STANSBURY BASIN

THE MARSDEN TREND AND INVESTIGATOR PROSPECT

1991

Archaeocyatha (Early Cambrian)
from archaeocyathid bioherm
Brachina Creek, Flinders Ranges
(D.I. Gravestock)

Tabulate coral from reef block,
Moorowie Mine, Flinders Ranges

EXECUTIVE SUMMARY

The Stansbury Basin is a relatively unexplored basin of South Australia (Figure 1). Good quality seismic data has defined a large untested prospect, the Investigator Prospect, with the potential to contain 200-300 million BBL of oil, or 170 plus BCF of gas and 4 million BBL plus of condensate. The area has strong affinities with prolific petroleum-producing basins in Central Siberia and the Sultanate of Oman.

With the evidence of success already demonstrated in Oman and Siberia it is timely to focus on the equivalent part of the geology in Australia. In addition the selection of Australia as a target country for exploration is favourable because of its political stability.

Southern and central Australia are among the few places in the world where Late Proterozoic and Cambrian rocks and their associated geological history match those of the Central Siberian Platform and Oman and these areas provide analogues with the Stansbury Basin. The Oman and Central Siberian fields are major world hydrocarbon resources and include several giant fields as defined by the American Association of Petroleum Geologists.

It is significant that the first production of Proterozoic oil, gas and condensate began in central Australia, just south of Alice Springs. A gas pipeline from these fields now services Alice Spring and the city of Darwin, 1000 miles distant on the continent's northern seaboard.

The Cambrian rocks of South Australia have prolific oil shows in outcrop and extensive oil bleeds from vugs and fractures in dolomitized limestones intersected in drillholes. These indications occur in a wide area throughout the state and indicate the high potential for Cambrian and Precambrian oil and gas south of the central Australian fields.

This proposal focuses attention on the Stansbury Basin of South Australia in close proximity to the state's capital city, Adelaide (population 1 million), and to refining facilities and an undersupplied market for gas. The Stansbury Basin covers about 4000 square miles and lies partly onshore on Yorke Peninsula and partly offshore beneath Gulf St. Vincent, which consists of relatively quiet sheltered shallow waters (80-120 ft.).

No exploration wells have been drilled to date in the most prospective section beneath the waters of the Gulf. The main trend of interest is a reef-rimmed platform and shelf margin developed in a back-arc basin, with hydrocarbon source potential from black marine shales lying in deeper parts of the section to the east. There is abundant evidence to indicate that the reef-like facies are dolomitized with resultant secondary porosity, and that they have remained unbreached since deposition. Other structural plays are present in the form of large gently dipping anticlinal structures after the style of the giant Siberian fields, plus structures associated with wrench faults.

Petroleum exploration carried out to date has been sparse considering the areal extent of the basin. Much of the early effort was based on technologically poor and inadequate seismic data. Exploration has, however, established that the primary reservoir has, from cores and well logs, excellent reservoir characteristics. Drill stem tests in several Yorke Peninsula onshore wells, drilled on doubtful structural closure, yielded traces of gas and highly saline water confirming the integrity of the seal and that no flushing has occurred.

The best quality seismic to date was acquired offshore in a speculative survey conducted by GSI in late 1985. The results of this have been interpreted and form the basis of this proposal. The Investigator Prospect is a drillable structure, delineated in shallow water (80 to 100 feet).

South Australia has a favourable economic and legislative regime and is politically stable. The South Australian Department of Mines and Energy is enthusiastic about the concept of Cambrian and Proterozoic oil within the State and recognises the potential of the Stansbury Basin.

Petroleum exploration and development in South Australia are administered under the Petroleum Act, 1940 which covers all of onshore South Australia including the waters of St. Vincent Gulf. Stansbury Basin is held by Petroleum Exploration License 53 (PEL 53) awarded 4 December 1990, to Preview Resources Pty. Ltd. and Oakman Pty. Ltd.. PEL 53 covers approximately 10,136 sq. km. (2,505,000 acres) and not only contains proven structures but also encompasses all known trends.

An exploration program is in progress starting with a detailed review and reprocessing of available seismic data. This review also includes an organic chemistry program, including TOC, Rock Eval pyrolosis, gas chromatography, mass spectrometry and thermal modeling. Basement tectonics are also being reviewed using both potential field data together with reprocessed seismic.

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FIGURES

FIGURES

PALEGEOGRAPHY AND GEOLOGICAL SETTING

The proto-Australian continent stabilised during the Early to Middle Proterozoic and a period of quiescence existed until the Late Proterozoic, when supercontinental breakup began through plate divergence by seafloor spreading along the eastern and northwestern margins. It is the eastern margin that concerns us here.

Late Proterozoic breakup (650 to 575 My) along this margin occurred close to the so-called Tasman Line (Figure 2) that divides the present Australian continent north-south into Precambrian terrain on the west and Phanerozoic terrain on the east.

In the Gulf St. Vincent region, the main feature affecting sedimentation was the Torrens Hinge Zone situated immediately east of present-day Yorke Peninsula. As breakup proceeded, the Paleopacific Ocean, precursor to the present Pacific Ocean, formed in the east. A deep trough, the Adelaide Geosyncline, began accumulating a great thickness of sediments (Figure 2). The Gulf St. Vincent region marks the western edge of Early Proterozoic block faulting of the shallow water sandstones, shales and carbonates that had formed in sags and rift valley complexes in the relatively quiescent conditions prior to breakup. In the shallow seas facing the Paleopacific Ocean, evaporitic conditions prevailed through to the Early Cambrian (Figure 3).

A paleographic sketch of the situation during the Early Cambrian is shown in Figure 4. The rock relation diagram in Figure 5 summarises the significant Cambrian units. A selection of sectioned drill cores are shown in Figures 6-12. A broad seaway (the Flinders Sea) extended north-south along the eastern coastline. In the Gulf St. Vincent region, a shelf-ramp-basin facies formed facing a progressively deepening Flinders Sea towards the southeast. Sediments deposited in this region comprised the Stansbury Basin and its distally steepened eastern hinge zone, the now-metamorphosed and uplifted Kanmantoo Trough (Figure 13).

PRIMARY RESERVOIR
Carbonates (Kulpara Limestone)
including reef complexes prevailed in
shallow waters ...

Carbonates (Kulpara Limestone), including reef complexes, prevailed in tropical shallow waters on the platform beneath the Flinders Sea, while finer-grained slope carbonates, siltstones and shales (Wangkongda Formation) were deposited in deeper waters of the outer Stansbury Basin.

SEAL AND POSSIBLE SOURCE
... fossiliferous wackestones and black lime mudstones (Parara Limestone) ...

Subsequently, fossiliferous wackestones and black lime mudstones (Parara Limestone) covered these beds through deposition in moderately deep quiet waters, while in the deep waters of the outer Stansbury Basin a black, pyritic, phosphatic and sparsely fossiliferous shale accumulated (Heatherdale Shale).

PROBABLE SOURCE ROCK
The Heatherdale Shale ... is considered to have had high hydrocarbon source potential.

The Heatherdale Shale has only been sampled in weathered outcrop, close to metamorphosed rocks, but nevertheless has yielded significantly high Total Organic Content (TOC) values. It is considered to have had high hydrocarbon source potential.

Late in the Early Cambrian, a major tectonic phase (the Kangarooian Movements) led to localised pronounced uplift along north-south trends in the western Stansbury Basin and shedding of fauna-rich limestone boulders and basement clastic debris from an emerging highstand. It is important to note that this tectonic phase did not lead to basin-wide unconformity, but was restricted to well-defined structural trends.

During the following period of quiescence, a shoaling-upward sequence of organic-rich marine lime muds (Ramsay Limestone) was deposited over the Kulpara Limestone, followed by fine-grained epeiric sea clastics, and finally by widespread marine to peritidal carbonates.

MATURATION AND GENERATION
... this thermal episode may have served to enhance ... hydrocarbon generation and maturation ...

A reversal of continental plate motion occurred during the Late Cambrian (516 to 508 My), and the Paleopacific Ocean was subducted back beneath eastern Australia.

Initially, this produced mainly localised heating in the eastern zone, leading to mild folding and metamorphism of the Kanmantoo Group rocks which were more deeply buried and closer to the source of heat. A build up of pressures, directed to the northwest and west, eventually led to a belt of thrust faulting along the Fleurieu Peninsula - Kangaroo Island arc. This phase of tectonism, called the Delamerian Orogeny, culminated in the Late Cambrian to Early Ordovician with the folded and regionally metamorphosed rocks of the eastern zone being thrust upwards along steeply dipping reverse faults to form part of an arcuate mountain chain called the Delamerides, stretching south into eastern Antarctica which then lay juxtaposed to South Australia. The sediments of the western Stansbury Basin, being at shallower depths and distal from the heat source, were largely unaffected by heat, and only experienced gentle, broad folding and little or no faulting except along existing trends. This thermal episode may have served to enhance the processes of hydrocarbon generation and maturation, as well as migration and prior development of secondary porosity in reservoir rocks.

A long period of quiescence and relative stillstand ensued. Glacial conditions prevailed during the Late Carboniferous and Early Permian (300 to 280 My), leading to a thick blanket of glacigene diamictites over much of the area.

Dramatic changes to the Australian continent began with the fragmentation of Gondwanaland following rift valley formation during the Middle Jurassic, although the only significant effects at this time in the Gulf St. Vincent area were through minor extrusion of basalt along the present margins of Kangaroo Island (160 My).

Renewed tectonic activity (again restricted to well-established trends) occurred with uplift of the South Australian Highlands (ancestor to the present Mount Lofty and Flinders Ranges) around 65 My (Early Paleocene). Later pulses of uplift and denudation in the east led eventually to uplift of the Mount Lofty Ranges in the late Miocene. However, apart from reactivation of major faults in the east and an unconformity caused by regression of the sea during the Middle Miocene, the Stansbury Basin itself has been little affected.

HISTORY OF EXPLORATION IN THE STANSBURY BASIN

> No drilling has occurred to date in the most prospective part of the Stansbury Basin beneath offshore Gulf St. Vincent.

Oil exploration in the Stansbury Basin began in the 1930's, and a few shallow wells were drilled with very little structural control to guide their locations (Figure 13).

A more rational approach began in 1964 when Beach Petroleum NL took up a licence and flew an airborne magnetic survey. The resulting magnetic basement depth estimates showed that the sedimentary sequence achieved thicknesses in excess of 10,000 feet and that the basin was best developed beneath Gulf St. Vincent (Figure 14 & 15).

Prior to this, two stratigraphic holes (Minlaton Stratigraphic Bore and Stansbury Bore) had been drilled by the Department of Mines in 1956-58 as a test of the potential for Cambrian oil in the basin. This was stimulated by oil show discoveries by Santos Ltd. in the Arrowie Basin located to the north and possibly interconnected with the Stansbury Basin.

During the decade 1964-74, Beach Petroleum carried out a number of seismic surveys and gravity surveys, and drilled 7 exploration wells. The deepest of these were:

* Stansbury Town 1 (4162 feet)
* Stansbury West 1 (5724 feet)
* Edithburgh 1 (3444 feet)

These deep holes were logged geophysically and in addition a well shoot velocity survey was carried out in Stansbury West 1.

The seismic surveys carried out by Beach Petroleum were sparse and technologically poor by today's standards, and consequently exploration wells were sited on largely inconclusive interpretations of structural trends. On shore, seismic reflection surveys featured single fold recording on paper records with 20 lb. charges in 100 ft. shotholes with a total of 296 miles being shot. Offshore, large explosive charges were used and recording was mostly single fold analog with some 3-fold and an minor amount of 6-fold analog. A total of 578 miles of poor quality data with suspect navigational control was acquired (Figures 16 & 17).

Beach was unable to finance offshore drilling and the licence was surrendered in 1974.

A somewhat desultory exploration program by Pan Pacific Petroleum NL began on acquisition of a licence in 1982. The only work of any consequence was a Vibroseis seismic reflection survey (24-fold) of 37 miles on Yorke Peninsula which tied together 6 existing wells. The licence was surrendered without further work because of financial difficulties.

The only survey which has achieved some systematic reconnaissance of the basin proper was a speculative seismic program shot offshore by GSI in 1985. A total of 190 miles of 60-fold digital data was acquired using a tuned airgun array (4075 cu in and 1900 psi) (Figure 17). A TI TSR001 240-channel recording system was used in conjunction with an 12000 ft. streamer. The primary navigation system was GEONAV satellite control. The results of this survey have now been interpreted and form the basis of this proposal.

HYDROCARBON POTENTIAL

CAMBRIAN

The rock relation diagram in Figure 5 summarises the major Cambrian units. The available source rock geochemistry is summarised in Figures 18, 19 & 20. Figures 18 and 19 are provided by David McKirdy of The University of Adelaide.

The maximum thickness of Cambrian sediments intersected by drilling to date is approximately 4400 ft. in Stansbury West 1 on Yorke Peninsula, where the target was fractured and vuggy dolomitized limestone of the Kulpara Limestone sealed beneath tight shaley Parara Limestone. In this test (probably not on a valid structural closure due to poor seismic definition), the Kulpara was about 1500 ft. thick and flowed highly saline water together with gas shows from drill stem tests of a number of intervals. These test results together with water flow imply good seal integrity and absence of reservoir flushing.

Source Rocks:

Lower Cambrian rocks are widespread throughout South Australia. The epoch was dominated by carbonate and evaporitic deposition and characterized by broad regional affinities. From tests on the wide range of bleeds and shows discovered, it is abundantly clear that oil has been generated extensively within the Cambrian sequence. Examples of this are the following:

> Marine source rocks of the Arrowie Basin to the north of the Stansbury Basin have TOC values measured of up to 1.4% in argillaceous limestones and shales. The first oil shows in the Cambrian were in fact discovered in the Arrowie Basin by Santos Ltd in a number of shallow wells. These consisted of 26# API paraffinic crude oil and semi-consolidated wax in vuggy dolomitized limestones unconformably overlain by Tertiary sediments. Traces of free oil were also found in a thin limestone at 5350 ft. in Moorowie 1 in the western Arrowie Basin.

> Oil-prone source rocks also occur in marine and non-marine sediments of the Eastern Officer Basin in the far north of South Australia, where Byilkaoora 1 (drilled in 1979) recovered core from the Observatory Hill Formation with oil bleeding from vugs at approximately 800-900 ft. depth. Subsequently, boreholes have been drilled throughout an extensive area, most of which have encountered similar shows in a variety of beds in the sequence. TOC values are around 1.0% and Rock Eval data indicate that the zones of interest have been in the oil generating window for some time.

In the Stansbury Basin, surprisingly few wells have been drilled as Cambrian tests, and consequently representative TOC and Rock Eval measurements are not necessarily definitive (Figure 18). Some of the results come from restricted outcrops lying close to metasediments and high heat flow. The Heatherdale Shale, for example, yields good TOC values of 0.6% in weathered outcrop, close to zones of metamorphism with unreliable Rock Eval measurements. The Parara Limestone, Ramsay Limestone and Kulpara Limestone yield encouraging TOC values of 0.3% and more reliable EOM values (extractable organic matter) of 150 - 505 ppm.

Figure 19 show a summary of the sparse number of available Vitrinite Reflectance Values (calculated from Methylphenanthrine Index data) for a combination of oils, oil stains and sediments from the Officer, Warburton, Arrowie and Stansbury Basins. These results mostly lie in the mature to overmature ranges and suggest that the Stansbury Basin is in the wet gas and dry gas windows (eg. oil window 0.5 - 1.0, wet gas 1.0 - 2.0, dry gas 2.0 - 3.0). This is, however, a very preliminary assessment.

Figures 18 and 20 give an indication of the maturity indicated in various wells on Yorke Peninsula. In Figure 18 it is indicated that mature rocks are found in Minlaton - 1, SYC - 101, Stansbury West - 1 and Stansbury Town - 1. Overmature rocks are found in Minlaton - 1 and SYC - 101 and in other wells and outcrops in the Fleurieu Peninsula. McKirdy's results have been interpreted to indicate that proximity to basement is a factor in the overmature rocks, presumably indicating thermal influence of the Ordovician Delamerian Orogeny.

In Figure 20 the TOC and VR calc measurements are shown against well sections. This figure indicates that at least 600 metres (2000 ft.) of section lies in the wet gas to oil window while at least 200 metres (650 ft.) lies in the overmature dry gas window.

McKirdy interprets his data to indicate evidence of migration of hydrocarbons into the Ramsay Limestone and Kulpara Formation. This migration was probably onto basement highs from the deeper section of the Stansbury Basin beneath the Gulf St. Vincent, possibly including the Adelaidean Section.

Prediction of organic geochemical conditions beneath the Gulf is speculative as there are no deep holes to date. Evidence, however, from the basin periphery is extremely encouraging.

Further encouraging new evidence on thermal maturity is emerging in the south of the basin. A recent sample from the north shore of Kangaroo Island, where heat flow has been moderate, has yielded vitrinite reflectance values of 0.6% - within the oil window.

> Recent discoveries of the reef making fossils, Archaeocyaths . . . . has significant implications for petroleum exploration.

Sampling of rocks on Kangaroo Island in the same vicinity has resulted in recent discoveries of the reef making fossils, Archaeocyaths and Algae and has required recalibration of the Early Cambrian section in this area. The work of state geologists is revising the stratigraphy and changes concepts of sedimentary models dramatically. This has significant implications for petroleum exploration as it now places a thick sequence of organic rich algal silts, overlain by sandstones, contemporaneous with thick carbonate sequences on Yorke Peninsular.

The Algal component which is set in a muddy matrix, is of the Nuia family. This green algae, which is capable of producing enormous amounts of carbonates and hydrocarons, is found in Siberia and among other areas, also in Middle Cambrian to Ordovician in Southern Nevada and Texas.

Similar fossils are known from Yorke Peninsula and Fleurieu Peninsula which extends the correlation across Gulf St. Vincent.

The indications are that good potential source rocks occur in the subsurface beneath the floor of Gulf St Vincent. The Heatherdale Shale, for example, is believed to have been delineated in a broad zone extending west for some 30 miles away from the metamorphosed zone and downdip from known structures. Deeper within the section, Proterozoic source rocks also exist, while higher in the section the following are potential source rocks:

Parara Limestone - fossiliferous lime mud and wackestone with a conformable to disconformable contact with the Kulpara;
Minlaton Fm - stromatolitic dolostone facies;
Ramsay Limestone - marine carbonate muds.

Reservoir Rocks

The Lower Cambrian Kulpara Formation is the primary target for potential reservoir rocks. It is extensively dolomitized with fracture, intercrystalline and vuggy porosity. On testing in Stansbury West 1, it yielded highly saline water with traces of gas from drill stem testing. It is suspected that fluids expelled through shale compaction ahead of hydrocarbon generation led to this dolomitization.

Other potential reservoirs are extensive sand sheets of the basal Winulta and Mount Terrible Formations, plus fluvial channel sands which prograded across the Kulpara carbonate mudflats. Higher within the Cambrian sequence, the bioherm complexes of the Koolywurtie Limestone Member have local caprock with possible secondary porosity.

Seals:

For the Kulpara Formation and earlier reservoirs, the main seals are expected to occur within shales and wackestones of the overlying Parara Limestone.

For the Koolywurtie Limestone and earlier reservoirs, local seals of evaporitic beds and dolostones occur with the Minlaton Formation, while Middle Cambrian redbeds form a regional seal which is well identified across southern Yorke Peninsula. Thick Permian glacigene diamictites blanket most of the Stansbury Basin.

Traps:

Well-identified plays occur along the Marsden Trend, a presumed extensive zone of carbonate bioherm mounds and reef complexes. These are believed to have well-developed secondary porosity in the primary reservoirs.

Broad, gently dipping anticlinal folds associated with tear faults and basement horst blocks are thought to exist in the thrust belt foreland. Local wrench faults display associated anticlinal rollover structures.

SUMMARY OF PLAY TYPES

Play Type	Reservoir	Seal	Trap Type	Main Risk
Bioherm-reef or stroma-tolitic	Dolomitized carbonates with 2ndary porosity	Mudstone, wacke-stone,	4-Way dip structural with strat. component	Reservoir
Broad fold structures	As above, plus sandstones	Evap. beds, dolo-stones, shales	Anticlinal structure	Reservoir
Rollovers/ fault plays	As above	As above	As above	Seals (although abundant thick plastic clays in Permian expected to act as fault seals)

PRECAMBRIAN

The area is underlain by rocks of the Adelaide System, (figure 3) a sequence of Late Proterozoic rocks up to 65,000 ft. thick which are exposed extensively to the east in the Flinder Ranges and Mount Lofty Ranges over a distance of some 850 miles.

The Adelaide System has essentially untested petroleum potential, probably because where exposed in the Flinder and Mount Lofty Ranges, the rocks are folded and metamorphosed. Seismic data in the Stansbury Basin indicate minimal folding of the Adelaide System in this area, indicating minimal to probably nil metamorphism has occurred here.

It is considered that the Adelaide system provides potential source, seals, reservoirs and traps for petroleum in the Stansbury Basin, akin to the Siberian, Oman and central Australian fields. Recent oil drilling adjacent to diapiric structures in Adalaide System rocks in the North Flinder Ranges is reported to have yielded methane shows.

Source rocks:

Organic carbon content is often mentioned in the literature, but rarely quantified for the extensive shales, carbonates and dolomites (Preiss, 1987). Indicative values are available only for the Tindelpina Shale Member: McKirdy et al (1975) measured up to 1.1% organic carbon. It is likely that this level is present in other units, and it is certainly comparable to the Siberian rocks.

There are several good potential sources of hydrocarbons in the Upper Proterozoic Adelaide System with relevance to the Stansbury Basin. We focus on two.

The older of these is the mid-Torrensian aged Balhanna Shale Member, a widespread black shale of basinal facies, and time equivalent of the extensive, locally stromatolitic, Skillogalee Dolomite. Preiss (1987) interprets an environment of black muds in the east of the Stansbury Basin, and suggests a rapid marine transgression over a deltaic sequence.

The younger is the Sturtian aged Tapley Hill Formation, which contains extensive carbonaceous shales and silts and is up to 8000 ft. thick. A particularly prominent member is the extensive Tindelpina Shale Member which comprises about 200 ft. of dark gray to black dolomitic or calcareous, pyritic silty shale with up to 1.1% organic carbon (McKirdy et al 1975).

Reservoirs:

Several potential reservoir formations are likely to exist in unmetamorphosed Adelaide System sediments. Lenses of dolomitised columnar stromatolites and algal mats or of sandstones form common interbeds with the more abundant shales and siltstones.

It is likely that a reservoir for petroleum generated in the Balhanna Shale is provided by coarse feldspathic sand of the Undalya and Stonyfell Quartzites, which represent delta topset beds deposited in coalescing distributary channels.

Reservoirs to petroleum generated in the Tapley Hill Formation could be provided by arkoses and dolomitised algal mats of the Woocalla Dolomite Member and lateral equivalents. Others could be proved by dolomitised grainstones and algal mats of the Balcanoona Formation.

Other reservoirs could be present in the extensive quartzites of Marinoan Age, which overlie both of the potential source rocks discussed above.

Seals:

A seal to reservoirs in the Undalya and Stonyfell Quartzites can be provided by the overlying basinal silt and shale of the Saddleworth Formation. (Interbeds of dark grey carbonaceous and silty dolomite may provide on additional source.)

A seal to reservoirs in the Woocalla Dolomite equivalents may be provided by shales of the overlying Tarcowie Siltstone.

Traps:

Interpretation of the seismic data suggests that Late Proterozoic rocks underlying the Stansbury Basin area appear to have undergone only minor folding and faulting during the Delamerian Orogeny, and only minor folding and faulting during the Cainozoic uplift. It is considered likely that unflushed and unbreached major structures with four-way closure occur, and that these should form the initial Late Proterozoic targets. However, it is quite possible that carbonate / dolomite / stromatolite reefs, overlain by thin shales, will form traps. In addition, it is likely that stratigraphic traps are common.

PRECAMBRIAN PETROLEUM - CHANGING PERCEPTIONS

In a 1990 public lecture \ David McKirdy of The University of Adelaide, summarised the importance of Percambrian - Source rocks.

"Multidisciplinary studies during the last decade have identified hitherto unrecognised controls on the distribution and composition of organic matter preserved in the Earth's Precambrian and Early Paleozoic sedimentary rock record (>0.4 Ga). Carbonaceous shales and cherts
(TOC > 1%) containing isotopically inhomogeneous kerogen ($\delta^{13}C_{PDB}$ = -42 to -10 per mil) of prokaryotic origin occur sporadically in Archaean sequences. The precursor microbiota were confined to the lower levels of the photic zone in restricted aquatic environments. By Early Proterozoic time (2.5 - 1.8 Ga) epeiric seas had developed, allowing for widespread cratonic sedimentation and burial of organic matter from an expanding biomass of prokaryotic phytoplankton, now shielded from lethal UV radiation by atmospheric ozone. Pyrobitumens associated with uranium mineralisation provide strong evidence for petroleum generation from Early Proterozoic shales in the Franceville Basin, Gabon, and in the Great Lakes region of Canada and the USA.

Optimum conditions for the deposition of potential source rocks were first attained in rift-related tectonic settings during the Middle Proterozoic. Organic-rich shales and siltstones (TOC = 1-10%) in the McArthur Basin, northern Australia (1.7 - 1.4 Ga) and in the Mid-Continent Rift of North America (1.1 Ga) contains well preserved lacustrine (Type 1) and marine (Type 11) kerogen. These sediments are associated with oil shows and (in places) Pb, Zn and Cu mineralisation. The Late Proterozoic (0.9 - 0.57 Ga) was a time of prolonged oceanic anoxia and high rates of accumulation of organic matter in marine sediments. Rich source rocks (TOC up to 30%) and the world's oldest commercial oil and gas reserves occur within aulacogens on the Siberian Platform (Lena-Tunguska region) and Arabian Shield (Oman) where Riphean and/or Vendian siliciclastics and carbonates pass upwards into thick evaporite deposits which acted as regional seals. Gas fields of similar Late Proterozoic age occur in southern China (Sichuan Basin) and central Australia (Amadeus Basin). In South Australia, thick sequences of Late Proterozoic sediments are also considered to be prospective for hydrocarbons.

Catastrophic overturn of the oceans led to a global phosphogenic event around the Precambrian / Cambrian boundary. Thereafter the Early Paleozoic marine realm periodically attained a polytaxic, greenhouse state when sea level rose and deposition of the petroleum source beds was widespread on the Australian, North American, Baltic and Afro-Arabian cratons. The isotopic and biomarker geochemistry of these ancient oils and organic-rich sediments casts new light on the microbial ecosystems which preceded the appearance of continental floras in the geological record."

The recognition of the importance of Precambrian and Cambrian rocks as sources and traps for commerical hydrocarbons is increasing. For example, Mary Fritz (AAPG Explorer, September 1989) comments on Oman:

> The geology of the South Oman Basin is a case in point. Large amounts of oil believed to be of Late Precambrian origin have been discovered there in Precambrian reservoirs which are sealed by Precambrian salt.
>
> But the Precambrian is only the older part of the hydrocarbon equation in south Oman. The new part is that the mega-giant fields that produce from younger reservoir rocks in south Oman appear to have been charged by the same Precambrian source rocks - and recent data suggest that Oman's 570 million-year-old source rocks may still be within the oil window in some areas generating "new" Precambrian oil.
>
> Geologists who have spent a great deal of time studying Oman's geology say that while Precambrian source rocks are an interesting phenomenon, the fact that such vast amounts of oil in younger reservoirs have been traced to a Precambrian source is the big suprise.

COMPARISON WITH OMAN OIL AND GAS FIELDS

There is a clear comparison between some of the hydrocarbon bearing rocks of the Upper Proterozoic and Cambrian rocks of Oman and equivalent aged rocks of South Australia. The comparison includes the lithologies and aspects of structural history. Stratigraphy and rock unit nomenclature and the origin of crude oils in Oman are discussed in Journal of Petroleum Geology and AAPG papers (Hughes Clarke, 1988; Grantham et al, 1987, Gorin et al 1982; Al - Marjebry et al, 1936; Husseini, 1989).

Oman forms the eastern corner of the continental part of the Arabian Plate, and is bounded to the southeast and northeast by the oceanic crust forming the Arabian Sea and the Gulf of Oman. This area extends some 500 miles north - south and is approximately 50 miles wide.

Large scale hydrocarbon exploration in the south of Oman began in the late seventies after the discovery of hydrocarbons in shallow Palaeozoic sandstones near Marmul. Exploration has defined a belt of similar prospects, 20-30 miles wide, extending 200 miles along the edge of the South Oman Salt Basin in the area known as the Eastern Flank Hydrocarbon Province. The present volume of discovered oil in South Oman is around 10 billion BBL of oil. Oils are typically heavy, early expulstion crudes, high in sulphur with little associated gas.

Stratigraphy:

The sedimentary rock sequence in the oil field areas of Oman ranges from Late Proterozoic through Palaeozoic, Mesozoic, and Tertiary age.

In Oman, commercial fields have been found in rocks ranging in age from Infra-Cambrian (Upper Proterozoic), through Cambrian, Ordovician, Upper Carboniferous, Permian, Jurassic and Cretaceous. For comparison with South Australia the Huqf group, of Upper Proterozoic to Lower Cambrian age, is of particular importance for source rocks. Source rocks are found at several intervals within the Huqf.

The Huqf Group, consists of a complex of continental to marine clastics carbonates and evaporites with total stratigraphic thickness of approximately 16,000 feet, overlying a crystalline, igneous and metamorphic basement (Gorin et al 1982). The salt became the prime structure control of most of Oman's oil fields. The Huqf Group has similarities with the Parara and Kulpara Limestones of Cambrian age and the Upper Proterozoic aged Adelaide System of South Australia. The main difference is that extensive evaporites are not established in the Parara and Kulpara.

Structural History:

Tectonics in the Huqf Basin are dominated by basement block faulting and this may have been active since late Pre-Cambrian time. Faults were rejuvenated during the late Palaeozoic and the drift of the Arabian and Indian continents during the Mesozoic and Cenozoic. Late Palaeozoic glaciation in Oman was also recorded in South Australia and has resulted in Permian clastic sediments shed from Kangaroo Island being deposited into the Stansbury Basin to overlie Early-Cambrian, Kulpara and Parara Formations, possibly forming reservoir rocks similar to some of those in Oman.

Traps:

The principal reservoirs and seals are poorly consolidated Palaeozoic clastics which drape, due to salt dissolution, over cores composed of either Lower Palaeozoic sandstones, or Late Proterozoic carbonates (Huqf Group).

Source of Hydrocarbons:

The petroleum geochemistry of Oman provides a picture of considerable variety since crude oils and their source rocks are found both throughout the country and thoughout the stratigraphic column for the Infra-Cambrian to the Tertiary.

"The oils can be geochemically classified into five groups. The groups can be related to good oil source rocks found within the Pre-Cambrian Huqf Group, the Silurian Safiq and the Cretaceous Natih Formations. The fifth group of crudes (named 'Q') cannot be correlated to a known source rock but is inferred to have originated from an unsampled Huqf level."

Oils have been geochemically correlated with algal source rocks of the Huqf Formation, which again may have implications for the Stansbury Basin.

The areal distribution of the Huqf/Hormuz salt is widespread over the Gulf. This suggests that hydrocarbons from source rocks associated with these levels maybe more wide spread than has been previously recognised. This might help to explain the huge amount of oil found in Arabia as compared to the questionable inadequate volumes of Jurassic source rocks present...

COMPARISON WITH GIANT USSR OIL AND GAS FIELDS

> ... the first production of Proterozoic-source oil and gas was from the Bitter Springs Formation south of Alice Springs, and crude oil bleeds and shows abound in Cambrian rocks throughout South Australia...

There is a striking comparison between the Upper Proterozoic and Early Cambrian rock units which host the giant oil, gas and condensate fields of Central Siberia and similar rocks in South Australia. Giant fields of the Lena-Tunguska Province are discussed in the AAPG paper by Myerhoff (1980). A concise summary is given below, including comparisons with the South Australian situation. As the AAPG paper indicates, the potential of rocks of this age should not be underestimated, particularly if a favourable geological regime has prevailed. This is certainly true of southern and central Australia - the first production of Proterozoic-sourced oil and gas was from the Bitter Springs Formation south of Alice Springs, and crude oil bleeds and shows abound in Cambrian rocks throughout South Australia.

The Lena-Tunguska Province includes the entire Central Siberian Platform and is one of the largest stable platform areas in the world. In areal extent and in lithology, Upper Proterozoic and Lower Cambrian rocks of the central and southern Australian platform and shelf compare favourably.

In the Lena-Tunguska Province, commercial field are found in Upper Riphean, Vendian and Lower Cambrian rocks, a marine - terrigenous - clastic sequence that grades into a thick Lower Cambrian section with evaporitic interbeds. Direct correlation has been made with the South Australian Cambrian through identification of worm tube and other fossils.

The sequence is 10,000 to 15,000 feet thick, mainly marine in origin, and flat-lying to gently-dipping. Tectonism and erosion have not adversely affected the region for more than 400 My. Drilling depths have been in the 4000 to 9000 ft. range on the Nepa-Botuoba arch but are expected to become deeper as exploration shifts into the deep basins.

Hydrocarbon generation has occurred within and is trapped within the Proterozoic and Cambrian. Production of oil, gas and condensate is made from at least 14 zones - 9 in the Lower Cambrian and 5 in the Upper

Proterozoic. Several giant fields have been discovered, the largest of which has proved and possible reserves of 10.5 TCF of gas and 300 MBBL of condensate.

Structural History:

The platform is bounded to the southwest, south and southeast by the Baykalian Geosyncline, which may extend from Finland in the west to the Pacific coast, a length of at least 4000 miles, not dissimilar to that of the Adelaide Geosyncline which extends from central Australia across the now rifted Antarctic continent.

While the miogeosynclinal strata are severely folded, almost no deformation has occurred on the platform, where most movements have been vertical. The abrupt platformward facies change is accompanied by almost as abrupt dying out of the folds, a situation which again finds parallels in the Stansbury area.

Traps are mainly of two types:

- large basement drape anticlines
- stratigraphic traps, including the flanks of salt pillows.

In general, the traps formed early and have suffered little deformation, making it possible for entrapment of hydrocarbons over a long period of generation and migration.

As for the sources, it is suggested that hydrocarbon generation, migration and entrapment were a nearly continuous process during the more than 120 My involved in the formation of the Upper Proterozoic and Lower Cambrian sediments. There is some association of light crude with the terrigenous Proterozoic units, while heavier oil and condensate are more likely to have been derived from the younger evaporitic - carbonate marine Lower Cambrian sequence from organic-rich marine shales. Proterozoic source rocks have organic matter up to 3 or 4% by weight. Cambrian limestones have organic contents ranging from 0.5% to 2.4% by weight.

The reservoirs consist of Proterozoic sandstones with intergranular porosities of from 8 to 26%, and Cambrian carbonates with fracture porosity and dolomitized zones, ranging in value from 4 to 25%. In 1981, Early Cambrian bioherms were discovered in the Nepa-Botuoba arch region, leading to new play concepts. The parallels with the Stansbury area are again compelling.

Seals are generally provided by shales in Proterozoic traps (in some cases providing both lateral seal and source within the same horizon). In the

Cambrian, seals are provided either by salt or marine marls and shales.

> "The Lena-Tunguska area is one of great geological interest, because the reserves are the world's largest deposits of indigenous Late Proterozoic gas, condensate and oil."
> A.A. Meyerhoff, 1980. AAPG Memoir 30: Giant Oil and Gas Fields of the Decade: 1968-1978.

DISCUSSSION OF INVESTIGATOR PROSPECT

The Marsden Trend is represented in Figure 21, a schematic cross - section west to east across Stansbury Basin.

The Investigator Prospect is located on the Marsden Trend. It is believed to be associated with an outward-building reef-rimmed platform and shelf which developed in shallow tropical seas during Kulpara time, continuing into the late Early cambrian with intermittent deposition of lime muds and wackstones. There is seismic evidence that the reservoir is unbreached and that the structure was present from the time of deposition. Good secondary porosity is believed to have been developed prior to possible hydrocarbon entrapment.

A detailed montage and prognosis for this proven structure is provided in Figure 22.

SUMMARY

Reservoir	Category	Source	Comments
Koolywurtie	Secondary	Parara/ Minlaton	Bioherm Complex possibly with extensive dolomitization
Lower Parara/ Sellick Hill	Secondary	Heather-dale	Basal fluvial channel sands
Kulpara	Primary	Heather-dale or Parara	Bioherm/reef complex with extensive dolomitization
		Mount McDonnell	Algal rich silts
Winulta/ Mount Terrible	Secondary	Precamb. Entina Fm?	Extensive sheet sands with local underlying stromatolitic carbonates
Precambrian	Secondary	Various: Balhanna Shale; Tapley Hill Fm	Delta topset beds and dolomitised algal mats and grainstones

The proposed wildcat Investigator 1 seeks to test a mapped culmination with an area of closure in excess of 10,000 acres and a closing height of approximately 400 ft.

The potential area of closure mapped from the seismic shot to date is in excess of 30,000 acres.

The Marsden Trend itself has been mapped from earlier seismic and is know to extend without interruption for at least 30 miles north of the Investigator Prospect. Within this fairway, a number of culminations equivalent in size to the Investigator Prospect are inferred. There is little doubt that the main trend extends throughtout the PEL area.

> Assuming an average porosity of 10%,
> a maximum oil saturation of 60%, and
> an oil shrinkage factor of 2,
> possible reserves could be of the
> order of 300 MBBL.

A comparison with similar structures in the Central Siberian Platform produces the following estimates:

> For oil, by comparison with the Yaratka Oil field (45,000 acres, 9-10% porosity and 85 ft of pay, and with 210 MBBLs of P+P+P reserves), possible reserves in the Investigator Prospect could be of the order of 220 MBBL.

> For gas and condensate, by comparison with the giant Sredne-Batuobin Field (425,000 acres, with similar porosities and up to 300 ft of pay, and with 6 TCF of gas and 150 MBBL of condensate), possible reserves in the Investigator Prospect could be of the order of 170 BCF of gas and 4 MBBL of condensate.

ACKNOWLEDGEMENTS

This report draws heavily on both published and unpublished work done by South Australian Department of Mines and Energy (SADME) personnel (David Gravestock, Reg Nelson, Elinor Alexander) and University of Adelaide researchers (David McKirdy). We are particularly grateful for information and encouragement freely given in discussions and for prepublication data of critical importance to the Stansbury Basin.

Various figures used in this report are taken from SADME publications and other published work.

SADME, 1981. Depth To Magnetic Basement South Australia. 1:1000000 scale map. South Australia Department of Mines and Energy.

SADME, 1986. Exploration Opportunity, Stansbury Basin. SADME data package, April 1986.

SADME, 1989. Petroleum Exploration and Development in South Australia, 6th edition. SADME Report Book Number 89/18.

Veevers, J.J. (Ed.), 1984. The Phanerozoic Earth History of Australia. Clarendon Press, Oxford: pp 423.

REFERENCES FOR STANSBURY BASIN PETROLEUM GEOLOGY

Mr. Bill Stewart, National Centre for Petroleum Geology & Geophysics, Adelaide.

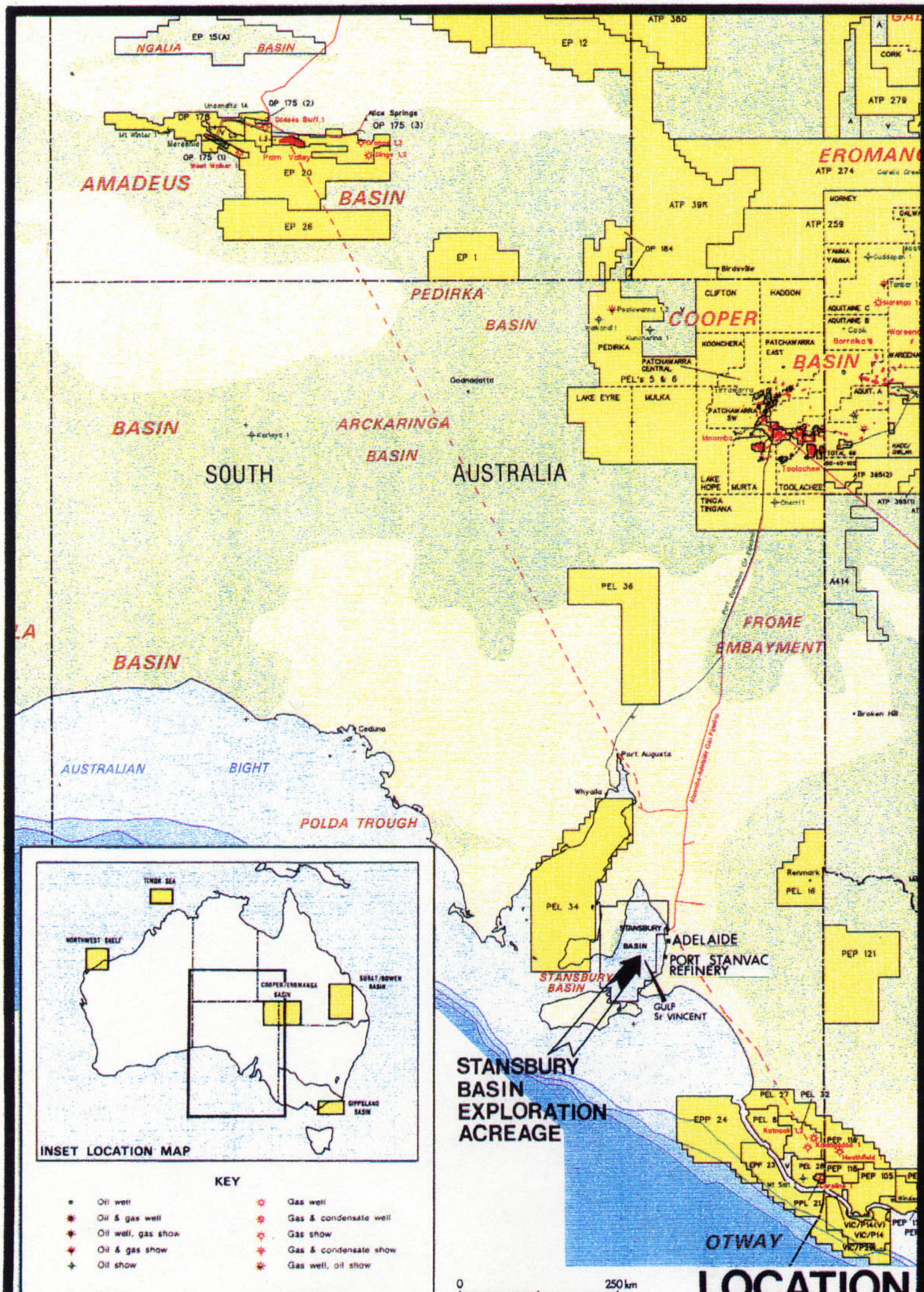
Mr. Bob Laws, Director Oil & Gas, SADME, Adelaide.

Mr. Reg Nelson, Director of Mineral Development, SADME, Adelaide.

Dr. David Gravestock, SA Geolgical Survey, - Cambrian Expert, Adelaide.

Dr. David McKirdy, Organic Geochemistry Laboratory, Department of Geology & Geophysics, The University of Adelaide, Adelaide.

Dr. Andre Zhuralev, Palaeontological Institute, Soviet Academy of Science, Moscow.



LOCATION

(After ENCOM TECHNOLOGY Pty. Ltd.)

FIGURE 1

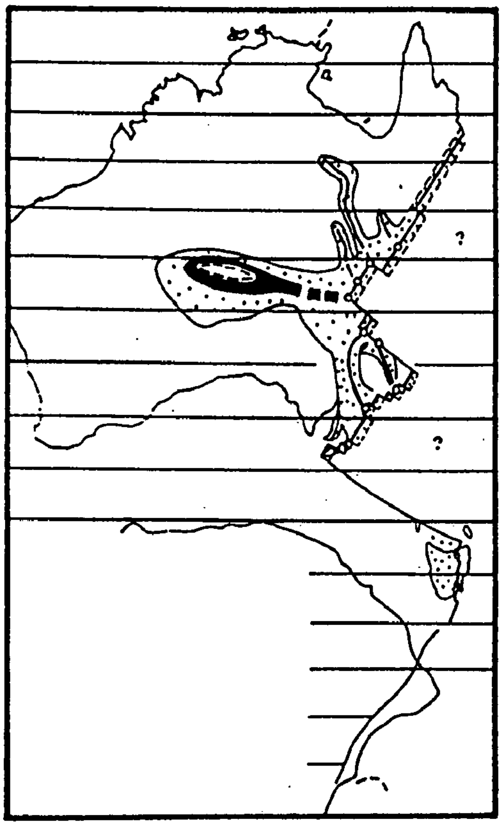


Fig. 232. Adelaidean Regime, from c. 850 to 650 Ma ago. From Fig. 178. To the south, in Antarctica, the continental margin lay along the present Transantarctic Mountains, and to the north at an unknown distance east of the Tasman Line. This interval was quiescent compared with earlier and later times. On mainland Australia, igneous activity was minimal, and shallow water, probably non-marine, sandstone, shale, and carbonate accumulated in rift-valley complexes north and south of a broad sag or syneclise across the centre. All these structures branched off the Tasman Line, the north-east-trending segments of which were probably marked by rift valleys too. Evaporites in the Amadeus Transverse Zone and subsequent glacigene sediment in all the basins suggest a change of climate within the Adelaidean Regime comparable to the subsequent change from the Uluru Regime to the Innaminka Regime. Not shown is the sheet of sediment that extended north-west of the centre into the Kimberley region. Probably reflecting its position nearer the continental margin, Tasmania had older Adelaidean sediment, including turbidites, metamorphosed and intruded by granite and dolerite by 700 Ma ago.

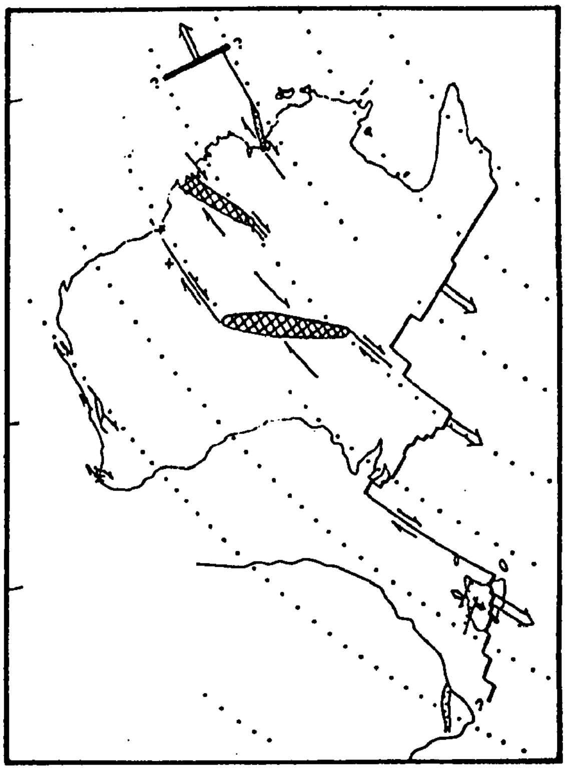
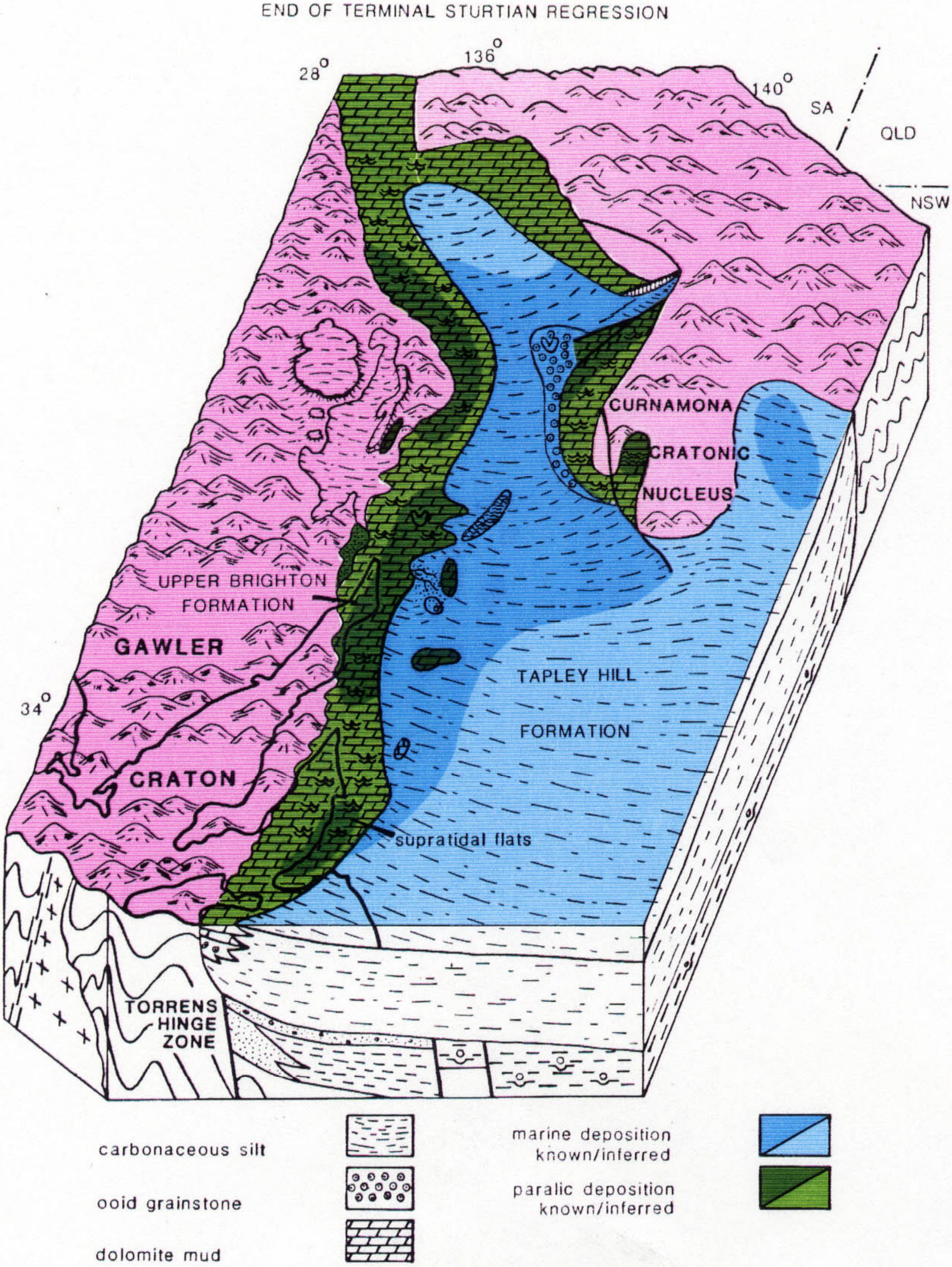


Fig. 233. Terminal (or epi-Adelaidean) phase of the Adelaidean Regime, from 650 to 575 Ma ago, during the Ediacaran, up to the time of breakup along the east and north-west at the start of the Uluru Regime. From Fig. 182.

The quiet of the Adelaidean was broken c. 650 Ma by a change from extension to dextral shear (about a pole to the north-east) that led finally to breakup by plate divergence (about the same pole) in the north-west and the east. As during the interval immediately before the Adelaidean Regime, so during the epi-Adelaidean stage, the Amadeus Transverse Zone, in particular the Musgrave Block, was the centre of activity, with thrusting, the formation of nappes, metamorphism, and, during uplift, the northward sliding of the Adelaidean sequence above a decollement of evaporites. The western part of the Amadeus Transverse Zone was intruded by granite, and its north-western part was deformed by thrusting. Outside the Amadeus Transverse Zone, in the south-west, a volcanic pull-apart basin and a deeply eroded block uplift were mirrored in the north, beneath the Bonaparte Gulf Basin, by an inferred pull-apart basin. In the Flinders Ranges, notable uplift of rift-valley shoulders and the deep erosion of canyons c. 650 Ma ago were followed by continuous quiet deposition marked by the appearance of marine metazoans of the Ediacara Fauna.

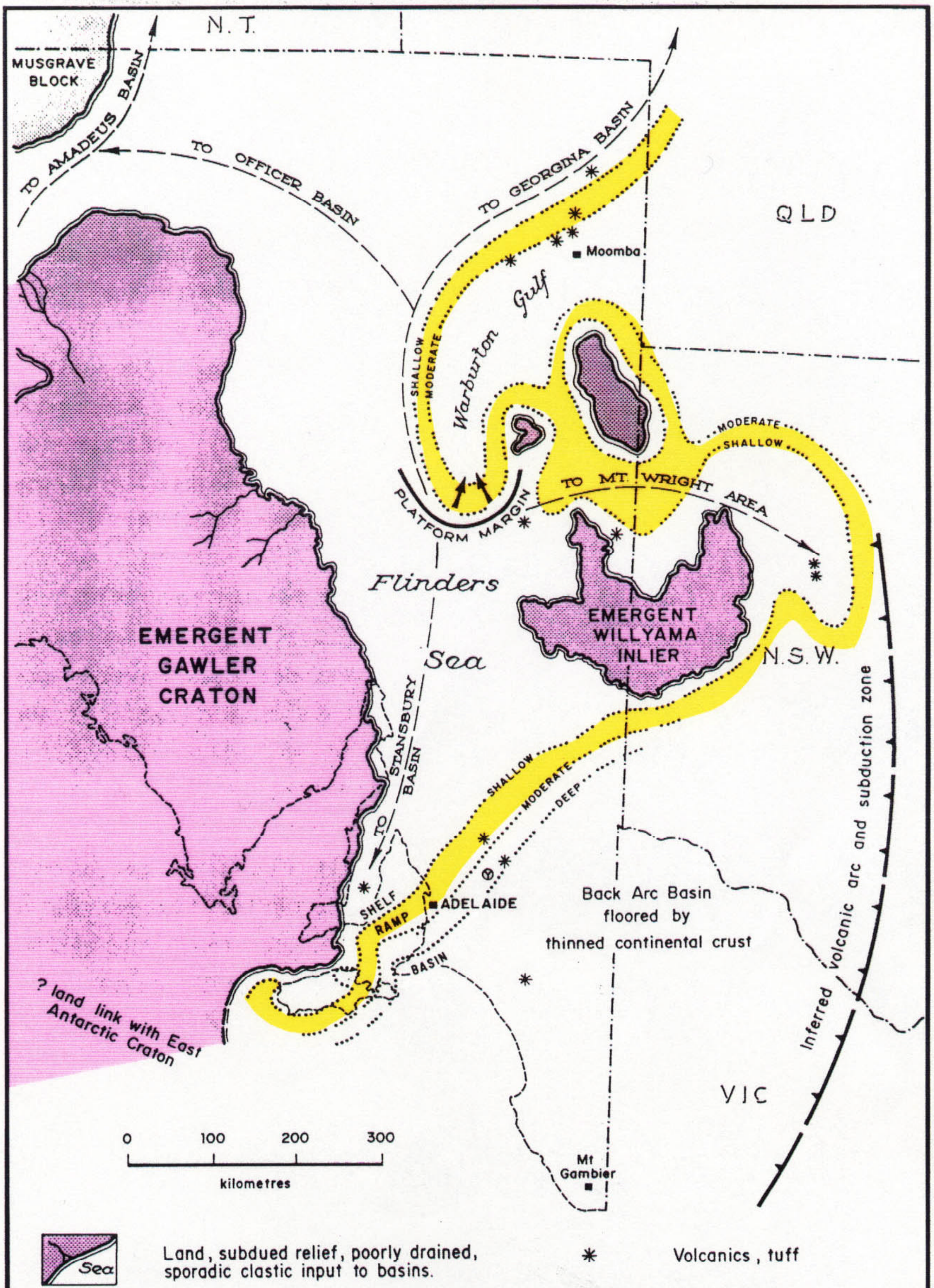
After a regional lacuna, the Adelaidean Regime passed to the Uluru Regime with a change from regional shear to plate divergence by seafloor spreading along the newly formed eastern and north-western margins.

REGIONAL PALAEOGEOGRAPHY – PROTEROZOIC
(AFTER VEEVERS)



PALAEOGEOGRAPHY FOR LATE BRIGHTON TIME **FIGURE 3**

UPPER PROTEROZOIC (after Bulletin 53, Geological Survey of S.A.)

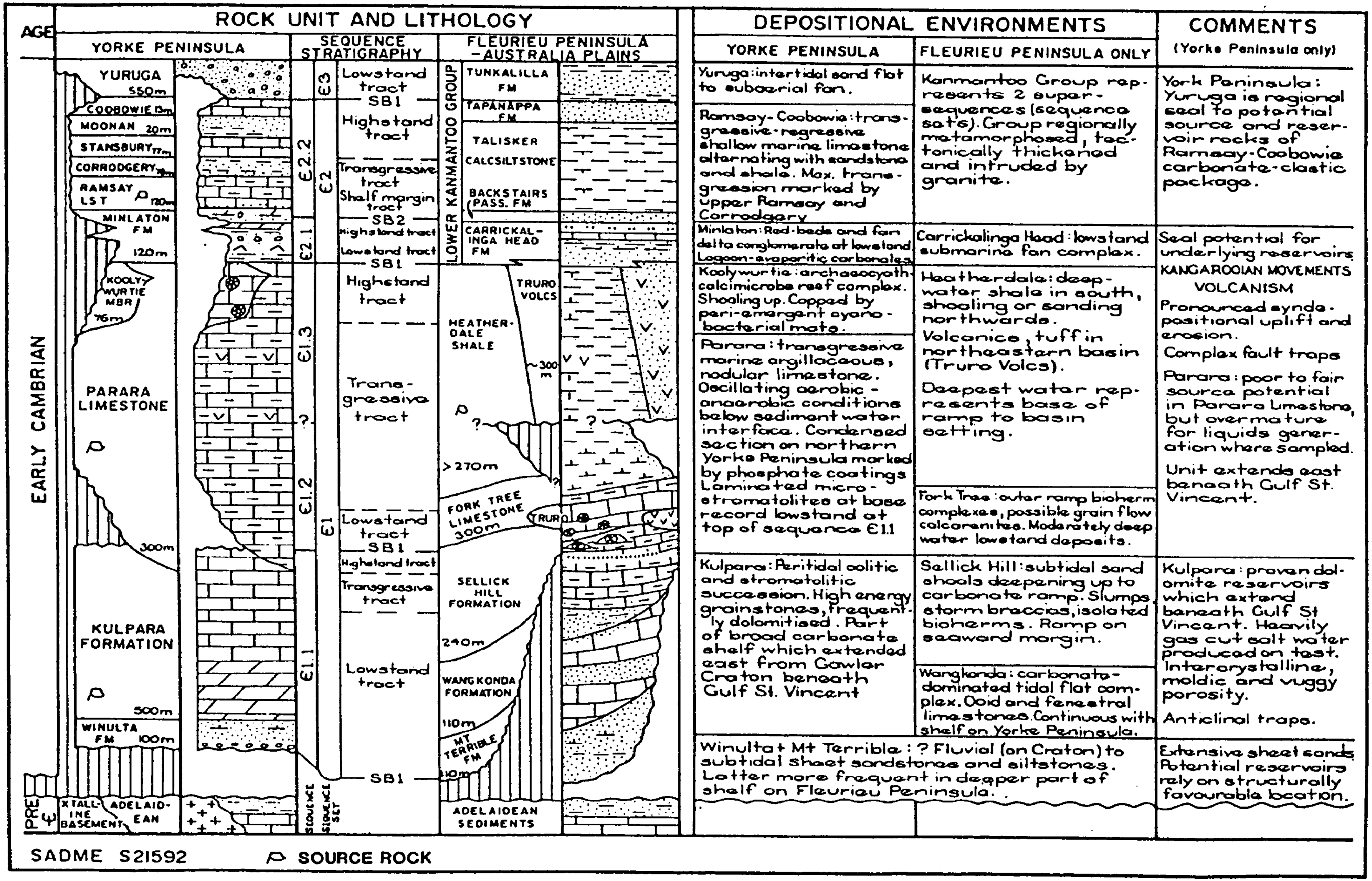


PALAEOGRAPHIC SKETCH OF EASTERN SOUTH AUSTRALIA DURING EARLY CAMBRIAN

(AFTER GRAVESTOCK)

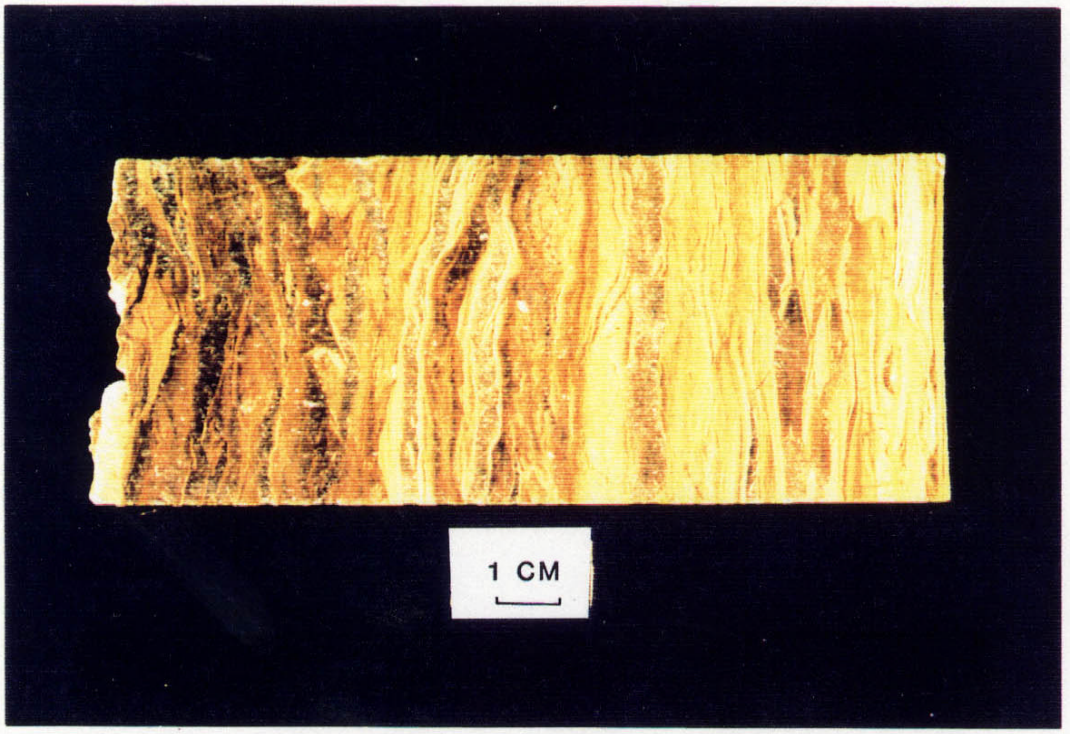
FIGURE 4

SADME S20700



STANSBURY BASIN GEOLOGICAL SUMMARY

FIGURE 5

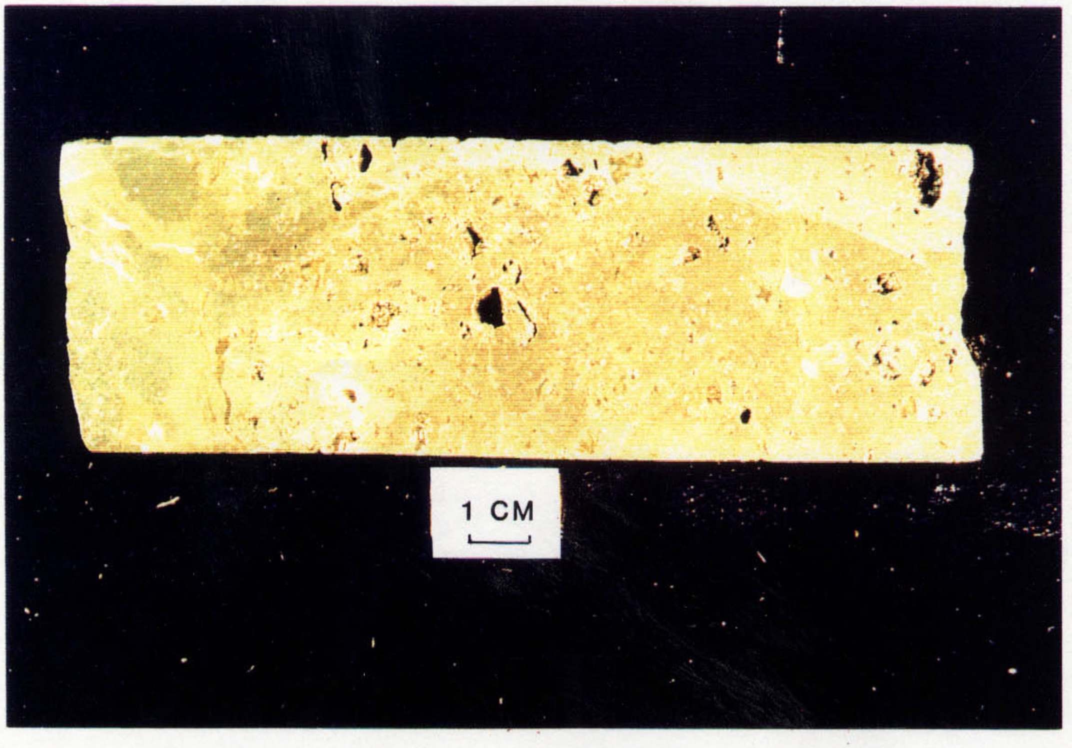


MINLATON 1

236.5 M

MINLATON FM

EARLY CAMBRIAN



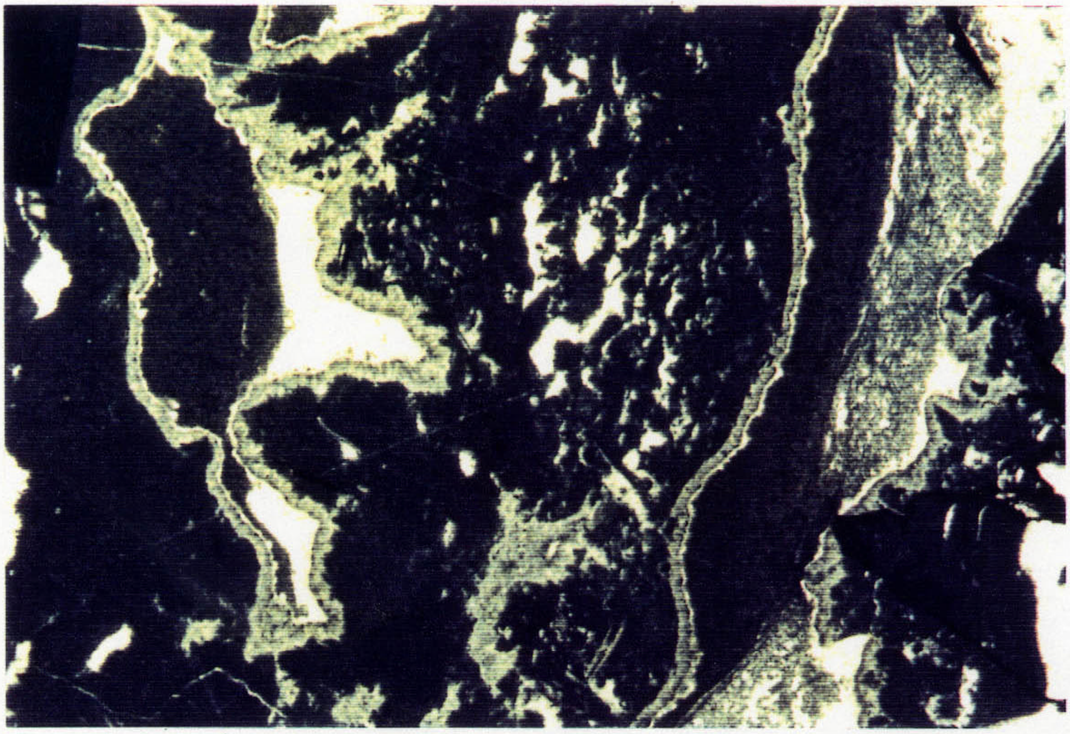
MINLATON 1

264.1 M

MINLATON FM

EARLY CAMBRIAN

FIGURE 6



MINLATON 1

430.6 M

KOOLYWURTIE LST

MEMBER

EARLY CAMBRIAN

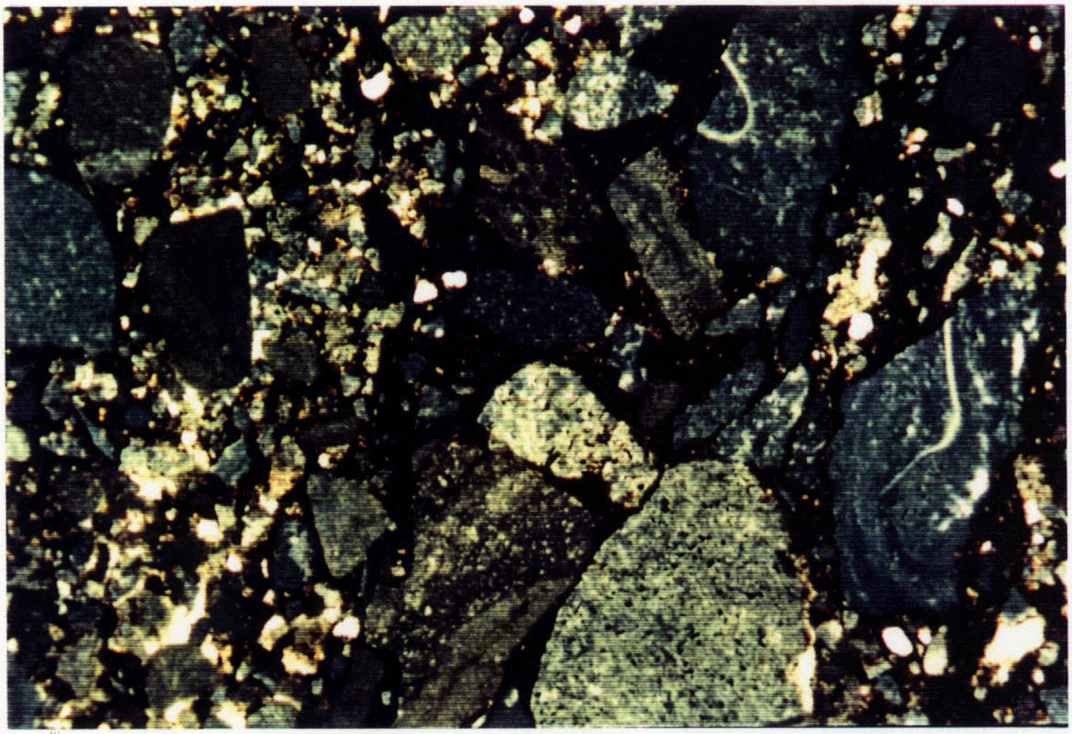
MINLATON 1

527.9 M

PARARA LST

EARLY CAMBRIAN

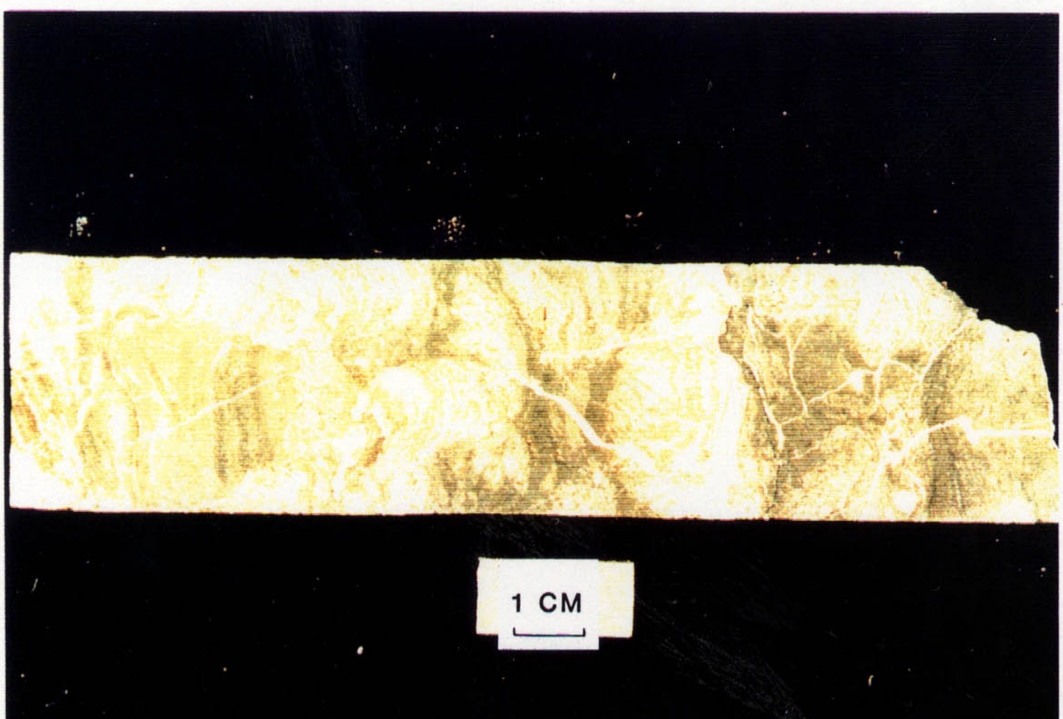
FIGURE 7



MINLATON 2

84.0 M

MINLATON FM
CONGLOMERATE FACIES
WITH REWORKED PARARA
AND KULPARA FM



AQUITAINE SYCIOI

359.5 M

KULPARA FM

EARLY CAMBRIAN

FIGURE 8

STANSBURY WEST 1

957.1 M

PARARA LST

EARLY CAMBRIAN

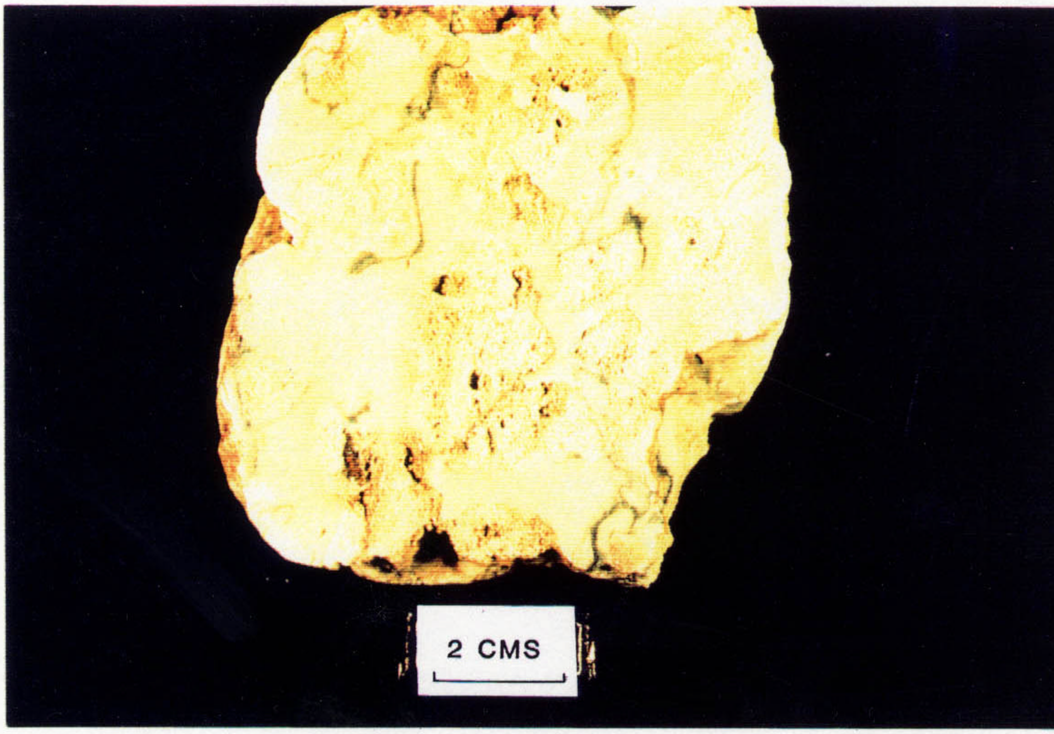
STANSBURY WEST 1

1010.9 M

PARARA LST

EARLY CAMBRIAN

FIGURE 9

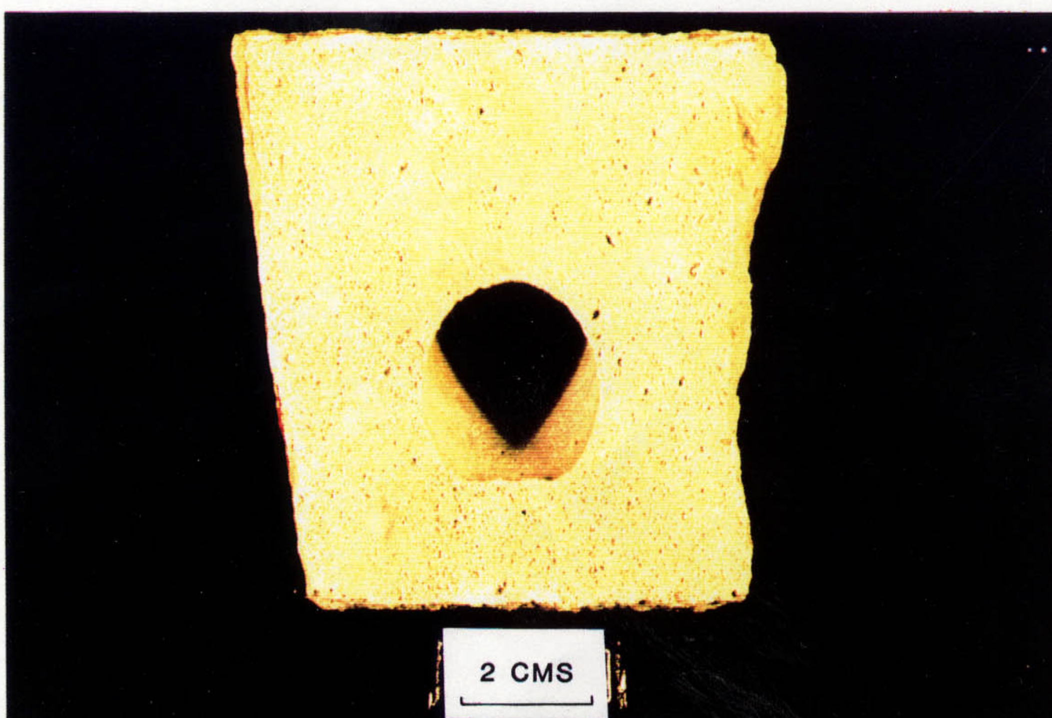


STANSBURY WEST 1

1292.4 M

KULPARA FM

EARLY CAMBRIAN



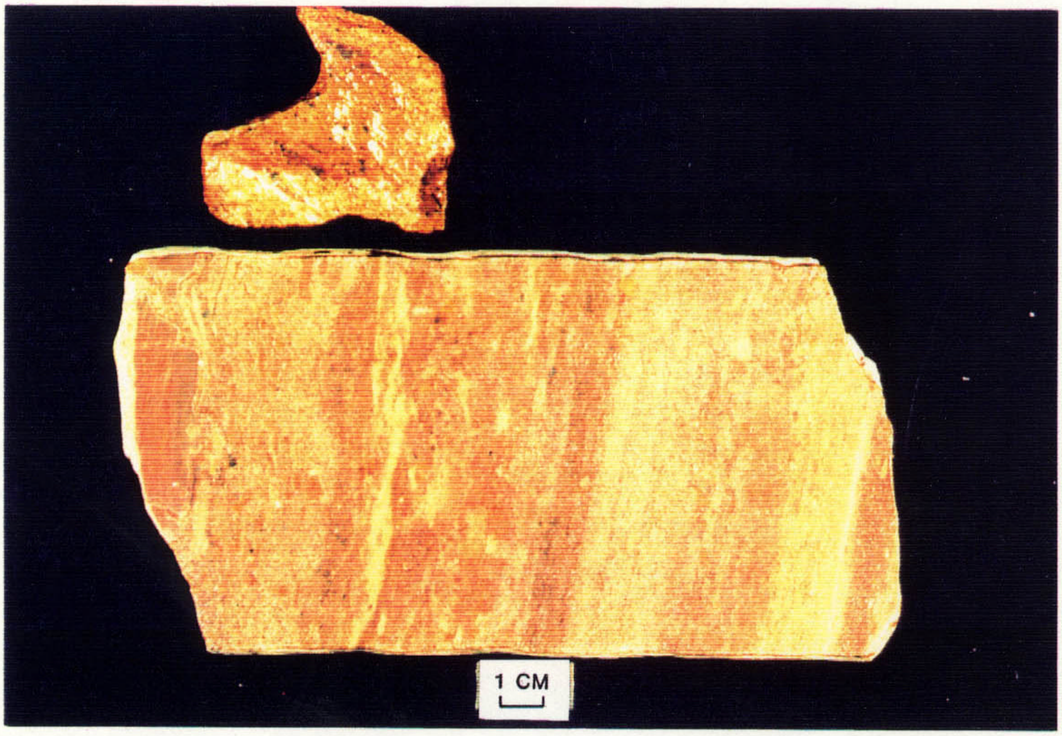
STANSBURY WEST 1

1467.9 M

KULPARA FM

EARLY CAMBRIAN

FIGURE 10



STANSBURY WEST 1

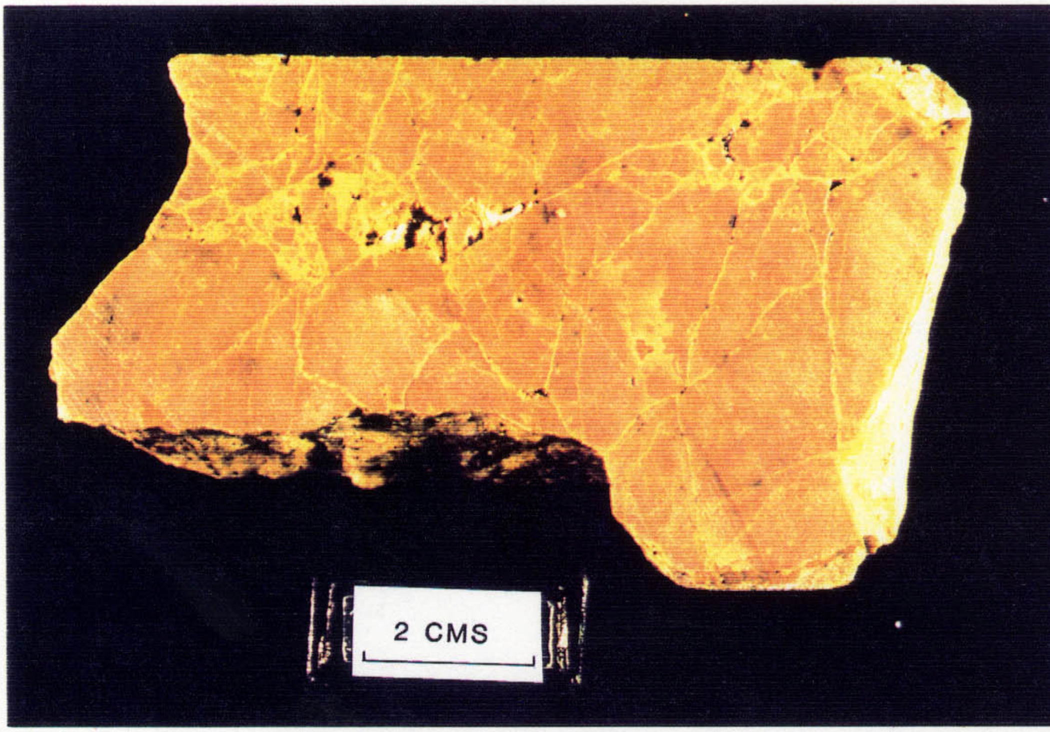
UPPER 1642.3 M

LOWER 1743.4 M

WINULTA FM

EARLY CAMBRIAN

FIGURE 11



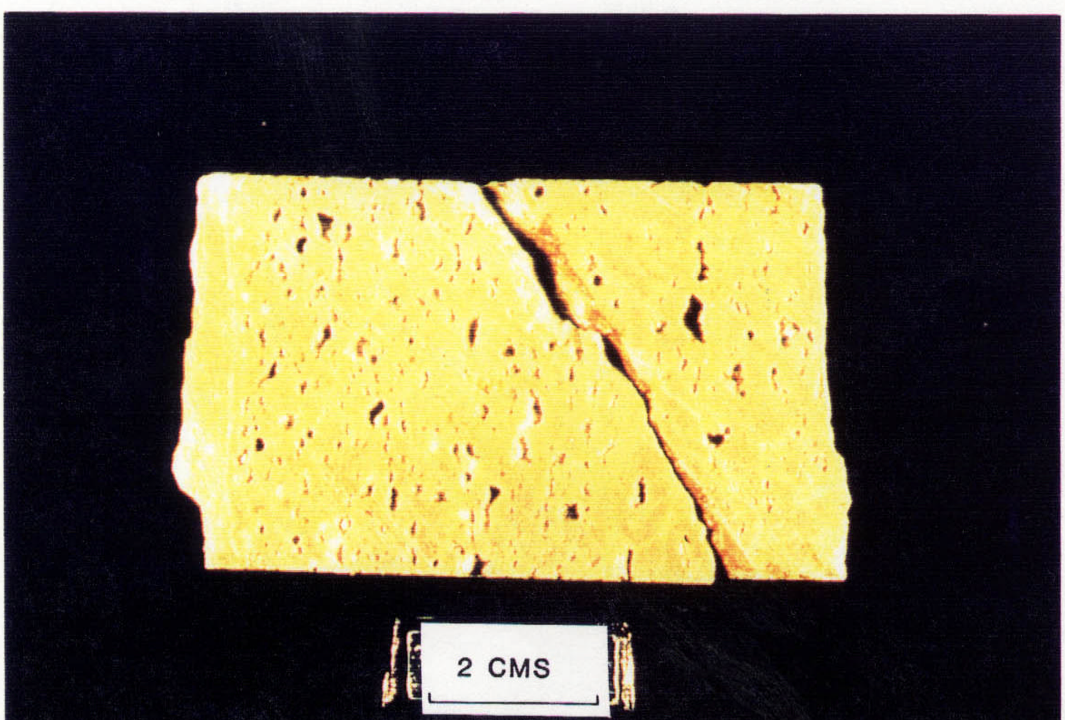
ARDROSSAN 1

56.4 M

FRACTURE POROSITY

KULPARA FM

EARLY CAMBRIAN



ARDROSSAN 1

82.7 M

MOULDIC POROSITY

KULPARA FM

EARLY CAMBRIAN

FIGURE 12

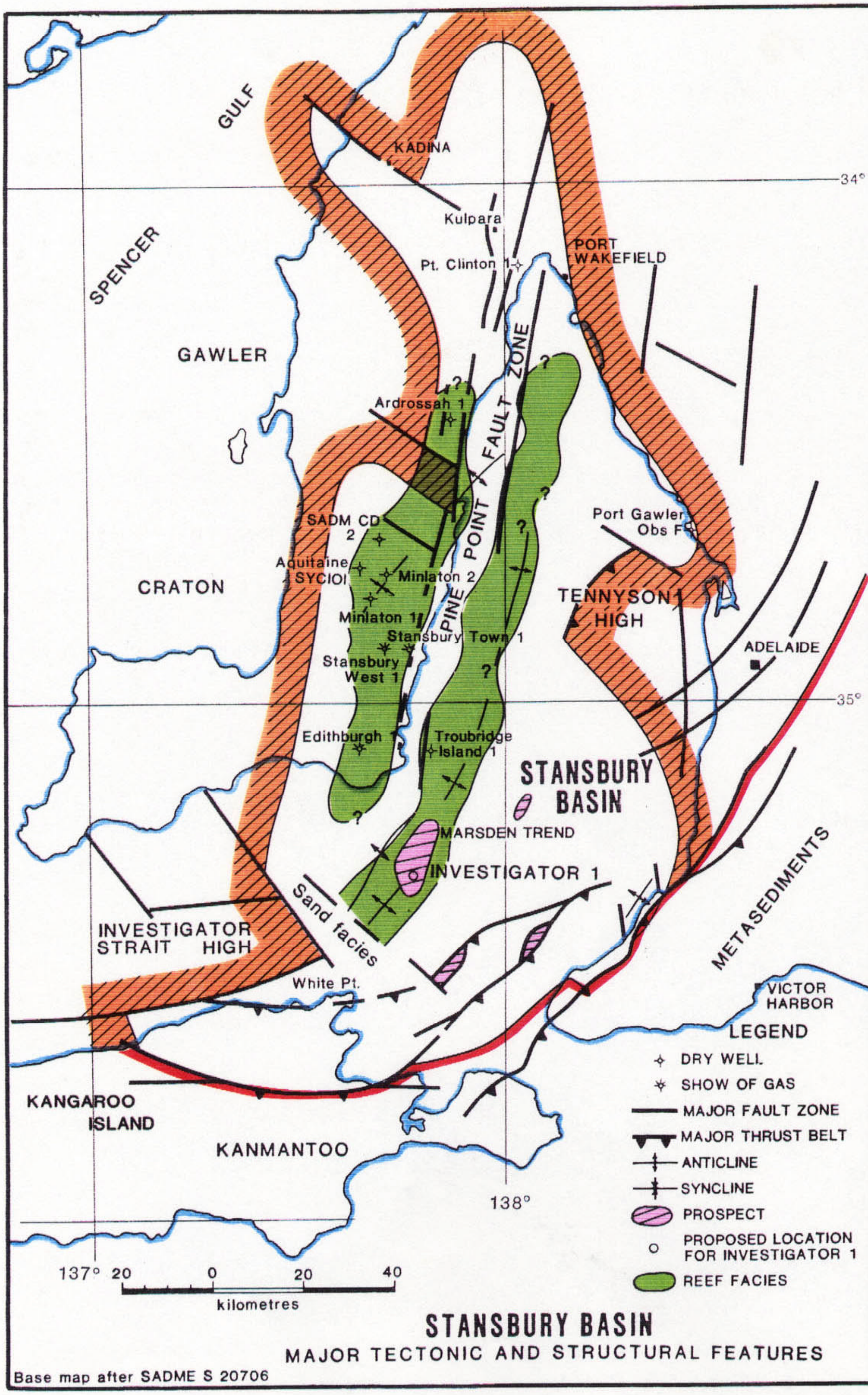
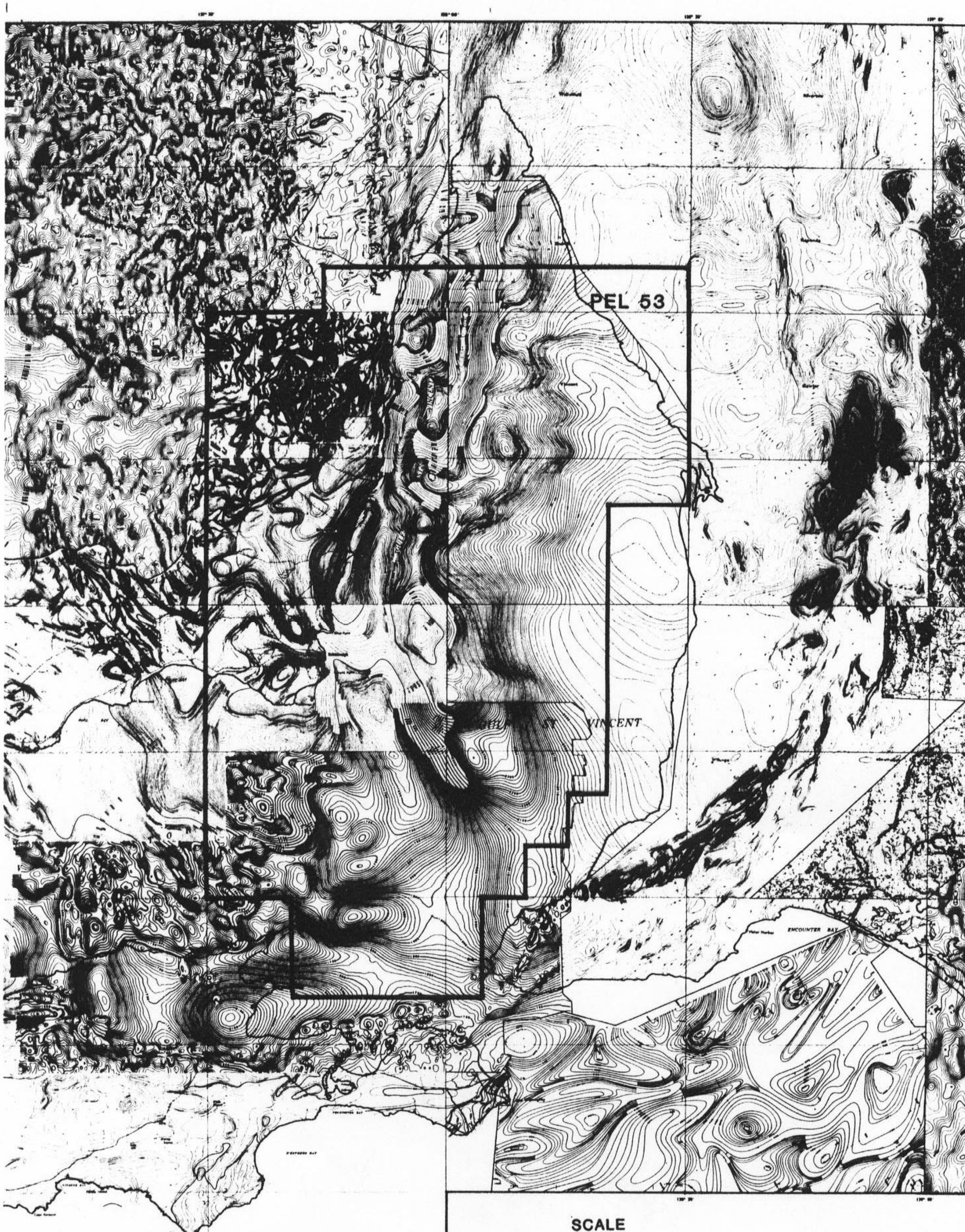
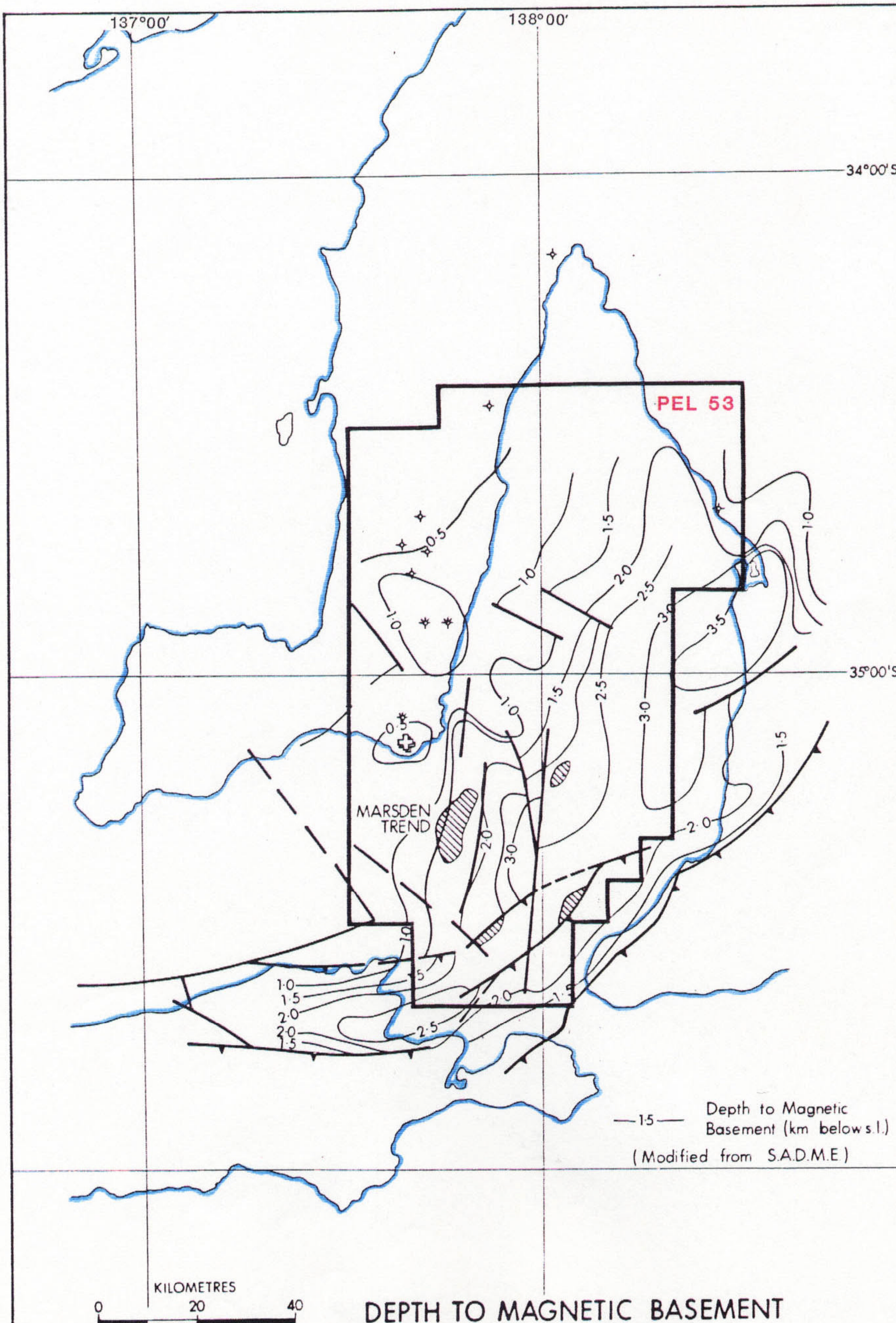

GULF
SPENCER
GAWLER
CRATON
KADINA
Kulpara
Pt. Clinton 1
PORT WAKEFIELD
PINE POINT FAULT ZONE
Ardrossan 1
SADM CD 2
Aquitaine SYC101
Minlaton 2
Minlaton 1
Stansbury Town 1
Stansbury West 1
Edithburgh 1
Troubridge Island 1
Port Gawler Obs F
TENNYSON 1
HIGH
ADELAIDE
STANSBURY BASIN
MARSDEN TREND
INVESTIGATOR 1
Sand facies
INVESTIGATOR STRAIT HIGH
White Pt.
METASEDIMENTS
VICTOR HARBOR
KANGAROO ISLAND
KANMANTOO
34°
35°
137°
138°
20 0 20 40
kilometres
LEGEND
DRY WELL
SHOW OF GAS
MAJOR FAULT ZONE
MAJOR THRUST BELT
ANTICLINE
SYNCLINE
PROSPECT
PROPOSED LOCATION FOR INVESTIGATOR 1
REEF FACIES
STANSBURY BASIN
MAJOR TECTONIC AND STRUCTURAL FEATURES
Base map after SADME S 20706

FIGURE 13



TOTAL MAGNETIC INTENSITY (after SADME)

FIGURE 14



DEPTH TO MAGNETIC BASEMENT

FIGURE 15

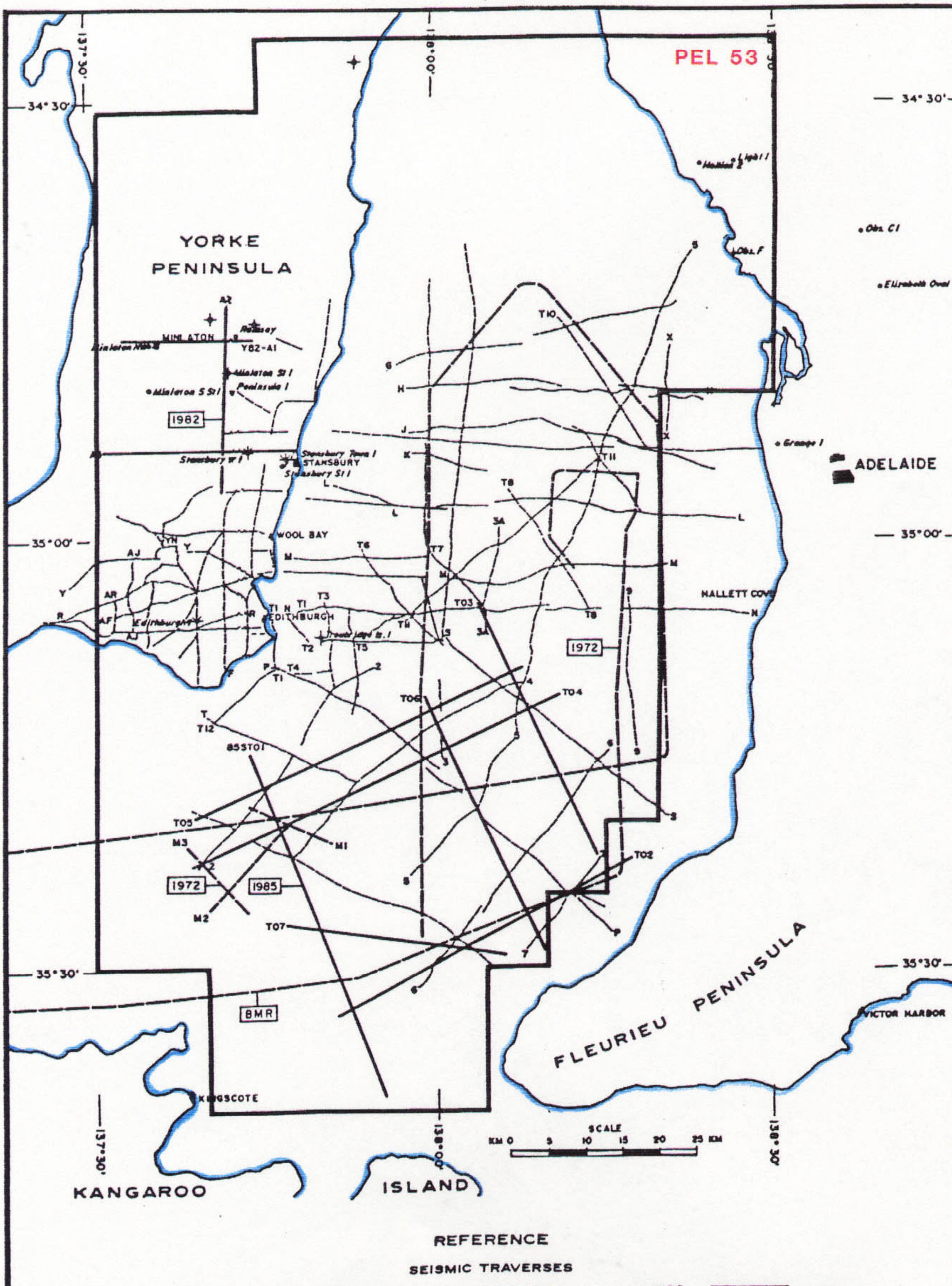


FIGURE 16

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED R.A.G.	C.D.O. 24·3·86	DATE
STANSBURY BASIN SEISMIC COVERAGE	DRAWN R.J.B.	SCALE approx. 1:700 000	
	DATE 17/3/1986	PLAN NUMBER	
	CHECKED	S 18567	

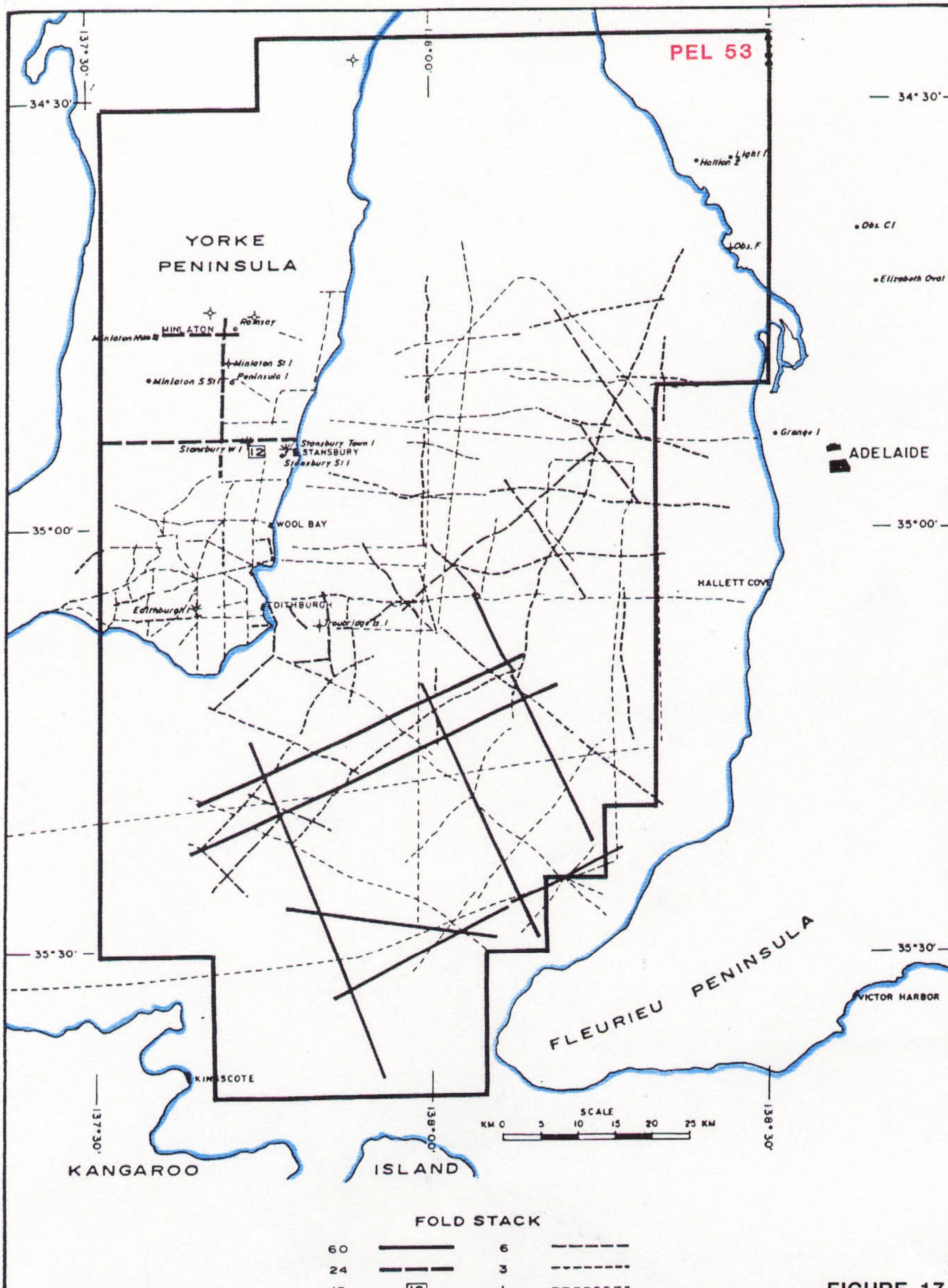


FIGURE 17

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

COMPILED R.A.G.	C.D.O. 24-3-86	DATE
DRAWN J.B.	SCALE 1 : 700 000 (approx)	
DATE 17 March 1986	PLAN NUMBER	
CHECKED	S 18568	

STANSBURY BASIN
SEISMIC COVERAGE
FOLD OF STACK

STANSBURY BASIN SOURCE ROCK DATA

Unit	Sequence	TOC (%)			EOM (ppm)	Kerogen	
	C	max	mean	n	max	H/C	type
PARARA LST	2.2	0.57	0.27	4	150		? III
RAMSAY LST	1.2–1.3	0.91	0.30	8	425*	0.50	II–III
HEATHERDALE SH	1.2–1.3	1.62	0.64	4	25	0.19	II
KULPARA FM	1.1	0.63	0.29	3	505*		? III

*migrated hydrocarbons

MATURE

Minlaton-1
SYC-101
Stansbury West-1
Stansbury Town-1

OVERMATURE

Minlaton-1
SYC-101
Curd-1B,12
Port Clinton-1
Fleurieu Peninsula

525m ABOVE BASEMENT

FIGURE 18