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# GEOLOGICAL CROSS-SECTION OF THE VLAMING SUB-BASIN, SOUTH PERTH BASIN

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# **SUMMARY**

The offshore Vlaming Sub-Basin comprises up to seven kilometres of Cretaceous to Cainozoic sediments, a postulated seven to ten kilometres of Jurassic sediments and an estimated thickness of two to three kilometres of Permo-Triassic sediments. As the depocentres are not coincident the maximum estimated sedimentary thickness is 16 kilometres.

Strata older than the Tithonian have not been penetrated by wells in the area of study, however, Late Permian and Early Triassic strata were recently dredged from the flanks of the offshore submarine Perth Canyon. Seismic and other dredge samples indicate that this shallow Permo-Triassic occurrence is from a localised high block.

An angular unconformity of mid Valanginian age dominates the section. The unconformity formed in response to intense short lived structuring which took the form of block and listric faulting. This resulted in a hiatus ranging from less than one million years to more than ten million years. Sedimentation was very rapid prior to structuring with up to 6,000 metres of fluvio-lacustrine, paralic, and lacustrine sediments deposited over the six million years spanning the Berriasian and early Valanginian (1,000 metres/my). Marine, restricted marine, paralic and minor fluvio-lacustrine sedimentation occurred after the unconformity, at the slower rate of 100 metres/my.

The cessation of the main phase of structuring coincided with the resumption of sedimentation above the unconformity surface, with the formation of the first oceanic crust in the Perth Abyssal Plain and with a major drop in sea level. This initial deposition occurred in the topographic lows in a paralic environment. The erosion of palaeo highs associated with the unconformity is therefore subaerial. Sequence analysis shows that the Neocomian stratigraphic record matches the sea level curve of Haq et al. (1987).

Despite some uncertainty about the oil sourcing potential of the section, rich oil prone coaly source units exist in the latest Jurassic to earliest Cretaceous section, within the "oil window". To date two valid traps have been tested and both contain oil. Gage Roads-1 and 2 intersected three oil pools which potentially reservoir a total of 500 MMSTBO, recoverable. All the other wells studied in the area had major structural or stratigraphic complications, negating a valid trap.

Considerable petroleum exploration potential exists in the Vlaming Sub-Basin with the presence of three regional sealing units, two very thick sandstone reservoir units and complex structure. These combine to provide numerous trapping mechanisms for giant hydrocarbon pools.

The complex structure and stratigraphy prevented effective evaluation of the Sub Basin in the past. However, major technological advances in seismic acquisition and processing, seismic stratigraphy and the much finer micropalaeontological subdivision of the sedimentary section have occurred since most of the exploration was undertaken in this area. This has allowed the key Neocomian and Barremian unit (spanning 25 my and up to 6,000 metres) to be subdivided into ten time zones. All the exploration in this area was carried out prior to the palaeontological subdivision of Backhouse (1988) and all but two wells were sited using seismic data which denied adequate recognition of either the complex structural geology or the sequence stratigraphy.

# INTRODUCTION

## DATA SET

QUINNS ROCK 1 (WAPET, 1968) GAGE ROADS 1 (WAPET, 1968) ROE 1 (WAPET, 1970) CHARLOTTE 1 (WAPET, 1970) WARNBRO 1 (WAPET, 1970) GAGE ROADS 2 (WAPET, 1971) PEEL 1 (PHILLIPS, 1978) MINDER REEF 1 (ESSO, 1984) MULLALOO 1 (ESSO, 1984)

VLAMING SEISMIC SURVEY - V82A (ESSO, 1982 : V82A) SOUTH PERTH BASIN SEISMIC SURVEY 80 - (BMR, 1988: 80) SOUTH PERTH BASIN SEISMIC SURVEY 81 - (BMR, 1988 : 81)

# SCALE

The cross-section has been drawn at 1:100,000 scale with a vertical to horizontal exaggeration of 1. The total length of the line is 220 km, with a secondary line of 70 km. It has a maximum depth of approximately 16 km which is interpreted to coincide with intra Jurassic strata over much of the area.

# HORIZONS DRAWN

A total of 12 horizons were carried on the offshore seismic and drawn on the cross-sections (Plate 1). These are related to the microfossil zones of Backhouse (1988) and the time slices (TS) of the project.

- 1) Tertiary Base Tertiary unconformity -base Cz1 or base Cz4
- 2) Cretaceous top Aptian unconformity top of K2-K5 sequence
- 3) Cretaceous top A. alata intra Hauterivian top K2
- 4) Cretaceous near top P. lowryi intra Hauterivian mid K2
- 5) Cretaceous top G. <u>mutabilis</u> mid Valanginian lower K2
- 6) Cretaceous Valanginian unconformity base K2/top K1
- 7) Cretaceous Intra Berriasian reflector intra K1
- 8) Cretaceous Intra Berriasian sequence boundary intra K1

- 9) Jurassic Top Tithonian top J9/J10
  10) Jurassic Intra Late Jurassic J7?-J8? (undated)
  11) Jurassic Intra Middle Jurassic J5?-J6? (undated)
- 12) Jurassic? Intra Jurassic? horizon (undated)

Beyond the continental shelf, where the seismic data are poor and where there is no time control, few of the above events could be Several additional horizons have been drawn here correlated. instead. Some of these horizons represent sequence boundaries but most simply represent the morphology and dip of a set of seismic reflectors. Few of these have been significant correlated.

# TIME DEPTH PLOTS

Time/depth plots have been drawn for nine wells in the offshore section: Minder Reef-1, Roe-1, Gage Roads-2, Gage Roads-1, Warnbro-1, Peel-1, Mullaloo-1, Charlotte-1 and Quinns Rock-1 (Plate 2). These plots are not burial history curves, but simply represent the palaeontological dating performed in each well, and show the precise nature of the biostratigraphic control which exists for the cross-section. The boxes drawn on the time/depth curves are the actual depth range of the palaeontological zones assigned in the well.

The Late Jurassic to Early Cretaceous (Time Slices J9-K5) age control for these wells was supplied by J. Backhouse of the W.A. Geological Survey. This dating is an expansion of his published research work (Backhouse, 1988).

The rapid deposition in this area and the fine dinoflagellate zonation in the Valanginian to Albian (Time Slices K2-K5)(Backhouse, 1988) has resulted in much finer time definition than the Time Slices from the project allow. Microfossil zonations are therefore referred to extensively.

The latest Jurassic to mid Valanginian (TS J9-K1) was deposited very rapidly but only the broad subdivision allowed by spore/pollen analysis was possible due to the lack of dinoflagellate assemblages. However, sequence stratigraphy has enabled a three fold subdivision of TS K1.

The Helby et al. (1987) dinoflagellate zonation for the Early Cretaceous is inappropriate for the Vlaming Sub-Basin due to palynological provincialism. Therefore, the zonation of Backhouse (1978), based on the Perth Basin, has been used and tied back to Helby et al. (1987) for consistency within the project.

The Late Cretaceous and Cainozoic section (K6-Cz6) is poorly dated. The ages of this section are based on sparse data from Playford et al. (1976), well completion reports, lithofacies correlation between wells and outcrop onshore, and rare palaeontological updates. The results for this time span must be used with caution.

# RESULTS

# DATING OF SEQUENCES

# Pre-Jurassic

Playford et al. (1976, figs 21, 22, 25-29, 32, 34, 37, 46-50) show a 2000-3000 metre Permo-Triassic section in the offshore Vlaming Sub-Basin overlain by up to 14,000 metres of Jurassic and younger strata. The Permian to Triassic are better known onshore, to the north and east, and are described and discussed by Playford et al. (1976).

Grab samples from the submarine Perth Canyon in the middle of the study area (see Plate 2) contain sediments of Triassic and Permian age (Marshall et al., 1989). The lack of control on the location of the samples in the canyon walls precludes a precise tie into recent BMR seismic lines recorded across the canyon. Also, these seismic lines do not (currently) tie to any regional high resolution seismic lines. Regional seismic lines which tie these lines have been recorded by the BMR but had not been processed at the time of writing. The occurrence of shallow Permian and Triassic strata has major structural implications for this area. Elsewhere in this area the base of the Jurassic is believed to be at a depth of 7,000 to 14,000 metres sub sea (see section A-B on Plate 1).

# Jurassic

Only the latest Jurassic (TS J9/J10) has been encountered by the wells used in this cross-section. Backhouse (1978) cites up to 3000 metres of Middle to Late Jurassic sediments in the vicinity of the study area. These probably overlie an Early to Middle Jurassic section of up to 2,000 metres. The depth and nature of the boundary between the Jurassic and underlying units is unknown here.

# Earliest Cretaceous (TS K1)

The Berriasian to early Valanginian (TS K1) is encountered and dated in all the wells used in the cross-section. In each instance an incomplete section was encountered due to:

- \* truncation by a mid Valanginian unconformity (all wells);
- \* by the faulting out of section (Peel-1) or
- \* incomplete penetration (Charlotte-1, Mullaloo-1, Roe-1 & Minder Reef-1).

On seismic Line V82A-51, west of Roe-1 (see section A-B & Plates 1, 3 & 4), sediments from this time slice are interpreted to be up to 5,000 metres thick.

# Early Cretaceous (TS K2-K5)

The Early Cretaceous section overlying the mid Valanginian unconformity is dated in each of the wells studied for this cross-section. Substantial lateral thickness variation occurs

for this sequence with a maximum of 2,000 metres being preserved in the Rottnest Trough (see Plate 1 & 2). The Late Valanginian to Hauterivian (TS K2) is divided into four dinoflagellate zones, enabling a detailed analysis of post-unconformity deposition. Few wells contain ages younger than Time Slice K2 but Warnbro-1 extends as high as TS 5 (late Aptian to earliest Albian) and Peel-1 extends up to TS 4.

# Late Cretaceous and Cainozoic

The offshore Late Cretaceous and Cainozoic section has not been systematically and reliably dated so the following interpretation is based on descriptions and discussion by Playford et al. (1976) and on litho-stratigraphic correlation.

A marine sandstone, shale and carbonate sequence encountered in Warnbro-1 and Peel-1 is interpreted as part of the Coolyena Group which is an unconformity bounded sequence of Late Albian to Late Cretaceous age (TS K8-K11)(Playford et al., 1976).

A Paleocene to Early Eocene (TS Cz1) marine sand is dated in Quinns Rock-1 and Warnbro-1 (Playford et al., 1976). Playford et al. (1976) interprets this section as a channel deposit associated with the development of the Perth Canyon.

A carbonate dated as late Early Miocene to early Middle Miocene age (planktonic foraminifera zones N7 to N9) (TS Cz4) occurs in Gage Roads-1 & 2, Roe-1 and Charlotte-1 (Playford et al., 1976). This is described as a dolomitised carbonate in the well completion reports. A unit of similar lithology also occurs in Warnbro-1, Peel-1, Mullaloo-1 & Minder Reef-1. All of these carbonate occurrences are assumed to be the same age.

Various Quaternary (TS Cz7) carbonate and clastic units have been dated in the onshore Perth Basin but Late Miocene to Pliocene units are rare. A time break between the Middle Miocene and the Pleistocene (TS Cz5-Cz6) is therefore likely.

More detailed palaeontological analysis has been undertaken in the offshore (Marshall et al., 1989) but this is from dredge samples in the Perth Canyon. Unfortunately dredge samples do not allow the exact sampling position in the canyon wall to be determined. An accurate tie to seismic is therefore impossible. Also, available seismic does not allow correlation to the high resolution V82-A seismic data so the structural and stratigraphic significance of these analyses cannot be further assessed. A detailed re-analysis of petroleum wells, in light of these new analyses, needs to be undertaken and the results tied into the seismic.

# TIME AND FACIES DIAGRAMS

# Time Slice Correlation

Only Cainozoic to latest Jurassic sediments have been penetrated in the wells studied. However, horizons representing sediments

possibly as old as latest Triassic, occur on seismic data. The Permian (TS P6-late P4) and Triassic (late TS T1) aged samples recovered in the Perth Canyon indicate the presence of an older, more typical onshore Perth Basin section beneath the Jurassic.

The oldest section intersected in the wells studied is of Tithonian age (TS J9/J10). Over 1,000 metres of strata of this age are preserved in Gage Roads-1 with much greater thicknesses possible. No finer subdivision of the Tithonian is possible due to a lack of dinoflagellates.

The K1 aged section is very thick, not being fully penetrated in any well. Seismic shows that this section thickens further to the west (5,000 metres thick on Plate 2) despite partial truncation by the mid Valanginian unconformity in this direction. The original thickness would have been in excess of 6,000 metres. Peel-1 displays an apparent full section of TS K1 but intensive faulting at the well has resulted in an estimated 50% of the stratigraphic column of this age, being faulted out. Sequence stratigraphic analysis has enabled a four fold subdivision of this very thick, prospective unit (see SEQUENCE ANALYSIS).

The post unconformity section (TS K2 to K5) is most fully represented in the southern Rottnest Trough at Warnbro-1 (see Section F-D-G & correlation diagrams, Plates 1 & 2). In the north of the trough a much thicker TS K2 section occurs at the expense of the younger units (see Section A-B & correlation diagrams, Plates 1 & 2).

The Late Cretaceous (TS K8-K11) section has poor age control and has restricted distribution in the study area. This is due to early Tertiary erosion by an early development of the Perth Canyon (Playford et al., 1976). The Czl section is limited in extent and represents a depositional phase during the channel development (Playford et al., 1976). Strata of TS Cz4 age are interpreted to blanket the area.

The whole Cainozoic also has poor age control.

# Time Space

The high rate of deposition (up to 1,000 metres /my) has resulted in most of the sedimentary section (Late Jurassic to Early Cretaceous) being represented by a narrow time band. This sequence is therefore very detailed on this diagram. The angular mid Valanginian unconformity is shown to be associated with a short lived tectonic event. The maximum hiatus associated with this unconformity is 10 my (at Quinns Rock-1) and the smallest hiatus is less than one million years (at Mullaloo-1).

Other regional hiatuses occur and span the Albian (K6-K8); Maastrichtian to Paleocene (TS K11-Cz1) and Eocene to Oligocene (TS Cz2-Cz3). A post Late Miocene to Pliocene (TS Cz5-Cz6) break is also presumed.

# Time Slice Facies

Tithonian (TS J9/10) fluvio-lacustrine sedimentation gave way to widespread marine sedimentation at the beginning of the Berriasian (basal TS K1). This was followed by very rapid fluvio-lacustrine and paralic to lacustrine sedimentation which continued until the end of TS K1. The thick paralic to lacustrine unit occurs in the middle of the TS K1 aged sequence.

Extensive structuring accompanied by a short hiatus and a major regression occurred during the mid Valanginian, at the TS K1/K2 boundary. Paralic sedimentation began in the Late Valanginian ( $\underline{G}$ .  $\underline{\text{mutabilis}}$  zone of Backhouse, 1988) with coalescing fans forming in palaeo-valleys adjacent to high areas. This represents the onset of a general transgression which saw widespread restricted marine shale deposition follow. The latest TS K2 ( $\underline{A}$ .  $\underline{\text{alata}}$  zone) is represented by a regressive sequence of paralic, marine and fluvio-lacustrine units. Open marine conditions followed and persisted until at least TS K5.

Late Cretaceous marine clastic sediments were deposited on an unconformity surface and are restricted to the south due to erosion associated with later channelling. The channel facies is represented in Quinns's Rock-1 and Warnbro-1 and consists of a marine sandstone. Widespread platform carbonate deposition occurred during Cz4. This is dolomitised where intersected. Younger marine carbonates (TS Cz7) are recorded in the area but have not been confirmed in the wells studied.

# SEQUENCE ANALYSIS AND EUSTATIC SIGNATURE

# PRE MID VALANGINIAN UNCONFORMITY SEQUENCE

The lack of detailed palaeontological age subdivisions in the rapidly deposited TS K1 sequence has been overcome through the use of seismic sequence analysis techniques (Vail et al., in prep; Vail, 1987; Van Wagoner et al., 1987; Shell, 1987).

The sea level curves of Haq et al. (1987) were amended by Partridge and Helby (Haq et al., 1987) to correlate with Australian micropalaeontological schemes. The sequence analysis and the following discussion are based on their edited chart for the Cretaceous.

The major sequence boundaries (unconformities) in this sequence are as follows:

# Berriasian (near base TS K1)

The lower major sequence boundary occurs towards the base of the thick TS K1 sequence (Line V82A-51, Plates 3,4). It is expressed by eastward truncation of underlying units and by eastward onlap and roughly coincides with the base of the Carnac Member. This is correlated with the "128.5" major sequence boundary of Haq et al.(1987)(top of  $\underline{\text{K.}}$  Wisemaniae of Helby et al. (1987)).

# Approximate base Valanginian (near top TS K1)

This is a major unconformity identified to the west of Roe-1 on Line V82A-51 (Plates 3,4). It is limited in extent due to truncation by the mid Valanginian unconformity and is expressed by substantial eastward onlap and by minor eastward truncation of underlying units. This is correlated with the "126" major sequence boundary of Haq et al.(1987)(top of  $\underline{D}$ . lobispinosum of Helby et al. (1987)).

# Mid Valanginian (top TS K1)

This is the major mid Valanginian unconformity which coincides with the timing of major faulting in the area. It is expressed by major truncation and by major onlap. This coincides with the "123.5" major sequence boundary recently identified by Vail (pers. comm with M. Ross - May, 1990) (top of E. torynum of Helby et al. (1987)).

There are two marine incursions in the TS K1 sequence also. According to Vail et al. (in prep) these represent maximum flooding or inundation surfaces.

# Base Berriasian (base of TS K1)

The Otorowiri Member is a widespread thin marine shale unit, occurring at the Jurassic/Cretaceous boundary and clearly identified on seismic and in wells. On seismic it is a major seismic reflector and displays minor eastward thinning but with minor localised truncation of underlying units (Line V82A-51, Plates 3,4). This coincides with the

" 131" condensed sequence, or maximum flooding surface of Haq et al.(1987)(top of lower <u>P. Iehiense</u> of Helby et al. (1987)) although no downlap is recognised.

# Intra Berriasian (mid TS K1)

The younger marine incursion is evident in the west in the Bathurst Syncline, at the base of the Carnac Member in the middle of TS K1. The base of this transgression coincides with the sequence boundary near the base of the TS K1 The top of the transgressive unit (the maximum flooding surface) appears to coincide with near the top of the Carnac Member, beneath a westward progading fluvial sand sequence, expressed by downlap to the west (Line V82A-51, Plates 3,4). According to Vail et al. (in prep.) the base of such a basinward progradation indicates the maximum The marine transgression is therefore flooding surface. represented by virtually the whole Carnac Member, which is estimated to be 500-1000 metres thick, and according to Vail et al. (in prep.), the maximum flooding surface would be the top of this sequence (a paralic depositional environment is possible for the whole of the Carnac Member). This is interpreted to tie to the "127.5" condensed section of Haq et al (1987) (top of C. Delicata of Helby et al. (1987)). There is therefore no condensed sequence here but a maximum flooding surface, indicating a basin margin location and reflecting the high rate of sedimentation.

# POST MID VALANGINIAN UNCONFORMITY SEQUENCE

For the Early Cretaceous post unconformity sequence Backhouse (1988) constructed a plot of the percentage of marine dinoflagellates relative to the percentage of non marine miospores, resulting in a consistent "inundation curve" for four of the wells he studied in the area. This tied conclusively with the curve constructed by Wiseman & Williams (Backhouse, 1988) for DSDP site 263 offshore Carnarvon Basin. Backhouse concluded that post unconformity deposition was controlled by eustacy.

On seismic data, three major sequence boundaries occur in the post-unconformity section (Plates 3, 4, 5, 6).

# G. mutabilis

The top of the <u>G. mutabilis</u> zone correlates with a sequence boundary on seismic. This is expressed as a strong seismic horizon with overlying events onlapping on the flanks of highs and downlapping in the troughs with minor truncation of underlying events (see eastern Line V82A-51, Plate 3). This is correlated with the "121.5" sequence boundary of Haq et al.(1987)(top of <u>S. Areolata</u> of Helby et al. (1987)).

# P. lowryi

The top of the <u>P. lowryi</u> zone occurs up to two cycles above a sequence boundary which is expressed by onlap of overlying horizons (including top <u>P. lowryi</u>) onto high

blocks and truncation of underlying events, especially over structural highs. This is most clearly illustrated on the western end of the reprocessed and migrated version of V82A-35 (not included), between Charlotte-1 and Quinns Rock-1. This is correlated with the "118.5" sequence boundary of Haq et al.(1987)(top of P. Burgerii of Helby et al. (1987)).

Early Cretaceous / Late Cretaceous unconformity
This major sequence boundary is expressed as the base of channelling (eastern Line V82A-51, Plate 3), a downlap surface and a truncating surface (central Line V82A-67, see Plate 5). Over much of the area studied the Late Cretaceous is not preserved so the unconformity may be due to Tertiary events. The channelling is most likely related to the formation of the Perth Canyon.

The post unconformity sequence also displays a substantial prograding sequence. To the north of Quinns Rock-1, on Line V82A-38 (not included) it is expressed as a southward prograding complex occurring between the <u>G. mutabilis</u> and <u>P. lowryi</u> sequence boundaries. Here the toplap to downlap interval is 200 to 260 msec (TWT) giving a water depth of 300-400 metres at the time of deposition. Also, changes in level of the top lap surface indicate periodic drops in water level of up to 50 metres. In the south, on Line V82A-67 (see Plates 2, 5 & 6) the prograding is westwards and is much thinner but it covers a greater time span, from the <u>G. mutabilis</u> sequence boundary up to at least the top of the <u>B. jaegeri</u> zone (mid TS K3). This southward and westward prograding explains the increased shale percentage and the reduced thickness of the TS K2-K3 aged sequence to the south.

# **STRUCTURE**

## PRE VALANGINIAN

Faulting associated with the mid Valanginian unconformity heavily overprints pre-existing structure, making identification and analysis difficult. The sedimentary thickness of units older than TS K1, is interpreted to be preserved across faults indicating a general lack of pre Valanginian faulting.

The pre Valanginian sedimentary sequences thicken to the west on seismic (see Line V82A-51, Plates 3 & 4) indicating active structural downwarp in that region during deposition. This can only be surmised for TS J9/10 and TS K1 as older strata have not been intersected here (apart from the anomalous Permo-Triassic strata recovered).

The presence of the Triassic and Permian strata on the flanks of the Perth Canyon indicate the presence of a high block during the Jurassic to Cretaceous or the occurrence of a major uplift during the Valanginian or both. This would have been expressed by either the erosion of the younger section over the high or the onlap of the younger section around the high. Current seismic data do not allow this to be assessed. The thickness of the Jurassic and earliest Cretaceous is 5,000-10,000 metres in this vicinity, indicating the magnitude of such a high or the scale of such an uplift.

# VALANGINIAN UNCONFORMITIES

The Time Space diagram shows the hiatus associated with the mid Valanginian unconformity to be least at Mullaloo-1. Here the  $\underline{G}$ .  $\underline{\text{mutabilis}}$  dinoflagellate zone of basal TS K2 age extends down to beneath the angular unconformity, giving a maximum interpreted time hiatus of 1 my. Elsewhere, erosion followed by gradual onlap resulted in a hiatus of up to 10 million years (Quinns Rock-1).

The faulting began during middle TS K1 time (middle TS K1 sequence boundary) as revealed by structuring and onlap on seismic (Line V82A-23 - not included). Intensity increased with an angular unconformity developing during late TS K1 time (late TS K1 sequence boundary) as shown on line V82A-51 to the west of Roe-1 (see Plates 3, 4). The rapid uplift of the western margin of the Rottnest Trough and the associated down faulting of the Rottnest Trough is implied by this unconformity. This unconformity has not been identified in the highly faulted Rottnest Trough due to the complex faulting and the poor seismic data quality. The main mid Valanginian unconformity followed.

Backhouse (1988) discusses the presence of extensive pre Cretaceous palynological contamination of the TS K1 section. This is indicative of extensive reworking of older, adjacent Perth Basin sediments in the area and highlights the localised nature of the downwarping and down faulting at this time. The

contamination occurs throughout the TS K1 sequence but is noticeably absent before and after. The onset of the structuring which culminated in the mid Valanginian unconformity is therefore likely to have occurred at the beginning of TS K1 with the deposition of the Otorowiri Member shales.

The main unconformity is significant because it represents the climax and the cessation of the main structuring. The sedimentation which followed (during early K2) was much slower, roughly 50-100 m/my, as opposed to 500-1,000 m/my for TS K1. The age of the mid Valanginian unconformity corresponds with the age of the oldest oceanic crust in the Perth Abyssal Plain (M10 magnetic anomaly.

# POST MID VALANGINIAN

Structuring continued to occur during the Early Cretaceous, after the main mid Valanginian unconformity. This was restricted to the reactivation of major faults, especially those bounding the Rottnest Trough and to continued subsidence over the Rottnest Trough. This mainly occurred as two events, one at the end of TS K2 and the other during the Albian (K5-K8) hiatus. This is based on the height to which the faults cut, the differential amount of throw on individual faults and isopaching to determine the timing of downwarping. The sequence analysis identified two lesser structural events within TS K2. One at the top of the G. mutabilis zone and the other just below the top of the P. lowryi zone.

Younger structure is mainly Tertiary in age, associated with gentle westward downwarp of the continental shelf and progradation of the continental rise.

# HYDROCARBON PROSPECTIVITY

#### RESERVOIR

The primary reservoir horizons are Late Jurassic and Early Cretaceous sandstones that were deposited in fluvio-lacustrine and paralic conditions. The Late Jurassic sandstones are over 1,000 metes thick, are widespread and have average porosities from 5 to 28% with permeabilities ranging from 0 to 1300 md. The Early Cretaceous (TS K1) sandstones are also widespread, are thicker than 1,000 metres and have average porosities from 15% to 30% and permeabilities ranging from 350 to 5600 md. The post unconformity sandstones (early TS K2) are thinner than 200 metres, are localised to post unconformity depressions and have average porosities of 19% to 25%, with permeabilities ranging from 9 to 1300 md. The later Early Cretaceous, Late Cretaceous and Early Tertiary sandstones (late TS K2-Cz2) have porosities greater than 35% and permeabilities in excess of 150 md (where consolidated) but with unconsolidated sands being common. TS Cz4 carbonates are dolomitised and exhibit porosities as high as 50% and permeabilities as high as 7000 md.

## SEAL

Regional seals occur at the base of the Cretaceous (base of TS K1)(Otorowiri Member), in the middle of TS K1 (Carnac Member), and in TS K2 (South Perth Shale). The Late Cretaceous exhibits localised sealing qualities but is generally sandy and lithologically unpredictable. The Tertiary is highly permeable at all localities.

The Otorowiri Member which is approximately 50 metres thick would be breached by most faults. The Carnac Member is up to 1000 metres thick and would form an effective seal across most faults. The South Perth Shale has variable thickness and becomes more sandy to the north and over the Roe High to the west, grading into the Leederville Sandstone.

# SOURCE AND MATURATION

Marshall et al. (1989) discuss the source and maturation of the Vlaming Sub-Basin and provide a compilation of geochemical data (from Burns ,1982 and Surdan, 1982) from the offshore Vlaming Sub-Basin which includes TOC and Rock Eval Pyrolysis analyses on 232 samples from the ten wells drilled prior to 1982. The following discussion is based on this data compilation and on these reports.

Relatively low geothermal gradients result in source rocks being immature for oil generation shallower than approximately 2500 metres (approximate level where a modelled vitrinite reflectance of 0.65% is reached (Marshall et al.,1989)). This coincides with the lower South Perth Shale (TS K2) in the Rottnest Trough, the top to middle of the Carnac Member (TS K2) shale unit in the Bathurst Syncline, the top of the Jurassic (TS J9/10) on the Roe

high and intra Jurassic units on the eastern terrace (see structural elements map - Plate 2). Modelled vitrinite reflectances give a uniform gradient with depth, implying a very recent maturation. More vitrinite reflectance data from these areas, especially from the structural high areas is required to ascertain whether maturation occurred before or after the mid Valanginian, or more recently.

The South Perth Shale (TS K2) appears to be a moderate to rich mainly gas prone source rock but with some oil potential. The thin shaly units within Parmelia Formation (TS K1) sandstone section form a moderate to rich mixed oil and gas source. The thick shales of the Carnac Member (TS K1) and the Otorowiri Member (TS K1) generally form a marginal to moderate gas source with some oil potential but with some rich oil prone zones. Similarly the Yarragadee Formation (TS J9/10) sandstone section contains thin shaly units which constitute a moderate to good mixed gas and oil source.

The Yarragadee Formation (TS J9/10) and the Parmelia Formation (TS K1) contain scattered coals with up to 30% exinite and 50% inertinite (Kanstler and Cook, 1979) and must therefore be regarded as excellent oil prone source rocks. The high wax paraffinic oil recovered from the Parmelia Formation in Gage Roads-1 is consistent with a Parmelia Formation (TS K1) or Yarragadee Formation (TS J9/10) source.

Earlier Jurassic (TS J1-J6?) source rocks are likely beneath the thick Yarragadee Formation (J7?-J10) but their characteristics can only be guessed at.

As oil discoveries and oil shows have been identified in the Vlaming Sub-Basin rather than gas discoveries, future discoveries are likely to be oil or oil and gas, rather than gas.

# HYDROCARBON INDICATIONS

# Gage Roads-1

Parmelia Formation (earliest TS K1)(1743-1767 metres) directly beneath the Carnac Member:

Flowed oil at a projected rate of 350 Barrels per day on production test. The gross oil column is interpreted to be 50 metres thick on the basis of electric logs and gas readings. The logs indicate a high water saturation in shaly sandstone. Core analysis reveals porosities of 25-30% and permeabilities generally ranging from 100-1000 md.

Yarragadee Formation (2615-2652 metres) directly beneath the Otorowiri Member shale (latest TS J9/10):

Gave strong fluorescence with cut and large high homologue gas readings. Wireline logs indicate a gross hydrocarbon column of 35 metres with high porosity and permeability and low water saturations but core revealed low porosity and permeability so no test was performed. Considering the excellent SP, and Induction response it is believed the

core analysis may have been misleading leaving a potentially productive gas/oil pool untested. The calliper shows no mud cake build up, supporting the low permeability interpretation. Also, the sandstone is immature (less than 40% quartz grains) with considerable lithic and clay components so the simple, fresh water/ gel drilling mud may have destabilised the clay chemistry (the formation water is saline) resulting in clogged pore throats. The reservoir quality of the sandstone improves substantially beneath the hydrocarbon/ water contact. This gives encouragement for any up dip extension of this pool.

Gage Roads-1 was drilled to evaluate a fault bounded structural closure. It proved that sub-unconformity traps of the Parmelia Formation and fault bounded traps of the Yarragadee Formation can hold significant volumes of hydrocarbons. It also identified a new exploration target, the Gage Sandstone Member.

# <u>Gage Roads-2</u>

- Gage Sandstone Member (1350-1375 metres sub sea):
  Strong log anomaly over this zone, good fluorescence and cut with Formation Interval Tests (FITs) recovering oil and indicating excellent permeability.
- Parmelia Formation (1764-1811 metres sub sea) directly beneath the Carnac Member:
  Fluorescence and cut but no log anomaly, indicating a low hydrocarbon saturation. An RFT at 1772 metres sub sea recovered filtrate but no formation fluid.
- The two Gage Roads wells identify two proven oil pools and one possible oil pool:
- 1. The sub Carnac pool with a maximum vertical closure of approximately 300 metres above the interpreted oil water contact (1765 metres sub sea in Gage Roads-1 and supported by Gage Roads 2)
  - This has potential reserves of 250 MMSTBO using 200 bbls/acreft, width of 2 km (measured from seismic section), length of 5 km and height of 300 metres with a triangular cross-section.
- 2. The Gage Sandstone Member pool, an up dip pinch out wedge
  - This gives potential reserves of 16 MMSTBO using 200 bbls/acreft, width of 1 km (approximately half of the distance between the two wells), length of 5 km and average thickness of 20 metres.
- 3. The sub-Otorowiri pool with a maximum vertical closure of approximately 300 metres above the interpreted oil water contact (2630 metres sub sea in Gage Roads-1)

This has potential reserves of 250 MMSTBO using 200 bbls/acreft, width of 2 km (measured from seismic section), length of 5 km and height of 300 metres. This pool is likely to be smaller due to poor reservoir development.

This interpretation is based on a zone of poor seismic data quality.

# Warnbro-1

Fluorescence, cut and oil staining were observed throughout the Early Cretaceous (Parmelia Formation of TS K1 age) and Late Jurassic sandstones (Yarragadee Formation of TS J9/10 age), beneath the Valanginian unconformity.

#### Peel-1

Fluorescence and cut were observed in the Late Jurassic sandstone section (Yarragadee Formation) beneath the Otorowiri Member seal (earliest TS K1).

# WELL ASSESSMENT

Of the wells used in this study only two: Gage Roads-1 &-2; tested valid structural or stratigraphic traps and both these wells intersected significant oil pools. These were not considered commercial at the time of discovery due to the low flow rate, water cut, the thin pay encountered in the wells, the low oil price and the high cost of exploration at the time.

Minder Reef-1, Roe-1 and Warnbro-1 encountered sandstone rather than the prognosed sealing shale above the mid Valanginian unconformity, resulting in no valid trap. In the case of Warnbro-1 the post unconformity sandstone (Gage Sandstone Member) is covered by a good seal but a southerly plunging nose occurs at this level, negating closure as shown from modern data.

The Quinns Rock-1 well is located on a fault block. Seal is breached as the sealing South Perth Shale is faulted out. This means that the bounding fault juxtaposes the target sub-unconformity sandstones (Parmelia Formation of TS K1 age) against post unconformity sandstones (Leederville Sandstone of TS K2-K3 age) on the down thrown side.

Mullaloo-1 tested a valid structural trap but the target Gage Sandstone Member shaled out locally, resulting in no closure at the top of porosity.

Peel-1 was drilled on a highly faulted structure, not the prognosed fault bounded anticline. Also, no valid fault block trap was intersected.

Charlotte-1 was drilled in a poor seismic data area on what appears to be a southerly plunging structure, possibly a fault block.

# CONCLUSION

This study has revealed considerable petroleum exploration potential in the Vlaming Sub-Basin. The presence of three regional sealing units, two very thick sandstone reservoir units and complex structure provide numerous trapping mechanisms for giant hydrocarbon pools. The two valid traps which have been tested contain oil and geochemical studies indicate the presence of mature oil and gas source rocks.

These new findings are due to technological advances in seismic acquisition and processing, seismic stratigraphy and in the much finer micropalaeontological subdivision of the sedimentary section. These allowed the <u>B. eneabbaensis</u> zone of Backhouse (1978) & Helby et al. (1987), which spans up to 6,000 metres and 25 my, to be subdivided into ten time zones. This sequence was previously unable to be subdivided except by lithology. All the exploration in this area was carried out prior to the palaeontological subdivision of Backhouse (1988) and all but two wells were sited using seismic data which denied adequate recognition of either the complex structural geology or the complex sequence stratigraphy.

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# VLAMING SUB-BASIN STRUCTURAL CROSS-SECTION ROBERT SEGGIE LOCATION MAP SCALE 1:100000 Mid-Valanginian Unconformity (Palaeogeographic Maps Project - Phase 2) Phanerozoic History of Australia Project 175 A

# VLAMING SUB-BASIN BIOSTRATIGRAPHY ROBERT SEGGIE

LOCATION MAP

Bathymetry contours in metres

After Marshell et. al. 1989.

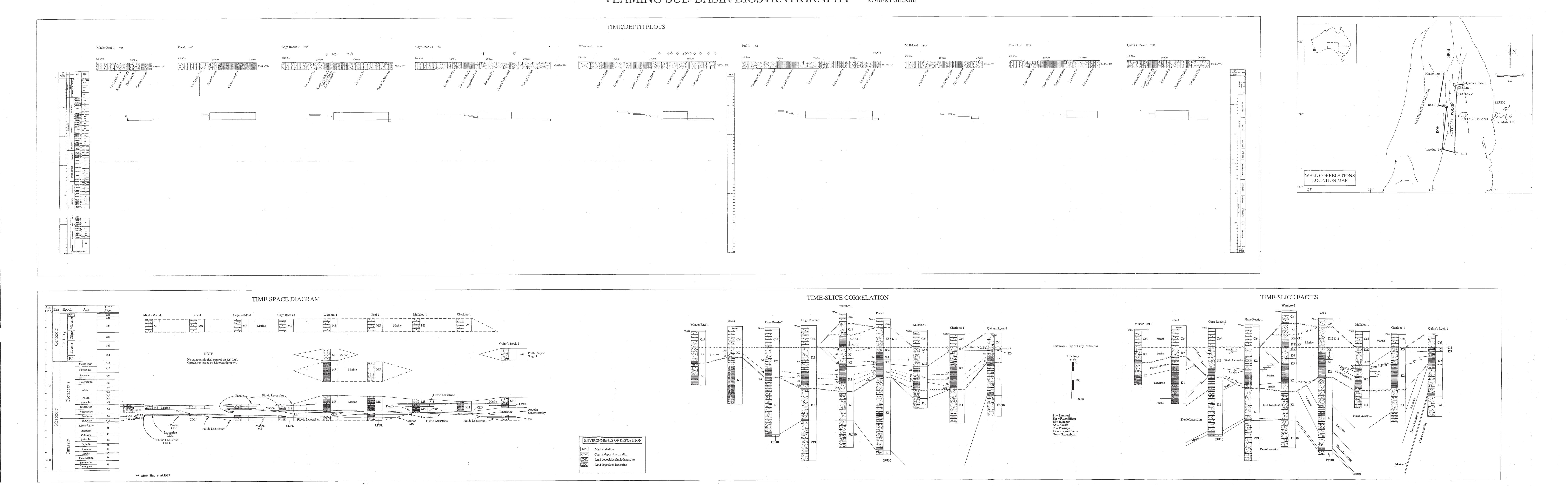
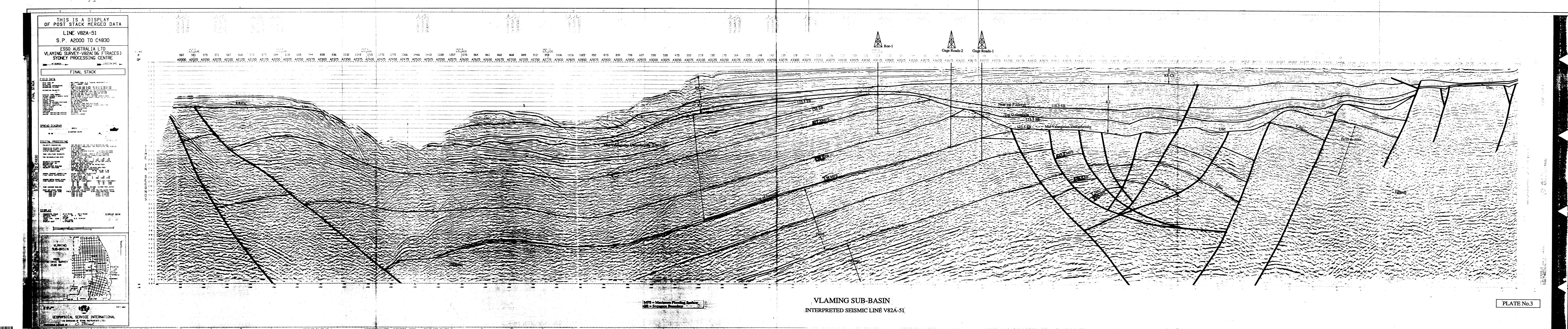
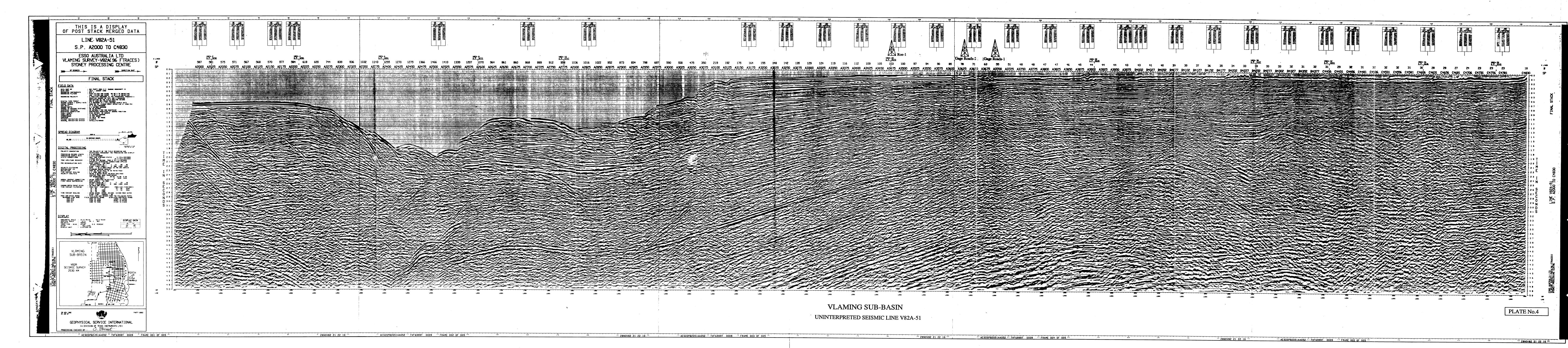


PLATE No.2







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