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Vulcan Tertiary Tie (VTT) Basin Study

Vulcan Sub-basin, Timor Sea Northwestern Australia

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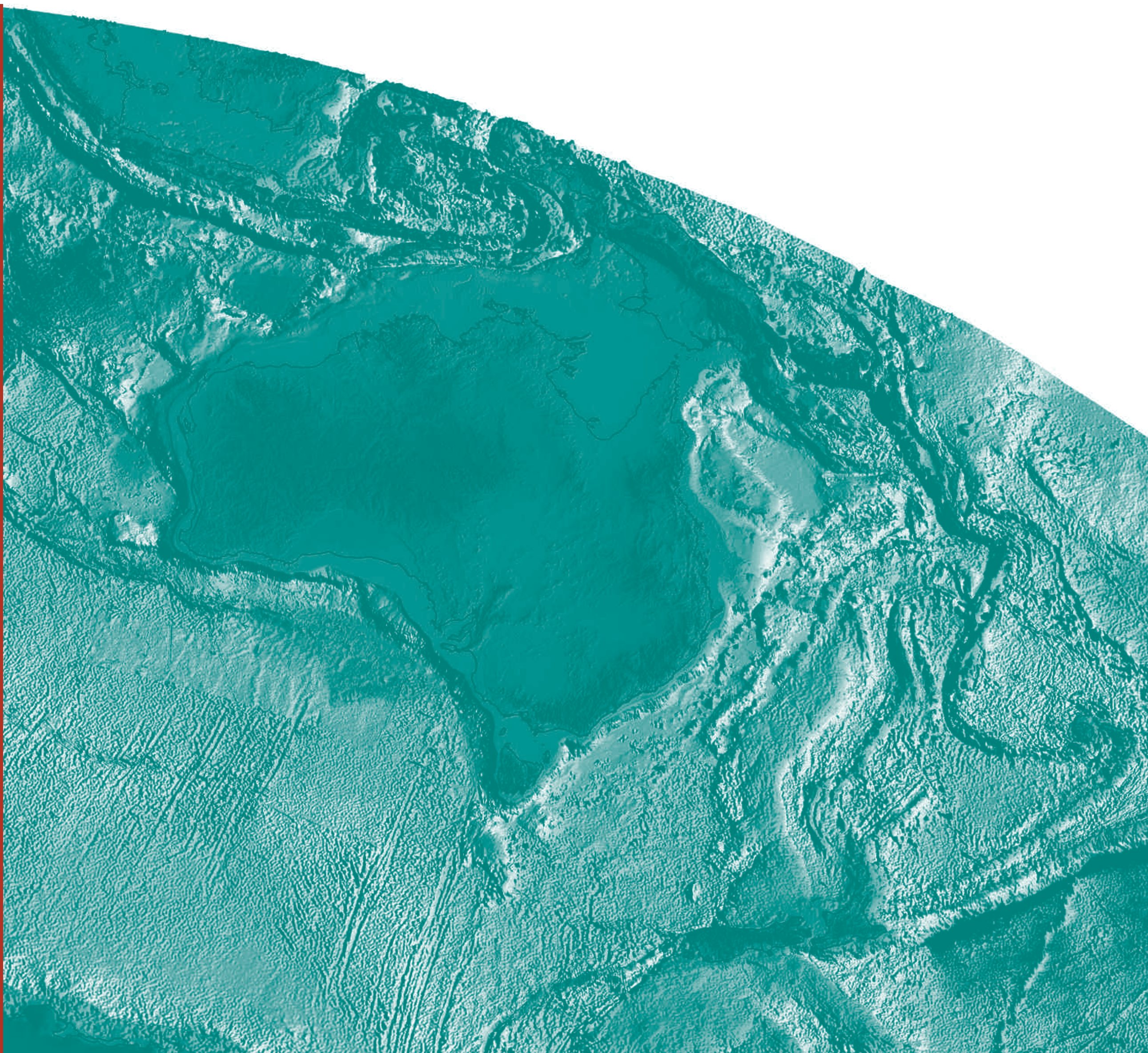

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Summary

As part of its ongoing investigations into the basin evolution and petroleum systems of the Australian continental margin, the Australian Geological Survey Organisation (AGSO) carried out two high resolution seismic acquisition programs (the VTT and VTX surveys) in the Vulcan Sub-basin (and surrounds), Timor Sea. In this report, the 5000 km of VTT and VTX seismic data have been interpreted and integrated with well and other data to provide a regional structural and sequence stratigraphic framework for this highly prospective, but geologically complex, region. It is hoped that this study will both provide AGSO with a sound interpretative framework for its ongoing regional studies, as well as providing an important data base for companies exploring in this area.

The study had the specific aim of providing structural maps and a sequence-stratigraphic framework for the post-Callovian to Recent section in the Vulcan Sub-basin; included in the current work are time-structure and time-thickness maps of pre-selected horizons and the resultant sequence-stratigraphic analyses. Products and findings within this report include:

- 10 time-structure and 7 time-thickness maps have been generated from AGSO's VTT/VTX seismic data in the Timor Sea, forming the basis for a sequence-stratigraphic study of the Permian-Recent section.

- Confined structural entities such as the Vulcan and Swan Grabens can clearly be seen on structure maps especially at pre-Valanginian levels. In this instance, horst trends containing hydrocarbon fields such as Jabiru, and Challis, clearly form peri-rift shoulder re-entrants into source kitchens. Late Cretaceous and younger horizons demonstrate the overall offlap nature of the post-rift succession and development of the Cartier Trough during the Tertiary.

- Sequence-stratigraphic analyses has identified 5 mega-sequences, punctuated by several sequence boundaries and flooding episodes, indicating regressive and transgressive events of varying magnitude, related to progressive rifting and breakup of the northwest continental margin of Australia.

  These mega-sequences are:

  1. Triassic - Mid Jurassic thermal subsidence aggradation (mainly highstand)
  2. Late Jurassic-Early Cretaceous late syn-rift to post-rift retrogradation (highstand & lowstand)
  3. Valanginian-Barremian post-rift flooding (mainly transgressive & highstand)
  4. Late Cretaceous post-rift regression (mainly highstand)
  5. Tertiary aggradation & progradation. (highstand & lowstand)

- Biostratigraphic well control calibrated to seismic has allowed detailed systems tract analysis of the highly prospective Late Jurassic-Early Cretaceous depositional sequence, with the development of prolific Oxfordian-Kimmeridgian restricted-marine shale in narrow grabens and interrelated fan-delta and submarine fan sand reservoirs.

- In particular, the interplay between syn-rift extension and relative sea level during Late Jurassic time has led to several cycles of fan-delta development along the peri-rift hanging wall terraces (ie Montara Terrace) and corollary submarine fan sand debouchment to deep graben axes.

- Submarine fan sands in compaction -drape or structural traps in the Oxfordian and Tithonian sequence represent the most outstanding untested play in the basin. This is especially true of the Oxfordian basin floor sand cycles where capped by thick Kimmeridgian shale which comprises the main oil-prone source sequence, but also provides critical regional seal. In contrast, Tithonian basin floor sands may be overlapped by prograding lowstand wedge thief zones (leaky seals), unless they occur in detached basinal settings.

- Oxfordian source rocks in the Swan Graben probably generated oil in the mid to Late Cretaceous, whereas those in the Skua Trough probably only generated in the Miocene.

- Traps in the Timor Sea fall into three categories: Low, Medium and High Integrity (LIT, MIT, HIT).

- Leaky traps induce the formation of hydrocarbon-related diagenetic zones (HRDZs) above themselves.

- The size and velocity characteristics of the HRDZs can indicate whether a trap is an LIT, MIT or HIT.

- MITs are the most prospective for oil; HITs are typically gas flushed.

- Mio-Pliocene migration through LITs and MITs produced anomalous thermal effects.

- HITs are probably most representative of the thermal histories of the source rock depocentres.

- Sniffer and ALF data are useful in evaluating the likely projectivity of traps in the southern Timor Sea.

Introduction

Objectives & scope of study

This work forms an integral part of continuing studies by the Australian Geological Survey Organisation (AGSO) on the basin evolution and petroleum systems of the North-West Shelf as a whole and the Vulcan Sub-basin in particular. It has the specific aim of providing structural maps and a sequence-stratigraphic framework for the post-Callovian to Recent section in the Vulcan Sub-basin, using AGSO's recently acquired (1995) VTT/VTX regional seismic data (Figs 1 & 2).

Following this introductory section, the report is divided into two sections. Section 1, which was produced almost entirely by Oil & Gas Consultants Pty Ltd, focuses primarily on the development of a structural and sequence stratigraphic framework for the Vulcan Sub-basin using the VTT/VTX data set. Included in this section are time-structure and time-thickness maps of pre-selected horizons and the resultant sequence-stratigraphic analyses. Section 2 was produced exclusively by AGSO as a appendum to Section 1, and includes some new research into the evaluation of fluid flow histories and trap integrity in the Timor Sea, including recently acquired geochemical sniffer and Airborne Laser Fluorescence (ALF) data from the southern Vulcan Sub-basin.

For ease of reading and brevity, this much of this report is presented in a series of concise paragraphs and key 'bullet' statements.

Much of the work has concentrated on mapping of time-structure and time-thickness maps for regional maturation studies and migration fairway trends, along with generation of gross depositional environment maps for reservoir distribution. It is not the intention of this report to unravel the complexities of the tectonic evolution and hydrocarbon generation in the area, but to provide instead, a basic interpretational framework for work of this nature, currently in progress by research institutes such as AGSO. On the other hand, on the basis of sequence-stratigraphy, this study can be also used as a stand-alone document for exploration companies to high-grade specific areas for reservoir development, which, when used in conjunction with maturation studies, will assist in identifying 'sweet spots' for hydrocarbon entrapment.

In particular, this approach, when integrated with the work of O'Brien & Woods (1995) and O'Brien et al (1996a), which uses the size and velocity characteristics of hydrocarbon-related diagenetic zones (HRDZs) within the Eocene Grebe Formation sands to identify underlying, valid, hydrocarbon-charged structural traps, will hopefully reduce exploration risk in the area, which to date has been extremely high. Indeed, some of the richest source rocks of Late Jurassic age in Australia occur in the Vulcan Sub-basin, and the large number of breached traps, along with current production at Jabiru, Challis and Skua, testify to the enormous hydrocarbon charge potential of the region.

Database

The following data were used to provide the interpretations presented in this report:

- 5000 km VTT/VTX regional seismic data

- 33 well synthetics.
- 79 well composite logs and associated well completion reports.
- 49 biostratigraphic well control (source: Helby & Associates)

This report provides all interpretational maps and sequence-stratigraphic work in hard copy, with the entire data base and interpretation, including synthetics also available in digital format. Tables 1, 2, & 3 list the well data base, interpretational tops, and colours for selected horizons mapped in the study.

It should be borne in mind that interpretations presented here are essentially regional in nature, being entirely based on AGSO's VTT/VTX seismic data, correlated back to wells where appropriate. As such, the minimum grid layout for the VTT/VTX seismic grid is around 5-10 km on dip lines with strike line spacing being around 20 km (Fig 2). It is hoped that regional structural maps and sequence-stratigraphic interpretations, when used in conjunction with maturation modelling, will allow operators to high-grade key areas to proceed with prospect/lead mapping.

Data quality of the VTT/VTX seismic is fair to good and many wells have been tied back by dip-line correlations affording excellent control in this direction. As virtually all strike lines tended to also cross through well locations, which for the most part have been drilled on structural highs, considerable difficulty was experienced in making strike-line correlations, especially since the Vulcan Sub-basin is an intensely faulted terrain with several sub-basins and terraces.

In this regard, it should be remembered that strike-line and regional interpretations far away from dip-line control have been made in good faith, since it is beyond the workscope of the project to use open-file infill seismic of extremely variable quality (some of it in 3D). Indeed, it is recommended that should more regional seismic be acquired, strike-lines be shot along basinal axes in areas of minimal faulting, since well ties are sufficiently calibrated by existing dip lines.

Geographical location

The Timor Sea is located on the NW Australian margin between the Kimberley Block and the island of Timor, from which Australia is separated by the Timor Trench obduction zone (Fig 3). The general area has undergone a complex structural history, resulting in several Palaeozoic and Mesozoic sub-basins, terraces and platforms (O'Brien & Woods 1995).

Inshore, the Timor Sea is dominated by the NW-trending Petrel Sub-basin which is located in the Joseph Bonaparte Gulf. As described by O'Brien et al (1993), this basin developed during early Devonian rifting and contains salt diapirs and withdrawal features which extend as far northwest as the Vulcan Sub-basin. The latter is a Late Permian to Jurassic age extensional system which extends NE-SW, orthogonally overprinting earlier NW trends. The Vulcan Sub-basin, which is the subject of this report, has been sub-divided into a number of smaller sub-basins and grabens, mainly of Jurassic age, which contain the prolific Late Jurassic hydrocarbon source rock (Vulcan Formation). Major intra-grabens are the Swan and Paqualin Grabens which die out north-eastwards beneath the younger (Miocene-Recent) Cartier Trough (Fig 4).

The Vulcan Sub-basin is flanked by Permo-Triassic platform areas - the Londonderry High and the Ashmore Platforms - to the southeast and northwest respectively. On the southeastern margin of the main Vulcan Sub-basin trough, the Montara Terrace separates the Swan Graben from the Londonderry Platform.

Exploration & Development History

Exploration in the Vulcan Sub-basin began in the 1960's with the drilling of Ashmore Reef-1 on the Ashmore Platform, by the Burmah Oil Company in 1967. The first oil discovery was achieved in 1974 at Puffin-2 which flowed at a rate of 4,608 BOPD from Late Cretaceous turbidite sands, perched on the southeastern peri-rift shoulder of Ashmore Platform. Unfortunately, despite good flow rates the Puffin Field was deemed sub-commercial with potential reserve of only some ~ 5 MMBO recoverable. It was not until after some 20 wells later in 1983, that the first commercial oil discovery was made at Jabiru-1, which flowed a stabilised 6,809 BOPD from syn-rift Mid-Jurassic Plover Formation (Fig 4) sands at a depth of 1,683m. The Jabiru Field is located within a prominent intra-terrace horst block on the northwestern flank of the Londonderry High.

The Vulcan Sub-basin became the focus of an extensive exploration effort by the international oil industry. The economic potential of the area was subsequently confirmed in 1984 with the discovery of the Challis Field, also productive from an intra-basinal horst trend. This field has some 50-60 MMBO of recoverable reserves, reservoired in Triassic sands. The innovation use of FPSO production systems allowed rapid development of the Jabiru and Challis Fields with enhanced economic returns due to extremely high flow rates and production characteristics. As Jabiru production indicated recoverable reserves in the order of 100 MMBO instead of the 15 MMBO which originally formed the basis for development, even further emphasis on exploration was placed in the area, resulting in aggressive bidding for acreage (ie: up to 6 wells in AC/P13 by WMC) in the late 1980's.

However, expectations for the discovery of additional major reserves tapered off into the early 1990's as the drilling of up to 100 exploration wells resulted in only 2 additional commercial discoveries, albeit small (Skua-1987 & Cassini-1988). Production from these fields including Jabiru and Challis peaked at 100,000 BOPD in 1991, declining to around 30,000 BOPD at the present day. During this time, several small non- to sub-commercial discoveries were made, notably at Talbot, Oliver, Montara, Bilyara, and Tahblik). As described by O'Brien et al (1996), many of these fields have complex charge history, with multiple phases of oil and gas entrapment and subsequent leakage depending on trap integrity.

This apparent lack of commercial success is due to two main factors - firstly, due to lack of seismic resolution and secondly, the aforementioned lack of understanding of trap integrity, especially related to timing of hydrocarbon generation and trap reactivation, which allowed several prior hydrocarbon pools to be breached.

Most of the seismic data base in the area has been recorded since 1983, following the discovery of the Jabiru Field. However, despite modern acquisition and processing technology, data quality over much of the basin remains only poor to fair within the commercially-attractive syn-rift (pre-Upper Cretaceous) section. This is due to the presence of thick Late Cretaceous-Tertiary carbonates causing seismic energy absorption and multiple aberrations in the deeper prospective section, seriously hampering prospect definition.

In addition, not only has the deeper prospective section been poorly defined on seismic, but structural patterns, especially at the prospect level are also severely obscured. Radically different interpretations of basin genesis and structural styles have resulted ranging from structural patterns primarily derived by wrench tectonics (Nelson 1989), extensional tectonics (Woods 1992) or a combination of both. Moreover, during the Miocene when the Australian plate collided with the Indonesian arc system, many structures were reactivated, extending deep bounding faults to the sea floor, breaching prior traps. Indeed, several dry wells were drilled on apparently bona-fide traps which turned out to be of Miocene-age inversion structures, post-dating hydrocarbon charge. During the late 1980's, with up to 3 drilling rigs working in the area at any one time, prospect drilling tended to be "rig-driven " without the benefit of an integrated model to explain the distribution of known fields, related breached traps and the reason why seemingly bona-fide, valid structures were dry.

During the early 1990's, as exploration slowed down and seismic resolution improved, key models were evolved which have gone a long way to understand trapping styles and general prospectivity of the area (see in particular the work of Woods, 1992 & O'Brien et al, 1996a).

More recently, coincidental with improved understanding of the basin, Woodside have made a large discovery in 1994 at Laminaria (Smith at al 1996) in the northern Vulcan Sub-basin, where the Cartier Trough is juxtaposed to the Sahul Trough at the northern tip of Londonderry High, causing industry attention to again be re-focussed on the area.

Summary Of Basin Evolution

As mentioned, it is not the intent of this study to provide a detailed tectonic treatise of the area, but rather offer the structural mapping project as the basis for further work. Nevertheless, a basic understanding of the structural history of the area is useful in order to allow the current sequence-stratigraphic interpretation to be placed in a tectonic framework.

Drawing on the work of O'Brien et al (1993; 1996a,b), the overall tectonic history is para-phrased as follows:

- **Proterozoic (1,800 Ma):** Kimberley Basin formation. Formation of NE and NW-trending conjugate fault sets.

- **Early Ordovician**: Extension with formation of broad sag basins.

- **Late Devonian-Early Carboniferous**: Development of NW-trending Petrel Sub-basin Rift System. Large displacement, upper crustal rift segments extend out from the Joseph Bonaparte Gulf. Outboard segments underpin what will become the Malita Graben and Vulcan Sub-basin. Large displacement fault provide conduit for later Siluro-Ordovician salt diapirism. Paqualin salt diapir probably located in a similar relative structural position to the Sandpiper diapir in the Petrel Sub-basin 'proper'.

- **Late Carboniferous-Early Permian**: Orthogonal overprinting of NW trends by NE trending Permian (and later Jurassic) rift systems as a prelude to breakup of Gondwanaland. These rift systems form part of the

Westralian Superbasin leading to proto-development of Vulcan Sub-basin and Malita Grabens as major entities..

- **Late Permian - Mid Triassic**: Thermal subsidence phase - little to no faulting.

- **Late Triassic-Early Jurassic**: Fitzroy Movement: minor north-south compression evident in intra-cratonic basins such as Petrel Sub-basin and Canning Basin. Formation of low amplitude arches and sags through Vulcan Sub-basin; uplift on flanks facilitates erosion of Triassic silici-clastics into structural and topographic lows.

- **Latest Callovian-Early Oxfordian**: Main breakup phase as evidenced by the initiation of seafloor spreading in the Argo Abyssal Plain (at ~155 Ma). Development of an array of extensional half-grabens such as the Paqualin & Swan Grabens, with restricted marine conditions favourable to source rock preservation (Lower Vulcan Formation).

- **Kimmeridgian-Early Cretaceous**: Regional uplift of platform areas with oblique reactivation of earlier extensional structures. Development of Jabiru, Challis & Skua horsts as prominent features.

- **Miocene-Recent**: Collision of Australian Plate with Indonesian arc system induces the development of the Timor Trough, and the associated down-warping of the Australian Plate. Dilatational reactivation of deeper fault systems at about 5 Ma produces producing ENE-EW, small displacement (<250 msecs) faults. Decreased seal integrity and numerous examples of trap breach or partial leaching. Reactivation ceases at ~3 Ma.

Despite the fact that this report deals with chronostratigraphic mapping principles, a general Permian to Recent stratigraphic column (Fig 4) is offered for ease of reference to prior lithostratigraphic studies of the area, which enables the overall sequence to be seen with respect to major tectonic events.

In essence, one of the most meaningful reflectors for petroleum exploration work in the basin is the near Top Permian limestone reflector, which frequently occurs as booming high-amplitude doublet across the entire basin. Since seismic character of much of the overlying Mesozoic succession is sometimes weak, the near Top Permian limestone indicates deep structural patterns that sets up the basin architecture for younger hard-to-map reflectors. The succeeding Triassic era saw a continuation of intra-cratonic sedimentation with deposition of the Mount Goodwin pro-delta marine shales, followed by fluvio-deltaics of the Sahul Formation, which in turn is overlain by Malita Formation red beds of Early Jurassic age. Syn-rift sedimentation continued into the Middle Jurassic with deposition of thick fluvio-deltaics of the Plover Formation in a northeast trending thermal sag basin.

The Mid-Callovian unconformity marks the beginning of late-stage rifting in the Vulcan Sub-basin as spreading began in the Argo Abyssal Plain to the east of the Ashmore Platform. Renewed tectonism and subsidence in the Oxfordian followed, forming deep local depocentres (ie: Swan & Paqualin Grabens) with over 1000 m of Oxfordian oil-prone shales laid down in these depressions. Oils recovered at Jabiru Field, for example, can be typed to these source rocks (Woods 1992). Further subsidence continued in these depocentres during the following Kimmeridgian, Tithonian to Berriasian periods, allowing over 500 m of basinal shales and submarine sands to be deposited.

The intra-Valanginian Unconformity marks the beginning of the post-rift subsidence phase, as pronounced transgression pushed the shoreline onto the craton, reaching a zenith by Cenomanian times, followed by a major offlap sequence of argillaceous shelf-slope deposits known as Bathurst Island Group, with various formational sub-units (ie Borde Formation etc). In contrast to the overall calcareous shale and marl-prone nature of most of the Bathurst Island Group throughout the Vulcan Sub-basin, several aggradational and progradational cycles of submarine sand turbidites derived from the Browse Basin margin to the south are found in the southern area. These are known as the Puffin Sands (reservoir at Puffin Field) and range in age from Campanian to Maasthrichtian and even early Paleocene.

Carbonates form the dominant lithology throughout the succeeding Tertiary era with argillaceous and arenaceous cycles associated with major lowstand conditions noted during the Eocene (Grebe Formation sands) and Late Miocene (Oliver Sands). It is worthy of note that no Oligocene sediments are known in the basin due to the result of pronounced glacio-eustatic lowstand at this time, with the Oliver Sands resting directly on Eocene carbonates. The lack of angular truncations suggest that it is not a major erosional event, despite the impending onset of major obduction in the Timor Trench, as the Australian plate collided with the Indonesian arc system.

SECTION 1: STRUCTURAL AND SEQUENCE STRATIGRAPHIC FRAMEWORK FOR THE VULCAN SUB-BASIN

Geophysical Mapping

Table 3 indicates 10 mapping horizons for which time-structure maps have been created at 1: 500,000 scale (also see enclosures 1-10). Although several more horizons could be identified throughout the area, the project workscope deemed that the ten horizons indicated were the most useful horizons to map, not only for structural configuration, but also for generation of time-thickness maps (enclosures 11-17). The latter are required to determine both sediment-distribution patterns and hydrocarbon-migration drainage cell fairways associated with peak periods of hydrocarbon expulsion.

The Near Top Permian limestone map (Enc 1) demonstrates deep-basin architecture, while the succeeding Mid-Callovian, Mid-Kimmeridgian, Mid-Tithonian time-structure maps (Encs 2,3, & 4) show the confines of the restricted syn-rift system between the Ashmore Platform and the Londonderry High (see also Figs 5 & 6). Structural re-entrants associated with plunging horst trends such as at Jabiru, Challis and Skua are clearly the loci for hydrocarbons migrating from the basinal areas. Intervening cols or saddles formed conduits for focussed clastic sediment input debouched from the platform areas into the depocentres as submarine fans.

With the return of widespread marine conditions throughout the post-rift Late Cretaceous to Tertiary sequences (Encs 5,6,7,8, & 9), the influence of elevated horst trends appear to become less and less, although relief at some levels will be related to Miocene fault rejuvenation. Even so, the Skua horst, for example can still be seen at the

Eocene level (Enc 7). Later structure maps, notable at the Oligocene and Miocene levels (Encs 8 & 9) demonstrate pronounced Mio-Pliocene age subsidence of the Cartier Trough.

Sequence Stratigraphy

Sequence stratigraphic concepts

Sequence stratigraphic concepts used in this study are based on the pragmatic application of the Valian model (Vail, 1976, Posamentier and Vail, 1988). Sequence stratigraphic surfaces, defined through the integration of seismic, wireline log and biostratigraphic data, have been used to subdivide sedimentary deposits in the Vulcan Graben. The recognition of these surfaces permits subdivision and correlation of basin stratigraphy in a predictive manner not previously possible using lithostratigraphy. These surfaces comprise:

- **The Sequence Boundary** which represent a relative fall in sea-level and a basinward shift in depositional facies.

- **Flooding Surfaces** which represent marine transgressive events that form boundaries between parasequences, the building blocks of systems tracts.

- **The Transgressive Surface** which is a Flooding Surface representing the marine transgression across the exposed topsets of the previous systems tract, deposited prior to a drop in relative sea-level.

- **The Maximum Flooding Surface** which represent the maximum landward extent of the transgression and the culmination of the transgressive systems tract.

Topset environments (paralic and shallow marine) are the best settings in which to construct a detailed sequence-stratigraphic scheme for a basin, as they are the most sensitive to rise and fall of relative sea-level. The lateral relationship between successive accumulations of such deposits are difficult to resolve in faulted terranes and without good seismic. In such circumstances a high resolution biostratigraphic scheme is essential for accurate correlation of sequences and systems tracts. Fortunately the Late Jurassic and Early Cretaceous of the Vulcan Sub-basin possesses sufficient palynological control to permit a detailed correlation. The palynological scheme used in this study is that of Helby (1196). Figure 7 shows the chronostratigraphic correlation between major sequence stratigraphic events and the Helby biostratigraphic scheme.

Compared to topset sediments, a more continuous depositional record may be preserved in deep marine deposits, although slope erosion, reworking and condensation events are commonly misinterpreted in such settings. However, basinal deposits are usually mud-prone and recognising sequence stratigraphic events in them is often problematic, particularly on electric logs. According to the Vailian model, basinal deposits found in the initial lowstand systems tract are likely to be sand-prone, although sand-rich deposits may reach the deep basin at anytime, especially at times of high sediment provenance supply where sand-rich deltas are perched on the shelf-slope offlap break.

Changes in relative sea-level control both the creation or destruction of accommodation space and, together with the rate of sediment supply, the distribution of depositional facies. Relative sea-level is a product of both eustatic sea-level change and local subsidence or uplift. In this study, it is suggested that the Jurassic and Cretaceous Periods were not times of dramatic global eustatic sea-level change, although long periodically change (2nd order sequences) associated with ocean-spreading rates did occur. Consequently the driving force for higher frequency sequence-stratigraphic change is related to tectonic movements. Unlike eustatic sea-level change, tectonic uplift or subsidence is a local phenomenon with the potential for simultaneous differential change within a single basin. Hence, stacking patterns of systems tracts are a function of the interaction of long periodicity eustatic sea-level change, the subsidence history of the basin and the rate of sediment supply. During periods of overall retrogradation, the effects of downward shifts at sequence boundaries are suppressed relative to transgressions while during periods of overall regression the converse occurs.

In the following discussion, a sequence-stratigraphic scheme is presented for the Vulcan Sub-basin. Although reference has been made in this report to previous workers in the area, we hasten to add that this sequence-stratigraphic interpretation has been accomplished from first principles, without assistance of prior studies. This is in order that an unbiased interpretation could be presented. This being the case, it was decided to concentrate on elucidation of the important Late Jurassic-Early Cretaceous syn-rift sequence with its inherent abundant source rocks and interbedded turbidite systems. The availability of detailed palynological control (Helby, 1996) for most of the key wells in the basin in this section has enabled reasonably detailed sequence-stratigraphic correlations to be undertaken. Equally attractive exploration objectives of a similar nature have been noted in the post-rift late Cretaceous Puffin Sands. However, given existing time constraints and the lack of detailed modern biostratigraphic zonations (nanno-plankton etc) available for the Late Cretaceous section, further work is precluded beyond the basic interpretation for this interval presented in this report. It is a recommendation of this study that a sequence-stratigraphic study of the Puffin Sands be carried out.

Enclosures 18, 19, 20, 21, & 22 comprise sequence-stratigraphic well correlation sections over three key areas of the Vulcan Sub-basin and related seismic montages, which illustrate key systems tract units observed in this study. These sections will be referred to from time to time in the following discussion.

General post-Permian sequence-stratigraphic signature for the Vulcan Sub-basin

In contrast to the lithostratigraphic subdivision of the post-Permian section, this particular section of the report offers a very general chronostratigraphic interpretation for the same interval, as a prelude for detailed discussion of each major sequence-stratigraphic unit. Where appropriate formation names have been indicated for reference and continuity, although this is not strictly in keeping with sequence-stratigraphic principles. Figure 8 illustrates succeeding tectonic episodes and resultant sedimentation patterns throughout Late Jurassic time.

The onset of Early Triassic retrogradation was heralded in the Late Permian by the widespread development of shallow marine carbonates, indicating a reduction in clastic supply. These carbonates form a prominent seismic marker in the basin. The termination of the carbonate factory's was probably the result of subaerial exposure, and was unable to become re-established during subsequent Early Triassic flooding event. A transgressive sand of this age, observed in the Osprey-1 well (Pattillo & Nicholls 1990), supports this theory. During the Early to lowermost Mid Triassic, sediment supply increased relative to the formation of accommodation space and a regression occurred from the east (op cit), as indicated by the presence of basinal shales and turbidites (Mt Goodwin Formation), overlain by later pro-delta slope deposits and finally coarse clastic delta plain sediments

The Early to Mid Triassic regression was reversed in the Mid Triassic by a transgressive event that saw a return to carbonate deposition (Osprey Formation). A second regression occurred in the Mid to Late Triassic with the development of thick deltaic sandstones that pass into marine mudstones towards the northwest (Sahul Group). A subsequence increase in accommodation space relative to sediment supply occurred in the Late Triassic producing a mixed coarse clastic sequence that passed westwards into thick shallow marine carbonates. Clastic supply increased relative to accommodation space in the latter part of the Late Triassic with the development of coarse clastic delta-front and delta-plain deposits. This continued into the Middle Jurassic (Plover Formation) as sediment-supply matched the creation of accommodation space, although a comparatively minor marine transgression occurred in the Toarcian.

The Mid-Callovian is marked by a pronounced unconformity and mega-sequence boundary that has been related to the break up of Gondwana and the onset of oceanic spreading. This sequence boundary is overlain by transgressive marine sands indicating the start of an overall retrogradational phase which continued through the Late Jurassic and into the Early Cretaceous (Vulcan Formation), culminating in a major period of widespread marine flooding in the Valanginian to Barremian (Echuca Shoals Formation). This retrogradational period is punctuated by sequence boundaries, indicating regressive events of varying magnitude related to numerous rifting events in the Vulcan Sub-basin. Significant extensional events occurred in the Early and Late Oxfordian, Mid Kimmeridgian and Mid Tithonian resulting in major sequence boundaries, not all of which were mapped due to time constraints. Other events may also be present as regionally correlatable events. The interplay between individual fault block movement and relative sea level during this time led to either fan delta and/or submarine fan deposition as shown in the block diagram (Fig 9).

Following the Valanginian to Barremian period of maximum flooding and condensed sedimentation, an overall regression occurred, which continued throughout the rest of the Cretaceous period into the Early Paleocene. Deposits were predominantly pelagic argillaceous-calcareous sediments with pronounced episodic maximum flooding events in the Late Albian, Cenomanian and Turonian (Bathurst Island Group). In addition, lowstand-related events in the Santonian, Campanian, Maastrichtian, and to a minor extent into the early Paleocene, introduced progressively coarse-grained submarine fan clastics derived from the Browse Basin margin into the southern part of the Vulcan Sub-basin area.

The Tertiary is dominated by biogenic carbonates, firstly as a bioclastic ramp system and latterly as a reefal system with well-developed ‘wedding cake’ buildups. This reflects changing climatic conditions related to northward drift during the Tertiary, together with a reduction in clastic sediment supply, which may also be related to precipitation/runoff and ultimately climate. The fact that the continental margin continued to regress has more to do with the carbonate factory’s ability to produce sufficient biogenic sediment than a reduction in the rate of accommodation space generation. During this time, highstand carbonate ramp/shelf deposition was periodically interrupted by glacio-eustatically controlled lowstand system tracts which bypassed the carbonate margin. Sequence boundaries associated with these events occurred in the Late Paleocene, Early Eocene, Middle Eocene, Oligocene, Miocene and Late Miocene.

Late Callovian to Late Jurassic systems tract model

Mid Callovian Unconformity

This surface is interpreted as a mega-sequence boundary. It is defined as the boundary between the *Lower W. digitata (7bi)* and *R. aemula (7ai)* biozones, the oldest sediments overlying the sequence boundary being transgressive sands of Late Callovian age. These sands are ubiquitous throughout the Swan and Paqualin Grabens and extend across the Montara Terrace. The succeeding maximum flooding event following on from this transgression occurs within the latter part of the *R. aemula (7ai)* biozone.

The widespread presence of *R. aemula (7ai)* transgressive deposits within the Vulcan Sub-basin indicates that post Mid-Callovian extension and faulting occurred subsequent to this transgression. These transgressive sands represent a potential play but also a thief zone to underlying Bathonian to Triassic sands in horst block traps.

Early Oxfordian Regression

The creation of accommodation space on the eastern Montara Terrace resulted in the accumulation of stacked lowstand delta systems, separated by flooding events as the rate of sediment supply decreased relative to creation of accommodation space. They were deposited during the early part of the *W. spectabilis 6ciiia, 6ciiib & 6ciib* biozones. Their presence indicates local sediment supply through lateral ramps from the newly elevated Londonderry Platform indicating initiation of post Callovian extension in the Vulcan Sub-basin (Fig 10)

Seismic facies patterns further downdip, in the centre of the Swan Graben, suggest that sand-rich submarine fan systems may exist (Fig 11). These are believed to be axially-derived, probably sourced from different sediment entry points along the Londonderry scarp to Montara Terrace fan-deltas, since the eastern part of the latter was a sediment trap for coarse clastics locally derived from the Londonderry Platform. Further basinward still, into the southern part of the Paqualin Graben occur mud-prone sediments. These muds are relatively thin, suggesting a low sediment supply. This could be caused by an absence of a pronounced sediment source from the Ashmore Platform due to either low topography, or orientation of the sediment-transport directions away from the graben depocentre. Moreover wells such as Maple-1 and Paqualin-1 wells in Paqualin and Swan Graben settings were drilled on highs, and accumulation of coarse-grained submarine fan facies may have occurred instead on the flanks of such structures. An analogue in the North Sea exploration arena is the Miller Field (Garland 1993) reservoired in Late Jurassic turbidite sands which exhibit superior reservoir characteristics off the flanks of a topographic high on the palaeo-sea floor, around which turbidity currents were deflected.

During the latter part of the *W. spectabilis 6ciia* biozone, the character of sediments on the Montara Terrace became retrogradational, with deposition of siltstone and silty claystone slope deposits, culminating in a maximum flooding event within the same biozone. A pronounced angular unconformity from this time can be observed in sediments of the Paqualin Graben (Woods, 1994), indicating that an extensional event took place. There is no evidence for a significant influx of coarse clastics at this time in the wells on either the Montara Terrace or in the Swan or Paqualin Grabens. This is not to say that they do not exist, since sharp-based submarine fan sands possibly of this age occur in Elm-1 on the edge of the Swan Graben, and thin sands can be observed in Vulcan-1b within the graben itself. However, neither of these wells were drilled in an optimal position to test this play. In addition, most wells drilled on the Montara Terrace are located on structural highs that may have been topographic highs at the time of deposition and hence demonstrate lack of reservoir facies at this time

Late Oxfordian - Basal Kimmeridgian retrogradation

Basinal fine-grained siltstone and silty claystone slope deposits accumulated on the Montara Terrace during the Late Oxfordian to basal Kimmeridgian *W. spectabilis (6ci)* and *W. clathrata (6b)* biozones (Fig 11). A high gamma interval in the *W. clathrata (6b)* biozone suggests a maximum flooding event during this period.

Mid-Kimmeridgian tectonic event

The Swan Graben became the loci for thick accumulations of mud-prone basinal deposits during the Late Kimmeridgian (Fig 12), while similar-aged deposits are absent from most of the Montara Terrace. The implication is that extension in the Vulcan Sub-basin was focused on the Swan Graben axis at this time, resulting in uplift of the graben margins. The apparent absence of coarse clastic influxes or the presence of shelf/delta systems, suggests that this period of extension occurred while the basin was in a deep marine setting. The Montara Terrace was probably not subaerially exposed at this time, nor was it overlain by thick sedimentary deposits, as these would not have been entirely removed by the erosion at the time of the subsequent Tithonian and Berriasian sequence boundary unconformities.

The presence of marls belonging to the *D swanense (6a)* biozone, particularly on peri-rift margin and fault block crests indicates possible argillaceous sediment starvation on topographic highs, supporting the idea that extension occurred in a deep marine setting.

The continuous, parallel seismic character in the deeper parts of the Swan Graben also suggest that pelagic and hemipelagic sedimentation occurred. Under these conditions it is not surprising that rich source-rock sequences accumulated.

Deep marine mud-prone deposition continued through the Kimmeridgian into the earliest Tithonian.

Tithonian Regression and Tectonic Event

A drop in relative sea-level along the basin margin during the Early Tithonian (*C. perforans 5d* biozone time), resulted in a return to coarse-clastic topset deposition on the flanks of the Londonderry High, as evidenced at the Rainier-1 well, where the latter unconformably overly Late Oxfordian topset sands (Fig 13). An increase in clastics to the Swan Graben also occurred at this time, although sand-prone fans were probably confined to the basin depocentre, as the topographic highs in the graben upon which wells are located (eg. Maple-1 & Vulcan-1b) indicate non-deposition and or the presence of silty-claystone distal submarine fan deposits.

A further drop in relative sea-level on the basin margin occurred during the Mid Tithonian (*D. jurassicum (5a/b)* biozone) producing a more obvious influx of coarse turbidite clastics to the basin, as observed in both well penetrations and in the form of mounded seismic facies within the Swan Graben and Cartier Trough depocentres. Thick massive topset-sands occur in the well Rainier-1, while sands interpreted to be submarine fan deposits have been penetrated in the Nancar-1 well. In the latter, three cycles of blocky sands with high gamma ray breaks, are overlain by a cleaning-up section, possibly a delta-front lowstand wedge. The Nancar turbidites appear to be derived locally from the Londonderry High. Conversely, along the flanks of the southern and central Vulcan Sub-basin, thin, stacked sharp-based sands of this age at Octavius-1 and 2, and at Champagny-1, have been interpreted as shelfal nearshore deposits, but could alternatively represent turbiditic sands. In the same general vicinity as Octavius-1 &-2, a massive Mid-Tithonian sand in the Douglas-1 well unconformably overlies Early Jurassic strata and possesses what is interpreted as a transgressive upper section.

Late Tithonian retrogradation

Well penetrations into Late Tithonian to Berriasian (*Upper P. iehense 4ci* biozone) sediments in the axis of the Vulcan Sub-basin tend to exhibit mud/silt prone characteristics and are interpreted to indicate a period of retrogradation and coarse clastic starvation, being related to a maximum flooding event.

Early Cretaceous Systems Tract Model

Berriasian regression

A small regression occurs in the Early Berriasian (*upper P. iehiense to K. wisemaniae (4ci to 4biii)* biozones) as indicated by thin, shallow-marine sands overlying Late Tithonian marine shales in Fulica-1 (Fig 14). This was followed by a marine flooding event occurring within the *K. wisemaniae (4biii)* biozone in the well Halcyon-1, which in turn is overlain by another regression within the later Berriasian *lower C. delicata (4biib)* biozone.

To the north in the Sahul Syncline, the equivalent interval comprises a Berriasian regressive interval (Robinson et al 1994), two sands of which in the Iris-1 well, are interpreted to comprise lowstand shoreface sands. These could equally re-interpreted, on electric log evidence, to be lowstand submarine fan sands. The thick prograding lowstand wedge reported by Robinson et al (1994) in the Sahul Syncline to exist between the base and intra-Valanginian surfaces is equivalent to the Late Berriasian of this study and their maximum flooding surface corresponds to the condensed section of the *upper C.delicata (4bii)* biozone.

The remaining Berriasian is largely mud-prone, deposited within a distal marine environment, with evidence for condensed sections, indicating sediment starvation in the *upper C. delicata (4biia), D. lobospinosum (4bi) & E. torynum (4ai-ii)* biozones. There is no evidence during this time for significant deep or significantly shallow marine-clastic deposition at this time throughout the Vulcan Sub-basin, although a regressive event may have occurred during the *B. reticulatum (4aiii-iv)* biozone.

The limited distribution of Early Berriasian shallow-marine coarse clastics to the vicinity of the Londonderry High, with widespread marine muds elsewhere in the basinal depocentre indicates that local sediment sources were progressively reduced during Berriasian time.

Valanginian-Barremian retrograde/condensation

In the study area, the Valanginian to Barremian sequence (Fig 15) is marked by a major condensed section which forms a significant and prominent high amplitude seismic marker. This interval probably comprises a series of maximum flooding surfaces, correlative conformities, and sequence boundaries all very close together. These are therefore difficult to date or correlate, because of the limited age resolution due to coarse sample spacing.

However, major gamma ray surface intervals interpreted to represent maximum flooding events occurring in the following biozones:

- Early Valanginian: *S. aerolata - E. torynum (3c-4ai/ii)*
- Middle Valanginian: *Lower S. tabulata (3bii)*
- Barremian: *Lower M.australis (2diii)*

The most pronounced of these three events appears to be that represented by the Barremian maximum flooding surface.

Thin Valanginian-age glauconitic sands and silts do occur on the Londonderry High, such as at Avocet-1A and Cygnet-1. These represent distal, shallow marine shoal deposits laid down on the sediment-starved Londonderry High. The absence of coarse clastics from this time throughout the Vulcan Sub-basin reflects isolation from cratonic sediment sources, and a loss of local supply from the Londonderry High, following the pronounced relative sea level rise that began during Berriasian time. Deeper in the basinal depocentres, such as the Sahul Trough, mud-prone condensed sequences were drilled and dated by Robinison et al (1994) to be of Hauterivian to Barremian age; these are, however, now known to be time-equivalent of the Valanginian-Barremian section as described in this study.

Late Cretaceous systems tract model

A significant change in depositional style occurred throughout the Vulcan Sub-basin following the Barremian maximum flooding event. The Late Cretaceous Aptian-Maastrichtian sequence (Fig 16) comprises argillaceous marls with limestone hardgrounds representing maximum flooding events in the Late Albian, Cenomanian, Turonian, Coniacian, and Santonian. Marly high gamma intervals are interpreted as candidate sequence boundaries at times where more argillaceous clastic material reached the basin centre. These occur in the Late Albian, Cenomanian, Coniacian, and Santonian. Increased argillaceous clastic input to the Vulcan depocentre in the late Campanian is indicated by the presence of higher gamma log signature and progrades on seismic over the Londonderry High.

Although early signs can be observed in the Campanian, coarse blocky submarine fan sands are evident within the Maasthrichtian sequence in the southern Vulcan Sub-basin. This depositional pattern reflects the relative *positive* topographic expression of the Vulcan Sub-basin and surrounding platforms with respect to the both the Browse Basin and the Sahul Syncline to the south and north respectively, resulting in sediment bypass and sediment starvation during most of the Early-Mid Cretaceous (Valanginian-Coniacian) highstand of relative sea level. As described earlier, this appears to have been overcome by the latest Cretaceous, as Browse Basin coarse clastic sedimentation encroached northwards into the southern Vulcan Sub-basin by Maastrichtian times.

Tertiary

The early Tertiary saw some minor continuation of submarine fan development into the early Paleocene times within the lowermost Vulcan Sub-basin where they have been penetrated in Keeling-1. In this well submarine fans occur as a retrograde facies as the Late Cretaceous sediment pulse diminished.

Depositional styles throughout most of the remaining Tertiary are considerably different from the underlying Cretaceous sequence. These differences are in response to changing climatic conditions to a more dry subtropical environment. Under these conditions, a bioclastic carbonate ramp system developed throughout the Vulcan Sub-basin.

Continued climatic warming occurred throughout the Tertiary as the Australian continent drifted northward, resulting in the development of carbonate reef development by Plio-Pleistocene times and the formation of 'wedding cake' carbonate buildups over the Ashmore Platform.

The carbonate ramp was interrupted periodically by the bypass of coarse clastics during glacio-eustatic lowstand events. Owing to the lack of good micropalaeontological control, these submarine fan and delta deposits are difficult to date from information available to this study, but appear to occur in the Late Paleocene, Early Eocene, Middle Eocene, Oligocene, Late Miocene, and Plio-Pleistocene. In particular, Late Paleocene, Early Eocene and Middle Eocene (Grebe Sands - Fig 17) form extensive sand-rich deposits over the Vulcan Sub-basin that progressively building out towards the northwest.

The extensive carbonate ramp nature of the Tertiary section has precluded the development of major sealing facies. Tertiary lowstand turbidite sand plays must therefore be considered extremely high risk. It has been previously tested by the Warb-1 well drilled on the northeastern margin of the Vulcan Sub-basin.

Play Types

As noted by Woods (1992), the effects of late stage tectonism has tended to mask the seismic expression of Mesozoic hydrocarbon traps, resulting in many wells being off-structure at the target horizon. With increased seismic resolution it should be possible to elucidate not only deep traditional structural plays, but also new traps, particularly those of a stratigraphic nature.

Traditional structural traps for sands in the Triassic (Challis Fm), Lower-Middle Jurassic (Plover) and Late Jurassic (Vulcan) include:

- Detached rotated fault blocks
- Tilted fault blocks
- Salt-associated features
- Hour-glass horsts

This sequence-stratigraphic study has drawn attention to the existence of several lowstand submarine fan cycles, especially in the Late Jurassic Vulcan Formation. Specific moundforms can be observed in the main depocentre axes above sequence boundaries in the Early-Late Oxfordian section and throughout the Tithonian (see distribution of basin-floor sands in enclosures 10, 11, & 13).

Unconventional traps associated with these play include:

- Floor-way dip closed moundforms with compaction drape.
- Three-way dip closed mounds closed against updip slope.

It is important that the existence of regional seals be considered in developing these play types, since attached basin-floor sands frequently exhibit leaky seals due to the existence of overlapping lowstand wedge thief zone downlaps. In this case, the most optimal play will be Oxfordian moundforms, which ere overlain by an excellent regional seal, being the extremely thick marine shale of Kimmeridgian age.

Similar basin floor sand objectives exist in the Late Cretaceous Puffin basin-floor sands, which, if they occur within four-way dip closures, should offer good targets, albeit at shallower drilling depths. Required requisite seals comprise transgressive-highstand system tract marine shales, without which such plays exhibit poor cap rock mechanisms, such as is the case for Tertiary Sands (Grebe and Oliver Sands), which lack good seals and hence must be considered extremely high risk objectives. As mentioned in the text of the report, a sequence-stratigraphic study of the Puffin submarine sand system is recognised to be of value in elucidating post-Jurassic plays in the basin.

SECTION 2: MATURATION, FLUID MIGRATION AND TRAP INTEGRITY, VULCAN SUB-BASIN

Introduction

Two of the key issues facing explorers in the Timor Sea are the maturation and expulsion histories (and associated fluid flow pathways), and trap integrity. In the following section, a brief review of published information is presented, as well as some recently acquired AGSO and World Geoscience Corporation (WGC) geochemical sniffer and Airborne Laser Fluorescence data from the southern Vulcan Sub-basin. This information can be integrated by explorers into Section 1 of this report, to provide a more complete understanding of the petroleum prospectivity of the Vulcan Sub-basin.

Maturation Histories

While no maturation modelling was carried out as part of this report, a significant amount of published material is available. Available information includes flexural isostatic modelling and associated palaeo-heat flow determinations for the southern Swan Graben (Baxter et al., 1997), apatite fission track data for the entire Vulcan Sub-basin (O'Brien et al., 1996a) and tradition maturation modelling data for the Sahul Syncline, in the northern part of the studied area (Brooks et al., 1996). Some vitrinite reflectance plots have also been included.

Present Day Oil Window

Data from over thirty wells from the Vulcan Sub-basin 'proper' and Sahul Syncline were used to construct Figure 18, which shows the relationship between measured vitrinite reflectance and depth. Whilst there is some scatter, particularly at the deeper levels, it is clear that, overall, the region is characterised by a reasonably deep oil window. The assumed onset of generation (R_v = ~0.6) occurs at a depth of about 3,000 m, with many values still <0.8 R_v at 3,500 m. Even given that some vitrinite suppression might occur, the data suggest that the present day oil window is located at about 3,000-3,200 m, with the onset of thermal gas generation (Rv = 1.3) being located below 4,000-4,500 m.

Data from individual wells (Fig. 19), which have been plotted to help remove scatter, confirm these observations.

Swan Graben: Southern Vulcan Sub-basin

Maturation modelling through the Swan Graben (Baxter et al., 1996), the main source rock depocentre, suggests that the principal oil-prone source rocks in the region, the Late Jurassic Lower Vulcan Formation, started generating oil in about the mid-Cretaceous (~100 Ma). Since the major horsts in the area developed as a result of fault reactivation in the Tithonian (~145 Ma), with the age of the sealing facies being Early Cretaceous (~132 Ma), the comparative ages of generation, trap formation and seal emplacement are very favourable. Structures such as Skua and Puffin have probably been face-loaded directly from the Swan Graben, whereas Jabiru, for example, has probably received oil which migrated a significant distance north-east, out of the Swan Graben.

Skua Trough: South-eastern Vulcan Sub-basin

Fission track thermal data for the Montara-1 well in the Skua Trough (Fig. 20), another major Late Jurassic depocentre (Pattillo & Nichols, 1990) indicate that maturation of the Late Jurassic Lower Vulcan Formation source rocks took place much later than in the Swan Graben (Fig. 20; modified from O'Brien et al., 1996a). In fact, if peak generation for the Type 2 source rock is assumed to be between about 100 and 120 ^{o}C, then the Lower Vulcan Formation probably did not reach peak generation before the Early to Middle Miocene (~20-10 Ma). Examination of Enclosures 1 & 2 suggests that oil generated within the Skua Trough in the Late Tertiary might have charged the Talbot and Challis structures.

Sahul Syncline: Northern Vulcan Sub-basin

Maturation modelling in the Sahul Syncline by Brooks et al. (1996) indicates that the Late Jurassic source rocks in this area entered the oil window at about the mid-Cretaceous (~100 Ma). As such, the timing of generation within both the Swan Graben and the Sahul Syncline appears similar.

Fluid Flow Histories And Trap Integrity

During the latest Miocene and Early Pliocene, the collision of the Australian and Eurasian plates resulted in significant tectonism in the Timor Sea. Flexural extension (resulting from the down-warping of the Australian plate and the associated formation of the Timor Trough between 5-3 MaBP) resulted in the dilatation of the major Jurassic and older extensional faults which defined the petroleum traps in this area. Contemporaneously, small displacement, Mio-Pliocene fault sets formed which often, but not always, linked with, and were controlled by, the deeper faults. In the Mio-Pliocene, convergence of the Australian and Eurasian plates produced an oblique collisional setting. This tectonism led to the partial to complete breaching of numerous accumulations. Clearly, a better understanding of trap integrity is essential to improved exploration success in this area.

To address this issue, the Australian Geological Survey Organisation (AGSO) has, over the last several years, been carrying out a major multi-institutional research program to address the issue of trap integrity. Seismic, sniffer, airborne laser fluorescence (ALF), fluid inclusion, stable isotopic and petrographic studies have been carried out on a representative suite of traps, from gas charged, through oil charged, to breached. Below is a review of some of the key results, with the presentation of new geochemical sniffer and ALF results from the southern Vulcan Sub-basin.

HRDZs, charge histories and trap classification

A key result of this investigation was the recognition of Hydrocarbon-Related Diagenetic Zones (HRDZs) within the Timor Sea (O'Brien & Woods 1995). HRDZs are localised, generally fault-related zones of intense carbonate cementation within Eocene sandstones. Stable isotopic investigations of the calcite and ankerite cements within the HRDZs demonstrated that they have extremely light isotopic compositions ($^{o}/_{oo}$PDB to -25 d^{13}C), which confirms their hydrocarbon-related nature. Moreover , the HRDZs have a strong seismic response (Fig. 21), which allows them to be mapped confidently using seismic data. An integrated mapping and structural study has revealed that the HRDZs are best developed above the breached Mesozoic traps, are smaller, but present, over oil accumulations, but are absent over gas accumulations. Fluid inclusion investigations have also demonstrated that in all cases the gas accumulations contained pre-existing oil columns (which were subsequently displaced via Gussow Displacement), and that the oil accumulations all have significant residual zones below the present day OWC.

These observations have led to the development of a simple model for the formation of HRDZs. This model involves Mio-Pliocene fault reactivation (contemporaneous with, and driven by, the downward flexing of the Australian plate and the associated formation of the Timor Trough), which decreases the fault seal integrity of the Mesozoic traps and facilitates hydrocarbon leakage up the rift and Mio-Pliocene faults (Fig. 22). Hydrocarbons migrating into shallow, Eocene aquifer sands are oxidised, thereby facilitating localised carbonate cementation and the formation of HRDZs. Since the size and intensity of the HRDZs are directly related to the amount of hydrocarbons which have passed through the trap, HRDZs are largest over breached accumulations. Their absence over gas accumulations is explained by the fact that these traps never leaked and the oil columns were subsequently displaced by later gas charge. In contrast, oil accumulations always contain small HRDZs over them; the preservation of the oil in these traps results from the fact that the Mio-Pliocene fault reactivation resulted in a trap which had a low capacity to trap gas, but an adequate capacity to trap oil. As a consequence, later gas entering the trap was not trapped, and continued leaking up the fault, thereby facilitating preservation of the oil charge.

Tripartite trap classification

Integration of observations on the size of HRDZs and the nature of the Mio-Pliocene faulting have provided a sound predictive capability for evaluating the likely integrity, and charge history, undrilled traps. It appears that a simple, tripartite trap classification is applicable to the Timor Sea (O'Brien et al. 1996a).

The classification consists of:

- *High Integrity Traps* (HITs): High seal integrity with respect to oil and gas; largely unreactivated; have never leaked and are now gas flushed (providing they have access to charge).
- *Moderate Integrity Traps* (MITs): Moderate seal integrity with respect to oil, low for gas; moderately fault reactivated; have leaked partially and contain oil columns (providing they have access to charge).
- *Low Integrity Traps* (LITs): Poor seal capacity for oil and gas; strongly fault reactivated; have leaked completely (providing they have access to charge).

Since the size and acoustic response of the HRDZs are directly proportional to the amount of hydrocarbons which have leaked from the traps, their presence or absence provides a powerful indicator, pre-drill, of both trap integrity. These observations are summarised in Figures 23 and 24.

Fluid flow histories and thermal implications

Investigation into representative examples of these three trap types using detailed fluid inclusion and apatite fission track (AFTA) data has revealed that this trap classification also defines far more fundamental factors than just trap integrity. This study identified the presence of a key deep basinal fluid flow event in the latest Miocene/Early Pliocene, which coincided with, and was driven by, the fault reactivation associated with the collision of the Australian and Eurasian plates; the same faulting event that induced trap breach. This event involved the flowage of hot (90-120 ^{o}C), saline (>200,000 ppm) brines, probably from deeply buried Palaeozoic evaporite sequences, up major faults and through the Mesozoic and Tertiary sequences (Fig. 25).

The passage of these hot brines produced a Late Tertiary (<5 Ma), transient heating event which is evident in fission track and fluid inclusion data; the heating is most evident in MITs, as these apparently leaked for a relatively extended period (>100,000 to 1,000,000 years). In contrast, strongly reactivated, LITs appear to have been breached too quickly (<100,000-10,000 years) to have equilibrated thermally with the transient heat pulse. High integrity traps did not experience late stage brine migration (because of a lack of fault reactivation and attendant fluid flow pathways) and consequently are now at their maximum temperatures. These traps probably most accurately reflect the maturation history of the source rock kitchens in the Timor Sea.

Where MIT and LIT traps were charged, HRDZs were formed contemporaneously with brine migration. It seems likely that the brines themselves provided some of the cations and anions necessary for HRDZ formation within the shallow aquifer sands. Where these traps were not charge, the passage of the brines produced thermal (and some diagenetic) effects, through no HRDZs were formed. ***Failure to recognise the transient and localised (fault-related) nature of this fluid flow/thermal event could lead to significant 'over-modelling' of maturation histories in the Timor Sea. It is likely that the thermal histories of the source rock depocentres within the grabens is best represented by the high integrity traps (HITs), which did not experience brine migration and now typically contain gas.*** The most commonly drilled structures, namely fault-bounded horsts (MITs & LITs) are probably the least representative of the regional thermal history!

Importantly, these observations demonstrate unequivocally that the traps have breached from the 'bottom up', via the reactivation of deep, Jurassic and older-aged faults, and not the 'top down', via Mio-Pliocene, shallow faulting. Dilatational reactivation of the deep, basement-involved rift and older faults ultimately induced fault rupture of the seal, with the resulting shallow, Mio-Pliocene faults simply providing local fluid migration conduits to the surface. In the Timor Sea, this extension was probably related to the relatively local lithospheric downwarping and the development of the Timor Trough, rather than more far-field effects of the collision of the Australian and Eurasian plates.

ALF And Geochemical Sniffer Results: Southern Vulcan Sub-basin

Alf Acquisition

In order to further characterise the present day leakage characteristics of assorted traps and trap types within the Timor Sea, two Airborne Laser Fluorescence (ALF) acquisition programs have recently been carried out in the Timor Sea. Both of these programs were located within the southern Vulcan Sub-basin, namely:

- Skua-Swan Graben region.
- Haydn region.

The Skua-Swan Graben program was a joint AGSO-WGC program, whereas the Haydn program was carried out on a speculative basis by WGC. The results of both programs are presented in this report (Enclosures 23 & 24). The results of the ALF programs clearly demonstrate that the southern Vulcan Sub-basin is an area of active, present day seepage (Enclosures 23 & 24). These data can be used by explorers evaluating the area prior to bidding rounds. Alternatively, they could be used during the prospect development phase and might be useful in 'rating' a suite of prospects.

Skua-Swan Graben region

The Skua-Swan region is characterised by three zones of active seepage.

1. The most prominent is located southwest of the East Swan wells. This anomaly is composed of a number of large, individual anomalies which appear to have linked to define a zone of continuous seepage all the way across the survey area.

2. The next most prominent is located within to the northeast of the East Swan wells and consists of several small anomalies. One of these anomalies is directly associated with the Eclipse-1 well, which contains a significant residual oil zone (O'Brien, unpublished data).

3. The southernmost group of anomalies is clustered around the Skua Field, in the southern part of the survey area.

Significant differences exist between the characteristics of the seepage in anomalies 1 and 2 versus 3. *The seepage around Skua has a very 'wet', oil-prone signature, whereas those around East Swan and Eclipse are quite 'dry' and are more consistent with a gas condensate source.* This observation is in accord with geochemical sniffer results through this same region (O'Brien et al., 1992), *which suggested that seepage around East Swan was significantly drier than that near Skua.*

Haydn region

The Haydn survey area, directly west of the Skua-Swan survey, was carried out to investigate the seepage characteristics of a large, undrilled structure (the Haydn Prospect) which is present on VTT line 163/002 (see O'Brien et al., 1996a and Figure 21, this report). The eastern faulted flank of this structure has a prominent HRDZ associated with it, which shows that the trap has, at least in part, been charged. The overall velocity and size characteristics of this HRDZ appear to be broadly similar to those associated with the Skua Field (see O'Brien & Woods, 1995), which would place the structure into the 'MIT' category.

ALF acquisition through the Haydn area (Enclosures 23 & 24) revealed that four areas of active hydrocarbon seepage were present. The most central of these was directly associated with the eastern bounding fault of the Haydn Prospect, which suggests that the structure is actively leaking hydrocarbons at the present day. Given that it is on strike with the Puffin oil fields, about 20 km to the north-east, this structure may, given addition mapping, prove quite interesting. The other three anomalies detected within the Haydn survey area are all located around the periphery of the survey area, and so it is difficult to relate them directly to any geological feature.

Significantly, the Haydn and other anomalies have characteristics which suggest that they are very wet (oil-prone source), and are in fact identical to the seeps around Skua.

A series of reconnaissance lines were also flown over the Montara gas accumulation to the southeast of Skua. These lines revealed no active seepage, which is consistent with Montara being a HIT (O'Brien & Woods, 1995; O'Brien et al., 1996a).

Geochemical Sniffer Acquisition

In view of the success of a pilot sniffer program in 1990 (O'Brien et al., 1992; O'Brien & Woods, 1995) and the results obtained from the ALF surveys, a detailed geochemical sniffer program was carried out through the southern Vulcan Sub-basin in mid-1996, using RV Rig Seismic. A principal goal of this survey was to compare (in a way 'ground-truth) the ALF results obtained in the Skua-Swan and Haydn areas with measurements made near the seabed (within ~10 m). Sniffer data were initially acquired at a 1,000 m line spacing, then were infilled down to 330 m when anomalies were detected. In this report, only the 1,000 m results are discussed.

The results of the survey are presented as a series of colour contour maps in Enclosures 25, 26 and 27. These maps show, respectively, measured ethane data for the Skua Swan area, measured hydrocarbon wetness data for the Skua-Swan area and measured ethane data for the Haydn area.

Skua-Swan Area

Within the Skua-Swan area, there is a zone of significant hydrocarbon seepage in the southern part of the survey area, in the vicinity of the Skua Field (Enclosures 25 & 26). There, methane increases to about four times background, but ethane increases to some 38 times background. The signature of the seepage is very wet (Figs 26 & 27), with both ethane and wetness increasing strongly with increasing methane concentration.

Overall, there is good agreement between the sniffer and ALF data for the southern part of the Skua-Swan area: there is almost a one to one agreement between the approximate locations of the ALF and sniffer anomalies (within ~1-2 km), and the hydrocarbons detected by both techniques are very wet.

In the northern part of the Skua-Swan area, no sniffer anomalies were detected, even though large ALF anomalies were detected through this region.

Haydn Area

The sniffer results from the Haydn area did not reveal any significant present day hydrocarbon seepage (Enclosure 27). As such, the results appear to disagree with those obtained by ALF for the same area.

Discussion Of Sniffer And ALF Results

In terms of detecting anomalies, the ALF and sniffer data agree closely in one area, namely the southern Skua-Swan area, but disagree elsewhere. Both techniques have, however, indicated that the seepage in the southern Skua-Swan area is very 'wet', whereas further north, it is drier.

An important observation can be made from these apparently conflicting results, however: *where sniffer anomalies are detected, ALF anomalies are invariably present*. There is no example, either from the present sniffer survey, or from the 1990 program, where this is not true. An explanation for this may be as follows.

O'Brien & Woods (1995) and O'Brien et al. (1996a) have shown *that faults in the Timor Sea leak from very localised points along their length*. Zones of leakage might only extend for a few hundred metres, at most. Moreover, *fault leakage is likely to be episodic*. Given that the sniffer is towed within about 10 m of the seafloor, *it is likely that many zones of seepage will be missed completely at a 1,000 m line spacing*. In contrast, ALF measures seepage at the sea surface, and is capable of measuring minute amounts of seepage. Moreover, the seepage is likely to disperse significantly as it travels up through the water column, particularly if the upper parts of the water column are well-mixed and strong currents are present. ALF in effect 'averages out' the seepage over a wider area.

Considering all available information, the most likely explanation is that the seepage around Haydn and East Swan-Eclipse that was detected on ALF, but was missed on sniffer, is probably real (as supported by the presence of HRDZs etc), and is due to very localised, very minor seepage foci.

Summary

- Oxfordian source rocks in the Swan Graben probably generated oil in the mid to Late Cretaceous, whereas those in the Skua Trough probably only generated in the Miocene.
- Traps in the Timor Sea fall into three categories: Low, Medium and High Integrity (LIT, MIT, HIT).
- Leaky traps induce the formation of hydrocarbon-related diagenetic zones (HRDZs) above themselves.
- The size and velocity characteristics of the HRDZs can indicate whether a trap is an LIT, MIT or HIT.
- MITs are the most prospective for oil; HITs are typically gas flushed.
- Mio-Pliocene migration through LITs and MITs produced anomalous thermal effects.
- HITs are probably most representative of the thermal histories of the source rock depocentres.
- Sniffer and ALF data are useful in evaluating the likely projectivity of traps in the southern Timor Sea.

Selected Bibliography

K. Baxter, K., G. T. Cooper, K. C. Hill & G.W. O'Brien, 1997: Flexural isostatic modelling as a constraint on basin evolution, the development of sediment systems, and palaeo-heat flow: Application to the Vulcan Sub-basin, Timor Sea. APPEA Journal (in press).

Etheridge, M.A. & O'Brien, G.W. 1994. Structural and tectonic evolution of the Western Australian margin basin system. *PESA Journal* , 22, 45-63.

Garland, C.R., 1993. Miller Field: reservoir stratigraphy and its impact on development. In: J.R. Parker (ed) - Petroleum Geology of NW Europe: proceedings of the 4th Conference. Geol. Soc Lond., 401-414.

Gradstein, F. M. & Von Rad, U. 1991. Stratigraphic evolution of Mesozoic continental margin and oceanic sequences: Northwest Australia and northern Himalayas. *Marine Geology* , 102, 131-173.

Helby, R., 1996. Timor Sea permit releases - palynology reviews of selected wells. Multiclient reviews.

Nelson, A.W., 1989. Jabiru Field - horst, sub-horst or inverted Graben? *APEA Journal*, 29, 176-194.

Nelson, A.W., 1993: Wrench and inversion structures in the Timor Sea. PESA Journal, 36:399-427.

O'Brien, G.W., G. Bickford & J. Bishop, D.T. Heggie & J.F. Marshall:- Light hydrocarbon geochemistry of the Vulcan Sub-Basin, Timor Sea: Rig Seismic Survey 97. BMR Record 1992/62.

O'Brien, G.W., 1993—Some ideas on the rifting history of the Timor Sea from the integration of deep crustal seismic and other data.*PESA Journal,* 21, 95-113.

O'Brien, G.W., M.A Etheridge, J.B. Willcox, M. Morse, P. Symonds, C. Norman & D.J. Neadham, 1993. The structural architecture of the Timor Sea, north-western Australia: implications for basin development and hydrocarbon exploration. APEA Journal, 33, 258-278.

O'Brien, R. Higgins, P. Symonds, P. Quaife, J. Colwell & J. Blevin, 1996a. Basement control on the development of extensional systems in Australia's Timor Sea: An example of hybrid hard linked/soft linked faulting? APPEA Journal, 36, 161-201.

O'Brien, M. Lisk, I. Duddy, P.J. Eadington, S. Cadman & M. Fellows, 1996b. Late Tertiary fluid migration in the Timor Sea: A key control on thermal and diagenetic histories? APPEA Journal, 36, 399-427.

Pattillo, J. & Nicholls, P.J. 1990. A tectonostratigraphic framework for the Vulcan Graben, Timor Sea region. *The APEA Journal* , 30(1), 27-51.

Robinson, P.H. et al., 1994. Meanders to fans: a sequence stratigraphic approach to Upper Jurassic-Lower Cretaceous sedimentation in the Sahul Syncline, North Bonaparte Basin. In: P & R Purchell (eds) - Sedimenray Basins of Western Australia PESA Symposium Volume, 223-241.

Smith, G.C., et al., 1996. Laminaria - a new Timor Sea discovery. APPEA Journal, 36:12-29.

Wellman, P., AND O'Brien, G.W., 1991—Vulcan Graben, Timor Sea: regional structure from a magnetic survey. Exploration in a changing environment*Exploration Geophysics,* 22, 433-438 (1991).

Woods, E.P., 1988—Extensional structures of the Jabiru Terrace*. The North West Shelf, Australia*, Petroleum Exploration Society of Australia Limited, 1988, 311-330.

Woods, E.P., 1992—Vulcan Sub-Basin fault styles - implications for hydrocarbon migration and entrapment. *APEA Journal* 32, 138-158.

Woods, E.P., 1994—A salt-related detachment model for the development of the Vulcan Sub-basin. In: PURCELL, P.G. and R.R., (eds) The Sedimentary Basins Of Western Australia, Proceedings of the Western Australian Basins Symposium, 259-274.

WELL	WELL COMPLETION REPORT	WELL COMPLETION LOG	BIOSTRAT DATA (Helby)	DIGITAL LOG DATA (Wiltshire)	SYNTHETICS (Completed for VTT/VTX Project)
ALLARU-1	YES	YES	YES	YES	YES
ANSON-1	YES	YES		YES	YES
ARUNTA-1		YES	YES		
AVOCET 1A		YES	YES		
AVOCET 2	YES	YES		YES	
BARITA-1		YES	YES		
BILYARA-1			YES		
BIRCH-1		YES	YES	YES	YES
CASSINI 1		YES	YES	YES	
CASUARINA		YES	YES		
CASSINI 2	YES	YES		YES	
CAVERSHAM-1		YES			
CHALLIS 11	YES	YES	YES	YES	
CHAMPAGNY-1		YES		YES	YES
COCKELL-1		YES	YES		
CLIEA 1	YES	YES	YES	YES	YES
DELAMERE-1		YES	YES		
DELTA 1	YES	YES	YES		
DILLON SHOALS 1		YES		YES	YES
DOUGLAS-1	YES	YES	YES	YES	YES
DRAKE-1		YES			
EAST SWAN 1		YES	YES	YES	YES
EAST SWAN 2	YES	YES		YES	
ECLIPSE 1	YES	YES		YES	
ECLIPSE 2	YES	YES	YES		
ELM-1	YES	YES			
FAGIN-1		YES	YES	YES	YES
FULICA-1		YES	YES		YES
GARGANEY-1		YES	YES		
GREAT EASTERN-1		YES			
GREBE-1		YES			
HADRIAN-1			YES		
HALCYON 1	YES	YES	YES		
JABIRU-1A			YES		
JABIRU-2	YES	YES		YES	YES
JABIRU-3		YES			
JACANA-1		YES			
JARRAH-1			YES		
KATERS 1	YES	YES		YES	
KEELING 1				YES	YES
KEPPLER 1	YES	YES		YES	YES
KIIMBERLEY-1		YES			
LAMINARIA-1	CONFIDENTIAL				
LONGLEAT-1	YES	YES	YES	YES	YES
LORIKEET-1		YES	YES		
LUCAS-1		YES			

Table 1: Vulcan Sub-basin well data base

WELL	WELL COMPLETION REPORT	WELL COMPLETION LOG	BIOSTRAT DATA (Helby)	DIGITAL LOG DATA (Wiltshire)	SYNTHETICS (Completed for VTT/VTX Project)
MAPLE-1	YES	YES	YES	YES	YES
MARET-1	YES	YES	YES	YES	YES
MEDUSA-1	YES	YES			
MONTARA-1	YES	YES	YES	YES	YES
NANCAR-1	YES	YES	YES	YES	YES
NOME 1	YES	YES	YES	YES	YES
OCTAVIUS 1	YES	YES	YES	YES	
OLIVER 1	YES	YES	YES	YES	YES
OSPREY 1		YES	YES		
PACQUALIN 1	YES	YES	YES	YES	
PARRY-1		YES			
PASCAL-1		YES			
PENGANA 1	YES	YES	YES	YES	YES
PITURI-1		YES			
PRION 1	YES	YES	YES	YES	YES
PUFFIN 2	YES	YES	YES	YES	
PUFFIN-1		YES		YES	YES
RAINBOW 1	YES	YES	YES		
RAINIER-1	YES	YES	YES	YES	YES
ROTHBURY-1		YES			
SAHUL SHOALS 1		YES		YES	
SKUA-1		YES			
SKUA 5				YES	
SKUA 6	YES	YES		YES	
SNIPE-1	CONFIDENTIAL				
SNOWMASS-1			YES		
STORK-1		YES			
SWAN-1		YES			
SWAN 3	YES	YES		YES	
SWIFT-1		YES	YES	YES	YES
TAHBILK-1	YES	YES	YES	YES	YES
TALBOT 1	YES	YES	YES	YES	
TALTARNI-1		YES	YES	YES	YES
TURNSTONE 1	YES	YES	YES		
VOLTAIRE 1		YES	YES	YES	YES
VULCAN 1B		YES	YES (VULCAN 1)	YES	YES
WARB 1	YES	YES	YES	YES	YES
YERING 1	YES	YES	YES	YES	YES

Table 1: Vulcan Sub-basin well data base (cont'd)

WELL	RKB	WATER DEPTH	TOTAL DEPTH	LATE MIOCENE SB	OLIGOCENE SB	EARLY EOCENE SB	EARLY PALAEOCENE SB	VALANGINIAN/BARREMIAN FS	MID TITHONIAN SB	MID KIMMERIDGIAN SB	MID CALLOVIAN SB	LATE PERMIAN SB/MFS
ALLARU-1	26	125	2986	NA	765	1286	1855	2343	2403	2411	2892	NR
ANSON-1	11	98	1860	NA	597	945		1705	NR			
ARUNTA-1	18	123	2500	NA	640	1020	1403	1803	ABSENT	ABSENT	2138 (FAULT)	NR
AUGUSTUS-1	29	297	3555	864	1397	1890	2396	2910	3288	3354	3514	NR
AVOCET 1A	12	106	2217	NA	500	835	1133	1752	1781	ERODED OUT	ERODED OUT	NR
AVOCET 2	25	106	2000	NA	713?	982?	1264	1758	1789	ERODED OUT	ERODED OUT	NR
BARITA-1	12	94	2500	NA	574	900	1100	1828	1854	ERODED OUT	ERODED OUT	NR
BIRCH-1	22	90	2822	NA	796	1362	1977	FAULTED OUT	ERODED OUT	ERODED OUT	2639	NR
CASSINI 1	26	116	1751	NA	449	872	1097	1421 (FAULT)	ERODED OUT	ERODED OUT	FAULTED OUT	NR
CASUARINA	22	95	1570	NA	465	724	988	1329	ERODED OUT	ERODED OUT	ERODED OUT	NR
CASSINI 2	26	113	2200	NA	418	786	1086	1462 (FAULT)	ERODED OUT	ERODED OUT	FAULT	NR
CAVERSHAM-1	22	115	3084	NA	1069	1959	2510	2920?	ERODED OUT	2960	NR	
CHALLIS 11	26	102	1700	NA	477	806	1054	1446 (fAULT)	ERODED OUT	ERODED OUT	1518 (FAULT)	NR
CHAMPAGNY-1	28	71	3491	NA	992	1661	2129	3069	3261	3306	3491?	NR
COCKELL-1	22	265	3274	846?	1320	1740	2227	2703	3070	3122	NR	
CLIEA 1	22	108	3789	730	1332	2006	2363	3189	3593	3597	3725	NR
CYGNET-1	12	80	2050	NA	493	642?(LOST CIRC)	768? (LOST CIRC)	1742	1825	ERODED OUT	ERODED OUT	NR
DELAMERE-1	22	101	1530	NA	408?	633? (LOST CIRC)	795	1267	1288	ERODED OUT	ERODED OUT	NR
DELTA 1	25	205	2900	607	1143	1728	1979	NR				
DILLON SHOALS 1	13	137	3970	NA	823 (FAULT)	1115	1513	1811	ERODED OUT	ERODED OUT	ERODED OUT	2681
DOUGLAS-1	29	196	2754	780	1217	1590	2110	2379	2485	ERODED OUT	ERODED OUT	NR
DRAKE-1	12	103	2380	NA	615	983	1285	1904	1930	ERODED OUT	ERODED OUT	NR
EAST SWAN 1	21	103	3038	396	728	1286	1862	2330	ERODED OUT	ERODED OUT	2731	NR
EAST SWAN 2	18	104	2855	NA	761	1311	1946	2217	ERODED OUT	ERODED OUT	2637	NR
ECLIPSE 1	9	107	3003	NA	787	1317	1925	2288?	2318?	ERODED OUT	2579	NR
ECLIPSE 2	8	117	2930	NA	889	1312	1935	2438	ERODED OUT	ERODED OUT?	2786	NR

Table 2-A

WELL	RKB	WATER DEPTH	TOTAL DEPTH	LATE MIOCENE SB	OLIGOCENE SB	EARLY EOCENE SB	EARLY PALAEOCENE SB	VALANGINIAN/BARREMIAN FS	MID TITHONIAN SB	MID KIMMERIDGIAN SB	MID CALLOVIAN SB	LATE PERMIAN SB/MFS
ELM-1	22	110	3060	NA	946	1464	2092	2572	2625	ERODED OUT	2984	NR
FAGIN-1	22	264	3262	786	1348	1710	2230	2734	2952	2964	3017	NR
FULICA-1	25	111	2674	NA	1017	1485	1901	2480	2632	ERODED OUT	NR	
GARGANEY-1	25	100	2481	NA	LOST CIRC	1059? (LOST CIRC)	1326	2093	2146	ERODED OUT	2217	NR
GREAT EASTERN-1	22	114	2800	590	1148	2036	2468	NR				
GREBE-1	30	69	3000	576	1155	1661	2061	2697	ERODED OUT	ERODED OUT	ERODED OUT	NR
HALCYON 1	18	98	2090	NA	339	515? (LOST CIRC)	680	1336	1375	ERODED OUT	ERODED OUT	NR
JABIRU-1A	31	119	3225	NA	LOST CIRC	LOST CIRC	LOST CIRC	1594	ERODED OUT	ERODED OUT	1604	NR
JACANA-1	18	65	1718	245?	LOST CIRC	552?	658	1486	1534	ERODED OUT	ERODED OUT	NR
KATERS 1	11	92	1962	NA	520	807	1147	1758	ERODED OUT	ERODED OUT	1835	NR
KEELING 1	11	194	3135	NA	1131	1536	1919	3025	ERODED OUT	ERODED OUT	ERODED OUT	NR
KEPPLER 1	22	112	1772	NA	610	934	1272	1658	ERODED OUT	ERODED OUT	ERODED OUT	NR
KIIMBERLEY-1	33	43	2300	496	861	1420	1842	NR				
LANGHORN-1	?	?	2600	NA	1111	2009	2290	2487	ERODED OUT	ERODED OUT	2507	NR
LONGLEAT-1	26	98	2330	NA	597	997	1420	1932	ERODED OUT	ERODED OUT	2214	NR
LORIKEET-1	26	108	1900	NA	636	995	1424	1752	ERODED OUT	ERODED OUT	ERODED OUT	NR
LUCAS-1	11	90	2796	479	1038	1976	2183	2587	ERODED OUT	ERODED OUT	ERODED OUT	NR
MAPLE-1	22	145	4239	536	1109	1848	2545	2843	FAULTED OUT	3105	3688	NR
MARET-1	22	131	3560	470?	814	1381	1726	3257	ERODED OUT	ERODED OUT	3385	NR
MEDUSA-1	26	111	1958	NA	1816	1152	1340	1792	ERODED OUT	ERODED OUT	ERODED OUT	NR
MONTARA-1	18	85	2444	NA	712	1210	1654	2388?	ERODED OUT	ERODED OUT	3145	NR
NANCAR-1	22	232	3650	769	1392	1979	2289	3043	3484	3551	NR	
NOME 1	8	129	1850	NA	506	758	1067	1475?	ERODED OUT	ERODED OUT	ERODED OUT	NR
OCTAVIUS 1	11	163	3204	NA	865	1297	1844	2530	2984	3117	NR	
OCTAVIUS 2	22	151	3300	NA	905	1344	1832	2516	2904 (FAULT)	FAULTED OUT	NR	
OLIVER 1	17	305	3500	924	1576	2003	2390 (FAULT)	2699	2896 (FAULT)	FAULTED OUT	2951	NR

Table 2-B

WELL	RKB	WATER DEPTH	TOTAL DEPTH	LATE MIOCENE SB	OLIGOCENE SB	EARLY EOCENE SB	EARLY PALAEOCENE SB	VALANGINIAN/BARREMIAN FS	MID TITHONIAN SB	MID KIMMERIDGIAN SB	MID CALLOVIAN SB	LATE PERMIAN SB/MFS
OSPREY 1	34	100	2185	NA	372	553	713	1247	ERODED OUT	ERODED OUT	ERODED OUT	2518
PACQUALIN 1	27	125	4245	653	1058	1516	1662	2524	2913	2935	4164	NR
PARRY-1	22	96	2469	517	1028	1801	2039	2385?	ERODED OUT	ERODED OUT	ERODED OUT	NR
PASCAL-1	26	100	2850	503	1088	927	2083	2525	ERODED OUT	ERODED OUT	ERODED OUT	NR
PENGANA 1	26	116	2095	NA	467	864	1218	1645	ERODED OUT	ERODED OUT	ERODED OUT	NR
PITURI-1	26	89	2124	NA	1011	1632	1997	NR				
PRION 1	25	70	2560	564	1055	1838	2114	2634	2639	ERODED OUT	ERODED OUT	NR
PUFFIN 2	25	78	2550	NA	1032	1734	1986	2441	ERODED OUT	ERODED OUT	ERODED OUT	NR
PUFFIN-1	34	102	2961	582?	1021	1744	1999	2362?	ERODED OUT	ERODED OUT	ERODED OUT	NR
RAINBOW 1	8	135	2700	478	1036	1935	2194	2392?	ERODED OUT	ERODED OUT	ERODED OUT	NR
RAINIER-1	18	112	2400	NA	477	859	1080	1659	1783	ERODED OUT	2118	NR
ROTHBURY-1	22	115	3027	578?	1053	1891	2485	FAULTED OUT	FAULTED OUT	2885	NR	
SAHUL SHOALS 1	10	28	3802	532?	988	1600	1651	1795?	ERODED OUT	ERODED OUT	ERODED OUT	3749
SKUA-1	30	80	3049	460	815	1372	1866	2417	ERODED OUT	ERODED OUT	ERODED OUT	NR
SWAN-1	34	109	3284	466	864	1606	2153	2628	2883	2904	NR	
SWIFT-1	8	81	2800	401	765	1330	1804	2392?	ERODED OUT	ERODED OUT	2466	NR
TAHBILK-1	26	87	3226	580	898	1250? LOST CIRC	1608	FAULTED OUT	ERODED OUT	ERODED OUT	3108	NR
TALBOT 1	11	104	1784	NA	497	832	1098	1507	ERODED OUT	ERODED OUT	ERODED OUT	NR
TALTARNI-1	18	75	3362	NA	700	1248	1846	2326	ERODED OUT	ERODED OUT	3282	NR
TANCRED-1	18	109	1660	NA	432	730	874	1347	ERODED OUT	ERODED OUT	ERODED OUT	NR
TURNSTONE 1	25	118	2019	NA	358	686	923	1424	ERODED OUT	ERODED OUT	ERODED OUT	NR
VOLTAIRE 1	15	331	2720	NA	1296?	1591	2035	2449	ERODED OUT	ERODED OUT	ERODED OUT	NR
VULCAN 1B	28	109	3745	457?	838	1411	1931	2281	2682	3069	NR	
WARB 1	22	329	2583	667	1218	1901	2207	2236	ERODED OUT	ERODED OUT	ERODED OUT	NR
WILLEROO-1	26	119	2676	NA	604	978	1469	1980	ERODED OUT	ERODED OUT	2366	NR
YERING 1	22	78	3011	NA	722	1267	1783	2432?	ERODED OUT	ERODED OUT	NR	

Table 2-C

HORIZON COLOUR	HORIZON TITLE
Dark Blue	Sea Floor
Orange	Intra Late Miocene SB
Light Blue	Mid Oligocene SB
Magenta	Early Eocene SB
Jade	Early Palaeocene FS
Dark Red	Valanginian SB/FS
Green	Mid-Tithonian SB
Blue	Mid-Kimmeridgian SB
Brown	Mid Callovian SB
Pink	Nr Top Permian Limestone FS

Table 3: Seismic horizon colours VTT/VTX data

BIBRA DRAFTING SERVICE (09) 481 3113

PMB96018

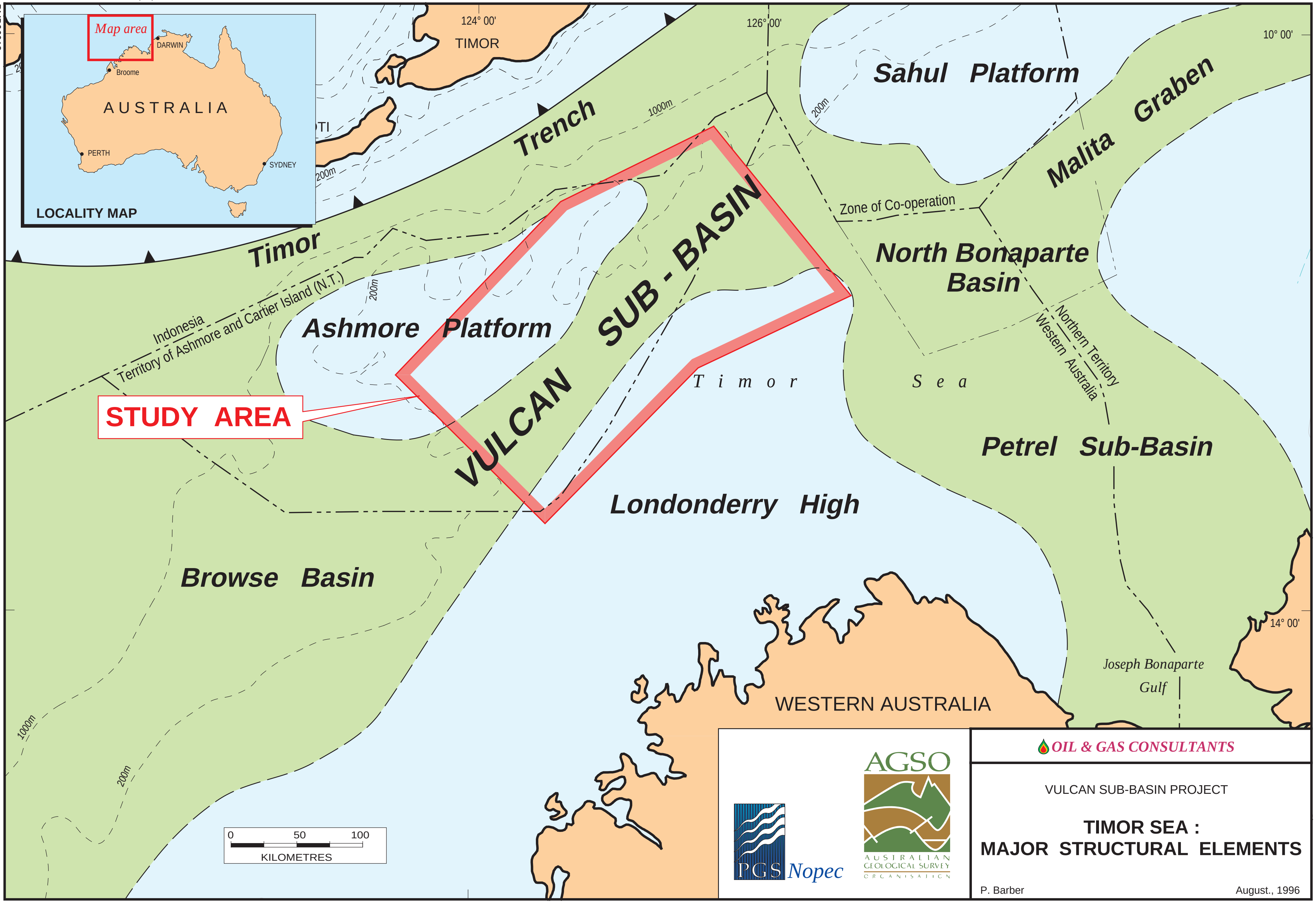
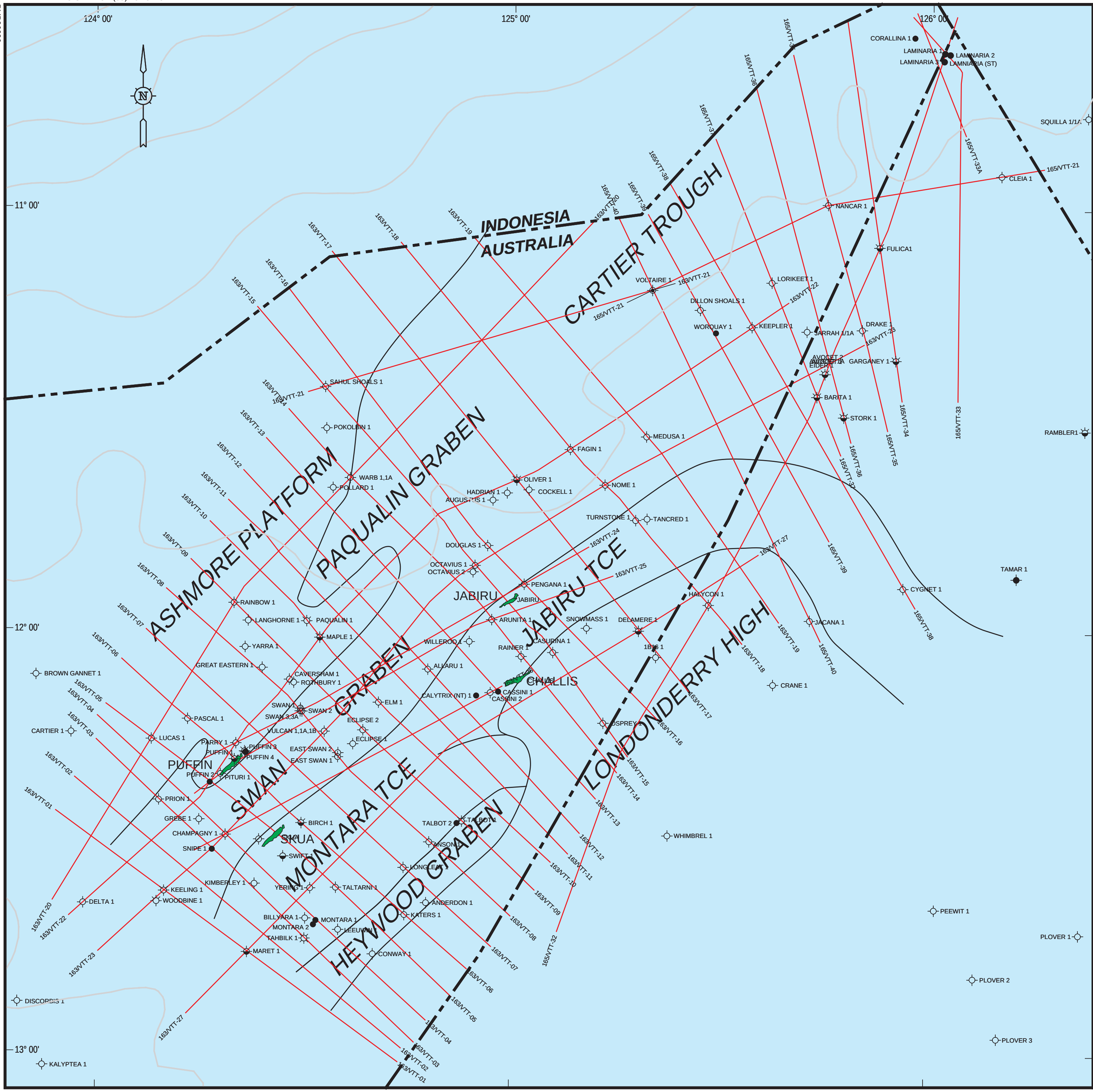
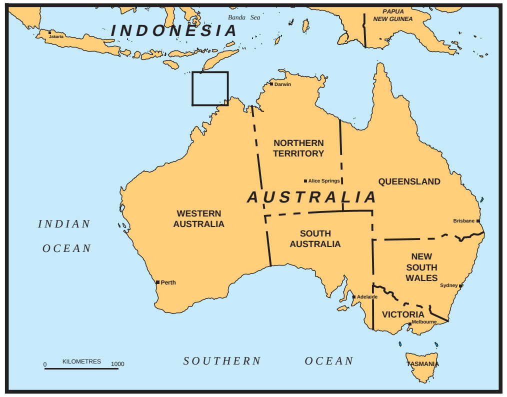


FIGURE 1

BIBRA DRAFTING SERVICE (09) 481 3113

PMB96026





PGS Nopec

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0 50
KILOMETRES

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

KEY WELLS AND VTT/VTX SEISMIC USED IN STUDY

S. Sturrock \ P. Barber

August, 1996

FIGURE 2

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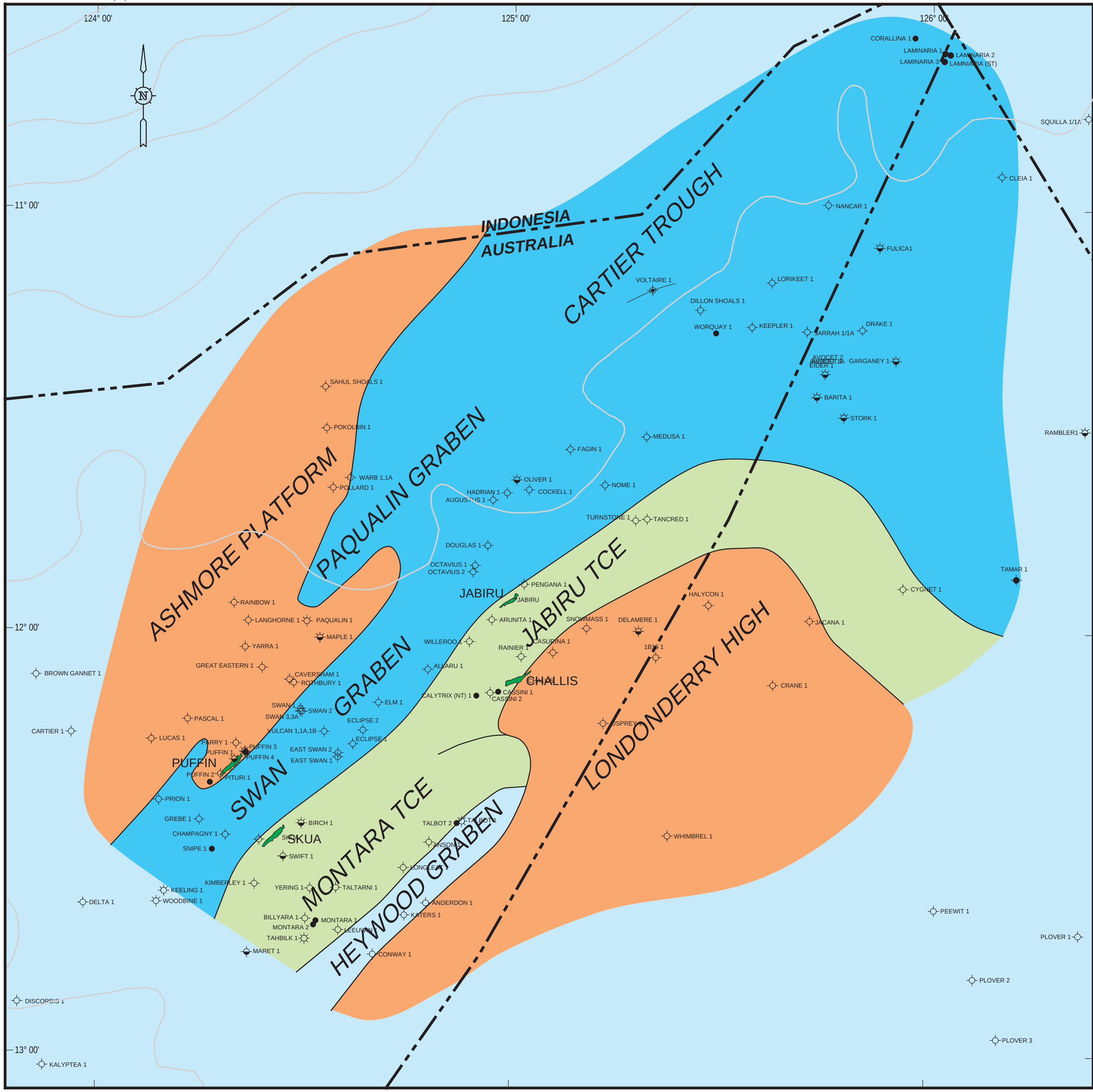
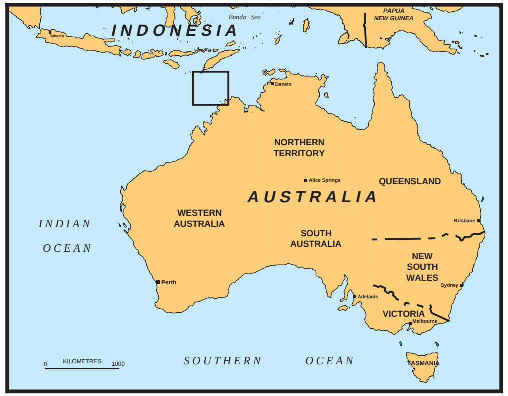
PMB96024





PGS Nopec

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KILOMETRES

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

BROAD STRUCTURAL ELEMENTS AND KEY WELLS USED IN STUDY

S. Sturrock \ P. Barber

August, 1996

FIGURE 3

TIMOR SEA : PERMIAN - RECENT GROSS LITHOSTRATIGRAPHIC COLUMN

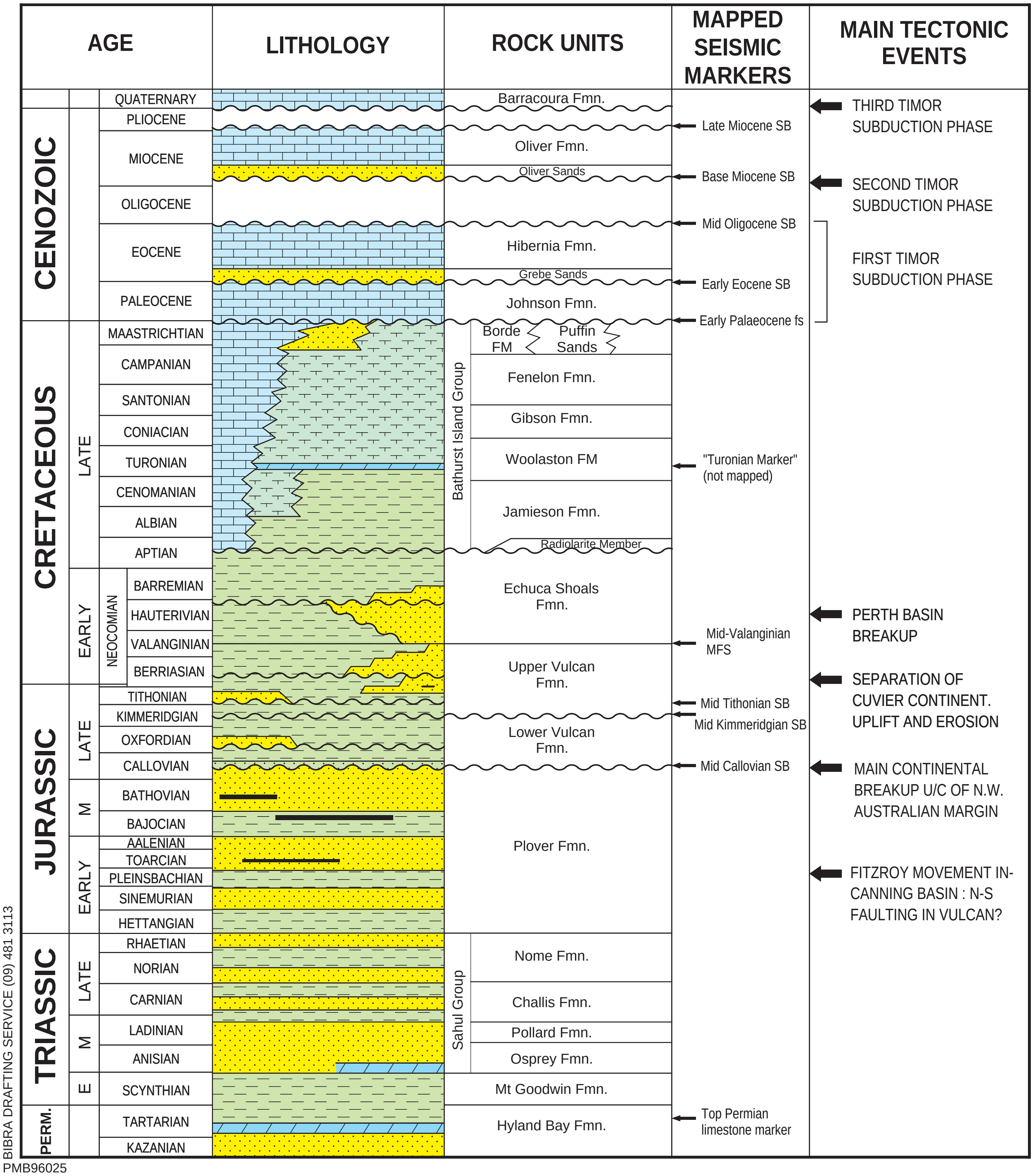

FIGURE 4

PGS Nopec

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BIBRA DRAFTING SERVICE (09) 481 3113

PMB96029

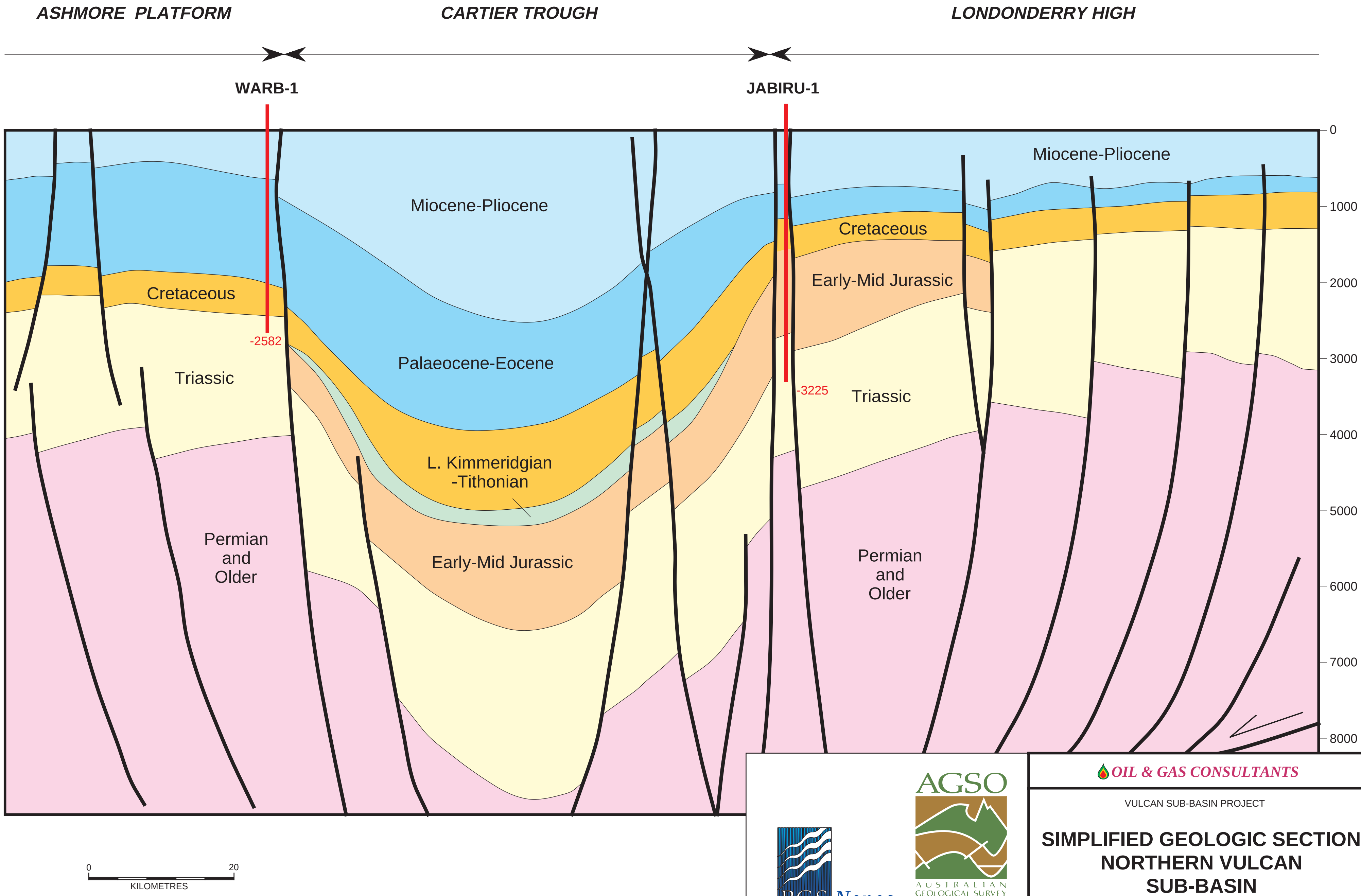

FIGURE 5

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

SIMPLIFIED GEOLOGIC SECTION NORTHERN VULCAN SUB-BASIN

S. Sturrock \ P. Barber

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BIBRA DRAFTING SERVICE (09) 481 3113

PMB96028

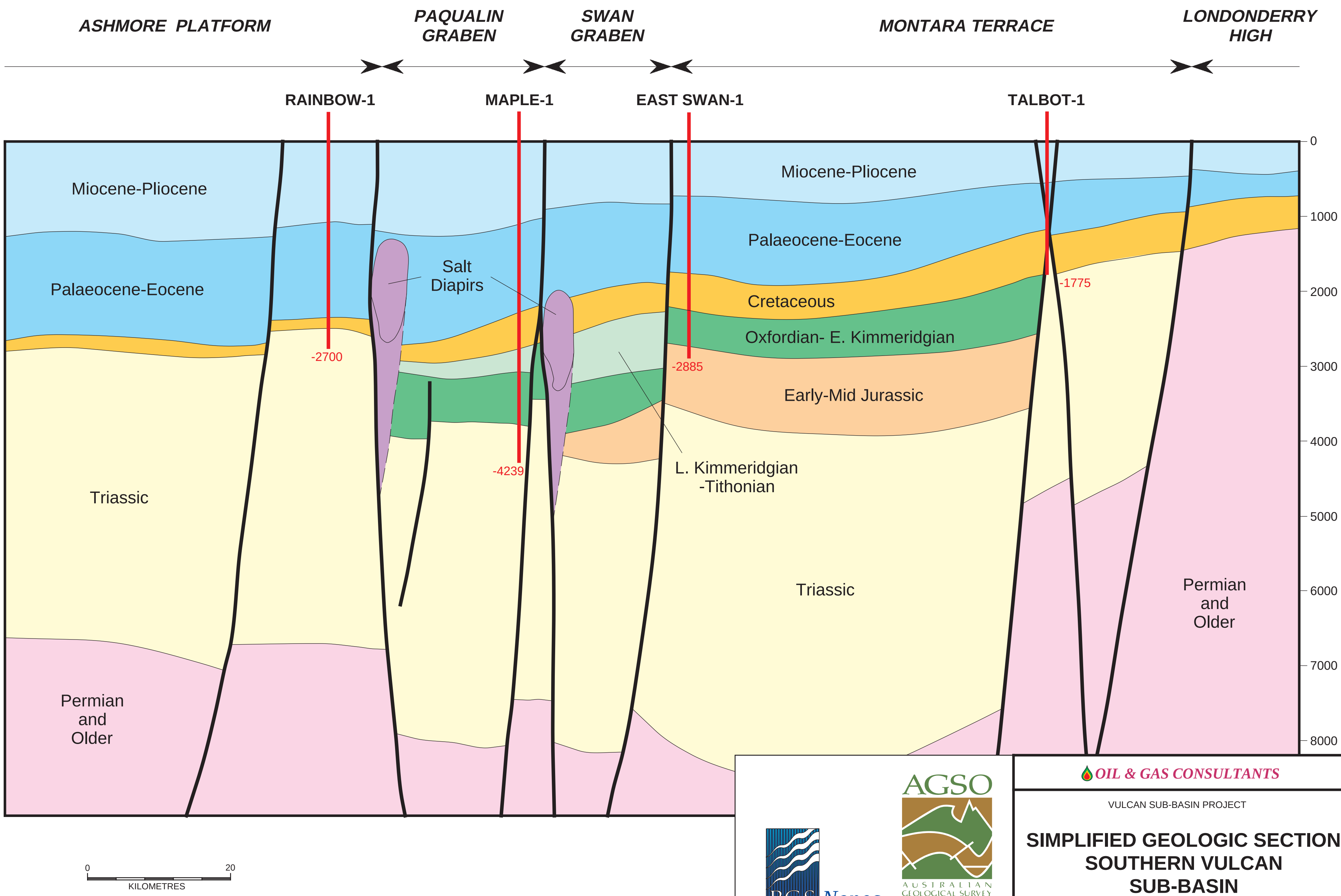

FIGURE 6

OIL & GAS CONSULTANTS

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VULCAN SUB-BASIN PROJECT

SIMPLIFIED GEOLOGIC SECTION SOUTHERN VULCAN SUB-BASIN

S. Sturrock \ P. Barber

Sept, 1996

BIBRA DRAFTING SERVICE (09) 481 3113

PMB96012

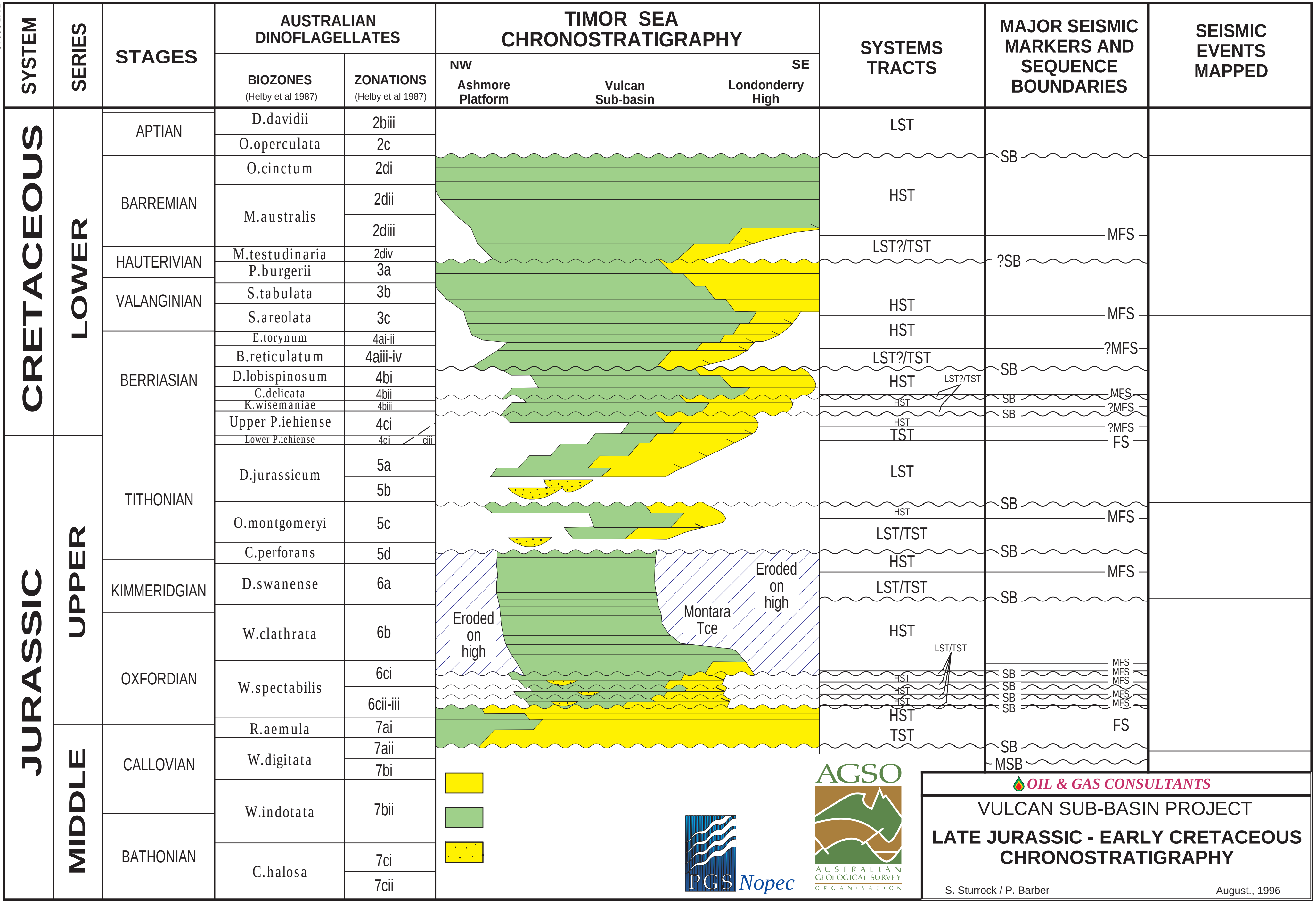


FIGURE 7

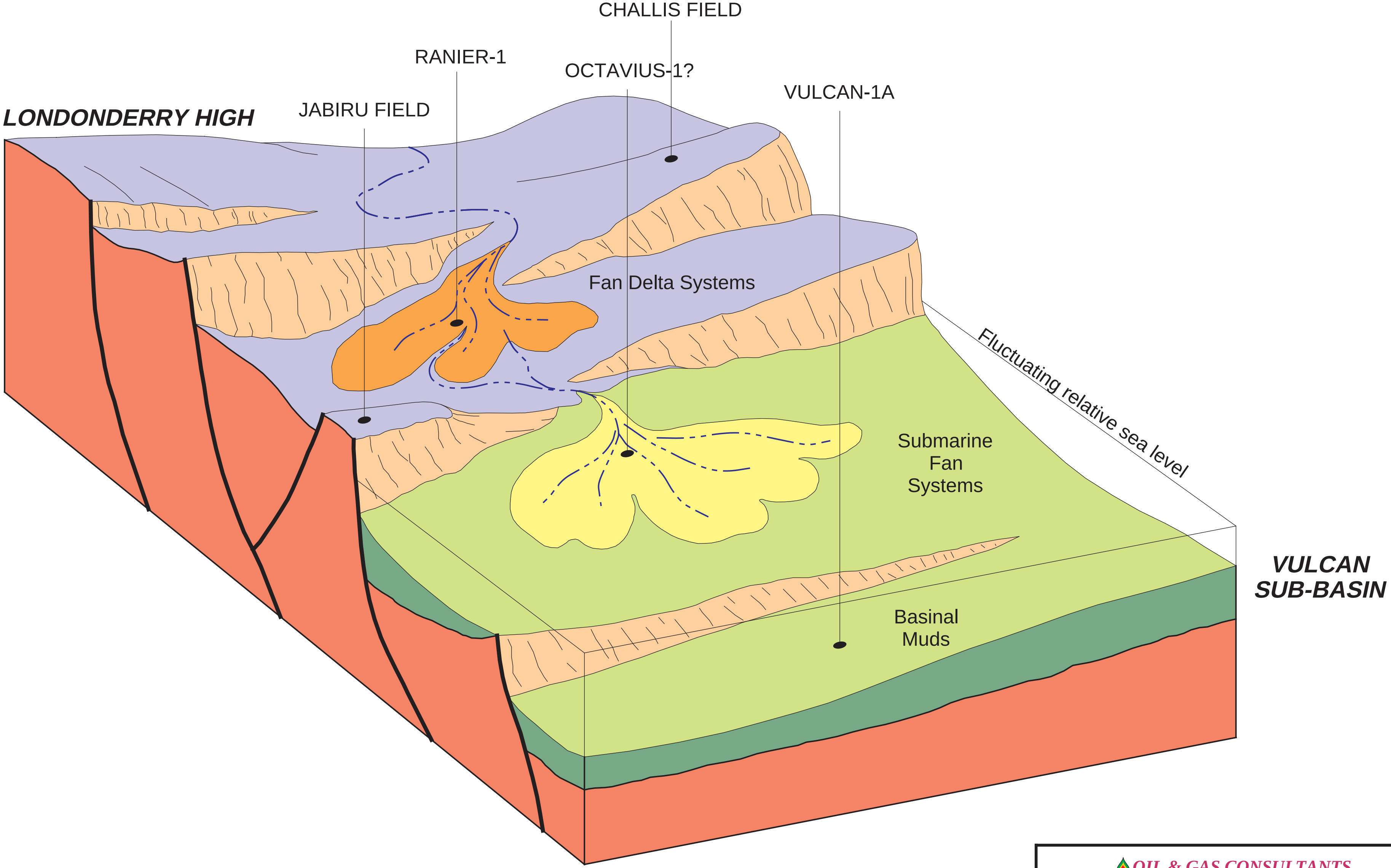
BIBRA DRAFTING SERVICE (09) 481 3113

PM96022

FIGURE 8

BIBRA DRAFTING SERVICE (09) 481 3113

PMB96023



OIL & GAS CONSULTANTS

PGS Nopec

AGSO AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

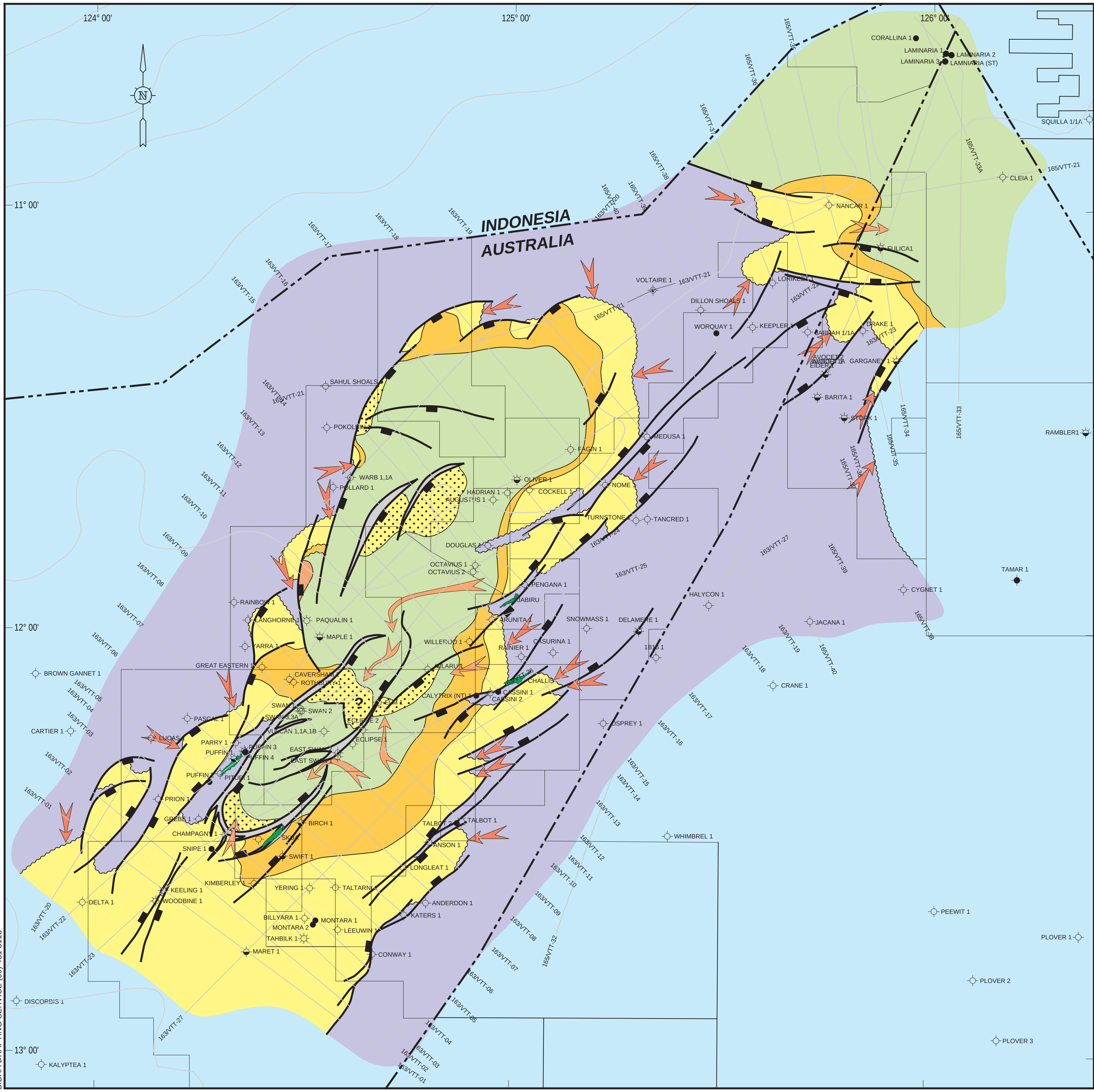
VULCAN SUB-BASIN PROJECT

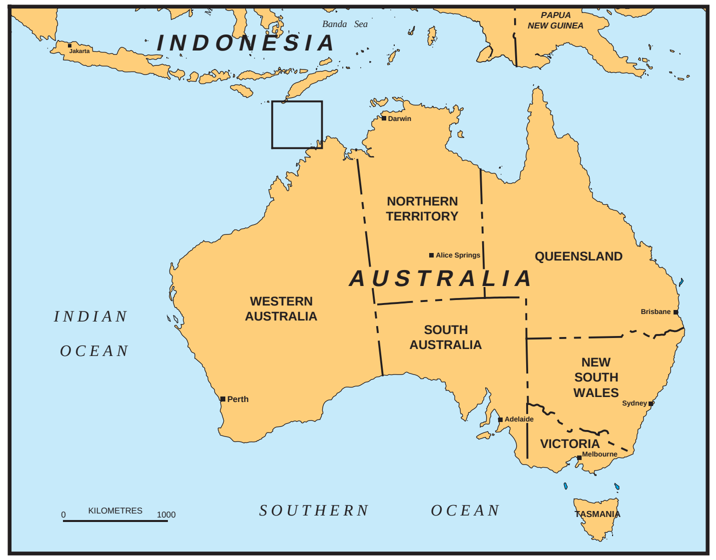
SCHEMATIC BLOCK DIAGRAM ILLUSTRATING SYN-TECTONIC DEPOSITIONAL SYSTEMS DURING LATE JURASSIC TIME

P. Barber / S. Sturrock

August., 1996

FIGURE 9





LEGEND

- Eroded or Subaerial
- Sand prone topsets
- Predominantly mud prone shallow marine to delta front
- Mud prone slope to basin
- Sand prone submarine fan / channels

PGS Nopec

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KILOMETRES

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VULCAN SUB-BASIN PROJECT

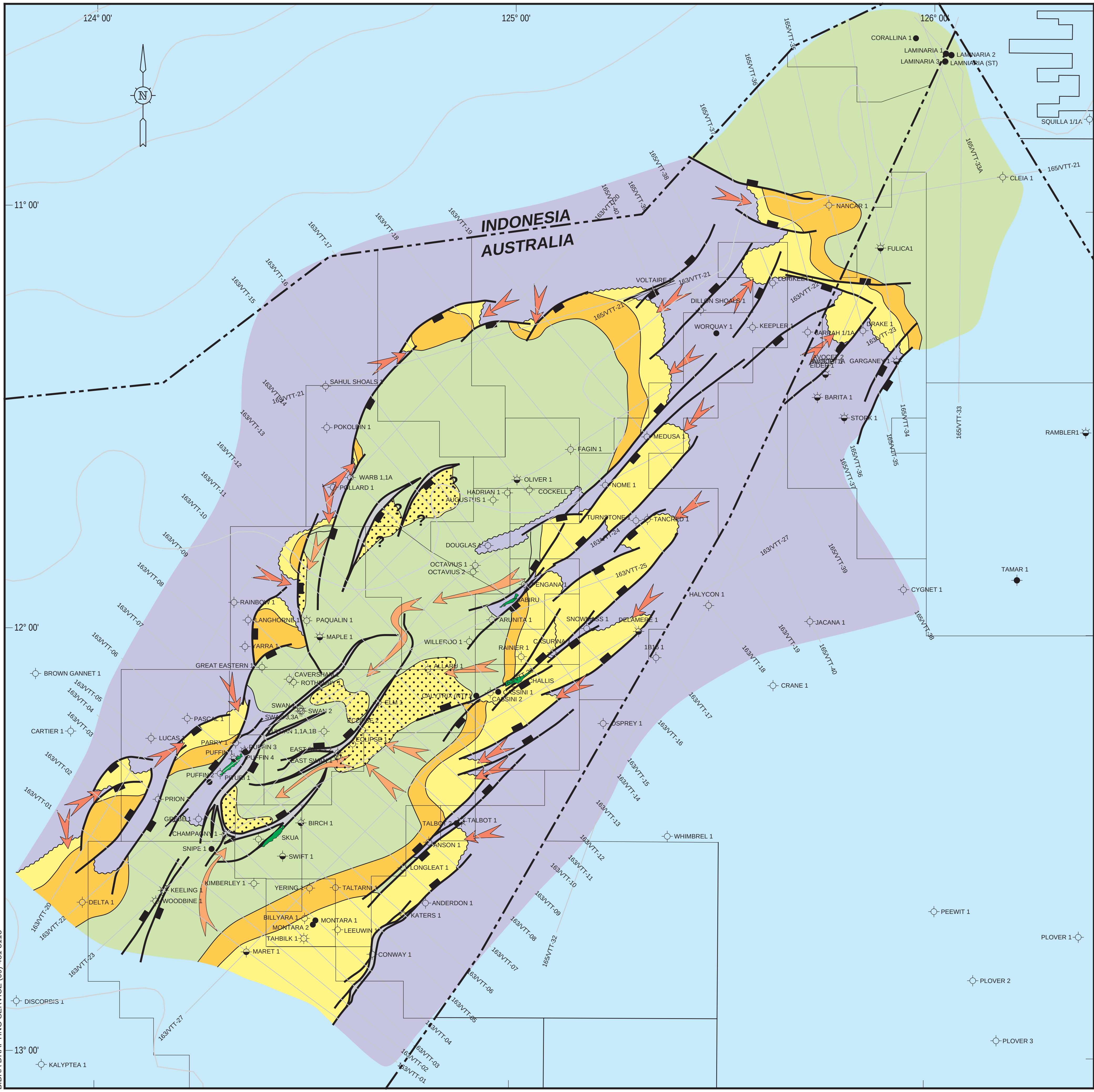
GROSS DEPOSITIONAL ENVIRONMENT EARLY OXFORDIAN (6ciii) Lowstand Systems Tract

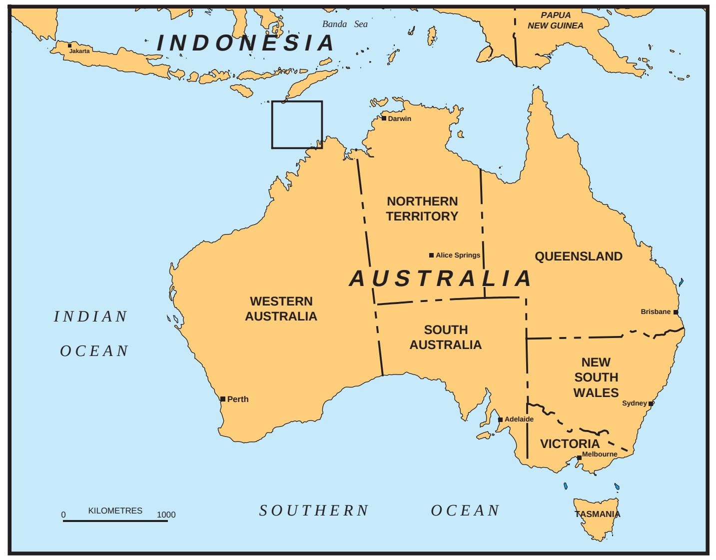
S. Sturrock \ P. Barber

August, 1996

FIGURE 10

File No. PMB96020





LEGEND

- Eroded or Subaerial
- Sand prone topsets
- Predominantly mud prone shallow marine to delta front
- Mud prone slope to basin
- Sand prone submarine fan / channels

0 50
KILOMETRES

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

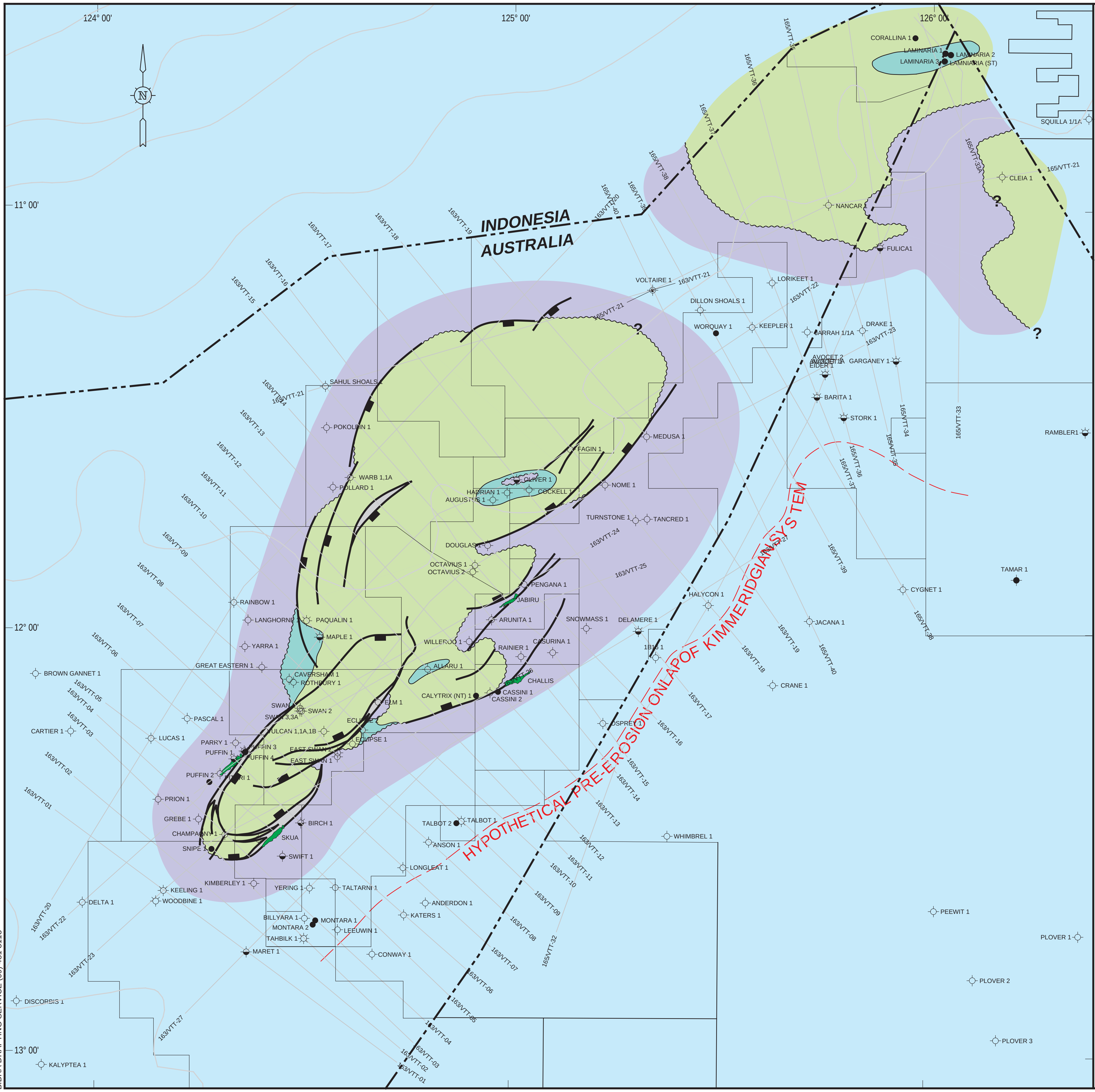
GROSS DEPOSITIONAL ENVIRONMENT LATE OXFORDIAN (6ci/ii) RETROGRADATION

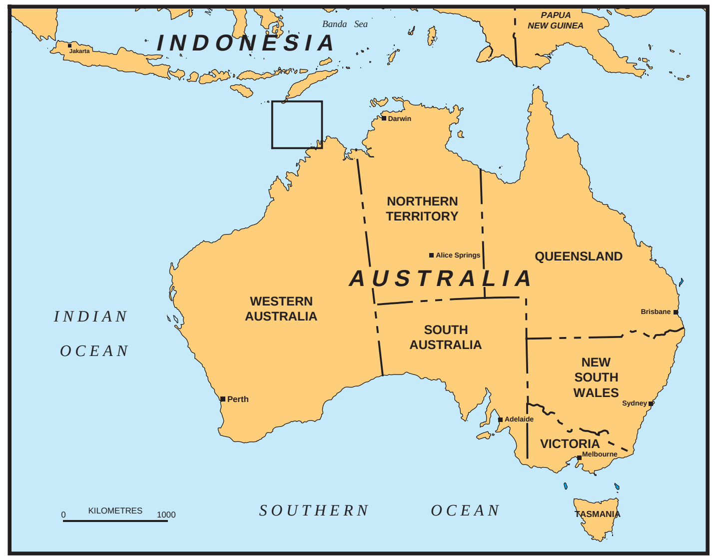
S. Sturrock \ P. Barber

August, 1996

FIGURE 11

BIBRA DRAFTING SERVICE (09) 481 3113
File No. PMB96021





LEGEND

- Eroded or Subaerial
- Mud prone shallow basin
- Marl

PGS Nopec

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0 50
KILOMETRES

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VULCAN SUB-BASIN PROJECT

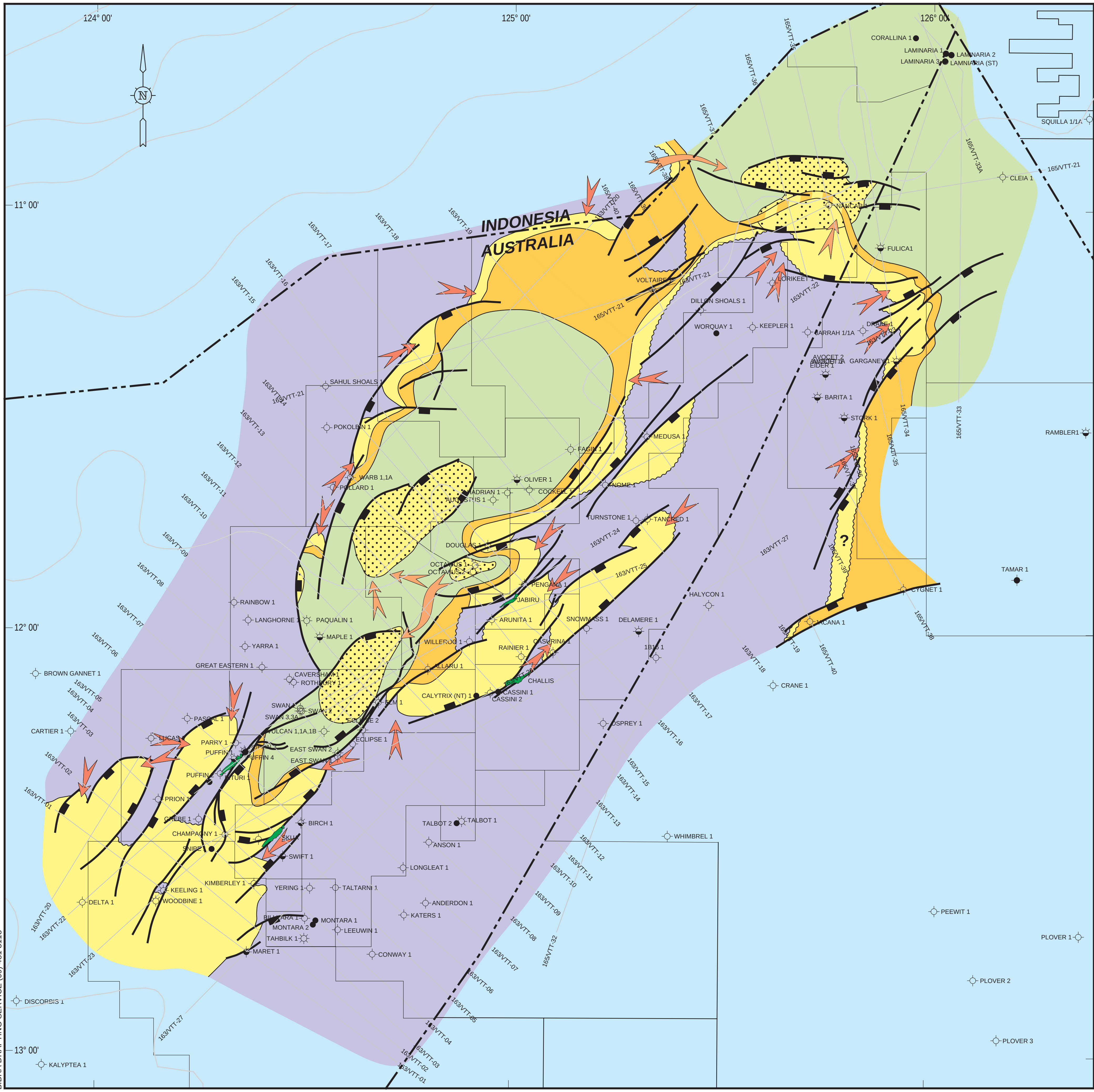
GROSS DEPOSITIONAL ENVIRONMENT KIMMERIDGIAN (6a)

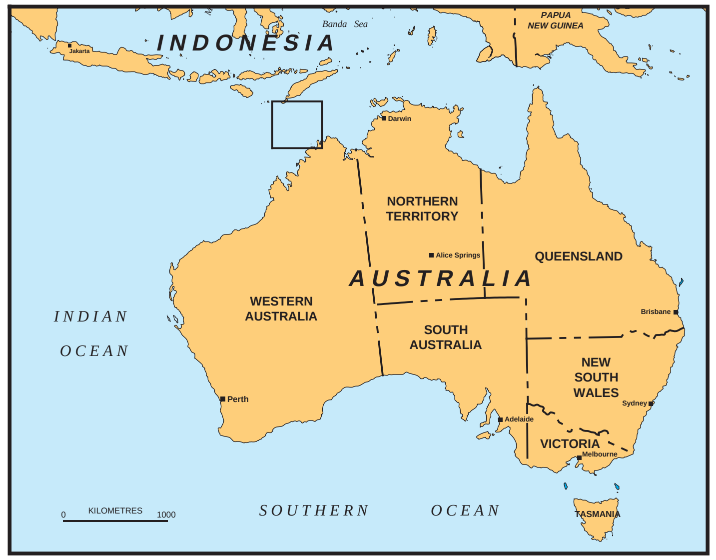
S. Sturrock \ P. Barber

August, 1996

File No. PMB96017

FIGURE 12





LEGEND

- Eroded or Subaerial
- Sand prone topsets
- Predominantly mud prone shallow marine to delta front
- Mud prone slope to basin
- Sand prone submarine fan / channels

PGS Nopec

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0 50
KILOMETRES

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VULCAN SUB-BASIN PROJECT

GROSS DEPOSITIONAL ENVIRONMENT MID TITHONIAN Lowstand Systems Tract

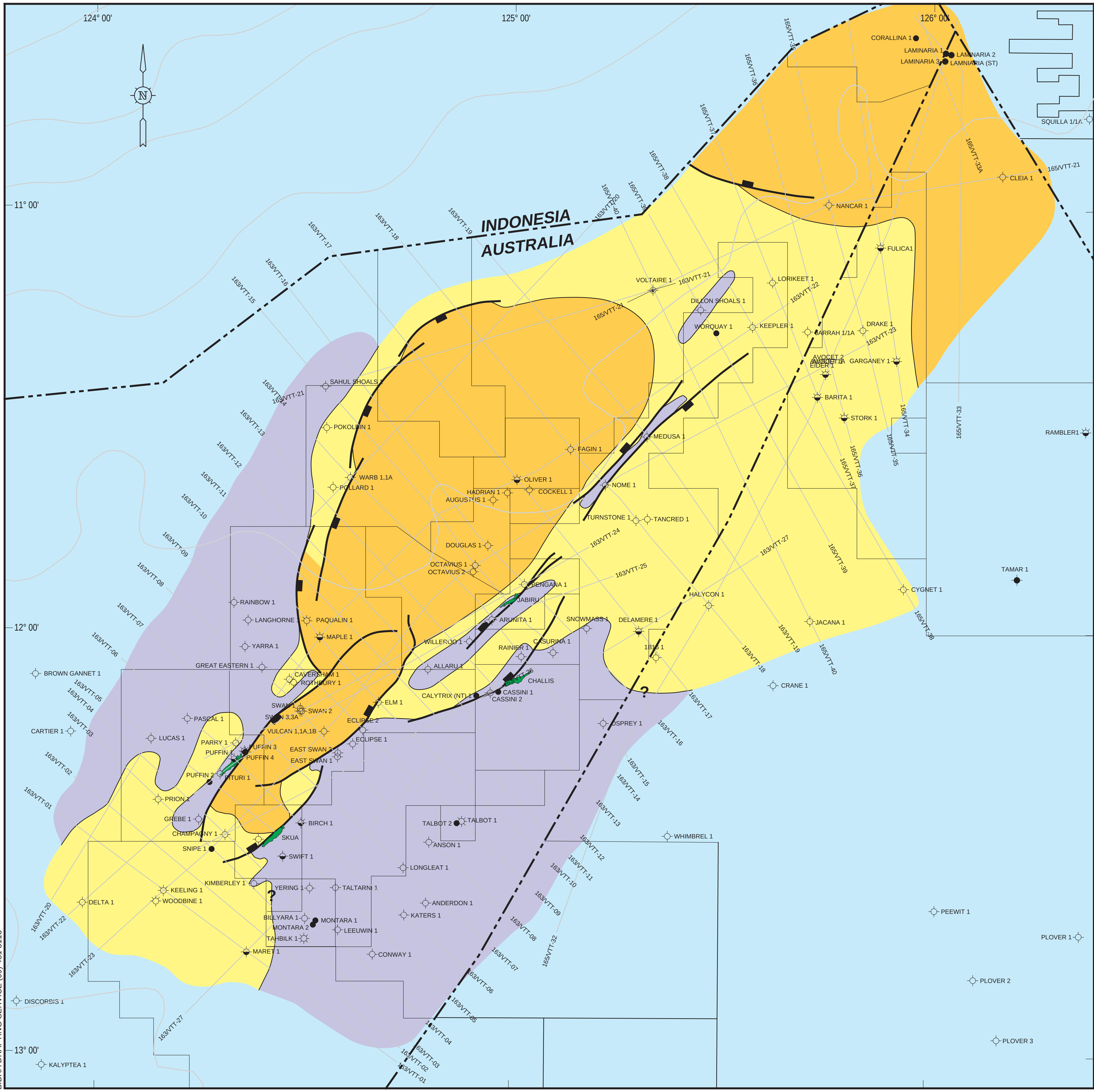
S. Sturrock \ P. Barber

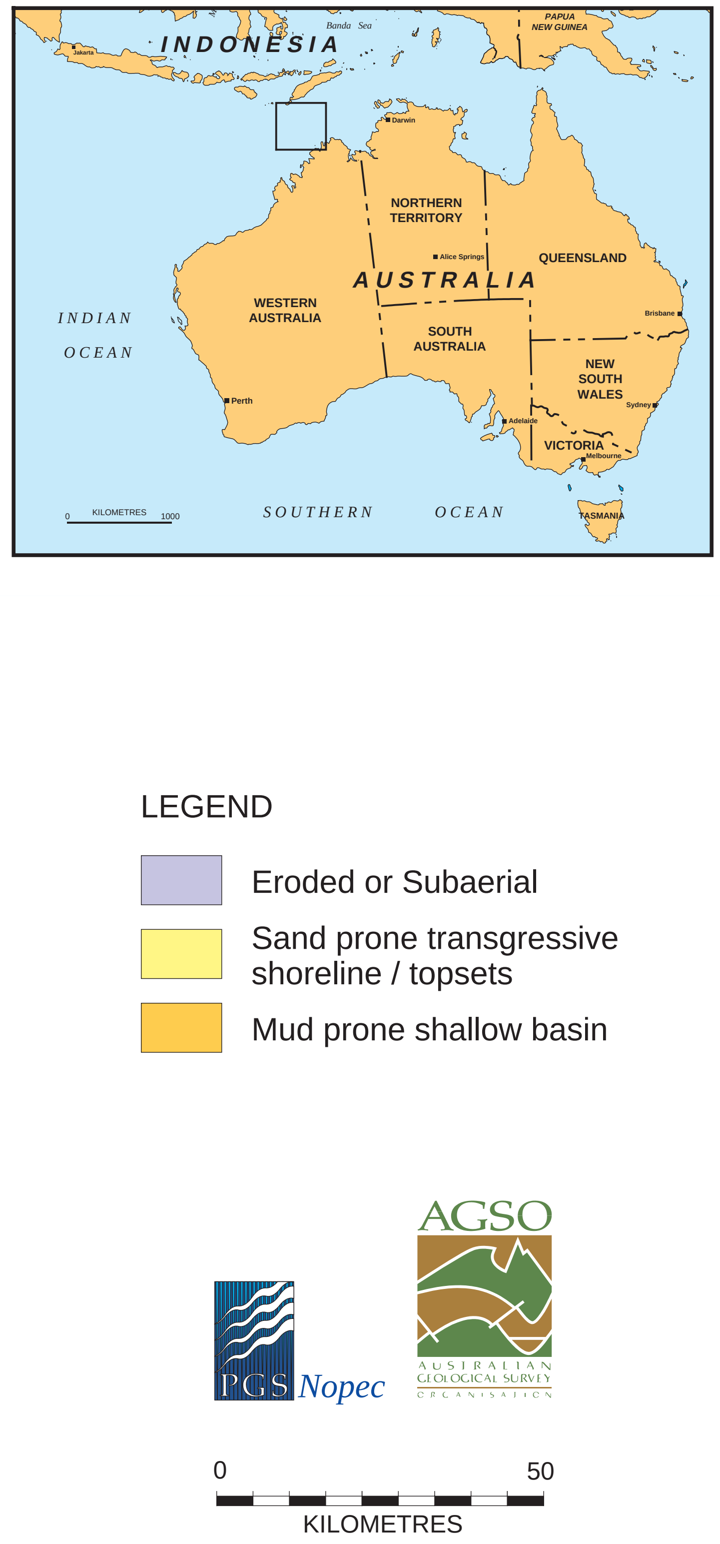
August, 1996

FIGURE 13

BIBRA DRAFTING SERVICE (09) 481 3113

File No. PMB96019





OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

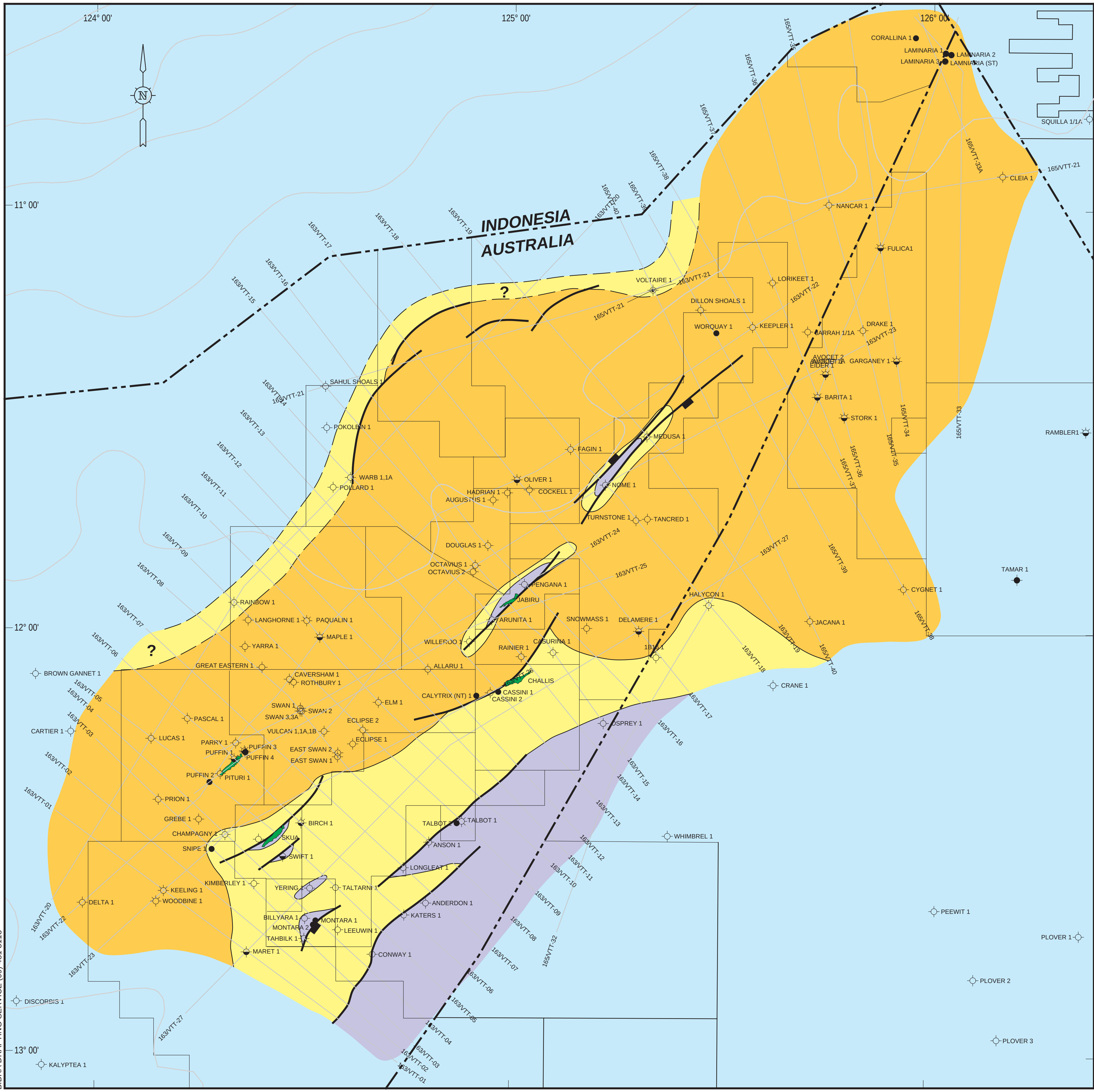
GROSS DEPOSITIONAL ENVIRONMENT BERRIASIAN (4bii/iii) Transgressive Systems Tract

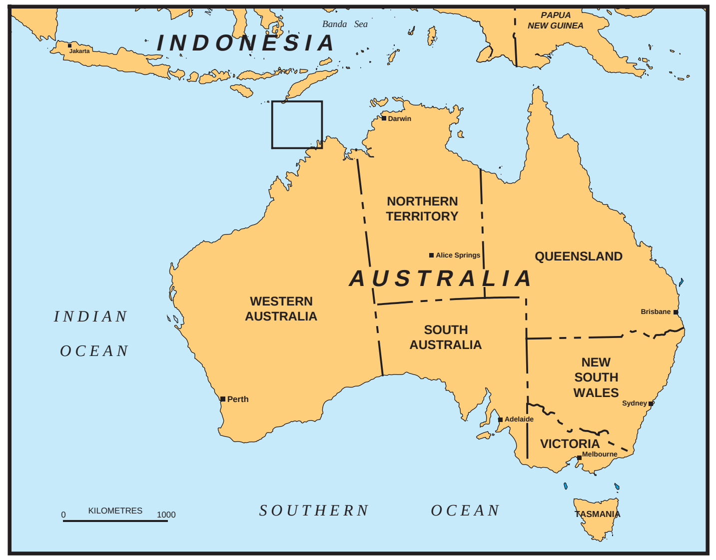
S. Sturrock \ P. Barber

August, 1996

FIGURE 14

File No. PMB96014





LEGEND

- Eroded or Subaerial
- Sand prone transgressive shoreline / topsets
- Mud prone shallow basin

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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION
PGS Nopec

0 50
KILOMETRES

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

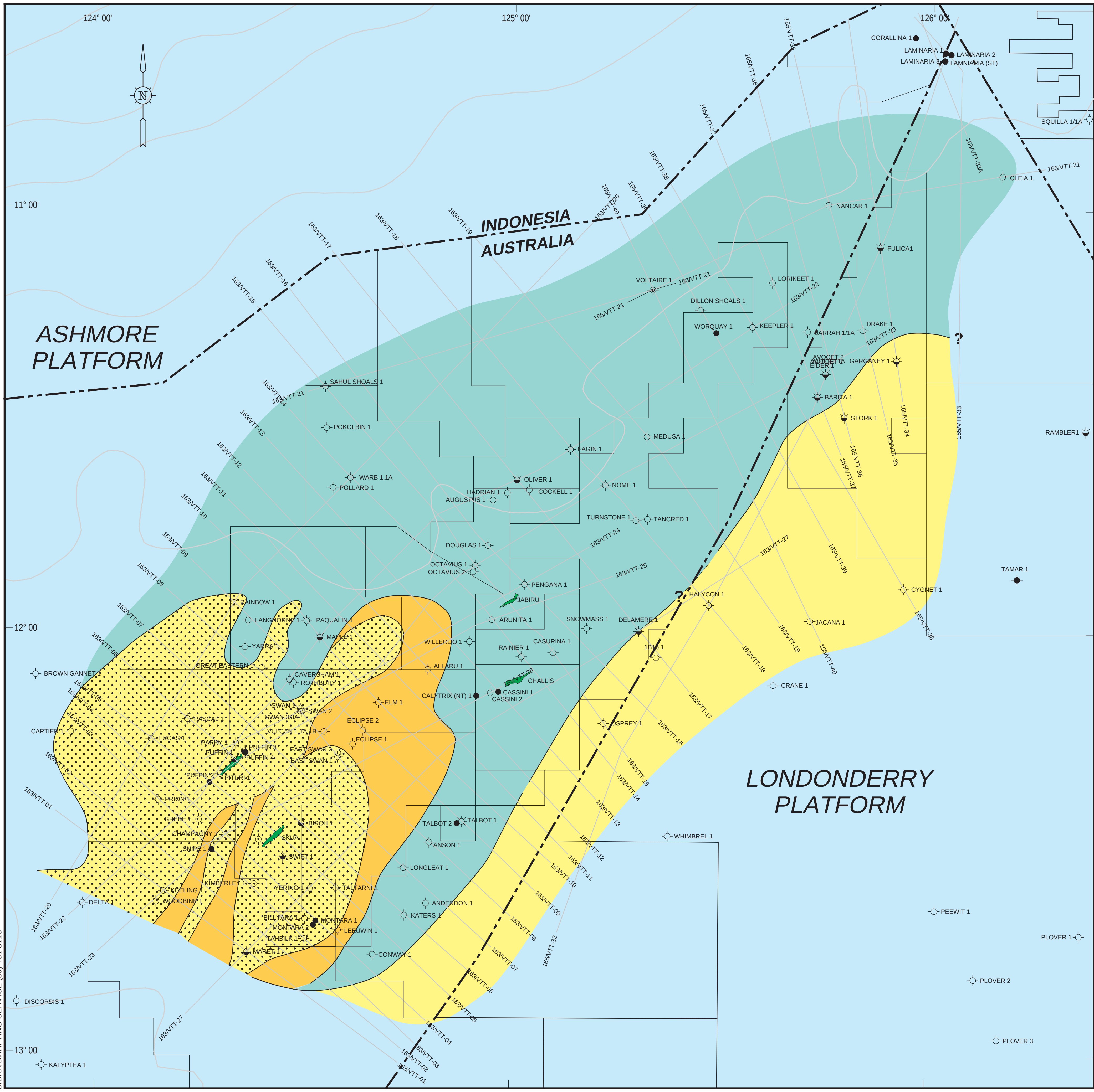
GROSS DEPOSITIONAL ENVIRONMENT VALANGINIAN (Biozone 3) Transgressive Systems Tract

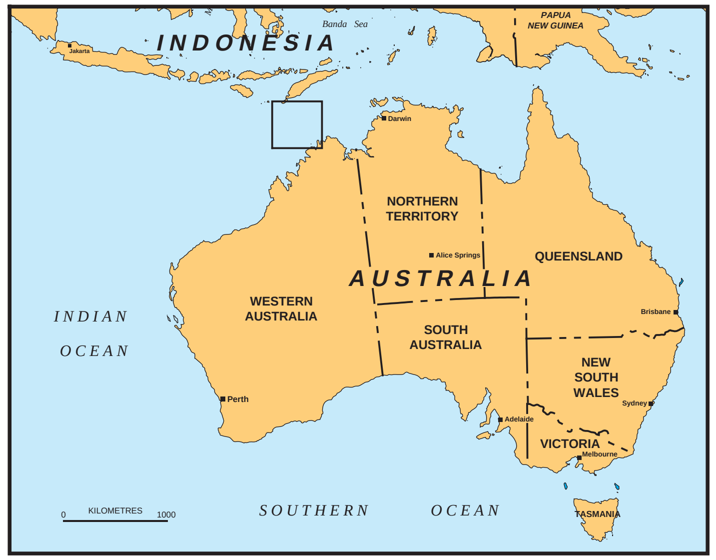
S. Sturrock \ P. Barber

August, 1996

File No. PMB96015

FIGURE 15





LEGEND

- Sand prone topsets
- Mud prone slope to basin
- Sand prone submarine fan / channels
- Marl

0 50
KILOMETRES

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

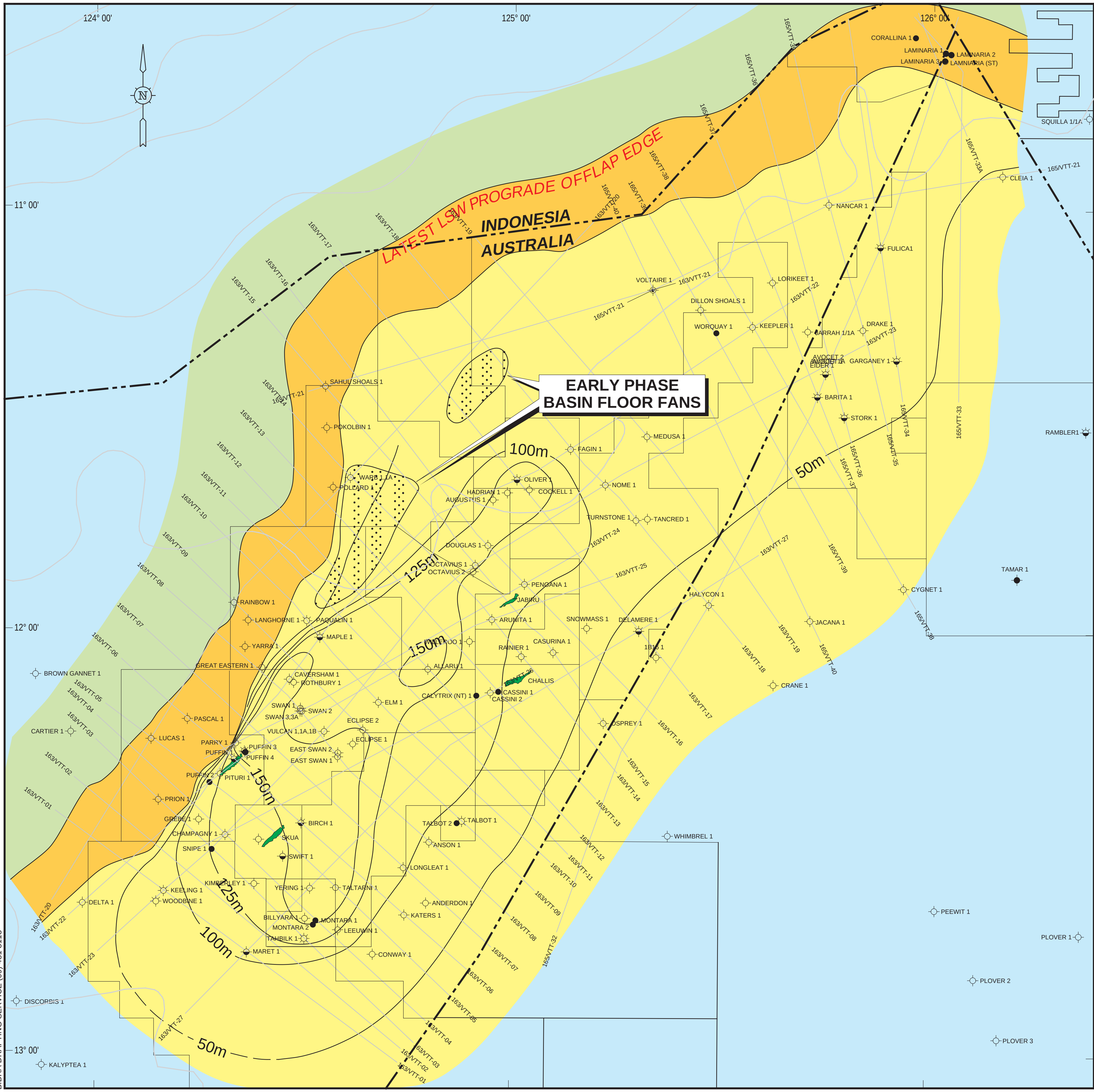
GROSS DEPOSITIONAL ENVIRONMENT MAASTRICHTIAN LOWSTANDS

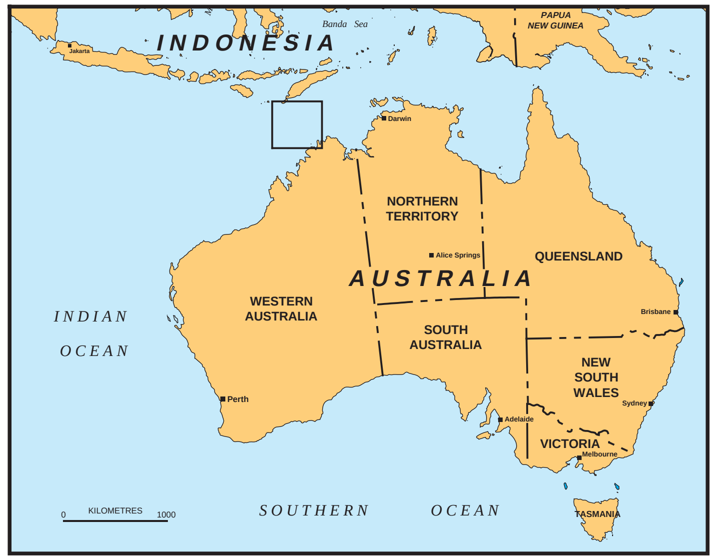
S. Sturrock \ P. Barber

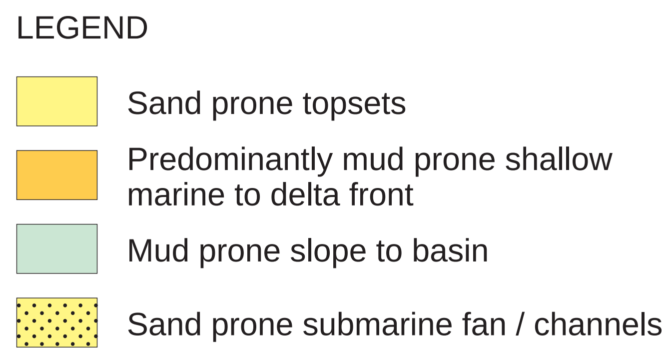
August, 1996

File No. PMB96027

FIGURE 16







PGS Nopec

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0 50
KILOMETRES

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

PALAEOENVIRONMENT EARLY EOCENE Lowstand Systems Tract and Gross Sand Thickness (m)

S. Sturrock \ P. Barber

August, 1996

File No. PMB96016

FIGURE 17

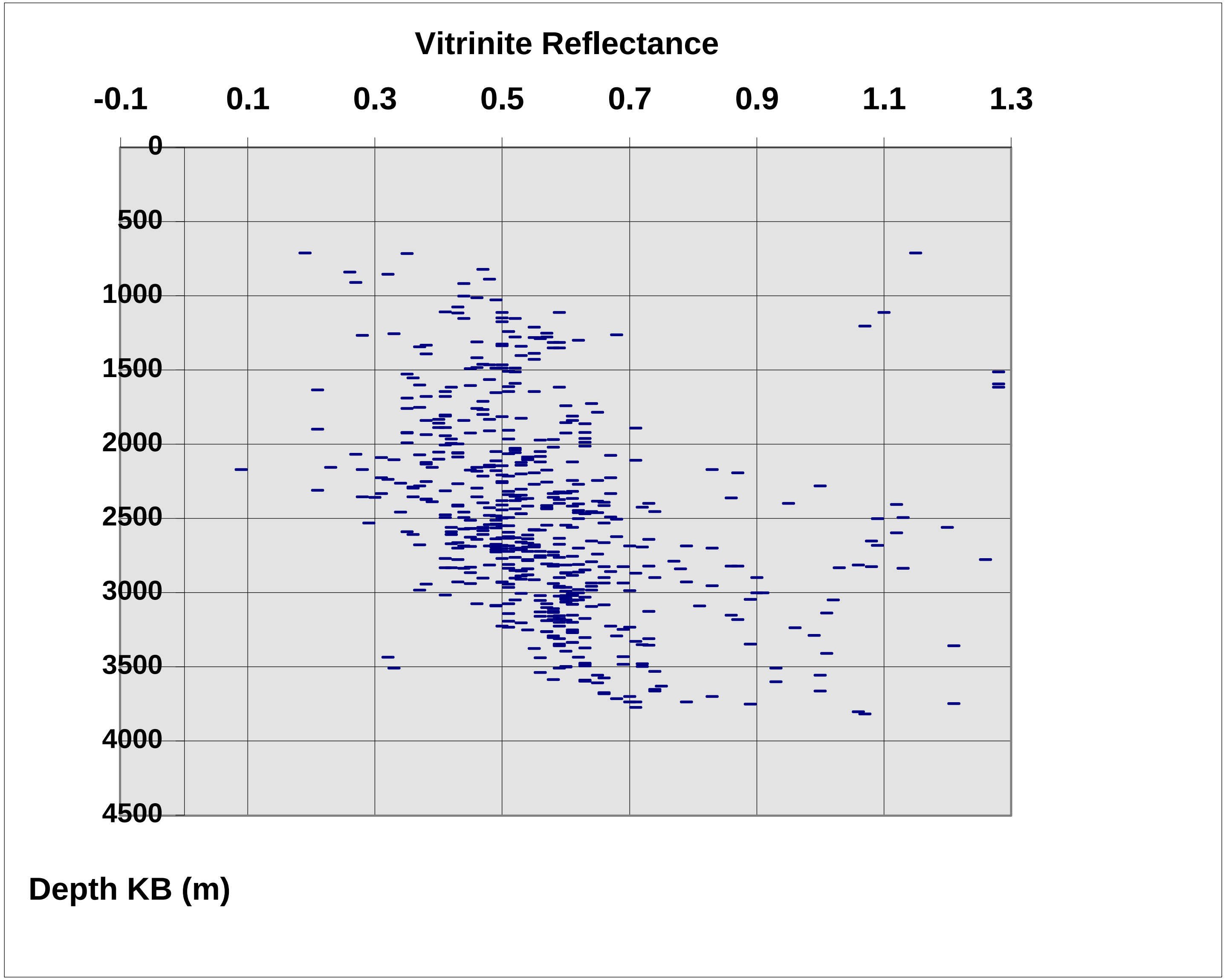


Figure 18. Vitrinite reflectance versus depth, Vulcan Sub-basin and Sahul Syncline (>30 wells).

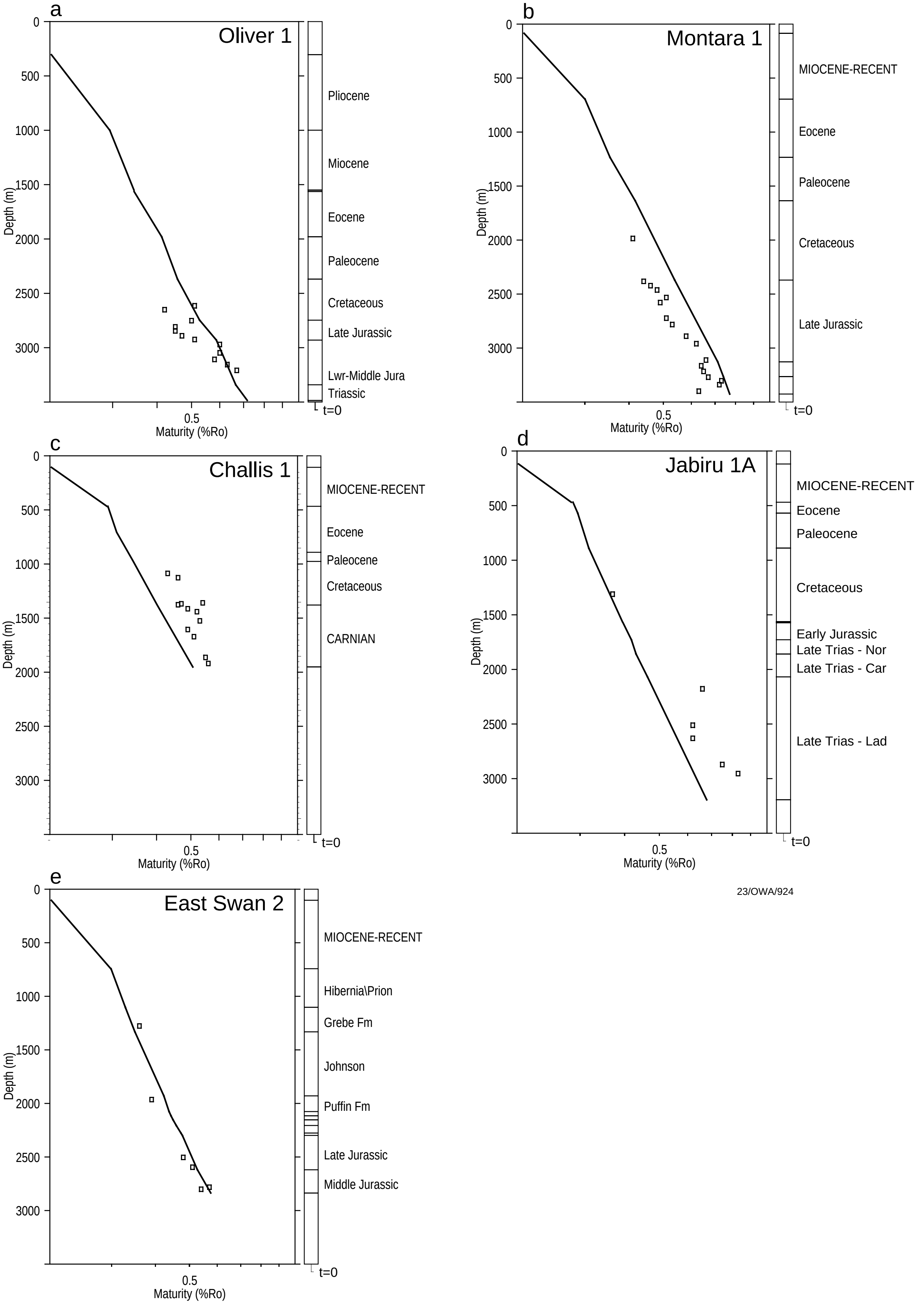


Figure 19. Vitrinite reflectance versus depth, individual wells, Vulcan Sub-basin.

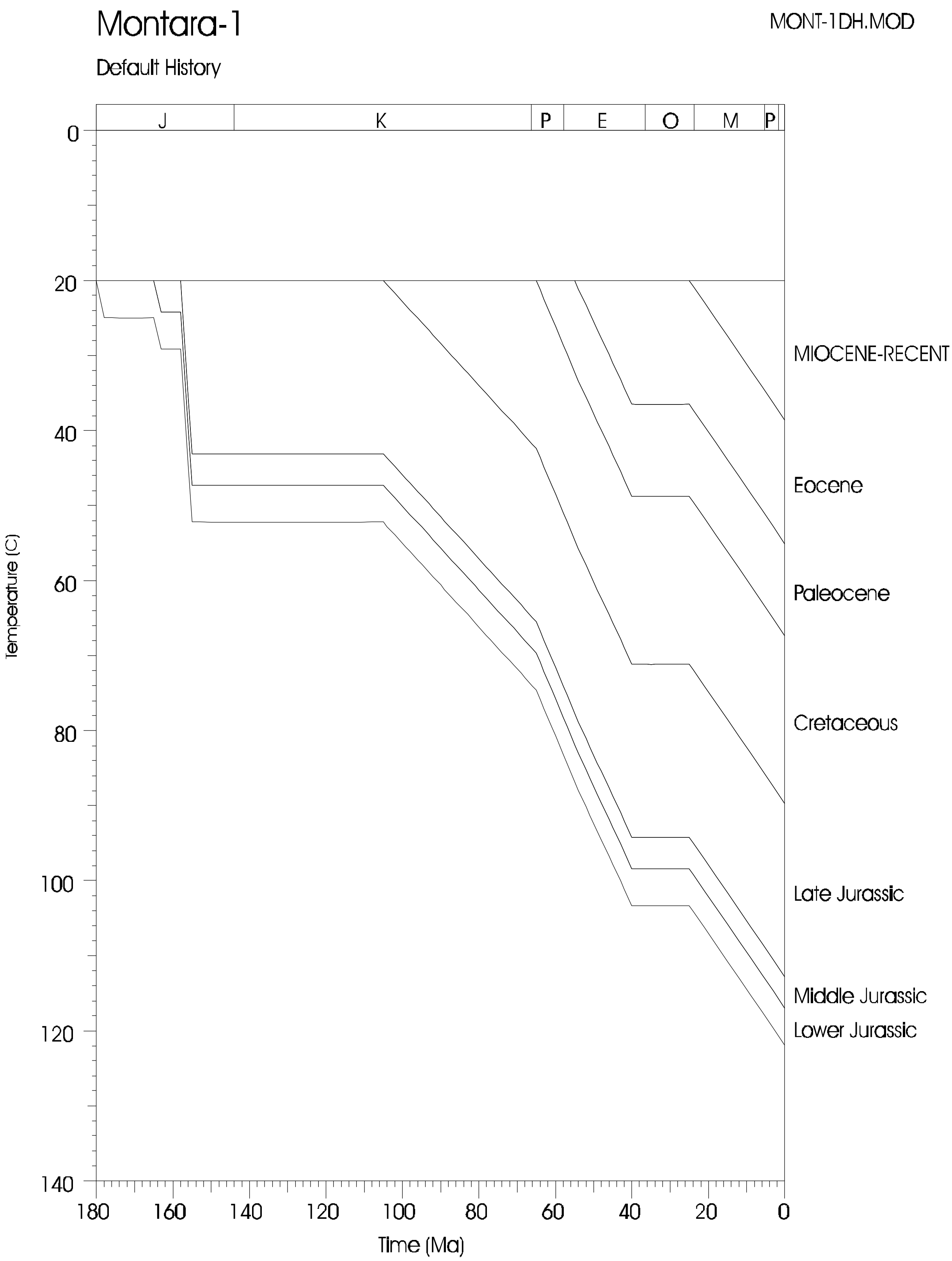


Figure 20. Thermal and subsidence history for Montara-1 well, Skua Trough.

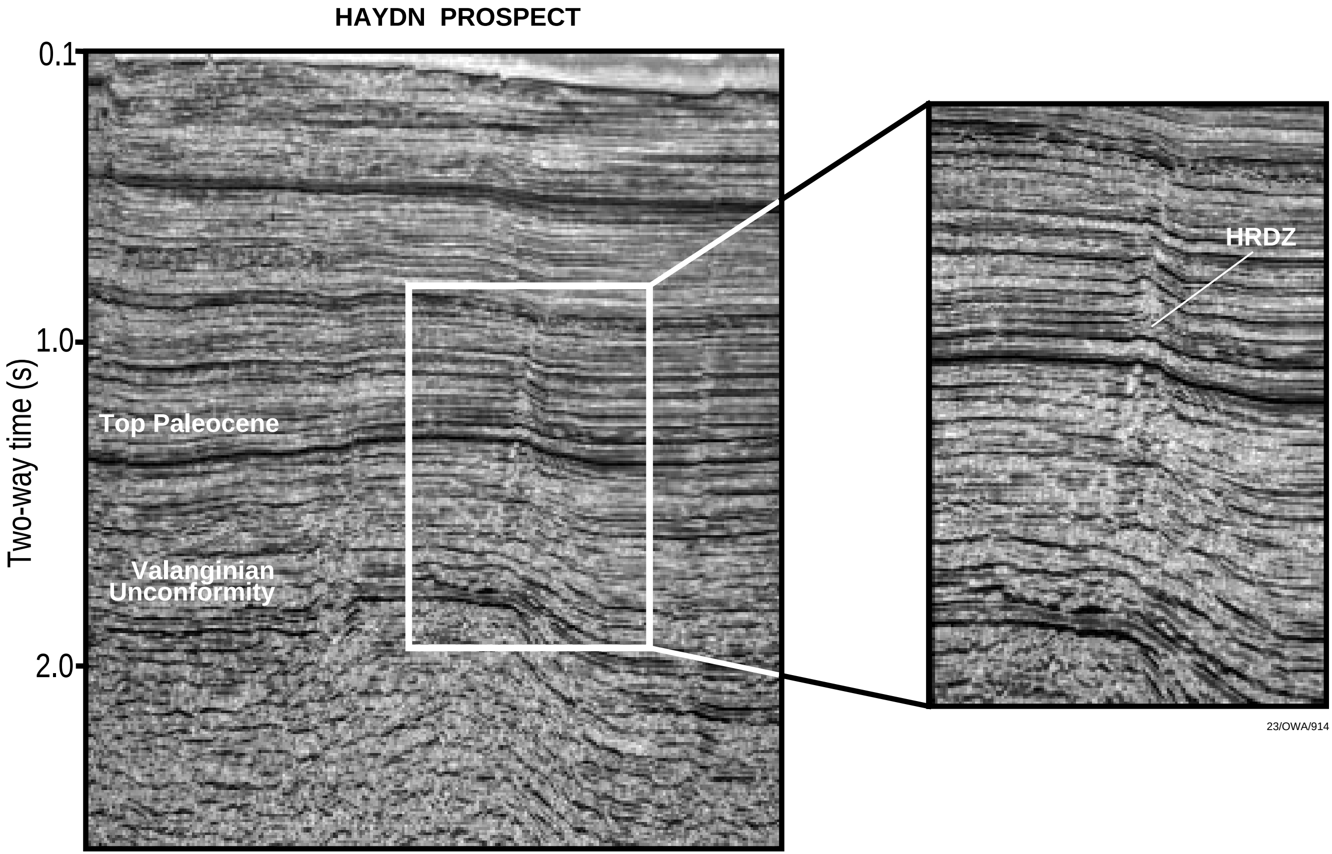


Figure 21. Seismic line showing hydrocarbon-related diagenetic zones (HRDZs) over extensional faults. Haydn prospect, VTT line 163/002.

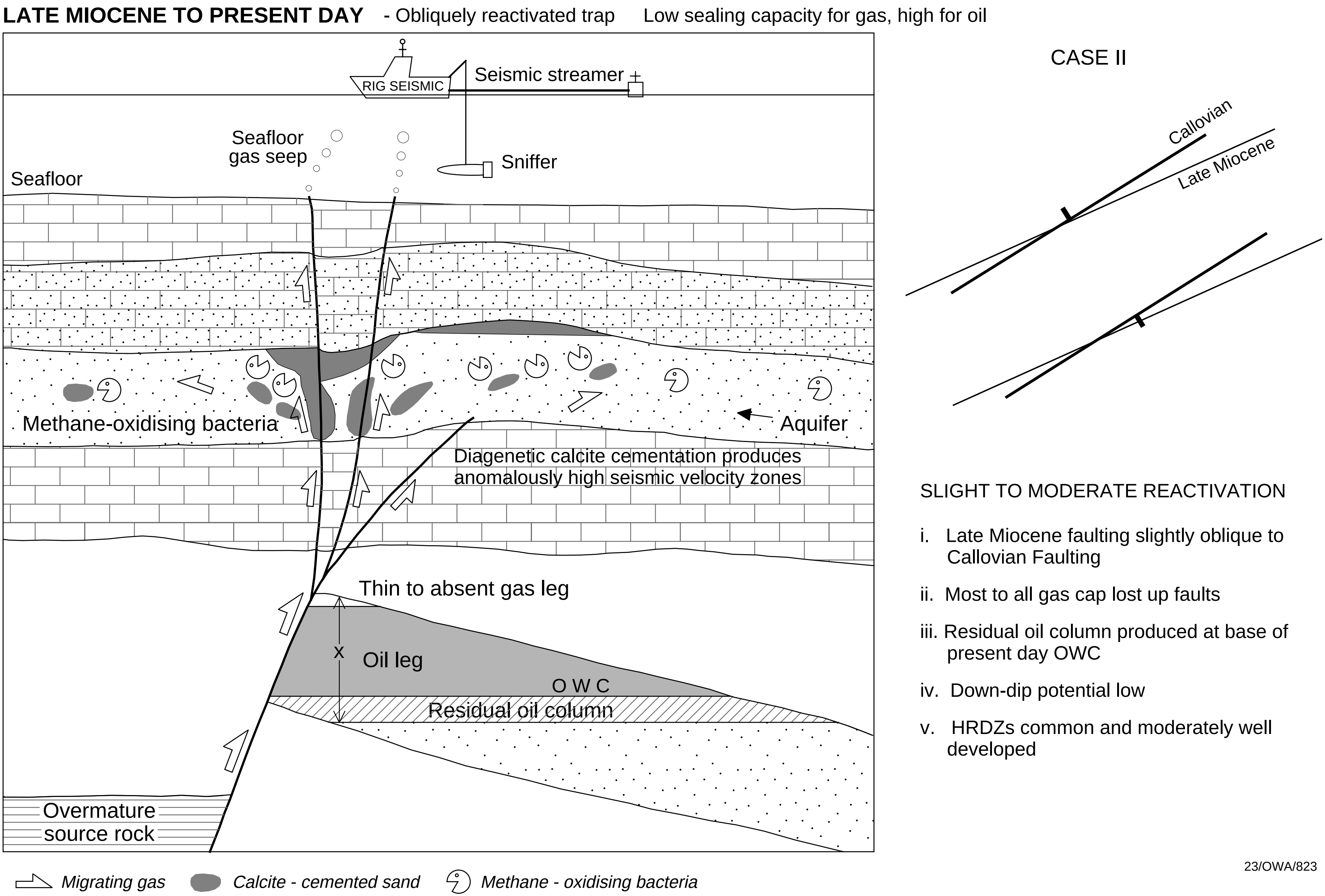


Figure 22. Schematic showing the development of HRDZs above a Moderate Integrity Trap (MIT) in the Timor Sea.

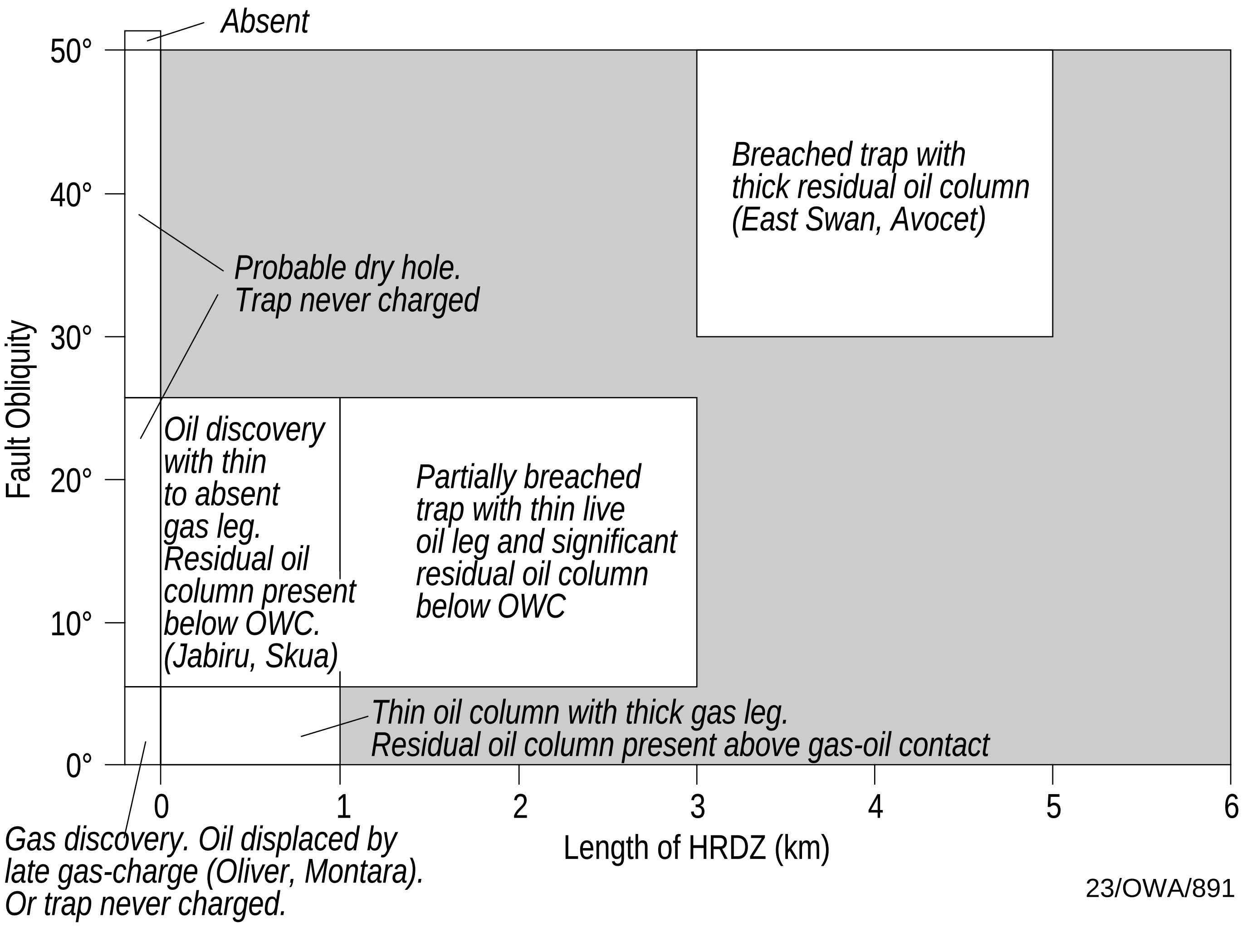


Figure 23. Schematic relationships between Mio-Pliocene/Jurassic faulting, size of HRDZs and prospectivity.

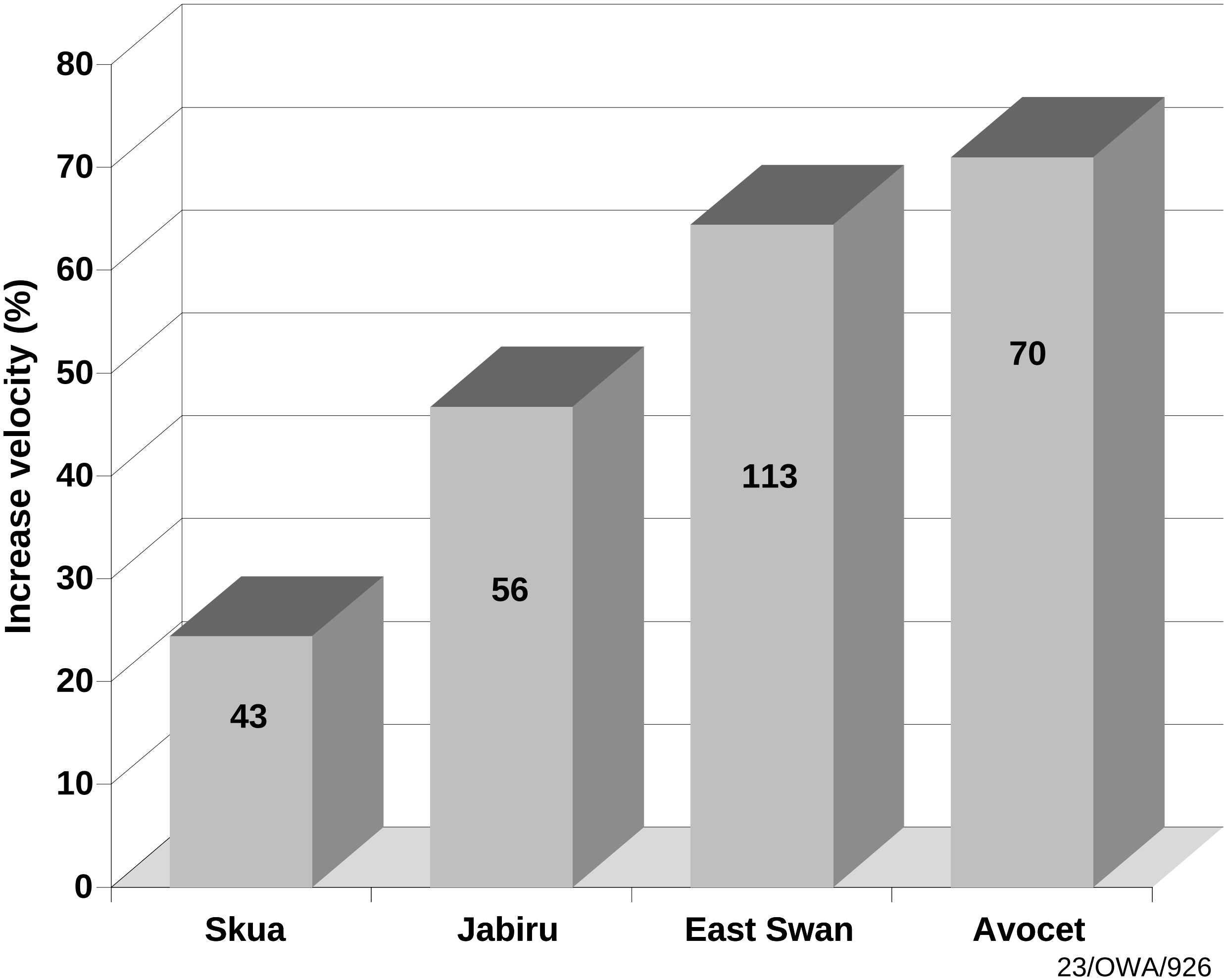


Figure 24. Velocity increases in carbonate-cemented Grebe Formation sands (ie. within HRDZs) as compared to uncemented equivalents for the Skua and Jabiru oil-fields and the East Swan and Avocet breached accumulations.
Milliseconds of seismic pull-up induced by the velocity increase is indicated (on each respective column) for each well.

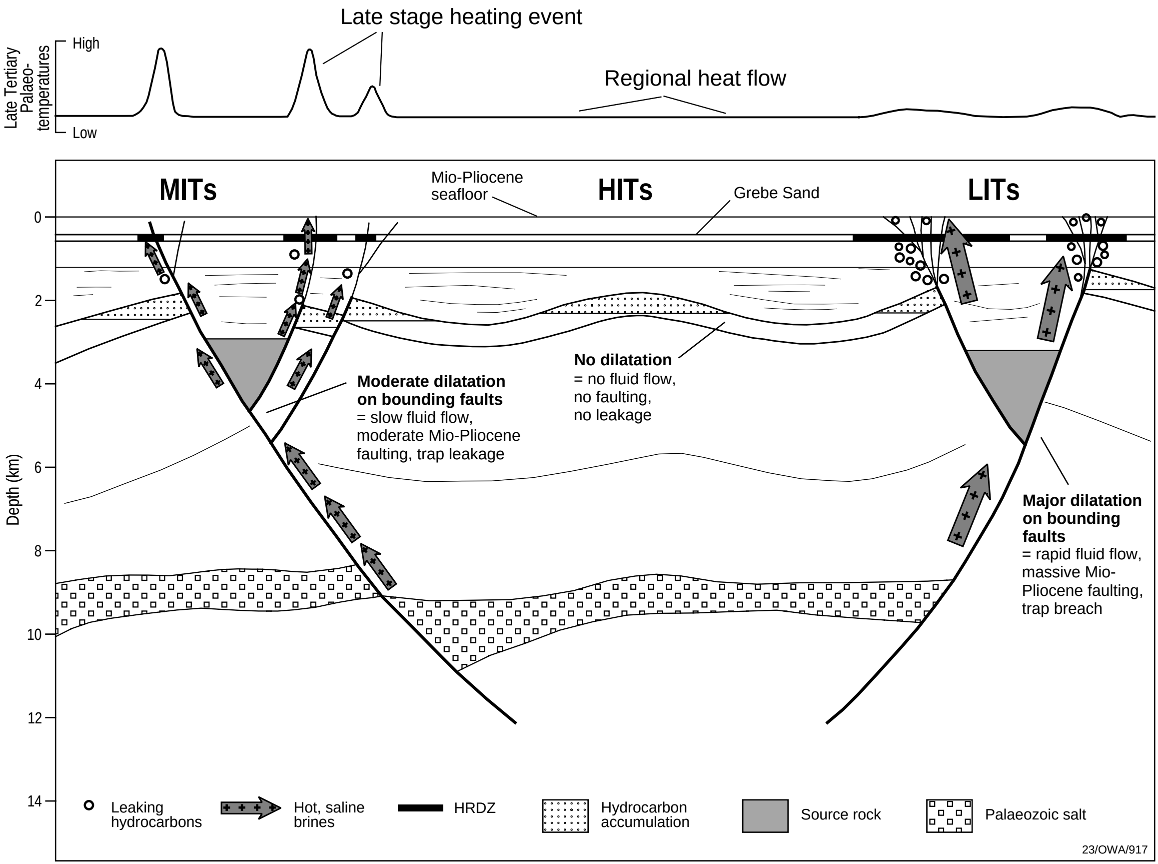


Figure 25. Schematic representation of the nature and effects of the latest Miocene/Early Pliocene fluid flow event in the Timor Sea.

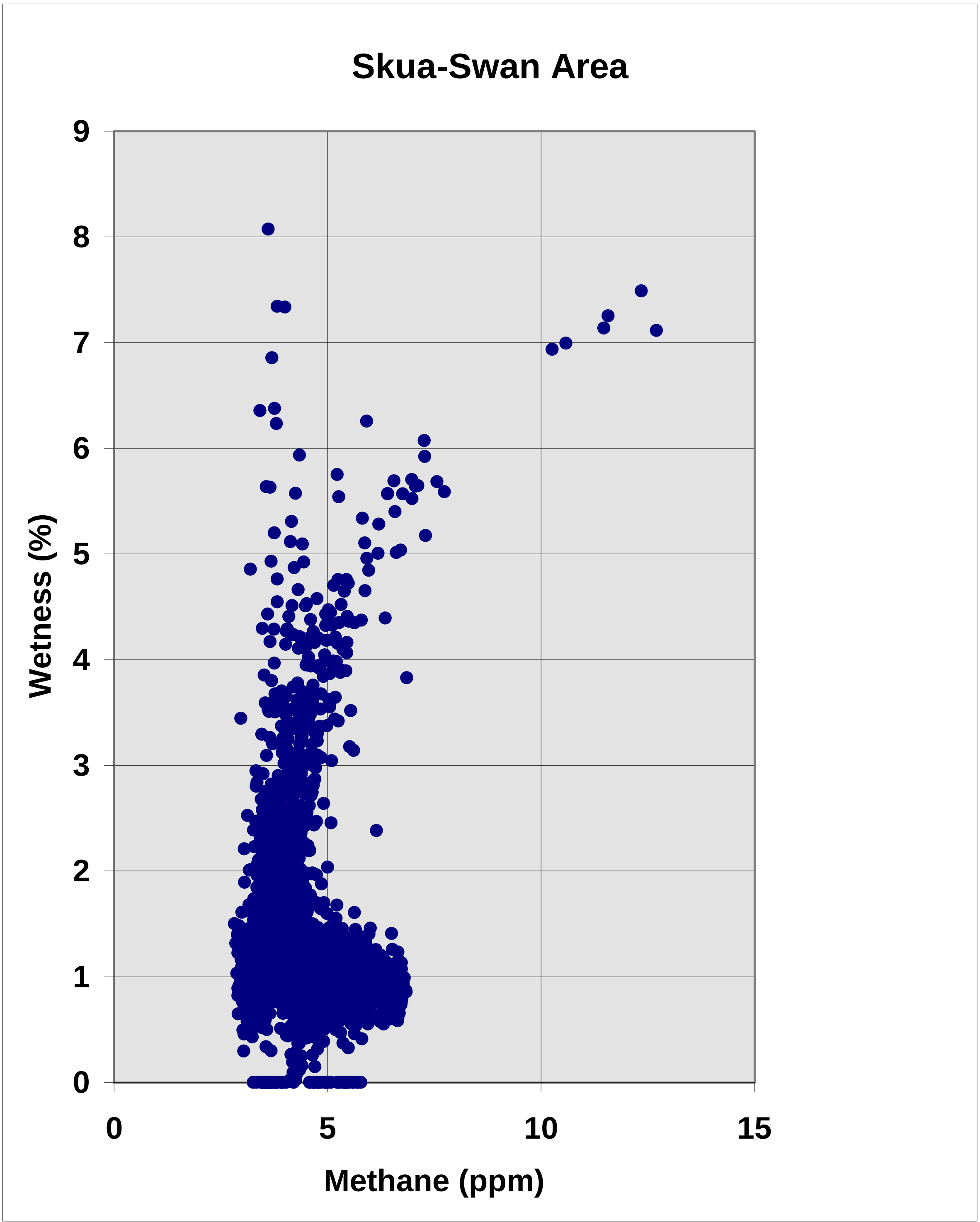


Figure 26. Methane versus hydrocarbon wetness for the sniffer data from the Skua-Swan survey area.

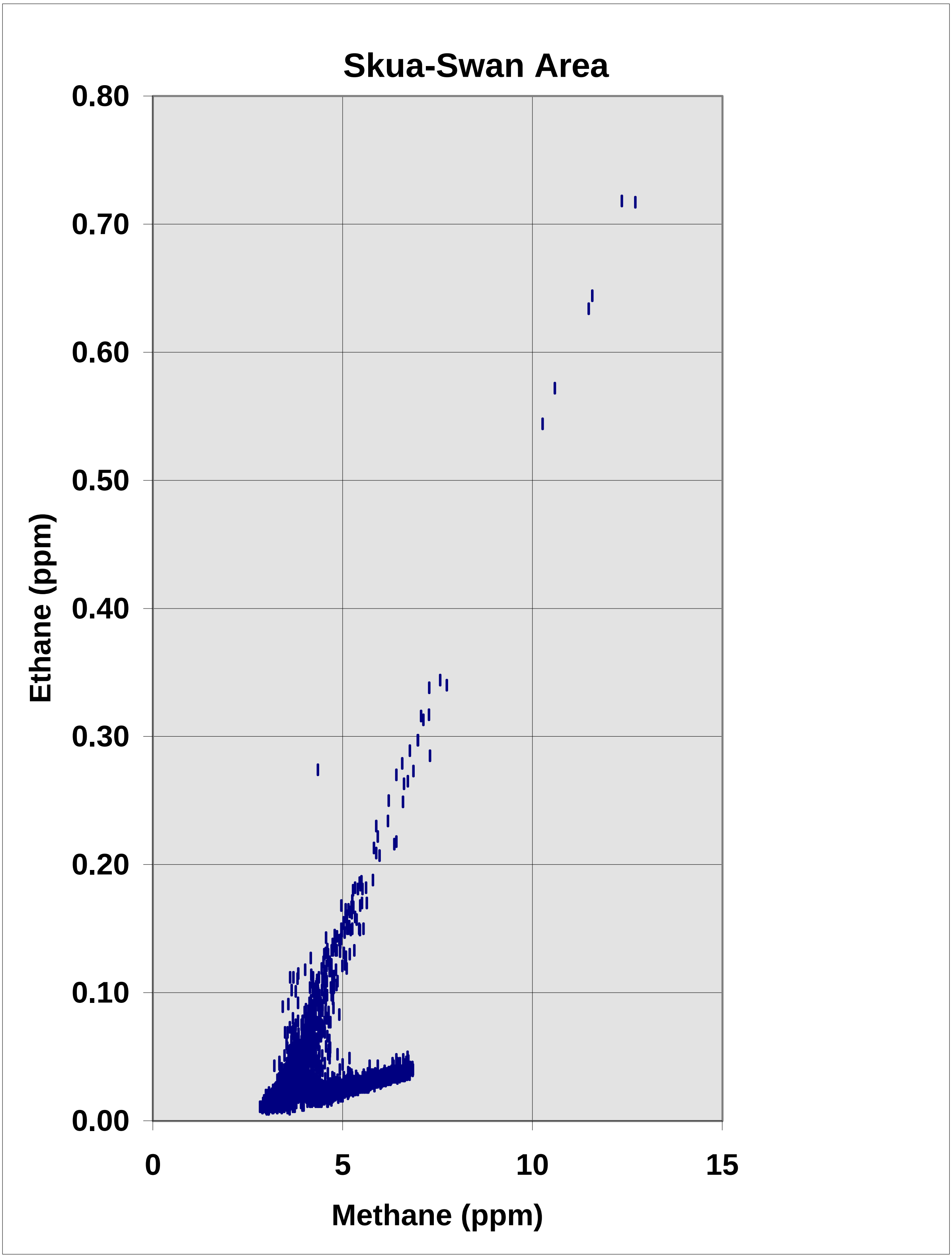
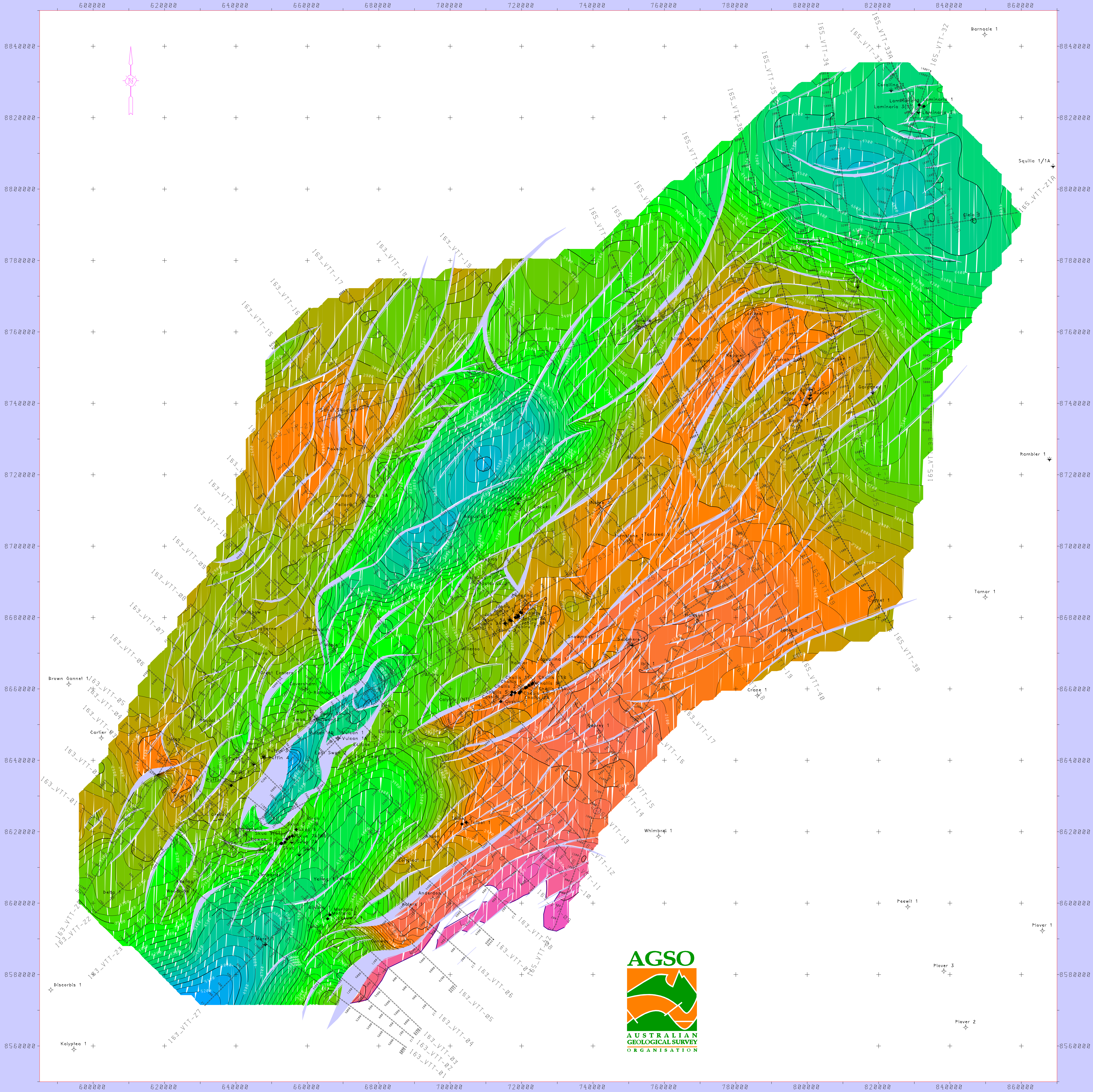
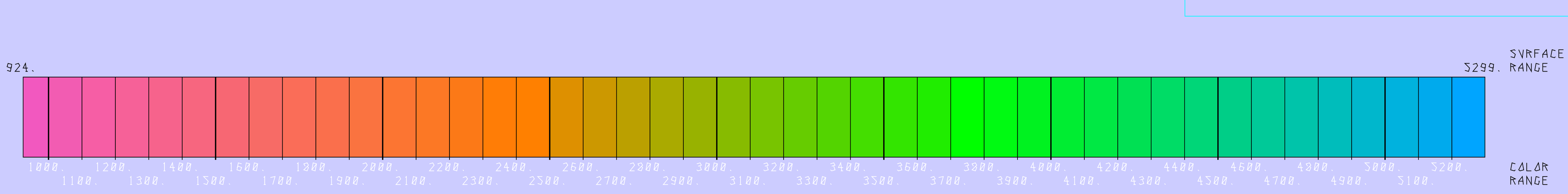


Figure 27. Methane versus ethane for the sniffer data from the Skua-Swan survey area.





VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

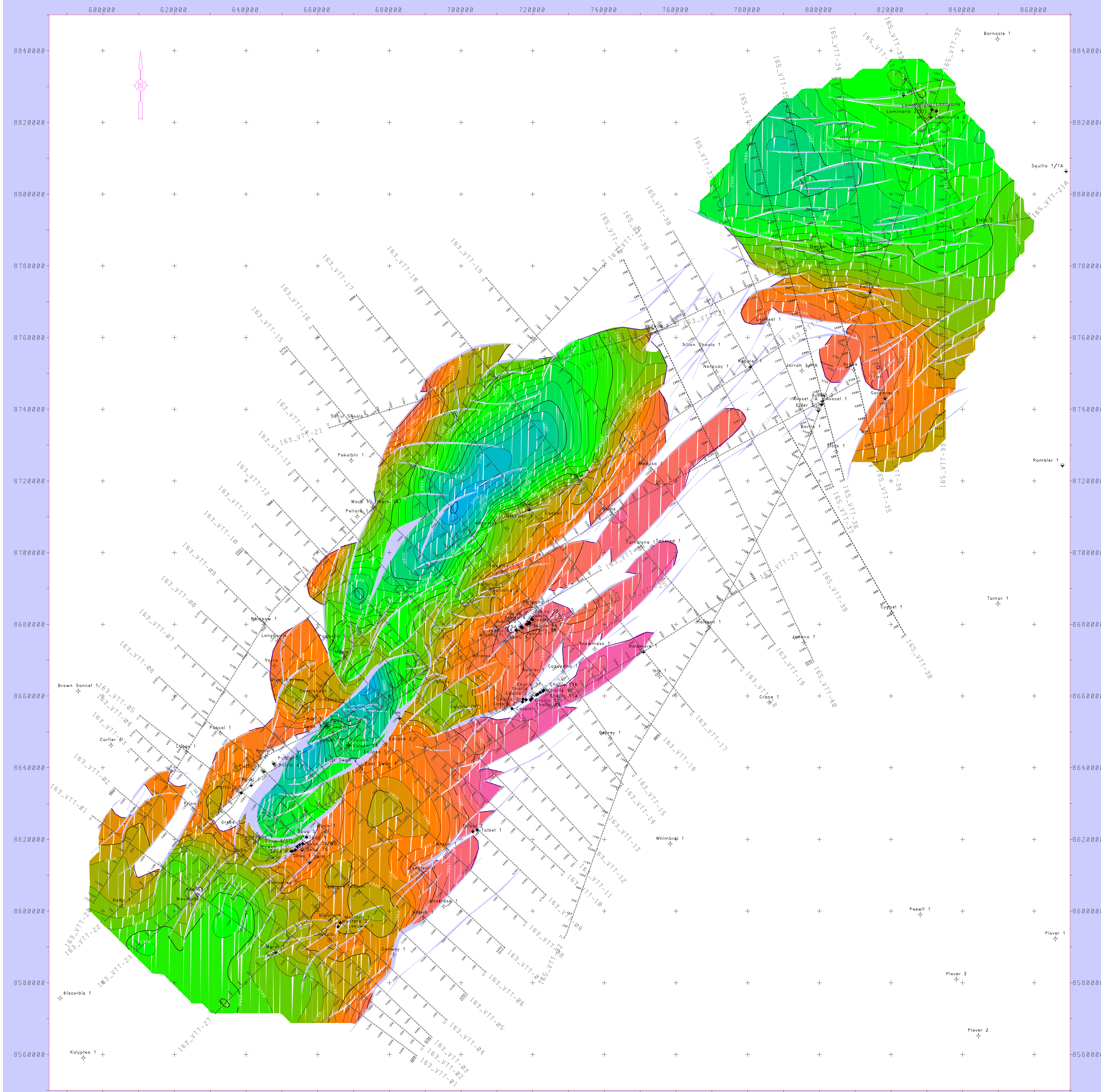
VULCAN GRABEN – TIMOR SEA

NEAR TOP PERMIAN LIMESTONE MFS

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96

DRAWING C.I. = 100MS	S. STURROCK	P. BARBER	R. DUNCAN	ENC 1



1092.
3514.
SURFACE RANGE
COLOR RANGE

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

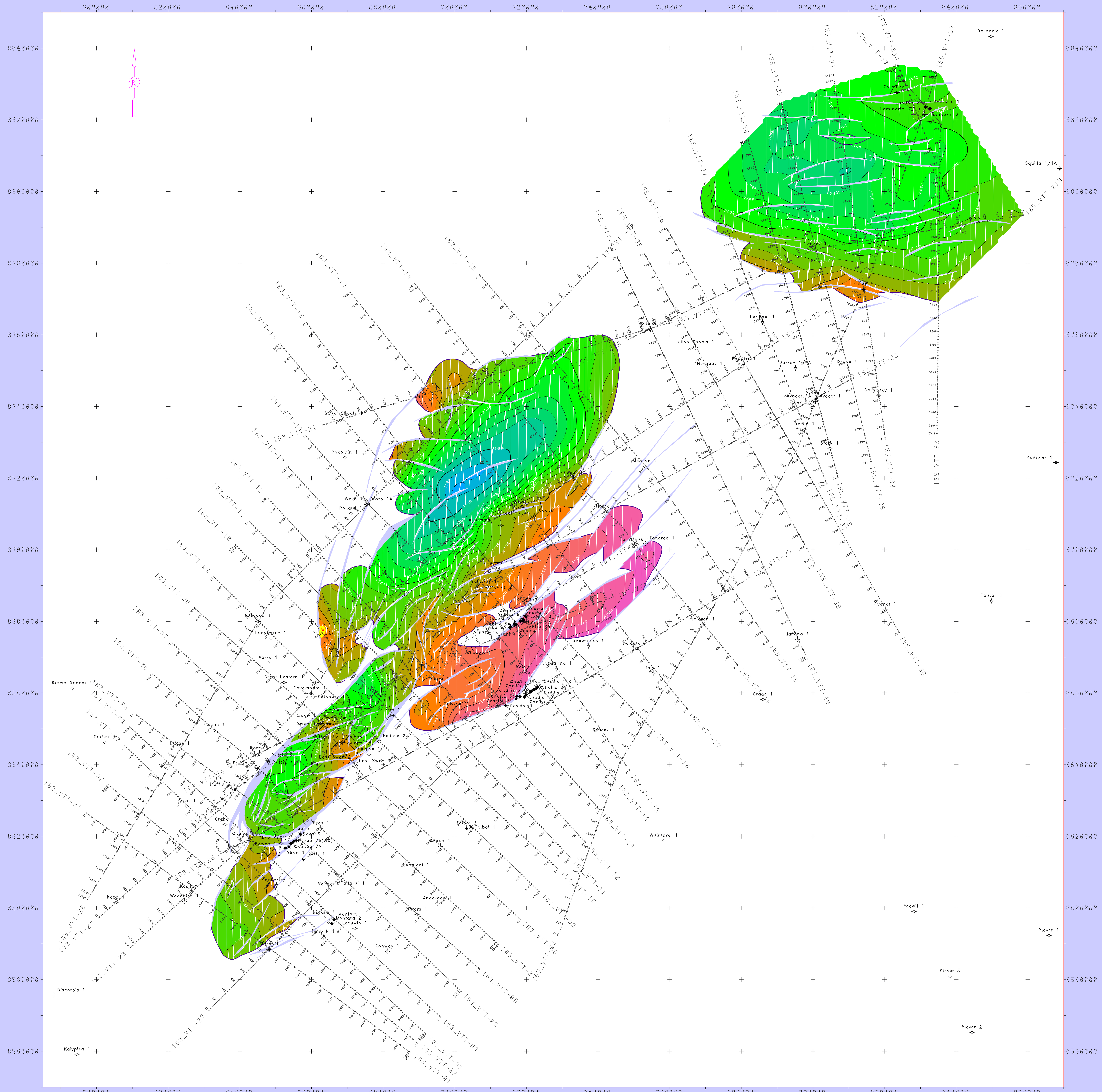
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN GRABEN - TIMOR SEA

MID-CALLOVIAN SB

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN		DATE 03-OCT-96	
DRAWING C.I. = 100MS	S. STURROCK P. BARBER	R. DUNCAN		ENC 2



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VULCAN TERTIARY TIE STUDY

1119. SURFACE RANGE 3241

COLOR RANGE

1:500000

KILOMETERS 0 10 20 KILOMETERS

METERS 0 10000 20000 METERS

OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

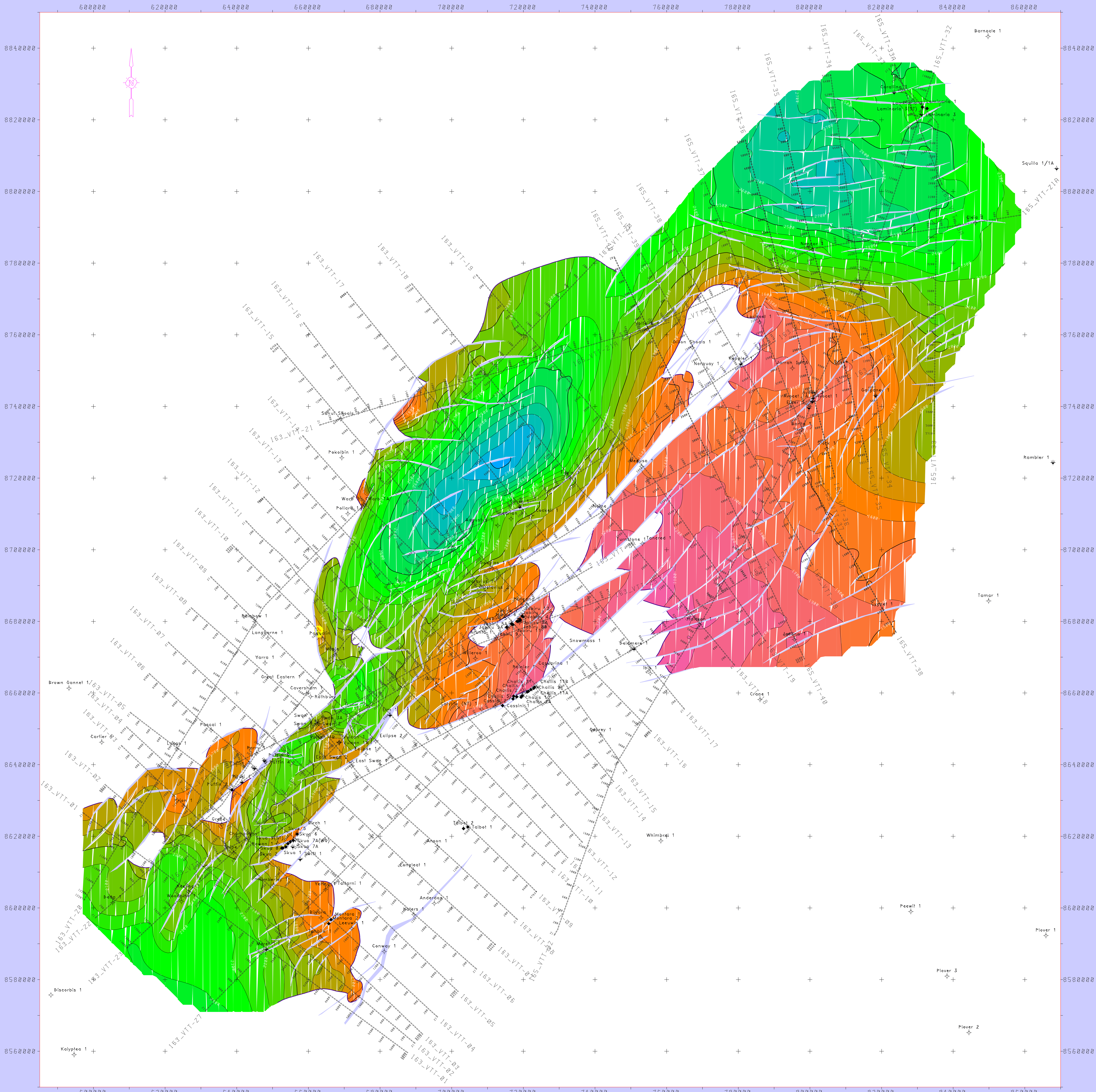
VULCAN GRABEN – TIMOR SEA

MID-KIMMERIDGIAN SB

TIME STRUCTURE MAP

SCALE 1:500000 | DATE 03-OCT-96

C.I. = 100MS | S. STURROCK P. BARBER R. DUNCAN | ENC 3



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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

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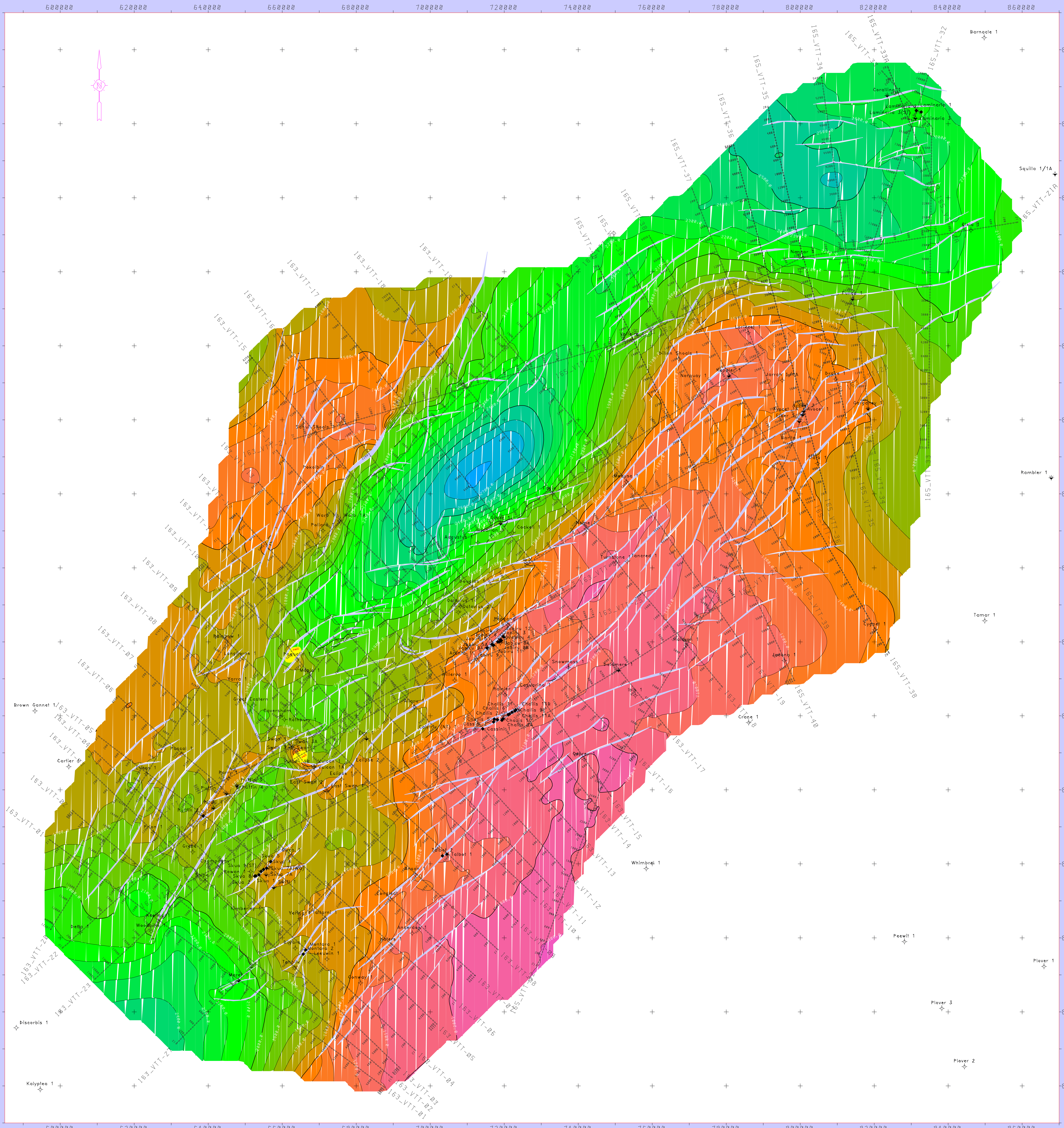
PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

MID–TITHONIAN SB

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96
DRAWING C.I. = 100MS	S. STURROCK P. BARBER R. DUNCAN	ENC 4



863.4 2912.3 SURFACE RANGE

COLOR RANGE

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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

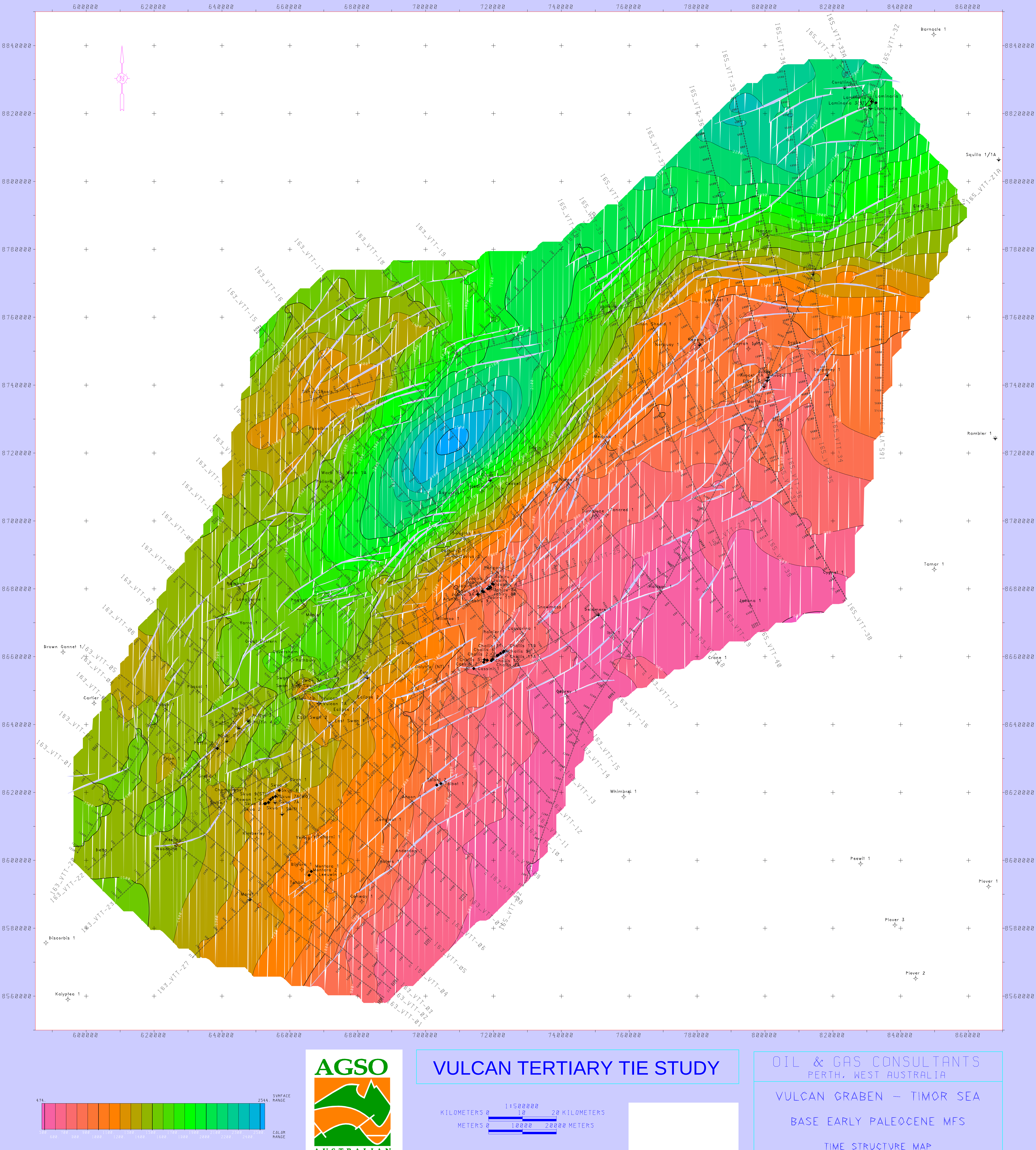
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

MID-VALANGINIAN SB/MFS

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN	DATE 26-OCT-96	
DRAWING C.I. = 100MS	S. STURROCK P. BARBER	R. DUNCAN	ENC 5



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VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

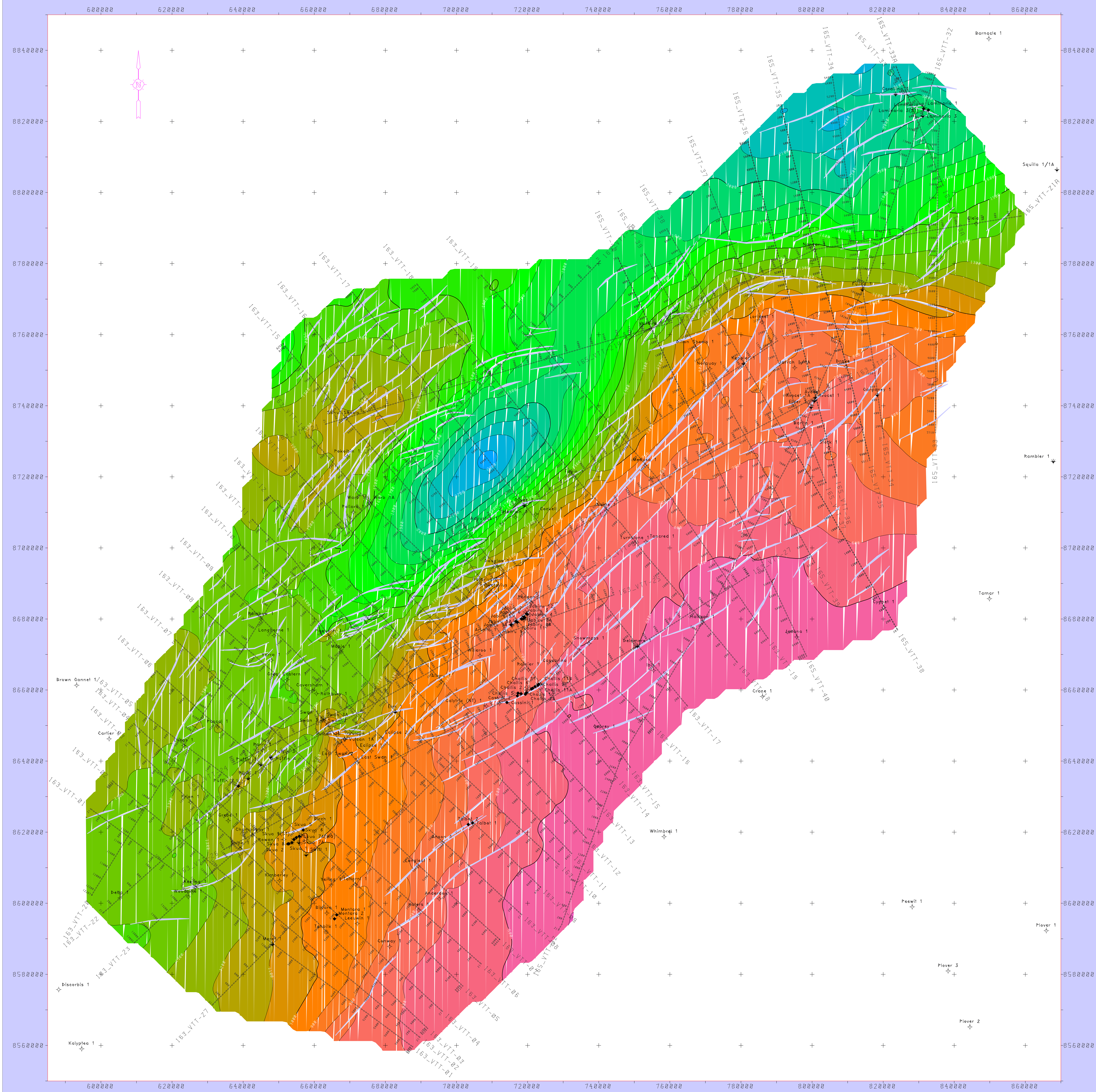
VULCAN GRABEN – TIMOR SEA

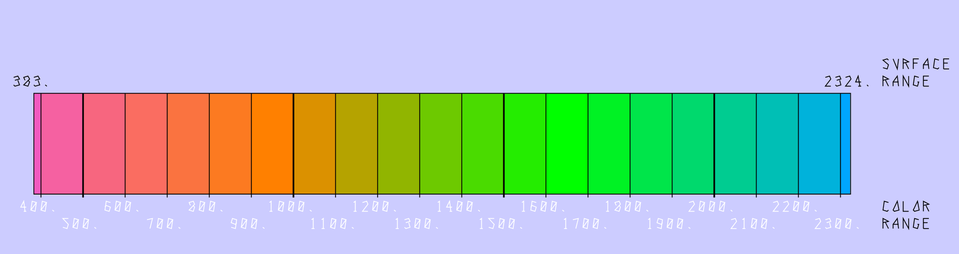
BASE EARLY PALEOCENE MFS

TIME STRUCTURE MAP

SCALE 1:500000 DATE 03-OCT-96

C.I. = 100MS S. STURROCK P. BARBER R. DUNCAN ENC 6





VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

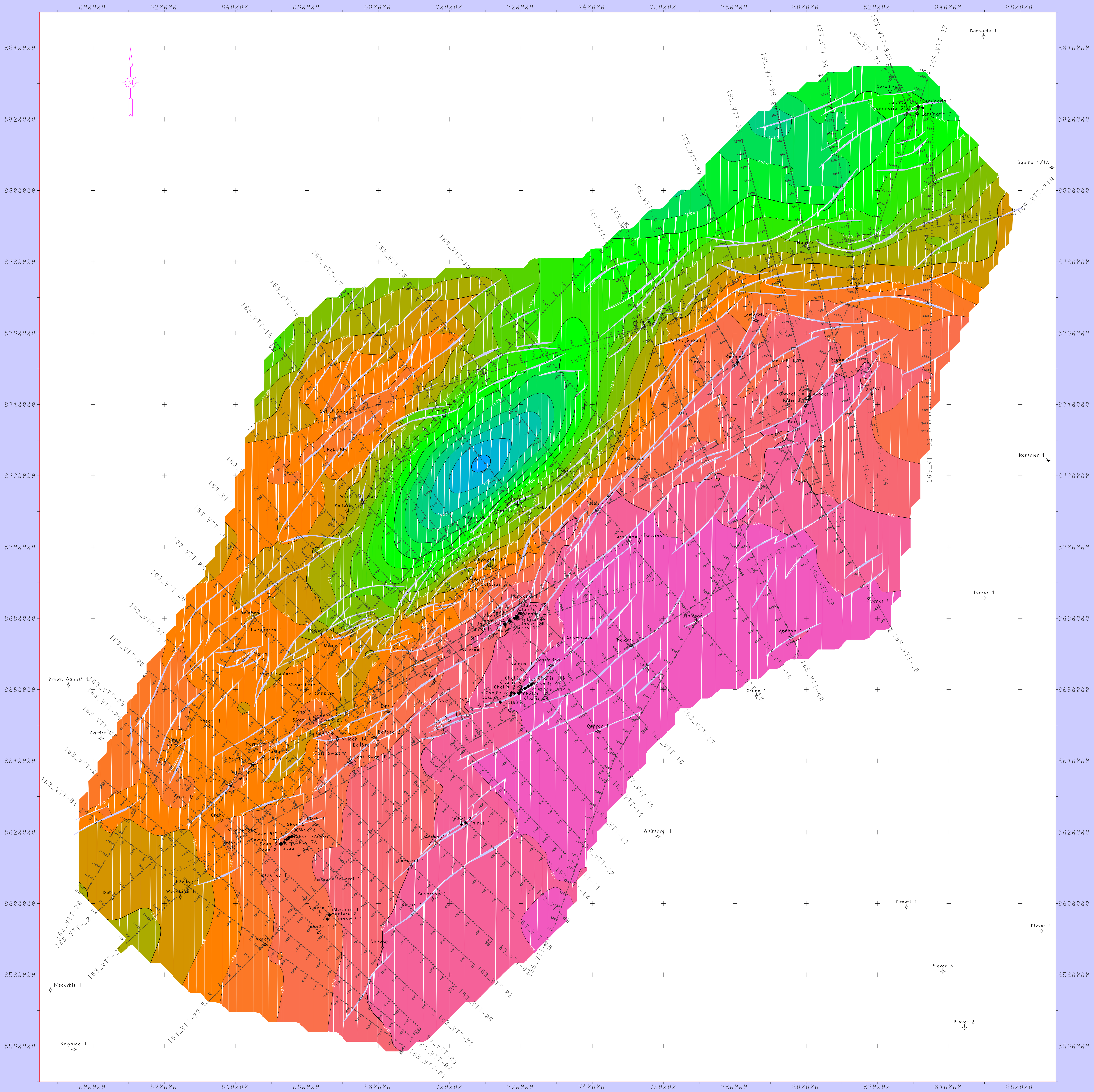
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

EARLY EOCENE SB

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN		DATE 03-OCT-96	
DRAWING C.I. = 100MS	S. STURROCK	P. BARBER	R. DUNCAN	ENC 7



303. 2020. SURFACE RANGE

COLOR RANGE

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000

KILOMETERS 0 10 20 KILOMETERS

METERS 0 10000 20000 METERS

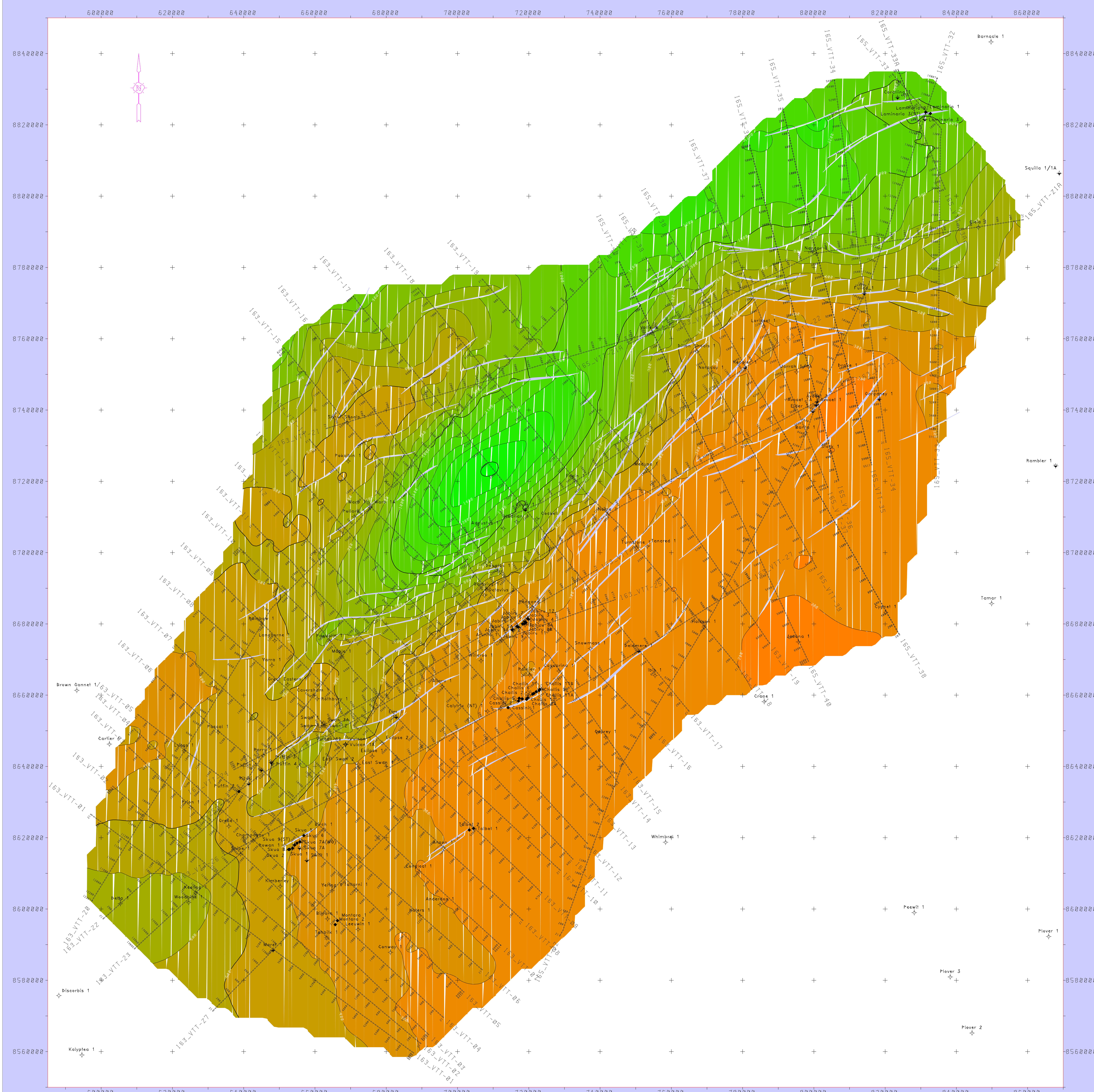
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

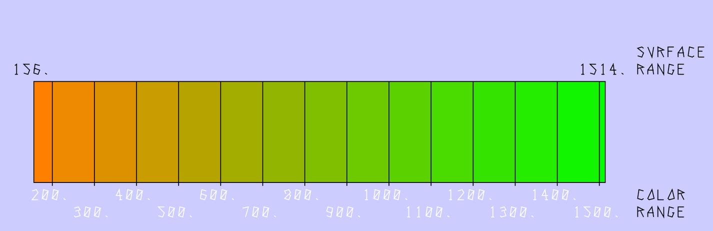
VULCAN GRABEN – TIMOR SEA

MID-OLIGOCENE SB

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96
DRAWING C.I. = 100MS	S. STURROCK P. BARBER R. DUNCAN	ENC 8





AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

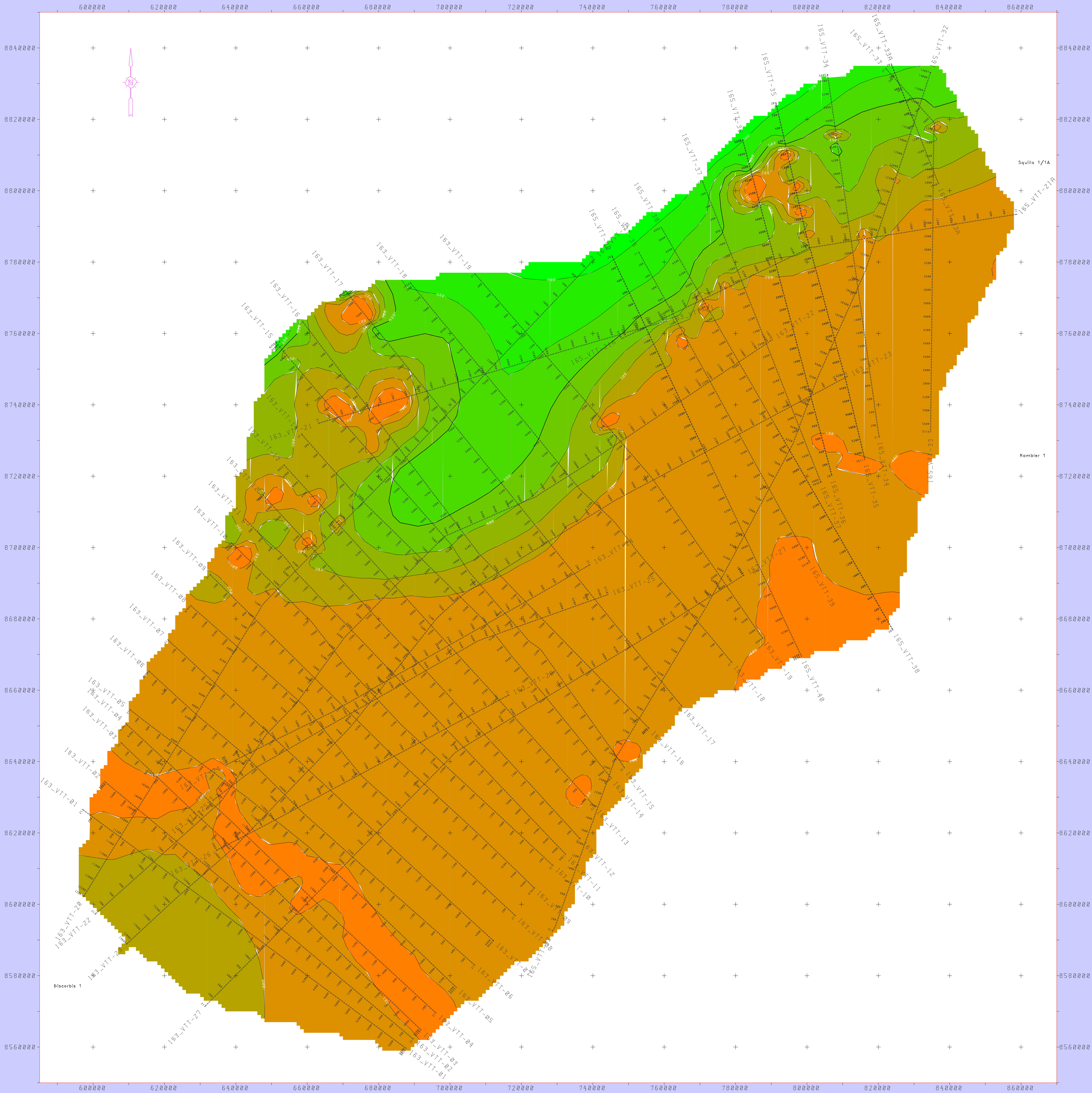
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

LATE MIOCENE SB

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96		
DRAWING C.I. = 100MS	S. STURROCK	P. BARBER	R. DUNCAN	ENC 9



AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

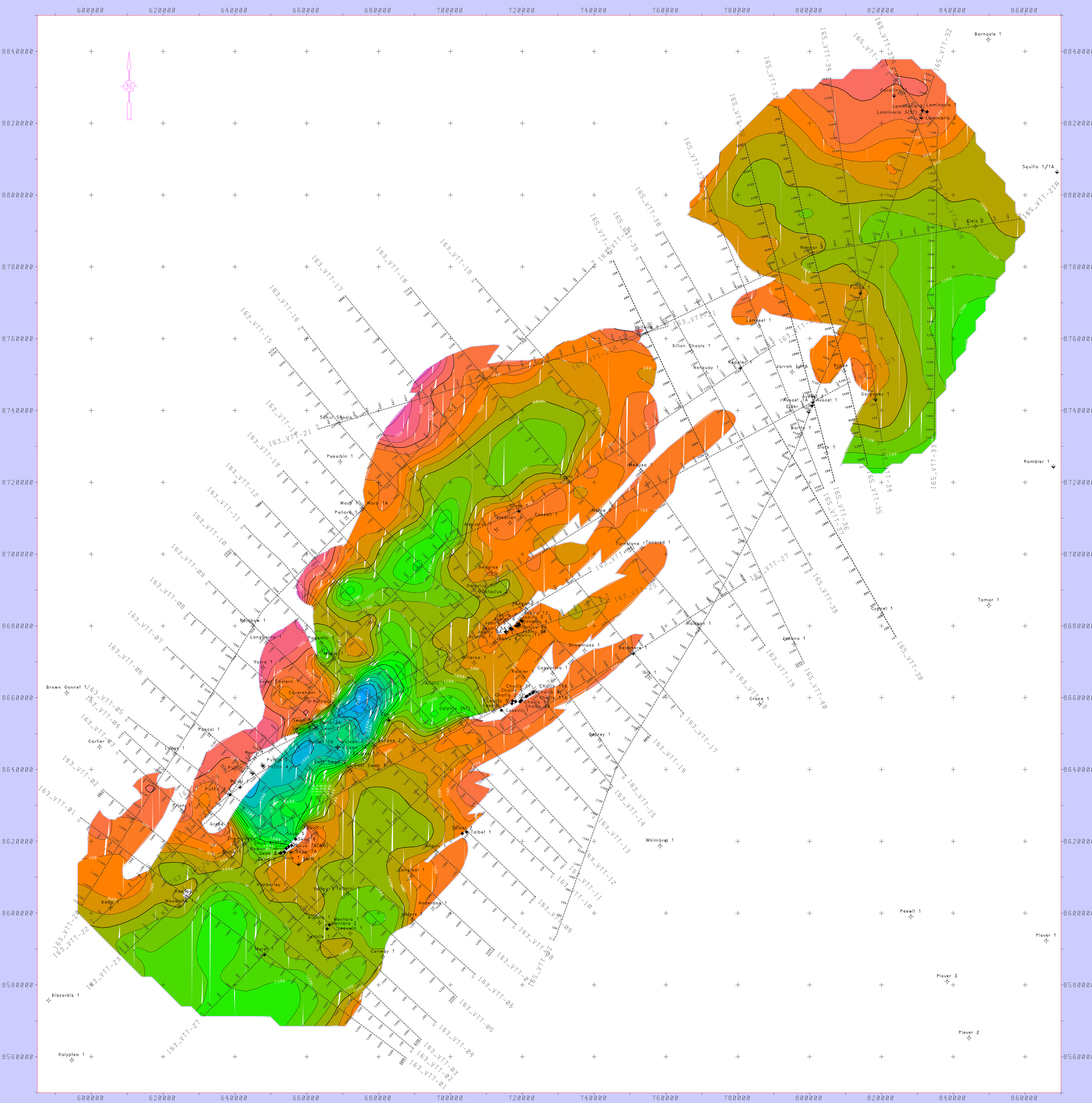
VULCAN GRABEN – TIMOR SEA

SEA BED

TIME STRUCTURE MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96

DRAWING C.I. = 100MS	S. STURROCK	P. BARBER	R. DUNCAN	ENC 10



149.
2139.
SURFACE RANGE
COLOR RANGE

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

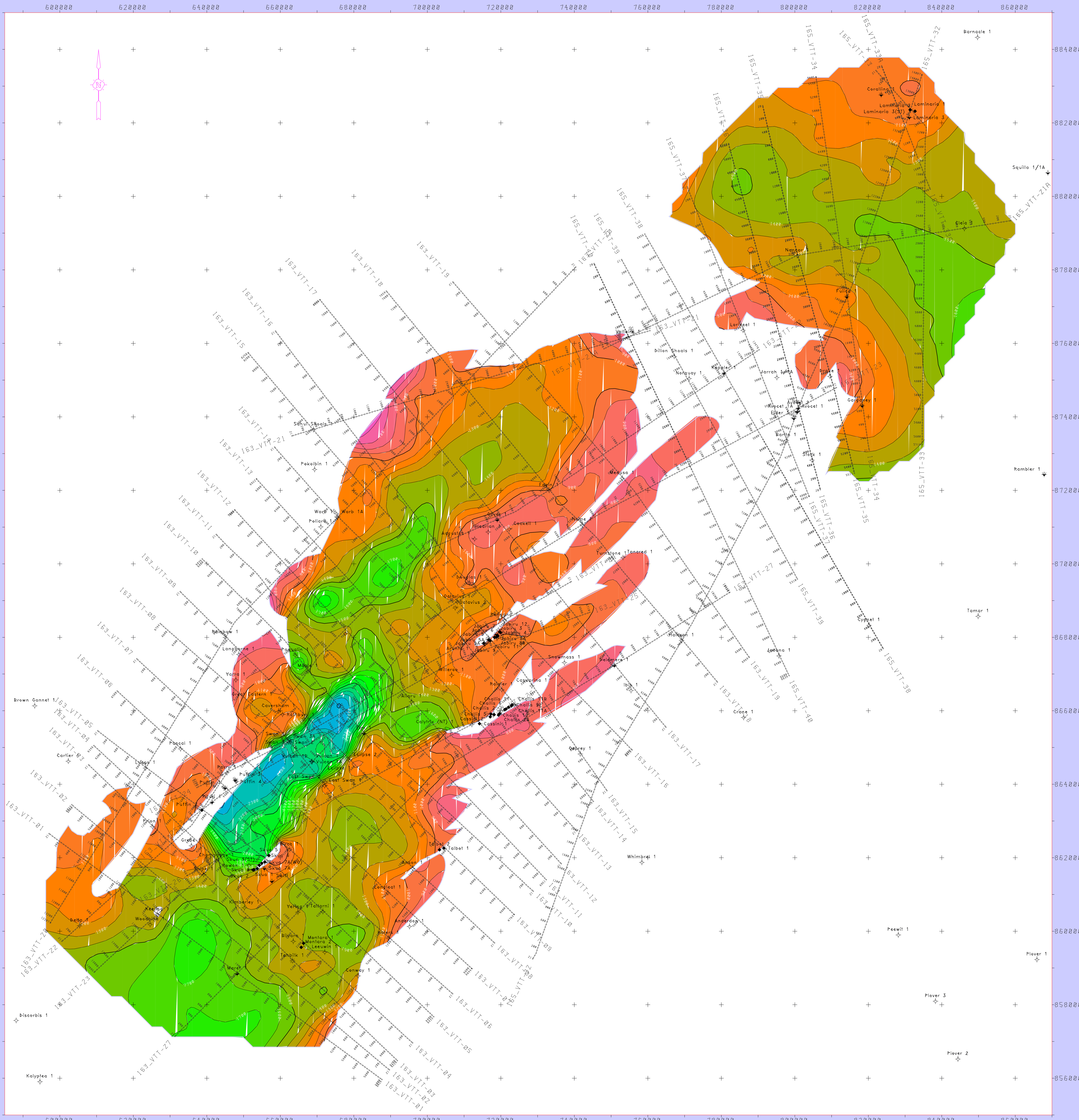
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

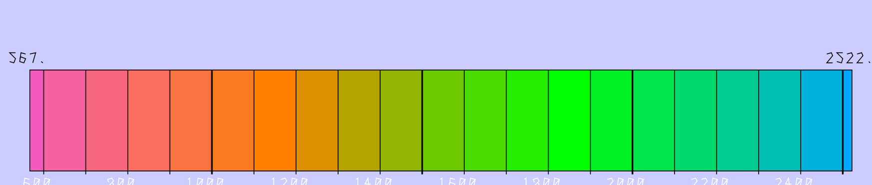
VULCAN GRABEN – TIMOR SEA

EARLY EOCENE SB – MID-CALLOVIAN SB

TIME THICKNESS MAP

SCALE 1:500000 | DRAWN | DATE 03-OCT-96
DRAWING C.I. = 100MS | S. STURROCK P. BARBER | R. DUNCAN | ENC 11





AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

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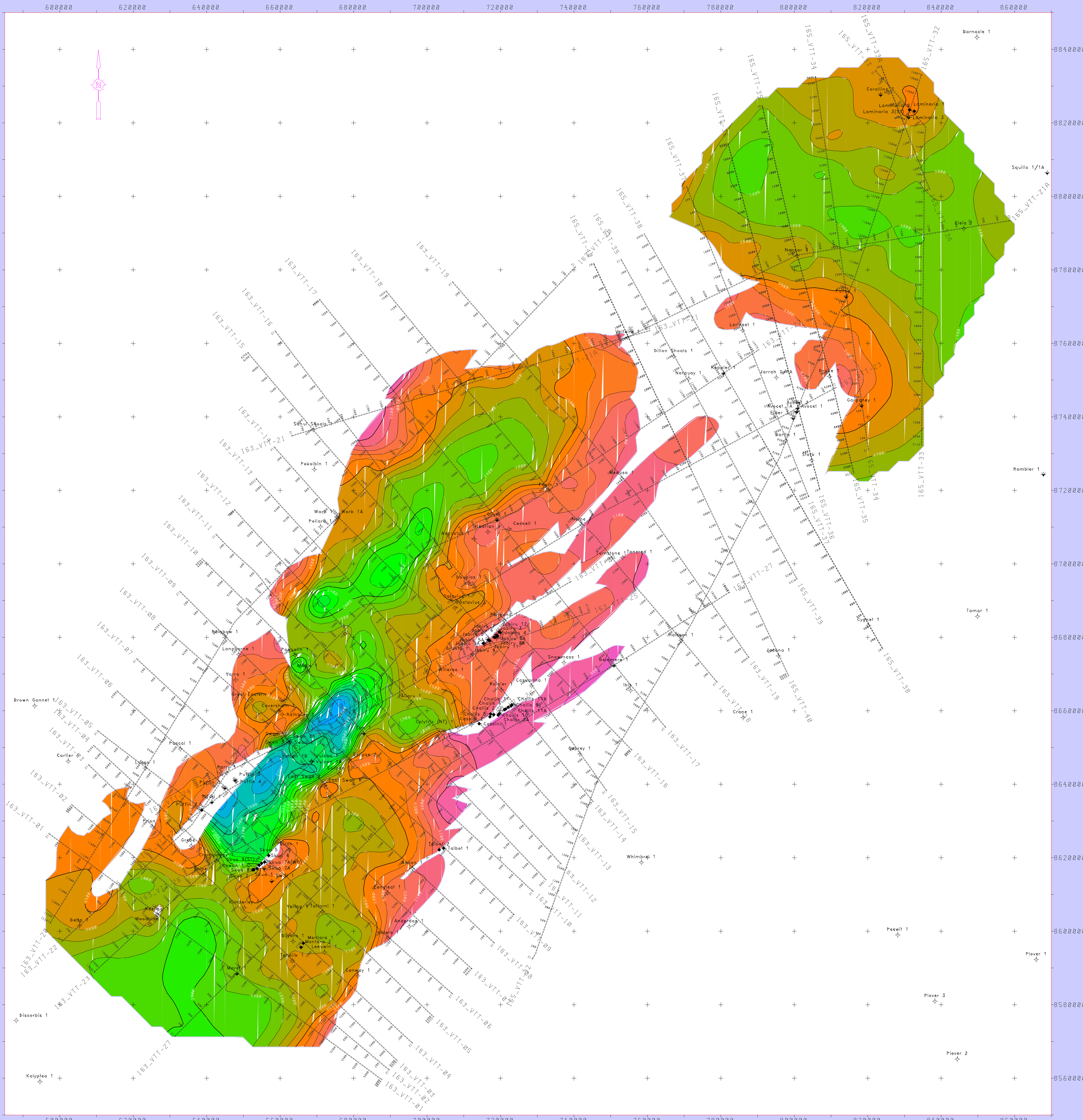
PERTH, WEST AUSTRALIA

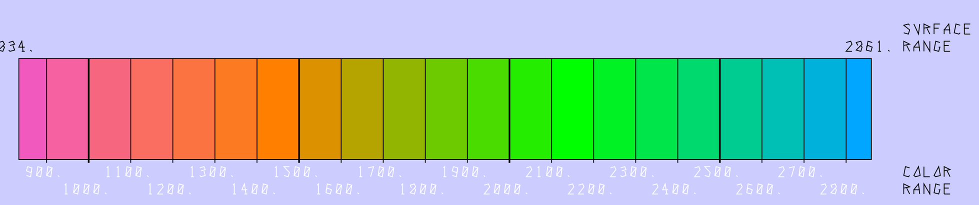
VULCAN GRABEN – TIMOR SEA

MID-OLIGOCENE SB – MID-CALLOVIAN SB

TIME THICKNESS MAP

SCALE 1:500000 DRAWN DATE 03-OCT-96
DRAWING C.I. = 100MS S. STVRROCK P. BARBER R. DVNCAN ENC 12





AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

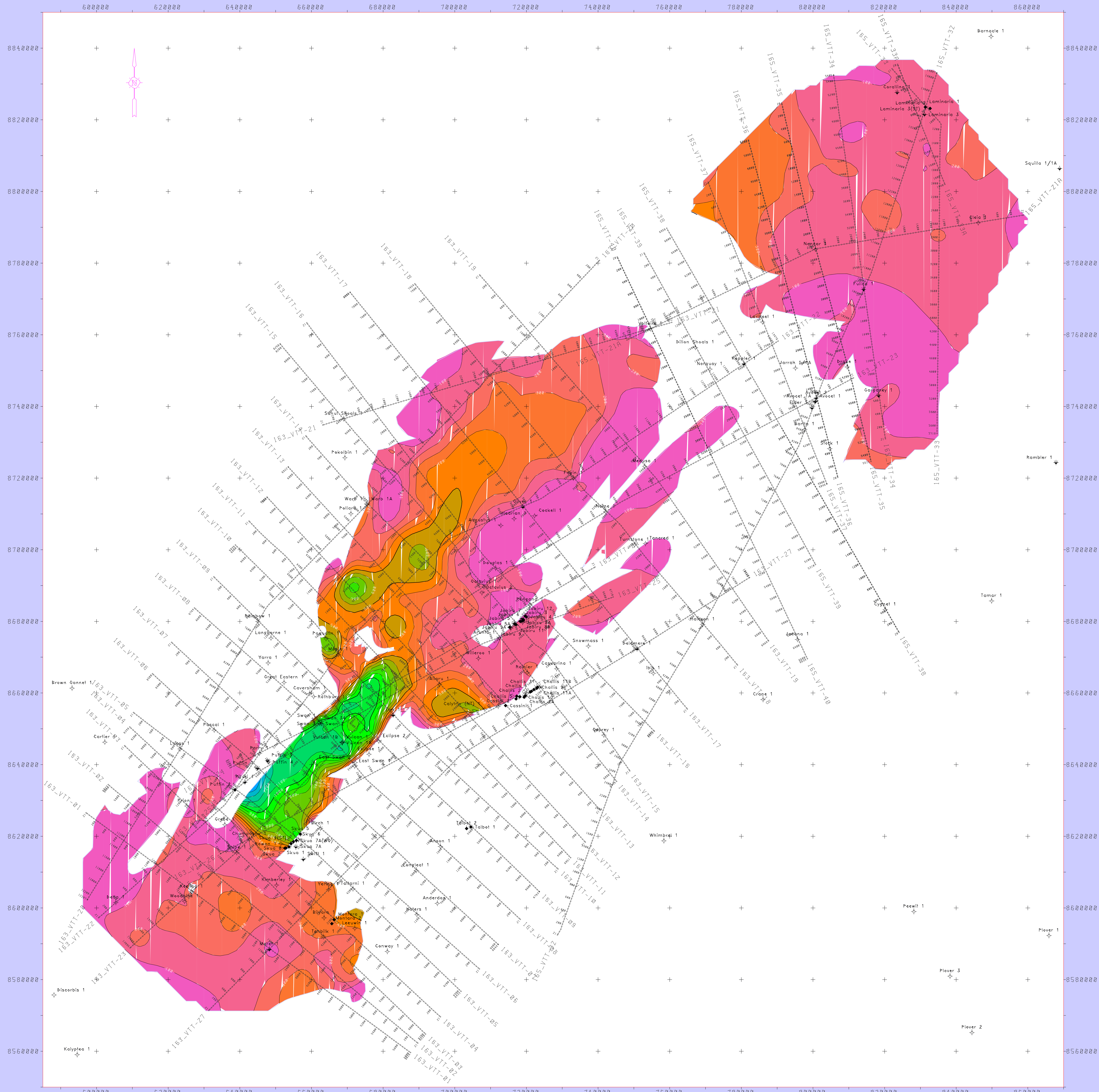
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

LATE MIOCENE SB – MID-CALLOVIAN SB

TIME THICKNESS MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96
DRAWING C.I. = 100MS	S. STURROCK P. BARBER R. DUNCAN	ENC 13



OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN TERTIARY TIE STUDY

VULCAN GRABEN – TIMOR SEA

MID-TITHONIAN SB – MID-CALLOVIAN SB

TIME THICKNESS MAP

1:500000

KILOMETERS 0 10 20 KILOMETERS

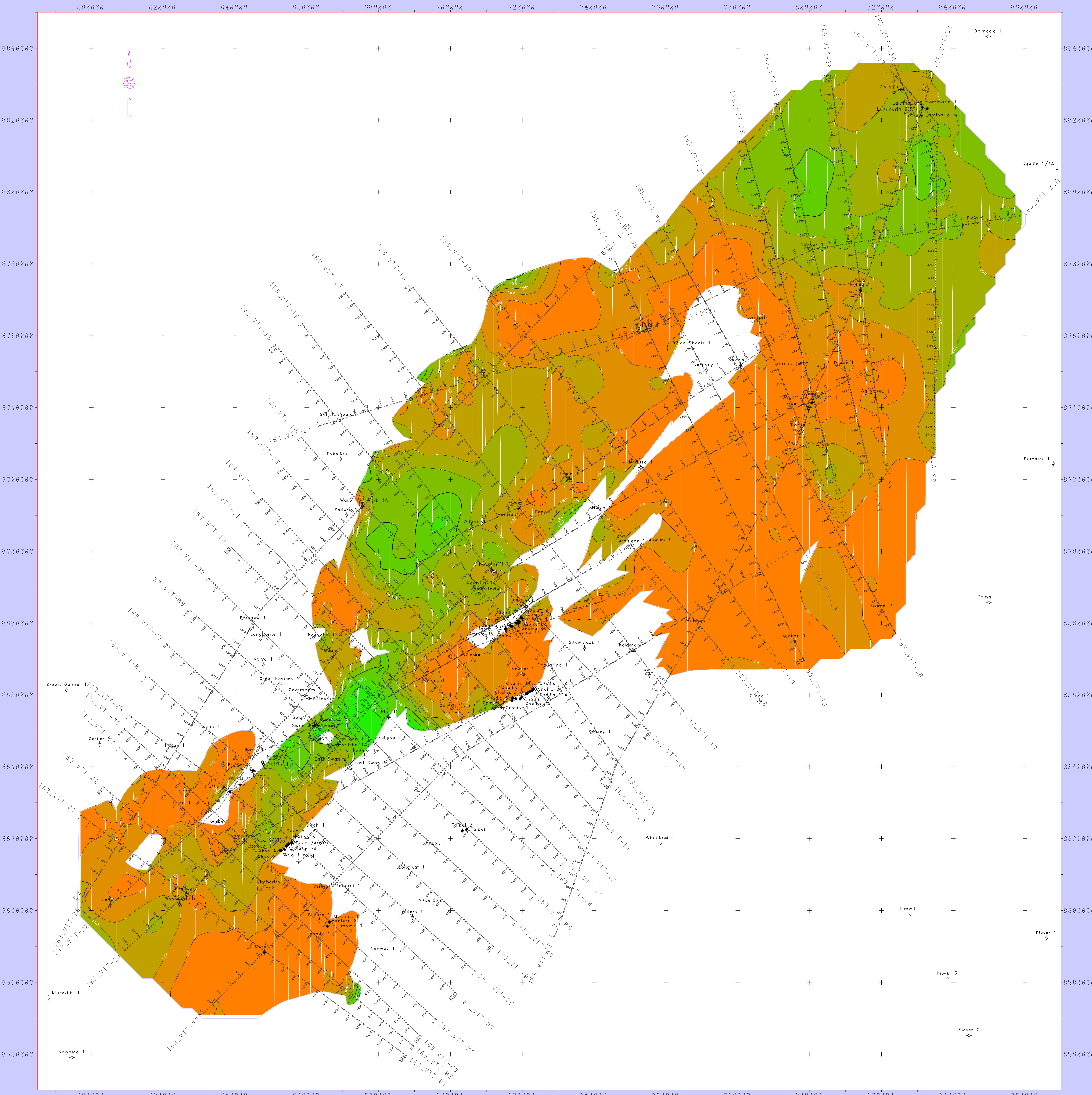
METERS 0 10000 20000 METERS

SURFACE RANGE

COLOR RANGE

AGSO AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

SCALE 1:500000	DRAWN	DATE 03-OCT-96
DRAWING C.I. = 100MS	S. STURROCK P. BARBER R. DUNCAN	ENC 14



1. 420. SURFACE RANGE

COLOR RANGE

AGSO

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000

KILOMETERS 0 10 20 KILOMETERS

METERS 0 10000 20000 METERS

OIL & GAS CONSULTANTS

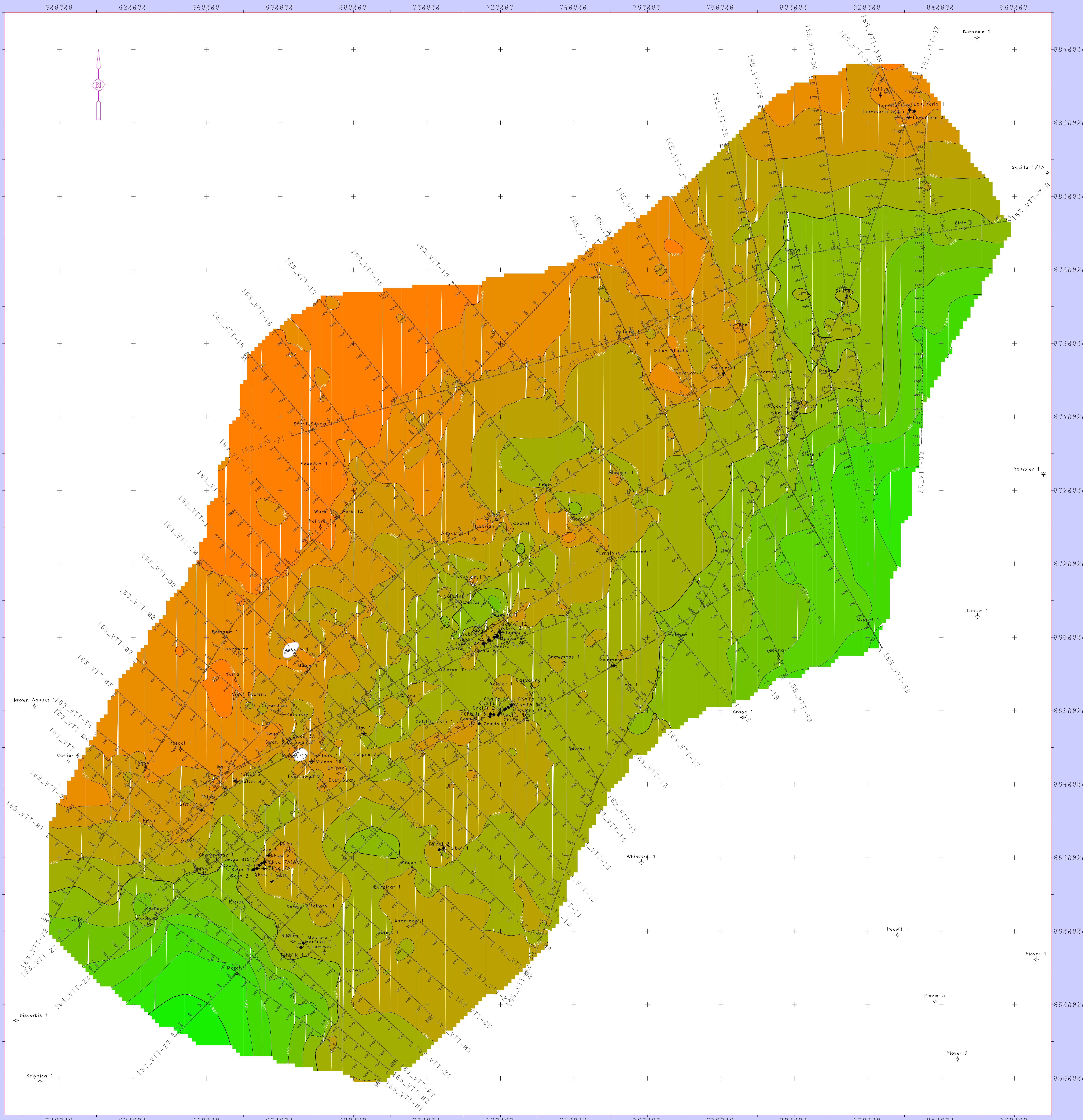
PERTH, WEST AUSTRALIA

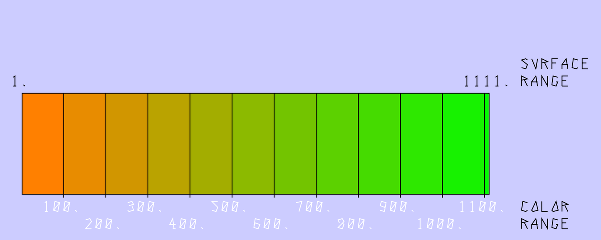
VULCAN GRABEN – TIMOR SEA

MID-VALANGINIAN SB/MFS – MID-TITHONIAN SB

TIME THICKNESS MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96
DRAWING C.I. = 50MS	S. STURROCK P. BARBER R. DUNCAN	ENC 15





VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

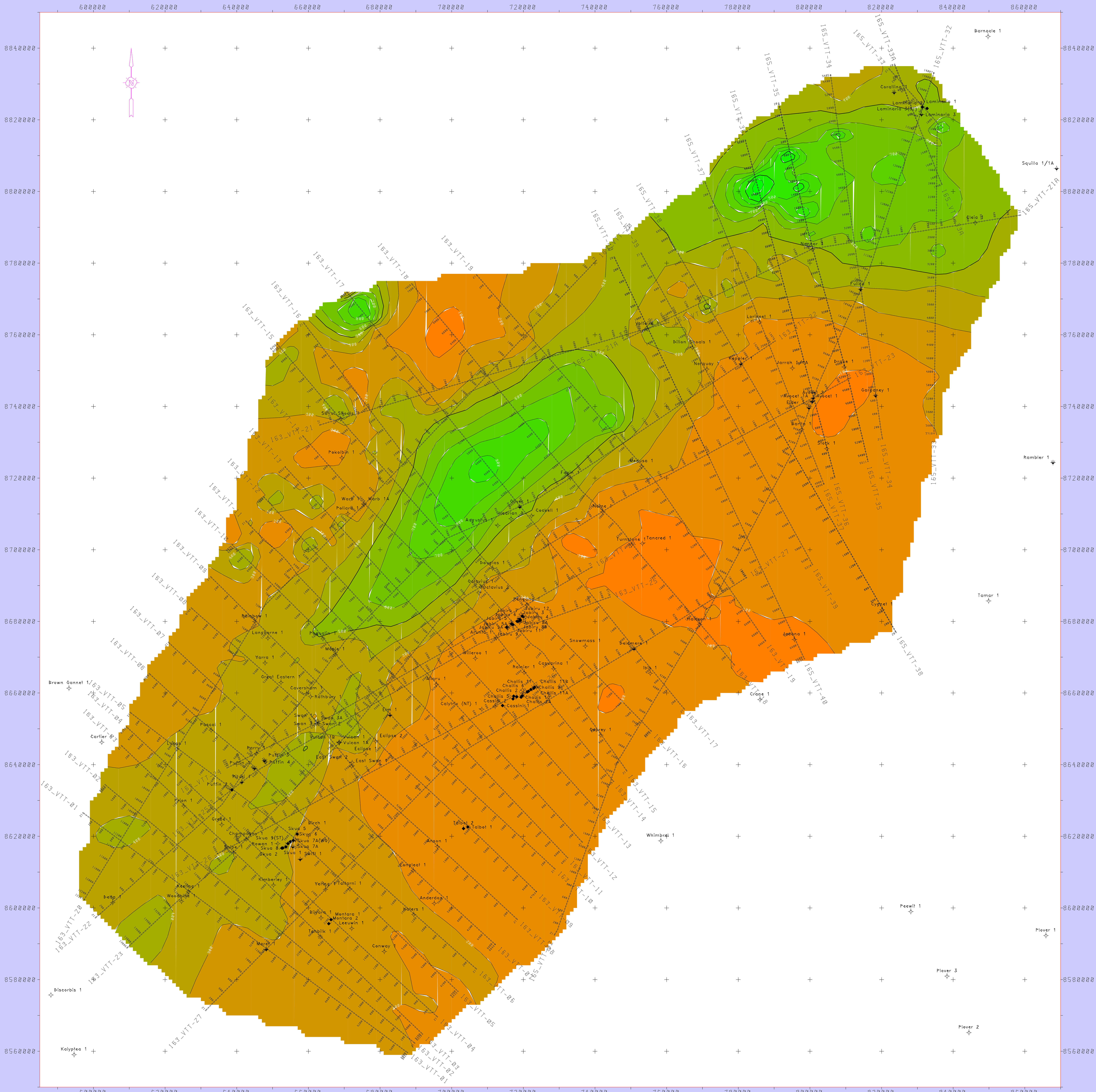
OIL & GAS CONSULTANTS
PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

BASE EARLY PALEOCENE MFS – MID-VALANGINIAN SB/MFS

TIME THICKNESS MAP

SCALE 1:500000 | DATE 03-OCT-96
C.I. = 100MS | S. STURROCK P. BARBER R. DUNCAN | ENC 16



55. 1129.
SURFACE RANGE
COLOR RANGE

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

VULCAN TERTIARY TIE STUDY

1:500000
KILOMETERS 0 10 20 KILOMETERS
METERS 0 10000 20000 METERS

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PERTH, WEST AUSTRALIA

VULCAN GRABEN – TIMOR SEA

SEA BED – LATE MIOCENE SB

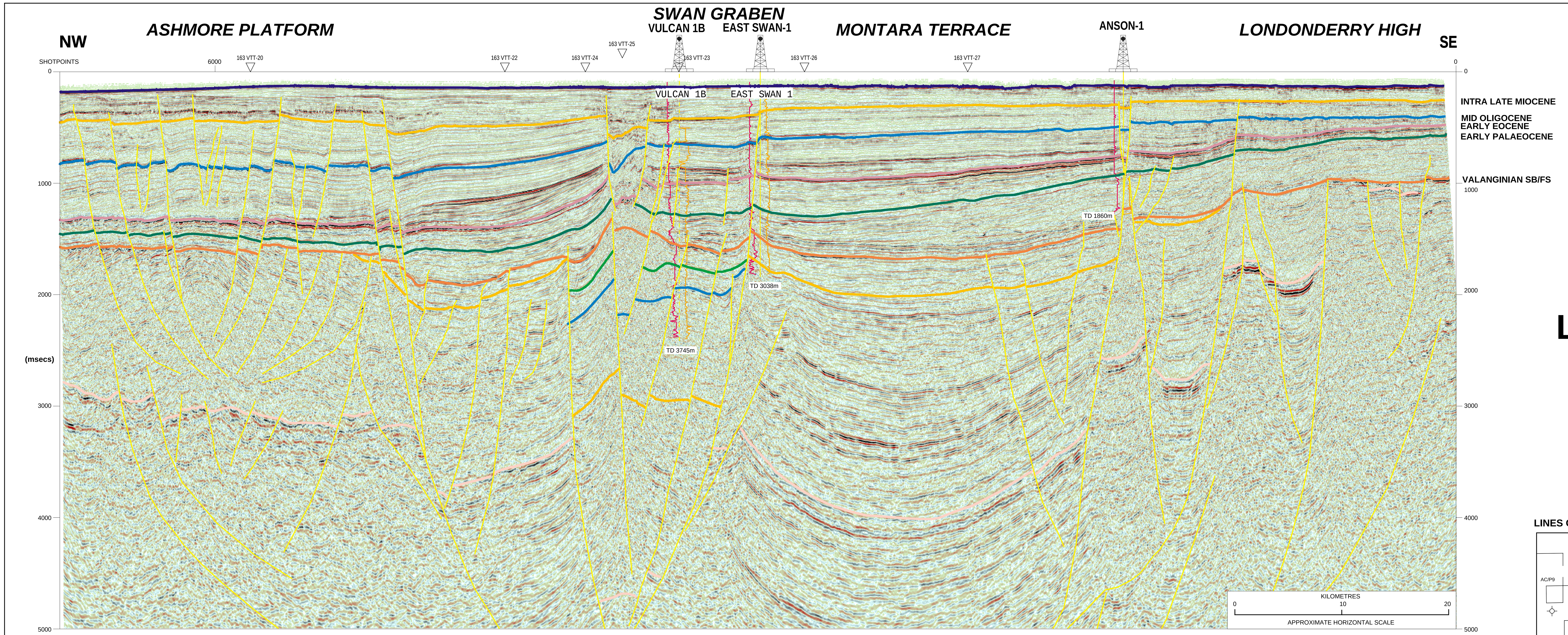
TIME THICKNESS MAP

SCALE 1:500000	DRAWN	DATE 03-OCT-96
DRAWING C.I. = 100MS	S. STURROCK P. BARBER R. DUNCAN	ENC 17

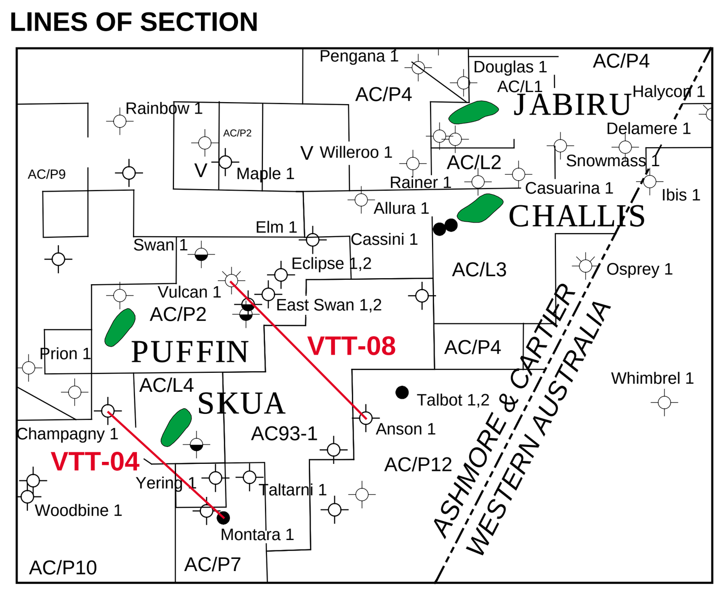
ENCLOSURE 18

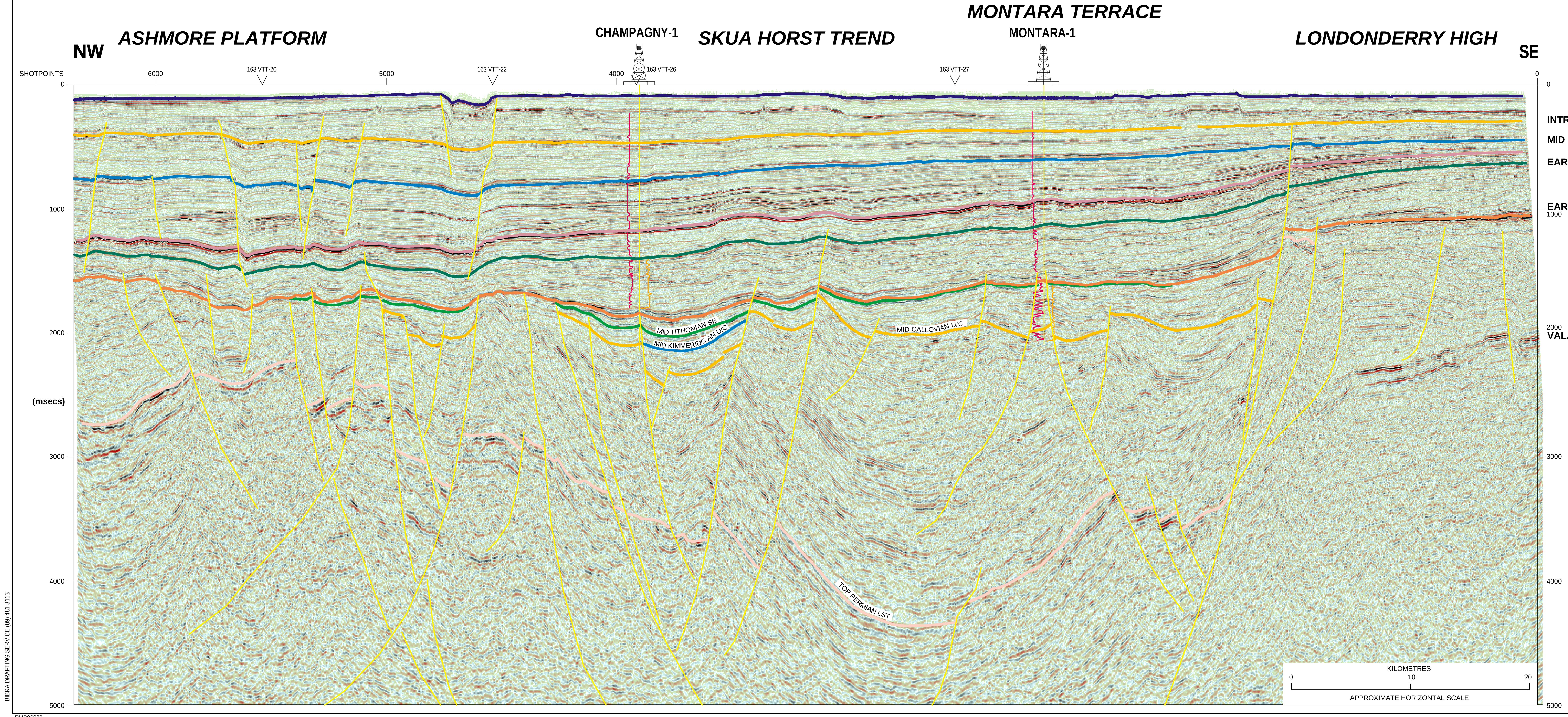
ENCLOSURE 19

RAINBOW-1
MAPLE 1
VULCAN 1
EAST SWAN 1
YERING 1
TALTARNI 1
ANSON 1
ASHMORE PLATFORM
PAQUALIN GRABEN
SWAN GRABEN
MONTARA TERRACE
HEYWOOD GRABEN
LONDONDERRY PLATFORM
SEA FLOOR
LATE MIOCENE SB
OLIGOCENE - EARLY MIOCENE SB
MIDDLE EOCENE SB
EARLY EOCENE SB
LATE PALEOCENE SB
BASE PALEOCENE MFS
MAASTRICHTIAN SB
CAMPANIAN SB
SANTONIAN SB
TURONIAN MFS
APTIAN SB
APTIAN / VALANGINIAN FLOODING EVENT
BERRIASIAN / MID CALLOVIAN SB's
BERRIASIAN - M. CALLOVIAN SB's
CENOMANIAN MFS
INTRA VALANGINIAN MFS
KIMM.- EARLY CRETACEOUS CONDENSED SEDIMENTATION AND/OR SUBMARINE EROSION
MID TITHONIAN MFS
MID TITHONIAN SB
MID KIMMERIDGIAN SB
MID CALLOVIAN SB
M.CALLOVIAN SB
RECENT TO PLIOCENE CARBONATE RAMP
MIOCENE CARBONATE RAMP
EARLY MIOCENE Lowstand Wedge
EOCENE CARBONATE RAMP
EARLY EOCENE Lowstand Wedge
L. PALEOCENE Lowstand Wedge
L.KIMMERIDGIAN - TITHONIAN
OXFORDIAN - E. KIMMERIDGIAN
DISTAL OXFORDIAN TURBIDITES
PALEOCENE CARBONATE RAMP
GREBE SANDS
PUFFIN Lowstand Fans
OXFORDIAN TO LATE CALLOVIAN
EARLY EOCENE AGGRADATIONAL LOWSTAND TOPSETS
Early Tertiary Carbonate Ramp
Submarine Canyon
KIMMERIDGIAN / OXFORDIAN TO MAINLY LATE CALLOVIAN-OXFORDIAN
Retrogradational Fan Delta's
MONTARA Fm.
Progradational Fan Delta's
Basal Transgressive Sand
Progradational Slope Facies
Lowstand Wedge
Paqualin Diapir
Swan Diapir
HST
LST
TST / HST
lvf
Mfs
TRIASSIC
EARLY-MIDDLE JURASSIC
PERMIAN
FAULTED OUT IN WELL
LINE OF SECTION
JABIRU
CHALLIS
PUFFIN
SKUA
12°00'S
Mfs — MAXIMUM FLOODING SURFACE
SB — SEQUENCE BOUNDARY
HST — HIGHSTAND SYSTEM TRACT
LST — LOWSTAND SYSTEM TRACT
lvf — INCISED VALLEY FILL
Fs — FLOODING SURFACE
LOWER MIOCENE — KEY SEISMIC MARKER OR EVENT
FACIES
CARBONATE PLATFORM / RAMP
SAND PRONE TOP SETS
MUD PRONE SLOPE / BASIN
SAND PRONE SUBMARINE FAN
SALT DIAPIR
AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION
PGS Nopec
Vertical Scale
400 metres
200
0
Approx. Horizontal Scale
0 5 10 kms.
OIL & GAS CONSULTANTS
VULCAN SUB-BASIN - AUSTRALIA
VULCAN GRABEN SEQUENCE STRATIGRAPHIC CORRELATION
Rainbow-1 to Anson-1
S.Sturrock \ P.Barber
August 1996
ENCLOSURE 20



LINE VTT-08





LINE VTT-04

OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

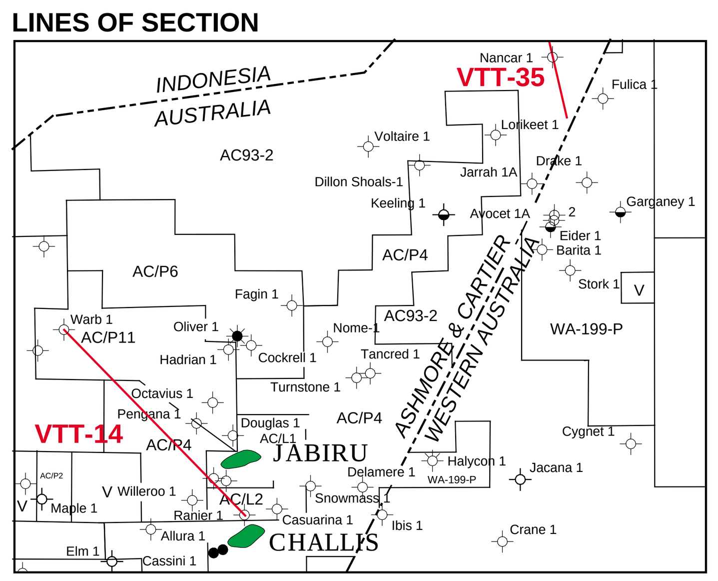
SEISMIC LINES
VTT-08 & VTT-04

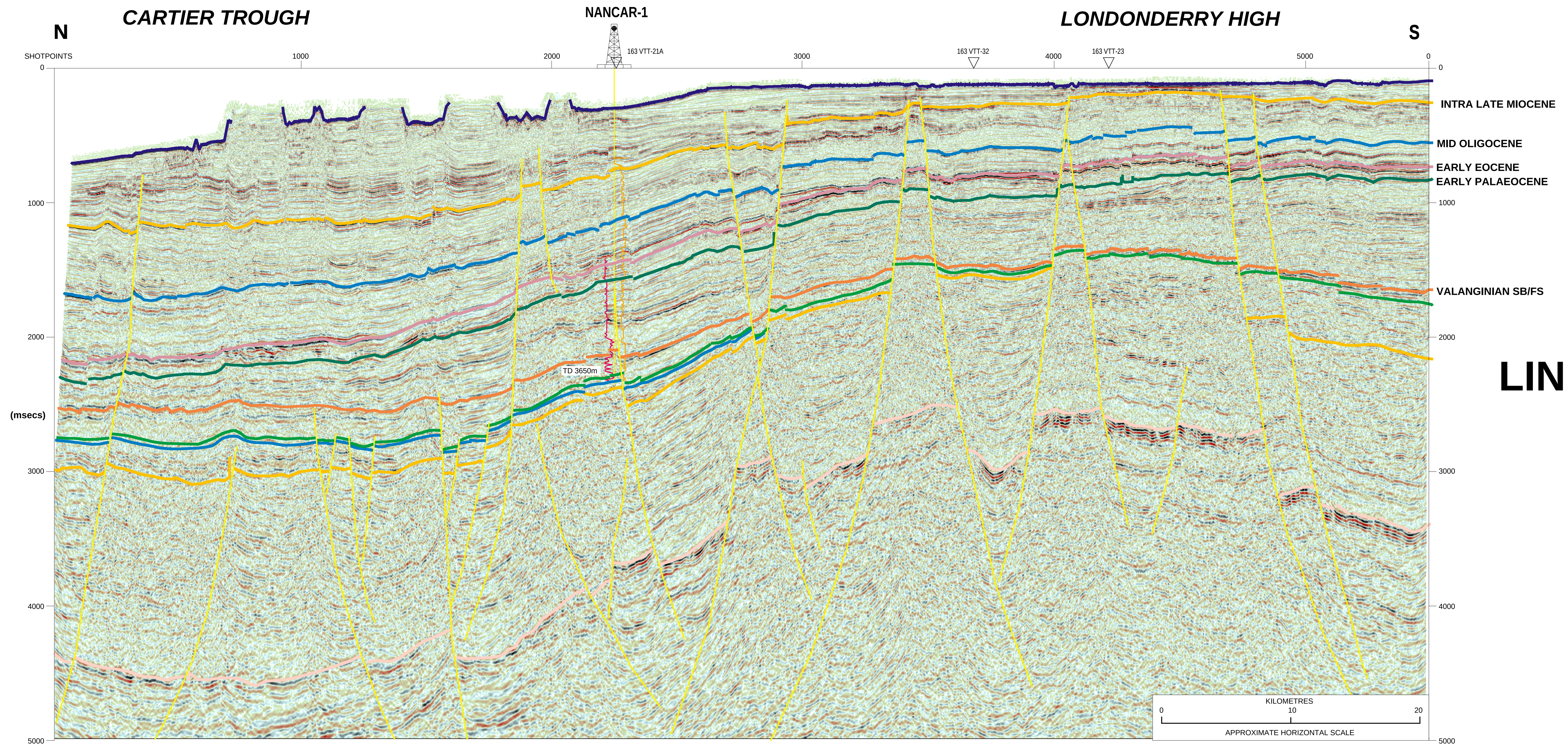
P. Barber / S. Sturrock

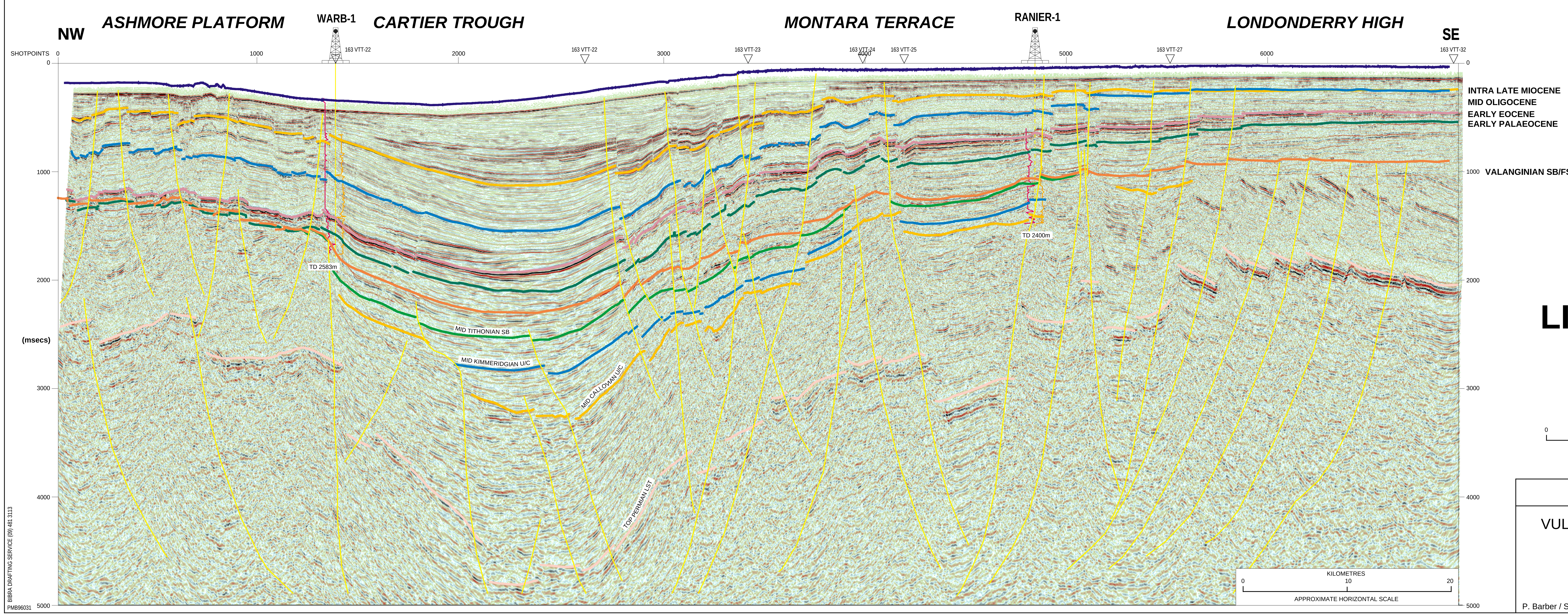
August., 1996

PM896030

ENCLOSURE 21







OIL & GAS CONSULTANTS

VULCAN SUB-BASIN PROJECT

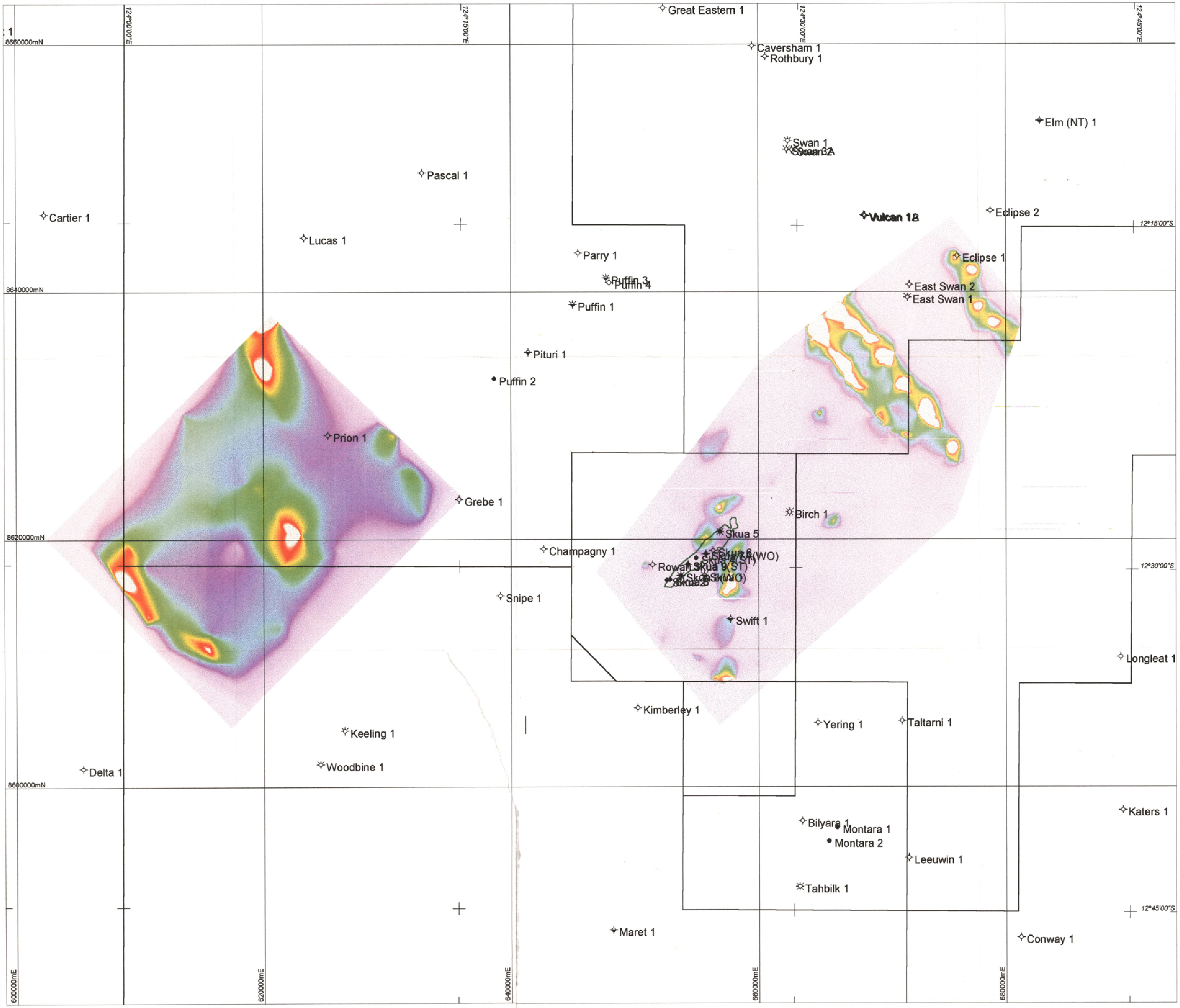
SEISMIC LINES VTT-35 & VTT-14

P. Barber / S. Sturrock

August., 1996

ENCLOSURE 22

Timor Sea



Legend

Wellsamg51.shp
- Current drilling
- Oil well
- Gas show
- Oil and Gas show
- Gas well
- Oil and gas well
- Dry well
- Oil show
- Oil well, Gas show
- Gas well, Oil show
- Injection well
- Gas and Condensate well
- Gas and Condensate show

Oil_fields_and_pipesamg51.shp
- Oil Fields
- Oil Pipelines

Statebordersamg51.shp

Permitsamg51.shp

Oil_fields_and_pipes.shp

Explanatory Notes:

Spheroid: Australian
Description: AMG ; Zone 51
Prime Meridian: 0
Universal Transverse Mercator Projection
Zone: 51
Cenral Meridian: 123
False Easting: 500000
False Northing: 10000000

Plot drawn with WGC Plot in ArcView 2.1b
Licenced to: Sandy Belford
Site: WGC
Serial No: 660370102227

N

5 0 5 10 Kilometers

Scale: 1:200000

IMAGING and G.I.S.
Department

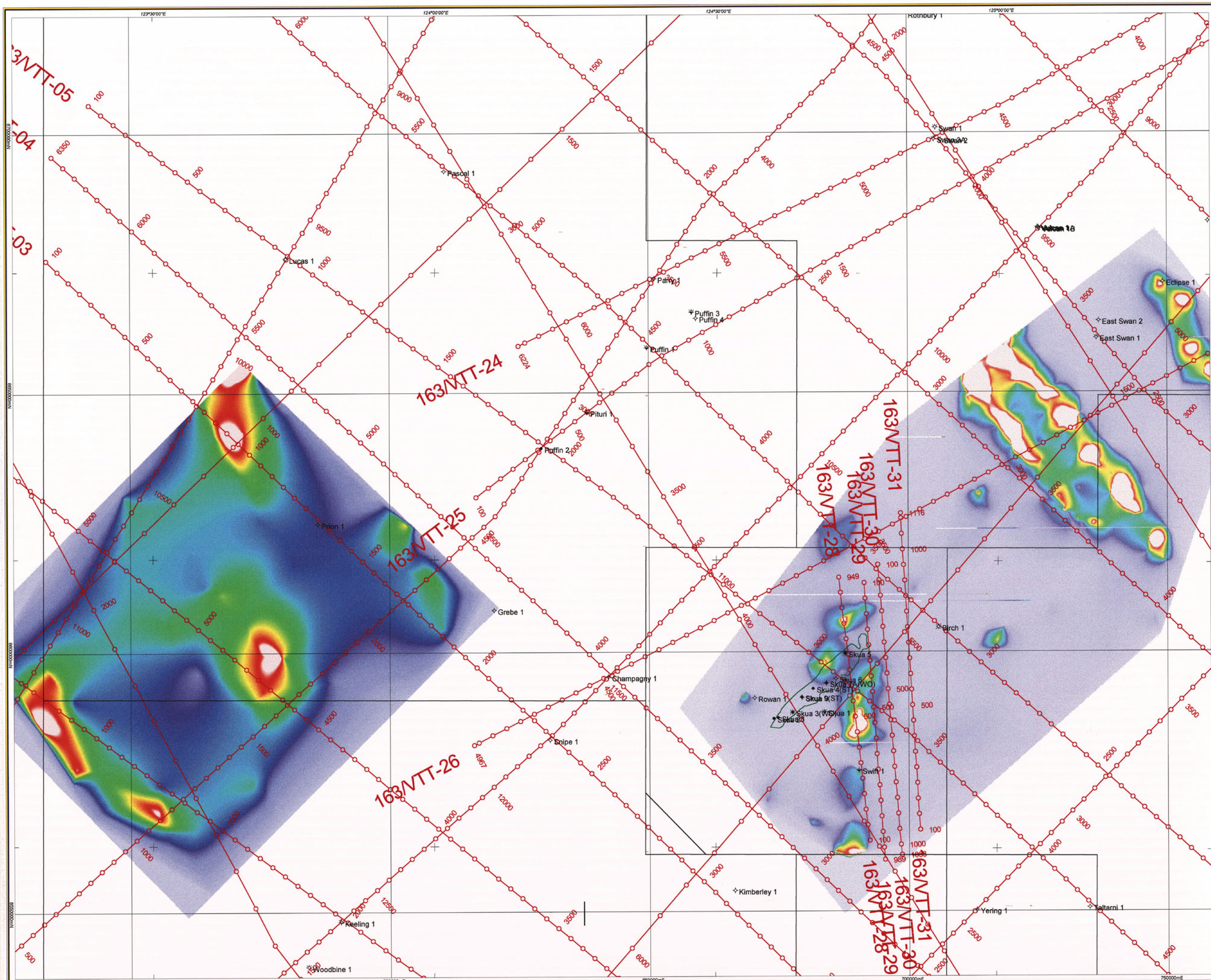
Haydn and Skua
ALF Data
Timor Sea

Created at WGC Consulting

Compiled:	Sandy Belford	Scale: 1:	200000
Drawn:	Sandy Belford	Date:	17:Dec:1996
Edition:			

Enclosure 23

Timor Sea ALF Data



Legend

Wellsamg51.shp
- Current drilling
- Oil well
- Gas show
- Oil and Gas show
- Gas well
- Oil and gas well
- Dry well
- Oil show
- Oil well, Gas show
- Gas well, Oil show
- Injection well
- Gas and Condensate well
- Gas and Condensate show

Oil_fields_and_pipesamg51.shp
- Oil Fields
- Oil Pipelines

Statebordersamg51.shp

Permitsamg51.shp

Agso.dxf
- Text 1
- Text 7

Agso.dxf
- 1
- 7

Oil_fields_and_pipes.shp

Explanatory Notes:

Spheroid: Australian
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Prime Meridian: 0
Universal Transverse Mercator Projection
Zone: 51
Cenral Meridian: 123
False Easting: 500000
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Plot drawn with WGC Plot in ArcView 2.1b
Licenced to: Sandy Belford
Site: WGC
Serial No: 660370102227

N

2 0 2 4 Kilometers

Scale: 1:100000

IMAGING and G.I.S.
Department

WORLD GEOSCIENCE

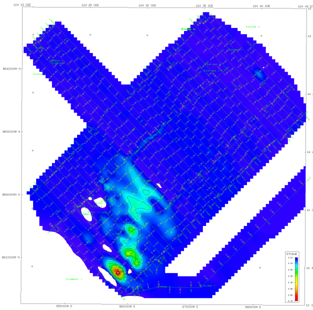
Haydn & Skua

Timor Sea ALF Data

(With AGSO Project 163/VTT Seismic Data)

Compiled: Sandy Belford	Scale: 1: 100000
Drawn: Sandy Belford	Date: 23:Jan:1997
Edition:	Fig #:

Skua-Swan Sniffer Area



1: 100000

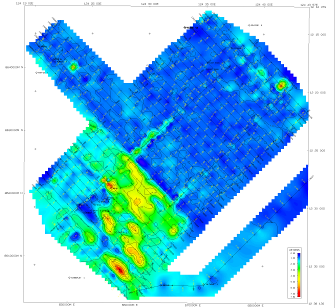
KILOMETRES

UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 123 00 00E

AGSO

Timor Sea - Sniffer Program
Skua-Swan Area
Measured Ethane

Skua-Swan Sniffer Area



1: 100000

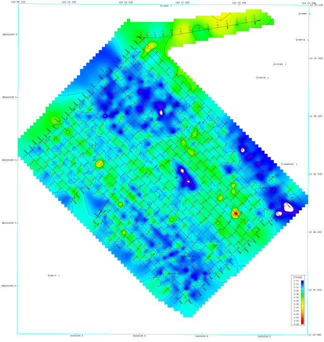
KILOMETRES

UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 123 00 00E

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

AGSO		
Timor Sea - Sniffer Program Skua-Swan Area Wetness Data		
SCALE: 1:100000		10-DEC-98
CELL SIZE = 500M	M. FELLOWS	ENC 28

HAYDN AREA



AGSO		
TIMOR SEA - SNIFFER PROGRAM HAYDN AREA MEASURED ETHANE		
SCALE 1:100000		10-DEC-98
CELL SIZE = 500M	M. FELLOWS	ENC 37