continuing to the Rhaetian, a cratonic downwarp accumulated more than 3000 m of sediments, represented on the southern Exmouth Plateau by package 1, over a previously rifted and thinned slab of continental crust (Williamson and Falvey, 1988; Williamson et al., in press). The early phase of this thick accumulation was fluviodeltaic, northwestward prograding, and arenaceous in nature, but by late Norian to Rhaetian had become primarily a transgressive marine mudstone (base of wedge 2 of Boote and Kirk, 1989). To the north on the Wombat Plateau, this transition began earlier and by Rhaetian time had begun to deposit limestones in reef and back-reef settings (Haq, von Rad, O'Connell, et al., 1990).

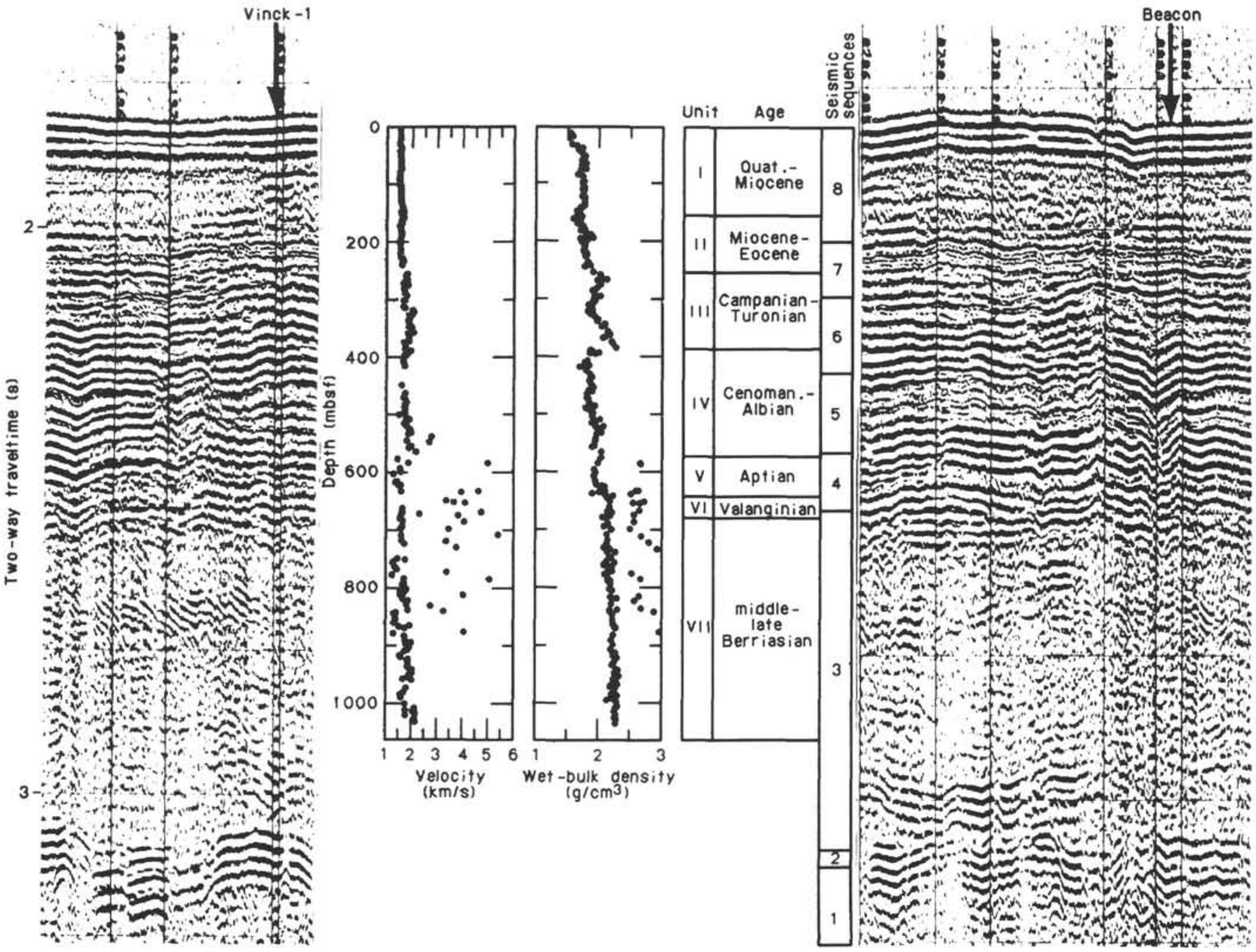


Figure 11. Correspondence between seismic packages, seismic reflections, velocity, wet-bulk density, and stratigraphy at Site 763. Also shown is the location of the adjacent Vinck-1 well site. This figure clearly shows the separation of Aptian-Berriasian clastics (variable velocity and density) and the overlying Albian to Quaternary marls and oozes. Seismic packages are not depth-corrected and therefore do not exactly match the well-derived physical properties and lithology (see Fig. 5 for synthetic seismogram correlation).

## Stage 2: Rift Onset and Initial Breakup

The end of the Triassic coincided with the end of the first depositional wedge and the beginning of a period of subcrustal heating, isostatic uplift, and erosion or nondeposition over most of the Early Jurassic on the Exmouth Plateau, leading to normal faulting and the development of a rift-onset unconformity. Because of erosion or nondeposition over much of the Exmouth Plateau, the rift-onset unconformity is typically developed on a Rhaetian surface. Off northwest Australia narrow zones, oriented north-south, of extensional faulting and subsidence developed the rift valleys of the Barrow-Dampier Sub-basin and the Kangaroo Trough, separated by a structural high over the Rankin Platform. A thick sequence of synrift clastics (wedge number 2 of Boote and Kirk, 1989) infilled the Kangaroo Trough from an eastern source and makes up the basal fill of package 2 in this area. The rift onset unconformity is best developed over the flanks of the rift valleys and their northward extension into the offshore Canning Basin, for example, on the Wombat Plateau. The period of Early to Middle Jurassic extension culminated in a Bathonian-Callovian rifting event and a Callovian breakup event along the present northern margin of the Exmouth Plateau, when south Tibet and Burma broke away from northwest Australia and formed Tethys III (Audley-Charles, 1988). Localized subsidence over the eastern Exmouth Plateau in the former rift valley sites produced a second clastic infill event with an eastern source (wedge number 3 of Boote and Kirk, 1989) of Late Jurassic age in package 2 of the Barrow-Dampier Sub-basin and Kangaroo Trough. This second infill phase in package 2 is separated from the first by a breakup unconformity (Veenstra, 1985; Barber, 1988). The remainder of the Exmouth Plateau remained high throughout the Jurassic deposition of package 2 and either underwent erosion of the Triassic strata (e.g., on the eastern rift valley flanks), accumulated an intermittent Jurassic sequence punctuated by nondeposition or erosion (e.g., the Saturn-1 and Mercury-1 well sites; Barber, 1988), or accumulated a condensed but continuous section in shallow basins such as at the Eendracht-1 well site. Although only a thin section accumulated in such sites as Eendracht-1, both rift onset and breakup unconformities can be seen in package 2, the former conformably involved in block faulting, the latter infilling grabens and onlapping the flanks of uplifted blocks.

### Stage 3: Second Rift to Final Breakup

The Callovian breakup event was unable to propagate southward along the Australian margin and terminated at the Wombat Plateau, in a location coinciding with the offshore extension of the southern boundary of the Canning Basin. Like many other examples on passive margins (e.g., the Jean d'Arc and Whale basins of the Canadian Grand Banks; Grant and McAlpine, 1990) where a failed breakup event results in the filling of the inshore rift valley and a subsequent shift to a new seaward rifting location, the Barrow-Dampier Sub-basin/Kangaroo Trough was infilled and abandoned. Heating and extension then shifted to the Gascoyne and Cuvier rifts at the western margin of the Exmouth Plateau and southward toward the Perth Basin. Like its Early Jurassic counterpart, the heating and uplift event was protracted and lasted from the Callovian to Hauterivian. During this interval, the majority of the uplift occurred southeast of the Exmouth Plateau in the Gascoyne Sub-basin of the Carnarvon Basin (where Hocking et al., 1988, noted an extended period of erosion) and not solely on the Australian craton to the southeast (e.g., Boote and Kirk, 1989) or the southern Exmouth Plateau transform margin (e.g., Veevers and Powell, 1979). A major depositional wedge (cf. number 4 of Boote and Kirk, 1989) prograded from the Gascoyne Sub-basin source northeast into the Barrow-Dampier Sub-basin and northwest across the Exmouth Plateau. Both areas were actively subsiding and accumulated 1000–1750 m of clastic progradation and infill in five depositional episodes of package 3 between the Tithonian and Valanginian.

### Stage 4: Postbreakup and Rift to Drift Transition

The southern clastic source was terminated by the Hauterivian continental breakup of Greater India along the Gascoyne Rift to the west and the Cuvier Rift to the south. The oldest magnetic anomalies in both basins are of M10 (early Hauterivian) age (Fullerton et al., 1989). The earliest sediments deposited at Site 766 (Leg 123 Shipboard Scientific Party, 1989) in the Gascoyne Abyssal Plain are synrift Valanginian clastics and the earliest sediments at Deep Sea Drilling Project Site 263 (Veevers, Heirtzler, et al., 1974) in the Cuvier Abyssal Plain are postrift Aptian-Albian neritic claystones. At Sites 762 and 763, a hiatus or unconformity of two dinoflagellate zones occurs at the Valanginian/Hauterivian boundary in a stratigraphic position comparable to the breakup unconformity of Falvey (1974). Along the southern margin, package 3 sediments are disrupted by transform faults and volcanic intrusions, indicating their prebreakup age. The two divergent margins of the Cuvier and Gascoyne rifts were connected by the 400-km-long Cape Range Fracture Zone. Valanginian-Hauterivian uplift along this fracture zone resulted in extensive erosion of earlier Neocomian sediments in package 3 and deposited the small 100–200-m-thick clastic wedge of package 4, 15 km northward across the southwestern Exmouth Plateau. Much of the sediment shed from this margin at this time may have accumulated on the new abyssal plain to the south. As the spreading center moved away and the two plates uncoupled, widespread subsidence began elsewhere and provided a location for deposition of a blanket of postbreakup, fine-grained clastics in packages 4 and 5, again with a source mainly from eastern cratonic areas. The dominance of clastic sediment supply waned from Hauterivian to Aptian times following an M4 (Hauterivian-Barremian) ridge jump in the Cuvier Abyssal Plain (Fullerton et al., 1989), which occurred at the same time as plate uncoupling along the Cape Range transform and signals the rift to drift transition. Continued postbreakup subsidence and westward sediment supply in package 5 enabled progradation of a 900-m-thick sediment wedge (cf. number 5 of Boote and Kirk, 1989) onto the eastern Exmouth Plateau from the Aptian to Cenomanian. The remainder of the Exmouth Plateau accumulated a sheet drape of claystones, chalks, and marls several hundred meters thick, primarily from the eastern continental or pelagic source but also from a secondary source along the southern margin. During this time both the southern and western plateau margins remained high and were onlapped by the sediments of package 5.

### Stage 5: Mature Ocean to Incipient Collision

The Cenomanian/Turonian anoxic and dissolution event brought an end to clastic deposition on the southern Exmouth Plateau. The southern margin source for clastic supply shown by downlapping seismic reflections in package 5 ceased and shifted to a pattern of nannofossil/foraminiferal ooze accumulation and progressive southward onlap of seismic reflections in packages 6 and 7. The eastern margin also ceased to supply clastic sediments to the Exmouth Plateau and instead switched to carbonate progradation, which slowly spread a carbonate wedge (post-wedge 5 of Boote and Kirk, 1989) westward from the Rankin Platform onto the Exmouth Plateau from Turonian to Holocene times. This latest wedge reached a thickness of more than 1000 m on the eastern plateau margins, beneath which the Kangaroo Trough deeply subsided. Elsewhere, deeper water carbonates accumulated in a blanket deposit, onlapping and finally covering the southern and western margins by Miocene times. Beginning in the early Cenozoic with subduction in the Timor Trench, the passive northwest Australian margin began to collide with the Indonesian crustal collage. This has continued to the present day with additional obduction in the Timor area and collision of the Australian plate in the area of the Java Trench occurring in middle Miocene and again in the Pliocene (Kopsen and McGann, 1985; Howell, 1988). The major structural effect of this collision 1000 km to the north has been to reactivate earlier faults with possible extensional wrenching. A second effect has been to initiate broad folding, particularly during the Miocene, which resulted in the elevation of the Exmouth Plateau Arch and depression of the Kangaroo Trough. Shorter scale but higher amplitude folding responding to the same lithospheric stresses also occurred in the Cape Range area at the same time. In the deeper water of the Exmouth Plateau submarine slopes steepened as folding continued, which in turn produced resedimentation of water-saturated, low-shear-strength oozes resulting in extensive submarine channeling and slumping, as seen especially in lower Eocene sediments but also continuing up to the present seafloor. The Miocene collision event correlates with a depositional hiatus across the Exmouth Plateau, the Wombat Plateau, and the Northwest Shelf.

## CONCLUSIONS

1. A tectonic-stratigraphic evolution of the southern Exmouth Plateau has been determined from the analysis of eight packages of seismic data, correlated with ODP drilling results and regional correlations. This evolution contains (1) intracratonic sedimentation (Norian-Rhaetian), (2) rift onset and initial breakup (Hettangian-Callovian), (3) second rift to final breakup (Callovian-Hauterivian), (4) postbreakup and rift to drift transition (Hauterivian-Cenomanian), and ending with a phase of (5) mature ocean to incipient collision (Turonian-Holocene).

2. A transition zone of Norian-Rhaetian seaward-thickening marine clastics is documented in package 1 north and west from Site 763.

3. Both synrift and postrift sediments are found on the western Exmouth Plateau in the thin Jurassic sequences of package 2. Like package 1, package 2 thickens northward and westward from Site 763.

4. The source of five depositional episodes of Tithonian-Valanginian age sediments of package 3 is clearly indicated to be from the Gascoyne Sub-basin. Progradation of package 3 was contemporaneous with rifting and prebreakup and did not owe its origin to uplift along the Cape Range Fracture Zone during seafloor spreading. Package 3 was dominated by Berriasian sediments on the southwest Exmouth Plateau and, unlike the Barrow Sub-basin, accumulated few Valanginian-age sediments (cf. Erskine and Vail, 1988), apart from a band of westward-transported contourites. The overall geometry of package 3 is that of a thin, but complete, prograding coastal plain to basin floor physiography with episodes of gravity-fed sedimentation. Package 3 is not simply a delta and does not consist only of deltaic topset, foreset, and bottomset beds.

5. The age of breakup on the southern Exmouth Plateau is clearly Hauterivian and corresponds with a period of intense uplift and the progradation of a previously undescribed sediment wedge in package 4.

6. Sediment supply shifted from a northward-prograding clastic source to a carbonate-dominated, southward-onlapping blanket at about the Cenomanian/Turonian boundary.

7. Folding related to collision of the Australian and Indonesian crustal collages farther north increased slopes on the southern Exmouth Plateau beginning in the Eocene and produced widespread submarine erosion and resedimentation in the water-saturated Cenozoic oozes.

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