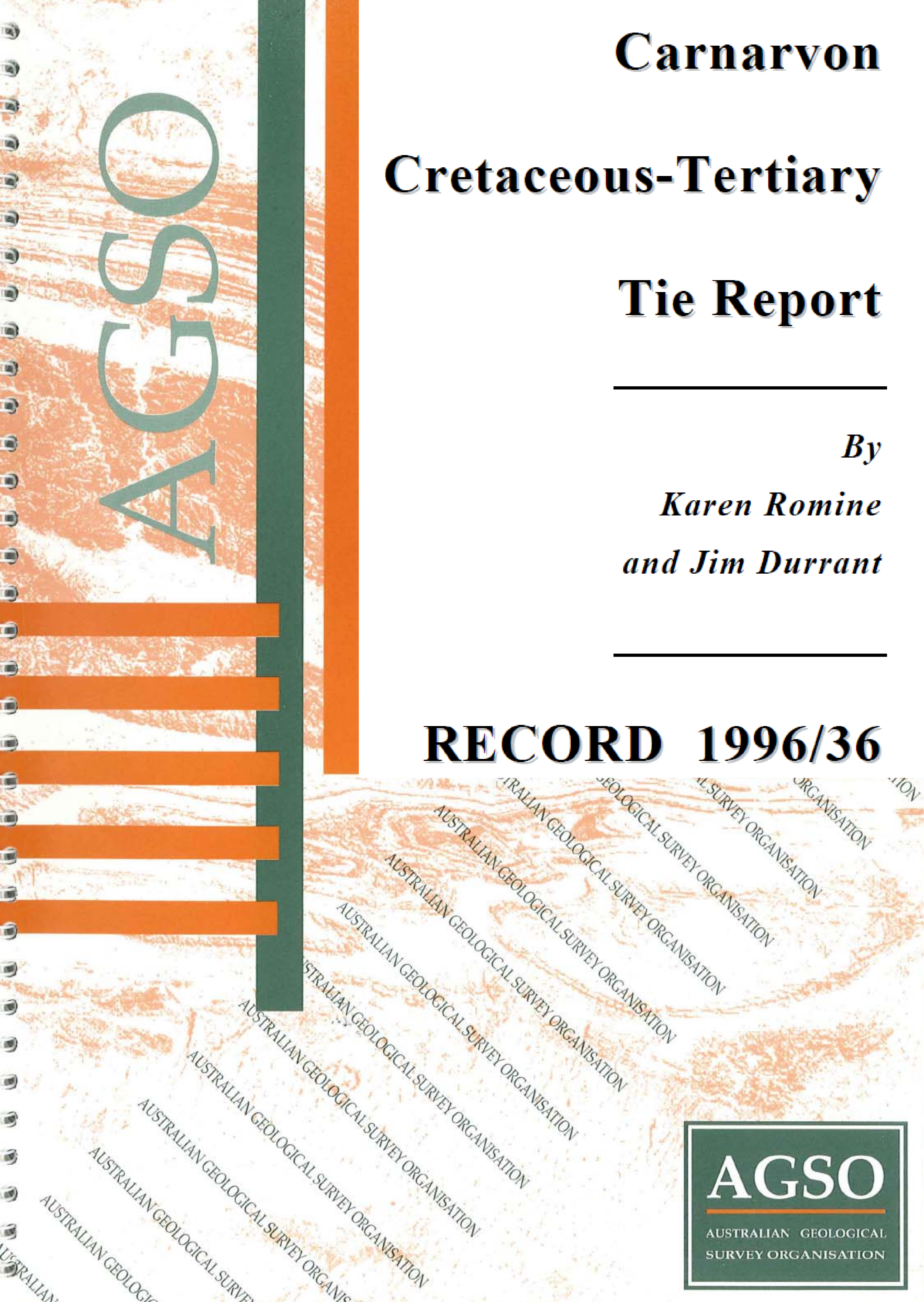

Carnarvon Cretaceous-Tertiary Tie Report

By

Karen Romine

and Jim Durrant

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1.0 EXECUTIVE SUMMARY

A regional, sequence stratigraphic study of the Cretaceous and Tertiary section in the Northern Carnarvon Basin has been completed, utilising 4200km of newly-acquired (1994) high-resolution seismic reflection data, and tying 80 wells. This study provides the first consistent sequence stratigraphic analysis of the Cretaceous and Tertiary section in the region, and has focused on the processes that control the deposition and distribution of facies during the basin's history in order to predict reservoir, source and seal.

Four supersequences corresponding to discrete phases in the development of the sub-basins in the region have been defined. The two older supersequences (intra-Valanginian to Early Campanian) represent deposition during the transgressive part of the basin phase, and the two younger ones (Early Campanian to Late Miocene) represent deposition during the regressive part. These supersequences have been subdivided into 15 sequences, each of which has regional significance. The sequence-based, tectonostratigraphic analysis provides a framework within which a number of new observations and interpretations can be made. The key results are:

- development of a new chronostratigraphic framework for the existing formations (lithostratigraphy)
- determination of stratal geometry above and below the intra-Valanginian unconformity, and redefinition of the distribution and timing of reservoir intervals (e.g. Flag Sandstone)
- determination of the stratal geometry and relationships between the Mardie Greensand and Birdrong Sandstone
- test of the biostratigraphic framework; further revision and more subdivision is needed
- recognition that the modern fluvial drainage systems developed at the time of intra-Valanginian break-up and that the palaeo- Robe-Fortescue System is associated with a Proterozoic lineament, a 'hard-link'
- recognition of a relay ramp accommodation zone between the Barrow and Dampier Sub-basins and between the Barrow and Exmouth Sub-basins, both associated with Proterozoic - Palaeozoic 'hard-links'
- recognition of the palaeogeographic control on sediment supply to the depocentres during rift and early post-rift deposition through relay ramps in two main accommodation zones linking the Barrow-Exmouth, and Barrow-Dampier Sub-basins
- recognition that accommodation zones act as migration pathways, e.g. Barrow Sub-basin hydrocarbons can migrate into *M. australis* traps on the Enderby Terrace
- development of a predictive framework for reservoir, source and seal, resulting in new petroleum systems identified in the early Cretaceous associated with potential source facies in the Muderong Shale and Gearle Siltstone
- recognition of contourite deposition during the Albian in the Barrow Sub-basin, and extensive Turonian and younger submarine erosion throughout the Carnarvon Basin
- deposition of potential reservoirs as lowstand fans and/or wedges can be predicted for each sequence boundary, especially during the regressive part of the Cretaceous-Tertiary basin phase (Early Campanian to Late Miocene)
- recognition of seismic expression of karst on Middle to Late Miocene carbonate platform margins
- identification of Late Oligocene and Miocene lowstand fan sandstones onlapping prograding carbonate platform margins
- recognition of a Middle Miocene prograding barrier reef system in the Beagle and Dampier sub-basins

2.0 SUMMARY

The Northern Carnarvon Basin is one of Australia's most prolific oil and gas provinces. However, residual oil columns and underfilled reservoirs associated with the traditional Triassic, Jurassic and earliest Cretaceous targets occur in many areas in the basin, implying breaches in the integrity of the Early Cretaceous Muderong Shale, the regional seal. Recent discoveries in the Barremian in the Dampier Sub-basin and the Paleocene in the Barrow Sub-basin indicate secondary and/or tertiary migration of oil and gas, and have acted as a catalyst to broaden the focus of exploration interest to include the younger Cretaceous and Tertiary section. These factors indicate the need to develop an understanding of the processes that controlled the distribution of facies in this interval. This Cretaceous-Tertiary Tie study, a joint project between AGSO and Durrant & Associates, responds to that need by providing a regional chronostratigraphic framework for the basin, placing traditional observations in a new context and creating a predictive tool for determining the occurrence and distribution of the lithofacies play elements, reservoir, source, and seal.

Beginning in the Early Cretaceous with the Valanginian break-up of Australia and Greater India, the Northern Carnarvon Basin moved from a dominantly extensional phase to a "sag" phase, marked by rapid tectonic subsidence, contemporaneous with the initiation of sea-floor spreading and subsequent thermal cooling in the adjacent Gascoyne and Cuvier Abyssal Plains. The post-Intra-Valanginian, Cretaceous-Tertiary megasequence can be subdivided into four supersequences bounded by unconformities, each characterized by major seismic downlap surface within it. The supersequence boundaries correlate with second-order falls in eustasy associated with global plate tectonic spreading events and plate reorganization. Stratal geometries and stacking patterns of the two oldest supersequences indicate deposition during the transgressive or "sag" part of the basin phase, the latter two during the regressive or "passive margin" part. A summary of the Cretaceous and Tertiary tectonic events and depositional history follows:

Extension

Commencement of a final period of rifting and extension between Australia and Greater India in the Late Tithonian coincided with a major second-order fall in eustasy and the initiation of syn-rift deposition of the Barrow Delta. Thermal uplift of the region to the south and southwest of today's Exmouth and Barrow sub-basins provided the relief required to source the massive sediment volume of the Barrow Delta. Localised mild inversion in the latest Tithonian may have been enhanced by this thermal uplift. The inversion is expressed on seismic profiles as a transpressional reactivation of some normal faults, and is probably coincident with the Base Cretaceous unconformity.

Final break-up of Australia and Greater India in the Valanginian was accompanied by uplift of the southern Barrow Sub-basin, and resulted in the development of several structures, particularly the Novara Arch and the Jurabi Horst. The break-up event and associated uplift is marked on seismic data by a major angular unconformity truncating the thick Barrow Delta section, the Intra-Valanginian Supersequence Boundary.

Deposition of the Barrow Delta ended at this time, as the break-up of Australia and Greater India and subsequent subsidence removed a major provenance area for the Delta. The uplift and structuring of the southern Barrow Sub-basin at break-up resulted in reorganisation of the existing river drainage patterns and the establishment of a new drainage system. A major fall in eustasy, coincident with break-up, enhanced the incisement of the major river systems that flow into the Northern Carnarvon Basin today, i.e. the Ashburton, Cane, Robe, Fortescue, Yule and De Grey Rivers. These Cretaceous river systems had a major impact on the supply of reservoir facies to the basin and were probably repeatedly incised during sea-level lowstands throughout the Cretaceous and Tertiary.

Intra-Valanginian-Mid Aptian Supersequence

A major shift in style of deposition, from syn-rift (Barrow Delta) to post-rift sag (Mardie Greensand, Muderong Shale) occurred at the Valanginian break-up. Sandstones of the Flag Sandstone Member of the Barrow Group were deposited on the Intra-Valanginian Supersequence Boundary within a lowstand fan and wedge systems tract, succeeded by deposition of the Mardie Greensand and Muderong Shale during the ensuing second-order transgression. The initiation of sea-floor spreading and increased rates of tectonic subsidence were responsible for this transgression, that marks the initiation of a new basin phase.

This Supersequence was deposited between the Intra-Valanginian and Mid Aptian sequence boundaries. It is characterized by a decrease in the deposition of coarse clastics and an increase in deposition of deeper-water facies. The bulk of the fine-grained shale deposited within the interval belongs to the Muderong Shale lithofacies, the regional seal for most of the basin's petroleum accumulations. Following the initial transgression and deposition of the Mardie Greensand (transgressive systems tract), a minor (low-amplitude) regression resulted in prograding highstand and lowstand interbedded sandstones and shales of the *M. australis* dinocyst zone age being deposited in the southern Dampier Sub-basin on the Enderby Terrace and within the Lewis Trough. Deposition of these sandstones in this part of the Northern Carnarvon Basin reflects the change in the dominant fluvial drainage patterns that took place during the intra-Valanginian break-up, from the Early Cretaceous focal point in the southern Barrow Sub-basin that supplied the Barrow Delta, to fluvial sources more widely distributed along the margin east of the Barrow and Dampier Sub-basins. The main contributors during this period were probably the palaeo-Ashburton, Fortescue, Robe, and Yule Rivers. These rivers have served as sources for siliciclastics throughout the later Cretaceous and Tertiary.

The pre-existing topography and relief was a key factor in the distribution of the relatively thin, sandy units (Mardie and Birdrong) that were deposited during the transgression. The earliest sediments were most likely focused and trapped first in the incised valley systems as they backfilled. Later, when the shelf was flooded, the downthrown sides of the faults and fault terraces would have acted as focal mechanisms for the deposition of sands, particularly in association with relay ramps connecting fault segments along the basin-bounding fault systems, e.g. the Flinders Fault System. The Flinders Fault System acted as a hinge between the starved shallow shelf (more subsidence) where Mardie greensands tended to develop and the innermost shelf (less subsidence) where the coeval deposition of nearshore beach and fluvial facies occurred as the Birdrong Sandstone. Winnowing of the shelf sediments by currents may have redistributed and/or concentrated glauconitic "sands" where sea-floor topography was created by buried faults and other features, and accentuated by differential compaction.

Mid Aptian-Early Campanian Supersequence

The long-term eustatic rise that began in the Valanginian was interrupted during the Aptian by a significant eustatic fall that brought sandy facies of the Windalia Sandstone onto the basin margin. These sands were focused around the Barrow Island area and probably represent the distal portion of a lowstand delta prograding from the mouth of the palaeo-Fortescue and Robe River System. Basinward of the Windalia Sandstone the basin accumulated shale that has been associated lithostratigraphically with the Muderong Shale, resulting in placement of the Windalia Sandstone within the Muderong as a member. However, facies stacking patterns suggest that the Windalia Sandstone is a lowstand wedge deposited on the Mid Aptian Supersequence Boundary, strongly implying a genetic relationship with the overlying supersequence and not the Muderong.

Changes in oceanic circulation patterns, concurrent with renewal of the long-term eustatic rise and transgression, produced conditions favorable to the deposition of the Windalia Radiolarite (contemporaneous with radiolarites in the Browse Basin and Vulcan Sub-basin). In addition, there is evidence of periods of submarine erosion on the basinward side of the Rankin Platform that occurred with increasing strength and frequency during the Albian and later Cretaceous, indicating the initiation and development of strong geostrophic and/or bottom currents and a vigorous oceanic circulation system in the young Indian Ocean.

Radiolarite deposition in the early Albian was followed by the aggradation of Albian siltstones, shales and marls of the massive Gearle Siltstone. In the early to mid-Albian, submarine contourite mounds were sculpted by currents at the base of the slope. Lower Gearle Siltstone deposition ceased in the early Turonian, coincident with the initiation of spreading between Australia and Antarctica, and at the time of the Cretaceous maximum in transgression, representing the highest sea-level for the Phanerozoic.

Early Campanian-Mid Oligocene Supersequence

The Early Cretaceous global trend of rising sea level reached a peak during the Turonian. By the Campanian, eustasy had begun a long-term decline. The depositional geometry became distinctly regressive and progradation characterises the stratal geometries of the upper Cretaceous and Tertiary sequences. Deposition in the Northern Carnarvon Basin was dominated by alternating carbonate and siliciclastic cycles, with potential siliciclastic reservoir facies being deposited predominantly during sea-level lowstands. Potential reservoirs are more likely to have been deposited in incised valley and lowstand wedge/fan systems, similar to lowstand sand plays in the Campanian of the Browse Basin. Although not drilled in the Northern Carnarvon Basin yet, such lowstand systems would be expected to be developed at the unconformity at the top of the Toolonga Calcilutite, as well as in association with a major unconformity in the Maastrichtian. The Campanian Withnell Formation was deposited during the transgression and highstand following the Top Toolonga unconformity (Early Campanian Supersequence Boundary), and would provide the seal for such a play. This incised valley play type may be an analog for the Paleocene sands that reservoir the gas in Maitland 1, although those sands may be part of the transgressive rather than the lowstand part of the valley fill.

Mid Oligocene-Late Miocene Supersequence

Separation of Antarctica and Australia was complete by the mid-Oligocene, resulting in deep circulation in the circumpolar region, a major drop in sea-level and the initiation of the Cainozoic glacial-interglacial climate cycles. Australia had moved into lower latitudes by the Oligocene and warmer-water carbonate shelves developed. The carbonate shelves evolved from ramps with occasional reefal buildups in the Oligocene, to prograding carbonate platforms by the Middle Miocene. A prograding barrier reef system developed in the Beagle and northern Dampier Sub-basins, with less continuous barriers throughout the rest of the Northern Carnarvon Basin. Although dominated by carbonate deposition, sandstones were deposited at the base of the platforms as fans during sea-level lowstands.

3.0

INTRODUCTION

The Upper Cretaceous and Tertiary section of the Northern Carnarvon Basin overlies the proven, hydrocarbon-mature Jurassic section. Despite major hydrocarbon discoveries within the Jurassic to Early Cretaceous section, the overlying Upper Cretaceous and Tertiary has been generally considered to be non-prospective, and hence has received little exploration attention.

Residual oil columns and underfilled reservoirs have been drilled in some areas of the basin (e.g. West Muiron, Leatherback), implying breaches in the integrity of the Early Cretaceous Muderong Shale, the regional seal. Moreover, the recent discoveries at Wandoo 1 and Stag 1 in Barremian strata on the Enderby Terrace, and at Maitland 1 in the Paleocene section of the Barrow Sub-basin, suggests the potential for secondary and/or tertiary migration of oil and gas during the Tertiary.

The exploration significance of these observations can only be assessed by better understanding the processes that controlled the distribution of facies in this interval. The Cretaceous-Tertiary Tie (CTT) Study was designed to address this need, with its chief objective being the construction of an improved chronostratigraphic framework for the basin, placing traditional observations in a new context, and providing a predictive tool for determining the occurrence and distribution of potential play elements, i.e. reservoir, source, seal.

To achieve the study objective, a new seismic survey, AGSO Survey 136, was designed to tie a maximum number of wells, especially those in locations where a mid-Cretaceous through Tertiary sedimentary section was preserved and logged. Approximately 4200 kms of high-resolution seismic data were acquired, tying more than 100 wells in the Exmouth, Barrow, Dampier and Beagle Sub-basins. The seismic program proposed by the project group (AGSO, PGS Nopec and Durrant & Associates) was undertaken by AGSO's marine seismic vessel, the Rig Seismic, as part of the Continental Margins Program. The seismic program was designed to complement the existing regional deep-seismic data (Fig. 1; Enclosure 1; Romine et al., 1995; AGSO North West Shelf Study Group, 1994; Stagg and Colwell, 1994). Although the deep-seismic data are of lower resolution than the new data, they provide the means for the integration of additional well-tie information and close the grid for mapping. The new seismic acquisition utilised the latest high-resolution seismic technology including bubble-free GI guns. Acquisition parameters were as follows:

19.66 liter GI gun array (1800 psi)

3000m streamer

12.5m hydrophone group interval (240 groups)

18.75m shot interval

80-fold

2 msec (4-180Hz) sample interval

5.5 second record length.

The approach used in this study follows the basic principles of basin analysis (Fig. 2). Plate interactions result in tectonic events that cause intraplate deformation which, in turn, controls the subsidence regime in a basin. Subsidence or uplift, plus the influence of eustasy and sediment supply, controls accommodation, the space for sediment to deposit. Changes in accommodation determine stratal geometries as the basin fills, and, with the influence of palaeogeography, the distribution of lithofacies and, therefore, play elements. Intraplate deformation also controls the style and timing of trap formation as well as the timing of fluid movement within a basin. Sequence stratigraphy is based on these fundamental concepts and was the primary tool for stratigraphic analysis in this study. With these methods, this study focused on definition of the role of the Cretaceous and Tertiary sequences in the development of the petroleum systems of the basin, and established a chronostratigraphic framework to underpin future exploration.

The study was undertaken by AGSO in association with Durrant & Associates, with principal input by Karen Romine and Jim Durrant. A regional sequence stratigraphic interpretation was undertaken on the seismic and well data by the joint study group. Initial interpretation was done on paper seismic sections, tied to 80 wells using synthetic seismograms (Table 1), and digitised before being finalised on an interactive workstation. Interpreted well summary sheets were produced for key wells, and structure and isopach maps were generated for key sequences using the Petroseis mapping software (Appendices 1, 2, & 3). Interpretive seismic "facies" maps and cross-sections, indicating sequence stacking patterns and the likely depositional systems, were produced for selected intervals (Appendices 1 & 3). Sequence depth picks for selected wells (Table 2) and the horizon interpretation are available in digital format.

Sequences and approximate correlative lithostratigraphy:

Intra-Valanginian-Mid Aptian Supersequence

Base	Intra-Valanginian (Barrow*) Sequence Boundary
dls**	Hauterivian-Barremian (Mardie) Sequence Boundary
Top	Mid Aptian (Muderong) Sequence Boundary

Mid Aptian- Early Campanian Supersequence

Base	Mid Aptian (Muderong) Sequence Boundary
dls	Early Albian (Windalia Radiolarite) Max. Flooding Surface (MFS) Turonian (Lower Gearle) Sequence Boundary
	Early Santonian (Haycock/Upper Gearle) Sequence Boundary
Top	Early Campanian (Toolonga) Sequence Boundary

Early Campanian-Mid Oligocene Supersequence

Base	Early Campanian (Toolonga) Sequence Boundary
dls	Base Tertiary (Miria) Sequence Boundary
	Late Paleocene (Dockrell / Lambert) Sequence Boundary
	Early-Middle Eocene (Wilcox) Sequence Boundary
Top	Mid Oligocene (Giralia) Sequence Boundary

Mid Oligocene-Late Miocene Supersequence

Base/dls	Mid Oligocene (Giralia) Sequence Boundary
	Early Miocene (Mandu) Sequence Boundary
	Mid Miocene A (w/in Trealla) Sequence Boundary Mid Miocene B (w/in Trealla) Sequence Boundary
	Late Mid Miocene (Trealla) Sequence Boundary
Top	Late Miocene (Bare) Sequence Boundary

*	Formation tops (indicate general coincidence or proximity to sequence boundaries)
**	Seismic downlap surface

4.0

REGIONAL TECTONO-STRATIGRAPHIC HISTORY

The Mesozoic Exmouth, Barrow, Dampier and Beagle Sub-Basins are located within the Phanerozoic, greater Northern Carnarvon Basin (Fig. 1), which was compartmentalised under the influence of an earlier, generally N- to NNW-trending, Proterozoic-Palaeozoic fault system and later NE-SW trending Palaeozoic-Mesozoic fault systems (Fig. 3).

The N-S trending Giralia Fault System separates the Early Palaeozoic Gascoyne and Ashburton sub-basins, and controls the southwestern extent of the Mesozoic Barrow Sub-basin. The Sholl Island Fault marks the offshore limit of the western edge of the Pilbara Block and eastern edge of the Ashburton Sub-basin, and separates and offsets the Barrow and Dampier Sub-basins. The Beagle Sub-basin is a transitional 'wrench' basin (Blevin et al., 1994) associated with a probable crustal-scale accommodation zone between the Canning and Northern Carnarvon Basins.

The Mesozoic sub-basins are underlain and strongly influenced by a Permo-Carboniferous rift basin formed during an early phase of major continental extension (the Westralian Superbasin of Yeates et al., 1987). The Permo-Carboniferous rifting reactivated older N-S trending Proterozoic structures and produced a series of NE-SW trending normal faults, the Yardie, Flinders, Mermaid and Rosemary Fault systems on the southeastern basin margin, and the Rankin and Alpha fault systems on the northwestern margin of the sub-basins. These fault systems and the incipient sub-basins were linked by accommodation zones that formed above and semi-parallel to the N-S Proterozoic lineaments.

Subsequent Mesozoic rifting along the NE-SW trends, and under the influence of the older N-NW trends, formed the rift basins which underlie the resulting sag and passive margin* sequences that are the subject of this report. The azimuth of extension was oblique to the underlying Proterozoic and early Palaeozoic structural trends, resulting in the formation of segmented, *en echelon* basin-bounding fault systems, with fault segment offsets accommodated by relay ramps (Figs 4 and 5; McClay & White, 1995; Larsen, 1988; Schlische, 1993). Relay ramps link fault segments and, at a larger scale, individual sub-basins, and basins, and play a fundamental role in the distribution of sediments and the migration of fluids (Gawthorpe & Hurst, 1993; Morley et al., 1990, 1995; Romine et al., 1994). Recognition of these structural features in the Northern Carnarvon Basin is critical to develop an understanding of the syn-rift and early post-rift distribution of reservoir and the later migration of hydrocarbons.

Mesozoic Extension

In the Early Jurassic a long-term transgressive eustatic trend commenced, marking a global trend that continued until the early Late Cretaceous as Pangaea progressively fragmented and new ocean floor was emplaced. Two periods of rifting and extension dominated the basin history from the Early Jurassic to the Early Cretaceous. On the North West Shelf and in the Northern Carnarvon Basin, northwestward extension in the Early Jurassic reactivated abandoned Permian rift faults that are now deeply buried and rotated basinward below the Triassic sag phase (Malcolm et al., 1991; O'Brien et al, 1993; Lemon & Mahmood, 1994; Baillie & Jacobsen, 1995; Durrant & Burt, 1994). The reactivated faults propagated into the overlying Triassic section at steep angles and minor extension produced significant subsidence along the active fault trends. The Exmouth, Barrow, Dampier and Beagle sub-basins developed at this time, along with the contemporaneous Perth, Browse and Bonaparte (Vulcan) rift basins.

Extension terminated in the Late Jurassic with break-up and the onset of sea-floor spreading in the Argo Abyssal Plain in the Oxfordian (155Ma, von Rad et al., 1992). The break-up event temporarily attenuated rifting and subsidence as the effects of lithospheric thinning initiated regional thermal uplift. Accompanying erosion cut into the rift sequence on high blocks, producing the so-called Callovian Unconformity, widespread across the entire North West Shelf. Renewed deposition within the rift basins commenced as thermal subsidence, amplified by sediment loading, became predominant.

Terminology: "Sag" is used here in reference to the subsidence associated with rifting within a basin/sub-basin that lacks major extensional faulting and that did not develop into a spreading center, and to the initial period of rapid thermal subsidence following the initiation of seafloor spreading. Break-up and the spreading centre developed outboard of the marginal rift/"sag" basins, and the margin ultimately evolved into a passive margin. The "passive margin phase" within this document refers to the phase of margin development after the rate of tectonic/thermal subsidence decreased and regression dominated the basin fill geometry.

This period of subsidence was interrupted in the Tithonian by thermal uplift, erosion and minor inversion preceding Gascoyne/Cuvier extension. The inversion is expressed on seismic data as minor transpressional reactivation of the earlier rift faults. At the global scale, this event is contemporaneous with the break-away of South America/Africa from Laurentia, resulting in a readjustment of continental stress, probably along a SSW-NNE vector in Western Australia, and in reactivation of the extensional fault system in a transcurrent sense. Locally, this tectonic event coincides with the abandonment of sea-floor spreading in the Argo Abyssal Plain and the switch to WNW-oriented, Gascoyne/Cuvier extension. The Tithonian event is marked by the regional Base Cretaceous Unconformity (Fig. 6).

In the late Tithonian, the commencement of the final period of rifting and extension between Australia and Greater India coincided with a fall in eustasy and the initiation of syn-rift deposition of the Barrow Delta. Another period of regional uplift, especially to the south and southwest of today's Exmouth and Barrow sub-basins, was probably associated with the thermal event preceding extension, creating the provenance area that sourced the massive siliciclastic volume of the Barrow Delta.

The end of the second extension phase in mid-Valanginian was also marked by uplift, particularly in the accommodation zones associated with the N-S Proterozoic lineaments, forming the Novara Arch, Jurabi Horst and Barrow Anticline (e.g. Fig. 4, Barrow-Exmouth accommodation zone and Barrow-Dampier accommodation zone). Deposition of the Barrow Delta ended at that time, with the final break-up of Australia and Greater India, the initiation of Gascoyne-Cuvier sea-floor spreading, and the abandonment of the rift system. The uplift and tilting episode that occurred at break-up may have been related to the proximity of the thermal anomaly from the incipient spreading centre southwest of the Cape Range/Long Island fault zones. This uplift event produced the Valanginian "break-up unconformity", and is best expressed in the southern Barrow Sub-basin (Novara Arch and Jurabi Horst; Figs 7 & 8). A major angular unconformity, the Intra-Valanginian Supersequence Boundary of this study, truncates a thick Barrow Delta section in this area. The supersequence boundary is also associated with the last step in the second-order eustatic fall that began in the Berriasian (Fig. 6), and marks the initiation of thermal subsidence and the deposition of the sag/passive margin sequence that is the subject of this study.

5.0

NORTHERN CARNARVON BASIN HYDROCARBON SYSTEM

Hydrocarbon Occurrences

In 1964, hydrocarbons were discovered in Barrow 1 in Early to mid-Cretaceous and Jurassic sandstones (Windalia Sandstone, Barrow Group, and Dupuy Member of the Dingo Claystone; Appendix 3, Fig. CC-1). Although the first commercial discovery and production in the Northern Carnarvon Basin was from the Aptian Windalia Sandstone Member of the Muderong Shale Formation, subsequent discoveries were exclusively from the older section spanning the Triassic (Mungaroo Sands) to Berriasian (Barrow Group sands). Consequently, until the relatively recent Wandoo, Stag and Maitland discoveries in the Barremian and Paleocene, exploration objectives focused on the older sediments, while the younger section was largely overlooked.

Offshore drilling began in 1968 with a non-commercial discovery at Legendre 1, followed by a number of wells with interesting, although non-commercial petroleum occurences. Then, in 1971, the first major offshore gas/condensate discovery was made at North Rankin 1, the first of a series of major discoveries on the Rankin Platform.

In 1983, oil was discovered in Lower Cretaceous (mid-late Valanginian), deep-water turbidite sands in the Harriet 1 well. Since 1984, numerous small- to medium-sized oil and gas fields have been discovered along the inboard margins of the Barrow and Dampier Sub-basins, with one small discovery, Nebo 1, in the Beagle Sub-basin. With the exception of Harriet 1, all of these discoveries were hosted in the Berriasian-early Valanginian Barrow Group or older sands. This situation changed in 1992 with a commercial oil discovery at Wandoo 1 in Barremian (*M. australis*) sands (Delfos, 1994). Subsequently, this play has been extended further southwest with the discovery of oil in similar sands at Stag 1 drilled in 1993 (Ballesteros, 1994). Reliable reserve estimates are not published but could be in the order of 100MMBO in place.

Source Rocks and Maturity

The following stratigraphic units contain recognised, potentially mature source rocks which have been identified in the Northern Carnarvon Basin, all of which could source the Cretaceous-Tertiary system (see Appendix 3, Fig. CC-1):

- Upper Jurassic Dingo Claystone
- Middle Jurassic (*W. digitata-indotata*)
- Late Triassic Mungaroo Formation
- Early Triassic Locker shale
- Late Permian Kennedy Group

The main source rock for hydrocarbons in the Northern Carnarvon Basin is generally acknowledged to be the Upper Jurassic, Oxfordian-Kimmeridgian marine shale of the Dingo Claystone. Recent reports indicate that the Middle Jurassic, Bathonian to Callovian age sediments associated with the *W. digitata* and *W. indotata* palynozones also have very good oil source potential(Scott, 1994). In the Dampier Sub-basin, these sediments are associated with the fluvio-deltaic Legendre Formation, but good source potential is reported in marine rocks in the Barrow Sub-basin.

Source rocks within the Triassic and Permian section seem to be less important. They are reported to be only locally developed (Scott 1994), and, where penetrated, are generally gas-prone and immature, or in an early stage of maturity because of their shallow burial. Potential source rocks are reported in Candace 1 and other wells in the Candace Terrace within the Late Permian Kennedy Group(Bentley, 1988). Here 1-2 metre thick, high gamma-ray claystones are interbedded in the upper and lower part of a massive shallow marine sandstone sequence. These coaly, organic-rich zones have TOC values of 3-5% with peaks greater than 8%, potential yields (S1 + S2) from pyrolysis of 5mg/g, and HI values of 200-300. The organic matter is type II/III mixed kerogen with good oil and gas potential. Oil- and gas-prone source rocks are developed in the Locker Shale in Candace 1, Sholl 1, Flinders Shoal 1 and Mermaid 1. The best source interval reported is in the lower part of the Locker Shale in Candace 1 where potential yields (S1 + S2) from pyrolysis are up to 6.0 mg/g and HI values are greater than 200. There are no available reports of significant source rocks within the Mungaroo Formation, but occasional thin lignites, coals and carbonaceous shales could provide localised gas- and oil-prone source facies.

Reservoirs and Seals

The main reservoir facies within the Northern Carnarvon Basin are:

- Early Cretaceous Birdrong and *M.australis* sands
- Early Cretaceous Barrow Group (including the Flag Sandstone Member)
- Late Triassic Mungaroo Formation sandstones

The Flag Sandstone is the producing reservoir for the oil and gas of the Harriet hydrocarbon province, while the underlying Barrow Group provides the main reservoir for most of the discoveries on the southeastern margin of the Barrow Sub-basin. The Late Triassic Mungaroo Formation is the main producing interval on the Rankin Platform. There, giant gas-condensate fields (eg: North Rankin, Goodwyn and Gorgon) occur in large tilted fault blocks below a mid-Jurassic (Argo breakup) unconformity. The Mungaroo Formation comprises a thick, fluvio-deltaic sandstone and shale sequence with subordinate thin limestones and coals/lignite beds. Massive sandstone complexes up to 200m thick occur mainly in the upper part of the Mungaroo, and individual sand bodies up to 35m thick and interbedded with thin shales occur in the lower part. Top and lateral seals are uncertain because of the absence of a regionally developed shale directly overlying the Mungaroo Formation.

Two regional seals identified are:

- Early Cretaceous Muderong Shale
- Early Triassic Locker Shale

Other, more restricted, intra-formational seals include:

- Triassic Mungaroo Formation Shales
- Early-Middle Jurassic Shales

The Early Cretaceous Muderong Shale is a transgressive marine shale sequence which is recognised as providing the seal for most of the hydrocarbon discoveries in the Northern Carnarvon Basin. It provides an excellent seal for the intra-Muderong (*M. australis*) and underlying sand reservoirs. These range from the Birdrong basal transgressive sand, through sands of the Barrow Group and older formations of Jurassic or Triassic origin. The Muderong shale, as defined litho-stratigraphically, is of the order of 50m thick on the eastern basin margin, but thickens appreciably in the Barrow and Dampier sub-basins where it exceeds 1000m.

Although unproven in terms of petroleum discoveries, other potential seals are provided by Early-Middle Jurassic shales and the Early Triassic Locker Shale. The Jurassic shales may provide intra-formational seals for Jurassic sands, and the Locker Shale, comprising thick marine shales, would provide excellent top and lateral seals for intra-Triassic and Permian sandstone objectives in basin flanking areas. Early-Middle Jurassic intra-formational shales, present within the main depocentres and extending onto the margins, are generally thin and of limited lateral extent, while a more marine influence has generated more extensive shales in some areas. Intra-formational, shallow-marine shales provide greater seal potential, because of their generally greater lateral extent. Other intra-formational shales, up to 20m thick, are interbedded with the sandstones. These shale intervals will be effective seals in dip closures, but their effectiveness as seals in fault traps is dependent on the amount of fault throw.

Trapping mechanisms within the system are generally structural, dip or fault closures. The only probable exception currently is the Barremian *M. australis* sand on the Enderby Terrace (Stag Field), which is believed to have a stratigraphic component (Ballesteros, 1994; Crowley & Collins, 1996).

6.0 BIOSTRATIGRAPHY AND AGE

The age scale used in the study is from the Cretaceous and Tertiary portion of AGSO's Phanerozoic Timescale (Fig. 6; Young & Laurie, 1996). The biozonation scheme is based on Helby et al., 1987, with modifications, and is contained within the AGSO STRATDAT database. Biostratigraphy for the study was extracted from well completion reports, then reviewed and compiled by M. Apthorpe (Appendix 4). Additional control for the age and correlation of sequence boundaries was provided by the internal AGSO STRATDAT database, but those data are confidential, and not distributed in this report. As a consequence, there may be some apparent biostratigraphic age conflicts in certain wells where the STRATDAT database provided more accurate, updated picks than the other open-file data. However, the consistency of the age correlations for the sequence boundaries is very good, and the control provided by tying 80 wells regionally is excellent.

During the progress of the study, there was some significant variability in correlations involving the *A. cinctum* dinocyst zone (uppermost Barremian). In a prograding sequence with 6 well-ties along a seismic line, the zone appeared inconsistently from well to well. The inconsistent correlation and the fact that it is an acme zone indicate that *A. cinctum* is probably environment-dependent and should not be relied upon to make regional correlations. The range of *A. cinctum* overlaps the younger end of the range of *M. australis*. Within the zone of overlapping ranges, when *A. cinctum* is present in abundance in a sample(s), the sample is considered to be from the *A. cinctum* zone. If it isn't abundant (but still present), the sample is dated as *M. australis* zone, implying that the sample(s) is older than it actually is (see zones on Fig. 6). The range of *M. australis* spans approximately 8 myrs, and coincides with a reservoir interval, so the need for more precise subdivisions in the interval is clear. However, the *A. cinctum* acme zone does not provide this precision regionally in a consistent or reliable way.

7.0 SEQUENCE INTERPRETATION

7.1 Intra-Valanginian to Mid Aptian Supersequence Lowstand fan and wedge/delta sands, transgressive greensands

Top age:	**Middle *O. operculata* dinocyst zone**
Base age:	***S. areolata/E. torynum* dinocyst zones**
Formations:	**Flag Sandstone, Mardie Greensand, Muderong Shale, Birdrong Sandstone**
Dominant lithology:	**Sandstone, greensand and shale**
Stacking pattern:	**Transgressive**
Stratal geometry:	**Prograding lowstand deltas, fans, transgressive beaches, prograding distal highstand**
Sequence boundaries:	**Intra-Valanginian Hauterivian-Barremian Mid Aptian**

Criteria and age

The Intra-Valanginian Sequence Boundary is a regional unconformity with angular character across the Jurabi Horst and Novara Arch in the northeastern Exmouth and southern Barrow sub-basins (Figs 7 & 8). The unconformity generally lies at the boundary between the *S. areolata* and *E. torynum* dinocyst zones (DZ) except in the deeper basin where it is conformable and occurs within the lower *S. areolata* DZ. Other significant sequence boundaries interpreted within this supersequence include the Hauterivian-Barremian (also known as the Intra-Muderong Hiatus) which occurs at the top of the Mardie Greensand (top *M. testudinaria* DZ) and generally at the base of the *M. australis* DZ; and the Mid Aptian (mid O. operculata DZ) at the top of the supersequence. The age of the top of the supersequence is an approximation within the 5+myr long *O. operculata* DZ. The Mid Aptian Supersequence Boundary truncates the Muderong Shale in some updip areas.

Tectono-stratigraphy

During the Valanginian, the abandonment of the Barrow Rift and uplift of the Novara Arch and Jurabi Horst in the southern Barrow Sub-basin resulted in reorganisation of the fluvial drainage patterns and the establishment of the contemporary drainage system. A major fall in eustasy enhanced the incisement of the major river systems that flow into the Northern Carnarvon Basin today, i.e. the Ashburton, Cane, Robe, Fortescue, Yule and De Grey Rivers (Fig. 3). The post intra-Valanginian Ashburton River was probably originally part of the massive system that drained the highland areas to the south and southeast (e.g. Bernier Platform) and supplied the Barrow Delta (e.g Wogatti Fluvial Facies of Fig. 16 from Boote & Kirk, 1989). The uplift of the Novara Arch and Jurabi Horst would have altered the course of that system leaving the Ashburton to supply sediment to the Exmouth and Barrow sub-basins. The distribution of the Yarraloola Conglomerate indicates that the Robe and Fortescue Rivers may have acted as a combined system to provide the main drainage of the Pilbara Block (Fig. 9). Together, these river systems provided reservoir facies to the sub-basins and were probably repeatedly incised to varying degrees during major sea-level lowstands throughout the rest of the Cretaceous and Early Tertiary.

The Intra-Valangininan Supersequence Boundary coincides with the break-up of Australia and Greater India and marks a changeover from syn-rift deposition of the Barrow Group (Delta) to the post-rift sequences, initially represented by lowstand fan and wedge sandstones of the Flag Sandstone Member of the Barrow Group. Deposition of the Mardie Greensand and Muderong Shale took place during the second-order transgression that coincided with early sea-floor spreading and thermal cooling of oceanic crust. The Hauterivian/Barremian Sequence Boundary (Intra-Muderong Hiatus) is coincident with the M5/M4 ridge jump and spreading re-adjustment. Truncation of the Muderong at the Mid Aptian Supersequence Boundary is associated with a second-order fall in sea level, probably related to plate reorganization and the ridge jump that occurred in the developing Indian Ocean (Fig. 6).

Stratal Geometry and Depositional Setting

The Intra-Valanginian to Mid Aptian Supersequence was characterized by a decrease in the deposition of coarse clastics and an increase in deposition of deeper-water facies of the Muderong Shale, an important regional seal for Cretaceous and Jurassic reservoirs in the Northern Carnarvon Basin (Fig. 6).

The intra-Valanginian unconformity is usually placed at the top of the Barrow Group, which incorporates both the Barrow Delta and, in some schemes, turbidites of the Flag Sandstone. Sequence analysis indicates that a basinward shift in facies, associated with a major second-order eustatic fall, occurred at the Intra-Valanginian Supersequence Boundary resulting in deposition of fan and lowstand delta facies of the Flag Sandstone in the Barrow Sub-basin (Figs 6, 10, DS1[&] , & M2). The Flag Sandstone refers to a number of stacked fans deposited basinward of the Barrow Delta. Some of these fans do occur in association with the deltaic sequences deposited below the Intra-Valanginian Supersequence Boundary. However, this study illustrates that the younger of these sands are deposited as a tectonically-enhanced lowstand, preceding the start of a new basin subsidence phase as tectonic subsidence rates increased and transgression commenced (Fig. 11).

The transition from the Barrow to the Dampier Sub-basin is a relay-ramp style accommodation zone, marked by the apparent bend in the Flinders Fault where the Sholl Island Fault trend extends into the basin, off-setting the Flinders and Rosemary Fault Systems (Fig. 12 & M1). The border fault systems are not hard-linked, but step to the north-northeast across the relay ramp. During rifting, footwall uplift on the rift flanks directed fluvial drainage sub-parallel to the border faults and down the dip of the ramp, funnelling sediments to the southwest. This drainage pattern would have persisted during the early post-rift phase, and probably until the rift basin filled. Later in the basin's history during periods of fluid migration, the ramp would have provided a pathway in the reverse direction for fluids migrating from the Barrow Sub-basin depocenter into and up the ramp, and onto the Enderby Terrace, supplying the *M. australis* sand reservoir at Wandoo 1 and Stag 1.

[&] *See Appendix 3 for 'WS' and 'XS' figures.*

Assuming the last Barrow Delta foresets define the intra-Valanginian shelf edge, lowstand wedge/deltas and fans are most likely to be distributed around the periphery of the Delta and this is largely what is observed. However, palaeogeography had a significant impact on the observed distribution. The Barrow Island Anticline existed at the time of deposition of the Flag Sandstone. The distribution of the Flag Sandstone 'fan' in the Harriet field area and the lowstand delta west of Barrow Island indicate that the incised fluvial systems and deposition were influenced both by the position of the anticline, and by the shelf margin formed by the last foresets of the Barrow Delta (Fig. 12). The fall in sea-level at the Intra-Valanginian Supersequence Boundary induced an abrupt basinward shift in the shoreline, and the palaeo-Ashburton River entered the Barrow Sub-basin at the southern end of the basin, where the Flinders and Long Island Faults intersect (possibly a relay zone). The river incised the shelf formed by the underlying Barrow Delta, 'cannibalizing' the older sediments for transport into the basin and depositing them as lowstand fan and delta deposits (Fig. 10, 13 & DS1). At the same time, the palaeo-Robe/Fortescue River system incised the Peedamullah Shelf and entered the accommodation zone. The combination of the Barrow Delta shelf edge and the Barrow Island Anticline forced the rivers to go around the topographic highs and down the faulted relief of the ramp, resulting in the 'dumping' of sandy turbidites within the ramp, east and northeast of Barrow Island. There would have been considerable erosion within the ramp, some of which is evident on the inboard end of Line 136/09. During the syn-rift phase (pre- intra-Valanginian), the system would have operated in a similar way during lowstands in sea-level, although the rivers would have made their way further down the ramp and into the Barrow Sub-basin towards the toes of the prograding Barrow Delta. This scenario may explain, at least in part, the massive character and stacking of fans in the area east of Barrow Island.

In the Exmouth Sub-basin, the equivalent lowstand facies have been identified as the "Zeepaard Sequence" by Arditto (1993). The high-resolution seismic and well coverage did not extend far into the Exmouth Sub-basin, but the Survey X78 lines referenced in Arditto (1993) have been tied into the CTT Survey. The apparently onlapping, lowstand portion of the Zeepaard Sequence in the Exmouth may have been deposited at the same time as the Flag Sandstone fans and wedge (approximately, S. areolata DZ), onlapping the distal edge of the Barrow Delta (Fig. 14). In this study, the well-ties indicate that the upper part of the Zeepaard Sequence, that Arditto (1993) refers to as highstand systems tract (HST), was deposited contemporaneously with the transgressive systems tract in the Barrow Sub-basin, when the Mardie Greensand was forming, and is late Valanginian to Hauterivian in age (*S. tabulata* and *P. burgerii* DZ). In the Exmouth Sub-basin, this HST (also known as the Upper Delta; Henderson, 1980) has 'backstepped' inboard across the Barrow Delta prograding section. It has a thinner stratal geometry than the Barrow Delta, but still retains a well-developed, sigmoidal progradational delta character, whereas in the Barrow Sub-basin and elsewhere, the backstepping parasequences and sequences of the same age are thin, and the internal stratal geometries are generally below seismic resolution. The absence of a lowstand delta or wedge in the Exmouth Sub-basin, compared with the Barrow Sub-basin, may indicate that subsidence rates increased abruptly in the Exmouth, probably due to greater crustal thinning during Gascoyne-Cuvier extension (Driscoll, PESA presentation, 1996) and its proximity to the spreading ridge. With this scenario, it would make sense that the 'backstepped' delta in the Exmouth Sub-basin was being deposited at the same time as the lowstand delta in the Barrow Sub-basin. However, the current interpretation of the age of each delta does not support this proposition. The source for the 'backstepped' delta in the Exmouth Sub-basin was most likely a branch of the palaeo-Ashburton River System, flowing along the western edge of the Alpha Arch, but another river system, coming from the south out of the modern Exmouth Gulf region, is also a possibility.

After deposition of the lowstand fan and wedge facies in the Barrow Sub-basin, increased rates of tectonic subsidence coupled with a second-order eustatic rise resulted in deposition of a transgressive systems tract (TST) that 'backstepped' over the lowstand and previous highstand delta deposition (Figs 6, M4 & DS2). Minor, third-order regressions punctuate the second-order transgression, resulting in the deposition of intra-Muderong sands, including the shallow-marine, very glauconitic Mardie Greensand Member, the *M. australis* sands, and the Birdrong Formation, a facies equivalent to the Mardie and *M. australis* sands (Fig. 6).

The TST is relatively thin (average total thickness ~70m) and was deposited over an approximately 10-15 Ma period across the broad shelf at the top of the Barrow Delta. The most proximal deposition within each parasequence was the Birdrong Sandstone lithofacies, a fluvial to nearshore sandstone, probably a beach sand in some areas. Downdip (west of the Flinders Fault System), the shallow shelf was starved during deposition of each subsequent parasequence, producing conditions favorable to the production of glaucony. Current-winnowing on the shallow shelf aided in the evolution of glaucony, developing the facies known as the Mardie Greensand. Both the Birdrong Sandstone and the Mardie Greensand are diachronous, from the initiation of the second-order transgression in the Valanginian through the Barremian.

Deposition of the Mardie TST ended in the Barremian, when diminishing tectonic subsidence and eustasy combined to produce a reduction in accommodation and a minor regression, resulting ultimately in the deposition of the Muderong Shale as a highstand system tract (HST; Fig. DS2). In the Barrow Sub-basin, updip of the Flinders Fault system, Birdrong Sandstone was deposited during the *M. australis* DZ, immediately prior to deposition of the Muderong HST. In the Dampier Sub-basin, transgression and Mardie TST deposition were interrupted in the Early Barremian by a minor regression and the deposition of a third-order, thin, prograding highstand, with sands of the lower to middle M.australis DZ age (Figs 15 & XS5[&] ; see Enderby 1 and Wandoo 1). This highstand was followed by a fall in relative sea-level that produced a fan and lowstand wedge of upper *M. australis* age (R. Helby, pers. com.) onlapping the eastern edge of the Lewis Trough (Figs 16 & XS5). An upper *M. australis* transgression flooded back over the top of the *M. australis* highstand on the Enderby Terrace, followed by minor regression and deposition of the Muderong Shale.

It is likely that the source of the *M. australis* sands along the Enderby Terrace was the palaeo-Yule River System. The direction of flow of the De Grey River was likely to have been controlled by the De Grey Nose (and its extension offshore) which was emergent during much of the Early Cretaceous and would have prevented the De Grey fluvial system from flowing into the Dampier Sub-basin (Figs M2 & M3). The thin Muderong Supersequence deposited in the Beagle Sub-basin suggests that when the De Grey River incised the Lambert Shelf, it flowed into the Bedout Sub-basin, rather than the Beagle Sub-basin (e.g. probably the source for the Broome Sandstone in Keraudren 1 in the Bedout Sub-basin). At the time of the intra-Valanginian break-up event and eustatic fall, footwall uplift (due to the earlier extension) along the main border faults resulted in the drainage pattern of the river systems (e.g. the Yule) developing semi-parallel to the fault systems on the footwall flank. The fluvial system(s) eroded and incised the Enderby Terrace before entering the relay ramp linking the Flinders and Rosemary Fault Systems, contributing to the deposition of the Flag Sandstone fan in the northern Barrow Sub-basin. This drainage pattern would explain the lack of comparable thick fan deposition in the Lewis Trough.

Some additional important observations about the depositional setting relative to known sediment distribution can be made here.

- The Fortescue River drains from and along the southwestern edge of the Pilbara Block, coincident with the Proterozoic Sholl Island Fault, an ancient Proterozoic lineament. The relay accommodation zone that developed between the Barrow and Dampier sub-basins during rifting/extension coincides with this "hard-link" (cf. O'Brien et al., 1996), which is well-imaged on the regional magnetic data (World Geoscience, 1994).

[&] *See Appendix 3 for 'WS' and 'XS' figures.*

- The distribution of the Yarraloola Conglomerate and Nanutarra Formation (Fig. 9) indicates that the Robe and Fortescue Rivers formed a major fluvial system, with the alluvial-to-fluvial Yarraloola deposited proximal to the Pilbara Block, and the Nanutarra Formation both a lateral fluvial equivalent as well as a younger, transgressing unit until the early Albian (Hocking et al., 1988). The distribution of the Mardie Greensand (Fig. 17), although a composite of several dinocyst zones, indicates again that the Robe-Fortescue river system formed a broad incised valley that, being slightly deeper than the surrounding shelf, became the site for greensand formation during transgression. The Birdrong Formation also comprises several dinocyst zones, but its distribution (Fig.18) clearly indicates that the it is only preserved *as Birdrong Sandstone* facies on the up-dip side of the basin-bounding Flinders Fault, south of the Long Island Fault and to the west of the Alpha Arch overlying the broad Barrow delta plain in the Exmouth Sub-basin. Birdrong Sandstone beaches that may have been deposited early in the transgression within the Barrow Sub-basin were subsequently starved and reworked to become *Mardie Greensand* facies. With continued transgression and movement of the shoreline landward, stacked Birdrong facies would eventually be overlain by Greensand facies on the 'high' side of the fault systems, but most likely not until fairly late in the transgression (e.g. *M. testudinaria* to *M. australis* DZ).
- Some Birdrong Sandstone deposition occurred during the *M. australis* DZ, probably contemporaneously with the *M. australis* sands being deposited on the Enderby Terrace (McLoughlin et al., 1995). The log character suggests that they represent different facies belts, for example, the Birdrong in the south probably represents fluvial or beach environments, while to the north on the Enderby Terrace, marine and potentially lower shoreface or delta front. These lateral differences may reflect differences in the width and relief of the shelf and the relative dominance of tidal, wave and/or fluvial processes in each area.
- The dinocyst zonation progressively onlaps shoreward during the transgression (Fig. 19). In the Barrow Sub-basin, on the relatively flat shelf provided by the Barrow Delta, the shoreline advanced rapidly, stranding the previous shoreline deposits. Wide areas of the shelf were starved at each flooding, and very little nearshore Birdrong facies were preserved without glaucony formation in the subsiding basin; thus, the Mardie Greensand dominates. In areas where the transgressing shoreline onlapped highs such as the Novara Arch or where subsidence was low (e.g. inboard of the Flinders Fault System), the shoreline did not move such great distances with each parasequence flooding. The nearshore Birdrong facies tended to stack and overlap rather than being 'stranded'on a starved shelf. Consequently, less Birdrong was starved and transformed to greensand, and more preserved as Birdrong.

Play Element Distribution

Reservoir

There are several proven reservoirs in the this supersequence. The oldest are the Flag Sandstone fan and wedge deposits which were dominantly deposited during the upper *S. Areolata* DZ, and were confined to the outer margin of the Barrow Delta and within the relay zone between the Barrow and Dampier sub-basins (Figs 6 & 13). The main locus of deposition of the lowstand fan and wedge facies was in the Barrow and Exmouth sub-basins, thinning to the north into the Dampier Sub-basin (Figs M2 & DS1). In the Barrow Sub-basin, the mapped distribution of the lowstand facies generally appears to be constrained distally by the outer Alpha Arch and Rankin Platform. The lowstand Zeepaard Sequence in Zeepaard 1 and York 1 to the west of the Alpha arch in the Exmouth Sub-basin may have been deposited from a more southwesterly or westerly source (Fig. DS1). In the Dampier Sub-basin, there may be some potential for a very thin fan package (1 reflection cycle) that onlaps structure at Montebello 1 (Fig. 16 & DS1).

After deposition of the lowstand fan and at the end of the relative sea-level fall, the incised valleys began to backfill and lowstand deltas/wedges were deposited (Figs 10 & 11). As mapped in the Barrow Sub-basin (Fig. DS1), the lowstand wedge downlaps the fans. The thickest part of the wedge is associated with an incised valley system that was probably cut by palaeo-Ashburton River (Fig.12). Valley incision and erosion is evident on seismic data in some areas, but is best developed on line 136/06 (Fig. 13). Note that the wedge deposited on the Intra-Valanginian Supersequence Boundary in the Lewis Trough appears to have developed during transgression and is S. tabulata and younger in age (Fig.16).

Deposition during the transgression was characterized by the deposition of the Birdrong Sandstone in the most proximal areas and the Mardie Greensand on the shelf proper. Both of these units are reservoirs, although the reservoir quality of the Mardie tends to deteriorate rapidly below a depth of around 1000m due to diagenesis. The Mardie is considered to be a thief zone for underlying Barrow Delta reservoirs. The Birdrong Sandstone is widespread, from the Murchison River in the south to the Enderby Terrace in the north and was not deposited (preserved) in the outer Barrow and Dampier sub-basins (Hocking et al., 1987). The depositional environment is fluvial delta plain to nearshore marine, wave-dominated and time-transgressive, representing transgressive deposition from minimum to maximum sea levels throughout this period. The Birdrong Sandstone is proximal, and age relationships suggest that it was deposited in equivalence with the Mardie Greensand facies that was forming in slightly deeper water on the starved shelf at the top of each backstepping parasequence (Fig. 19).

In general, the preserved geographic distribution of the Birdrong Sandstone facies is confined to the landward side of the Flinders Fault System (Fig. 18). Although there is evidence of some syndepositional growth along the fault system in the Berriasian and early Valanginian before the Intra-Valanginian Supersequence Boundary (e.g. Lines 136/07 and 136/09), there appears to have been little growth displacement afterwards. The Flinders Fault System probably acted as a hinge point and subsidence increased basinward of the hinge (Fig. 19). Any relief was probably relict topography that was continually accentuated by compaction, differential subsidence across the zone and fault reactivation. During transgression, the shoreline moved landward across the broad shelf formed by the underlying Barrow Delta, across the Flinders Fault System and onto the Peedamullah shelf. The proximal, wave-dominated Birdrong Sandstone was deposited initially on the old Barrow Delta shelf within the sub-basin, then stepped across the Flinders Fault System and onto the Peedamullah Shelf. During deposition of each backstepping parasequence, downdip and below the zone of wave action, the shelf was sediment-starved, setting up the conditions for the production of glaucony. Sometime during deposition of the younger, backstepping parasequences, current and storm action reworked the glaucony, winnowing and concentrating it. Thus, much of the Birdrong Sandstone underwent glauconitization, evolving into the Mardie Greensand. Starvation of the shelf, current action to rework the glaucony and sufficient time were the main requirements. Sediment accumulation rates during deposition of the Mardie TST were less than 0.5 to 1.0 cm/kyr over a period of greater than 10 myrs, providing sufficient time for glauconitization.

The *M. australis* sands are a proven reservoir at the Wandoo and Stag Fields. At Wandoo, the sands occur at shallow 600m subsea depth, thereby preserving very high porosites and permeability. Average porosity of 35% and permeability of 6-10 darcies are reported (Delfos, 1994). The unconsolidated sands are fine-grained with occasional thin coarse-grained zones and contain up to 40% glaucony pellets.

The *M. australis* sands represent deposition during highstand (lower to middle *M. australis*), lowstand and transgressive (upper *M. australis*) systems tracts within two, third-order sequences. Each systems tract has reservoir potential. Reservoir facies of the transgressive systems tract of the younger sequence are updip of seismic control, but would probably be identified lithostratigraphically as Birdrong (Fig. XS5, e.g. Strickland 1). There can be significant differences in the reservoir quality of sands in each of these systems tracts, and generally the updip lowstand and transgressive components are considered to have the best potential. However, on the Enderby Terrace, the prograding unit that is apparently highstand is also reservoir at Wandoo, Stag and elsewhere on the Enderby Terrace. There is apparent mounding and channelling within the M. australis sequence evident on seismic data in some areas, but Crowley & Collins (1996) describe the prograding sand in Stag as a sheet sand, possibly indicating widespread shelfal deposition related to tide- or wave-dominated systems rather than fluvial-dominated.

Source

The time of maximum accommodation for this supersequence occurred at the top of the *M. australis* sand deposition and is marked in both the Barrow and Dampier sub-basins by the seismic downlap of the Muderong Shale. Studies show that during maximum transgression, conditions of maximum water depth and starvation of the basin provide the environment for concentration of organic matter in condensed sections (Loutit et al., 1988). So, one could predict that the Muderong Shale may have unrecognized/unrealized source potential. TOC's up to 1% have been recorded in the Muderong Shale on the Candace Terrace (Bentley, 1988). On the Enderby Terrace, Barremian sediments (Muderong) in Strickland 1 have been evaluated as organically rich and gas/condensate-prone (Roestenburg & Eisenbarth, 1982). Further basinward, in ODP (Ocean Drilling Program) Site 763, TOC's (Rock-Eval) in the Muderong Shale range up to 1.8%, and average about 1% (Shipboard Scientific Party, 1990). While immature on the terraces, the Muderong Shale could be mature in the deeper basin depocentres.

Seal

The conditions produced by high rates of subsidence, maximum transgression and accommodation (see above) also favor the deposition of shale. The Muderong Shale is the regional seal for the older reservoirs in the Jurassic and Early Cretaceous within the Northern Carnarvon Basin.

7.2 Mid Aptian to Early Campanian Supersequence: Radiolarite, submarine erosion, contourites, fine-grained siliciclastics

Top age:	**C9 foraminifera zone**
Base Age:	**Mid *O.operculata* dinocyst zone**
Formations:	**Windalia, Gearle, Haycock, Toolonga**
Dominant Lithology:	**Siltstone, marl, calcilutite, radiolarite**
Stacking pattern:	**Transgressive**
Stratal geometry:	**Aggrading and prograding**
Sequence Boundaries:	**Mid Aptian**
	Early Albian Maximum Flooding Surface
	Mid Turonian
	Early Santonian
	Early Campanian

Criteria and age

The Mid Aptian sequence boundary is an unconformity at the top of the Muderong Shale, defining the base of this supersequence (mid *O. operculata* DZ). In areas where there is no preserved deposition of the upper *O. operculata* DZ, the boundary appears to be at the base of the Windalia Radiolarite and base of the *D. davidii* DZ. The top of the supersequence is defined by the Early Campanian sequence boundary (C9, foraminifera zone = FZ) at the erosional surface at the Top Toolonga Calcilutite. This supersequence contains uppermost Aptian through early Campanian-age strata. A major downlap surface associated with the Windalia Radiolarite has been interpreted within the supersequence, but no other major sequence subdivisions were made except for the Upper Gearle Sequence, which is limited in areal extent to the Barrow Sub-basin. A sequence boundary within the Gearle (~ C4/C5 FZ) shows the development of an angular unconformity on the Rankin Platform (Fig. 20) which can be correlated to Zeepaard 1 in the latest Cenomanian-early Turonian. Erosion and angular relationships appear in the younger section as well, suggesting that the sequence boundary marks the beginning of a period of uplift (mild inversion) within the Barrow-Dampier accommodation zone.

The sequence boundaries interpreted within this interval are the Mid Aptian, Early Albian Maximum Flooding Surface (top *D. davidii* DZ, base *M. tetracantha* DZ), Early Turonian (upper/lower Gearle break; ~ C4/5 FZ) and Early Santonian (near Base Toolonga Calcilutite; within C7 FZ). The top is defined by the Early Campanian Supersequence Boundary, occurring within the C9 FZ and at the top of the Toolonga Calcilutite.

Tectono-stratigraphy

A major ridge jump occurred in the Aptian (at magnetic anomaly M0 time) as India continued to rotate away from Australia/Antarctica (Fig. 6). Minor transtension and a second-order eustatic fall are associated with this event, resulting in a regional unconformity, the Mid Aptian Supersequence Boundary. Deposition of the supersequence commenced at this time when spreading between India and Australia/Antarctica had progressed to a stage such that the Indian Ocean was opened (Veevers et al., 1991). A threshold had been reached in the opening of the Indian Ocean, marked on the North West Shelf and in the Northern Carnarvon Basin by evidence of strong submarine current erosion, sculpting of contourites and a change in depositional facies with the introduction of fine-grained, more carbonate-rich marls and calcilutites. These changes indicate that the North West Shelf rift basins were now marginal basins on the edge of an ocean with well-developed oceanic circulation and upwelling conditions on the margins conducive to the proliferation of siliceous and calcareous plankton. High productivity and preservation of the biogenic sediments resulted in accumulation of the Windalia Radiolarite, the Haycock Marl and the Toolonga Calcilutite.

A second-order Cretaceous transgression began in Early Albian and culminated with maximum global sea levels at the end of the Cenomanian, coeval with the final fragmentation of Gondwanaland as Australia separated from Antartica. A major shift in spreading centre and direction (ridge jump) occurred during the Cenomanian when the Indian Continent began to drift to the NW and away from Australia/Antartica at the same time as Antartica broke away from Australia along the southern rift margin. Break-up on the southern and eastern margins ocurred during the Turonian to Campanian as Antartica began to break away from Australia; this event is recorded in the Northern Carnarvon Basin as a period of minor fault reactivation.

Stratal Geometry and Depositional Setting

This supersequence was deposited during a stage in basin evolution when subsidence rates were low and the impact of other factors on accommodation, such as sea level and sediment supply, were greater (Fig. 6). Eustasy was rising, so accommodation still increased, but not as rapidly as during the previous supersequence when tectonic subsidence rates were high. The result was fine-grained deposition, but aggrading and prograding stratal geometries within an overall transgressive stacking pattern for the supersequence.

The second-order, eustatic rise was interrupted during the mid Aptian by a major, second-order fall, creating the Mid Aptian Supersequence Boundary. The associated basinward shift in facies resulted in the deposition of sandy facies of the Windalia Sandstone onto the margin of the Barrow Sub-basin and focused around the Barrow Island area. The Windalia Sandstone is interpreted as the distal portion of a lowstand delta prograding out from the Robe-Fortescue River System (Fig. 21).

After deposition of the Windalia Sandstone, the combination of a long-term, second-order rise in eustasy and tectonic subsidence resulted in frequently emergent areas like the Rankin Platform becoming submerged, ending the relative isolation of the sub-basins of the Northern Carnarvon. The oceanographic changes associated with the opening of the Indian Ocean resulted in a very different sedimentary record for the basin during deposition of this supersequence. Rising sea level resulted in the trapping of terrigenous material updip in the old valley systems as shorelines moved inland, flooding the craton and forming epeiric seas. Upwelling along the margins of the new ocean basin resulted in the zones of high productivity affecting both siliceous and calcareous microfossils and the resulting sedimentary record.

Rising eustasy and transgression effectively shut off the influx of terrigenous material to Northern Carnarvon Basin, resulting in the deposition of the Windalia Radiolarite. The Windalia Radiolarite is associated with a regional seismic downlap surface and condensed section formed by the downlapping toes of the Albian and younger sequences (Gearle Siltstone). Radiolarians are present throughout the Gearle Siltstone, indicating relatively deep water and low terrigenous input. Later, in areas distal to the Gearle depocenter in the Barrow Sub-basin, marls (e.g. Haycock Marl) were deposited. During the Santonian and early Campanian, transgression and deposition of the Toolonga Calcilutite marked the beginning of dominantly calcareous sedimentation in the basin, and the transition to the regressive part of the basin phase.

During the early Albian there is evidence for current modification of basinal deposition, such as the section on line 136/05 (Fig. 22 & DS3). The edges of the mound on line 136/05 can be mapped in all directions, and truncation on the updip side is evident. A geostrophic current like the Gulf Stream or a bottom boundary current probably followed the outer flank of the Rankin Platform. At the Rankin Platform/Alpha Arch bend, the current moved south and westward into the Exmouth Sub-basin scouring and contouring the sediment on the lower slope and in the basin. The resulting sediment “mound” is therefore a contourite. This sort of current-modified deposition occurred throughout the Late Cretaceous and Tertiary in these base-of-slope and basinal positions.

Maximum sea levels occurred during the late Cenomanian and Turonian. A major sea-level fall in the Turonian produced an unconformity and sequence boundary that coincides with the Upper/Lower Gearle boundary in the Barrow Sub-basin. Along the Rankin Platform, outboard and downdip of Barrow Island, a major angular unconformity is interpreted on line 136/19 between lines 136/05 and 136/10 (Fig. 20). Beginning in the late Cenomanian, this area is repeatedly eroded, coincident with sequence boundaries during the Late Cretaceous and early Tertiary. There is erosion updip, but not to the same degree. The proposed interpretation is that the tectonic events occurring around Australia at that time produced intraplate stresses on the North West Shelf that were largely absorbed in the accommodation zones. For example, in the Northern Carnarvon Basin, this resulted in uplift/inversion and fault reactivation in the accommodation zone between the Barrow and Dampier sub-basins, and affected the corresponding part of the Rankin Platform. In concert with the tectonic ‘adjustments’, geostrophic boundary currents, shifting laterally in concert with relative changes in sea level, repeatedly scoured and truncated the section on the Rankin Platform which projected furthest basinward, producing the angular unconformity. An analog for this scenario may be the Blake Plateau and the Gulf Stream in the western North Atlantic (Pinet & Popenoe, 1982).

The structure maps from the Turonian to the Base Tertiary indicate that differential subsidence was maintained between the Barrow-Dampier accommodation zone and the rest of the basin during that interval (Figs M9, M11, M13, & M15). Basinward of the Rankin Platform, the area was sediment-starved as the basinal areas to the northeast and southwest filled. Inboard of the Rankin Platform, the structure maps indicate little change through this period, due either to low rates of deposition or erosion. In spite of the Tertiary sequence fill outboard of the Rankin Platform (e.g. Saturn 1, Fig. XS3), there is still a subsidence differential that persists today in this area, and is expressed as the propagation of the fault on the basinward side of the Rankin Platform, through the younger section to the sea-floor (see Lines 136/07, 08, & 09 for examples). This may indicate an accommodation response to the continued generation of intraplate stress by the subduction of the northern edge of the Australian plate.

Submarine erosion of the sea floor became more widespread in coincidence with the Turonian erosion on the Rankin Platform (Fig. 23). Some of the erosion was probably due to increasingly vigorous oceanic circulation and the development of bottom currents, some to mass and/or turbidite flows.

Play element distribution

Reservoir

The main identified reservoirs for this interval are the Windalia Sandstone and the fractured radiolarite over the Barrow Island Anticline. Deposition of the Windalia Sandstone was focused at the mouth of the Robe-Fortescue River System, and represents the distal part of a lowstand wedge/delta deposited during forced regression (Posamentier et al., 1988). Better quality reservoir would probably have existed further up-dip, but the combination of an anticlinal structure located within a relay ramp and associated migration pathway make this a successful play. Lowstand deposition like the Windalia Sandstone could have occurred elsewhere in the basin, but, in general, existing data indicates that the Robe-Fortescue River System was the primary fluvial system with enough sediment supply at the time to prograde out into the basin.

The Gearle Siltstone is thickest in the Barrow Sub-basin (Fig. M8) and forms a silty, shaley aggrading wedge, with generally poor reservoir quality. Gearle Siltstone deposition is thin throughout the rest of the basin except for a small depocenter at the southern end of the Dampier Sub-basin. In areas of minor Gearle deposition, the Haycock Marl was deposited as the Gearle Siltstone equivalent. This supersequence was deposited at the time of highest global sea-levels in the Phanerozoic. Shorelines were far inland from the depocentres and epeiric seas characterised the fringes of the Australian continent. During this period, the only opportunities for deposition of reservoirs in the study area would have been during major sea-level falls, and these would have had to have moved the shoreline a long way to bypass the shelf. There is little evidence for sands being deposited anywhere in the basin except for a trace of very fine sand that appears in Minden 1 during the Albian (Fig. 24). The intervals with relatively coarser-grained sediment have sharp bases on the gamma log and there is an overall backstepping trend related to increasing accommodation at the time, but the sand content is very low. In the early Albian, there is potential for current-related winnowing to concentrate any coarser fraction of the incoming sediment to the basin, such as in the contourite mound on 136/05 (Fig. DS3), and that mechanism may explain the fine sand in Minden 1. However, because the basin was experiencing a period of maximum transgression (and accommodation) during deposition of this supersequence, the likelihood of significant sandstone reservoir deposition in the depocentres is not great.

Source

This supersequence was deposited during a period of rising sea level and low tectonic subsidence rates. Maximum global sea-level was achieved with transgression and formation of epeiric seas worldwide. This period was a globally significant period for deposition of source rocks, and has been largely overlooked on the North West Shelf. In the Northern Carnarvon Basin, the Gearle Siltstone has TOC's up to 2% in Candace 1 (Bentley, 1988) and may have higher values elsewhere.

Seal

As with the Muderong Shale, times of rising sea level and maximum transgression provide the best opportunity for deposition of sealing shales. The downlapping toes of the Gearle Siltstone and Haycock Marl act as seal for the Windalia reservoir(s) at Barrow Island. If lowstand sands were brought into the basin during lowstands, they would be encased in fine-grained sealing facies during transgression and highstand.

7.3 Early Campanian to Mid Oligocene Supersequence: Alternating fine-grained siliciclastics and carbonates, incised valleys(?)

Top age:	**P21 foraminifera zone**
Base age:	**C9 foraminifera zone**
Formations:	**Withnell, Korojon, Miria, Dockrell, Wilcox, Walcott, Giralia**
Dominant lithology:	**Fine-grained siliciclastics with intervals of fine-grained carbonate**
Stacking pattern:	**Regressive**
Stratal geometry:	**Prograding siliciclastics, incised valleys, thin transgressive carbonates**
Sequence boundaries:	**Early Campanian** **Base Tertiary** **Late Paleocene** **Early-Middle Eocene** **Mid Oligocene**

Criteria and age

The base of the supersequence is defined by a major erosional surface at the top of the Toolonga Calcilutite (foraminifera zone, FZ C9) and is coincident with a change in rate of spreading between Australia/Antarctica and India (Fig. 6; Ross, 1995; Veevers et al., 1991). The main sequence boundaries interpreted within this interval are the Base Tertiary (FZ T1/C13), Late Paleocene (FZ T7/T8), and Early-Middle Eocene (~ FZ T9/T10; Fig. 6). The top of the supersequence is defined by the Mid Oligocene Supersequence Boundary (P21 FZ) which truncates the updip portions of underlying sequences in much of the basin. There is a considerable amount of erosional relief on this boundary, particularly in the transition zone between the Barrow and Dampier sub-basins on the Rankin Platform (Fig. 25).

Tectono-stratigraphy

During the latter half of the Cretaceous, rates of tectonic subsidence were low and fluctuations in eustasy were the dominant factor determining accommodation. During the Turonian, near the end of the peak period of global sea-floor spreading and production of new ocean floor basalts, Cretaceous sea level was at a maximum (Fig. 6). By the early Campanian, a long-term eustatic fall commenced as the rate of continental fragmentation and production of new ocean basins and sea floor decreased.

The end of the Cretaceous was marked by several major falls in eustasy as the Indian sub-continent moved rapidly northward, approaching collision with the Asian continent in the Paleocene. This collision precipitated a decrease in the rate of spreading between India and Australia that was balanced by a concomitant increase in spreading rates in the spreading ridge in the Southern Ocean. The transfer of stress across the Australian continent is believed to have produced minor fault reactivation in the Northern Carnarvon Basin, enhancing a significant early Tertiary unconformity (Base Tertiary Sequence Boundary).

An unconformity in the Early-Middle Eocene correlates with a ridge jump and change in spreading direction fron NW-SE to N-S in the Southern Ocean (Veevers et al., 1991). This event was followed by a period of transgression in the Late Eocene in the Northern Carnarvon Basin. Final clearance of the Antarctic and Australian plates south of Tasmania in the Oligocene permitted the development of the Circum-Antarctic Current and isolated Antarctica at the pole, resulting in the buildup of continental ice sheets and a rapid fall in eustasy. The Mid Oligocene Supersequence Boundary was formed during the eustatic fall, marking the upper boundary of this supersequence.

Stratal Geometry and Depositional Setting

Prograding siliciclastic wedges were puncuated by transgressive, fine-grained calcilutites and calcareous shales during deposition of this supersequence. Condensed sections and basinal deposition distal to the clastic sources are dominated by calcilutite and calcareous shale. By the Late Eocene/Early Oligocene, carbonate was the dominant lithology.

The main locus of siliciclastic deposition in the Campanian and Maastrichtian is east and north of Barrow Island in the northern Barrow and southern Dampier sub-basins (Fig. M13 & 14). In the mid-Campanian to early Maastrichtian (Withnell Formation and Korojon Calcarenite), sandstone deposition was greatest in the area around Rosemary 1 and Mawby 1A. Sandy facies also appear in wells further north in the Dampier Sub-basin, but to a lesser degree, indicating that the source of these sediments was from the northeast and east, and probably related to the Yule and De Grey River Systems. Downdip from this source area, in the southern Barrow and Exmouth sub-basins, the Withnell Formation is a calcareous claystone, and the geometry suggests substantial modification by submarine, geostrophic currents (Fig. 26). There is considerable evidence to suggest submarine channeling and erosion in the basin at the base of the sequence and associated with subsequent sequence boundaries (Fig. 23).

Globally, the Cretaceous-Tertiary boundary is a downlap surface. In the Northern Carnarvon Basin, the Base Tertiary is the major second-order downlap surface in this supersequence, but it is also a third-order sequence boundary. In Maitland 1, the potential for Base Tertiary, incised valley exploration targets was demonstrated by the discovery of gas in 1992 (Sit et al., 1994). The incised valley deposit at Maitland is sealed by a 4.5m thick Late Paleocene shale, formed by the downlapping toes of the Late Paleocene clinoforms in the overlying transgressive and highstand systems tracts (Fig. 27). In the Dampier and Beagle sub-basins, the Paleocene can be subdivided into two packages of prograding clinoforms, separated by a thin transgressive carbonate (Fig. 28). The Late Paleocene is truncated by the Late Paleocene Sequence Boundary (Fig. DS4). The distribution of sandstone within the Paleocene is geographically somewhat similar to that of the Campanian-Maastrichtian, but with a little more in the Barrow Sub-basin than the older sequences. The main Paleocene fluvial source may have been the ancestral Fortescue River System, with a lesser contribution from the Yule and De Grey Rivers further north.

The preserved Eocene has a clinoform geometry and largely represents deposition during transgression, with the dominant lithology being carbonate. There is potential for lowstand sandstones in the basin onlapping the Late Paleocene Sequence Boundary, particulary in the Early and Middle Eocene which onlaps the Late Paleocene in much of the area. The Late Eocene transgression that followed the Early-Middle Eocene Sequence Boundary re-established carbonate deposition which dominated the region by the Oligocene as the Australian Plate moved northward into tropical latitudes

Play element distribution

Reservoir

Reservoir potential associated with the Campanian Withnell Formation has been recognized and discussed by Rasidi (1995). The high-resolution seismic data in this study indicate a potential bright amplitude associated with an interpreted lowstand deposit on the Top Toolonga/Early Campanian Supersequence Boundary, and downlapped by the Withnell Formation (Fig. 29). The mapped distribution of this deposit coincides with an erosional thin in the underlying Toolonga Calcilutite (Figs DS4 and M12), providing some support for the current interpretation. Forrest 1A was drilled just downdip and had hydrocarbon shows in this interval, indicating that further investigation is warranted.

The discovery at Maitland 1 demonstrates the viability of the incised valley systems as . potential targets for the upper Cretaceous and early Tertiary. From the base of the supersequence, each sequence boundary potentially may have developed incised valley systems during lowstands in sea-level. During a fall in sea-level, the shelf would be incised by the fluvial systems, with the incised valleys providing the conduits for sediments to reach the basin and form lowstand fans. During the ensuing stillstand and rise in sea-level, lowstand wedge and transgressive deposition backfilled the valleys. The up-dip wedge and transgressive sands then potentially correspond to the reservoir at Maitland 1.

Another example of potential lowstand reservoir in the Paleocene occurs in North Rankin 1 on the Rankin Platform. North Rankin 1 drilled through a Paleocene sandstone with hydrocarbon shows (Fig. 30). The level of bioturbation and glaucony content described in core through the sandstone indicates a shelfal location and a period of starvation in order to form the glaucony, and is consistent with a late lowstand wedge or transgressive, incised valley depositional setting. Also in this area, an onlapping package with lowstand wedge/fan potential is shown in Fig. DS5.

The likelihood for lowstand sandstone deposition to occur increased during regression as the shorelines moved basinward with the lowering of global sea-level after the middle Cretaceous maximum. Lowstand fans and wedges may have been deposited in association with steeper margin geometries such as the Withnell Formation prograding wedge in the southern Dampier/northern Barrow sub-basins (Fig. 29), while the exposed shelf or ramp margin would have been incised and backfilled with late lowstand wedge and transgressive facies. Some of the sands deposited in the shelfal parts of the section are greensands associated with transgression, e.g. the Bongerooda Greensand in Outtrim 1 in the Barrow Sub-basin. In the right trapping situation, such as within an incised valley, these transgressive sands can provide excellent reservoir potential.

In this supersequence the key to locating reservoirs is identifying incised valleys in association with sequence boundaries. Incised valleys can be identified and mapped with amplitude or other seismic attribute mapping techniques. The drawback is a requirement for relatively closely spaced seismic data to develop a coherent picture. This sort of exploration and mapping technique has been used effectively in the Powder River Basin in the Cretaceous Interior Basins of the United States (Zelt, 1987, confidential report, Exxon Production Research Company).

Source

A regional downlap surface occurs just above the Base Tertiary and may be associated with the deposition and concentration of organic matter in a condensed section. There is, however, no proven source potential in this supersequence as yet.

Seal

Within the sequence stratigraphic framework the occurrence of seal can be predicted for each sequence. Each sequence boundary is likely to be overlain by the shaley toes of downlapping transgressive and highstand clinoforms which provide the best potential seal for incised valley fill (e.g. Figs 27 and 29). Thin transgressive sealing units, such as at Maitland 1, are not unlikely, but are below seismic resolution and consequently difficult to map. Just above the Early Campanian Supersequence Boundary in some wells (e.g. Rosemary 1, Montague 1) a shaley gamma signature with a "backstepping" stacking pattern is indicative of the transgressive systems tract (see also Rasidi, 1995).

7.4 Mid Oligocene to Late Miocene Supersequence: Prograding carbonate margins, barrier reefs and mixed carbonate-siliciclastic deposition

Top age: **N16/17 foraminifera zone**

Base age: **P21 foraminifera zone**

Formations: **Mandu, Trealla, Bare**

Dominant lithology: **Carbonate**

Stacking pattern: **Regressive**

Stratal Geometry: **Prograding carbonate margins, reef buildups, siliciclastic fans**

Sequence Boundaries:
Mid Oligocene
Late Oligocene
Early Miocene
Mid Miocene A
Mid Miocene B
Late Mid Miocene
Late Miocene

Criteria and age

The base of this supersequence is defined by the major erosional unconformity that formed in the mid-Oligocene (i.e. the "Oligocene Unconformity"; FZ P21), associated with a second-order fall in eustasy, the opening of a seaway between Australia and Antarctica, and commencement of the collision between the Asian and Australian Plates (Fig. 6). There are several third- (and higher) order sequence boundaries within this supersequence, including the Late Oligocene (~N4 FZ), Early Miocene (N5-6 FZ), Mid Miocene A and B (N8-9 FZ), and Late Mid Miocene (N10-12/13? FZ). The top is defined by the Late Miocene Supersequence boundary (i.e. the "Miocene Unconformity"; ~ N16/17 FZ), an unconformity defined by both onlap and truncation in the Dampier and Beagle sub-basins.

Tectono-stratigraphy

In the Oligocene, Antarctica became isolated about the pole when separation between the Antarctic and Australian Plates was sufficient to allow deep circulation and the formation of the Circum-Antarctic Current. These conditions precipitated the onset of continental glacial conditions in Antartica and the initiation of the Cainozoic glacial-interglacial climate cycles. The event corresponds to a major fall in eustasy and a regional unconformity in the mid-Oligocene on the North West Shelf.

By the Oligocene, the North West Shelf had moved into low latitudes, and deposition became dominated by prograding carbonate shelves. By the Middle Miocene, prograding carbonate platforms and barrier reef systems dominated the northern half of the Northern Carnarvon Basin.

The northern margin of the Australian continent was, by Miocene time, interacting with the Sunda/Banda Arc system (Fig. 6). In Papua New Guinea, the leading edge of the continental crust reached the subduction zone, collided with the southernmost islands of the Asian plate, and is now preserved in the New Guinea Highlands. The interaction between the northward-moving Australian Plate and the westward-moving Pacific Plate induced N-S compression and counter-clockwise rotation, resulting in dextral shear (Baille et al., 1994) and producing transcurrent movements in parts of Australia, including the Northern Carnarvon Basin. The age of collision with the Sunda Arc and docking of continental and oceanic terranes along the northern Australian margin is dated between 35 Ma (Middle Oligocene; AGSO North West Shelf Study Group, 1994) and 25 Ma (Late Oligocene-Early Miocene; Pigram & Davies, 1987).

Today, northward drift of the Australian continent is the cause of continued subduction of oceanic basement around the Sunda Arc and sinistral shear along the northern New Guinea Margin/Banda Arc. This movement is expressed as dextral shear along the northern Australian margin. The absence of accommodation against the Indian oceanic plate induces a predominantly E-W stress field to the contemporary Australian Continent.

Stratal geometry and depositional setting

This supersequence is dominated by prograding carbonate shelf margins throughout the Northern Carnarvon Basin, and is best developed in the Beagle and Dampier sub-basins (e.g. lines 139/13-18; Fig. 1 & DS-7). The stratal geometries change from oblique to sigmoidal, indicating a change from a ramp depositional geometry during the Middle and Late Oligocene when accommodation was low, to an aggrading and prograding series of carbonate platforms in the Early and Middle Miocene, when accommodation was somewhat greater due to rising sea level. Carbonate reefs can be observed on the seismic data throughout the basin as early as Mid to Late Oligocene, but are particularly well-developed in the Middle Miocene sequences (Trealla; Mid Miocene A, B and Late-Mid Miocene sequence boundaries; Fig. 31). In the Beagle and northern Dampier sub-basins, a series of linear, prograding reef complexes can be mapped, forming a prograding barrier reef complex (Fig. M22). The development of these reef complexes is coeval with development of barrier reefs in the Great Australian Bight (Eucla Basin; Feary & James, 1995).

During the Miocene, the input of siliciclastics during lowstands in sea level increased through time, particularly after the Oligocene ramps evolved into Miocene platforms. Seismically, fans appear as ‘transparent’ zones, defined by the downlap of the highstand carbonates above and as thin, channelized, reflective packages onlapping the slope (Fig. 32). By the Late Miocene, the shelf edge had prograded far out into the modern Northern Carnarvon Basin (Fig. M24). In the Late Miocene, siliciclastics on the broad shelf were common, particularly in some areas, e.g. around Finucane 1 and Bounty 1. The supply of siliciclastic material in this area was most likely through a palaeo-equivalent of the Yule and/or De Grey Rivers that today discharge onto the Lambert Shelf.

Another feature of interest in this supersequence is the apparent development of karst in the late Middle and Late Miocene along the Rankin Platform and focused in the accommodation zone between the Barrow and Dampier sub-basins (Fig. 33). This area underwent considerable erosion and possibly slumping during a major second-order sea-level fall coincident with (or just following) the Late Mid Miocene Sequence Boundary. Repeated subaerial or near-subaerial exposure may have induced the formation of karst or caves which, when loaded, subsequently fractured and partially collapsed, producing the observed seismic character. Biostratigraphy from Sultan 1 indicates the mixing of several biozones from the Middle and Late Miocene in this interval, lending support to this hypothesis. This zone of karst and erosion developed on the Rankin Platform adjacent to (and overlapping) the area of repeated erosion and incision that began in the Cenomanian-Turonian in the northern Barrow Sub-basin, which may be related to repeated episodes of tectonic adjustment within the accommodation zone (see earlier sections).

Play Element Distribution

Reservoir

The isopach maps for this supersequence illustrate the distribution of the prograding carbonate sequences from the Mid Oligocene to the Late Miocene (Figs M20, M22 & M24). Note that, for all three maps, the trend of the isopach thick follows that of the Rankin Platform and Alpha Arch.

Figures M20 and DS6 illustrate the widespread distribution of Middle Oligocene to Early Miocene sequences deposited during the the period of carbonate ramp geometry, indicated by the broad thick throughout the Barrow, Dampier and Beagle sub-basins. The arcuate onlap edge roughly coincides with the anticlinal structures forming the Barrow Island Anticline and the De Grey Nose. Movement of these structures in the Tertiary might have contributed to the differences in accommodation suggested by the changes in stratal geometry from Oligocene ramp to Miocene platforms. Some reef development occurred during this interval, especially in the Beagle Sub-basin (Fig. 34).

The main period of widespread reef deposition occurred in the Middle Miocene, during foram zones N9 and N10 (approximately; Fig. M22). The isopach thick is focused in the Beagle and Dampier sub-basins, following the pattern of the prograding barriers shown on the seismic facies map (Fig. DS7). The continuity of the barrier system breaks down in the northern Dampier, but scattered reefs do occur down into the Barrow Sub-basin.

Figure M24 shows a broad, Late Miocene thick confined to the area outboard of the northern Dampier and Beagle sub-basins. The Late Miocene is thin in the Barrow Sub-basin, and the arcuate nature of the prograded shelf edge is still evident. The interbedding of carbonates and siliciclastics in Finucane 1 and Bounty 1 suggests that a broad carbonate shelf existed at the time with a considerable amount of siliciclastic deposition, perhaps in the form of dunes and/or in tidal channels cutting across the shallow carbonate shelf. More siliciclastic deposition in the form of lowstand fans can be expected beyond the Late Miocene shelf edge, and, in fact, basinward of the isopach thicks for each interval.

Source

Potential source rock facies have not been reported, but could have been deposited in the basin during the Late Oligocene-Early Miocene transgression that followed the Middle Oligocene eustatic fall. The base of the supersequence, the Mid Oligocene Sequence Boundary, is also a major downlap surface. The facies overlying the boundary are shaley carbonates and calcareous shales, but the organic matter content is unknown.

Seal

Sealing lithofacies are dominantly shaley carbonates on the shelves and calcareous shales in the basin. The latter has seal potential for the lowstand siliciclastic fans, while the shaley carbonates of the shelves, if tight, may provide seal for reefal buildups and sub-unconformity porosity on the carbonate platform/shelf edges.

8.0

UPPER CRETACEOUS AND TERTIARY HYDROCARBON SYSTEMS

The discoveries in the Aptian Windalia Sandstone at Barrow Island, the Barremian *M. australis* sands on the Enderby Terrace and the Paleocene sands in the Barrow Sub-basin, have established that significant volumes of hydrocarbons have migrated large distances from the main source kitchen in the Barrow and Dampier sub-basins. These hydrocarbons have become trapped at the base of the regional seal, or migrated/leaked through it to become trapped in structural or stratigraphic traps within the overlying Cretaceous and Tertiary section.

Hydrocarbon shows are often associated with Lower Cretaceous sands throughout the Northern Carnarvon Basin, but the first commercial oil discovery was made in the Aptian Windalia sandstone at Barrow Island. Although over 95% of the recovered oil (~270 MMBLS) at Barrow Island has been produced from the Windalia Sandstone, other minor accumulations have been produced in the Mardie Greensand, the Tunney Member (Birdrong Sandstone equivalent) and concretionary carbonates within the Lower Gearle Siltstone (McClure et al, 1988; Ellis et al., 1994).

A new productive Cretaceous oil play is proven at Wandoo 1 in shallow marine sands within the Barremian *M. australis* palynozone (Delfos, 1994). Twenty kilometres to the southwest, a second significant oil discovery was made at Stag 1 in 1993 (Ballesteros, 1994). Wandoo is a low-relief drape structure over an older fault block. The top of the pay zone is at only 600m subsea depth, allowing very high porosities and permeability to be preserved. The unconsolidated sands are fine-grained and very glauconitic. The oil is severely biodegraded and the entire waxy N-alkane fraction has been removed. The resultant crude has an API gravity of 19% but is still able to flow at 10,000 BOPD due to viscosity of 14.4 cp. The Stag structure is also low relief with less than 10 msec of 4-way dip closure with minor faulting on its northwest flank. Seismic and field data suggest it is stratigraphically controlled, at least in part. The M.australis sands occur at 713m depth and are described as fine- to very fine-grained, very glauconitic sands of shallow marine origin (Ballesteros, 1994). The hydrocarbon column is 13m thick. An appraisal well, Stag 2, tested a 5m interval which flowed 1050 BOPD and 6.0 MMCFGD through 1.25" choke.

There are hydrocarbon shows in Paleocene sands in North Rankin 1 on the Rankin Platform. However, at this time, the only proven discovery of petroleum in the Tertiary section is from Maitland 1, drilled in 1992 into a Late Paleocene sand around 1266 metres, and exhibiting a strong seismic amplitude anomaly. The well flowed gas at 8.54 MMSCFD., (Sit et al, 1994). The significance of this discovery is the demonstration of a reservoir and seal combination to trap petroleum in the Tertiary. The Maitland field is located over the Jurassic depocentre in the Barrow Sub-basin, updip of the Rankin Platform. The shortest migration pathway from the likely Jurassic source is through a fault or linked network of faults and fractures in the Upper Cretaceous section. Faults are difficult to interpret on seismic data in the section below Maitland, probably because they have little displacement, and therefore are largely at or below the limit of seismic resolution. Alternatively, if hydrocarbons migrated up the major faults along the Rankin Platform, lateral migration along a carrier bed is required to reach the trap. There are no likely candidates for carrier beds recognized as yet, making this alternative the least likely.

Source Rocks and Maturity

Source rocks in the Cretaceous to Tertiary sequences have not been generally recognised, but have been deposited and may be mature in the right setting. Vitrinite reflectance values (Vr) in the Northern Carnarvon Basin generally range from 0.4-0.6 around 2000 metres below the sea floor, the higher values being corrected for reflectance suppression effects (Wilkins et al, 1994). These values indicate that it is possible that sediments at this depth could be within the initial oil generation window, depending upon the maceral content (Cook, 1986; Waples, 1985, Zaunbrecher,1994). Sediments around 2500 metres below sea floor, around Vr = 0.5-0.9, are more likely to be “main oil generative”, while those around 3000 metres (Vr = 0.6-1.0) could be considered to be definitely “main oil generative”.

Organic-rich, potential source facies are deposited during maxima in accommodation and transgression (Loutit et al., 1988). This relationship permits the prediction of potential source deposition within a sequence stratigraphic framework. In the Northern Carnarvon Basin, potential source rock deposition can be predicted at the times of maximum transgression during deposition of the two older supersequences, both being deposited during the transgressive phase of the Cretaceous-Tertiary megasequence. Transgression in the Early Cretaceous (Intra-Valanginian to Mid Aptian Supersequence) peaked in the Barremian in the upper *M. australis* palynozone, resulting in maximum water depths and sediment-starvation, and providing the environment for concentration of organic matter in a condensed section. Preservation of organic matter may also have been enhanced since Muderong Shale deposition occurred in a more restricted basin, preceding the final separation of India from Australia/Antartica and the opening of the Indian ocean to full oceanic circulation. The Muderong Shale is most likely to be main oil generative within and to the north of the Lewis Trough, in the Barrow Sub-basin depocentre just southeast of the Alpha Arch, and in the Exmouth Sub-basin west of the Novara Arch.

As with the Muderong Shale, transgression, high sea level, and starvation of the basin provided the opportunity for deposition of organic-rich shales within the Mid Aptian to Early Campanian Supersequence, in the Gearle Siltstone. Globally, the mid-Cretaceous is a period of deposition and preservation of organic-rich rocks, related to a period of oceanic oxygen depletion (Schlanger & Jenkyns, 1976; Waples, 1985). However, such known organic-rich rocks are seldom more than a few metres thick in this region. In the uppermost Gearle Siltstone the previous pattern is repeated, with the Lewis Trough, the Barrow Sub-basin depocentre just south of the Alpha arch, and the Exmouth Sub-basin west of the Novara Arch becoming marginally mature. The Rankin Platform and to the north would be main oil generative.

The Base Tertiary is just within the initial oil generative window at a depth of around 2000m in the deepest part of the Barrow Sub-basin (south of the Alpha Arch), and on the Kendrew Terrace, becoming more mature across the Rankin Platform. As previously discussed, a regional downlap surface occurs just above the Base Tertiary and could be associated with the deposition and concentration of organic matter in the condensed section.

Based on the broad assumptions stated, the youngest sediments that could currently fall just within the oil mature window are Oligocene just north of the Rankin Platform. Potential source rock facies have not been reported, but could have been deposited in the basin during the Late Oligocene-Early Miocene transgression that followed the mid-Oligocene eustatic fall. The facies overlying the boundary are shaley carbonates and calcareous shales, but the organic matter content is unknown. The sequence boundary is also a major downlap surface.

9.0

CONCLUSIONS

A regional, sequence stratigraphic study of the Cretaceous and Tertiary section in the Northern Carnarvon Basin has been completed, utilising 4200km of newly-acquired high-resolution seismic reflection data, and tying 80 wells. This study has produces a regional chronostratigraphic framework for the basin, placing traditional observations in a new context and providing a predictive tool for determining the occurrence and distribution of potential play elements, i.e. reservoir, source and seal.

Four supersequences corresponding to discrete phases in the development of the sub-basins in the region have been defined. The two older supersequences (intra-Valanginian to Early Campanian) represent deposition during the transgressive part of the basin phase, and the two younger ones (Early Campanian to Late Miocene) represent deposition during the regressive part. These supersequences have been subdivided into 15 sequences, each of which has regional significance. The sequence-based, tectonostratigraphic analysis has provided a framework within which a number of new observations and interpretations have been made. The most significant results from this study are:

I. Structure

- The Northern Carnarvon Basin experienced oblique extension in the Mesozoic, resulting in an en echelon configuration for the sub-basins and border faults. The sub-basins, border faults and fault segments are linked by relay ramps, which provide access for fluvial systems carrying sediments during the syn-rift and early post-rift periods, and migration pathways for hydrocarbons later in the basin history.
- The N-S trending Proterozoic lineaments (e.g. Scholl Island Fault) determined the position of development of the relay-style accommodation zones between the sub-basins, and strongly influenced the position of the fluvial systems (e.g. Robe - Fortescue) that drain the onshore basins and cratonic blocks.
- Several hydrocarbon accumulations are associated with these accommodation zones (e.g. Novara, West Muiron, Barrow Island, Harriet).
- The Barrow-Dampier relay zone may have acted as a migration pathway for hydrocarbons that are currently reservoired in *M. australis* traps on the Enderby Terrace.

II. Play elements

Reservoirs

- During the extension phase, Barrow Delta sediments entered the Barrow Sub-basin through the accommodation zone that had developed at the southwestern end of the basin. Some sediments also entered the Barrow Sub-basin down the relay ramp that links the Flinders and Rosemary Faults (and the sub-basins). The proximity of the sediment source, the Fortescue-Robe River System, to the ramp entry point meant that during lowstands in sea level, the river system dumped coarse clastics from the Pilbara straight into and down the ramp, resulting in massive turbidite sands, the Flag Sandstone, at the toes of the prograding Barrow Delta. Later, the intra-Valanginian 'event' and uplift created the Barrow Anticline within the accommodation zone. This resulted in the distribution of the Flag Sandstone turbidites to the east and northeast of the anticline.
- The palaeogeography that resulted from the position of the accommodation zones resulted in the Barrow Sub-basin becoming the main catchment for sediments during the rift and early post-rift periods, and precluded the deposition of Flag Sandstone turbidites in the Dampier Sub-basin.
- The Birdrong Sandstone was deposited as nearshore marine and non-marine facies during transgression. Each time the shoreline advanced inland, Birdrong Sandstone facies were 'stranded' on the shelf, starved and glaucony began to form. With the action of currents and later burrowing by benthos, the glaucony was reworked and redeposited, forming the Mardie Greensand. The preservation of Birdrong Sandstone in the sedimentary succession was dependent on relief and subsidence rate. Where subsidence was greater and shelf relief was low, Birdrong Sandstone was transformed into Mardie Greensand.
- The *M. australis* sands were deposited within the highstand (lower-middle *M. australis*), lowstand (upper *M. australis*) and transgressive (upper *M. australis*) systems tracts of two third-order sequences. At least some of these sands were deposited at the same time as Birdrong Sandstone was being deposited on the Peedamullah Shelf.
- In contrast to previous interpretations, the Windalia Sandstone at Barrow Island represents distal delta front facies, deposited during a fall in sea level in the mid-Aptian. It does not represent a highstand at the end of the Muderong Shale deposition, nor is it a result of winnowing as some authors have suggested.
- The probability of lowstand reservoir deposition on sequence boundaries increased during the Campanian through Late Miocene as accommodation decreased during regression.
- An amplitude anomaly and potential lowstand play on the Early Campanian Sequence Boundary has been identified in the Barrow-Dampier accommodation zone.

Source and Seal

- The sequence stratigraphic framework provides the basis for prediction of reservoir, source and seal. New petroleum systems have been identified in the early Cretaceous, associated with potential source facies in the Muderong Shale and Gearle Siltstone.
- The main regional source and sealing facies, the Muderong Shale and Gearle Siltstone, were deposited during the transgressive maxima associated with the two older supersequences, both deposited during the transgressive part of the basin phase. Additional potential source and sealing facies may be predicted in association with transgressions during the regressive part of the basin phase, but the quality and lateral extent are not likely to be as great.

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Table 1

SYNTHETIC WELL TIES

Alpha North 1
Anchor 1
Angel 2
Aurora 1
Bambra 1
Bluebell 1
Bounty 1
Brigadier 1
Campbell 1
Central Gorgon 1
Chervil 3
Cossack 1
Cossigny 1
Cygnus 1
Dampier 1
De Grey 1
Depuch 1
Eaglehawk 1
Echo 1
Enderby 1
Finucane
Flag 1
Forestier 1
Forrest 1A ST1
Gandara 1
Georgette 1
Goodwyn 2
Goodwyn 3
Goodwyn 6
Goodwyn 7
Griffin 1
Harriet 1A
Hauy 1
Jurabi 1
Koolinda 1
Legendre 1
Lenita 1
Lowendal 1
Madeleine 1
Maitland 1
Malus 1
Mawby 1A
Minden 1ST
Montague 1
Montebello 1
Nelson Rocks 1
North Gorgon 1
North Rankin 3
North Tryal Rocks 1
North Turtle 1
Novara 1
Outtrim 1
Pueblo 1
Ramillies 1
Resolution 1
Robot 1A
Ronsard 1
Rosemary 1
Rosily 1A
Sable 1
Saturn 1
Spar 1
Sultan 1
Talisman 1
Trafalgar 1
Tryal Rocks 1
Vlaming Head 1
Wanaea 1
West Barrow 1A
West Barrow 2
West Muiron 2
West Pepper 1
West Tryal Rocks 1
West Tryal Rocks 2
West Tryal Rocks 3
Wilcox 1
Wilcox 2
Withnell 1
Zeepaard 1
Zeewulf 1

Table 2 SEQUENCE DEPTH PICKS

SEQUENCE TOPS	BAMBRA 1	BAMBRA 2	BLUEBELL 1	CENTRAL GORGON 1	CHERVIL 3	DAILEY 1	DAMPIER 1
Late Miocene	167.99	155.14	1362.00	1198.60	57.00	-	426.00
Late - Middle Miocene	-	-	1598.00	1491.00	-	243.03	587.00
Middle Miocene B	188.00	184.11	1742.00	1532.00	105.00	-	612.00
Middle Miocene A	210.00	202.04	-	-	-	-	690.00
Early Miocene	230.00	221.35	1800.78	1675.00	-	-	758.00
Late Olig - Early Mio	-	-	1960.72	1726.00	-	-	865.64
Mid Oligocene	250.00	233.76	2092.00	1760.00	145.23	354.46	973.00
Early - Middle Eocene	-	-	2130.00	1776.51	-	-	1049.00
Late Paleocene	293.06	262.72	2130.00	1815.00	-	-	1099.00
Base Tertiary	364.74	341.34	2298.00	1866.00	220.00	578.16	1542.00
Early Campanian	979.23	950.28	2298.00	1866.00	-	703.38	2150.00
Early Santonian	-	-	2305.00	1925.00	-	721.61	2178.00
Early Albian MFS	1192.14	1200.01	2588.00	2540.00	801.00	915.96	2370.00
Mid Aptian	1245.94	1251.05	2691.22	2655.00	882.00	951.22	2430.00
Hauterivian - Barremian	1640.00	1660.77	3149.99	3102.01	1020.00	-	2573.00
Valanginian	2180.00	2147.73	3372.00	3473.00	1076.00	1017.34	2600.00
Base Cretaceous	2475.00	2514.69	3446.09	3623.55	2600.00	-	2905.00

SEQUENCE TOPS	ENDERBY 1	FINUCANE 1	FLAG 1	FORREST 1A ST1	GEORGETTE 1	GOODWYN 3	GOODWYN 6
Late Miocene	160.00	740.00	220.00	519.97	160.00	820.00	823.00
Late - Middle Miocene	-	1130.00	-	-	-	1249.00	1223.50
Middle Miocene B	172.00	1200.00	260.00	594.91	-	1380.00	1350.00
Middle Miocene A	190.00	1405.00	295.00	700.00	180.00	1517.00	1486.00
Early Miocene	215.00	1480.00	305.00	748.00	200.00	1605.00	1585.00
Late Olig - Early Mio	240.00	1600.00	-	780.00	-	1860.00	1937.00
Mid Oligocene	265.00	1970.00	320.00	972.00	230.00	2060.00	2060.65
Early - Middle Eocene	-	2040.00	-	1223.00	-	2190.00	2189.00
Late Paleocene	-	2125.00	348.00	1357.69	270.00	2363.98	2294.00
Base Tertiary	-	2450.00	430.00	1766.00	290.00	2500.00	2437.00
Early Campanian	415.00	2590.00	1067.00	1791.00	538.00	2680.00	2595.00
Early Santonian	-	2650.00	-	1829.40	-	2765.00	2658.00
Early Albian MFS	540.00	2700.00	1252.00	2144.00	806.46	2838.00	2725.00
Mid Aptian	555.00	2740.00	1348.00	2190.00	838.65	2855.00	2750.00
Hauterivian - Barremian	717.00	-	1773.19	2648.00	1032.00	-	-
Valanginian	758.16	2820.00	2220.00	2988.00	1380.00	2880.00	2771.00
Base Cretaceous	-	2980.00	2571.43	3291.99	1475.00	-	-

SEQUENCE TOPS	HARRIET A1	JURABI 1	KOOLINDA 1	LENITA 1	MAITLAND 1	MONTEBELLO 1	NORTH GORGON 1
Late Miocene	162.00	-	228.23	152.49	420.00	240.00	1275.00
Late - Middle Miocene	-	736.00	-	-	-	-	1550.00
Middle Miocene B	200.00	-	-	179.34	625.00	275.00	1600.00
Middle Miocene A	228.72	-	-	209.35	-	288.00	-
Early Miocene	241.77	-	-	228.72	695.00	315.00	1710.00
Late Olig - Early Mio	-	-	-	-	772.00	350.00	1769.00
Mid Oligocene	274.83	857.00	476.09	253.68	920.00	404.00	1801.00
Early - Middle Eocene	-	-	-	-	-	-	1860.00
Late Paleocene	290.49	-	-	289.54	1246.00	-	1971.96
Base Tertiary	345.00	935.00	-	352.98	1290.00	450.00	2030.00
Early Campanian	835.00	-	-	878.65	1345.00	790.77	2030.00
Early Santonian	-	962.64	-	-	1401.00	814.92	2043.00
Early Albian MFS	1091.59	1081.00	1058.38	1095.19	1908.94	980.00	2485.00
Mid Aptian	1164.95	1114.00	1105.00	1149.00	1930.58	1050.00	2615.00
Hauterivian - Barremian	1518.00	-	1225.10	1503.53	2260.06	1600.00	3114.99
Valanginian	2070.00	1143.00	1260.60	2058.16	2635.53	1680.00	3370.92
Base Cretaceous	2390.00	-	2002.29	2372.63	3300.00	1680.00	3477.30

SEQUENCE TOPS	N TRYAL ROCKS 1	NOVARA 1	OUTTRIM 1	PUEBLO 1	RESOLUTION 1	ROBOT 1A	SATURN 1
Late Miocene	1120.00	-	-	794.00	-	438.00	1705.00
Late - Middle Miocene	1349.00	898.00	328.00	1210.00	1258.00	645.00	1728.62
Middle Miocene B	1580.09	-	-	1335.00	-	759.00	-
Middle Miocene A	1627.98	-	-	1450.00	-	-	-
Early Miocene	1889.00	-	-	1553.32	-	926.00	1818.00
Late Olig - Early Mio	2052.68	-	-	1704.34	-	-	-
Mid Oligocene	2120.00	1012.00	673.15	2118.62	1308.00	1166.00	1818.00
Early - Middle Eocene	2505.00	-	-	2220.00	1434.00	-	2101.00
Late Paleocene	2529.00	-	-	2380.00	1570.00	1311.45	2181.00
Base Tertiary	2685.35	1012.00	855.00	2593.00	1655.00	1436.00	2527.00
Early Campanian	2710.46	-	945.00	2737.00	-	1502.00	2708.00
Early Santonian	2787.00	1032.04	971.12	2798.00	1689.86	1595.00	2794.50
Early Albian MFS	2883.00	1240.00	1182.50	2889.00	1875.51	2344.00	2852.00
Mid Aptian	2901.00	1252.00	1220.00	2910.00	1899.52	2363.00	2868.00
Hauterivian - Barremian	2979.33	1262.45	-	-	2001.45	2556.00	2900.00
Valanginian	3070.01	1273.00	1288.00	2957.00	2240.00	2826.00	2920.00
Base Cretaceous	-	-	1613.00	-	2940.00	3806.36	2987.00

SEQUENCE TOPS	SPAR 1	STRICKLAND 1	TRYAL ROCKS 1	WANDOO 1	WEST BARROW 1A	WEST BARROW 2	WEST PEPPER 1
Late Miocene	548.00	-	403.00	176.90	409.53	416.00	80.00
Late - Middle Miocene	685.00	-	-	-	664.06	683.00	-
Middle Miocene B	760.00	-	601.00	216.97	803.75	807.00	150.00
Middle Miocene A	-	-	-	234.56	-	-	-
Early Miocene	915.00	-	760.00	254.22	853.41	851.00	-
Late Olig - Early Mio	1220.00	202.38	941.00	302.85	-	-	-
Mid Oligocene	1237.99	234.00	1003.00	316.25	955.42	950.00	170.00
Early - Middle Eocene	-	-	-	-	-	-	-
Late Paleocene	-	-	1245.00	-	1180.85	1142.84	300.00
Base Tertiary	1303.72	-	1260.00	-	1312.99	1320.00	440.00
Early Campanian	1351.19	357.45	1310.00	450.00	1368.91	1408.00	480.00
Early Santonian	1495.00	-	1354.00	-	1455.85	1490.00	503.00
Early Albian MFS	2220.00	-	1931.00	-	2232.39	2245.00	1119.00
Mid Aptian	2307.40	415.84	1981.00	540.00	2260.35	2283.00	1169.00
Hauterivian - Barremian	2593.00	-	2510.00	-	2463.33	2476.00	1372.00
Valanginian	2911.00	500.00	2985.00	710.00	2598.11	2610.72	1390.00
Base Cretaceous	3853.36	-	3410.01	-	3674.78	3693.58	2890.00

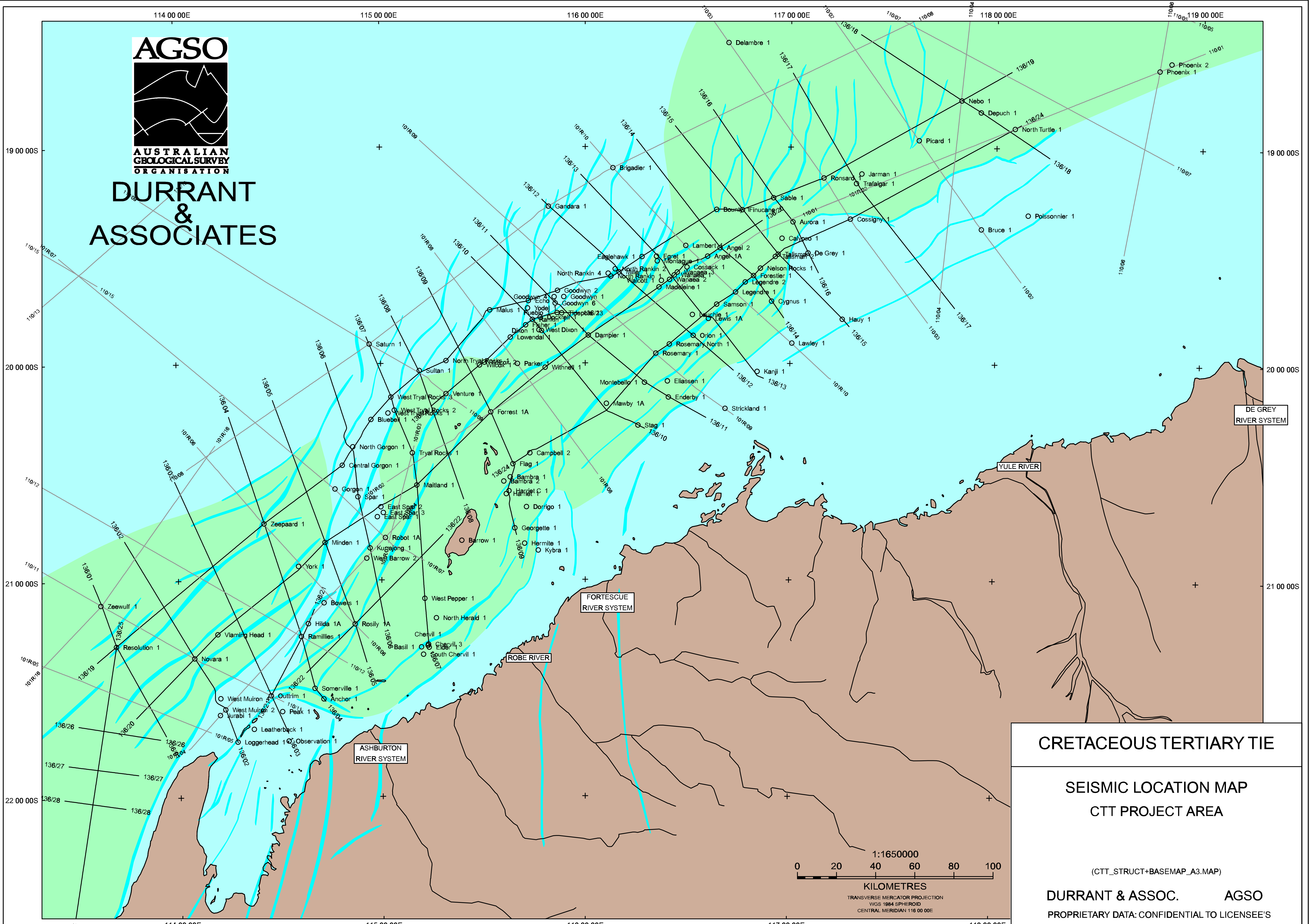
SEQUENCE TOPS	W TRYAL ROCKS 2	W TRYAL ROCKS 3	WILCOX 1	ZEEPAARD 1	ZEEWULF 1
Late Miocene	1180.00	1420.00	889.79	1225.00	-
Late - Middle Miocene	1473.00	1665.01	1216.13	1240.00	1416.00
Middle Miocene B	1503.00	1820.00	1340.47	-	-
Middle Miocene A	-	-	1412.36	-	-
Early Miocene	1720.00	1870.00	1507.57	1270.00	-
Late Olig - Early Mio	1888.00	1950.00	1632.48	-	-
Mid Oligocene	1945.00	2026.00	1934.45	-	1512.00
Early - Middle Eocene	2112.00	2205.00	2419.82	-	1612.00
Late Paleocene	2140.00	2260.00	2586.90	-	1700.00
Base Tertiary	2246.00	2420.00	2773.00	1320.00	1782.00
Early Campanian	-	-	2773.00	1520.00	2087.50
Early Santonian	2260.00	-	2833.42	1635.00	2203.41
Early Albian MFS	2632.00	2680.00	3120.91	-	2343.43
Mid Aptian	2680.00	2725.00	3144.87	2620.00	2361.00
Hauterivian - Barremian	2988.00	3010.00	3300.31	2815.00	2386.50
Valanginian	3194.00	3149.99	3372.19	3045.00	2670.00
Base Cretaceous	3275.01	3200.00	-	3925.00	3087.99

11.0

FIGURE CAPTIONS:

Fig. 1	Seismic location map, Northern Carnarvon Basin. Sub-basin depocentres are green (see Fig. 3). High-resolution CTT Survey 136 = black lines, AGSO deep seismic grid = grey lines. Small circles indicate well locations. Major fault systems and trends in dark blue. The location of the major river systems is indicated.
Fig. 2	Basin analysis procedures (from Loutit, 1996).
Fig. 3	Structural elements map, Northern Carnarvon Basin. Exmouth, Barrow, Dampier and Beagle Sub-basins in green. Major faults and fault trends in black.
Fig. 4	Photograph of deformation of a 60^{0} moderately oblique rift model after 5 cm of extension (modified with permission from McClay & White, 1995). Accommodation zones highlighted with diagonal line shading. Grey shading indicates local depocentres. For comparison with the Northern Carnarvon sub-basin depocentres, Ba = Barrow, D = Dampier, and B = Beagle. Note the location of major inter-sub-basin accommodation zones mentioned in text.
Fig. 5	Schematic of the 'Great Sandy Accommodation Zone', showing the position of relay ramps linking *en echelon* fault segments of the Admiral Bay Fault Zone in the Canning Basin (from Romine et al., 1994).
Fig. 6	Tectonostratigraphic summary diagram. AGSO timescale (Young & Laurie, 1996); sea-level curve (Greenlee & Lehmann, 1993) modified to AGSO timescale; subsidence curve from Dampier-Sub basin. The four supersequences are color-coded and numbered: 1- Intra-Valanginian to Mid Aptian; 2 - Mid Aptian to Early Campanian; 3 - Early Campanian to Mid Oligocene; 4 - Mid Oligocene to Late Miocene. Y = Yarraloola Conglomerate, approximate chronostratigraphy on the Peedamullah shelf (Hocking et al., 1988).
Fig. 7	Intra-Valanginian (Intra-Val) unconformity/supersequence boundary over the Novara Arch and Jurabi Horst, southern Barrow Sub-basin (dip section). * = off-line well position.
Fig. 8	Intra-Valanginian (Intra-Val) unconformity/supersequence boundary over the Novara Arch, southern Barrow Sub-basin (strike section).
Fig. 9	Distribution of the Yarraloola Conglomerate and Nanutarra Formation. Note the association of the conglomerate and the major river systems, the Ashburton, Robe and Fortescue (modified and reproduced with permission from Hocking et al., 1988).
Fig. 10	Flag lowstand delta and fan, Barrow Sub-basin, line 136/06. Inset is the gamma log through the reservoir interval. Note onlap of *M. australis* DZ age onto Hauterivian-Barremian sequence boundary. (This is a datummed section.)
Fig. 11	Lithostratigraphy of the "Barrow Group". Note that the part of the Flacourt Member which sits on the Intra-Valanginian sequence boundary in Spar 1 is actually Flag equivalent.
Fig. 12	"Barrow-Dampier" relay accommodation zone between the Barrow and Dampier Sub-basins. (a) Map view showing the coincidence in offset of border fault systems and position of the Proterozoic 'hard-link', represented by the Sholl Island Fault trend. Possible flowlines for the rivers are indicated by the arrows. (b) Schematic diagram of the zone, with lines 136/07, 136/09 and 136/11 in their estimated positions. The schematic cross-section at each line position shows how the maximum displacement on the border faults (line 136/07 and 136/11) is taken up in the accommodation zone by a larger number of small displacement faults (line 136/09).
Fig. 13	Intra-Valanginian incised valley erosion, line 136/06. (* = off-line well position)
Fig. 14	Zeepaard Sequence, Exmouth Sub-basin. Above the Barrow Delta is the 'backstepped' delta within the Zeepaard Sequence (reproduced with permission from Arditto, 1993).
Fig. 15	Seismic example: *M. australis* prograding wedge, (a) undatummed and (b) datummed sections. Haut - Barr = Hauterivian-Barremian sequence bounday.

Fig. 16 (a)	Seismic example: Reflection onlapping the Intra-Valanginian Supersequence Boundary that has fan potential. Above the Hauterivian-Barremian (Haut - Barr) sequence boundary is the upper *M. australis* fan and wedge penetrated in Montebello 1. (b) Schematic of *M. australis* sand deposition and systems tracts.
Fig. 17	Distribution and thichness of the Mardie Greensand (modified from Hocking et al., 1988).
Fig. 18	Distribution and thickness of the Birdrong Sandstone (modified from Hocking et al., 1988).
Fig. 19	Schematic illustrating the development of the Mardie Greensand from Birdrong Sandstones. Dinoflagellate zones onlap landward during the transgression. Heavy line marks areas of the shelf that are sediment-starved during transgression where greensands developed. Hypothetical well shows that Birdrong is preserved without glaucony where no starvation occurred. Note that the Flinders Fault Zone acts as the hinge point for basin subsidence. [HST = highstand, TST = transgressive, and LST = lowstand systems tracts. Dotted pattern = shelf sands.]
Fig. 20	Angular unconformities, Late Cenomanian - Early Turonian (Upper Gearle) through Mid Oligocene. This portion of Line 136/19 crossed the Rankin Platform along strike. The erosion may have been initiated by tectonic uplift within the accommodation zone, but is largely attributed to currents that periodically cross the outer edge of the Platform, probably associated with fluctuations in sea level. (a) Interpreted; and (b) uninterpreted.
Fig. 21	Windalia Sandstone and Radiolarite: (a) seismic expression; and (b) schematic of lowstand wedge stratal geometry. HST = highstand, TST = transgressive, and LST = lowstand systems tracts. SMW = lowstand shelf margin wedge.
Fig. 22	Early Albian contourite. Note erosional truncation within and downlap above mound.
Fig. 23	Submarine erosion in the Barrow Sub-basin. Note the shift in locus of erosion, probably marking shifts in the axis of eroding currents.
Fig. 24	Transgressive Gearle parasequences in Minden 1.
Fig. 25	Dip view, Oligocene erosion on Rankin Platform.
Fig. 26	Withnell “mound”, Barrow Sub-basin. Truncation on upper surface suggests post-depositional modification of deposit. Bi-directional downlap and shaley lithofacies may indicate original deposition as a shale-prone fan, or redeposition, in part, by contour currents. High amplitude refections above the Withnell mound are the Korojon Calcarenite.
Fig. 27	Paleocene sequence, line 136/07. Maitland 1 DHI is to the left off the end of figure. The transgressive (TST) and highstand (HST) systems tracts downlap and thin to a 4-meter thick shale that seals the gas reservoir at Maitland 1
Fig. 28	Paleocene sequence in the Beagle Sub-basin. The high amplitude horizon in the middle of the sequence is a flooding surface marked by a carbonate-rich bed.
Fig. 29	Withnell Formation, lowstand play, line 136/09. Note amplitude anomaly at top of potential LST (lowstand systems tract), and downlap of transgressive (TST) and highstand (HST) above it. Hydrocarbon shows occur in the interval in Forrest 1A, but this play remains untested.
Fig. 30	Seismic example (dip) near N. Rankin 1, showing Paleocene onlap onto tilted fault blocks.
Fig. 31	Middle Miocene prograding barrier reefs.
Fig. 32	Oligocene and younger potential lowstand fans.
Fig. 33	Miocene erosion and karst development.
Fig. 34	Oligocene carbonate buildups: (a) line 136/17; and (b) line 136/18.



CRETACEOUS TERTIARY TIE

SEISMIC LOCATION MAP

CTT PROJECT AREA

(CTT_STRUCT+BASEMAP_A3.MAP)

DURRANT & ASSOC. AGSO

PROPRIETARY DATA: CONFIDENTIAL TO LICENSEE'S

SEPTEMBER 1996 FIGURE 1

Integrated Basin Analysis Procedures

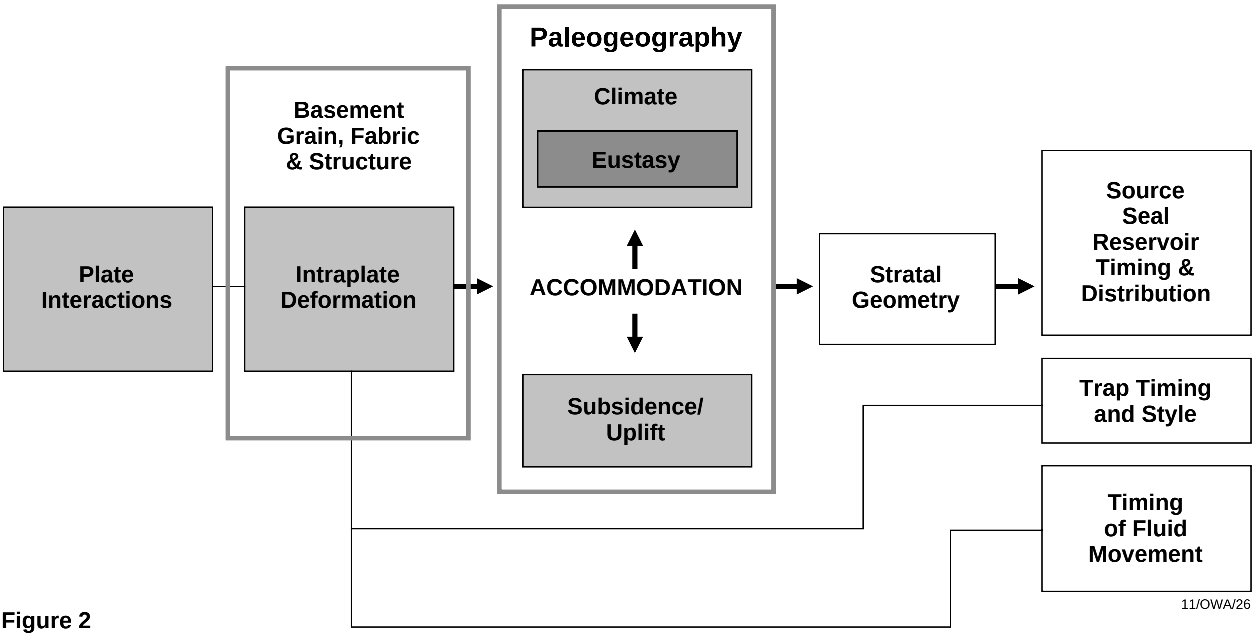
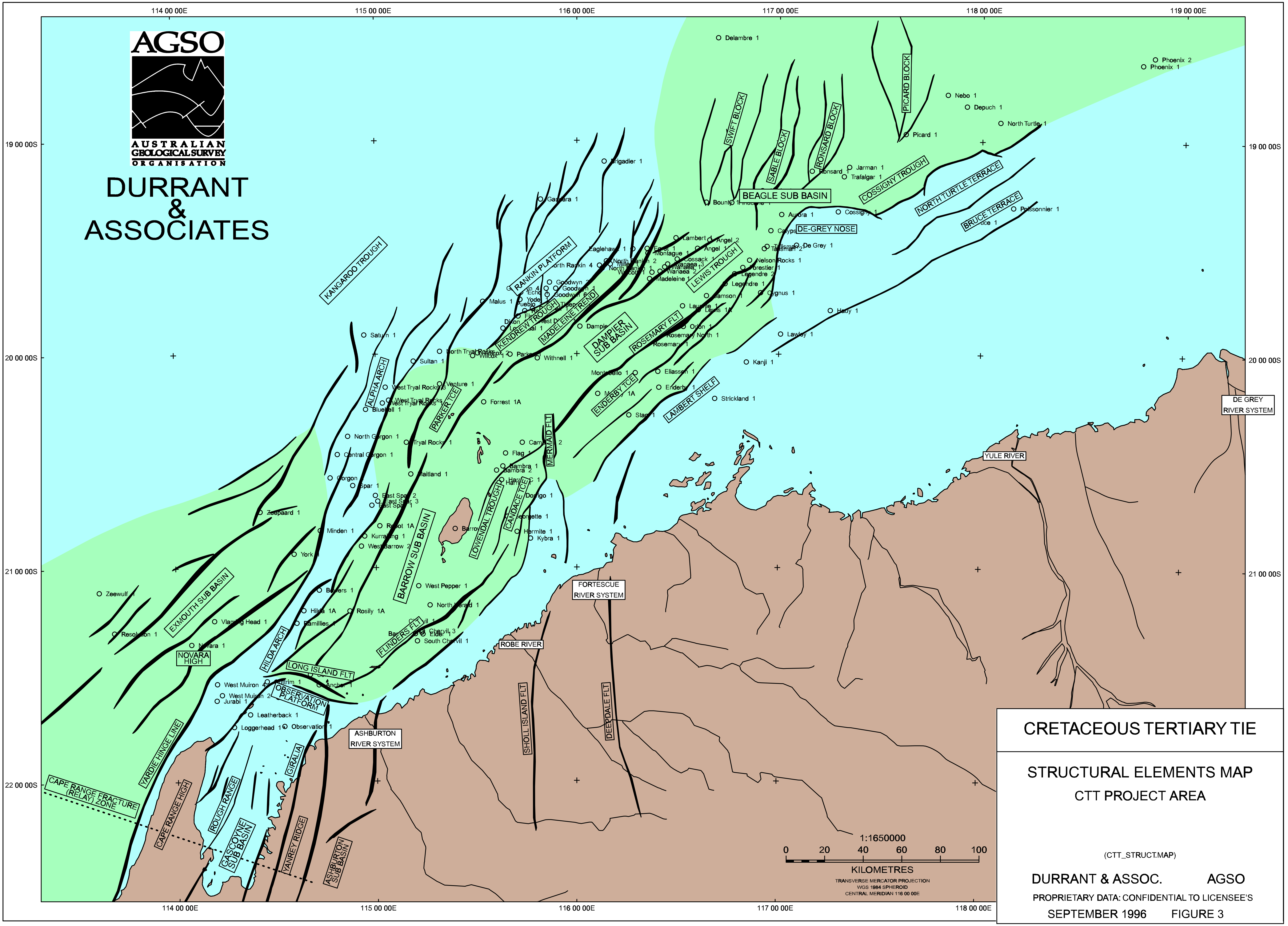


Figure 2



CRETACEOUS TERTIARY TIE

STRUCTURAL ELEMENTS MAP
CTT PROJECT AREA

(CTT_STRUCT.MAP)

DURRANT & ASSOC. AGSO

PROPRIETARY DATA: CONFIDENTIAL TO LICENSEE'S

SEPTEMBER 1996 FIGURE 3

User : petrosys File : px17531.hpgl Date : September 13, 1996

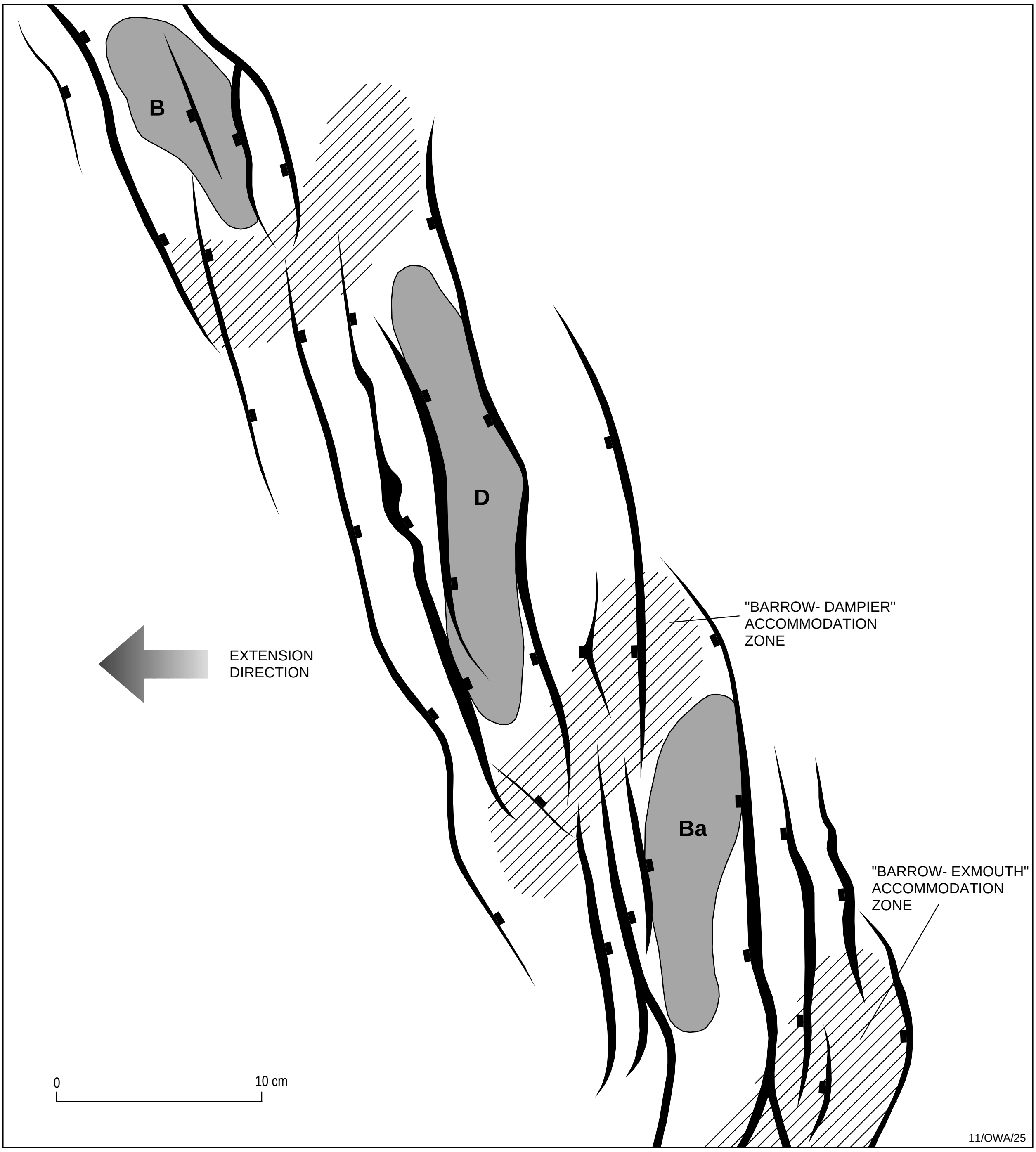

B
D
Ba
EXTENSION
DIRECTION
"BARROW- DAMPIER"
ACCOMMODATION
ZONE
"BARROW- EXMOUTH"
ACCOMMODATION
ZONE
0
10 cm
11/OWA/25

Figure 4

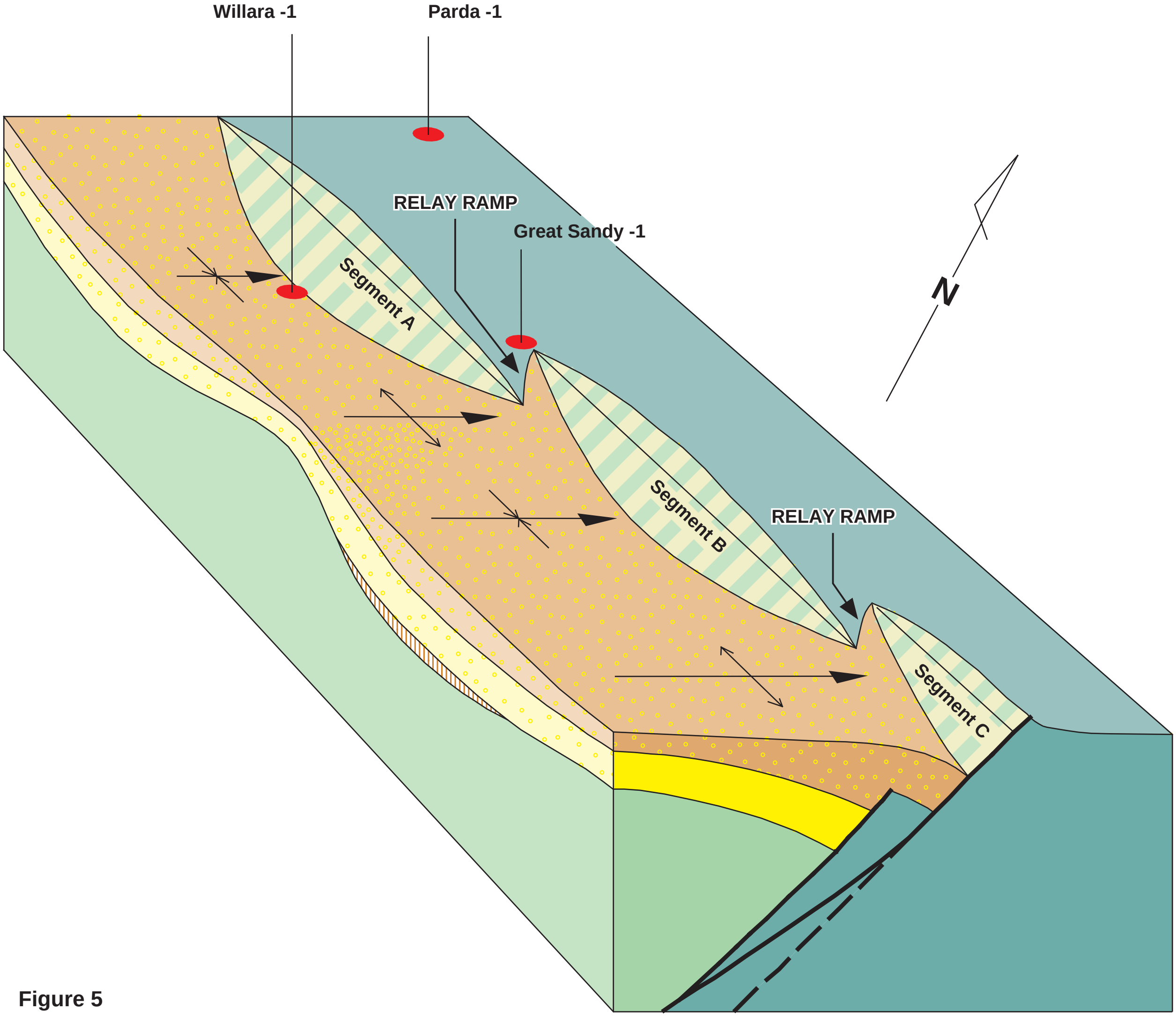


Figure 5

11/OWA/24

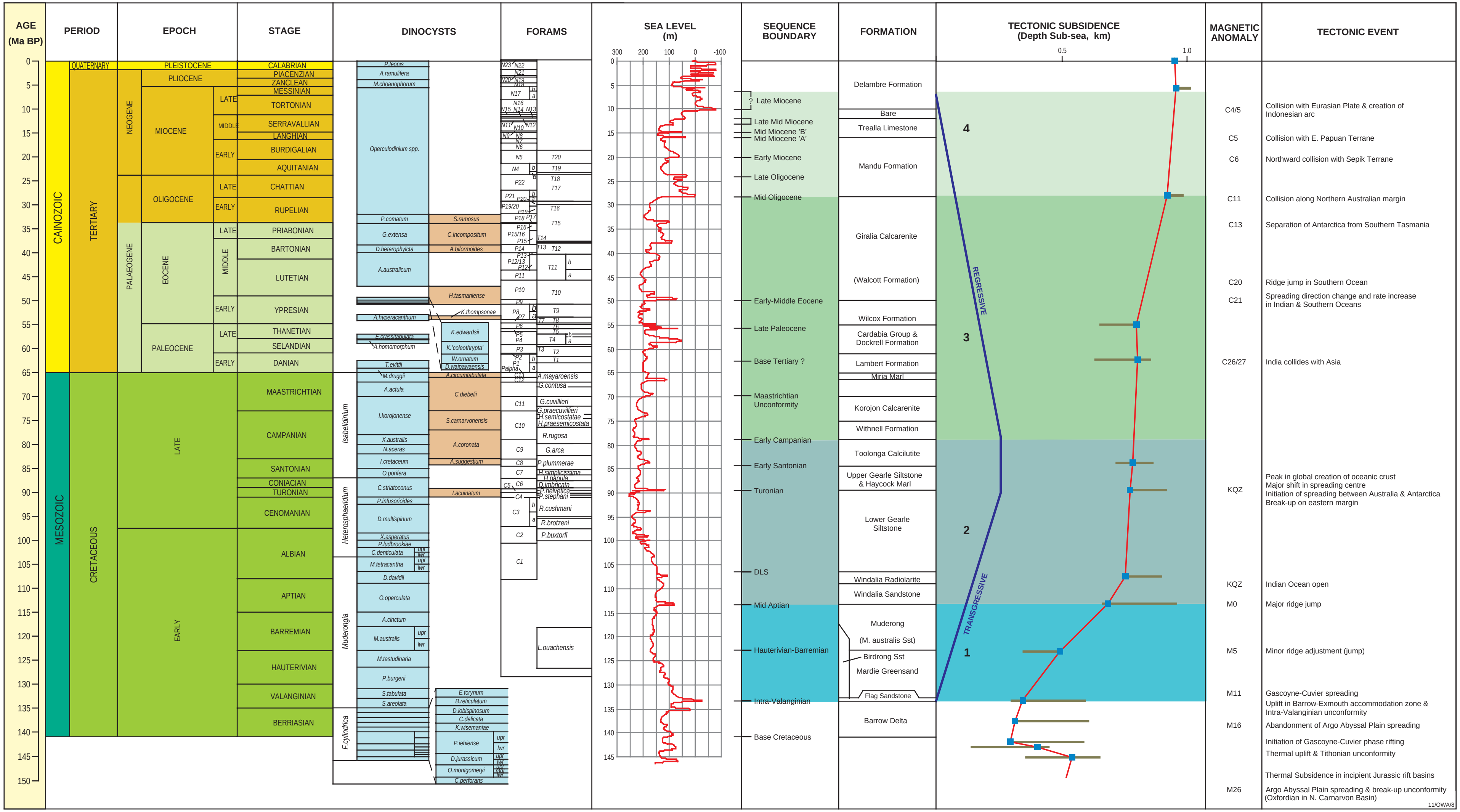

AGE (Ma BP)
PERIOD
EPOCH
STAGE
DINOCYSTS
FORAMS
SEA LEVEL (m)
SEQUENCE BOUNDARY
FORMATION
TECTONIC SUBSIDENCE (Depth Sub-sea, km)
MAGNETIC ANOMALY
TECTONIC EVENT
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
CAINOZOIC
MESOZOIC
QUATERNARY
TERTIARY
CRETACEOUS
NEOGENE
PALAEOGENE
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
LATE
MIDDLE
EARLY
CALABRIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
THANETIAN
SELANDIAN
DANIAN
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
P.leonis
A.ramulifera
M.choanophorum
Operculodinium spp.
P.comatum
S.ramosus
G.extensa
C.incompositum
D.heteophylcta
A.biformoides
A.australicum
H.tasmaniense
A.hyperacanthum
K.thompsonae
K.edwardsii
E.crassitabulata
A.homomorphum
K.'coleothrypta'
W.ornatum
D.waipawaensis
T.evittii
A.circumtabulata
M.druggii
A.actula
C.diebelii
I.korojonense
S.carnarvonensis
X.australis
A.coronata
N.aceras
I.cretaceum
A.suggestium
O.porifera
C.striatoconus
I.acuinatum
P.infusorioides
D.multispinum
X.asperatus
P.ludbrookiae
C.denticulata
M.tetracantha
D.davidii
O.operculata
A.cinctum
M.australis
M.testudinaria
P.burgerii
S.tabulata
S.areolata
E.torynum
B.reticulatum
D.lobispinosum
C.delicata
K.wisemaniae
P.iehiense
D.jurassicum
O.montgomeryi
C.perforans
upr
lwr
Isabelidinium
Heterosphaeridium
Muderongia
F.cylindrica
N23
N22
N21
N20
N19
N18
N17
N16
N15
N14
N13
N12
N11
N10
N9
N8
N7
N6
N5
N4
P22
P21
P20
P19/20
P19
P18
P17
P16
P15/16
P15
P14
P13
P12/13
P12
P11
P10
P9
P8
P7
P6
P5
P4
P3
P2
P1
Palpha
T20
T19
T18
T17
T16
T15
T14
T13
T12
T11
T10
T9
T8
T7
T6
T5
T4
T3
T2
T1
a
b
A.mayaroensis
C13
C12
G.contusa
C11
G.cuvillieri
G.praecuvillieri
H.semicostatae
H.praesemicostata
C10
R.rugosa
C9
G.arca
C8
P.plummerae
C7
H.simplicissima
H.paqula
C6
D.imbricata
C5
P.helvetica
C4
P.stephani
C3
R.cushmani
R.brotzeni
C2
P.buxtorfi
C1
L.ouachensis
300
200
100
0
-100
? Late Miocene
Late Mid Miocene
Mid Miocene 'B'
Mid Miocene 'A'
Early Miocene
Late Oligocene
Mid Oligocene
Early-Middle Eocene
Late Paleocene
Base Tertiary ?
Maastrichtian Unconformity
Early Campanian
Early Santonian
Turonian
DLS
Mid Aptian
Hauterivian-Barremian
Intra-Valanginian
Base Cretaceous
Delambre Formation
Bare
Trealla Limestone
Mandu Formation
Giralia Calcarenite
(Walcott Formation)
Wilcox Formation
Cardabia Group & Dockrell Formation
Lambert Formation
Miria Marl
Korojon Calcarenite
Withnell Formation
Toolonga Calcilutite
Upper Gearle Siltstone & Haycock Marl
Lower Gearle Siltstone
Windalia Radiolarite
Windalia Sandstone
Muderong
(M. australis Sst)
Birdrong Sst
Mardie Greensand
Flag Sandstone
Barrow Delta
0.5
1.0
4
3
2
1
REGRESSIVE
TRANSGRESSIVE
C4/5
C5
C6
C11
C13
C20
C21
C26/27
KQZ
KQZ
M0
M5
M11
M16
M26
Collision with Eurasian Plate & creation of Indonesian arc
Collision with E. Papuan Terrane
Northward collision with Sepik Terrane
Collision along Northern Australian margin
Separation of Antarctica from Southern Tasmania
Ridge jump in Southern Ocean
Spreading direction change and rate increase in Indian & Southern Oceans
India collides with Asia
Peak in global creation of oceanic crust
Major shift in spreading centre
Initiation of spreading between Australia & Antarctica
Break-up on eastern margin
Indian Ocean open
Major ridge jump
Minor ridge adjustment (jump)
Gascoyne-Cuvier spreading
Uplift in Barrow-Exmouth accommodation zone & Intra-Valanginian unconformity
Abandonment of Argo Abyssal Plain spreading
Initiation of Gascoyne-Cuvier phase rifting
Thermal uplift & Tithonian unconformity
Thermal Subsidence in incipient Jurassic rift basins
Argo Abyssal Plain spreading & break-up unconformity (Oxfordian in N. Carnarvon Basin)
11/OWA/8

Figure 6

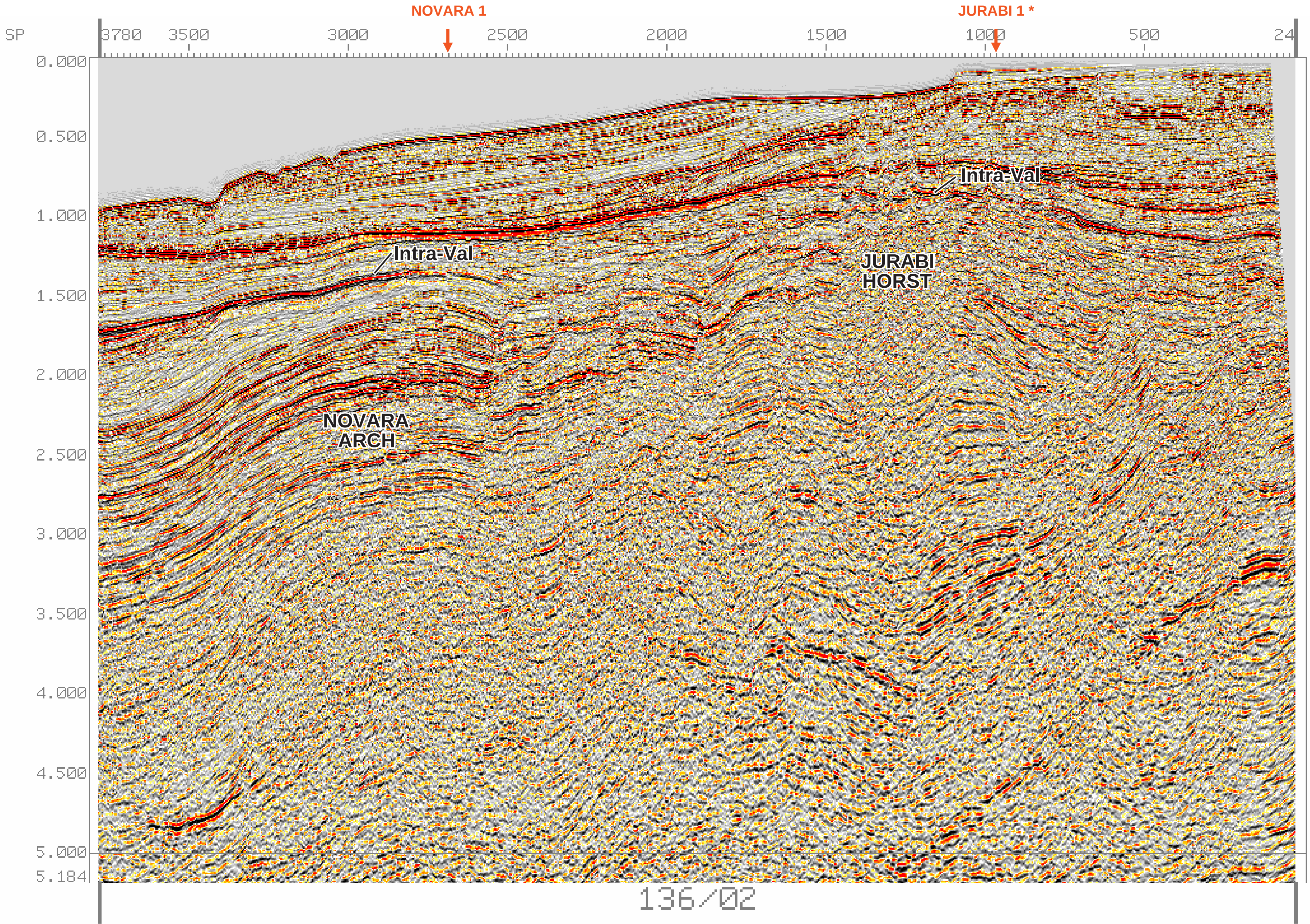


Figure 7

11/OWA/28

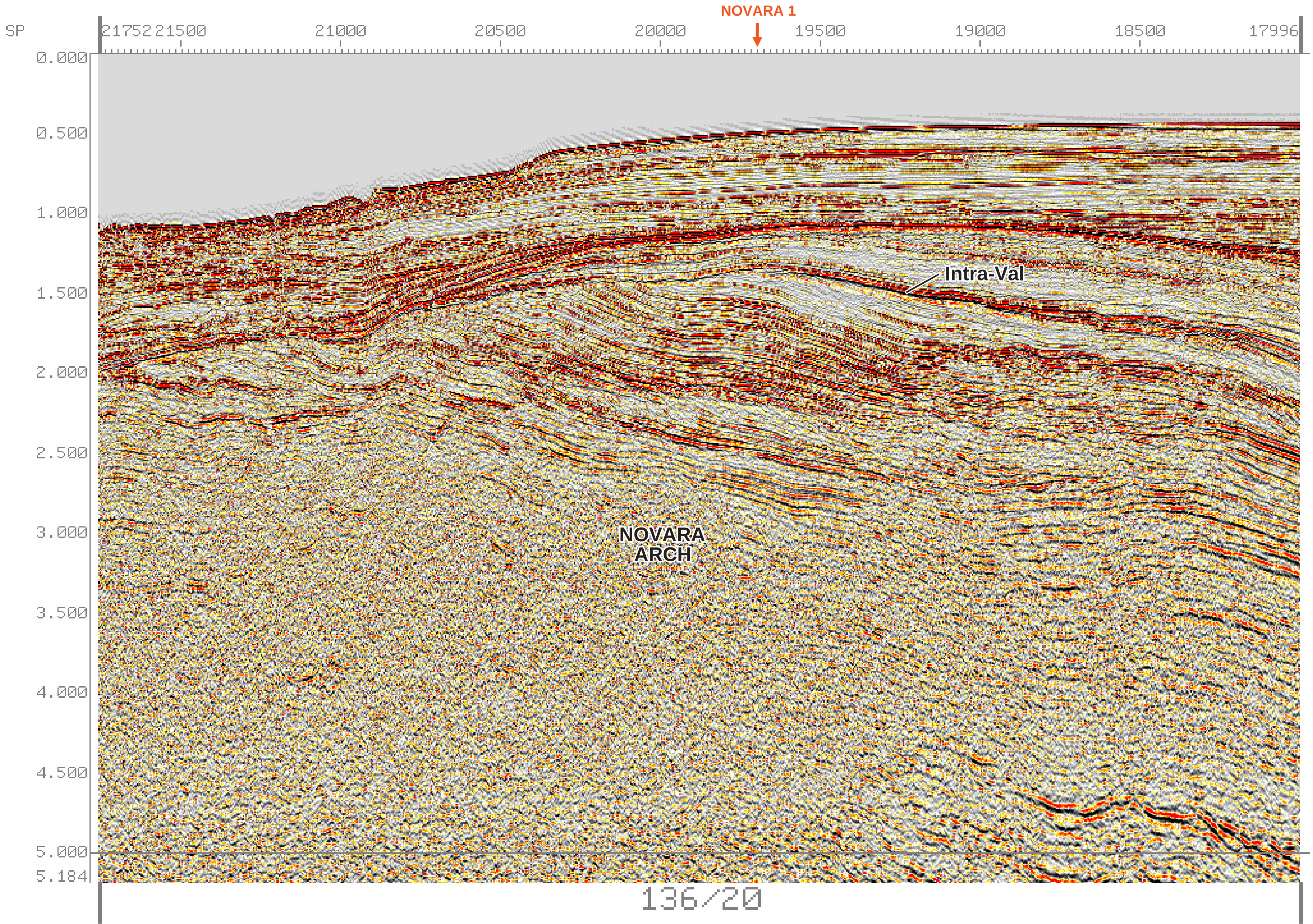


Figure 8

11/OWA/29

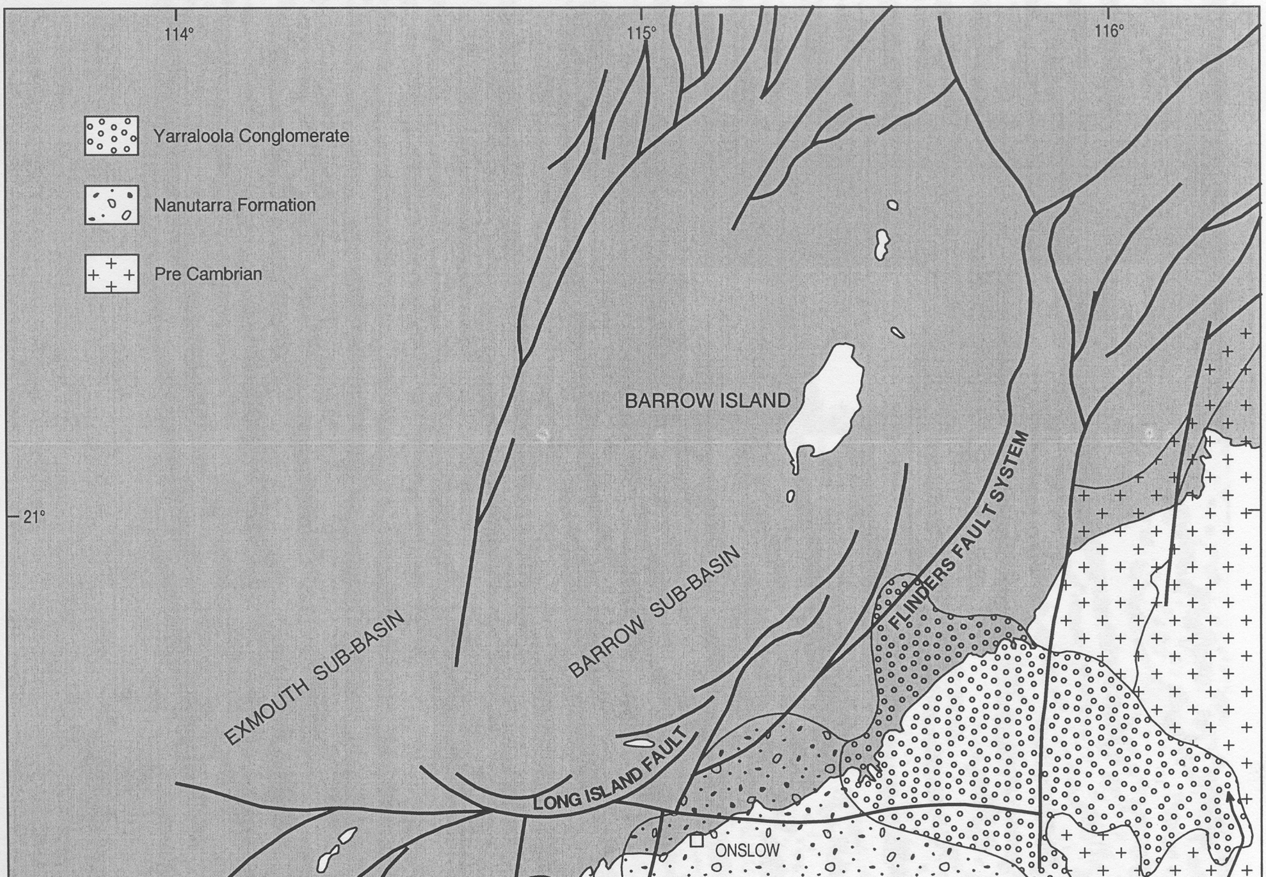

114°
115°
116°
21°
22°
Yarraloola Conglomerate
Nanutarra Formation
Pre Cambrian
BARROW ISLAND
FLINDERS FAULT SYSTEM
BARROW SUB-BASIN
EXMOUTH SUB-BASIN
LONG ISLAND FAULT
ONSLOW
Fortescue River
Robe River
EXMOUTH
PATERSON FAULT
ROUGH RANGE FAULT
CAPE RANGE FAULT
PEEDAMULLAH SHELF
Ashburton River
YANREY RIDGE
11/OWA23

Figure 9

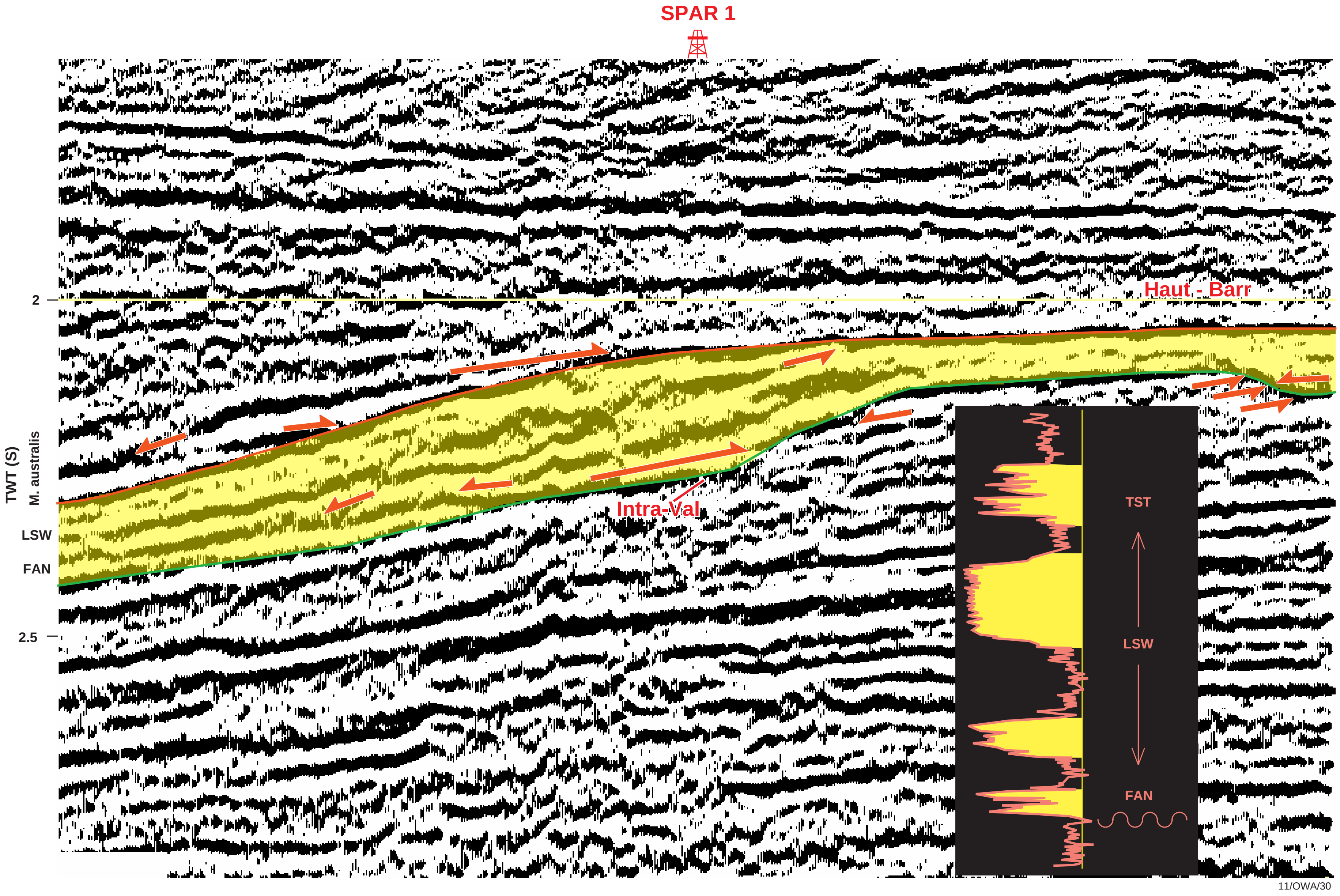


Figure 10

136/06

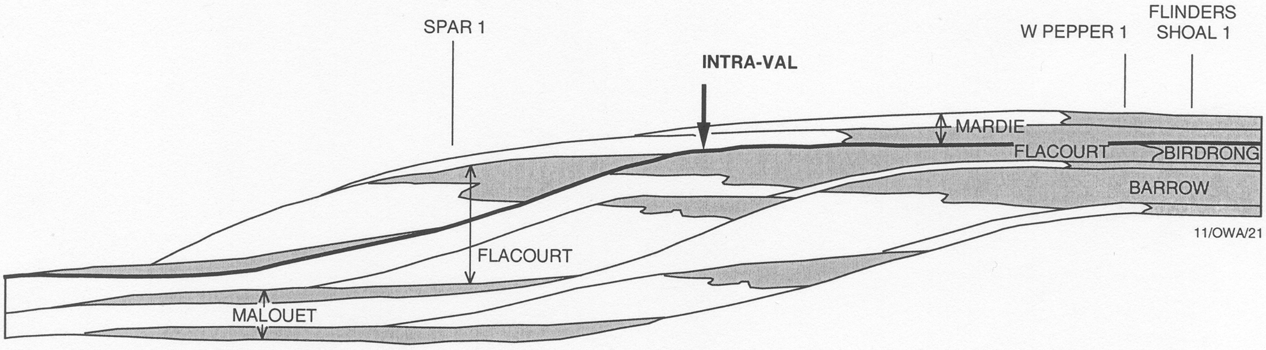

SPAR 1
INTRA-VAL
W PEPPER 1
FLINDERS SHOAL 1
MARDIE
FLACOURT
BIRDRONG
BARROW
11/OWA/21
FLACOURT
MALOUET

Figure 11

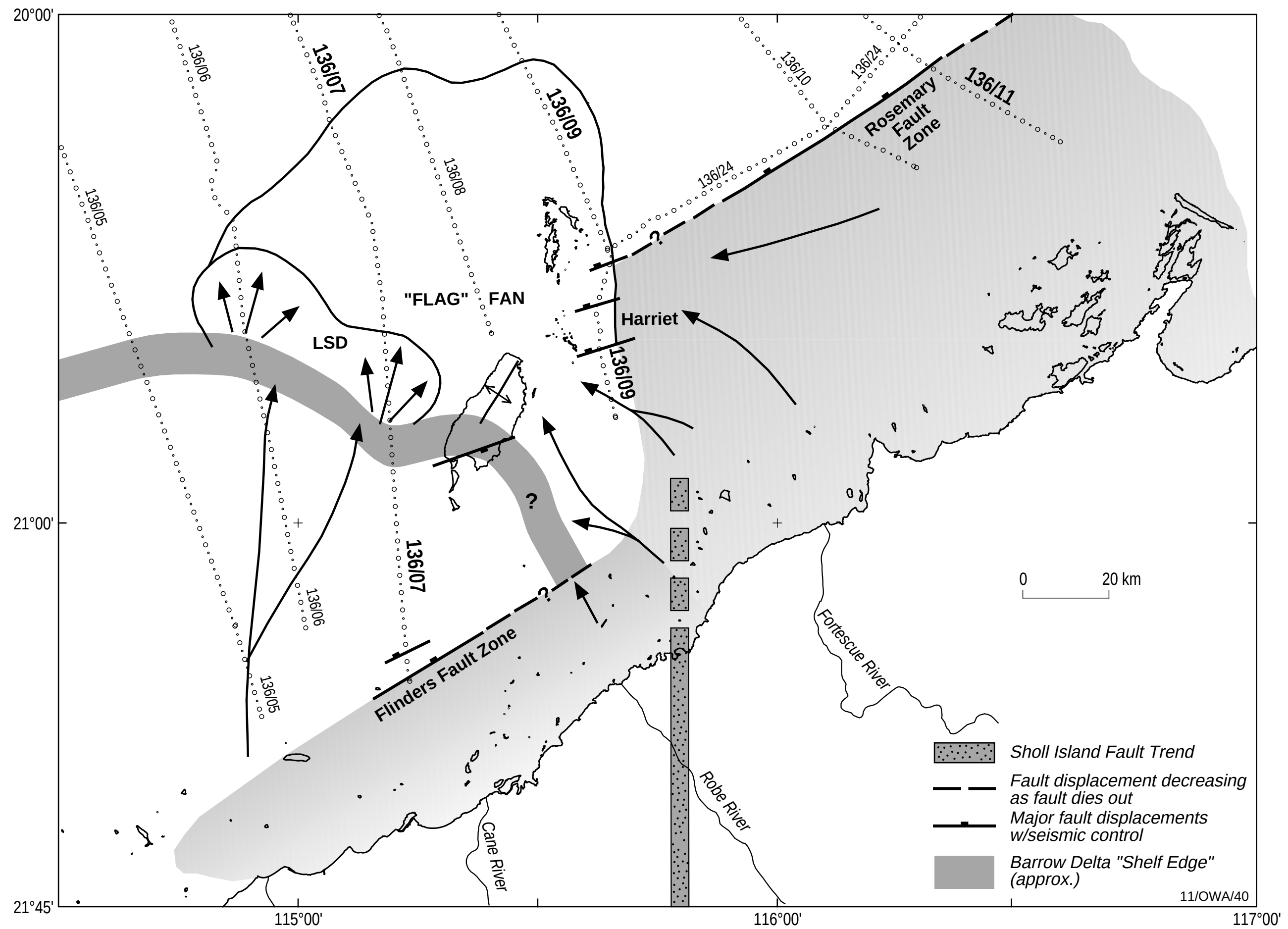


Figure 12a

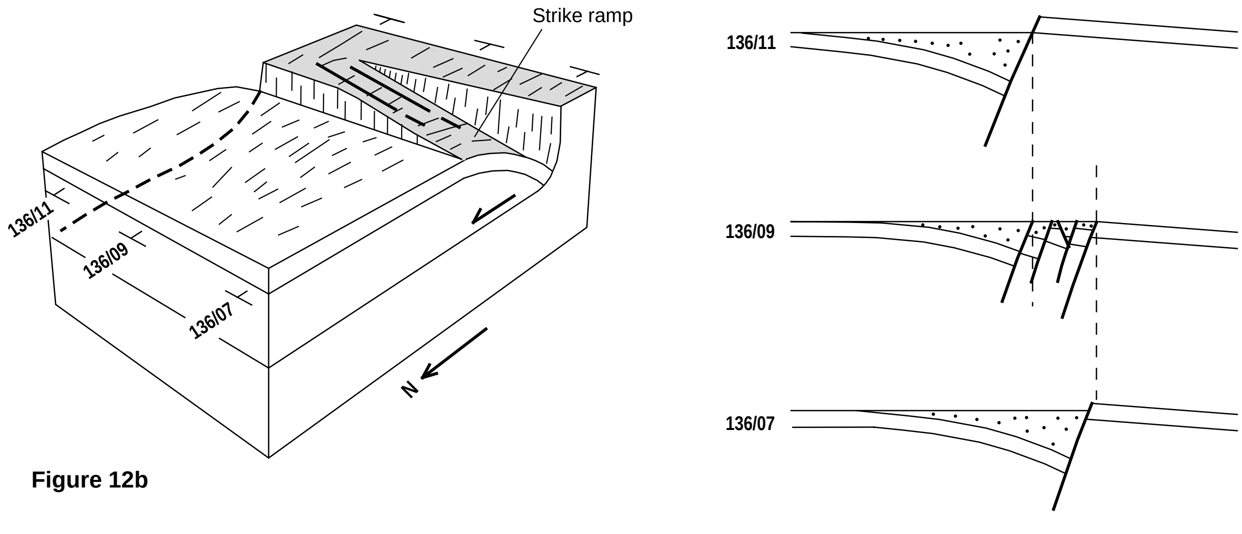


Figure 12b

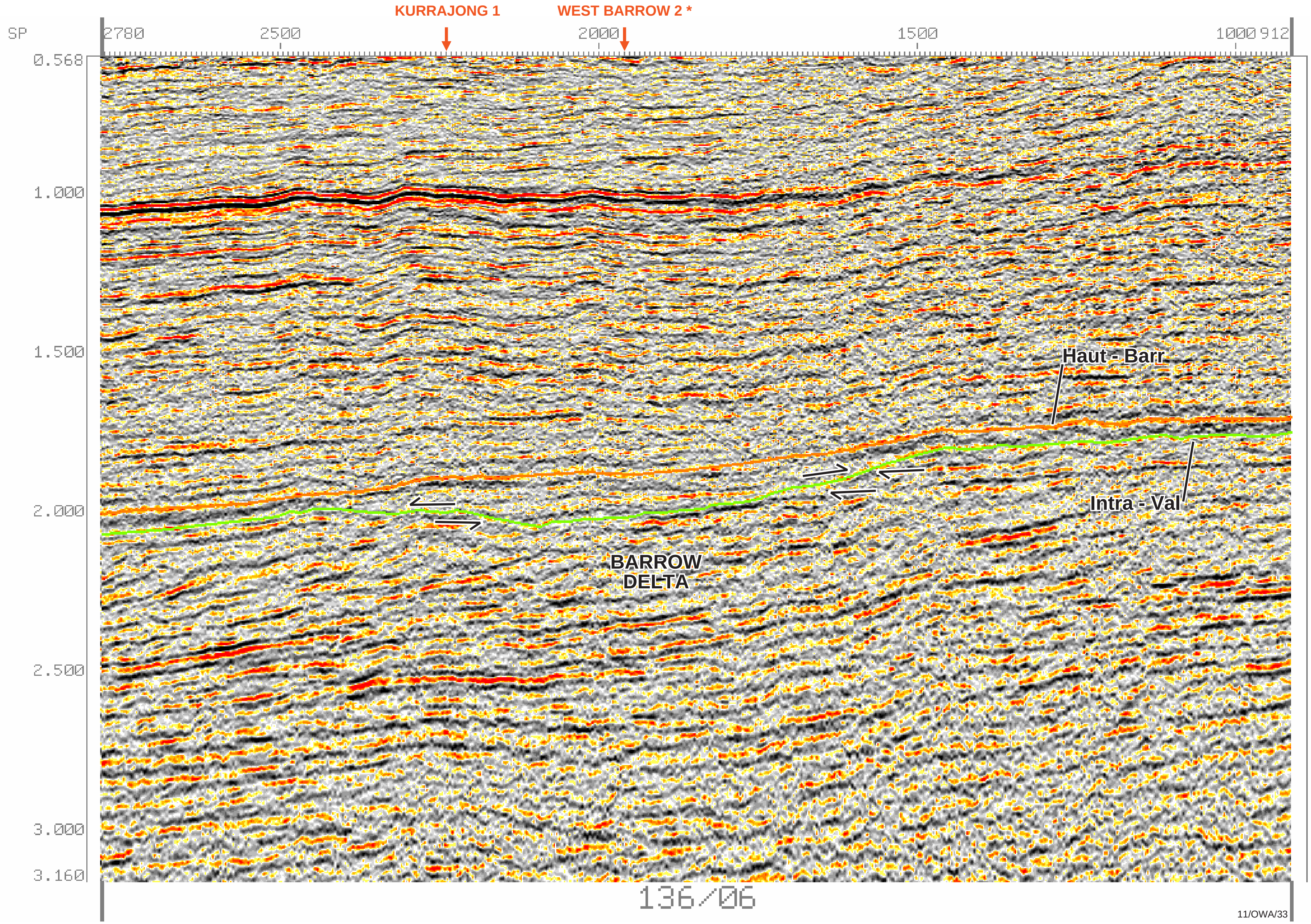

KURRAJONG 1
WEST BARROW 2 *
SP
2780
2500
2000
1500
1000
912
0.568
1.000
1.500
2.000
2.500
3.000
3.160
Haut - Barr
Intra - Val
BARROW
DELTA
136/06
11/OWA/33

Figure 13

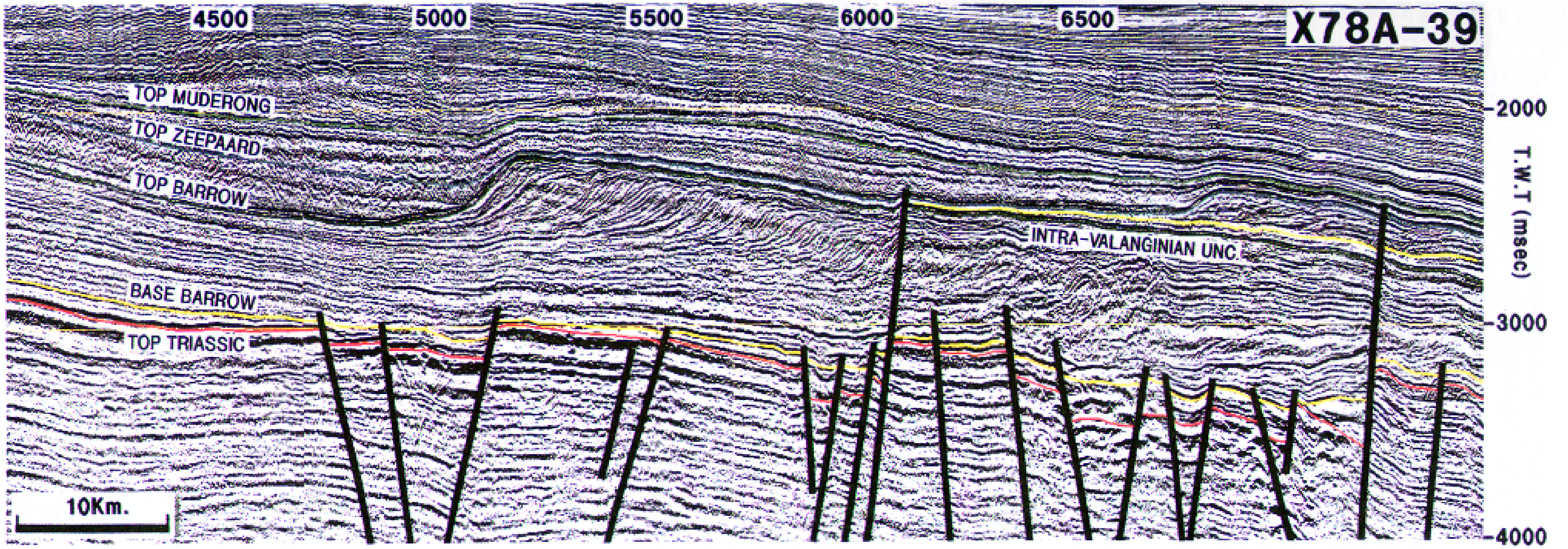

4500
5000
5500
6000
6500
X78A-39
TOP MUDERONG
TOP ZEEPAARD
TOP BARROW
INTRA-VALANGINIAN UNC.
BASE BARROW
TOP TRIASSIC
10Km.
2000
3000
4000
T.W.T (msec)

Figure 14

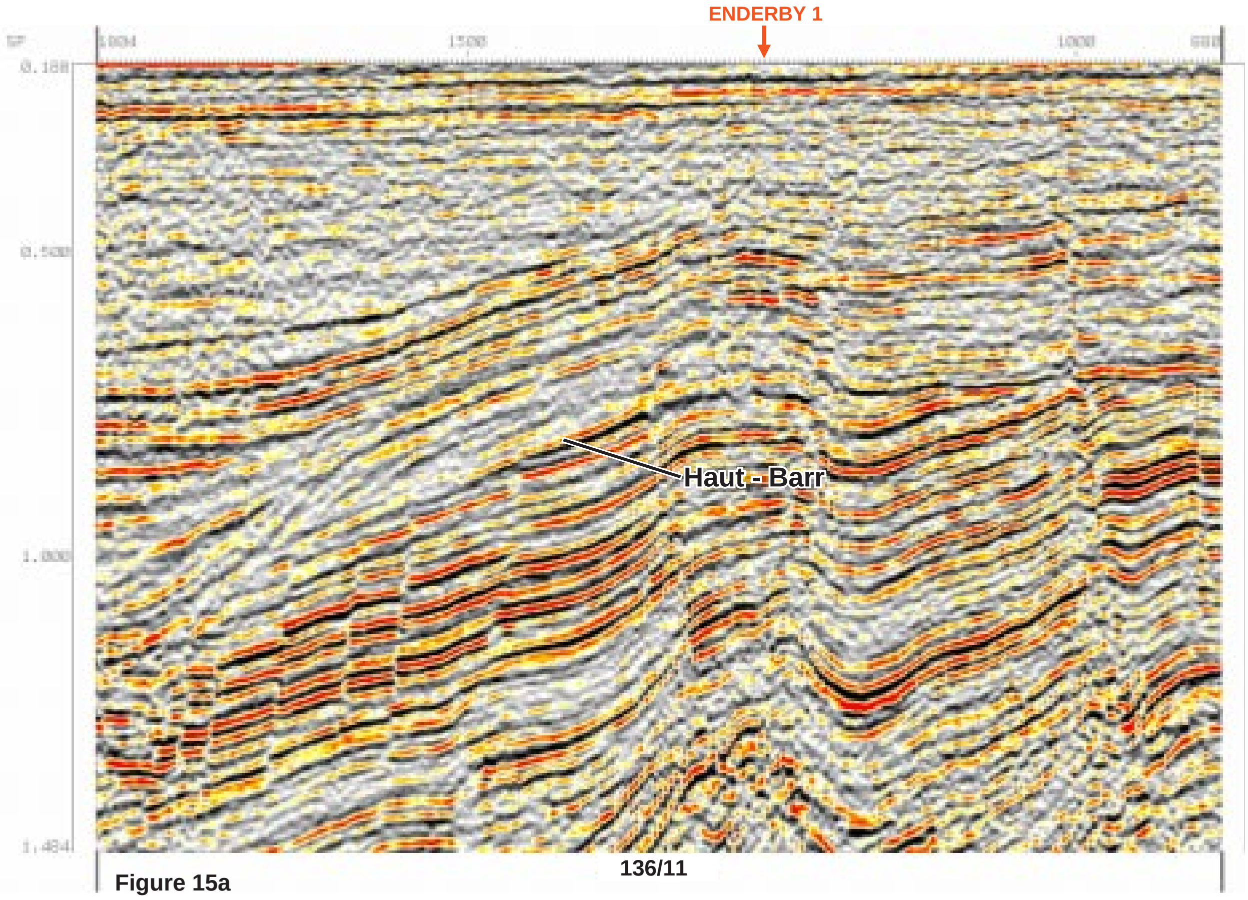


Figure 15a

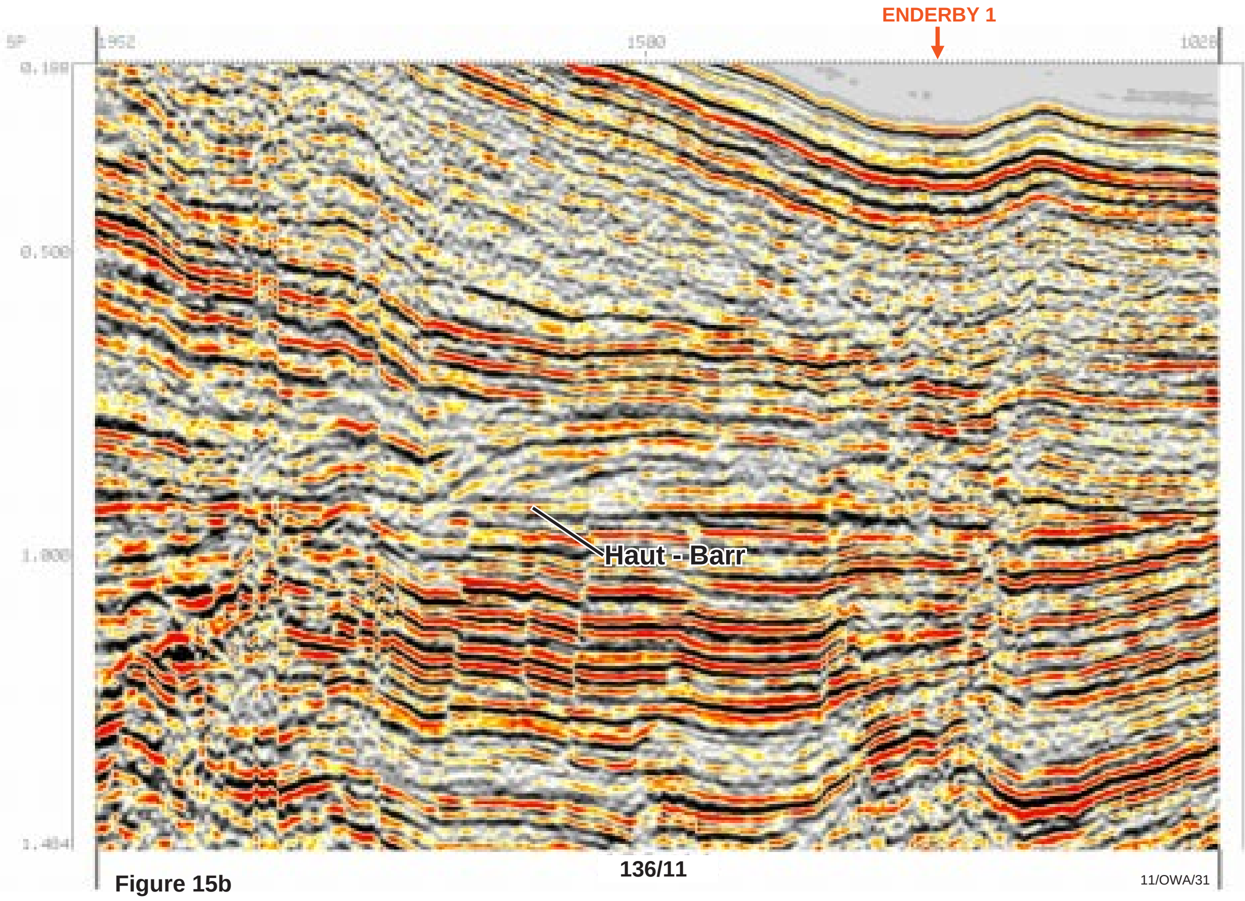


Figure 15b

11/OWA/31

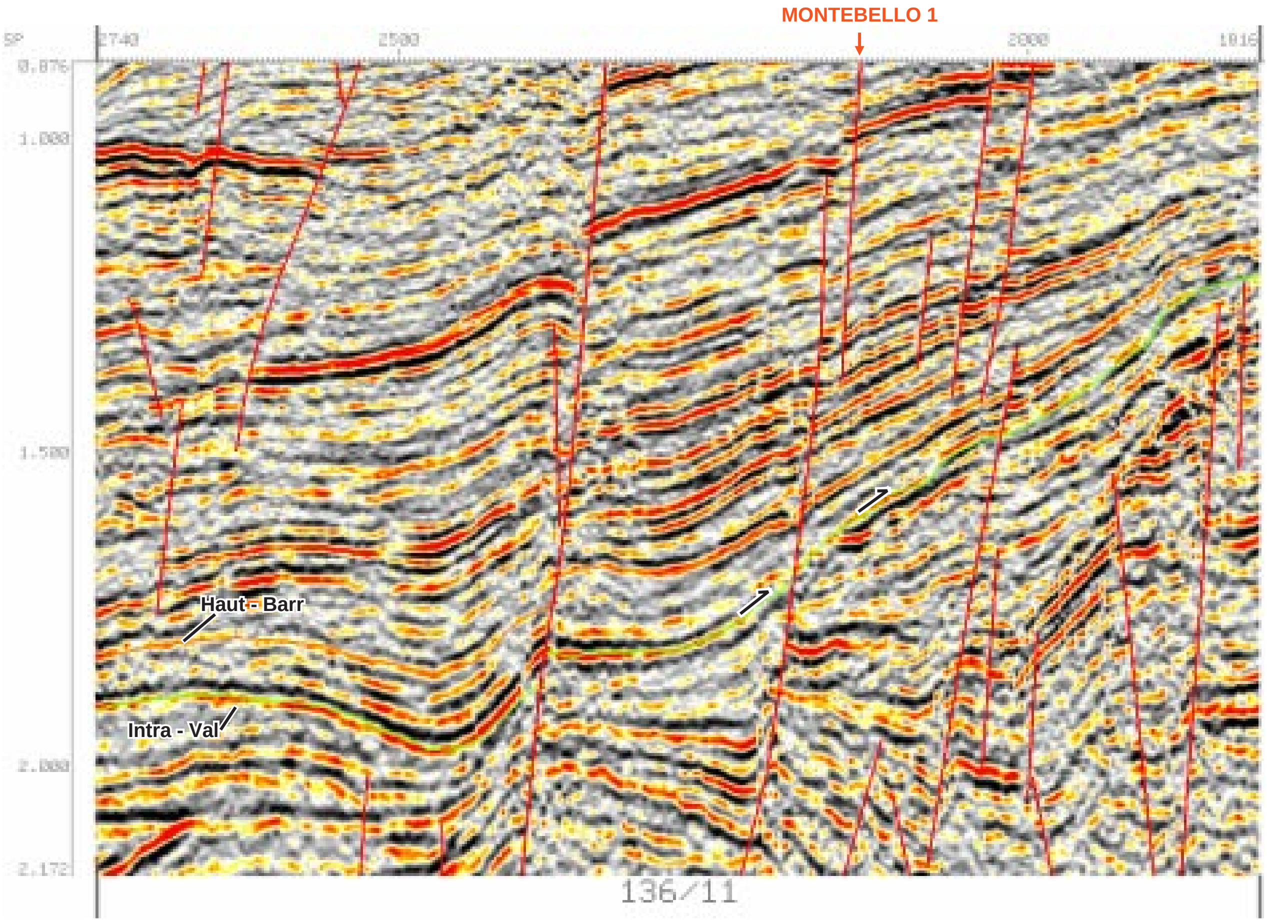


Figure 16a

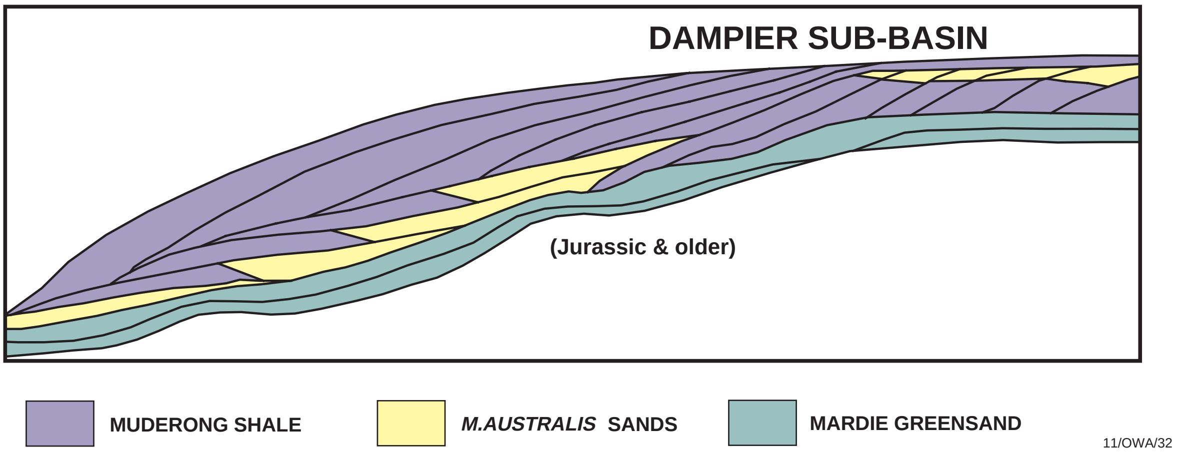
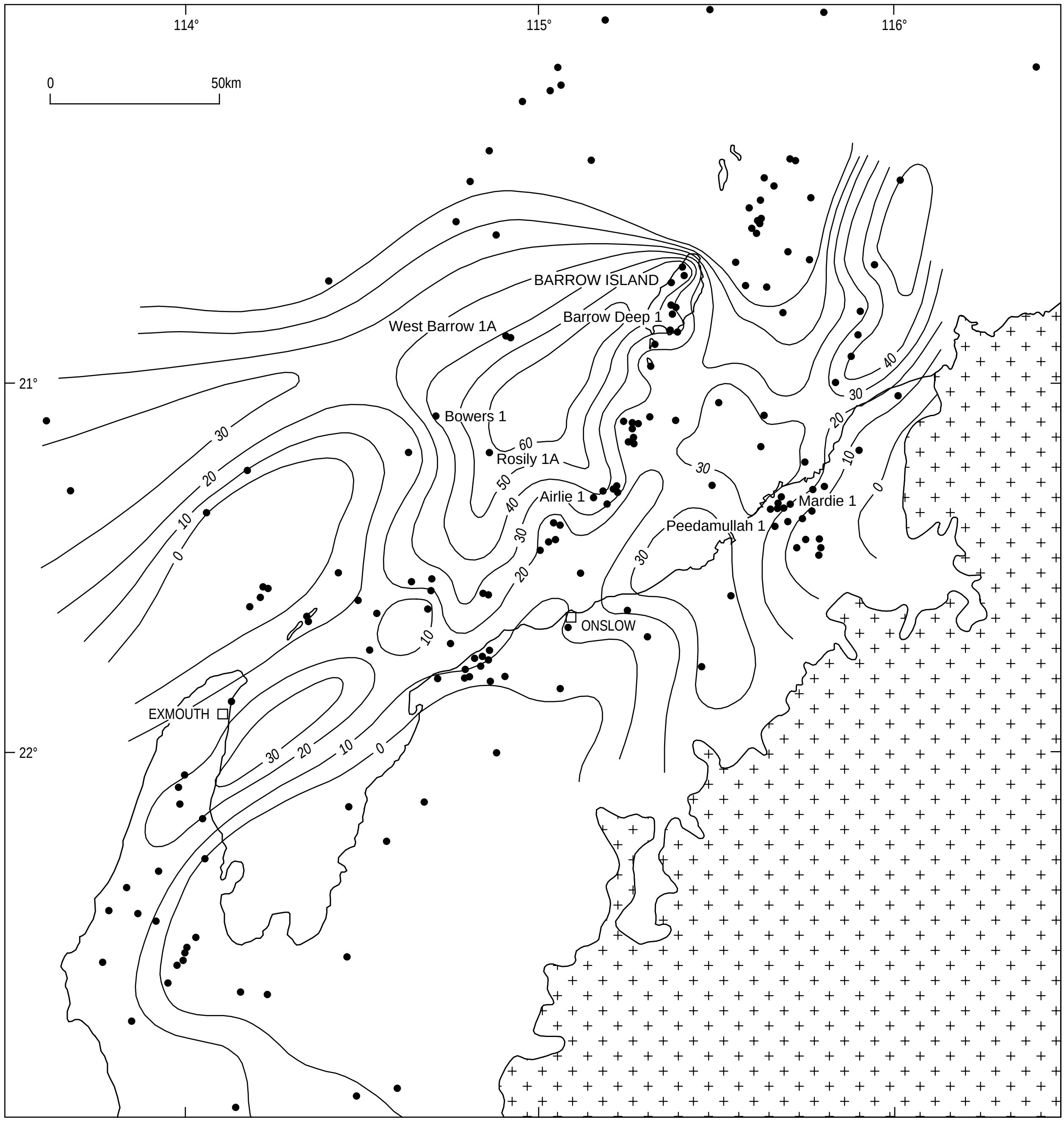
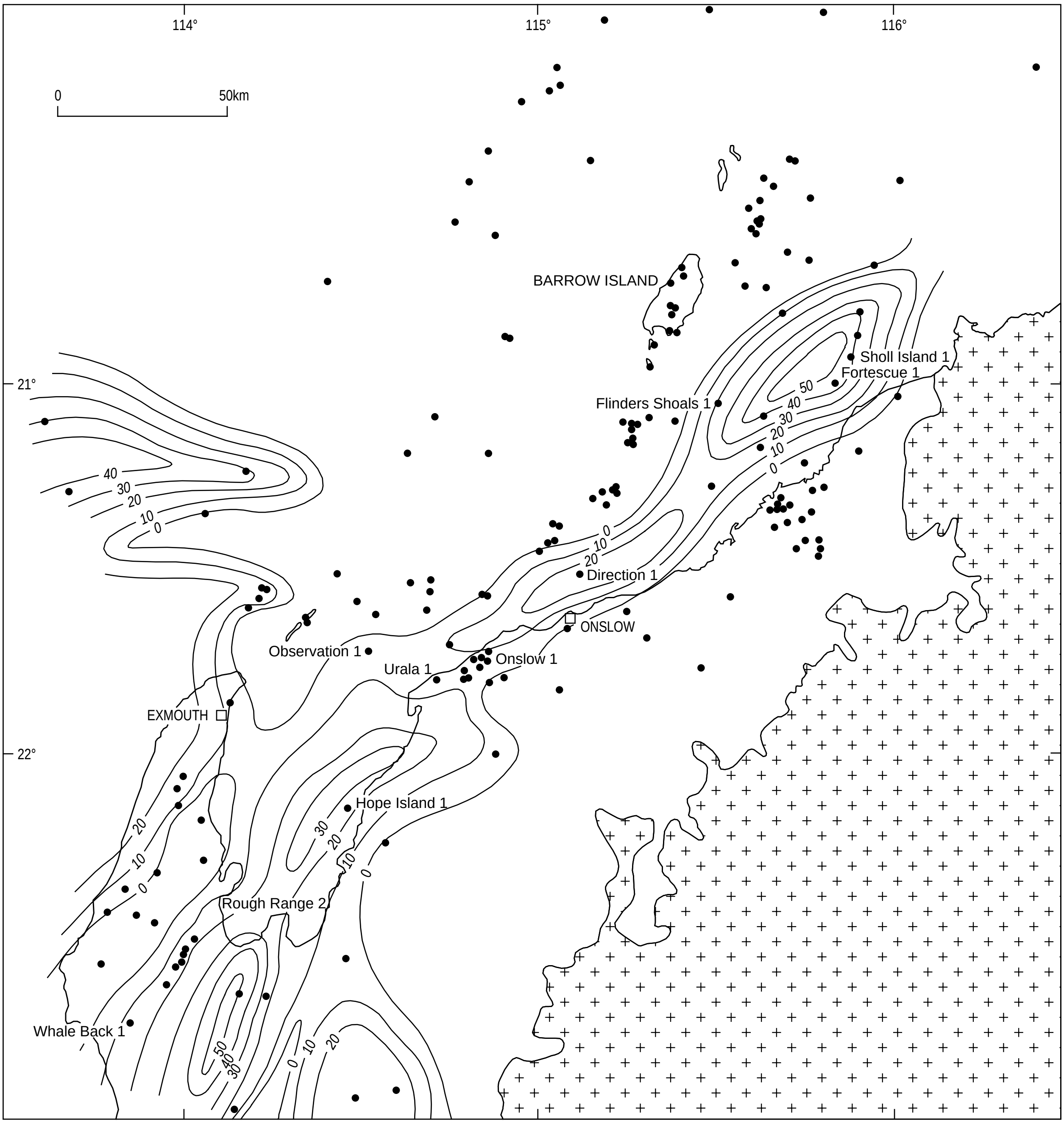


Figure 16b



11/OWA/11

Figure 17



11/OWA/10

Figure 18

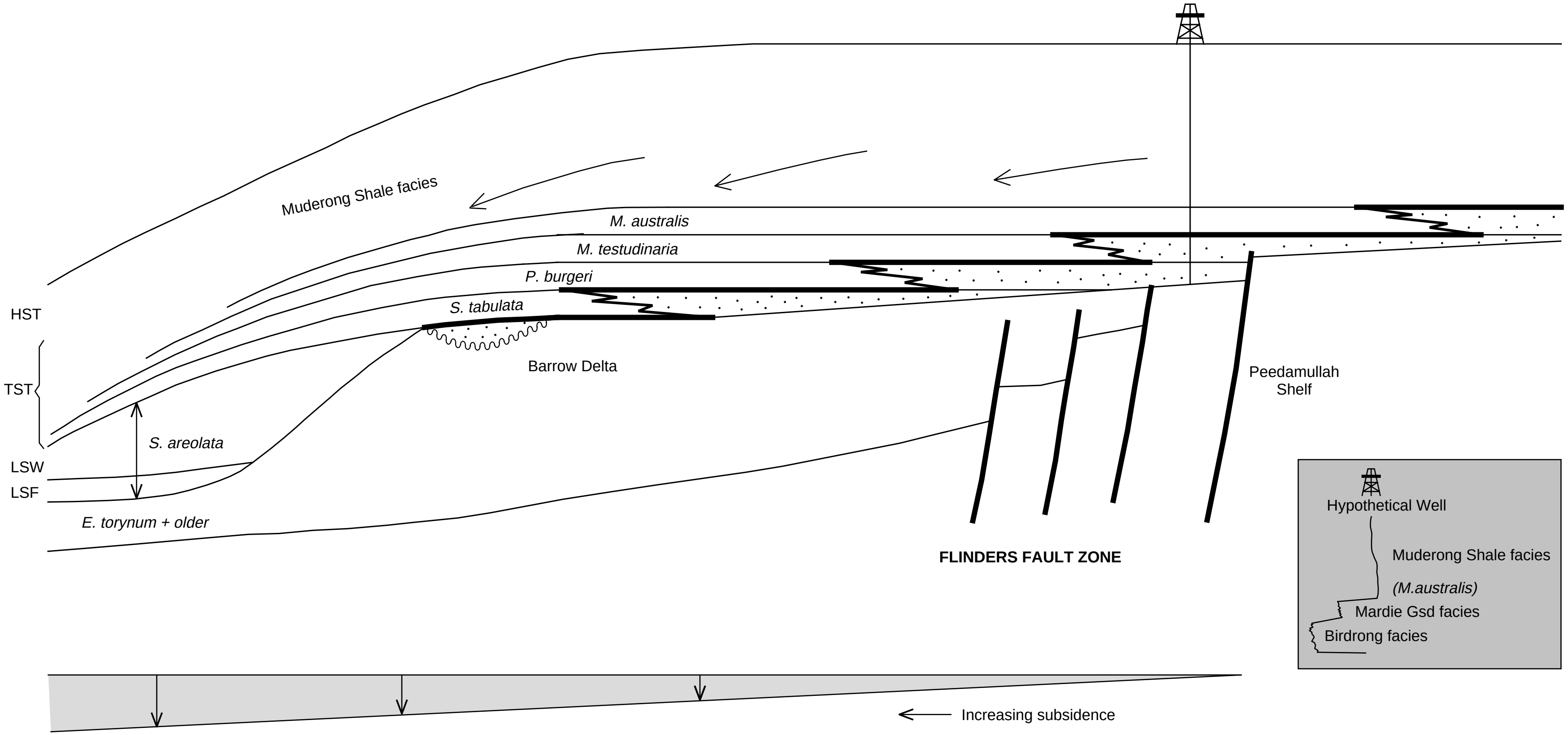


Figure 19

11/OWA/42

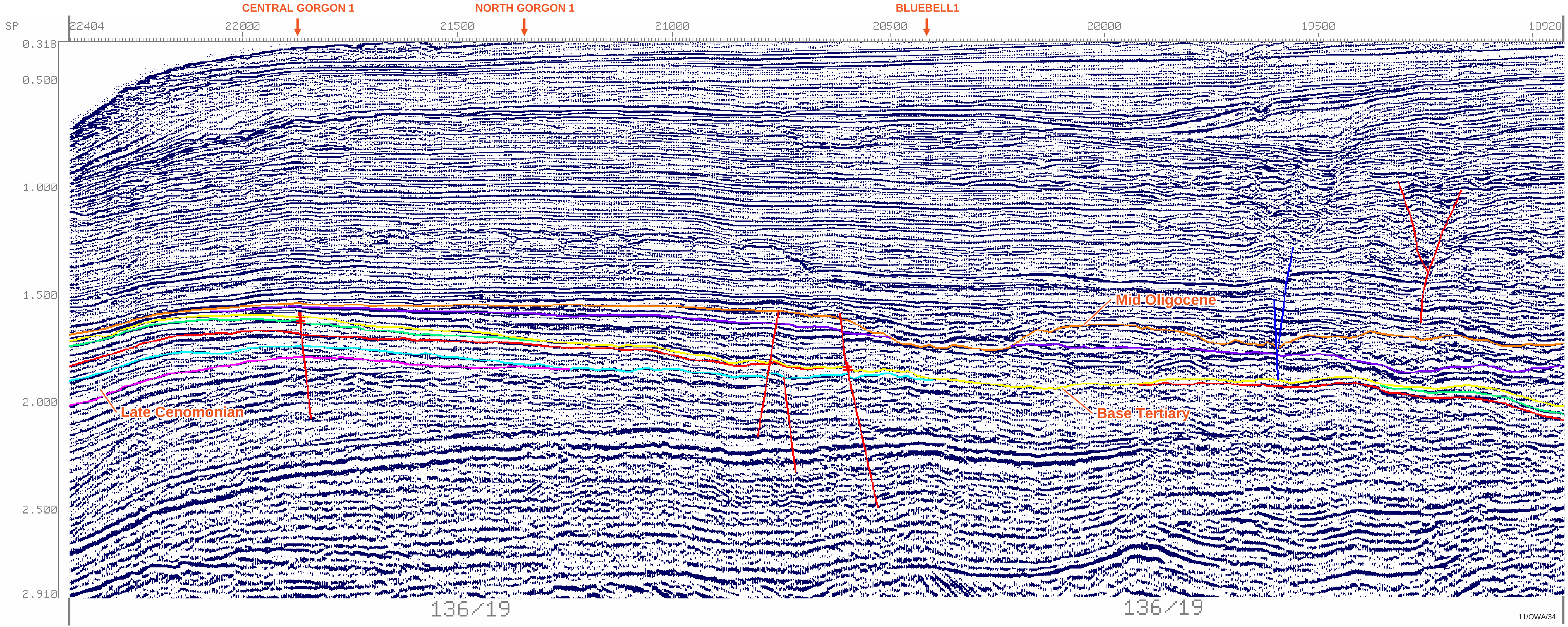


Figure 20a

Go to figure 20b

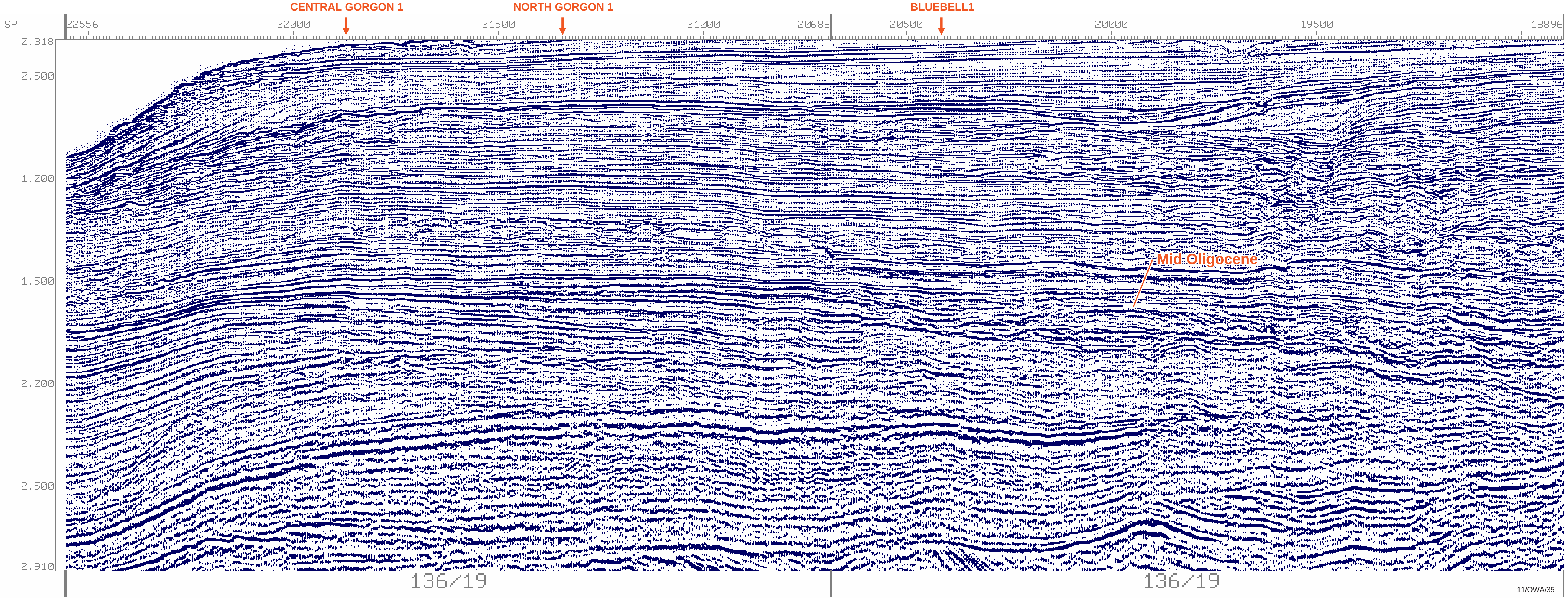


Figure 20b

Back to Figure 20a

APTIAN-ALBIAN
WINDALIA SANDSTONE and RADIOLARITE

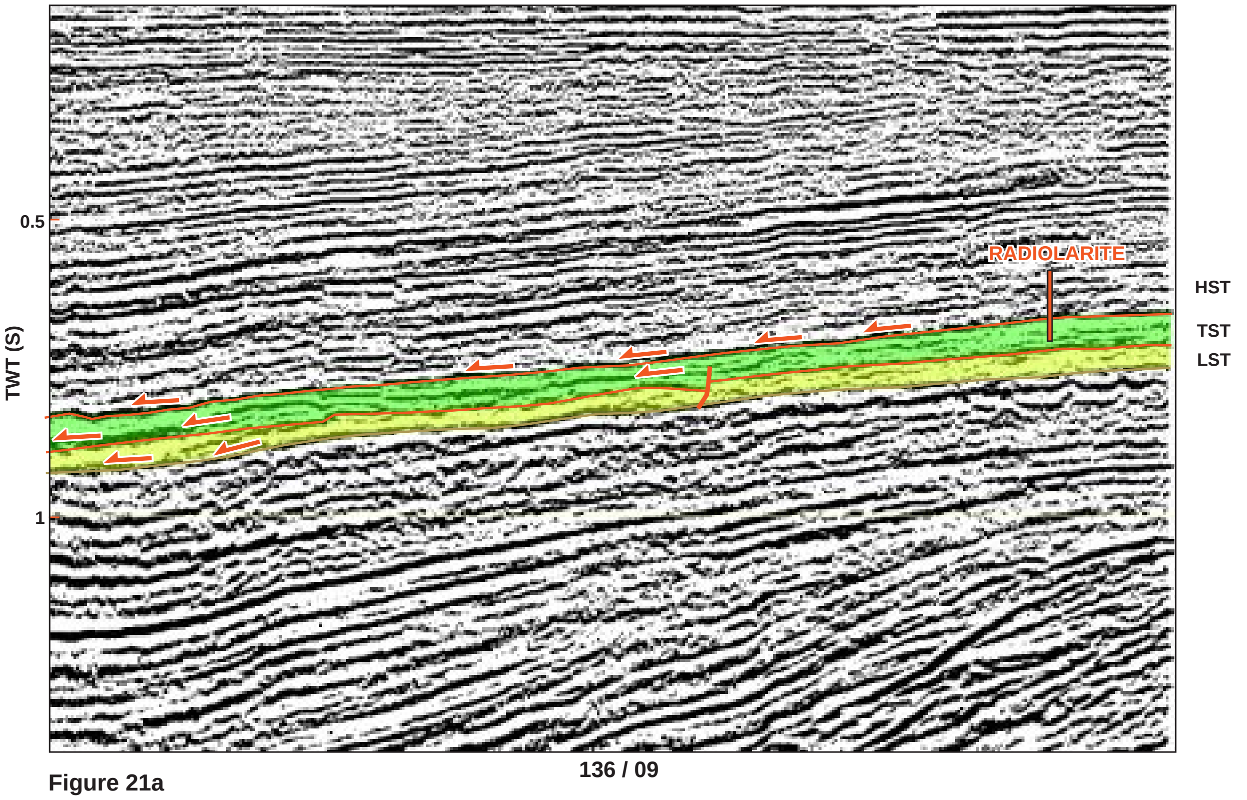
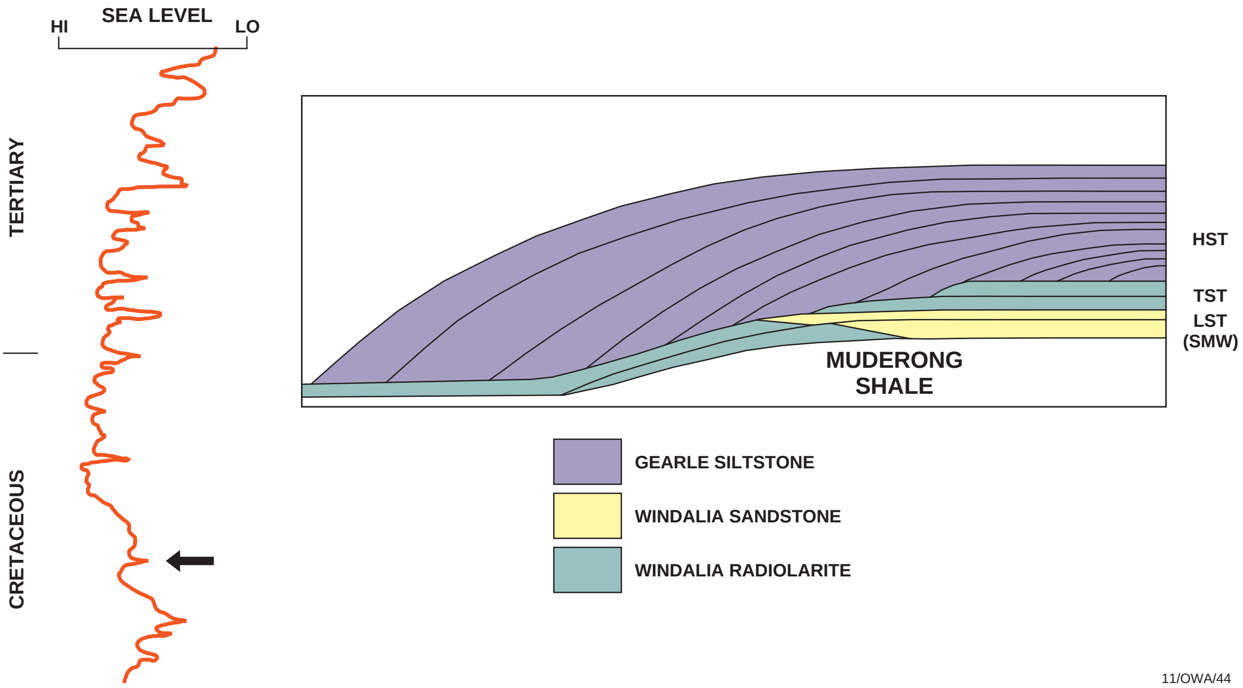


Figure 21a

APTIAN -ALBIAN
WINDALIA SANDSTONE & RADIOLARITE



11/OWA/44

Figure 21b

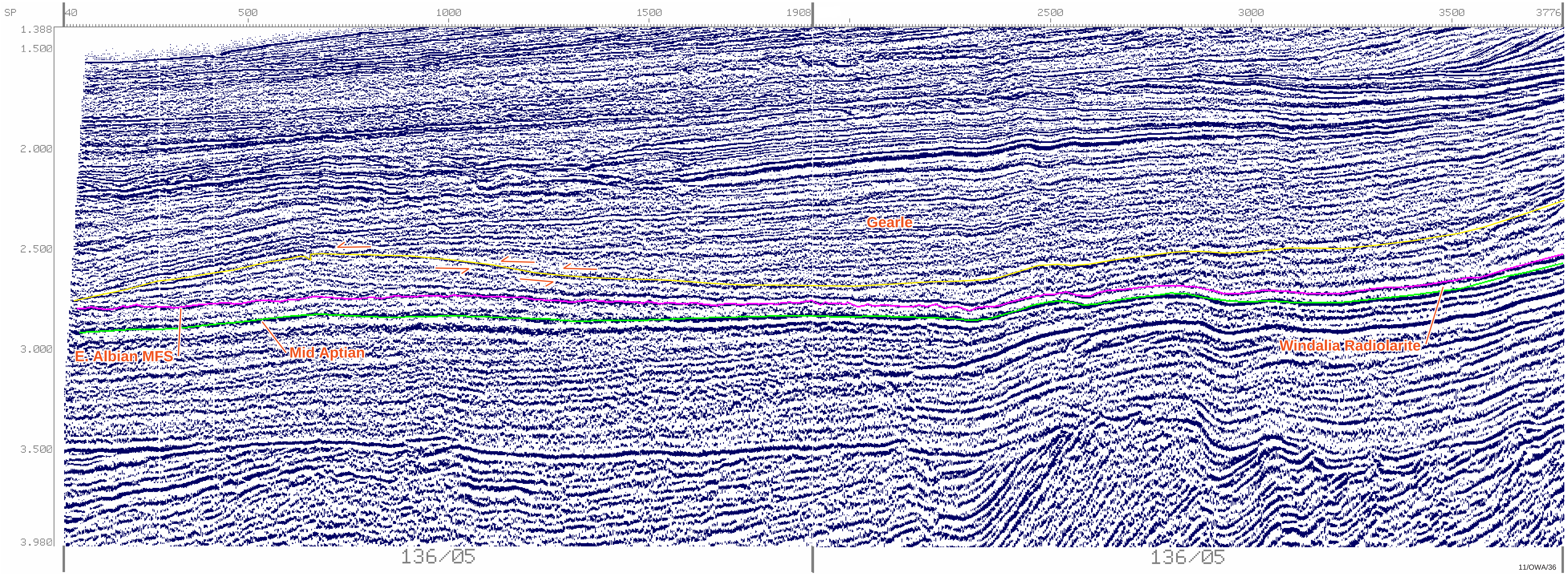

SP
40
500
1000
1500
1908
2500
3000
3500
3776
1.388
1.500
2.000
2.500
3.000
3.500
3.980
Gearle
E. Albian MFS
Mid Aptian
Windalia Radiolarite
136/05
136/05
11/OWA/36

Figure 22

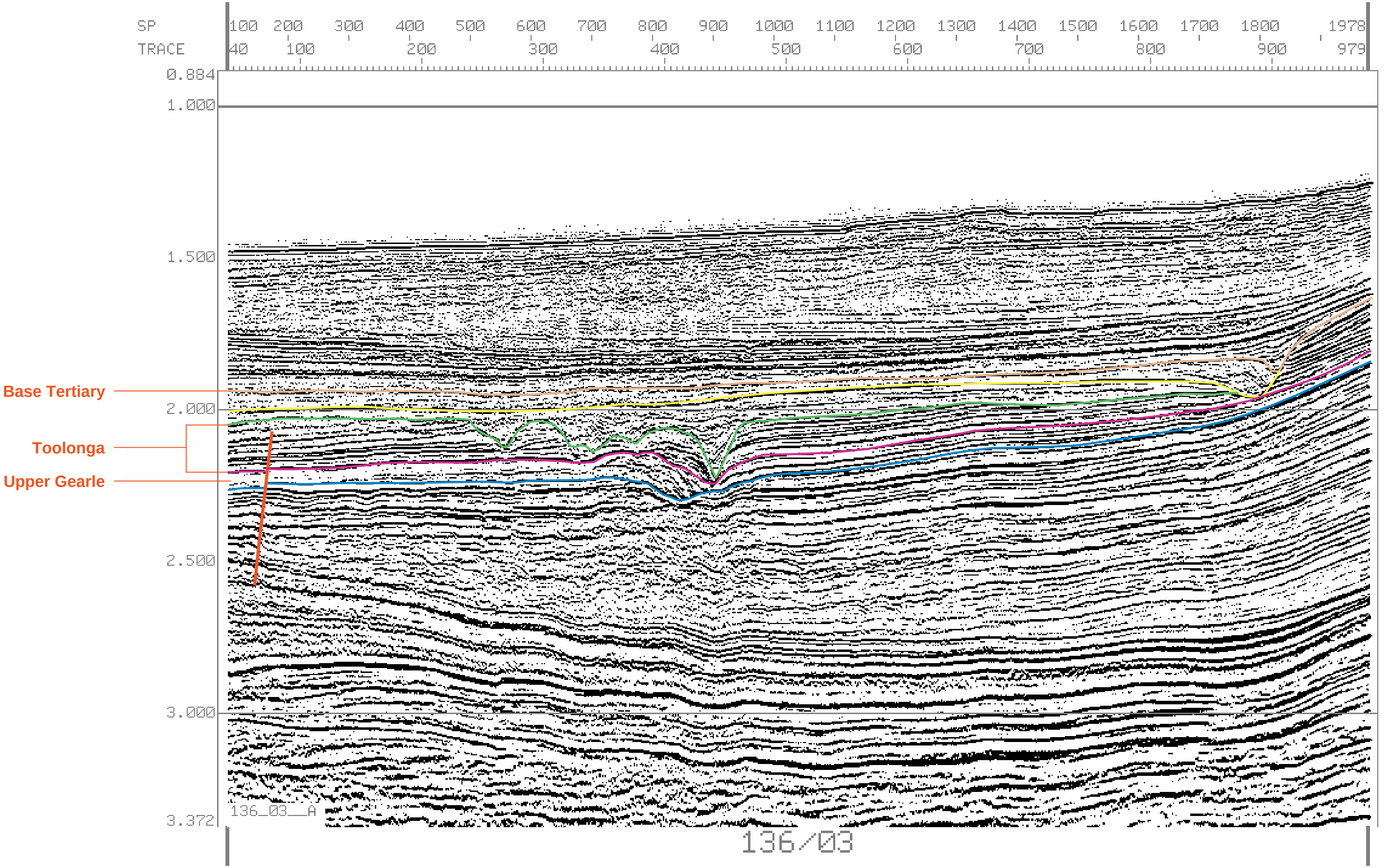

SP
TRACE
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1978
40 100 200 300 400 500 600 700 800 900 979
0.884
1.000
1.500
2.000
2.500
3.000
3.372
Base Tertiary
Toolonga
Upper Gearle
136_03__A
136/03

Figure 23

MINDEN 1

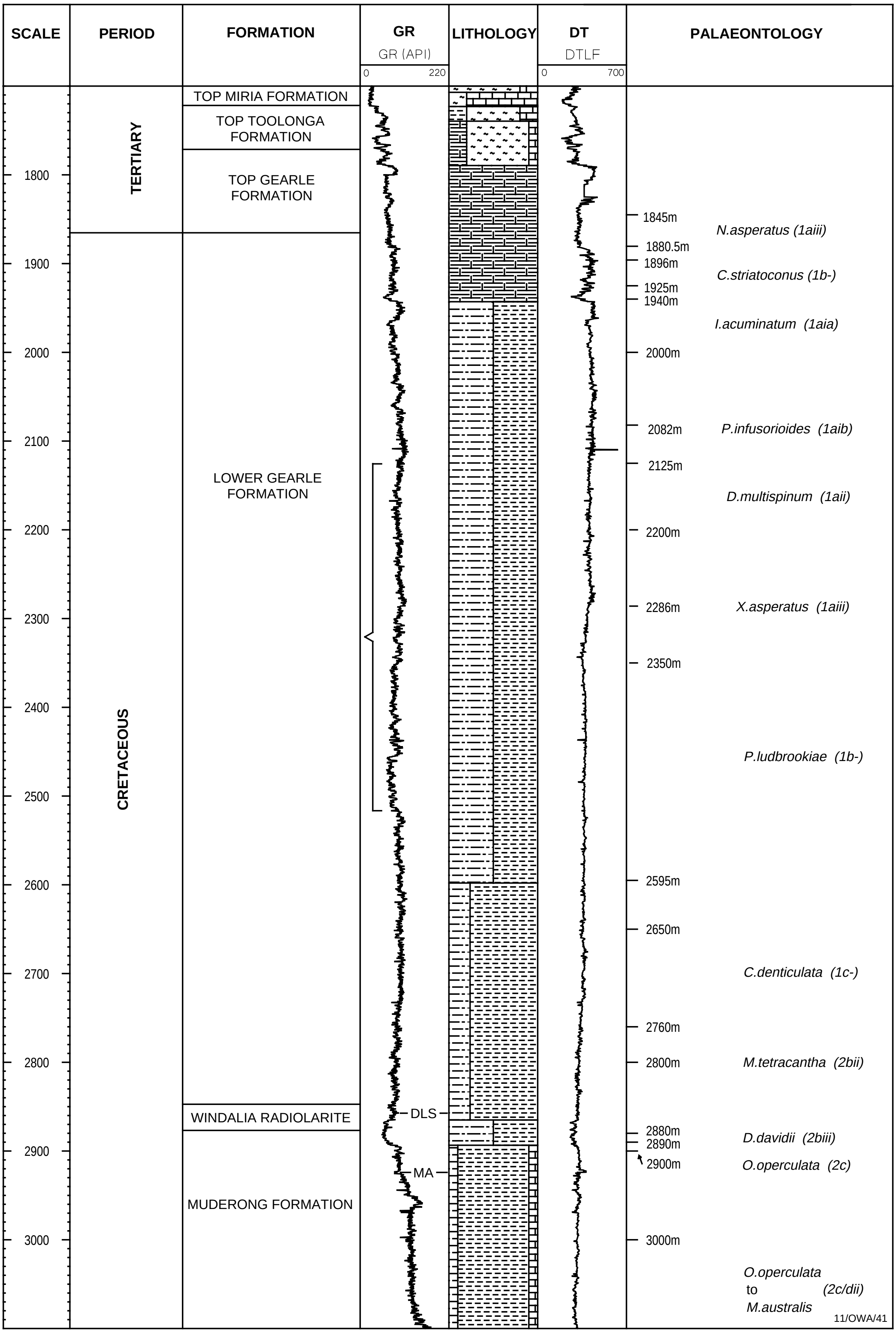


Figure 24

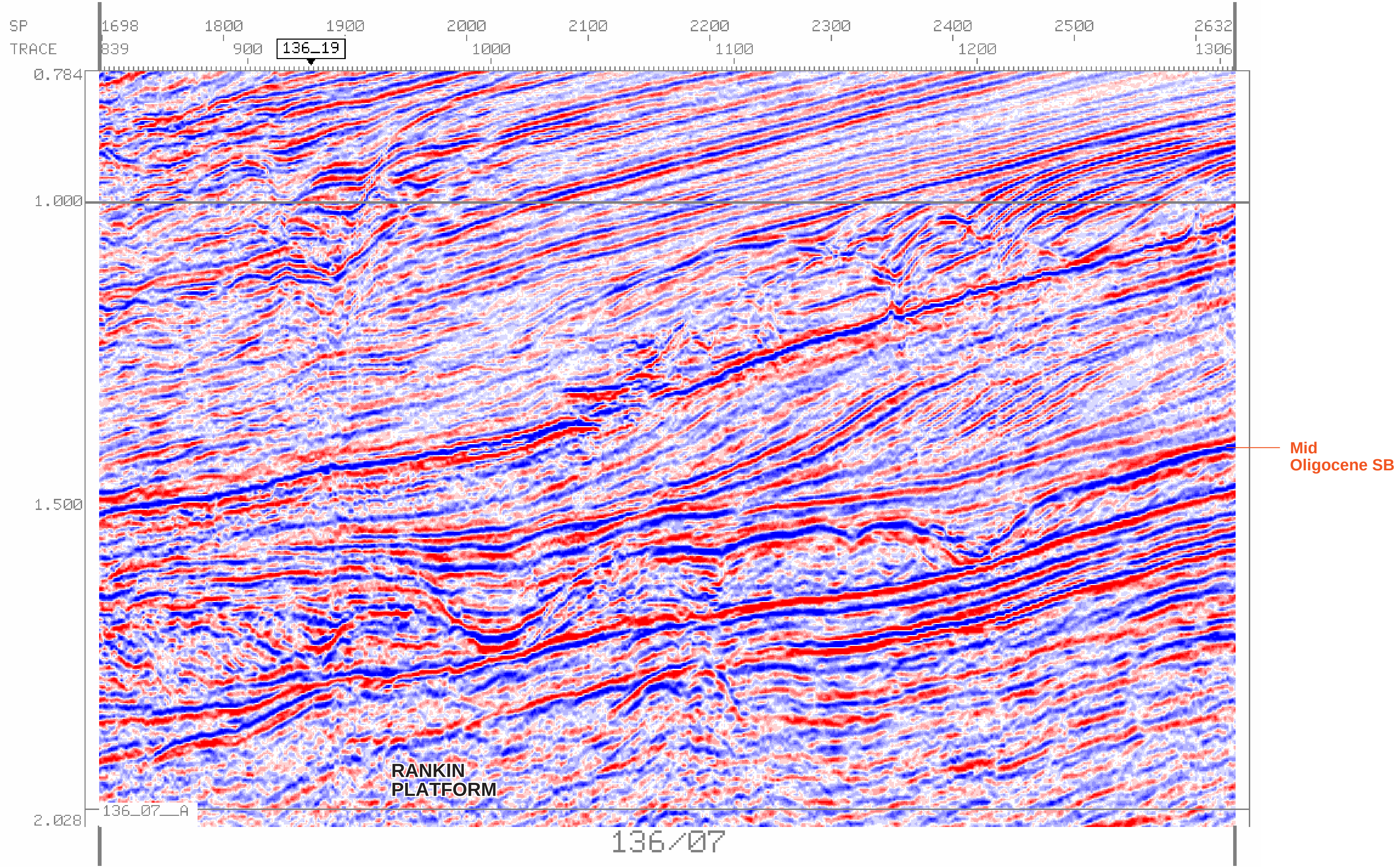

SP
TRACE
1698
1800
1900
2000
2100
2200
2300
2400
2500
2632
839
900
136_19
1000
1100
1200
1306
0.784
1.000
1.500
2.028
Mid
Oligocene SB
RANKIN
PLATFORM
136_07__A
136/07

Figure 25

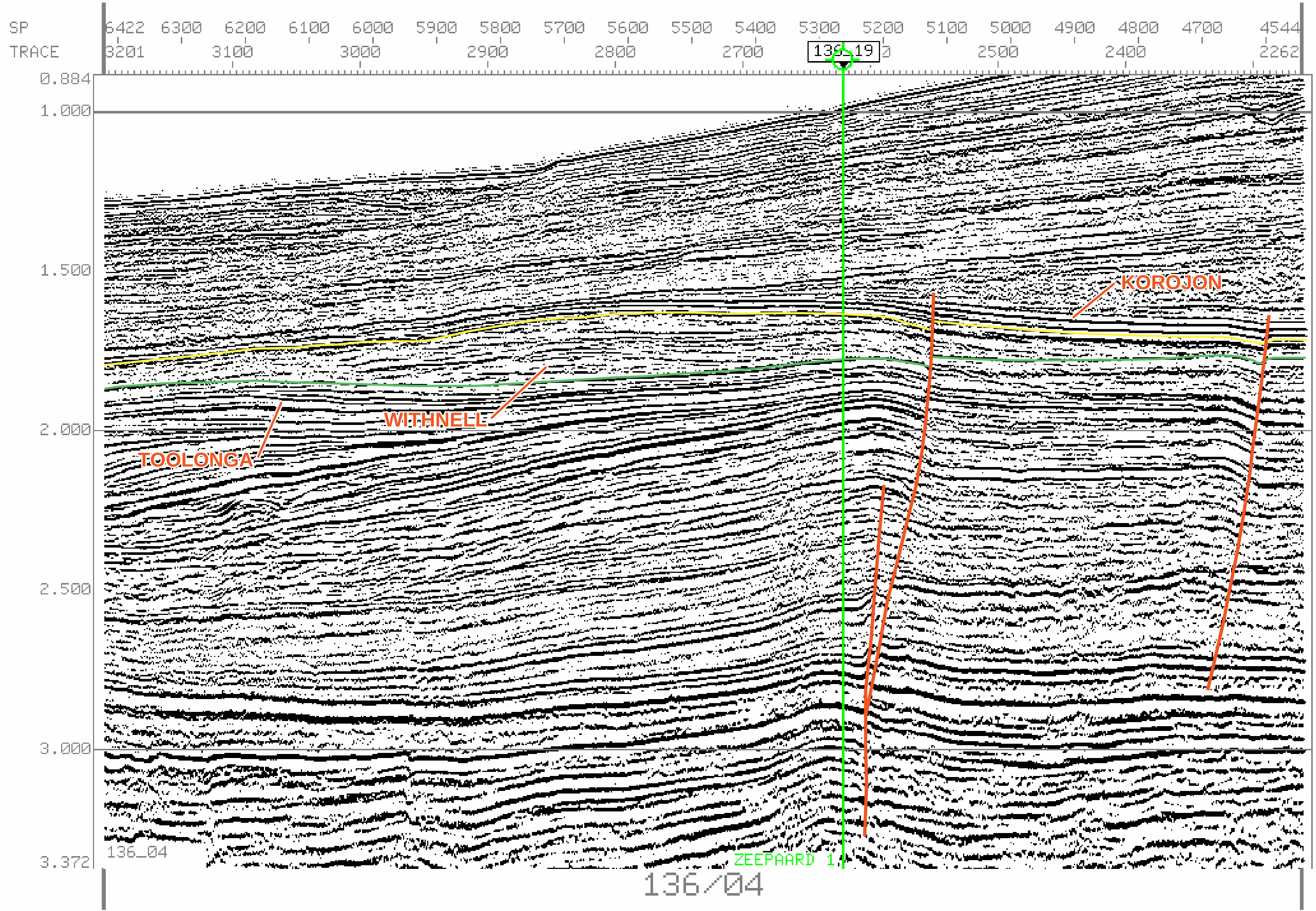

SP
TRACE
6422
6300
6200
6100
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
4900
4800
4700
4544
3201
3100
3000
2900
2800
2700
136_19
2500
2400
2262
0.884
1.000
1.500
2.000
2.500
3.000
3.372
KOROJON
WITHNELL
TOOLONGA
136_04
ZEEPAARD 1
136/04

Figure 26

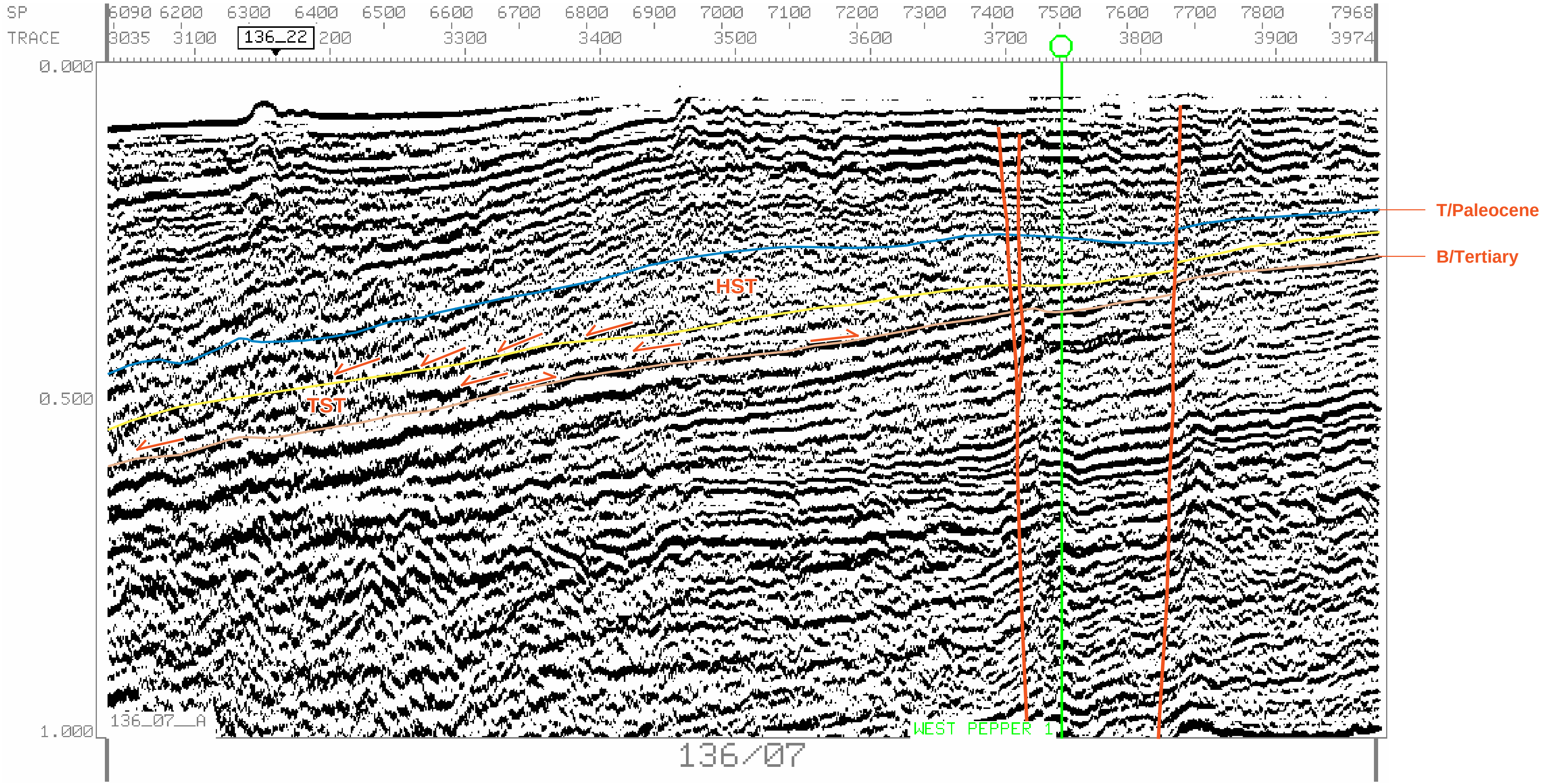

SP
TRACE
6090 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300 7400 7500 7600 7700 7800 7968
3035 3100 136_22 200 3300 3400 3500 3600 3700 3800 3900 3974
0.000
0.500
1.000
HST
TST
T/Paleocene
B/Tertiary
136_07__A
WEST PEPPER 1
136/07

Figure 27

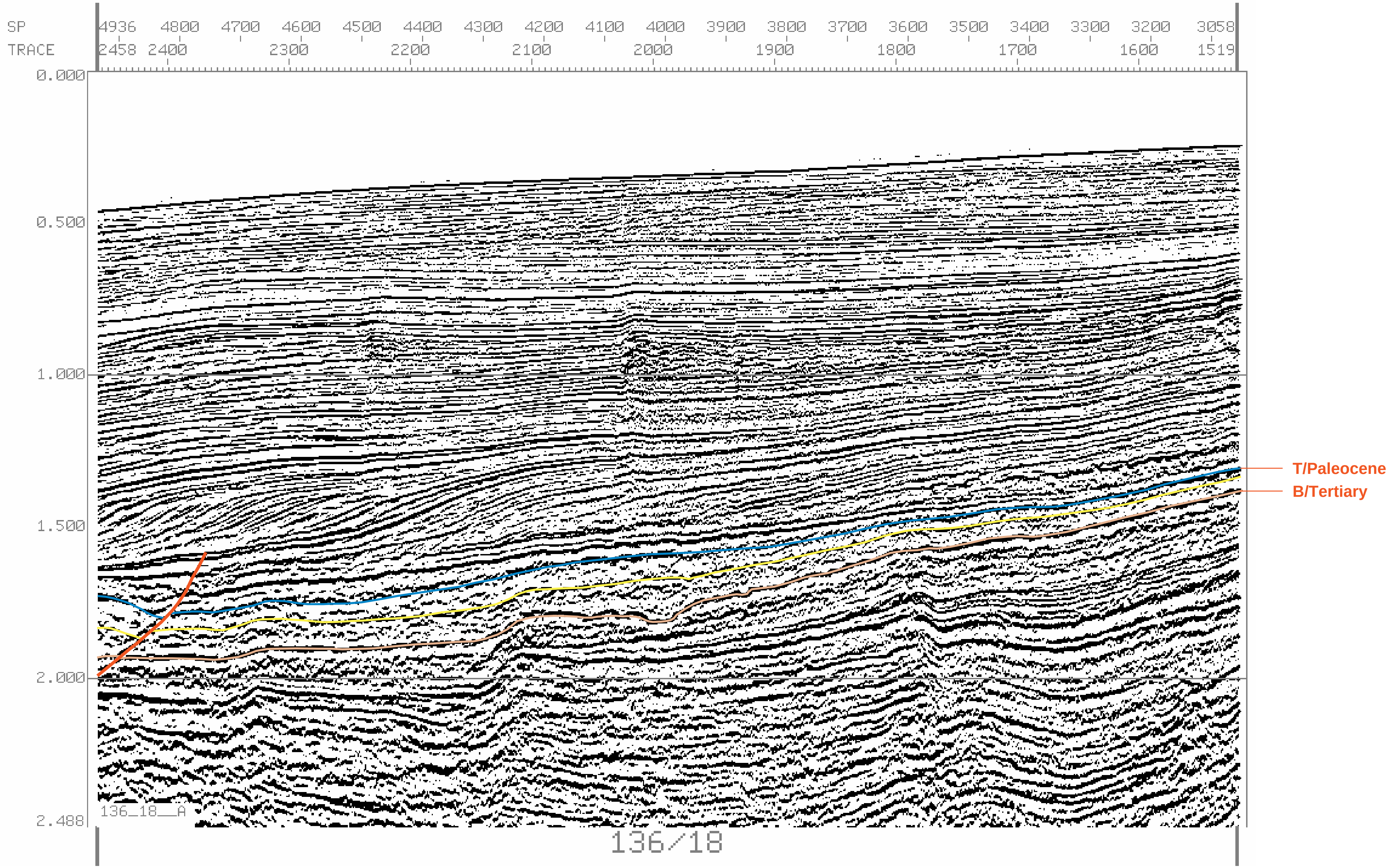

SP
TRACE
4936
4800
4700
4600
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3500
3400
3300
3200
3058
2458
2400
2300
2200
2100
2000
1900
1800
1700
1600
1519
0.000
0.500
1.000
1.500
2.000
2.488
136_18__A
136/18
T/Paleocene
B/Tertiary

Figure 28

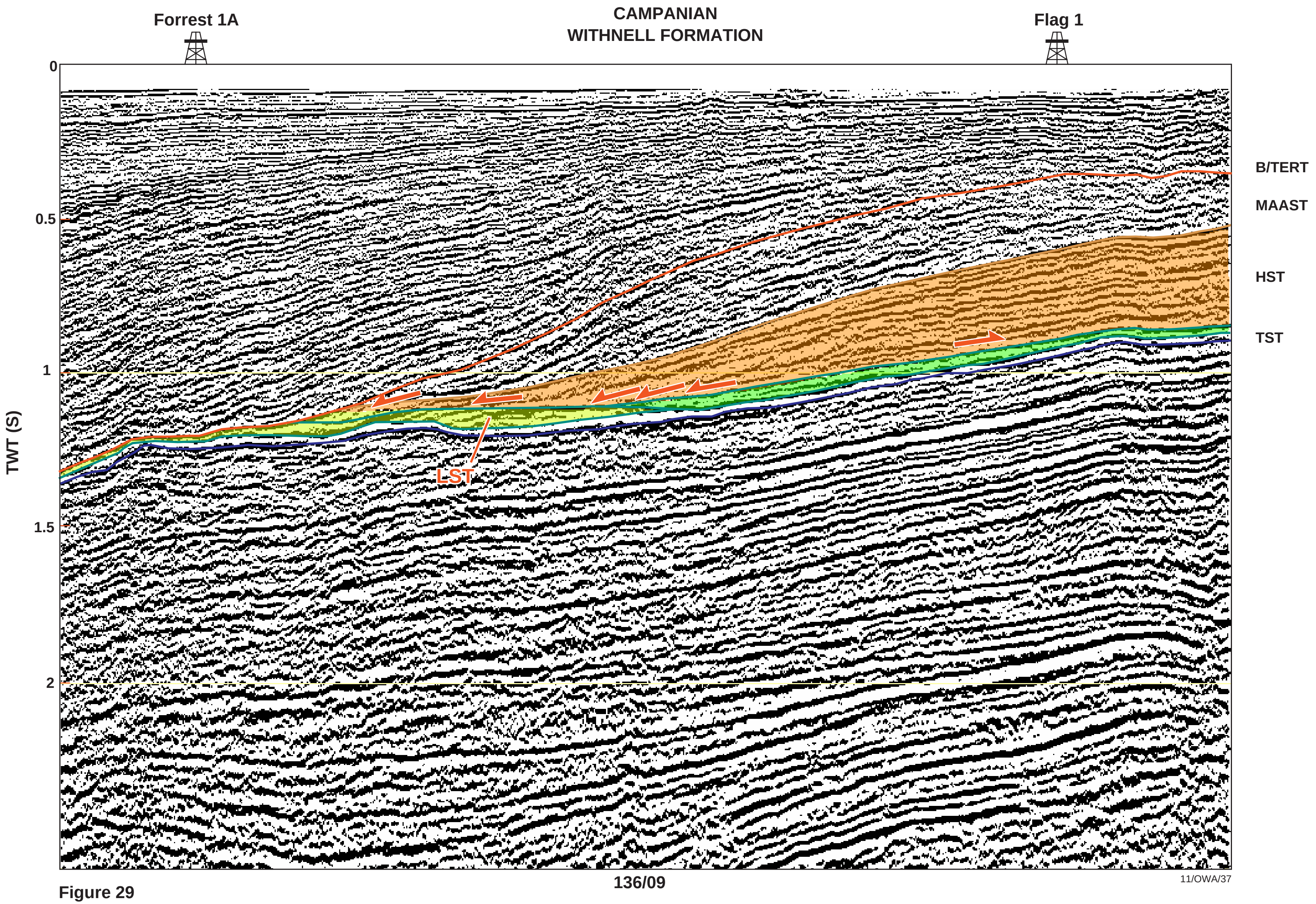


Figure 29

11/OWA/37

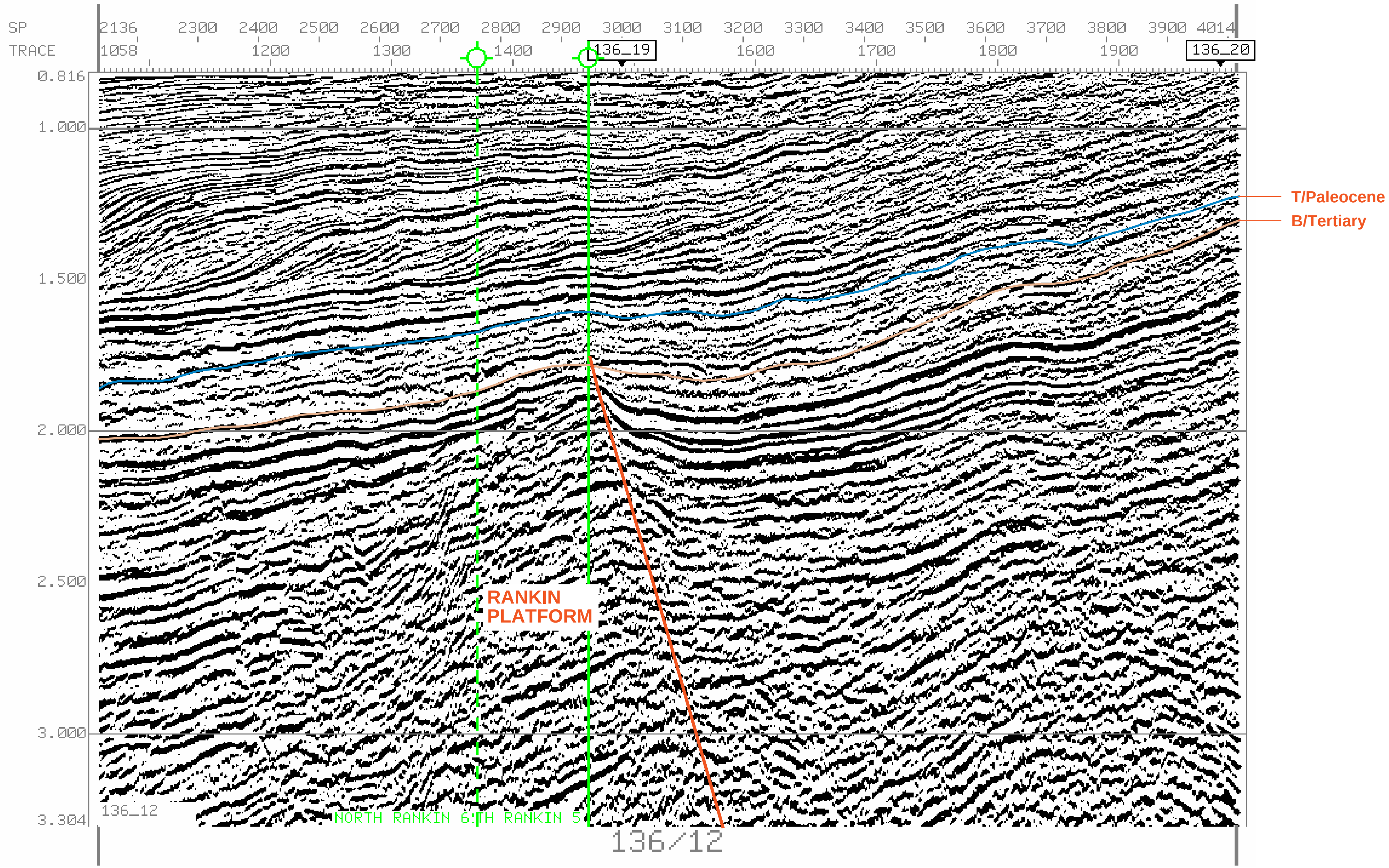


Figure 30

11/OWA/16

MIDDLE MIOCENE REEFS

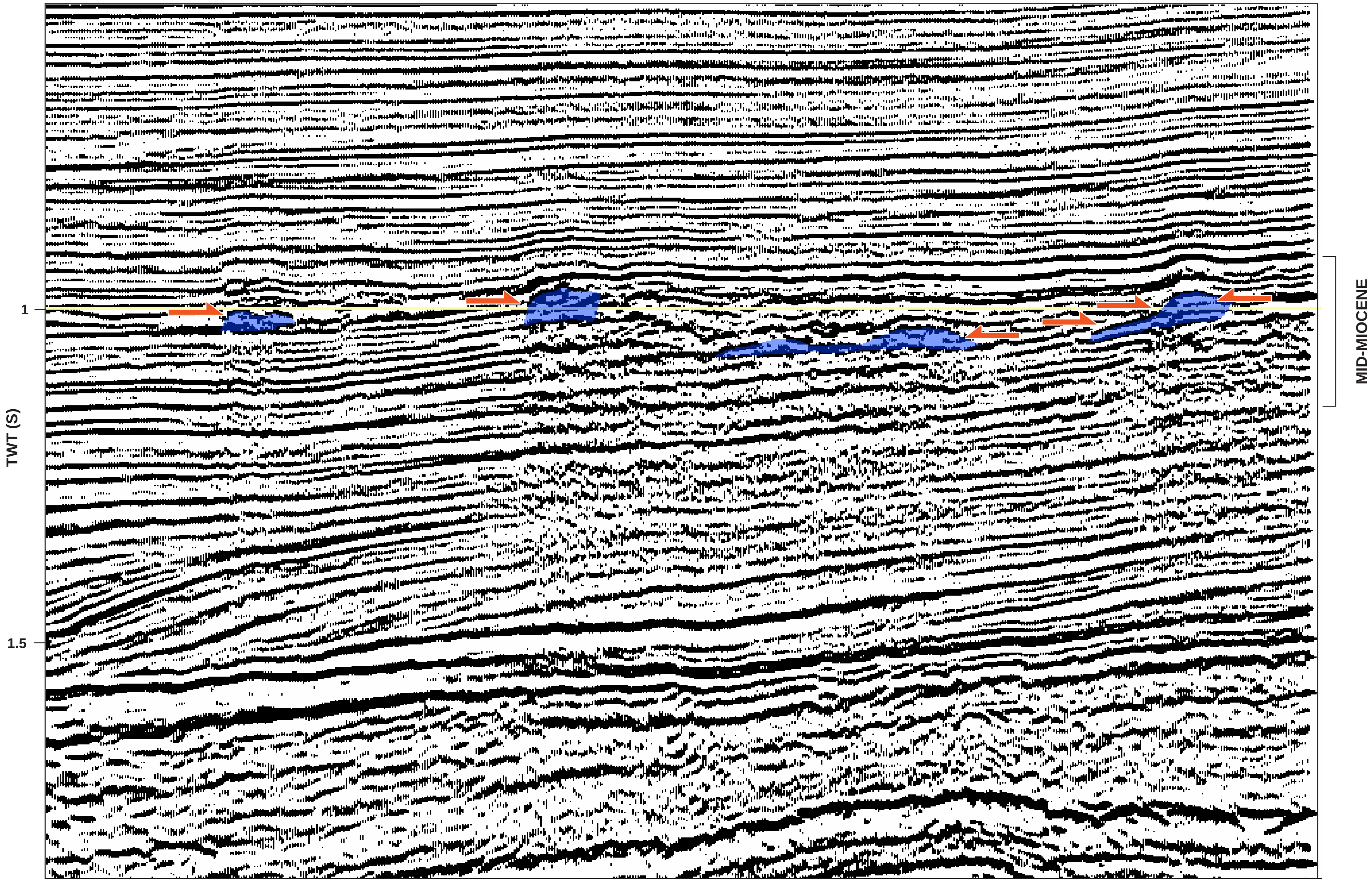


Figure 31

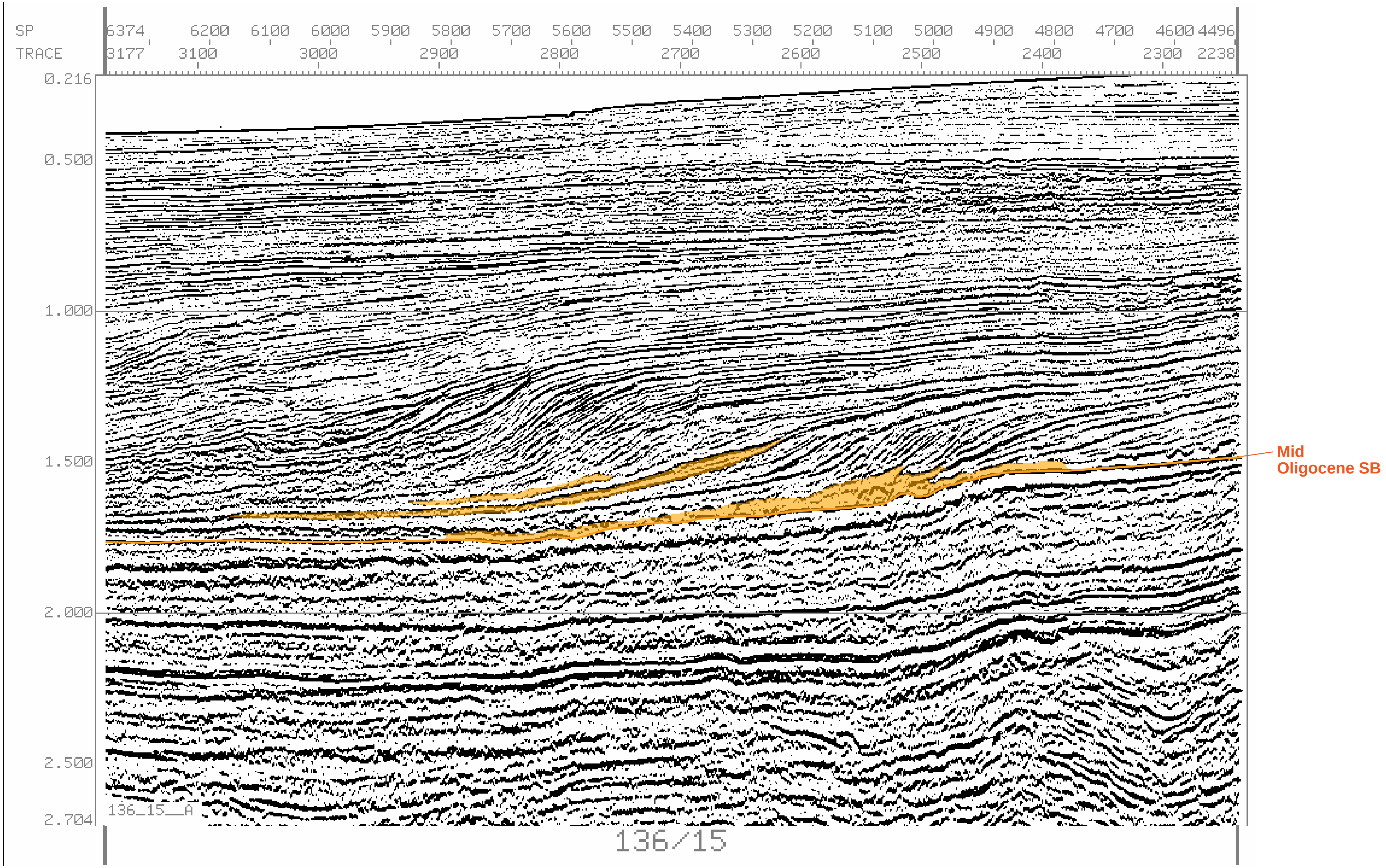

SP
TRACE
6374
6200
6100
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
4496
3177
3100
3000
2900
2800
2700
2600
2500
2400
2300
2238
0.216
0.500
1.000
1.500
2.000
2.500
2.704
136_15__A
136/15
Mid
Oligocene SB

Figure 32

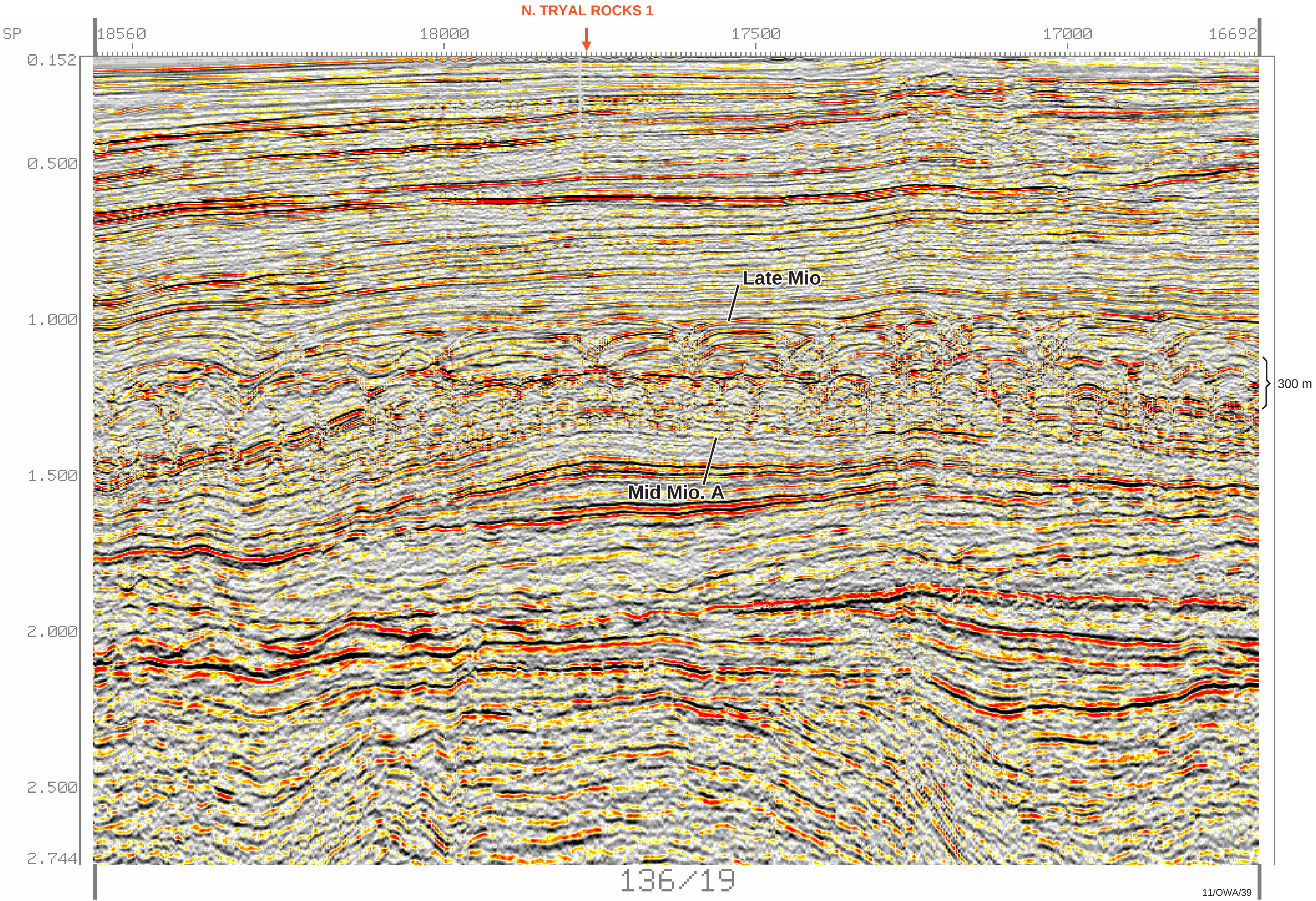

N. TRYAL ROCKS 1
SP
18560
18000
17500
17000
16692
0.152
0.500
1.000
1.500
2.000
2.500
2.744
Late Mio
Mid Mio. A
300 m
136/19
11/OWA/39

Figure 33

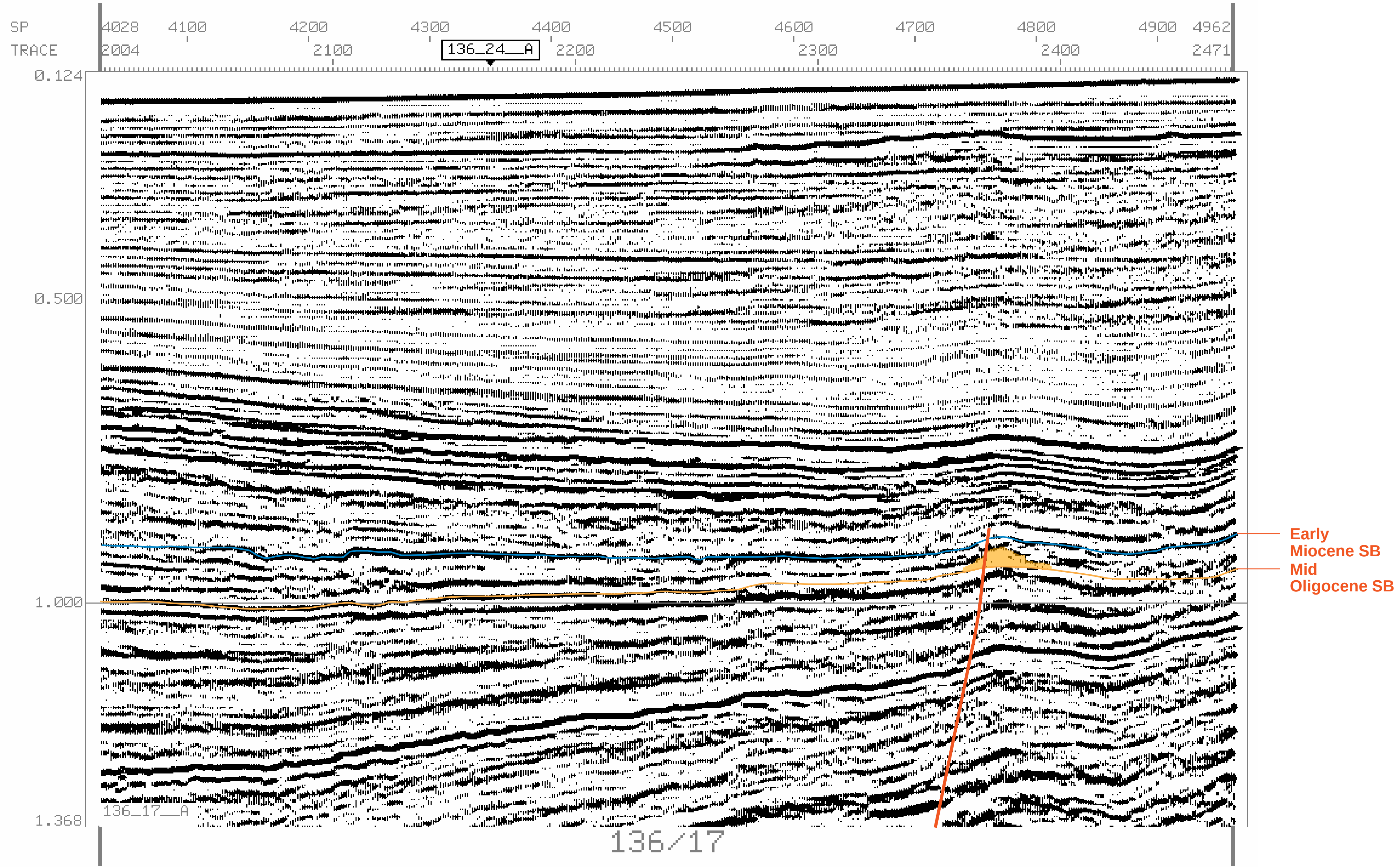


Figure 34a

Go to Figure 34b

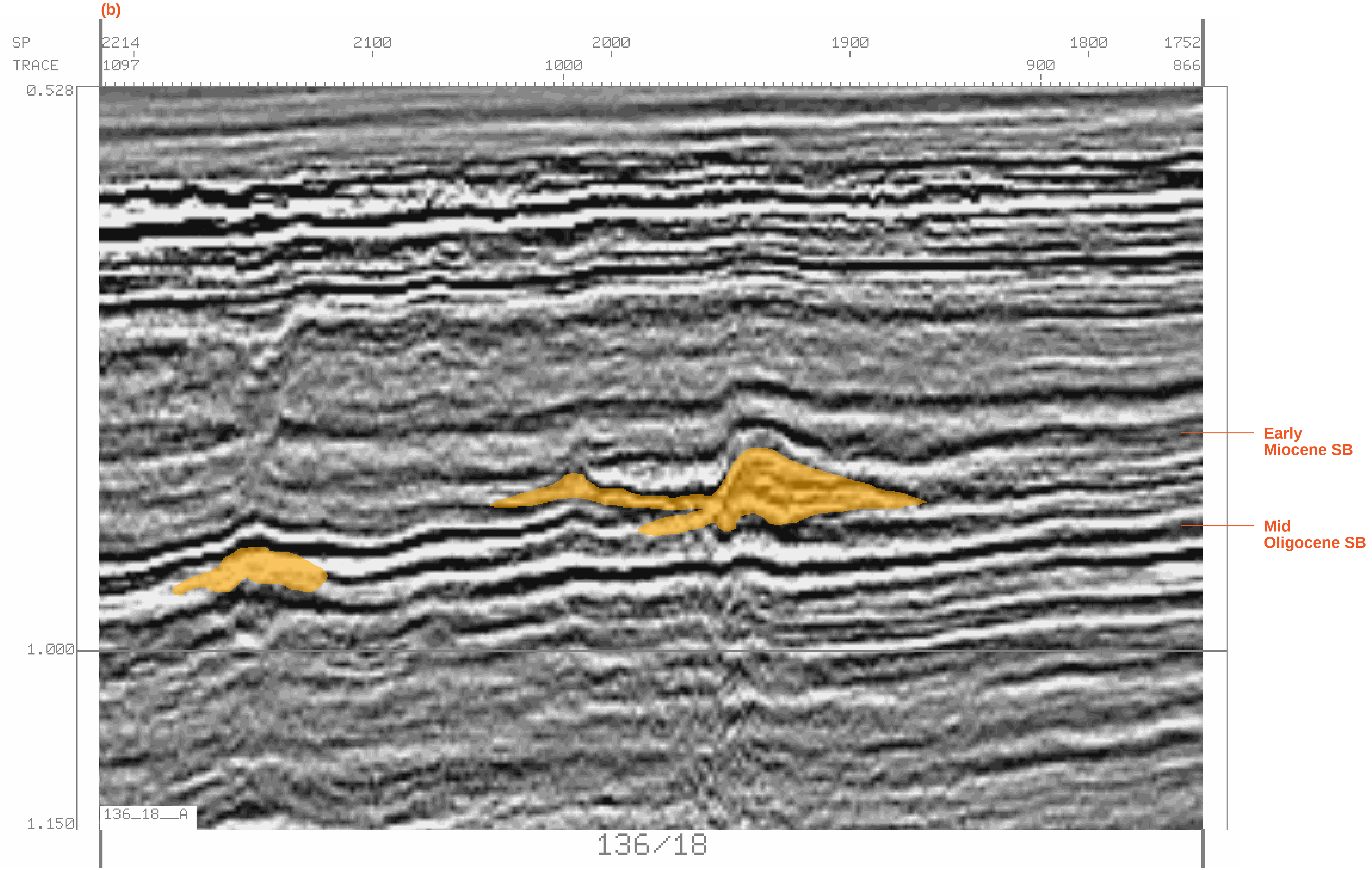


Figure 34b

11/OWA/13

Back to figure 34a