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GREAT SOUTHLAND MINERALS PTY LTD

ANNUAL REPORT

EL 1/88

1995

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ANNUAL REPORT 1995 EL 1/88
GREAT SOUTHLAND MINERALS PTY LTD
J SLOT

EL1/88
APR 1996
See folio 39

JASON SLOT
MANAGING DIRECTOR

MARCH 1996

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ABSTRACT

Shittim #1 at Variety Bay on Bruny Island was cored to a depth of 1021 metres. Gas was encountered below a 580 m sill and increased through the Woody Island Formation into 200 m of Truro Tillite.

Results from this hole, from the 228 m deep Jericho#1 and from all previous work of Condor and Great Southland Minerals Pty Ltd were assessed by independent consultants Jack Mulready (from Melbourne) and Bob Young (from Houston Texas), who found the results very encouraging

They have concluded that the Tasmanian Basin is prospective for commercial quantities of oil and gas.

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INTRODUCTION

Since the recent phase of oil and gas exploration started in 1984 and the first exploration licence was applied for, over 8 million dollars has been expended on research and development for the project, 3.5 million dollars of that being recent Federal Government funded Australian Geological Survey Organisation (A.G.S.O.) research.

Collaborative studies with many persons, groups and agencies, including those listed below, have considerably enhanced the understanding of the basin.

B.M.R (rock eval.)
University of Tasmania Honours students (basin studies)
Shell (seismic reprocessing)
B.H.P. (oil geochemistry)
State Mines Department (gravity and seismic)
C.S.I.R.O (seep studies and geochemistry)
Eugene Domack (maturation and depositional environment of the Tasmanites oil shale)

Three holes were drilled on the original 50 sqkm licence EL10/84 - now a part of EL 1/88. The holes were drilled on Bruny Island for the following reasons:

- **Onshore and offshore seismic existed in the area and needed velocity control, which was only obtainable by a down hole shot so that the previous processing could be repeated with actual real velocities.**

- **Historic records indicated:**
    - **that the area had had numerous seeps of both oil and gas**
    - **at least five shallow wildcat holes had been drilled but were depth-limited because of previous technology.**

- **Results of gravity and magnetic surveys indicated that the whole of North Bruny Island is on a basement high , with a good potential regional trap for oil and gas.**

- **Modern geochemical oil exploration methods indicated that there were crude oil seeps in creeks and around old drill sites that warranted investigation.**

- **The area was remote. Therefore private land access was not a problem and a 24 hour rig operation was possible without disturbing anyone.**

- **A recent Mines Department hole on the neck at Bruny Island had discovered oil in loose sand at 30m depth.**

The results of the drill holes are recorded in the next section of the report.

SUMMARY OF RESULTS

The drill holes on Murray field , North Bruny island , were called Shittim 1, Gilgal 1 and Jericho 1.

All three holes recorded petroleum hydrocarbons in a gaseous state.
- **Shittim 1 recorded tar with the zeolites in the fractured dolerite and gas from 810 metres depth . The hole was drilled on to 1021metres without reaching the unconformity due to overpressured gas.**
- **Gilgal 1 recorded gas at its total depth of 51metres**
- **Jericho 1 recorded gas from 15 metres to the bottom of the hole at 228 metres.**

The implications of these results are summarised in a report by Robert Young., (Appendix 1). This report was commissioned after a visit by Jason Slot and Gordon Wise to Houston, Texas and upon advice determined that a review of the significance of the results by a world expert was required to validate the results obtained to date.

Trent Woods summarises the stratigraphic correlations for Shittim 1 and Jericho 1 along with the timing of potential hydrocarbon generation and potential reservoir rocks in Appendix 2.

Appendix 3 is an internal summary of the results recorded in Shittim 1 and a gives a general overview of the project's progress.

At the request of the Mines Department an independent consultant was employed to assess the significance of the gas encountered in Shittim 1.

Jack Mulready is well known in the Australian oil and gas community, being the chief former geologist of Moonie oil and gas . Mr Mulready concluded (Appendix 4) that the hole established that a seal, reservoir and gas were present and that the results encouraged further investigation of the basin depocentre located in central Tasmania. Bob Young (Appendix 1) also suggests that the next hole should be on the mainland in a deeper part of the basin.

In regard to the location of that stratigraphic hole, Appendices 5 - 9 supply the current research results , which , when integrated , indicate sites for future drill holes.

RESULTS REPORTED PREVIOUSLY

The major work completed was the drilling of Shittim #1 to 1021m. Nearby, Jericho #1 well has been precollared to 228m with the intention of drilling to pre-Parmeener basement when a suitable drill rig is available Summary logs of Jericho #1 and Shittim #1 are attached (Appendix 10).

In addition, the necessary physical and chemical analyses have been performed on the core and on the gas . Basic geology has been carried out in and around the drill sites and calculations performed to assess theoretical maturation based on various models.

Shittim #1 spudded in in November 1994. HQ drilling below a precollar set at 80m commenced in March 1995. NQ coring was carried out from 181m to 888 m and BQ thereafter. Unfortunately, the hole did not reach pre-Parmeener 'basement' before technical difficulties (overpressured gas) necessitated re-siting of the hole.

Drilling at Shittim #1 has provided encouraging results for the company.

Formations encountered were as predicted by Dr David Leaman except that the dolerite was unexpectedly thick (580 m thick rather than the 250m predicted). The Deep Bay Fm is strongly metamorphosed to a calc-silicate hornfels and the Bundella Fm correlate and Woody Island Fm also , not surprisingly , show evidence of strong contact metamorphism.

Vitrinite reflectance on the Woody Island Fm indicate metamorphic temperatures of 300 C plus. Of interest are the fractures in the Woody Island Fm and the Truro Tillite that are increasingly lower in dip downhole, probably indicating the existence of low angle faulting at depths of 1000m+, as indicated on the Storm Bay seismic profile.

Porosities and permeabilities were carried out on core samples. Sandstone porosities from the Bundella correlate range from 7.4 to 11.9% whilst horizontal permeabilities range from 6.8 to 9.0 millidarcys, which values are regarded as fair by Levorson . By comparison, producing Cooper Basin reservoir sandstones range in porosity from 5-12% . Away from a thick dolerite sill we would expect correlative sandstones to have much higher porosities and permeabilities and the company now has much higher measurements from the Lower Parmeener in areas outside of 1/88.

Mr Ted McNally reports

> "Combustible gas vapours were first detected whilst drilling in open hole above the dolerite . The first documented gas show occurred shortly after a hotwire was installed whilst coring at 904 m. At 907 m the chart drove to a peak of 58 gas units which was 22 units above a steady gas

background. Two following cores to 910 m and 913 m recorded 20 units background generated as cuttings gas . At 944 m a further show above 100 units background generated as cuttings gas. At 944 m a further show above 100 units was noted.
The hole continued to produce high swab and bottoms up gas after each rig shutdown. The highest swab gas reading was 254 m at 988 m. The highest bottoms up gas was 390 units at 1021 m. The gas shows and the attendantly necessary mud weights are shown in appendix 3.
Drill fluid weights in excess of 9.5 ld/gal. were required due to overpressuring"

Samples of gas collected by Mr Ted McNally were fowarded to AMDEL and the CSL lab at the University of Tasmania for GCMS analysis . The samples contained methane and ethane in a ratio of 4:1 with significant concentrations of propane through to hexane

A report on the significance of Shittim #1 was compiled by independent consulting geologist Jack Mulready in September 1995 and submitted to the TDR earlier (Appendix 4). Mr Mulready examined all of the core , visited the rig and assessed the physical and chemical data acquired by the company and concluded (p.6) that Shittim#1

> **"...raises the possibility of *a sizeable column of gas , possibly in a stratigraphic trap* " and (p7) "...must certainly be viewed as *a most encouraging result so far.* "** (italics added).

Independent consultant geologist Bob Young, from Houston Texas, visited Tasmania in December 1995 and reviewed all of the company's data, reports and operations for the last 19 years (see Appendix 1). He concluded that:

> **" all of this *builds a good case for finding commercial oil and gas in the basin...*";**
> **"work to date has *certainly established a valid play for oil and gas* "; and "a core hole program to evaluate the basin and explore for hydrocarbons can be designed. *The economic factors for the area are very attractive* and would sustain the costs of such a program." (italics added).**

Jason Slot
Managing Director
Great Southland Minerals P/L

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APPENDICES

1. **POTENTIAL OF OIL AND GAS IN THE TASMANIAN ONSHORE BASIN**
   ROBERT YOUNG, March 1996
   (HOUSTON TEXAS BASED WORLD AUTHORITY ON OIL EXPLORATION)

2 **PETROLEUM PROSPECTIVITY OF THE PALAEOZOIC , SOUTH - EAST TASMANIA : AN INVESTIGATION ON THE TIMING OF POTENTIAL HYDROCARBON GENERATION FROM PALAEOZOIC SEDIMENTS AND CHARACTERISATION OF POTENTIAL RESERVOIRS OF THE LOWER PARMEEMER SUPERGROUP.**
   TRENT J WOODS B.Sc. December 1995

3 **OIL AND GAS PROSPECTIVITY OF THE TASMANIA BASIN A PROGRESS REPORT** September 1995

4 **REPORT ON THE SIGNIFICANCE OF THE SHITTIM NO 1 STRATIGRAPHIC CORE HOLE E/L 1/88 NORTH BRUNY TASMANIA AS AT SEPTEMBER 5TH 1995.**
   JACK MULREADY. September 1995
   Independent Consultant

5 **CONODONT GEOTHERMOMETRY IN PALEOZOIC CARBONATE ROCKS OF TASMANIA AND ITS ECONOMIC IMPLICATIONS**
   DR CLIVE BURRETT 1992

6 **HYDROCARBON BIOMARKERS , THERMAL MATURITY, AND DEPOSITIONAL SETTING OF TASMANITE OIL SHALES FROM TASMANIA , AUSTRALIA .**
   A.T.REVILL ET AL . March 1994

7 **CONGA OIL CURRENT EXPLORATION STATUS PROJECT DENTRECASTEAUX SOUTH EAST TASMANIA.**
   DR DAVID LEAMAN . 1987

8 **ACS LABORATORIES PTY LTD**
   WARREN FARLEY . JUNE 1995

9 **AMDEL , GEOCHEMICAL EVALUATION OF AN OIL SEEP SAMPLE FROM LONNAVALE , TASMANIA .**
   SCOTT WHYTHE AND BRIAN WATSON . January1996

10 **STRATIGRAPHIC LOGS OF SHITTIM #1 AND JERICHO #1**
   TRENT.J.WOODS December 1995

APPENDIX 1

POTENTIAL OF OIL AND GAS IN THE TASMANIAN ONSHORE BASIN.

BY ROBERT YOUNG : HOUSTON TEXAS BASED WORLD AUTHORITY ON OIL EXPLORATION . MARCH 1996

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March 13, 1996

Dr. Gordon Wise-Chairman
GREAT SOUTHLAND MINERALS PTY. LTD.
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Tasmania, Australia

At the request of Great Southland Minerals Pty. Ltd., I have reviewed the geological, geochemical, and geophysical reports made available over several years on the "Potential of Oil & Gas of Tasmania". I have also reviewed the recently completed No. 1 Shittin well drilled to a depth of 1021.4 meters on Bruny Island. The well bottomed in Permian Truro Tillite with an increase of methane gas upon penetrating the tillite. In December, I met with Dr. Clive Burrett, Chief Geologist for Great Southland Minerals; Malcolm Bendal, Director of Great Southland Minerals; Jason Slot, Director of Great Southland Minerals; and David Leaman, Geophyscist with the Geology Department of University of Tasmania. We had extensive discussions on the potential of oil and gas in the basin and also on the recent developments in the geochemical analysis of seep samples, the evaluation of the recently drilled No. 1 Shittin well on Bruny Island, and the recent "TASGO" seismic project onshore Tasmania Basin by Australian Geological Survey Organization (AGSO).

The geochemical analysis from several samples certainly indicate that the source for these many oil seeps could primarily be generated from the Ordovician limestones and the limestones and the Permian source rocks are in or very near the oil window. These rocks, and possibly additional source beds, could exist deeper in the basin.

The methane gas recorded in the Truro Tillite of the No. 1 Shittin well could be interpreted as being in place swamp or lake deposits of the tillite and were released by the coring and drilling. Or, the tillite could be highly fractured with gas seeping in from a deeper ordovician reservoir. Either way, the recording of gas was very important.

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Great Sonthland Minerals Pty. Ltd.
March 13, 1996
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The recent "TASGO" seismic lines were shot to test the recording response of shooting over dolerite for half the line and without dolerite for the other half. My observation of the unmigrated T-4 line had good results of energy being recorded on all of the line. I did not get to see the migrated processed line, but I understand it was very successful. This could open up a large area for reflection seismic exploration to define structures or potential traps.

All of this builds a good case for finding commercial oil and gas in the basin, but an extensive seismic program would take a great deal of time and money.

My recommendation would be for a core hole to be located in the deeper part of the basin on what is interpreted as a ridge of structure from magnetics and gravity, with possibly two seismic lines, crossing the well sight, perpendicular to each other and done prior to drilling.

Although the basin has shown potential for source, reservoir and seals, the picking of a location to find commercial reserves is going to be very difficult to impossible without the assistance of reflection seismic. Drilling core holes can also be very expensive and the need for a lot of luck.

Sincerely,

Robert S Young

Robert Young

xc: Dr. Clive Burrett

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POTENTIAL OF OIL AND GAS IN THE TASMANIAN ONSHORE BASIN

Robert S. Young
Consulting Petroleum Geologist
Houston, Texas

INTRODUCTION

There has been an early interest in oil in the Tasmania Basin, since the first sighting of oil seeps in 1880. Shallow wells were drilled in the early 1900's and the maximum depth of any well was about 400 meters. Gas shows were discovered in one well at Port Sorell and oil discovered in small quantities from Bruny Island, but since 1939, there has been little or no activity of serious exploring for oil and gas until recently. Recent drilling at Variety Bay, Bruny Island, had shows of methane gas of over a 200 meter column. The few wells to have penetrated Permian Pre-Parmeener basement have proven dolomitic Precambrian, turbidites or Cambrian volcanics. No hole is deeper than 100 meters.

The areal extent of Tasmania and all its smaller outer islands covers 16.8 million acres. The Tasmanian Basin covers over 5 million acres. These marine and non-marine sediments of upper Paleozoic and lower Mesozoic age are very widespread and are referred to as the Parmeener Super Group (Bank 1973). It is estimated the thickness of the basin is over 2,500 meters. In general, the Tasmanian Basin rests unconformably upon the Ordovician, Cambrian, and Pre-Cambrian rocks. Much of Tasmania consists of exposed Cambrian and Pre-Cambrian in the west and the Ordovician-Devonian turbidites in the northeast, all intruded by Devonian granitoids. The granitoids are inferred to occur at shallow depths beneath the unconformity. There are over 270 seeps discovered, which transect all rock types, strongly suggesting that deep crustal lineaments are still active" (Burrett). Many of the seep samples have been analyzed geochemically and found to be related in oil signatures with the potential source of the Ordovician limestones of the Gordon group and very little with the Tasmanite oil shale or

Quamby mudstones of Permian. It is also presumed that deeper and older formations in the basin could have source potential. The Permian sands make up the greatest potential for reservoirs and are intermixed with coal beds and an oil shale zone. A primary seal to these beds is the overlying Jurassic dolerite that covers nearly 3/4 of the basin. The Ordovician limestones of the Gordon Group are also considered possible reservoirs as paleokarsts, reefal or fractural. Structural features are difficult to define. To date there has been very little refection seismic coverage due to the poor quality of data beneath the blanket of dolerite. The present coverage of gravity and magnetics of the basin, have been used extensively to date and have been able to define regional older structural elements. Most of the younger Permian sediments in the basin will be structurally drapping, fault trapping or stratigraphic, which will be practically impossible to define with only gravity or magnetics.

HYDROCARBON POTENTIAL

The importance in the evaluation of any basin for commercial hydrocarbons are source, reservoirs, seals, and traps.

1. Source

Prolific oil producing basins, when geochemically evaluated are shown to contain at least one adequately mature, deeply buried source rock system. It is often stratigraphically widespread and was deposited in an oxygen-depleted environment. With over 200 hydrocarbon seeps and shows which have been studied geochemically and have identified at least four mature oils, it is very probable there are several possible hydrocarbon sources in the Tasmanian Basin. Geochemical comparisons of seeps shows that the most likely source would be the Ordovician of the Gordon Group Limestones. Ratios of C27: C28: C29 Steranes are identical between seeps of the Bruny Island Johnson well and the Ordovician Gordon Limestone and the predominance of C27 Steranes and the abundant diasteranes in Tasmanian bitumens suggests a widespread algae and clay rich source rock.

Conodonts color indicates that much of the Gordon Limestone, particularly in central and southern Tasmania, is in the oil and gas windows. This limestone is expected to underlay Permian and Triassic sediments in much of Tasmanian Basin.

Other sources include the Permian Quamby Mudstone, "Freshwater Sequence" and Preolenna coal measures. In all three rock units of which the total organic carbon may reach 25%, vitrinite reflectance data and fossil pollen colors show that these source rocks are within the oil window over large areas of the basin.

2. Reservoir

Reservoirs are very easily envisioned in the shallow marine Ordovician Limestones as paleo-karst, reefal, or fractural. Since the Limestones are considered source material, migration would be minimal. Additional potential reservoirs are within the Siluro-Devonian sandstones of the Eldon and Tiger Range Groups and within sandstones of the Permian Bundella Formation, Faulkner Group and Liffey Sandstone of the Lower Parmeener Super Group. Measured porosities in the Faulkner and Liffery are 13% and 12% respectively, while other Permian sandstones in the northern block of EL21/95 have porosities averaging 16% and horizontal permeabilities ranging up to 386 millidarcies.

3. Seals

Evaporites are most efficient seals mainly because they offer very little or no pore space; however, the long-term sealing properties of very fine grained, water-wet porous rocks such as shales are also remarkably efficient in the absence of open fractures. This is due to the displacement pressure barrier effect created by capillary pressure between oil and water in rock pores (Berg 1975, Schowalter 1976). Long-term sealing properties of very fine grained water-wet rocks are demonstrated by the excellant preservation of light oil and gas reserves in some very old sedimentary basins. For instance, shallow Paleozoic oil and gas in Illinois, Michigan and Applachian basins, major reserves in the Palezoic Volga-Ural Basin (USSR) and giant Devonian and Ordovician fields in the southern Algerian Sahara demonstrate the sealing efficiency of very low permeability rocks, provided geologic history following entrapment has remained quiescent. All the above basins feature stable tectonic conditions and a lack of adverse thermal history.

It would be anticipated that the Ordovician Limestone reservoirs would be sealed by additional limestone within the Gordon Group or by the Turo Tillite above the unconformity. Good seals of shale and silts are found throughout the Permian-Triassic sedimentary sequence. The Jurassic dolerite sills also make an excellent cap rock for the Permian-Triassic reservoirs.

4. <u>Traps</u>

Defining traps and structural features within the basin is very difficult to impossible without good reflection seismic records. To date, there has been very little reflection seismic data and most of the data is of poor quality due to the extensive dolorite blanket over a large part of the basinal sediments. Recent seismic work on the TASGO project seems to have improved the quality and depth of recordings through the dolerite, which will greatly assist in defining the structural traps. The present gravity and magnetics, which have been extensively used to date have been able to define regional structural elements of mostly Paleozoics. Structures in the Permian, or younger, are probably going to be faulted, and of low relief. Although I have not reviewed the recent migrated "TASGO" seismic lines T-4 or T-5, I did have the opportunity to see the lines unmigrated and they indicated low relief structural features. Line T-4 was part of an experiment to determine whether sediments within the Tasmanian Basin could be imaged beneath the cover of difficult to penetrate dolerite and to determine the depth of the basin. Previous estimates of the thickness of the carboniferous-Mezozoric basin was 2500± meters and there has been no new reported thickness based on the "TASGO" seismic program.

Except in unusual cases of very long range migration typically encountered on foreland basin plates, most untrapped oil in sedimentary basins originates from synclinal drainage areas that surround the trap itself. Thus, migration distances commonly range in tens rather than hundreds of miles, particularly on strongly structured and/or faulted basins.

RISK

Exploration risk, being defined as the probability of spending exploration funds without economic success, has always been at the heart of the oil business. Geologic risk, which is a part of overall exploration risk, is fueled by uncertainties in subsurface geologic conditions, prior to drilling. It can also be expressed in terms of the probability of simultaneous occurrence of the key factors that determine the habitat of oil and gas in the subsurface.

Successful exploration for producible hydrocarbons in the subsurface depends on satisfying the following probabilities: i) probability of existence of trap (structure x reservoir x seal); ii) probability that the trap has received and physically retained petroleum charge (source x maturation x migration paths x timing); and iii) probability that the entrapped petroleum has been preserved from the effects of thermal or bacterial degradation (temperature x meteoric water ingress).

Since these three probabilities are independent of each other, the overall probability of discovering producible hydrocarbons at a given location is the product (not the sum) of the probabilities of these individual factors, that is, if any one of these three main factors is 0, the overall probability of success is 0, regardless how favorable the other two remaining factors are.

In respect to the Tasmanian Basin. I believe the only probability that may be missing is the probability of trap. Not the probability that there won't be a trap, but how do you locate it? At the present, this makes any drilling program a high risk, and very costly. Hopefully, new and improved parameters in the reflection seismic data will overcome some of this risk.

LAND

Great Southland Minerals Pty. Ltd. holds 100% of exploration leases EL/188 (3500 KM^2; EL9/95 (3700 KM^2), and EL21/95 (6000 KM^2) comprising of a total of 13,200 KM^2 (3.2 million acres) which is located in the Deruent Valley. These leases are granted for six years and expire the year 2001. These exploration licenses cover about 60% of the Tasmanian Basin.

MARKET

Tasmania's primary source of energy has been by hydro-electric. Tasmania is approaching a decision point, in that new sources of energy supply will be required in a relatively near future to entice new industry to the area and to maintain a stable energy base for Tasmania. A commercial discovery of either oil or gas should have a ready market.

Conclusion

Work to date has certainly established a valid exploration play for oil and gas. Although the occurrence of seeps does not guarantee the potential for commercial hydrocarbons, it is encouraging to know that oil is generating in the basin. The recent analysis of the Ordovician and the methane shows in the No. 1 Shittin well lead you to believe that hydrocarbons in commercial quantities could be found in the basin. I believe that the criteria needed to establish hydrocarbons have been met in that source rock, within the oil or gas window, has been established. Reservoir rocks are present, seals are in place to trap migration, and if the recent "TASGO" seismic program is successful in penetrating the dolerite to receive good data, then the search for a trap should be made much easier. If it is not possible to use reflection seismic data, then the drilling risk will be considerably higher, but I believe a core hole program to evaluate the basin and explore for hydrocarbons can be designed. The economic factors for the area are very attractive and would sustain the costs of such a program.

March 13, 1996

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APPENDIX 2

**PETROLEUM PROSPECTIVITY OF THE PALAEOZOIC , SOUTH - EAST TASMANIA:
AN INVESTIGATION ON THE TIMING OF POTENTIAL HYDROCARBON GENERATION FROM PALAEOZOIC SEDIMENTS AND CHARACTERISATION OF POTENTIAL RESERVOIRS OF THE LOWER PARMEEMER SUPERGROUP.**

BY TRENT J WOODS B.Sc.

DECEMBER 1995

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PETROLEUM PROSPECTIVITY OF THE PALAEOZOIC, SOUTH-EAST TASMANIA:

An investigation on the timing of potential hydrocarbon generation from Palaeozoic sediments and characterisation of potential reservoirs of the Lower Parmeener Supergroup.

Trent. J. Woods B.Sc.

University of Tasmania

Geology Department/CODES

A research thesis submitted in partial fulfilment of the requirements for the degree of Bachelor of Science with Honours

December, 1995

Abstract

The Lopatin method is used to model the thermal maturity of potential hydrocarbon source rocks of the Lower Palaeozoic of south-eastern Tasmania. Results indicate that Early Permian sediments are likely to lie close to, or within the 'oil window'. Any petroleum generation from organic-rich rocks would not have commenced until after the deposition of potential reservoir and seal formations in the Lower Parmeener Supergroup. Increased burial and heating by the emplacement of dolerite in the mid-Jurassic may have enhanced the thermal maturity of potential source rocks.

The thermal maturity of potential Ordovician source rocks is likely to vary widely throughout southern Tasmania. Modelling suggests that potential source rocks have at least passed into the oil window and are probably currently generating gas in south-east Tasmania. The timing of hydrocarbon generation from Ordovician sediments will depend essentially on early burial history. Early burial to over 3000m would have resulted in the generation of petroleum before suitable reservoirs or seals were deposited.

Several Permian sandstone units represent potential reservoirs. Most are laterally extensive within the study area. The porosity of these units varies from 7% to over 20%. Sediments deposited in moderate to high energy environment, such as a shallow marine shelf or coastal fluvial setting were found to have the better reservoir characteristics. Proximal to igneous bodies, contact metamorphism has severely reduced porosity and permeability. On a regional scale, authigenic silica cement has been most detrimental to reservoir characteristics. Vuggy porosity is commonly observed in outcrop due to decalcification and also at depth in drill cores from decarboxylation. Dissolution of feldspars and lithic fragments has created secondary intergranular and intragranular porosity in some formations. This process has often resulted in the formation of authigenic clay which has helped preserve primary porosity.

Potential source rocks are likely to be at various stages of maturity throughout the Tasmania Basin. Thicker sequences are conducive to oil generation from the Lower Parmeener Supergroup, while hydrocarbon generation and preservation from Ordovician sediments is favoured by limited burial. Potential reservoir units have been identified and are laterally extensive with good porosity and permeability. Reservoir characteristics are similar to other known onshore petroleum provinces, such as the Cooper Basin of South Australia. There is good reason therefore, to believe that hydrocarbons have been generated and are emplaced within Palaeozoic reservoirs.

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Acknowledgments

There are a number of people I must thank for their help not only for assistance in producing this thesis, but also for making this year in Tassie enjoyable and memorable. So firstly, thanks to all my honours colleagues. I'll miss you guys.

A big thankyou to Great Southland Minerals for financial support and the opportunity to work on this project. Thanks to Clive Burrett for his assistance and guidance throughout the year, also to my co-supervisor Prasada Rao. Thankyou to those the people from the Tasmania Department of Mines that offered their time and assistance. To everyone around the department who made this ride as pleasant as possible...thanks!

And a special thanks to the people who've always been there for me, no matter how far away from home I am. Thanks Mum and Dad. This thesis is dedicated to you.
Oh yeah....my sisters too.

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Introduction 1

1.1 Aims

This research thesis is part of a larger project to determine petroleum prospectivity of the Palaeozoic sediments in Tasmania. The main aim of this thesis is to determine the reservoir characteristics of the Lower Permian sediments in south-east Tasmania. Secondary to this, is the determination of timing of possible hydrocarbon generation from potential source rocks of the Palaeozoic.

1.2 Study methods and locations

The location of diamond drill hole (DDH) sites and outcrop sections is given in figure 1.1 The Woodbridge, Granton and Glenorchy DDHs are housed in the Tasmania Department of Mines core library. Jericho 1 and Shittim 1 DDHs were drilled by Great Southland Minerals. All grid co-ordinates are quoted using the universal grid reference system.

Detailed logging of diamond drill core and outcrop was carried out in order to make stratigraphic correlations and thereby determine the areal extent and physical variations of potential reservoir units. Samples were taken for porosity, permeability and thin section analysis. X-ray diffraction (XRD) was used to determine fine-grained mineralogy. The diagenesis of potential sandstone reservoirs is determined by optical petrography. The above analysis and previous research are used to interpret facies and palaeogeography. Results are compared to similar, known petroleum provinces.

Results from thermal modelling of potential source rocks, using the Lopatin method, are compared to thermal maturity data from the literature. Mathematical modelling is used to determine the effect of intrusive igneous sills on the temperature of the host sediments

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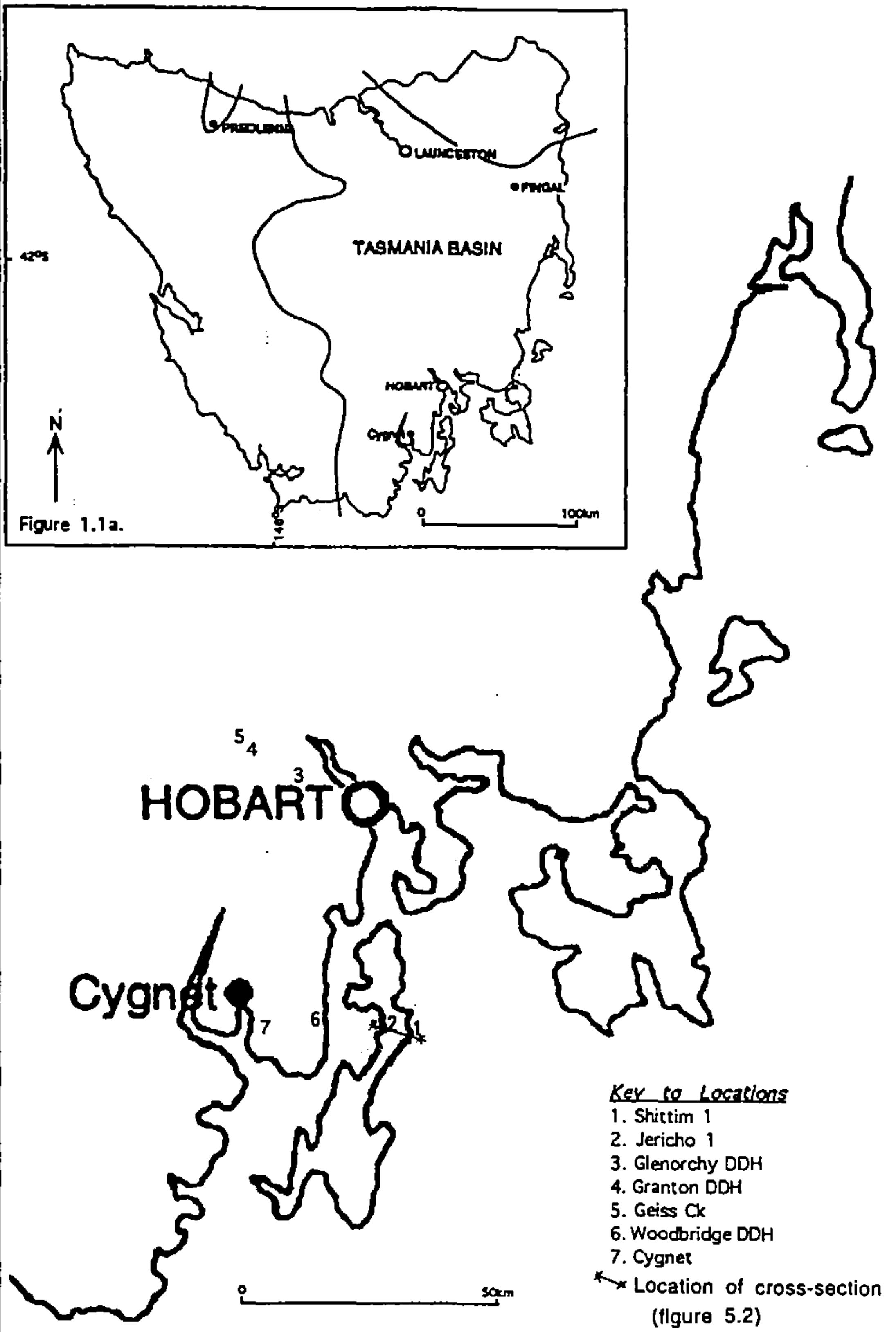

Figure 1.1a. Extent of the Tasmania Basin (after Bacon 1986).
Figure 1.1b. Locations of stratigraphic studies.

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1.3 Previous studies and exploration

A full account of the history of petroleum exploration onshore Tasmania can be found in Bendall (1990). Since 1871, there have been over 200 reported occurrences of tar, oil and gas seeps in Tasmania. Most of these occur within the Tasmania Basin, notably along the edges of the basin and along lineaments such as faults and fractures (Bendall, 1990). The earliest report on the topic of petroleum prospectivity in Tasmania was by Twelvetrees (1917) encouraging further study and exploration.

In the early part of this century, over 900 000 litres of oil was produced from Permian oil shale by artificial distillation. Prior to World War II a number of companies were formed to explore for oil. Due to limited drilling capacity and knowledge of geology or petroleum formation, most of these wells were aimed at shallow targets. A small amount of light oil was recovered from "Johnson's well" on North Bruny Island in 1929 from a depth of less than 30m. This triggered the formation of the short lived Tasmanian Oil Company. In more recent history however, the number of petroleum explorers has been minimal. Nudec Proprietary Limited drilled many holes in the 1960's and 1970's resulting in only one gas show and two oil shows. They too, were seeking shallow targets and did not investigate the possibility of a Lower Permian or Ordovician source.

More recently, studies have been done on heat flow and potential source rocks (Bendall *et al.* , 1991, Burrett, 1992, Campbell, 1992, Denwer, 1986, Revill *et al.*, 1994, Summons, 1981). All reports indicate favourable conditions for the formation of petroleum products. The most recent explorers in Tasmania have been Conga Oil, Condor Oil Investments and now Great Southland Minerals.

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Regional Geology and Stratigraphy 2

2.1 Pre-Carboniferous

General stratigraphic relationships in southern Tasmania are illustrated in figure 2.1. Precambrian rocks in Tasmania are predominantly metasedimentary, predominantly schist and quartzite. Dolomite, mostly secondary in nature, is also present. Granitic intrusions coincided with the Penguin Orogeny at around 725-750 Ma.

From the late Precambrian to the Cambrian, terrestrial and marine siliciclastics and dolomite were deposited unconformably on the older rocks. The volcanics and volcaniclastics of the Mount Read Volcanics and Dundas Group were deposited in the Middle to Late Cambrian. A Late Cambrian to Early Ordovician marine regression resulted in the deposition of fluvio-deltaic sediments. The following transgression deposited deep marine siliciclastics. These units are referred to as the Denison Group.

The shallow marine carbonates of the Gordon Group conformably overly the Denison Group. The carbonates grading laterally into deeper marine shales. The Gordon Group is overlain conformably by the sandstone and siltstone units of the Eldon Group. This Group is up to 2000m thick and ranges in age from Late Ordovician to Early Devonian (Summons, 1981).

Uplift and erosion during the Tabberabberan Orogeny was accompanied by granitic intrusions. Volcaniclastic sequences were also deposited during the uplift. The deformed rocks are overlain unconformably by the sediments of the Parmeener Supergroup (Clarke and Forsyth, 1989).

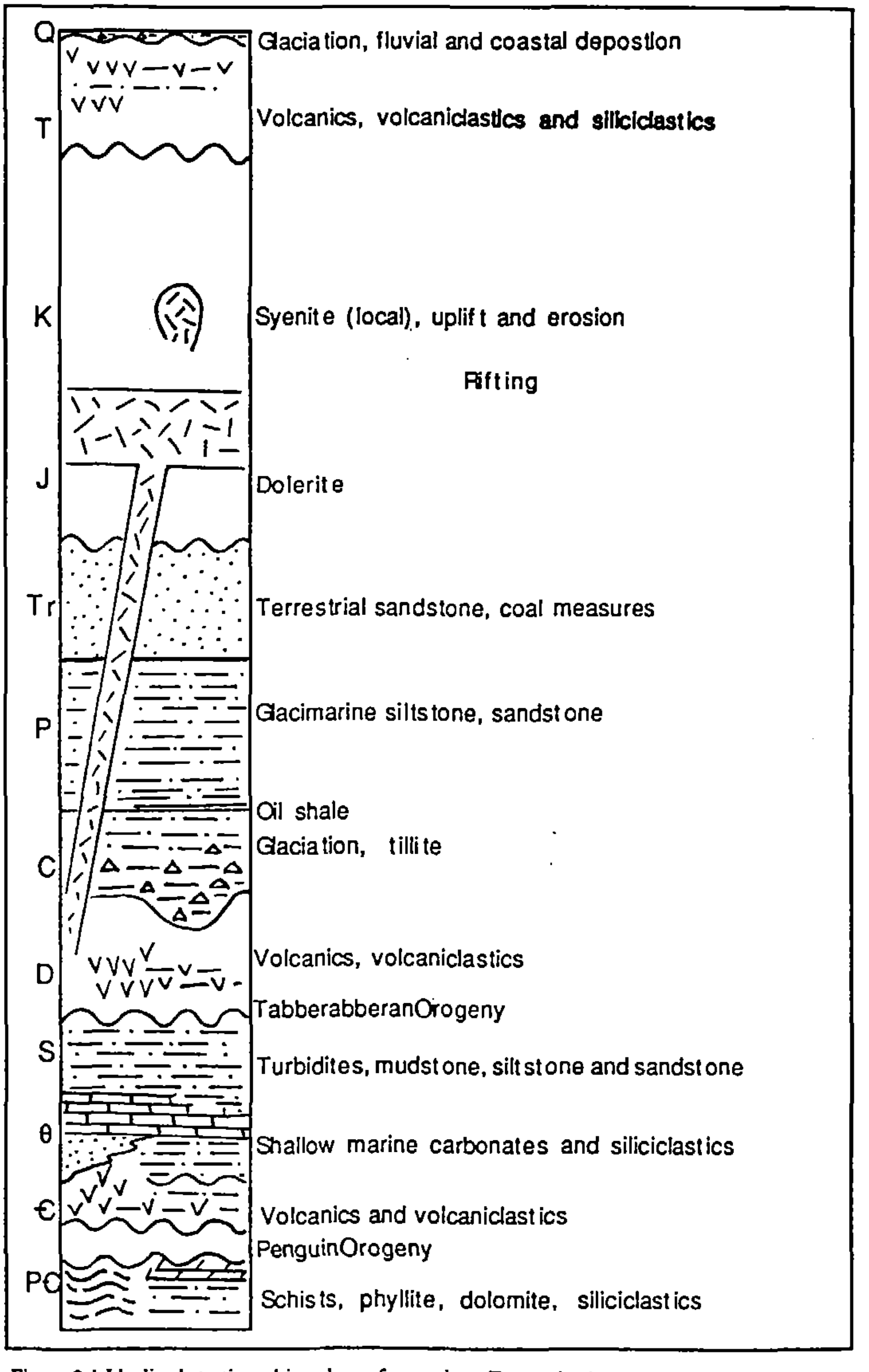

Figure 2.1 Idealised stratigraphic column for southern Tasmania showing very general relationships. Not to scale.

2.2 *Carboniferous-Triassic*

The Tasmania Basin (figure 1.1a), in which the Parmeener Supergroup was deposited was shaped by glaciers in the Late Carboniferous (Clarke and Forsyth, 1989, Martini and Banks, 1989). Up to approximately 1.5km thick of Parmeener Supergroup sediments unconformably overly the Lower Palaeozoic rocks. Figure 2.2 summarises the nomenclature and relationship of units within the Parmeener Supergroup in south-east Tasmania.

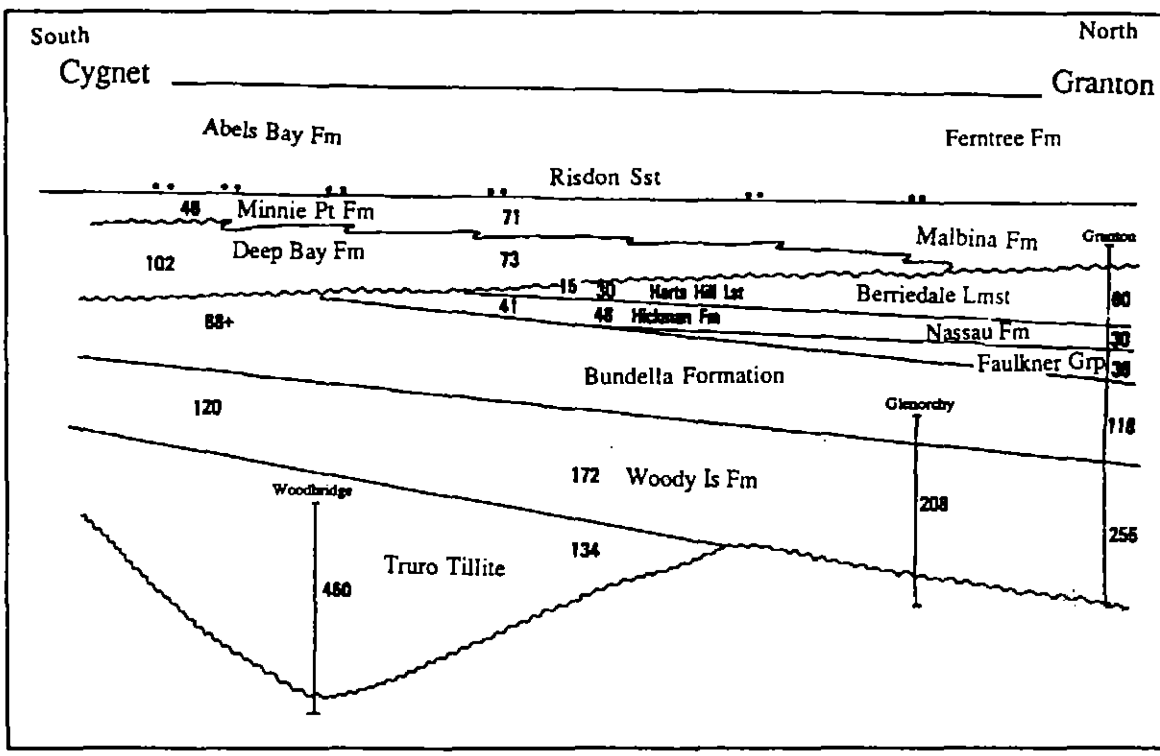

Figure 2.2 Nomenclature and stratigraphic relationships within the Lower Parmeener Supergroup (after Farmer, 1985). The relative location of some DDHs is also shown. Unit thicknesses in metres.

A basal tillite is usually present as the oldest unit in the Parmeener Supergroup (Truro Tillite). This sequence is predominantly an unfossiliferous, matrix supported glacial diamictite which is very variable in thickness. Subordinate sandstone, conglomerate and laminate sequences are present (Farmer, 1985). The tillite is overlain by a generally massive bedded, carbonaceous, pyritic and glendonitic siltstone unit

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(Woody Island Formation). In the north of the state several thin seams of tasmanite oil shale can be found at the base of this unit (Denwer, 1986). Conformably overlying the poorly fossiliferous siltstone unit is a highly fossiliferous unit of interbedded siltstone and sandstone (Bundella Formation). Lonestones are common throughout. Localised occurrences of calcareous siltstone and limestone can also be found in the southern part of the study region (Porters Hill Siltstone, Darlington Limestone). These units together constitute the "Lower Marine Sequence" (Clarke and Forsyth, 1989).

The "Lower Freshwater Sequence" conformably overlies the Bundella Formation. In the Hobart area, the sequence is represented by the Faulkner Group. It consists of wavy and flaser bedded siltstone and sandstone, conglomerates and very thin coal seams. In the north the sequence is represented by the Liffey Group, Preolenna and Mersey Coal Measures.

The 'freshwater' sequence is overlain by bryozoan rich, calcareous, marine siltstone (Nassau Formation, Hickman Formation). The basal unit is a poorly sorted sandstone (Rayner Sandstone). Following this siltstone unit is highly fossiliferous limestone with subordinate calcareous siltstone, shale and micrite (Berriedale Limestone, Hickman Formation and Harts Hill Formation). Bentonite layers are present and are useful marker beds (Pollington, 1974). Fossils include a range of spiriferids, strophalosiids, linoproductids, pectinids and bryozoans (Clarke and Forsyth, 1989). Lonestones tend to become more common higher in the sequence.

The Deep Bay Formation unconformably overlies the older calcareous beds in the Cygnet region. Around Hobart, the Malbina Formation unconformably overlies the Berriedale Limestone. These formations are varyingly fossiliferous, with spiriferids, fenestellids and *Stenopora* being the most common fauna. The correlate of the Malbina Formation at Cygnet is the fine grained, fossiliferous sandstone of the Minnie Point Formation. The Risdon Sandstone conformably overlies these units. It is a relatively thin (up to 8m) unit of poorly to well sorted, feldspathic sandstone.

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This is followed by interbedded fissile and non-fissile siltstone with subordinate sandstone (Ferntree and Abel's Bay Formations). Fossil and conglomerate horizons occur and are more common further south, notably around Cygnet and Bruny Island where the unit tends to be coarser grained.

The "Lower Marine Sequence", "Lower Freshwater Sequence" and "Upper Marine Sequence" make up the Lower Parmeener Supergroup. The Upper Parmeener Supergroup begins with the Cygnet Coal Measures of late Permian age, passing into fluvial Triassic sandstones.

2.3 Post-Triassic

In the mid-Jurassic, dolerite sills up to nearly 600m thick intruded into the sediments of the Parmeener Supergroup fed by thinner, vertical dykes (Clarke and Forsyth, 1989). This caused fracturing and faulting within the Permo-Triassic sediments (McDougall, 1961). During the Cretaceous minor syenite dykes intruded the sediments associated with extensional tectonics (Berry and Banks, 1985).

Cenozoic sediments are poorly preserved in Tasmania due to glacial and periglacial erosion in the Quaternary. Locally, Tertiary basalts and volcaniclastics may be found. Poorly consolidated Quaternary sediments are generally found in topographic lows. Scattered outcrops of ferricrete and silcrete can also be observed.

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Potential Source Rocks 3

3.1 Introduction

It is generally agreed that most of the world's petroleum is produced from the burial and heating of organic-rich rocks. Kerogen, an insoluble organic residue, is the most important organic compound in hydrocarbon generation (Selley, 1985) and is the source of most of the world's fossil fuels (Waples, 1985). There are three main types of kerogen representing their origins. Type I, lipid-rich kerogen is of algal origin and is oil prone. Type II, sapropelic kerogen is derived largely from phyto- and zooplankton and is oil and gas prone. Type III kerogen is humic in origin and is gas prone (Selley, 1985).

For hydrocarbon generation to occur, a source rock must have a sufficient amount of the right type of organic material preserved. A source rock is defined as one from which hydrocarbons are known to have been generated. A potential source rock is defined as a rock which has been tested for hydrocarbon generating characteristics (quality and quantity) and would produce petroleum given the appropriate thermal history. A rock which has not been tested for hydrocarbon generating potential but is thought to have been deposited in a suitable environment, is defined as a possible source rock (Waples, 1985).

In exploration it is important to know the quantity of organic carbon of the sediments and the form it is in. The economic potential of a source rock can be classed on total organic carbon content. A TOC of less than 0.5% is usually considered poor; 0.5% to 1.0% has slight source capacity; 1.0% to 2.0%, modest source capacity and greater than 2%, good to excellent source capacity (Waples, 1985). A number of potential source rocks exist in Tasmania.

3.2 Lower Parmeener Supergroup

The 'tasmanite oil shale' occurs in the lower part of the Quamby Mudstone (Woody Island Formation time equivalent). It consists of at least two thin seams of very organic rich sediment (Denwer, 1986, Campbell, 1992). The high organic content is due to the alga *Tasmanites punctatus* , producing type I, oil-prone kerogen (Denwer, 1986). The tasmanite oil shale can be considered an excellent potential source rock (Denwer, 1986, Revill *et al.*, 1994, Domack, 1995) with TOC values often over 20% (Campbell, 1992, Revill *et al.*, 1994).

The organic matter in the siltstone surrounding the oil shale is predominantly type III, gas prone kerogen (Denwer, 1986). Organic carbon content in the siltstone varies considerably, from being very lean to TOC values of over 3% (Revill *et al.*, 1994), making it a potential source rock given a suitable thermal history. While the tasmanite oil shale has not been identified in south-east Tasmania, the carbonaceous mudstone facies in which it occurs can be recognised in Shittim 1. This black mudstone unit, at the base of the Woody Island Formation, contains a small amount of what was probably algal material (TS48A).

The Faulkner Group and its correlates range in depositional environments form alluvial to sub-tidal. It is highly bioturbated, with carbonaceous material often filling burrows. Thin coal seams, for example in the Granton DDH, are obvious organic rich horizons. The predominant kerogen is likely to be humic in nature and therefore gas prone. The quality and quantity of kerogen in this unit has not been tested.

The basal tillite may also be a possible source rock. Organic rich environments, similar to those proposed for the deposition of the Truro tillite can be found off the coast of present day Antarctica (Domack *et al.*, 1993). The petroleum generating characteristics of this unit remain to be tested.

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3.3 Gordon Group Limestone

The Ordovician System in Tasmania consists of shallow marine shelf carbonates to deep basin siliciclastics. Fine grained carbonate rocks are able to produce more petroleum per amount TOC than most organic rich clastic rocks (Hunt, 1979). Type I algal kerogen is usually dominant, enhancing oil producing qualities even further. Shelf platforms and reefs are usually rich in marine life and are therefore considered to be prime potential source rocks for hydrocarbon generation (Palacas, 1984). Geochemical analysis has shown the organic signature of many oil seeps and bitumen around Tasmania closely match that of hydrocarbons within the Ordovician carbonates (Bendall *et al.*, 1991). Isotherms constructed by Burrett (1992) from conodont Colour Alteration Indices (CAI) and thermal modelling (this study), places the Gordon Group Limestone if present in south-east Tasmania within the oil and gas windows (figure 4.5).

3.4 Precambrian Dolomite

Marine carbonates and shales of the Tasmanian Precambrian are possible source rocks. While Precambrian rocks are not commonly prospective due to overmaturity, Precambrian carbonates are responsible for significant hydrocarbon accumulations in central Australia, Oman and Siberia. Relatively shallow burial depth could place the sediments within the temperature range for petroleum generation. The organic content of these rocks remains to be established.

3.5 Discussion

There are several possible and potential source rocks for hydrocarbons in southern Tasmania. Table 3.1 is a summary of some of the potential source rocks, indicating measured amounts and types of organic content.

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Age	Unit/Formation	Kerogen	TOC range	Reference
Precambrian	Dolomite	?II	.02%†	O'Leary, 1987
Ordovician	Gordon Limestone	II	.07-.23%*	O'Leary, 1987, Summons, 1981
Carboniferous-Permian	Truro Tillite	?I, III	?	
Permian	Woody Island/ Quamby Fm	III	0-3%	Campbell, 1992, Denwer, 1986
Permian	Tasmanite Oil Shale	I	15-35%	Denwer,1986, Revill et al., 1994
Permian	Faulkner Group	?II, III	?	

Table 3.1 Potential petroleum source rocks of onshore southern Tasmania. *Data for the Gordon Limestone is based on only three samples and †one sample from the Precambrian.

It is clear from the gaps in table 3.1 that much work needs to be done in quantifying potential source rock characteristics in Tasmania. However, it is clear that potential source rocks for hydrocarbon generation are present.

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Thermal Maturity 4

4.1 Introduction

Shows of a wet gas were recorded in the Shittim 1 hole on Bruny Island. To determine a likely source for the gas, thermal modelling of potential source rocks is carried out. Burial curves and geothermal histories are reconstructed using data from the Shittim 1 core and the literature. The Lopatin method is then used to calculate thermal maturity. The effect of heating on host rocks due to the intrusion of Jurassic dolerite is also examined.

The breaking down of the kerogen matrix to form hydrocarbons and bitumen requires heat. This process occurs during 'catagenesis'. The temperature range in which oil is produced from kerogen is called the 'oil window', that is from around 60°C to 120°C. Generation of gas from gas prone kerogen occurs between 120°C and 225°C, the 'gas window'. Overheating (above 225°C) will cause hydrocarbons to 'burn off' (Selley, 1985). Figure 4.1 (Selley, 1985, Rejebian *et al.*, 1987) illustrates the relationship between temperature, hydrocarbon generation and various maturity indicators. It is important to know whether potential source rocks are thermally mature or immature in order to warrant further exploration.

There are a number of methods used to assess the thermal maturity of sediments. Thermal indicators such as vitrinite reflectance, spore and conodont colouration (figure 4.1) can be used to estimate the maximum temperature range that a sediment has been subjected to.

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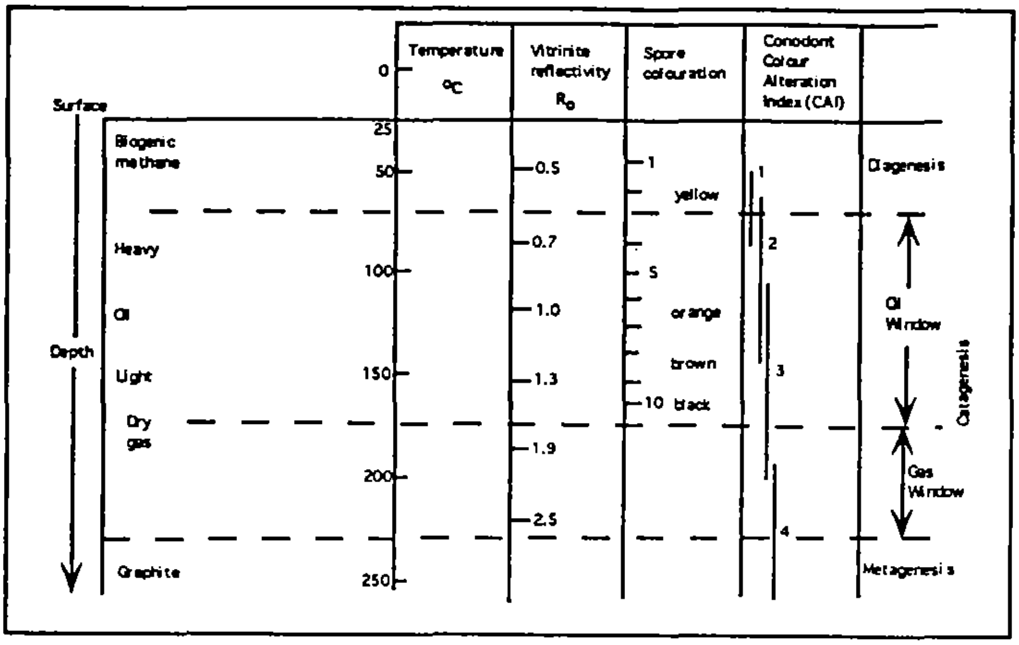

Figure 4.1 Hydrocarbon generation and thermal indicators (Selley, 1985, Rejebian, 1987)

Indicators of thermal maturity however, can only give an indication of the heating that a sediment has undergone. For petroleum to be preserved, a suitable trap, including reservoir and cap rocks must usually be in place before generation occurs from source rocks. Therefore, it is very useful to know when and at what depth petroleum generation may have occurred. Thermal modelling is often used to estimate the timing of hydrocarbon generation. One of the simplest thermal modelling methods available is Lopatin analysis.

4.2 Lopatin method

Thermal maturity is a factor of burial history and geothermal gradients. From known or estimated ages and depth of burial of sediments a hypothetical burial curve can be constructed. Using present measured geothermal gradients and interpreted palaeo-geothermal gradients, the thermal history of a sedimentary unit can be modelled. The

Lopatin method assumes that the rate of reaction for petroleum generation will double for every 10°C increase in temperature (Katz *et al.*, 1982). While this assumption has been greatly debated, especially if applied to higher temperatures, the method has proven successful and is valid for temperatures within the oil window (Waples, 1985). By taking a temperature factor and the time at which a particular stratigraphic level spends at each 10°C interval, time-temperature indices (TTI) can be calculated. The indices can then be correlated with vitrinite reflectance and a relationship with the oil and gas windows established (table 4.1).

R_o	TTI	
0.40	<1	
0.50	3	Oil generation from S-rich rocks
0.55	7	
0.60	10	
0.65	15	Onset of oil generation
0.70	20	
0.85	40	
1.00	75	Peak oil generation
1.15	110	
1.22	130	
1.30	160	
1.39	200	
1.50	300	
1.75	500	Maximum limit for occurrence of oil
2.00	900	
2.50	2700	
3.00	6000	
4.00	23000	
5.00	85000	

Table 4.1 Correlation of time-temperature indices and vitrinite reflectance (Waples, 1985)

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4.2 Thermal modelling of the Woody Island Formation

The Lopatin method was used in order to assess the thermal maturity of the Woody Island Formation and the top of the Truro Tillite. Based on the thickness of various units measured in the Shittim 1 drill hole, several possible burial curves were constructed for the base of the Woody Island Formation. Geothermal scenarios were overlain on these burial curves in order to determine a range of maturation histories.

Two burial scenarios are considered. To begin with, a linear sedimentation rate for the deposition of each formation is assumed in a continuously subsiding basin. Age estimates for the deposition of each formation are from Clarke and Forsyth (1989). This burial curve assumes that there has been no post-Minnie Point deposition or erosion and can be considered a minimum burial scenario (figure 4.2a).

A second burial curve is constructed taking into account erosion and deposition post Parmeener Supergroup (figure 4.2b). It is likely that erosion of the Permian sediments at the Shittim 1 locality occurred sometime in the Triassic as relative sea level fell and again, by periglacial erosion in the Quaternary. To consider a maximum probable burial scenario, all erosion is taken to be post-Triassic. Intrusion of dolerite is assumed to have been instantaneous. Sutherland (1977), using zeolite minerals within Jurassic dolerite estimates between 1.6km and 2.2km of sediments were deposited in the Cenozoic. Denudation of these sediments occurred at an average rate of 5-7m/my, due mostly to uplift (Wellman, 1987).

In order to calculate possible maturation histories, two geothermal histories are overlain on the burial curves. The first assumes constant, linear, present day geothermal gradients. The present day geothermal gradient for the Parmeener Supergroup has been measured at 29°C/km to 60°C/km (Green, 1989). An average value of 40°C/km and surface temperature of 10°C is used. There have been several

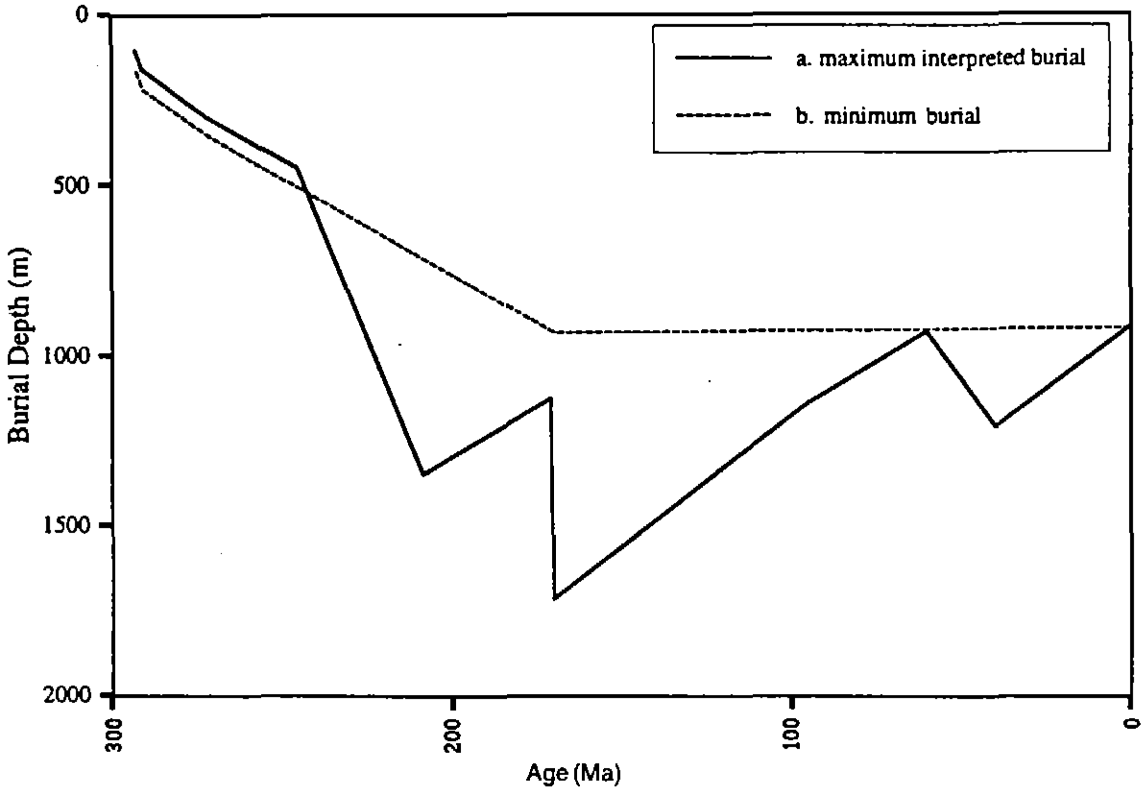

Figure 4.2 Maximum and minimum burial curves for the base of the Woody Island Formation on North Bruny Island.

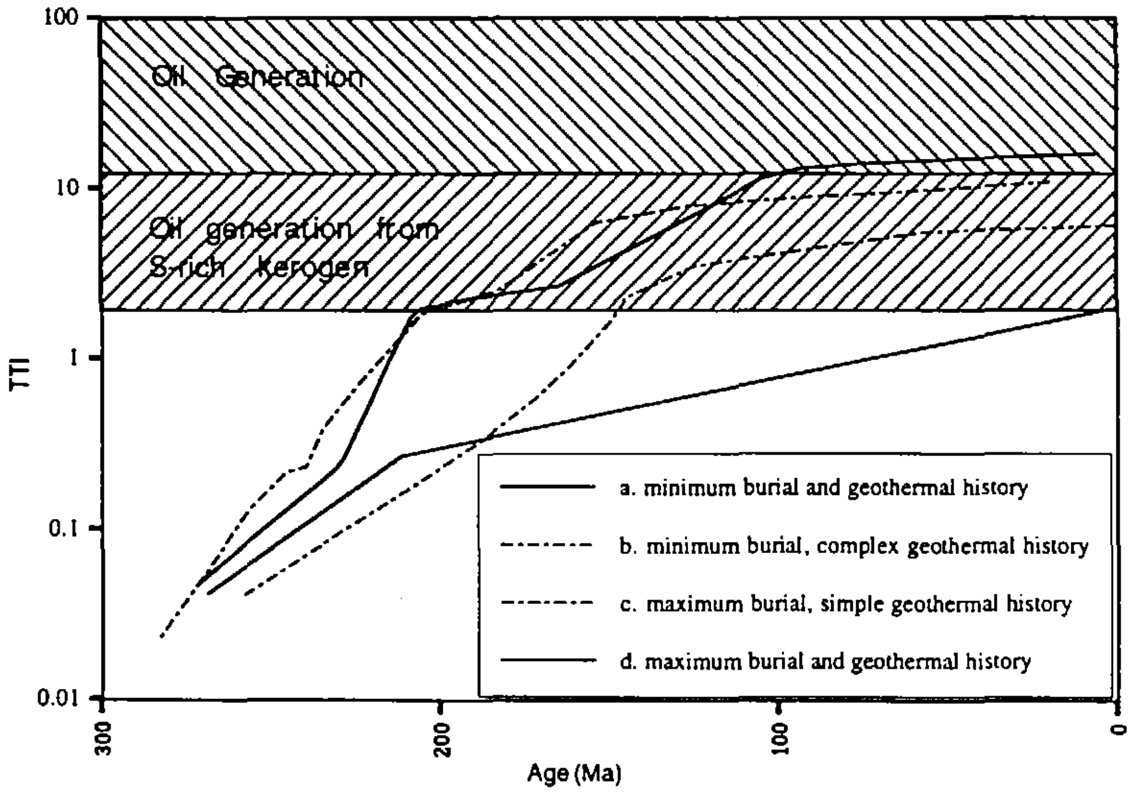

Figure 4.3 Thermal maturity versus time for the base of the Woody Island Formation using various heating and burial scenarios. Illustrating the timing of oil generation from sulphur-rich kerogen (Waples, 1985) and the conventional 'oil window'.

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periods of increased heat flow in Tasmania (Summons, 1981). This geothermal model is therefore taken to be a minimum maturation case.

It is however, not likely that geothermal gradients have remained constant. Based on the results of apatite fission track data (Hills *et al.*, 1995) a more realistic geothermal history is constructed for the Cretaceous onwards. Increased heat flow is assumed for the Jurassic. For this period a geothermal gradient of 60°C/km and surface temperature of 10°C is used. A geothermal gradient of 30°C/km and surface temperature of 0°C is assumed for the early Permian. This thermal history is used for later modelling and is illustrated in figure 4.4.

A minimum maturation path for the Woody Island Formation suggests that the minimum burial and heating model would result in the formation being immature (figure 4.3a). Using this unlikely scenario it is easy to see why there has been the common belief that potential source rocks within the Parmeener Supergroup have been considered too immature to be prospective for hydrocarbons.

Models assuming a constant geothermal gradient through geologic time place the Woody Island Formation at Bruny Island, near the base of the oil window. With a 'maximum' burial history, the Woody Island Formation is placed at least near the base of the oil window, where hydrocarbon generation may be expected from sulphur rich organic rocks (Waples, 1985). A greater burial depth and higher heat flow model places the Woody Island Formation within the oil window (figure 4.3d). In this scenario, petroleum generation would not begin until after increased burial in the Jurassic due to the intrusion of dolerite. The base of the Woody Island Formation at Bruny Island must therefore lie within, or close to the base of the oil window. The basal tillite will therefore be within the oil window at Bruny Island. Pyrolysis studies on the tasmanite oil shale has shown that in at least one location (north-eastern Tasmania) maturity is close to the oil window (Revill *et al.*, 1994), confirming the results of modelling.

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Burial depth obviously plays a major role in thermal maturity. The relatively thin estimate for Cenozoic cover on Bruny Island is due largely to its position on a graben margin. Greater Cenozoic cover and therefore burial depths would be expected towards the centre of grabens. Deeper burial of Lower Parmeener sediments would also be expected at other locations within the Tasmania Basin which are yet to be penetrated. Therefore, it is probable that potential Permian source rocks lie within the oil window at locations that have undergone deepest burial.

Heat flow, while varying, has been unusually high in Tasmania. Taking this into account and estimates of likely burial depth of potential source rocks, it is reasonable to assume that the sediments at the base of the Lower Parmeener Supergroup lie within, or close to the oil and gas windows. Any pre-Carboniferous rocks will therefore be within, or have passed through the hydrocarbon generating windows at some stage.

4.3 Thermal modelling of the Gordon Limestone

Few drill holes have penetrated the entire thickness of the Parmeener Supergroup in southern Tasmania. The lithology of 'basement' rocks is therefore largely unknown. Burrett (1992) suggests, from conodont colour alteration studies, that the Gordon Limestone is likely to lie within the oil and gas windows in south eastern Tasmania, if present at depth. Lopatin analysis was therefore applied to the base of the Gordon Limestone in order to establish possible thermal maturation histories.

Burial curves constructed for the base of the Gordon Limestone assume extreme circumstances of burial and erosion (figure 4.5) in order to determine maximum and minimum feasible maturities. Present day, average geothermal gradients were then overlain and thermal maturity indices calculated using the Lopatin method. The maximum burial scenario (figure 4.5a) assumes constant pre-Carboniferous deposition, using maximum unit thicknesses from Summons (1981). A minimum

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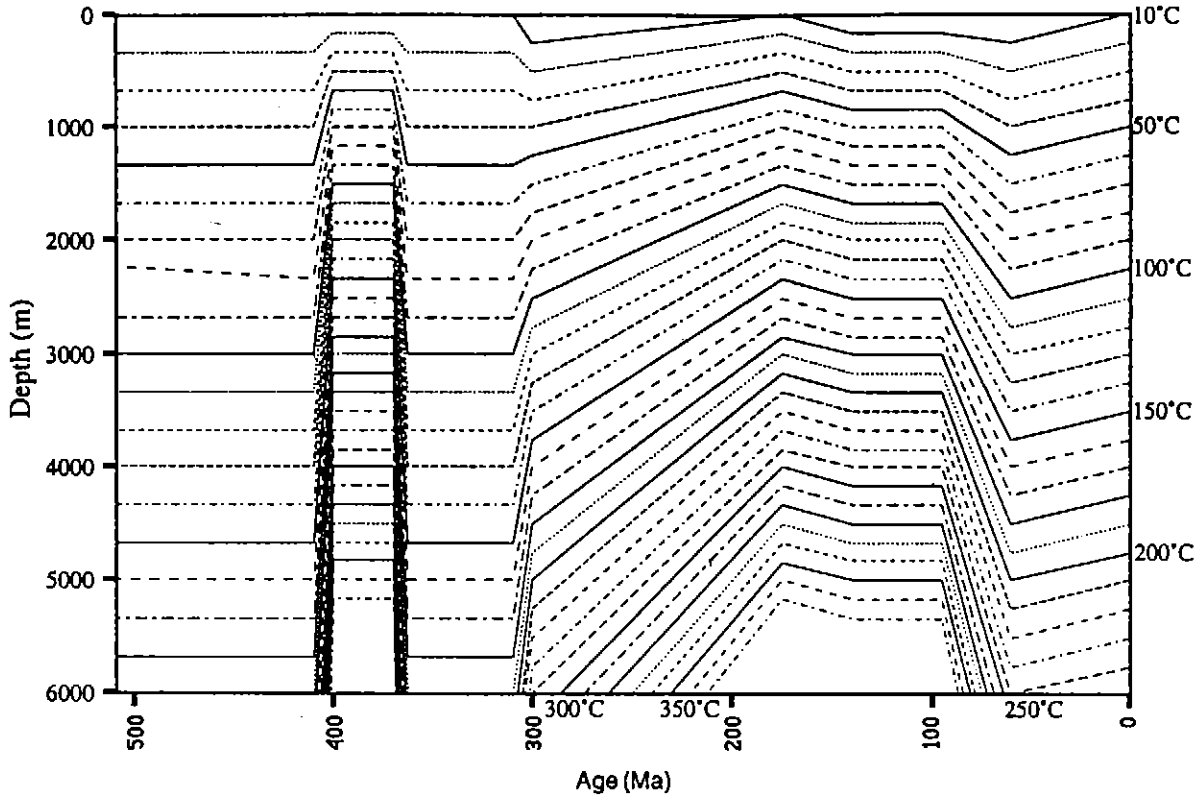

Figure 4.4 An interpreted geothermal history for south-east Tasmania. Geotherms are in 10°C intervals.

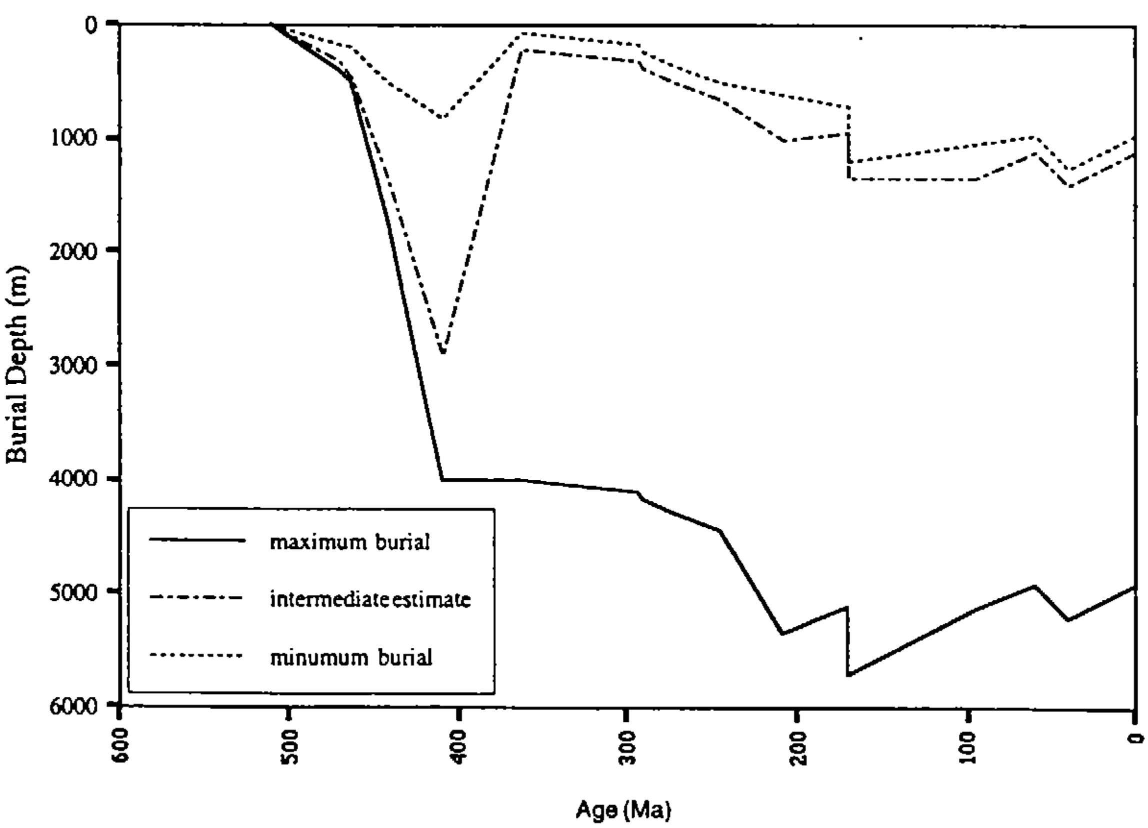

Figure 4.5 Burial curves for the base of the Gordon Limestone. Maximum and minimum limits of burial are estimated assuming its presence at depth in south-east Tasmania.

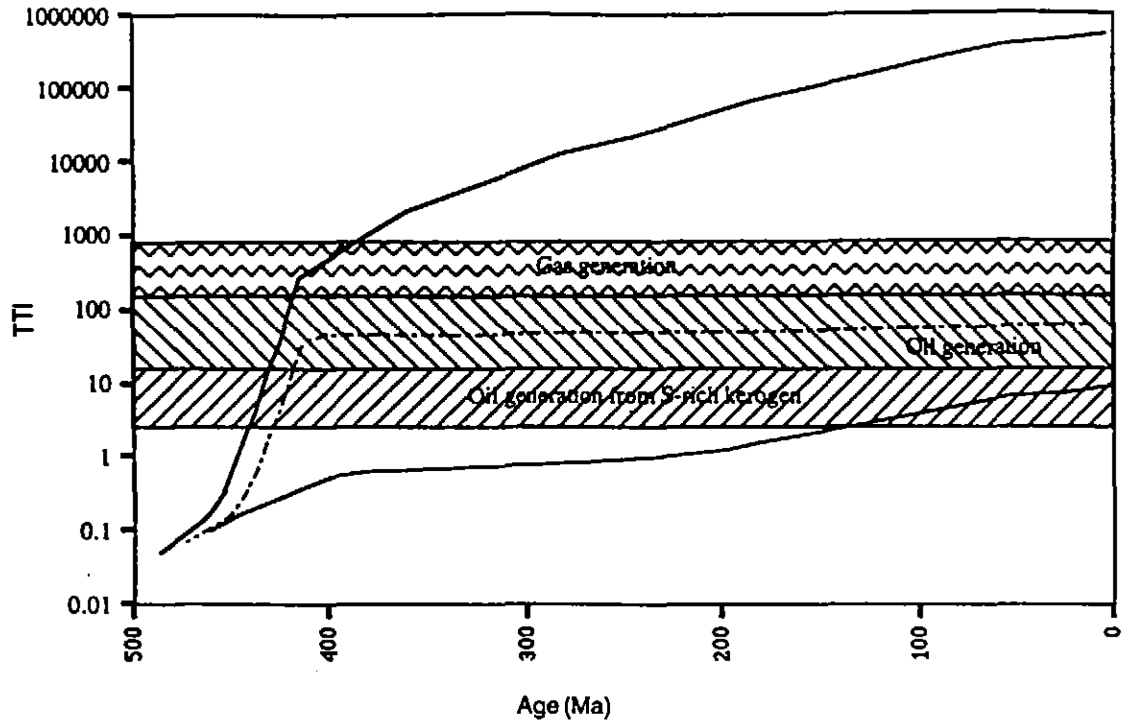

Figure 4.6 Thermal maturity versus time for the base of the Gordon Limestone. Simple geothermal history. See figure 4.7 for key.

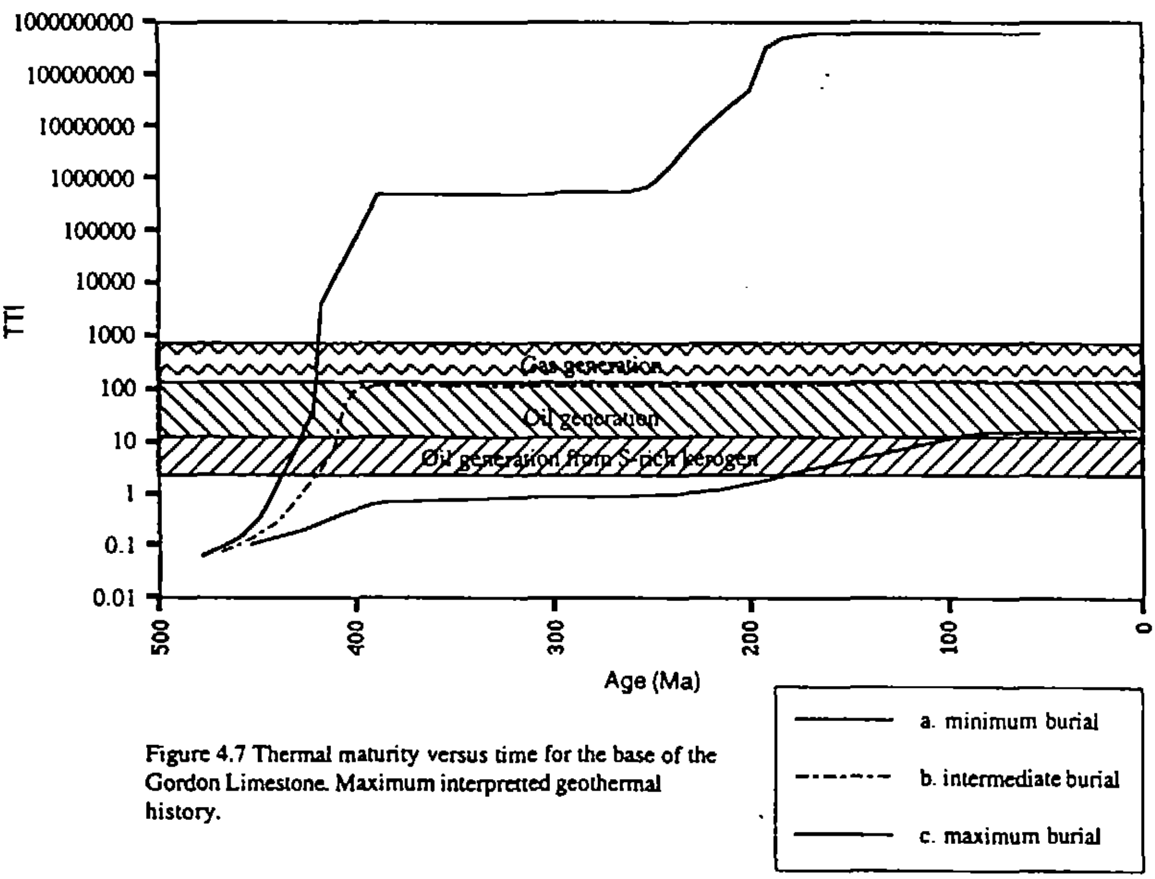

Figure 4.7 Thermal maturity versus time for the base of the Gordon Limestone. Maximum interpretted geothermal history.

burial scenario for the base of the Gordon Limestone assumes very thin Ordovician sedimentation, most of which was eroded during the Tabberaberran Orogeny in the Devonian (figure 4.5c). Due to the range in expected TTIs, an intermediate burial curve was also constructed (figure 4.5b).

To obtain an estimate of the limits of possible thermal maturity , 'maximum' and 'minimum' heating conditions are again considered. As before, an unchanging surface temperature of 10°C and constant geothermal gradient of 40°C/km were assumed for the minimum heating case. For the maximum geothermal history, the same gradients as for the Woody Island case are used for the post-Carboniferous. Prior to the Carboniferous, a constant surface temperature of 10°C and unchanging geothermal gradient of 30°C/km is assumed. Increased geothermal gradients are assumed during the Tabberabberan Orogeny in the Devonian. This thermal history is illustrated in figure 4.4.

A minimum maturity scenario places the Gordon Limestone presently at the base of oil window, hydrocarbon generating conditions having possibly been reached in the early Cretaceous (figure 4.6).

Maximum burial scenarios would have the Gordon Limestone entering the oil, then gas window relatively rapidly (figure 4.6c, 4.7c). Any hydrocarbons generated during this scenario would need to be trapped within the Gordon Limestone itself or, in the sandstone units of the Eldon Group immediately overlying. Maximum burial and high Devonian heat flow however, would mean any hydrocarbons present at these depths would be destroyed during the Tabberaberran Orogeny.

Interpretations from geophysical modelling indicate that if Ordovician to Devonian sediments are present at depth in Tasmania, there has only been relatively limited preservation (Leaman, 1990). A scenario similar to the intermediate burial curve is therefore the most likely. The Gordon Limestone, if preserved in south-east Tasmania is therefore most likely presently at the upper limits of the oil window or within the gas window. Migration of gas, up-dip from the west, from an Ordovician source may thus be an explanation for the gas encountered in Shittim 1.

The results of thermal modelling suggest that thermal maturity of the Gordon Limestone varies greatly throughout the state and will depend largely on the preserved thickness of Ordovician to Devonian sediments. Maximum burial would mean the base of the Gordon Limestone is overmature where complete stratigraphic sections have been preserved from the Ordovician onwards. Uplift and erosion during the Tabberaberran Orogeny means this is unlikely. The thickness of Lower Paleozoic sediments in south-eastern Tasmania is relatively thin, if present. The Gordon Limestone has therefore most probably passed into the oil window and within the gas window in this part of the state. In areas where Lower Paleozoic deposition was high, the oil window was probably entered in the early Devonian (figure 4.7b,c). In extreme burial cases the gas window is entered soon after. In these places, any hydrocarbons preserved must be trapped within sediments of the Gordon Limestone or Eldon Group.

In regions of low Ordovician to Devonian sedimentation, hydrocarbons would not have been generated until after deposition of the Parmeener Supergroup (figure 4.7a). In this case increased heat flow and burial due to the intrusion of dolerite in the Jurassic is conducive to higher thermal maturities. It must be noted that these calculations do not take into account regional change in heat flow. Higher than average heat flow is expected along graben margins and other tectonically active features. In these regions the results under-estimate thermal maturity. Likewise, geothermal gradients change in accordance to lithology. This factor is much more likely to affect modelled thermal maturity of the Gordon Limestone than it is, the Woody Island Formation, due to a greater overburden thickness with varying lithology.

4.4 The effect of intrusive Jurassic dolerite on thermal maturity

The intrusion of thick dolerite sills during the Jurassic has caused contact metamorphism in host sediments and may have enhanced the thermal maturity of potential source rocks at a distance from the sills.

Thermal indicators from the Woody Island Formation, such as a vitrinite reflectance value ($R_0 = 3.57$), palynology and mineralogy indicates that the igneous intrusions have caused metamorphism of most sediments in the Shittim 1 core. The first macroscopic observations that the host sediments are becoming contact metamorphosed is a more brittle nature and a more massive appearance. Thermal modelling using an equation (table 4.2) for 'the effect of thin igneous intrusions on host rocks' (Jaeger, 1965, Esposito and Whitney, 1995) is carried out in order to attain an estimate of the likely extent of heating that intrusive dolerite sills would have on the Permian sediments.

Using the Shittim 1 example, temperature profiles away from a 580m sill are calculated and plotted. An initial temperature of intrusion, $T_0 = 1000^{\circ}C$ is assumed. A thermal diffusivity of, $k = 0.01$ is used (as per Esposito and Whitney, 1995). Profiles are plotted for several time intervals.

$$T/T_0 = 1/2\,(\,erf\ (E+1)/(2\sqrt{t}) - erf\ (E-1)/(2\sqrt{t}))$$

where:

T = time dependant temperature at a given point,

T_0 = initial temperature of magma,

erf = error function

E = proportional distance from intrusion, that is, distance from the mid-plane of the intrusion over half the thickness of the intrusion,

t = dimensionless time

= ky/d^2,

d = half the thickness of the intrusion,

k = thermal diffusivity of country rock,

y = time since intrusion.

Table 4.2 (Esposito and Whitney, 1995, Jaeger, 1965). Effect of a cooling igneous intrusion on the temperature of host sediments.

The modelled results indicate that within a distance of between one third and a half of sill thickness, any potential source rocks, will be overmature due to contact metamorphism (figure 4.8). Heating to over 300°C will occur within this region and well over 500°C closer to the intrusion. Maximum heating in host sediments close to the sill, occurs at approximately 1000 years. This accounts for the high vitrinite reflectance and palynological data. Metamorphic mineralogy can also be adequately explained with the model. Calc-silicate mineral assemblages of wollastonite, grossular and vesuvianite confirm temperatures in excess of 550°C (Botrill, 1995) at a distance of at least 120m from the sill. Up to 100m from the dolerite, a spotted hornfels occurs

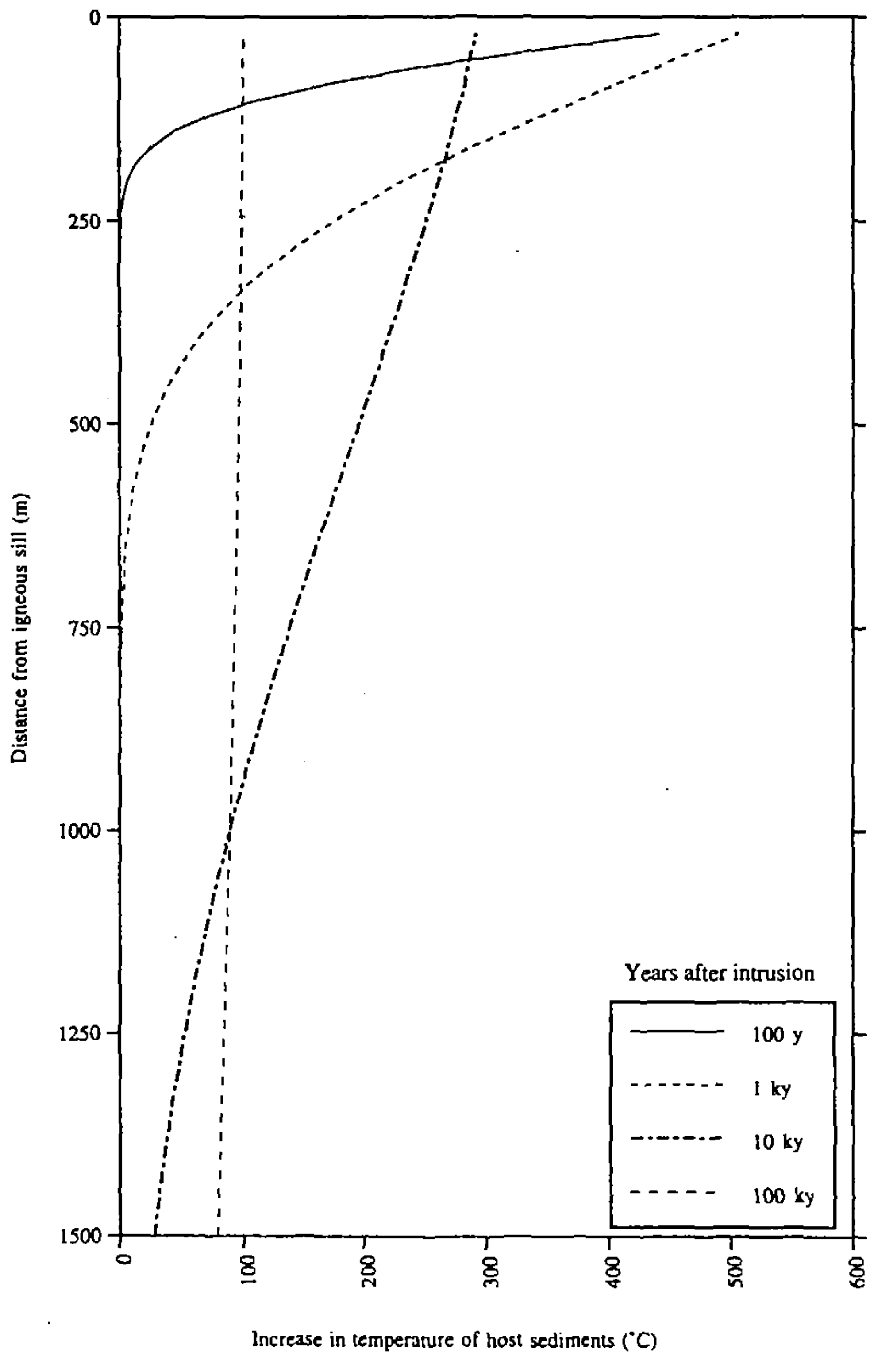

Figure 4.8 The increase in temperature expected in host sediments due to the intrusion of a 580m thick dolerite sill. Assumes instantaneous intrusion at 1100°C.

in the Bundella Formation. The 'spottiness' being due to the sericite porphyroblasts, possibly after andalusite (Botrill, 1995), which would be expected at temperatures of around 350°C. This may have been the result of a second heating event associated with veining or Cretaceous intrusions, or could be due to later retrogression during cooling of the intrusion.

At a distance of greater than about one half of the sill thickness, thermal maturity of the host sediments will be enhanced, so as to increase any petroleum generation from potential rocks. This is in addition to temperatures caused by burial. Between 1ky and 10ky since intrusion, the temperature away from the sill increases gradually as sediments close to the sill begin to cool. Temperatures within the gas window are maintained for up to almost 100ky at a distance of over 700m from the intrusion.

The effect of large igneous intrusions on thermal maturity of sediments is therefore twofold. Increased maturity should be expected beneath sills due to burial and due to direct heating of the host sediments. It is reasonable to assume that igneous intrusions could place what might otherwise be thermally immature sediments within oil and gas windows. Such a mechanism has been identified as significant in gas generation in the Gulf of Mexico region (Ezat *et al.*, 1994) and, oil and gas generation in the oilfields of Nevada (Allison and Hulen, 1990).

Heating from igneous intrusions also has an affect on porosity, changing textures and mineralogy of host sediments. This will be examined in a later chapter.

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Local Stratigraphy 5

5.1 Shittim 1

The Shittim 1 DDH is located on the southern side of Variety Bay, North Bruny Island (EN339161, figure 1.1a). The stratigraphy of the core is summarised in a graphic log (figure 5.1) and in detail in appendix I. Table 5.1 is the key to all graphical logs used.

Most of the sediments within the core have been metamorphosed to some degree due to the intrusion of thick dolerite sill. Xenoliths of fossiliferous siltstone are identifiable within the 580m thick intrusion. Sediments adjacent the sill are highly brecciated and poorly consolidated.

The Truro Tillite is present as a pebbly, granular siltstone to mudstone. The matrix is dark grey to black, fine siltstone to mudstone. Abundance of clasts decreases above 900m, where the formation grades into the Woody Island Formation. Clast lithology varies greatly from metamorphic fragments such as quartzite, schist and other metamorphics, to carbonate and quartz granules. Clasts size, shape and roundness vary greatly. Pebbles with a sharp flat base and rounded sides are not uncommon. Quartz granules are characteristically angular. A normally graded conglomeratic horizon occurs in the uppermost part of the formation (Plate 1b). Erratics between sand and granule size are most common.

Bedding is not readily identifiable in the Woody Island Formation due to baking and a high degree of bioturbation. Granular and pebbly horizons are common, particularly in the uppermost part of the formation. Rare fossils of fenestellids and a spiriferid also occur at the top of the formation.

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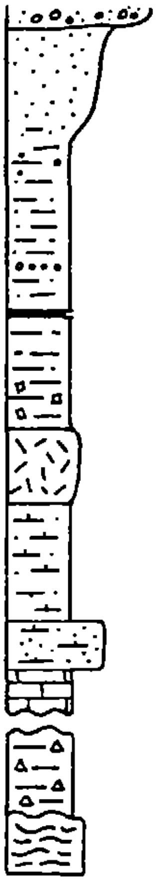
Key to Stratigraphic Columns

Lithology



- Conglomerate
- Sandstone (pebbly)
- Sandstone
- Siltstone (granular)
- Siltstone/Mudstone
- Granular horizon
- Coal seam
- Breccia
- Igneous intrusion (dolerite/syenite)
- Calcareous siltstone
- Calcareous sandstone
- Limestone
- Unconformity
- Tillite
- Schist

Sedimentary Structures

- Lamellar bedding
- Wavy bedding
- Cross bedding
- Graded bedding
- Bioturbated
- Symmetrical ripples
- Asymmetric ripples
- Sole marks
- Flame structures
- Dropstones
- Glendonites
- Flaser Bedding

Fossils

- Brachiopods
- Gastropods
- Bivalve
- Stenoporids
- Fenestellids
- Plant/Wood

Abbreviations

gry	grey
grn	green
crm	creamy/white
blu	blue
brn	brown
blk	black
l.	light
d.	dark
f.	fine
m.	medium
c.	coarse
v.c.	very coarse
↑	highly
↓	low/rare
mod.	moderately
calc.	calcareous
lmst	limestone
sst	sandstone
sltst	siltstone
fract.	fracture
F	Fault
⌊	perpendicular
py	pyrite/pyritic
pyh	pyrrhotite
TS###	Thin section
*###	Sample
* ##%	Porosity

Table 5.1 Key to symbols used in stratigraphic columns (incuding appendices).

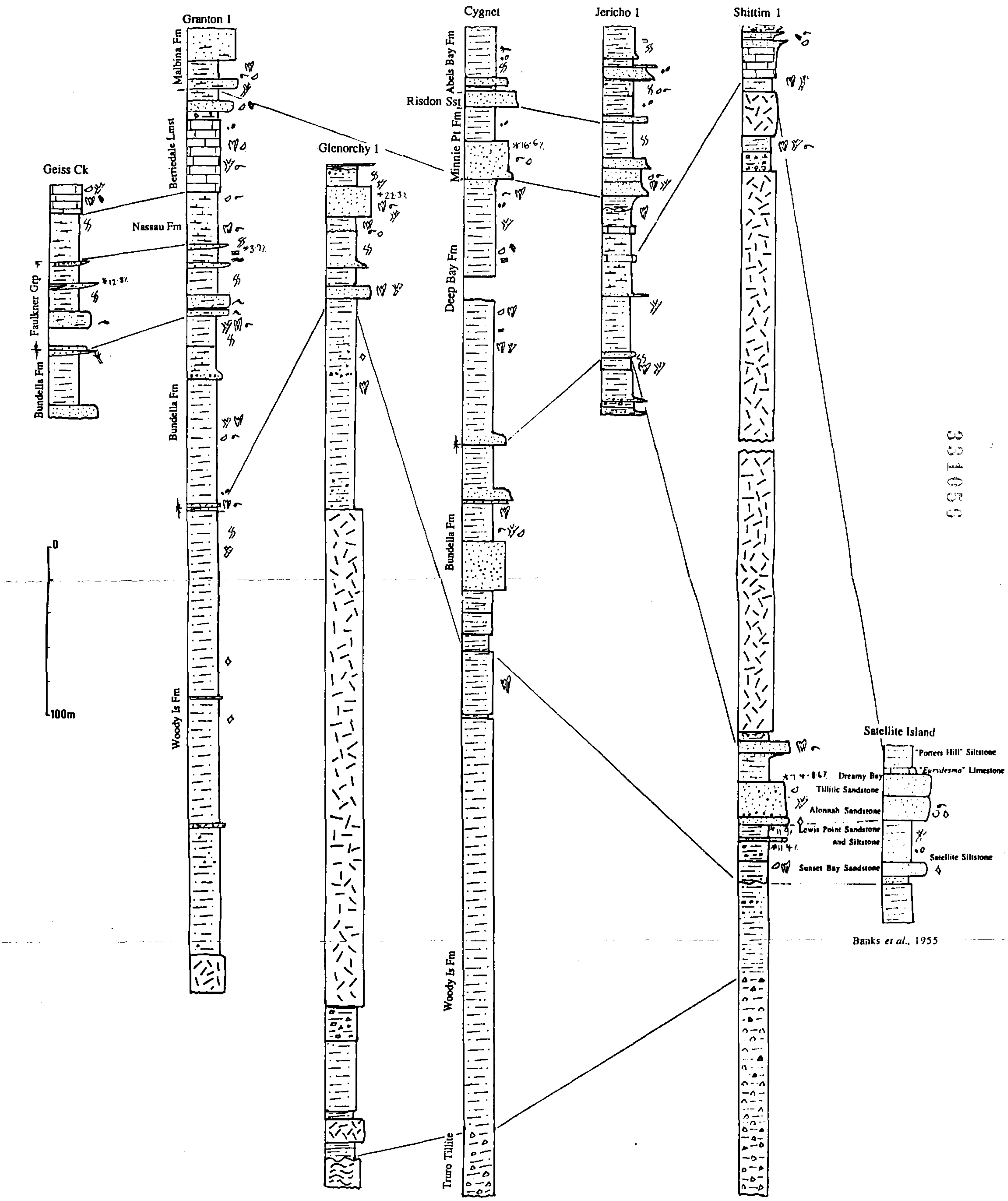


Figure 5.1 Stratigraphic correlations for south-east Tasmania. See figure 1.1b for guide to locations and table 5.1 for key. Stratigraphy for Satellite Island (previously Woody Island) after Banks *et al.*, 1955.

The rock is highly fractured in places, usually at an angle of about 30° to vertical to sub-vertical. Fractures are often filled with carbonate veins, euhedral pyrite grains are also common. Closer to dolerite sills, pyrrhotite can also be observed. Pyrite is also often found as rims around calcareous fossils. Disseminated pyrite occurs throughout the Woody Island, Bundella and Deep Bay Formations . The sediments become finer grained, less fossiliferous and more highly carbonaceous down-core. Poorly consolidated breccia with angular siltstone clasts and poorly consolidated, silty matrix occurs throughout the top of the Woody Island Formation and the Bundella Formation.

The Bundella Formation becomes evident by the presence of typically one to two metre thick, medium to coarse grained sandstone beds, interbedded with blue-grey bryozoa-rich siltstone. Sandstone beds are often graded, having a pebbly or granular base. Brachiopods and bivalves occur predominantly in the sandstone beds. A distinctive spotted, blue hornfels occurs within the Bundella Formation at a distance of over some 100m from a 580m thick dolerite sill. The rocks have been contact metamorphosed to a spotted hornfels. The speckled appearance being due to sericitised porphyroblasts (Plate 1a), possibly after andalusite (Botrill, 1995). A 30 cm thick, poorly sorted, pebbly sandstone at 795m is correlated with the D'Entrecasteux Tillite of Banks *et al.,* (1955).

The top 80m of the hole was not cored, so the exact thickness of the Deep Bay Formation at this location is not known. The contact with the Minnie Point Formation occurs at approximately 20m. Thin section and XRD analysis (appendix II) reveals that most of the core has been highly baked. Two other dolerite bodies are also evident in the core. The thicker of these has an upper contact which is at an angle of approximately 30° to vertical. Metamorphosed limestone and calcareous mud are evident as buff coloured calc-silicate hornfels and white spotted hornfels in the top 30m of the cored section of the hole. These rocks correlate with the 'Eurydesma' Limestone of Woody Island (Banks *et al.*, 1955). The units are highly fossiliferous, bryozoans, gastropods, brachiopods and bivalves being common. Fossil fragments are preferentially orientated parallel to bedding.

5.2 Jericho 1

Jericho 1 is located approximately 2km west of Shittim 1 at EN322167 (figure 1.1a). Core stratigraphy is summarised in figure 5.1 and detailed in appendix I.

From 222m to 193m the core consists of grey and blue-grey siltstone, the topmost part of the unit is calcareous and highly fossiliferous, fenestellids being the most common fossils. Below 200m the siltstone becomes spotted and poorly fossiliferous. The rock is brittle and commonly fractures into small, roughly equal size pieces of approximately 6cm in length.

Above 193m, blue siltstone passes into buff coloured calcareous siltstone with beds of impure limestone. Bryozoans, brachiopods and bivalves are common. Horizontal to sub-horizontal bioturbation obscures any bedding. These fossiliferous units can be correlated with the calc-silicate hornfels at the top of the Shittim 1 core which are equivalent to the 'Eurydesma' Limestone on Woody Island. Thin clayey units up to 10 cm in thickness could represent meta-bentonite units. Sub-ordinate medium bedded calcareous sandstone units also occur. One metre thick brecciated calcareous siltstone horizons appear towards the bottom of this unit. Erratics are not as common as in adjacent units. As in Shittim 1, a high degree of vuggy porosity is evident on several horizons .

A disconformity can be observed at 106m, above which, a calcareous siltstone grades into fine sandstone. Normally graded and massive bedded, very coarse to fine-grained sandstone follows. Conglomerate and fossil horizons occur sporadically. Brachiopods and bivalves are the prevalent fossils, fenestellids and stenoporids being be less common.

At 83.3m, the Risdon Sandstone, a 4m thick, normally graded, poorly fossiliferous, coarse-grained sandstone unit is observed. This unit interfingers with the poorly fossiliferous siltstone of the Abels Bay Formation above.

The uppermost 78m of the Jericho 1 core consists of poorly to moderately fossiliferous sandy siltstone. A 6m thick, coarse sandstone unit grades into a matrix supported conglomerate at 23m. The sandstone unit can be identified on a hill to the west of the drill hole. This is likely to the unit in which oil was discovered in Johnson's Well being highly porous. It appears to be a well sorted sandstone in which any previous matrix has been destroyed, the rock has then be silicified. Clasts of differing lithology as well as woody fragments were found in the sandstone. Occasional fossils include brachiopods, bivalves, gastropods and fenestellids.

5.3 Granton 1

The Granton DDH is located on Mount Nassau (EN515266), just outside the township of Granton. The hole was drilled by the Tasmania Department of Mines in order to fill gaps in the Permian type section of Rayner Creek. A detailed graphic log of the Granton 1 core can be found in appendix I, a stratigraphic summary with correlation to other cores studied is illustrated in figure 5.1.

The lowermost 21m of the core at Mount Nassau is dolerite. The next 180m consists of highly baked, veined and brecciated, pyritic and granular, dark grey siltstone of the Woody Island Formation. Reaction haloes commonly surround calcareous concretions. These may have been carbonate clasts or glendonites. The top of the formation is much less baked. The lowermost one metre of Woody Island Formation observed in the core is a very pebbly mudstone, probably representing the topmost portion of the basal tillite. Calcite rosettes, assumed to be glendonites, are most common in the uppermost 80m of the formation. Several dolerite sills occur throughout the lower half of the core. Contacts with host sediments are generally conformable with bedding. Brecciation, with associated carbonate veining often occurs close to the sills. Pyrite and pyrrhotite are also found in fractures and rimming calcareous fossils close to dolerite intrusions.

The Woody Island Formation is overlain by 118m of the Bundella Formation, which at this location is predominantly a highly fossiliferous, calcareous, blue-grey siltstone. Thin (up to 20cm) fossil rich limestone beds appear towards the base of the formation. Bryozoa, brachiopods, bivalves and crinoid debris are common fossils. Conglomeratic horizons of pebbles and shell fragments appear throughout the formation. Moderately fossiliferous, sandy siltstone towards the top of the formation is moderately bioturbated. Burrows are usually sub-vertical.

Above 162m, fenestellid- rich siltstone is replaced by flaser bedded, fine sandstone and carbonaceous siltstone. Plate 1c shows a typical flaser bedded sequence passing into highly bioturbated conglomeratic siltstone. A thin (<1cm) coal seam occurs at 157m. Unfossiliferous, highly bioturbated and carbonaceous siltstone and mudstone overlay the flaser beds. This unit is highly bioturbated, sub-horizontal burrows often filled with black mudstone. Where the unit is not heavily bioturbated, thin parallel bedding and occasional wavy bedding can be observed. Granular and conglomeratic horizons are common, often with a sandy matrix. A series of small (10cm) graded beds with sole structures occurs at 135m, overlain by a 30cm, highly bioturbated conglomeratic siltstone. A normally graded, coarse grained conglomerate 3m in thickness sharply overlies the siltstone (Rayner Sandstone). It is a very poorly sorted unit, bioturbation resulting in the inclusion of mudstone.

Marine fossils such as fenestellids and bivalves begin to appear again in grey, calcareous, granular siltstone above 123m. Spiriferids and bivalves are also present. This unit is defined as the Nassau Formation (Banks and Hale, 1957).

The Berriedale Limestone is a 60m thick, highly fossiliferous unit of interbedded calcareous siltstone and limestone. Erratics occur throughout, but are not as common as in the overlying formation. Sub-vertical joints are widespread and usually filled with calcite. Thin (1-25cm) clayey units occur throughout the formation. Previous XRD analysis (Pollington, 1974) has proven these to be meta-bentonite units. Very coarse, massive and graded sandstone units are more prevalent towards the top of the formation. A highly weathered brecciated unit occurs beneath the sandstone units. Bryozoa, notably *Stenopora*, are very common in the siltstone units,. Brachiopod and bivalves are typically large and occur predominantly within limestone units. Gastropods are also present throughout the formation.

Highly fossiliferous, medium bedded, calcareous, coarse-grained sandstone and siltstone of the Malbina Formation occupies the uppermost 32m of the Granton core. The siltstones are light brown and granular. Spiriferids are most common in sandstone beds, some in growth position with spines preserved. Large erratic clasts are common, especially in sandstone units where the base is occasionally a clast supported conglomerate.

5.4 Geiss Creek

The type section for the Permian in Tasmania is found in Rayner Creek a few hundred metres to the east of Geiss Creek. The section begins in the Bundella Formation along-side the Lyell Highway (EN145672). The outcrop along the highway is well exposed although the base of the Bundella Formation can not be seen. Exposure along Geiss Creek (EN143667 to EN145665) is good, some sections being covered with alluvium. As would be expected, lithologies are very similar to those in the Mount Nassau drill hole. Outcrop however, provides the opportunity to examine lateral variations and larger scale sedimentary structures more closely.

The lowermost exposed units of the Bundella Formation are medium to course grained, light brown sandstones interbedded with siltstone. Sandstone units exhibit a vuggy porosity due to decalcification of fossils and possibly glendonites. The

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uppermost units of the Bundella Formation consists of medium bedded, poorly fossiliferous, fissile and non-fissile siltstone. Fossils are the same as those in the Granton core.

A short distance up Geiss Creek, a thin, poorly sorted, matrix supported conglomerate represents the basal unit of the Faulkner Group. It irregularly overlies the siltstone beds of the Bundella Formation (Banks and Hale, 1957).

Alluvium covers the next several metres, the basal portion being a fine grained, medium bedded sandstone. Flaser bedded fine sandstone with carbonaceous mudstone drapes extend over the next 8m. The flaser bedded unit passes into highly bioturbated, carbonaceous siltstone often with coarse granular or pebbly horizons. The conglomeritic horizons are typically only several centimetres in thickness. Burrows within the siltstone are generally horizontal and filled with carbonaceous mudstone. A very coarse, well sorted, lenticular sandstone unit overlies wavy bedded, fine to medium-grained sandstone beds (figure 6.1, Plate 2.c). Carbonaceous plant fragments are occasionally observed in the siltstone. Dropstones are not present in the sandstone units and occurrence within siltstone units is sporadic. Approximately 10m of interbedded fissile and non fissile, highly bioturbated siltstone grades into calcareous marine siltstone of the Nassau Formation. Fenestellids are the most abundant fossils but brachiopods are also common.

Above the fenestellid siltstone, the Berriedale Limestone becomes evident as very calcareous siltstone and highly fossiliferous, impure limestone. Fossils are the same as those observed in the Granton core. Meta-bentonite units are frequently represented as highly weathered clay units.

5.5 Glenorchy 1

The Glenorchy core is summarised in figure 5.1, a detailed log can be found in appendix I. The drill hole is located at Glenorchy (EN230570). The lowermost rocks of the Parmeener Supergroup rest unconformably on albite-epidote schist of the Precambrian (Leaman, 1976). The lower part of the Woody Island Formation, the bottom several metres of which are a clast rich mudstone, rests unconformably on the basement rocks. A large dolerite sill intrudes the Woody Island Formation between 197m and 493m. This has resulted in the lower part of the formation being highly brittle and brecciated. Sub-vertical calcareous veins are often associated with pyrite and pyrrhotite. A black, 'shaley' horizon occurs at 564m. The uppermost half of the Woody Island Formation is also highly baked. Erratics are much more frequent up-sequence. Glendonites appear at the top of the formation with rare fenestellids.

The lower siltstone units of the Bundella Formation are highly bioturbated, most worm burrows being sub-horizontal. Fenestellids become common and rare shell fragments are present, commonly with pyritic rims. Poorly fossiliferous, blue-grey silty sandstone is overlain by grey, highly bioturbated, clast rich, sandy siltstone. These siltstone units are overlain by medium-grained, bryozoa rich sandstone. Bivalves are also appear. The uppermost 17m of the Glenorchy core consists of bryozoa rich, calcareous siltstone. The top several metres are beds of normally graded, coarse-grained, grey sandstone.

5.6 Woodbridge 1

The Woodbridge DDH it is located at Little Peppermint Bay (EN193226). The bottom 25m of the core is a black phyllitic siltstone with infrequent quartzite banding. Light grey, porphyritic intrusions of syenite together with fine grained dolerite have caused most of the sediments to be highly baked and brittle throughout the core. The tillitic mudstone overlies the phyllitic unit with a flat base (Plate 2a). Minor kink bands can be observed in the black phyllite. This unit closely resembles the black, shaley mudstone found in the Shittim 1 core at the base of the Woody Island Formation.

The tillite is a very pebbly, erratic rich, dark grey to black mudstone. Clasts, especially carbonate, often have reaction haloes up to several centimetres in diameter . Clast vary greatly in lithology, shape and size. Phyllitic clasts towards the base of the formation are typically 1.5cm long and show preferential orientation. Angular quartz granules occur throughout. Larger (>1cm) metamorphic clasts are sub-round to sub-angular. Boulder size clasts are increasingly common between 123m and 138m. Highly baked siltstone with rare pebbles occurs between 263m and 275m. Pebbles are generally not preferably orientated, although elongated clasts up to 2cm have a slight tendency to lie horizontally. The relationship with bedding can not be observed so it is not known whether this is due to gravitational settling during deposition or to compaction. It is most probably a factor of both.

At 100m, the tillite has a higher proportion of carbonate clasts and also a calcareous matrix. Calcareous veins up to 2mm in thickness are usually sub-vertical, but occasionally dendritic in nature. Disseminated pyrite appears throughout. Pyrrhotite is found in veins close to syenite and dolerite bodies.

5.7 Cygnet

Excellent cliff exposure along the coast at Cygnet enables easy access from Deep Bay Formation (EN083532) to Abels Bay (EN072033). The lowermost units of the Parmeener Supergroup from the Truro Tillite to the Bundella Formation are exposed along a road leading to Toby's Hill (EN080211-EN095222).

92m of granular, clast rich, basal tillite outcrops along Toby's Hill Road. Tillitic mudstone grades into massive, greenish-brown mudstone. The Woody Island Formation is highly fractured in places, producing a blocky appearance in which components are several centimetres in diameter. Rare glendonite moulds occur towards the top of the formation. The total exposed thickness of the Woody Island Formation is just over 150m.

Unfossiliferous Woody Island siltstone is overlain by poorly fossiliferous, light green siltstone of the Bundella Formation. Fossils become more abundant up-section. Sandstone units are common at the bottom of the formation. Brachiopods and bivalves are the dominant fossils on several horizons. Bryozoans appear throughout and erratic clasts are common. These fossiliferous units are overlain by 21m of poorly fossiliferous siltstone and subordinate sandstone. Grey and greenish grey calcareous bryozoa rich siltstone overlies this unit. Spiriferids are also common. The unit becomes more baked towards the top, where soil probably obscures a dolerite sill.

Deep Bay (EN078152), near the township of Cygnet is the location for the type section of the Deep Bay Formation. The formation is generally a poorly to medium bedded, highly fossiliferous, grey to dark brown siltstone. The basal sandstone units do not appear at this location, but are revealed in a nearby drill hole (Farmer, 1985). Brachiopods, particularly spiriferids and fenestellids are abundant throughout. Stenoporids are also very common. Ostracods are prevalent on several horizons. Erratics are common, clasts ranging in size up to approximately 40cm.

The Minnie Point Formation conformably overlies the Deep Bay Formation. The transition being marked by medium to very coarse-grained, poorly sorted, clast rich, highly fossiliferous sandstone units. Bedding is generally massive to medium. Subordinate siltstone and conglomerate units also occur. Total thickness of the unit at this location is 46m.

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The coarse-grained, poorly sorted Risdon Sandstone has an estimated thickness around 7m. The basal 30 cm of which is a matrix supported, pebbly conglomerate. The unit is cross-bedded. Beach sediment obscures the contact with the Abels Bay Formation.

As in the Jericho 1 core, the Abels Bay Formation at Port Cygnet consists predominantly of poorly fossiliferous, poorly sorted, fine-grained sandstone and sandy siltstone. Subordinate coarse-grained sandstone units become more common towards the top of the formation. Erratics are common throughout, occasional pebble horizons also appear.

5.8 Geology of North Bruny Island

The sediments of the Lower Parmeener Supergroup are readily identifiable in coastal cliffs on North Bruny Island. On the Eastern shore they outcrop as sheer cliffs of varyingly to highly fossiliferous siltstone and sandstone of the Deep Bay Formation. Dolerite sheets can be observed beneath the sediments, usually at, or near the waterline, contacts appear to be conformable with bedding.

Dips on the eastern shore typically vary between 12° and 16° to the west, striking approximately north-south. Dips very gradually become shallower to the west. At Jericho 1, the Abels Bay Formation is dipping 10° west. On the western shore, dips of 6° to 8° west are recorded. This information and drill hole data from Shittim 1 and Jericho 1, were used to construct a geologic cross section of North Bruny Island. (figure 5.2). The section was drawn on a line passing through both DDHs.

The blue spotted hornfels at the base of the Jericho 1 core is interpreted as representing part of a contact aureole. Further drilling is expected to encounter a substantial thickness of dolerite.

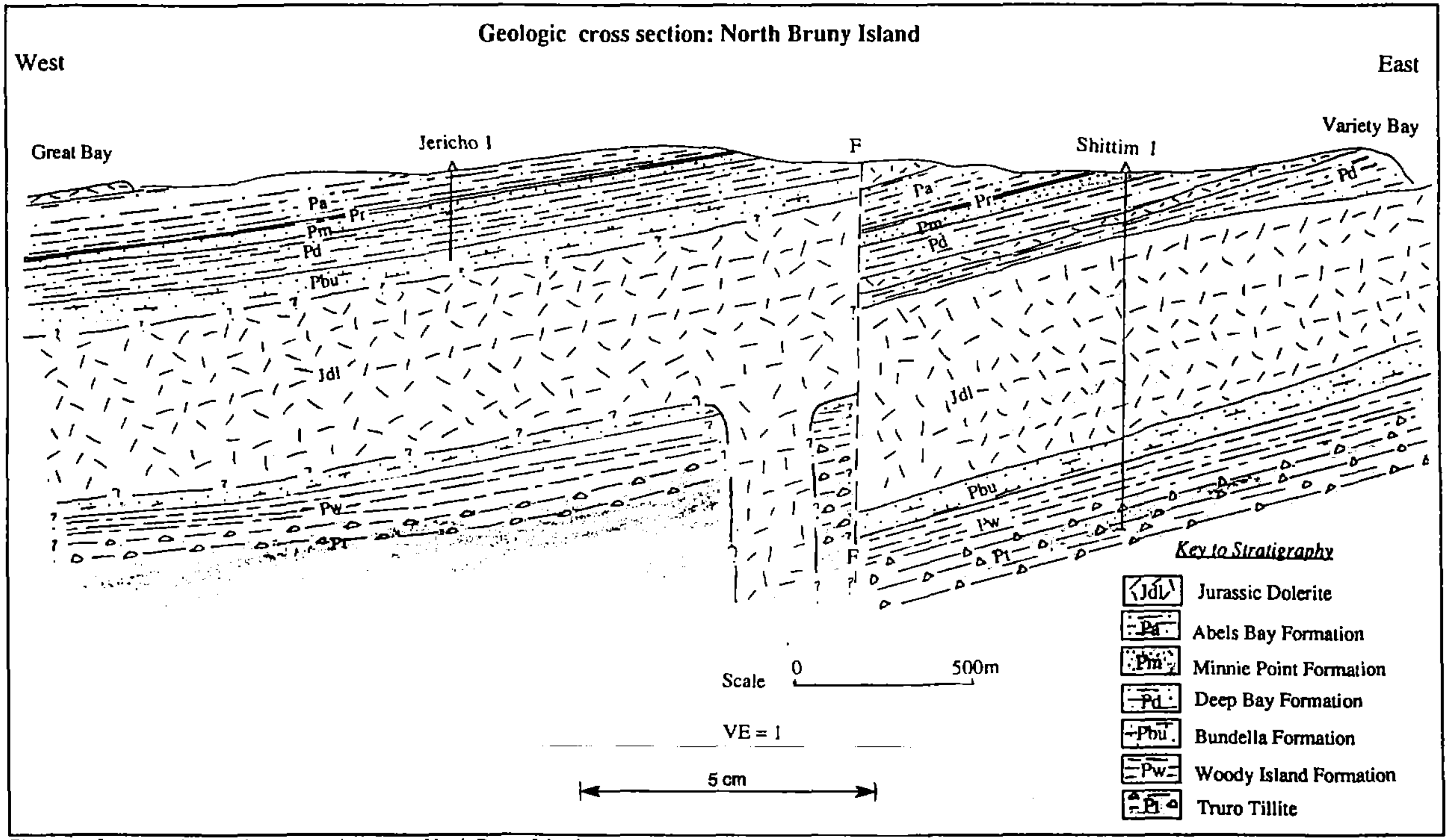
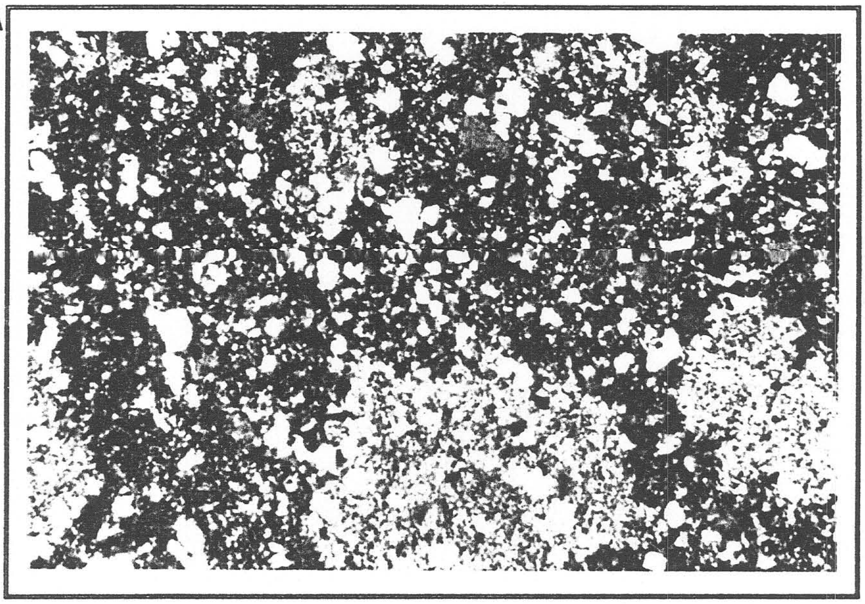


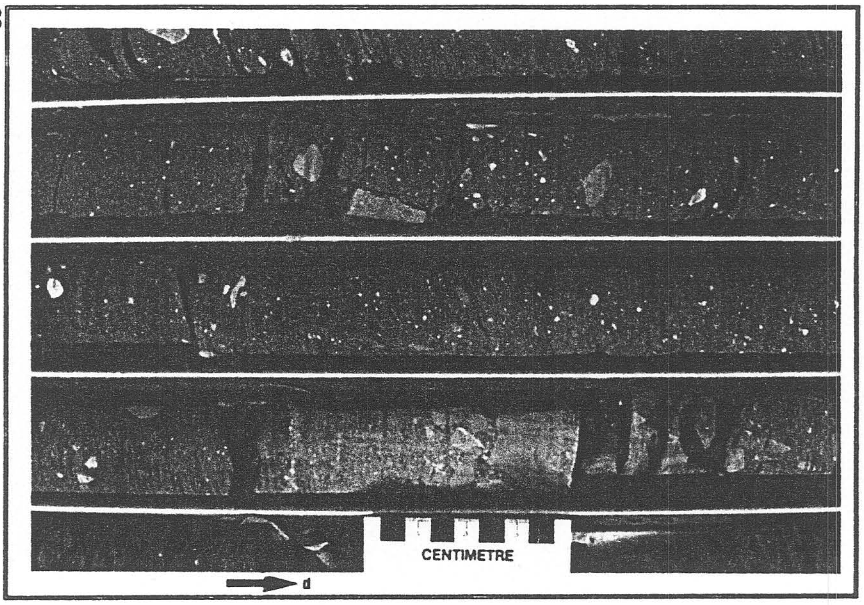
Figure 5.2 Interpreted geologic cross section across North Bruny Island. See figure 1.1b for cross-section location.

Surface outcrop between Shittim 1 and Jericho 1 is scarce. Boulder float between the two holes suggests an anomalous thickness of Minnie Point Formation and the possibility of at least one fault, as mapped by the Tasmania Department of Mines. The cross section (figure 5.2), drawn to scale, with no vertical exaggeration confirms this. Floats of dolerite occur extensively over between the drilling sites, suggesting there was another, stratigraphically higher dolerite sheet. At Great Bay (EN312171), the contact between the Abels Bay Formation and a dolerite sill is obscured by beach sediment. It appears however, that dolerite is dipping under the Abels Bay Formation.

A



B



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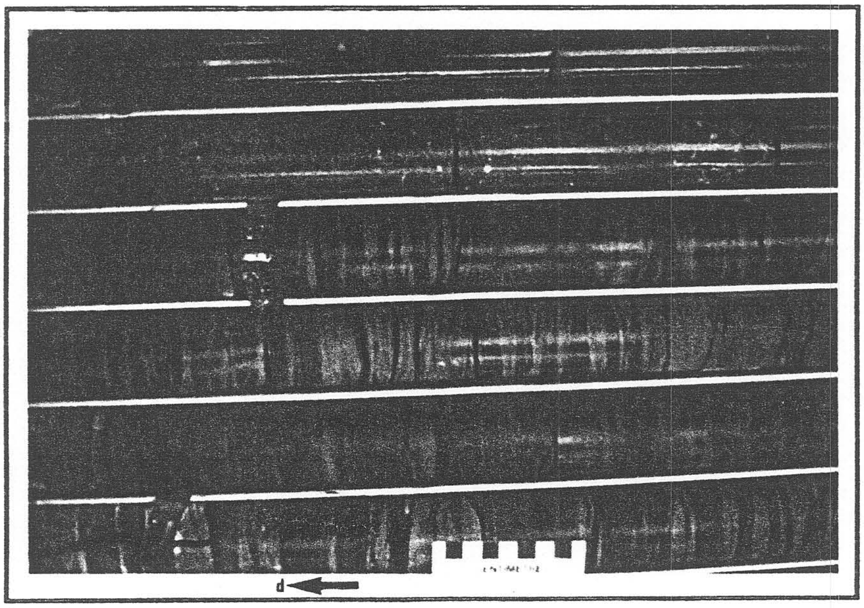

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Facies Analysis and Palaeogeography

6

6.1 Truro Tillite

The abundance of poorly sorted clasts of greatly varying lithology and size, in a very fine grained matrix which persists for several hundreds of metres has led to the interpretation of this formation as a glacial tillite (Farmer, 1985). Pebbles with a flat base and rare striations are also supportive of glacial transport at some stage. The thickness of this formation varies greatly throughout Tasmania. It is not present in the Glenorchy DDH, while in the Woodbridge DDH and surrounding outcrop, a thickness of at least 450m is proved. Thus far, a thickness of just over 100m has been proved on North Bruny Island. Hand (1993) suggests that the boundary between the basal tillite and the Woody Island Formation is diachronous. The greater thickness of tillite being found in near shore, proximal environments, with siltstone predominating in deeper, distal environments. Many of the clasts within the tillite have a similar lithology to pre-Carboniferous rocks in western Tasmania, a likely provenance for much of the material (Farmer, 1985). Some of the larger clasts are an albite-epidote schist, the same as found at the base of the Glenorchy core.

The great thickness of tillite in the southern portion of the study area and the near absence near Hobart, suggests a proximal environment grading to distal from south to north. It is generally agreed that the tillite is the result of at least several glacial/interglacial cycles, with tillitic siltstone interfingering with deeper, distal mudstone and siltstone (Domack *et al.*, 1993, Hand, 1993).

The phyllite at the base of the Woodbridge DDH has previously been interpreted as basement for the Parmeener Supergroup sediments (Farmer and Clarke, 1985). As mentioned previously, the lithology of the phyllite is similar to that of the basal unit of the Woody Island Formation. In thin section (Plate 2b), the rock is a phyllitic, fine grained siltstone, consisting predominantly of quartz, mica, chlorite and some feldspar. Carbonate veins up to 0.5mm thick are at angle of approximately 35° to core length. XRD analysis (appendix II) indicates the phyllite (W1011.8) has very similar mineralogy to the black shale of the Woody Island Formation (48A). Samples from the base of Woody Island Formation in Shittim 1 show the same wavy cleavage as that in the Woodbridge phyllite, that is, a very fine foliation, with a wavelength of 20mm and amplitude of 1mm. The similarities in lithology and structure of lowermost phyllitic unit in the Woodbridge DDH and the base of the Woody Island Formation on Bruny Island suggests they are facies equivalents.

The lack of a fault breccia suggests the phyllite is an interfingering of siltstone within tillite, caused perhaps, by a brief transgressive pulse during a larger regression. Alternatively, the overlying tillitic sequence could represent a large scale regressive event which caused distal siltstone to be overlain by a thick tillitic sequence. Kink banding, which only occurs in the uppermost several metres of the phyllitic siltstone, may have been produced by a prograding glacier. Whatever the scenario, the implication is that, in the Cygnet region the palaeo-basin is deeper than previously thought and that the lithology of basement rocks is unknown.

More recently the debate has been whether the tillite was deposited in a marine or lacustrine environment (Farmer, 1985). The thickness of the formation in the Cygnet and Bruny Island regions, coupled with the siltstones massive nature, would suggest glacio-marine deposition. Some sections, for example in the Woodbridge DDH, exhibit minor laminated siltstone sequences. Domack *et al.* (1993) claims that pebble-free, rhythmite within the tillite is indicative of glacio-lacustrine deposition. Minor cross-bedded sandstone and conglomerate horizons could represent glacio-fluvial conditions (Farmer, 1985). Contrary to this, Hand (1993) claims the rhythmite banding is due to tidal influence and can only have occurred in a very large body of

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water. As tides large enough to produce these varves are not found in any of the largest modern day lakes, glacial marine deposition is assumed for the whole of the formation. It is difficult to determine whether the rhythmic nature of the siltstone is tidal, seasonal or, due to some other environmental mechanism. Therefore, it is impossible to conclude whether the tillite was deposited entirely in a marine environment or, is partly terrestrial in nature. In the Shittim 1 core, a graded conglomeratic horizon in the uppermost part of the tillite, indicates a proximal environment (Plate 1b). This may represent a fluvio-glacial deposit, a turbidite from a wet base glacier or, graded bedding near a glacial grounding line. Lack of diagnostic features inhibits a conclusion, other than its proximity to a terrestrial source.

6.2 Woody Island Formation

Domack *et al.* (1993) identifies two main facies within the Quamby Mudstone; a carbonaceous mudstone, which includes the tasmanite interval and, a massive, glendonitic, silty mudstone. Both these facies can be identified in the Shittim 1 DDH. The basal, carbonaceous mudstone lies conformably above tillite. An abrupt boundary between the black mudstone and lighter coloured, silty mudstone is observed at 870m.

Glendonites are calcite pseudomorphs after ikaite, $CaCO_3.6H_2O$ (Suess *et al.*, 1982). Ikaite is formed in sub-freezing, anoxic, carbonate and phosphate rich marine environments (Jansen *et al.*, 1987). Less commonly, it has been observed precipitating in lacustrine brines, where mixing with calcium rich groundwater occurs at near freezing temperatures (Council and Bennet, 1993). Above 5°C, the mineral becomes unstable and reverts to calcite and water, resulting in porous calcite pseudomorphs (Jansen *et al.*, 1987). High concentrations of orthophosphate inhibits the initial formation of calcite from carbonate waters, while not affecting the growth of ikaite crystals (Council and Bennet, 1993). Cold, anoxic waters are favourable for the production of HCO_3^- and PO_4^{3-} from organic matter. Organic rich environments

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therefore provide the optimum conditions for ikaite precipitation (Bischoff *et al.*, 1993).

Pseudomorphs of ikaite formed by lacustrine processes are generally poorly preserved due to fluctuating temperatures. Where glendonites are produced they tend to be concentrated in mounds, close to sub-lacustrine springs (Council and Bennet, 1993). Glendonites in the Woody Island Formation are laterally extensive and randomly distributed along stratigraphic horizons. The widespread abundance of glendonites at the top of the Woody Island Formation suggests deposition in a cold, poorly oxygenated, low energy environment. A lack of sedimentary structures supports low energy conditions, while the abundant pyritic and carbonaceous material supports reducing conditions (Banks and Clarke, 1987).

The lower, dark mudstone facies is less glendonitic. The tasmanite oil shale at the base of the Woody Island Formation equivalents was deposited largely from algal blooms as sea ice melted (Banks and Clarke, 1987, Domack *et al.*, 1993).There has been recent debate over the depositional environment of the lower Woody Island Formation and correlates, in particular, the tasmanite oil shale (Revill *et al.*, 1994, 1995, Domack *et al.*, 1993, 1995). Domack *et al.* (1993) interpreted the black mudstone unit, including the tasmanite horizons, as being deposited in a deep, sub-freezing, oxygenated, low energy environment. Revill *et al.* (1994) propose a shallow, sub-freezing, dysaerobic environment of deposition.

Revill *et al.* (1994) argue that the abundance of terrestrial spores and a number of intact, shallow marine fossils found in the mudstone in the north-east of the state are difficult to explain using a deep water deposition model. The shallow water model explains the absence of oil-shale from within the basin as being controlled by distance to the palaeo-shoreline. Domack (1995) favours a deep marine environment for tasmanite deposition. This model more easily explains the large areal extent of oil shale over the high relief, glacial basin. In the deep water model concentration of *Tasmanites* within mudstone is controlled by the flux of terrigenous sediment. The

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concentration of organic material will therefore occur in distal environments, where biogenic flux dominates.

Oil shale has not been identified within the Woody Island Formation. As the facies in which it appears is present throughout south-east Tasmania, it seems deposition of tasmanite is controlled by factors other than depth. This fact would favour Domack's model. There is however, no evidence to put depth constraints on the Woody Island Formation. The relative lack of structures suggest a very low energy environment, while glendonites and occasional dropstones are evidence of near freezing water temperatures. The formation of glendonites, pyrite and preservation of carbonaceous material throughout the formation suggests anoxic to dysaerobic conditions.

6.3 Bundella Formation

Fossils within the Bundella Formation are indicative of an open marine shelf environment (Clarke and Forsyth, 1989). Erratics within the formation tend to be rounded and smaller compared to those of the basal tillite. They can be observed breaking bedding (TS26A), suggesting they are dropstones. Therefore, rather than solely glacial processes, the clasts have probably undergone fluvial or beach reworking, with final transport by fast ice (Martin, 1986).

Normally graded beds occur throughout the formation. A number of these show an association between well-sorted coarse sandstone and brachiopod and bivalve-rich horizons. Fossils are mostly oriented parallel to bedding and relatively intact. Martin (1986) suggests that normally and reverse graded beds within the formation are due predominantly to changes in terrigenous input, rather than to changes in the energy of depositional environment resulting from fluctuating sea level. Evidence of this is in the limited lateral extent of coarse graded units and relatively immature mineralogy; feldspar content is usually greater than 20% (figure 7.1). It is likely that many of the graded sandstone beds are deposits from both mechanisms as a relative rise in sea

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level will, at first, inhibit fluvial input. Likewise, a prograding shoreline will increase the terrestrial flux of sediment.

The presence of glauconite suggests sedimentation rates were very low. A lack of turbidite deposits suggests a gently dipping slope in a relatively calm environment. Fossils, glendonites and sedimentary structures suggest a shallowing upwards sequence, which begins in a cold and deep, low energy environment and grades into a shallow, sloping, marginal marine depositional setting. The limestone units found within the Bundella Formation on Bruny Island are correlates of the *Eurydesma* Limestone on Woody Island (Banks et al., 1955) and probably the Darlington Limestone on Maria Island (Banks, 1957). This unit has been interpreted as being deposited in a cold, 'normal' salinity, and mostly low energy environment which allowed the formation a shell banks (Rao and Green, 1982, Brill, 1982). The units below the limestone originate from similar, but deeper depositional environments.

The Bundella Formation is conformably overlain by freshwater sequences in the north of the study area and unconformably by the highly fossiliferous marine sediments further south. It represents a marine shelf environment deposited during a marine regression.

6.4 Faulkner Group

The Faulkner Group and its terrigenous correlates are often referred to as the "Lower Freshwater Sequence". The lack of marine fossils and presence of thin coal seams would confirm its 'freshwater' origins.

Martini and Banks (1989) conducted a detailed study of the Lower Freshwater Sequence throughout Tasmania. Many of the facies they define are identified at Mount Nassau (Granton 1 and Geiss Creek), as shown in figure 6.1. The proximal marine facies (Mp) of Martini and Banks (1989) occurs in the uppermost portion of the

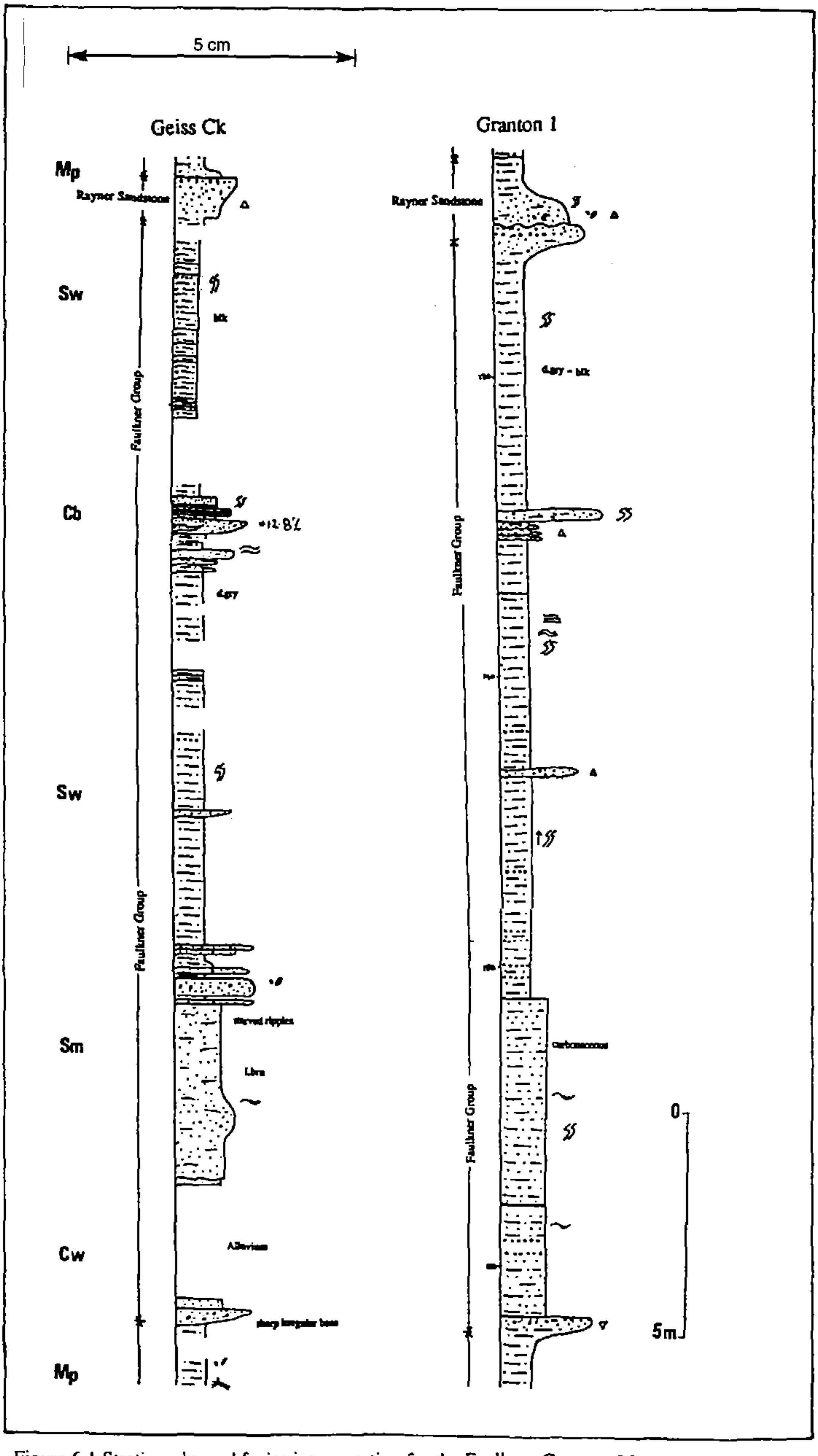

Figure 6.1 Stratigraphy and facies interpretation for the Faulkner Group at Mount Nassau. See text for discussion.

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Bundella Formation. Regression results in the Bundella Formation being overlain by carbonaceous siltstones and a thin coal seam, having been deposited in a coastal swale or marsh environment (Cw). A tidally dominated system is indicated by flaser bedded fine sandstone and carbonaceous mudstone of a tidal mixed flat (Sm). A near shore swale facies (Sw) is interpreted as being represent by well sorted, carbonaceous and bioturbated siltstone. Thinly laminated beds of well sorted silt and fine sand are thought to represent storm layers or channel splay (Martini and Banks, 1989). Granular and pebbly horizons are interpreted as being due to changes in terrestrial input. A coastal floodplain facies (Cb) is evident, being dominated by well sorted, wavy bedded fine to medium-grained sandstone and siltstone (Plate 2c). Flaser bedding also occurs, but ripples are generally 'starved'. A well sorted, coarse grained, lenticular sandstone unit was interpreted as a point bar of a coastal or tidal channel (Cd, Plate 2c). The coastal floodplain deposit grades again, into nearshore swale deposits, followed by proximal marine sediments, signifying the end of 'freshwater' deposition and a renewed marine transgression.

Flaser bedding is interpreted as being due to tidal influence. Massive bedded, lenticular sandstone units were interpreted as being channel lag from small tidal channels.

6.5 Berriedale Limestone

After brief freshwater deposition, marine conditions once again became prevalent. The calcareous, fossiliferous siltstones of the Nassau formation grade into highly fossiliferous, impure limestone and calcareous siltstone. Meta-bentonite units testify to distant volcanic activity. Erratics, some which break bedding planes (Pollington, 1974), faunal assemblages and oxygen isotope studies (Rao and Green, 1982) indicate a cold water environment.

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Pollington (1974), proposes that deposition occurred in a marine gulf, mostly below the wave base. The alternating calcareous siltstone and limestone sequences having been attributed to changes in the flux of terrigenous material. Rao and Green (1982), attribute this to glacial/interglacial cycles.

6.6 Deep Bay Formation

A marine transgression from the south-east resulted in an overlapping unconformity. The Deep Bay Formation was deposited paraconformably above the Bundella Formation, Hickman Formation, Harts Hill and Berriedale Limestones. An oscillating low to moderate energy, near shore environment has previously been interpreted for the Deep Bay Formation (Farmer, 1985). This is supported by faunal assemblages, most fossils being very well preserved. Alternations between well sorted sandstone and siltstone units is further evidence.

6.7 Minnie Point Formation

An increase in erratics is noted towards the top of the Berriedale Limestone and into the conformably overlying Malbina and Minnie Point Formations. This may represent increased float ice or a more proximal environment. The well sorted, coarse grained texture of the basal sandstone units suggests the later.

The formation was deposited in a shallow marine shelf environment, which was at first transgressive, as marked by the transition from fossil rich sandstones into poorly fossiliferous siltstone. The transition to predominantly coarse sandstone at the top of the formation marks a rapid regression resulting in a sand bar facies being deposited over offshore sands (Willink, 1974). The 'sudden' change in lithology may be due to the large aerial extent of the shallow environment. Any relative drop in sea level would

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cause rapid progradation of the shoreline. This unit proves to be the beginning of a large scale regression.

6.8 Risdon Sandstone

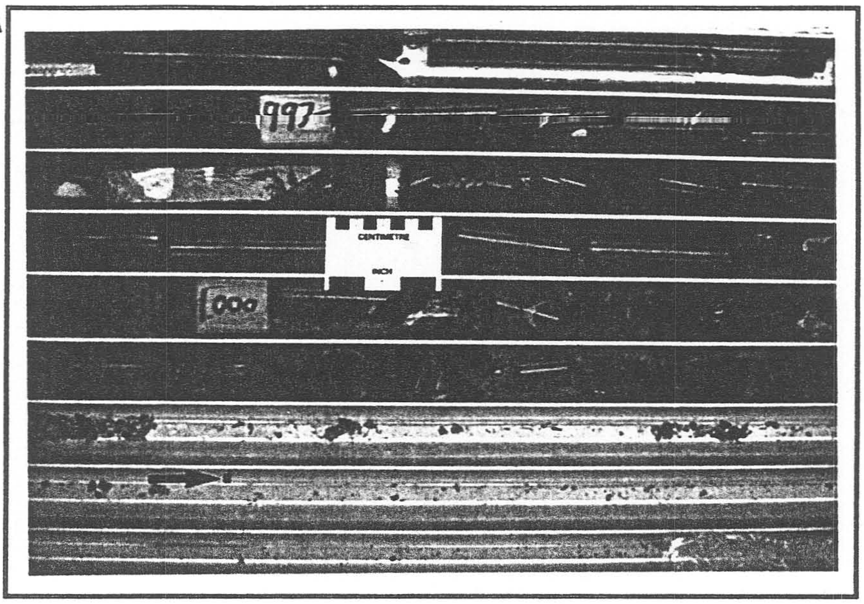
The near-shore shelf sediments of the Malbina and Minnie Point Formations are overlain by the Risdon Sandstone. This unit has previously been identified as an offshore barrier bar (Ellis, 1974). It is consistently thin, usually less than 8m. Sorting varies between locations and stratigraphically. This has been explained by a facies variation between the aeolian influenced dunes, a high energy, shallow marine barrier and bioturbated lagoonal sands. Well sorted, mature, cross-bedded sandstone is characteristic of the dune facies. The submerged facies are generally poorly sorted, with the offshore side having a less mature mineralogy.

6.9 Abels Bay Formation

Continuance of the regression resulted in the deposition of highly bioturbated lagoonal siltstones over the Risdon Sandstone (Abels Bay and Ferntree Formations). A proximal environment can be established for these formations due to the abundance of lonestones, plant and woody material. Stratigraphic relationships and a low diversity fauna also support the low energy, near shore model (Ellis, 1974). The porous sandstone unit that occurs within the Abels Bay Formation is likely to be of the same depositional environment as the Risdon Sandstone. Evidence of terrestrial influence comes from the abundance of drift wood in the unit, while marine fossils are found in siltstone both above and below the sandstone.

A large scale regressive sequence is further evidenced by the stratigraphic gradation of near shore sediments into the Cygnet Coal Measures and overlying Triassic fluvial and aeolian sandstones.

A



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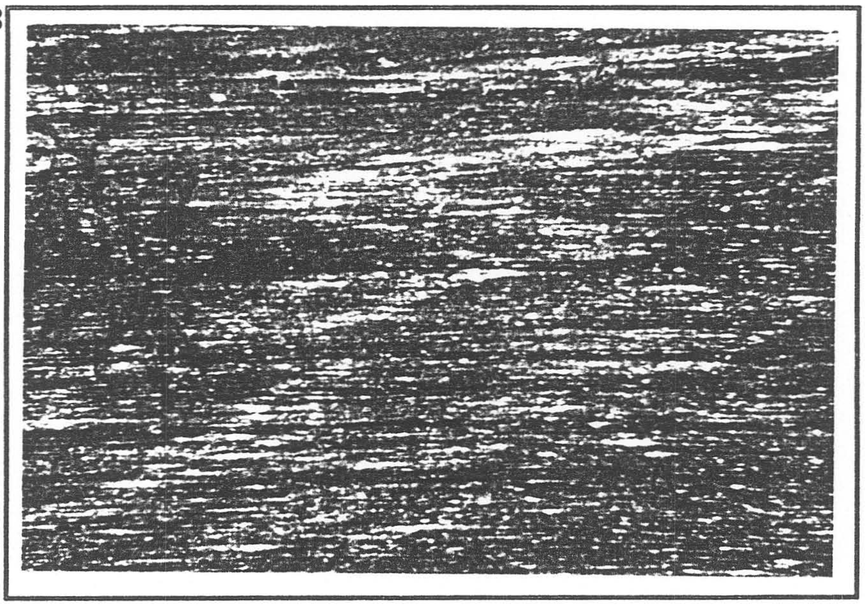

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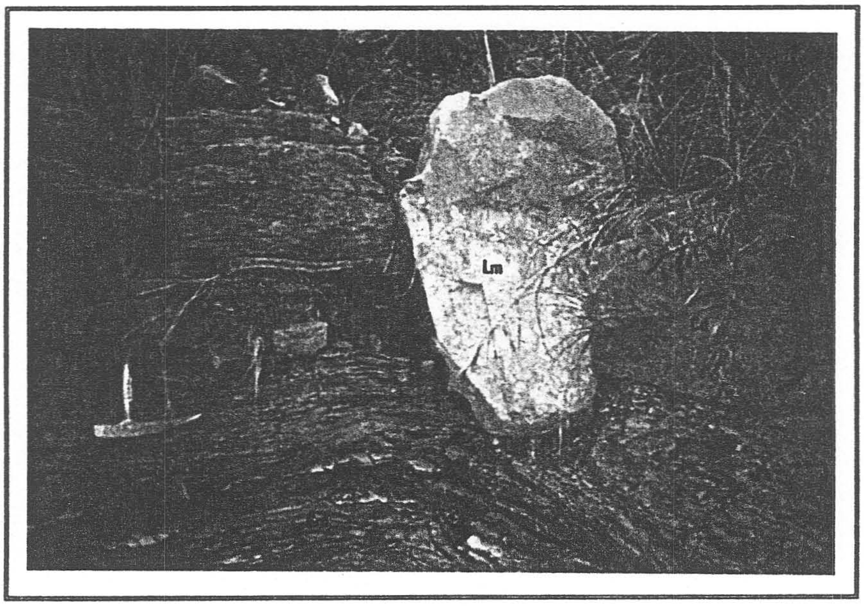

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Potential Reservoirs 7

7.1 Introduction

The most important reservoir characteristics are porosity and permeability. Porosity is the percentage of total rock volume that is occupied by pore space (North, 1985). Permeability is a factor of the rock which controls the ease at which a fluid passes through it. It is a function of pore throat diameter and connectivity. The proportion of total porosity through which fluid is able to flow is termed effective porosity (Selley, 1985).

This chapter examines the results of porosity and permeability determinations for potential sandstone reservoirs of the Lower Parmeener Supergroup and also briefly examines other possible reservoirs in south-east Tasmania. All porosity measurements were performed by ACS Laboratories Proprietary Limited, using helium injection methods as outlined in appendix III. Optical petrography and facies analysis (previous chapter) is used to establish how diagenetic, metamorphic and depositional factors influence porosity. Ideally, a scanning electron microscope would have been used to examine clay textures and morphology in more detail, but one was not available for use at the time of this study.

7.2 Potential reservoirs formations in Tasmania

The Lower Palaeozoic of Tasmania has several possible reservoirs, although data on such units are scarce. The process of dolomitisation increases porosity as the pseudomorphing of calcite results in a loss of volume of up to 12.3% (North, 1985).

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Precambrian dolomite may therefore provide both source and reservoir sediments. A similar scenario can be envisaged for the Gordon Limestone, where a palaeokarst topography provides a high porosity reservoir for source rocks within the same formation (Bendall *et al.*, 1991). Dolomitisation has also occurred locally within the Gordon Group, thereby enhancing potential reservoir qualities.

Sandstone units within the Eldon Group are also reported to be potential reservoir rocks for any hydrocarbons that may have been produced prior to the mid-Devonian (Summons, 1981). The sediments of the Lower Parmeener Supergroup are predominantly siltstones. There are however, many potential reservoir units which will be examined in more detail.

7.3 Potential sandstone reservoirs of the Lower Parmeener

Porosity determinations were done on a number of sandstone units from the Lower Parmeener Supergroup. The results are shown below (table 7.1).

Formation	Porosity (%)	Environment of Deposition
Risdon Sandstone	13.7- 14.7	barrier complex
Malbina Formation	2.1	shallow, marine shelf
Minnie Point Formation	14.1- 16.6	shallow marine shelf
Rayner Sandstone	3.97	?basal conglomerate
Faulkner Group	12.8	coastal channel
Bundella Formation	7.4- 22.3	shallow, marine shelf

Table 7.1 Porosity of sandstone units within the Lower Parmeener Supergroup (ACS Laboratories, 1995a, 1995b, 1995c).

North (1985) considers porosity values less than 5% to be negligible, 5-10% poor, 10-15% fair, 15-20% good and greater than 20% very good. Using this classification

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scheme, only samples from the Rayner Sandstone and the Malbina Formation have porosity that can be considered negligible. Porosity determinations for other sandstone units lie mostly in the fair to good range. One core sample from the Bundella Formation (G33.9) had a porosity which could be considered very good.

7.4 *The effect of depositional environment on reservoir characteristics*

Point counting is used to classify sandstone units of the Lower Parmeener Supergroup according to sand-size mineralogy. A minimum of 250 points was counted for each thin section. The results are shown in figure 7.1.

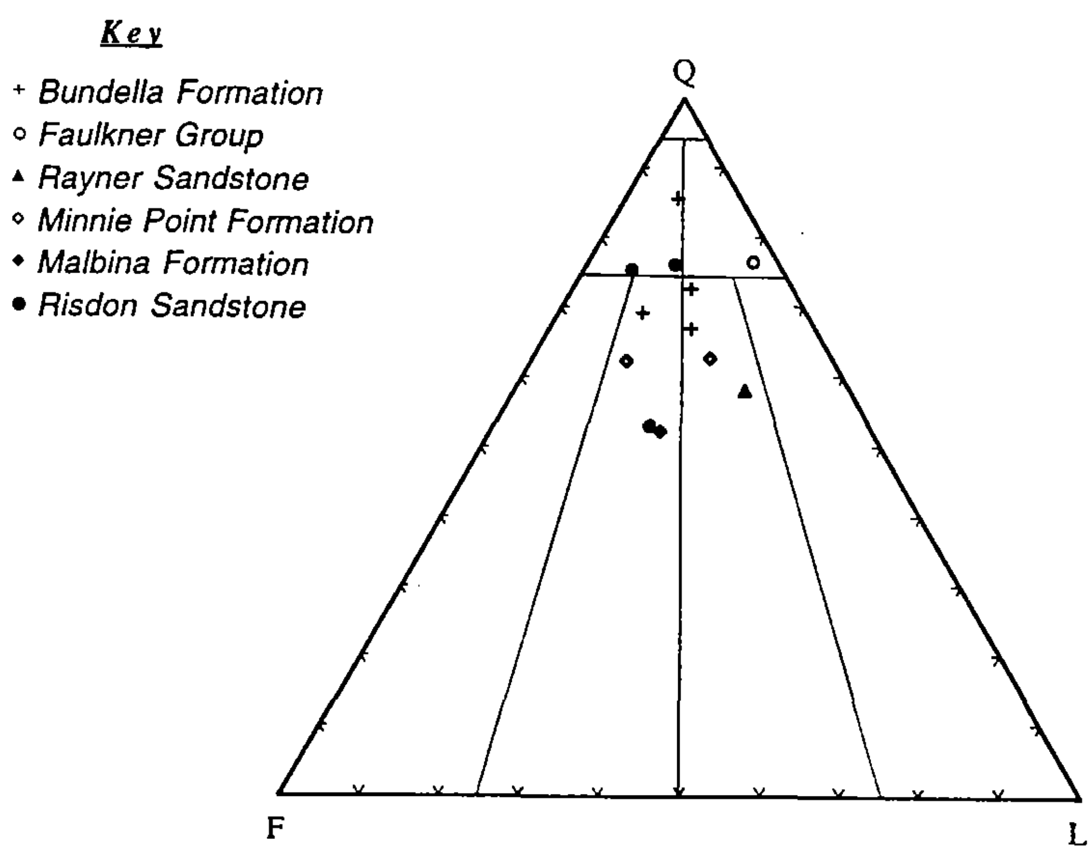

Figure 7.1 Ternary plot of quartz (Q), feldspar (F) and lithic (L) components of sandstone units within the Lower Parmeener Supergroup.

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It is not surprising that the Rayner Sandstone and Malbina Formation samples exhibit a relatively immature mineralogy compared to the more porous samples. Feldspars breakdown relatively easily by chemical and physical weathering. Mineralogically mature sandstones consist predominantly of quartz with very little feldspar. Sandstone dominated by quartz, has therefore, often undergone a higher degree of reworking or has been subject to higher energy conditions. Both of these processes are conducive to sorting. Porosity is controlled more by sorting than by grainsize (Selley, 1985). Well sorted fine-grained sandstones have much a much higher porosity than coarse grained, poorly sorted sandstones. This is most evident on comparison of the highly bioturbated and poorly sorted Rayner Sandstone and the very well sorted, channel facies of the Faulkner Group.

The Risdon Sandstone is prominent throughout the study area, with a thickness of usually 4m to 8m. So far, limited porosity measurements from outcrop have yielded consistently good results. The Minnie Point/Malbina Formation is also extensive throughout the study area, but becomes much thinner to the south. Well to moderately sorted sandstone units occur at the base and top of the formation. Porosity varies markedly between sandstone units, which are up to several metres in thickness.

Unlike its marine counterparts, the Faulkner Group is confined to the north of the study area. Alluvial correlates of the freshwater sequence are extensive in the northern portion of the Tasmania Basin (Martini and Banks, 1989). The mature mineralogy of the channel sand facies (figure 7.1) is further evidence that the unit has been deposited in a high energy environment. The coastal plain facies, within which, the coarse channel sand is found, consists primarily of very well sorted, fine to medium-grained sandstone. High primary porosity and permeability would therefore be expected. Alluvial correlates of the sandstone unit in the central and northern areas of the Tasmania Basin are also likely to be well sorted and thus have high primary porosity. Point bar facies are often laterally extensive, while braided streams often have a high degree of connectivity. These facies often grade or pinch-out into well consolidated

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siltstone and shale, thus providing stratigraphic traps for the accumulation of hydrocarbons (North, 1985).

The Bundella Formation has a consistent thickness throughout the study area. Sandstone units are usually graded and dominant in the upper and lowermost sections of the formation. Thus far, porosity has been found to be consistently fair to good. Fissile and non-fissile siltstone units dominate much of the lithology of the Bundella Formation. Fissile siltstone units exhibit a regular foliation parallel to bedding and are readily friable in outcrop. These units may therefore provide an alternative to sandstone reservoir units. Compact siltstone beds on either side of these units may represent potential seal rocks.

Readily identifiable potential reservoir units in the Deep Bay and Abels Bay Formations are rare. They consists predominantly of poorly sorted, sandy siltstone, with occasional interbedded sandstone. The 8m thick, coarse sandstone unit within the Jericho 1 core is an exception. Porosity is expected to be similar to that of the Risdon Sandstone. In outcrop the rock appears to be silicified, in core the cementing os not as pronounced. The unit can recognised on the foreshore at Cygnet and, is likely to be as extensive as the Risdon Sandstone.

7.5 Diagenesis of potential reservoirs

Risdon Sandstone

Thin section analysis of Risdon Sandstone samples (VB004, K008 and D005) indicates that the majority of porosity is secondary intergranular, resulting from the dissolution of minerals or organic material (Plate 3a). Primary intergranular porosity has been severely reduced by compaction and silica overgrowths on quartz grains. Partial dissolution of feldspars provides secondary, inter- and intragranular porosity

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(Plate 3a). Minor secondary mouldic porosity is also evident from the dissolution fossil material.

Several diagenetic events preclude primary porosity in the Risdon Sandstone. Silica overgrowths on quartz grains are well developed, often growing into adjacent grains. Many quartz-quartz grain contacts are angular, clay grain coatings are generally absent from these boundaries. Silica cementing of the Risdon Sandstone therefore occurred early, caused by pressure-solution at quartz-quartz grain contacts during early burial. At first, compaction produced the sutured texture between these grain contacts. Further burial, solution, and then re-precipitation, resulted in syntaxial silica overgrowths that further precluded porosity. Quartz overgrowths from this second phase of silica cementation are sometimes coated with authigenic clay, which, perhaps inhibited further growth of silica cement.

Smectite, identified by XRD analysis (VB004), occurs predominantly around feldspar grains, lithic clasts and immediately adjacent to grain boundaries. The clay is therefore, mostly authigenic, resulting from the partial dissolution of feldspar grains. Smectite can be formed from potassium feldspar by the dilution of waters with an initially high silica activity and low K^+/H^+ activity ratios (Velde, 1992). The inverse conditions are applicable to silica cement. Therefore, it is likely that the dissolution of feldspar was coincident with the second phase of silica precipitation. The formation of loose packing, authigenic cement and partial dissolution of feldspar has probably resulted in secondary porosity. Clay however, does not intrude into secondary, macroscopic pores, suggesting that dissolution of these grains occurred after the formation of smectite. The macropores are probably the result of decalcified fossil casts, caused by the relatively recent weathering by meteoric water. Figure 7.2 is summary of the diagenesis of the Risdon Sandstone.

Thin section porosity appears to be much less than measured core porosity. The precipitation of loosely packed authigenic clays from the dissolution of feldspar has therefore significantly increased intra- and intergranular porosity. Well developed

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silica overgrowths on tightly packed quartz grains and the lack of intrusive authigenic clay along these grain boundaries, suggests, that while porosity for the Risdon Sandstone is fair, permeability is probably low, having been severely degraded by the precipitation of authigenic silica cement.

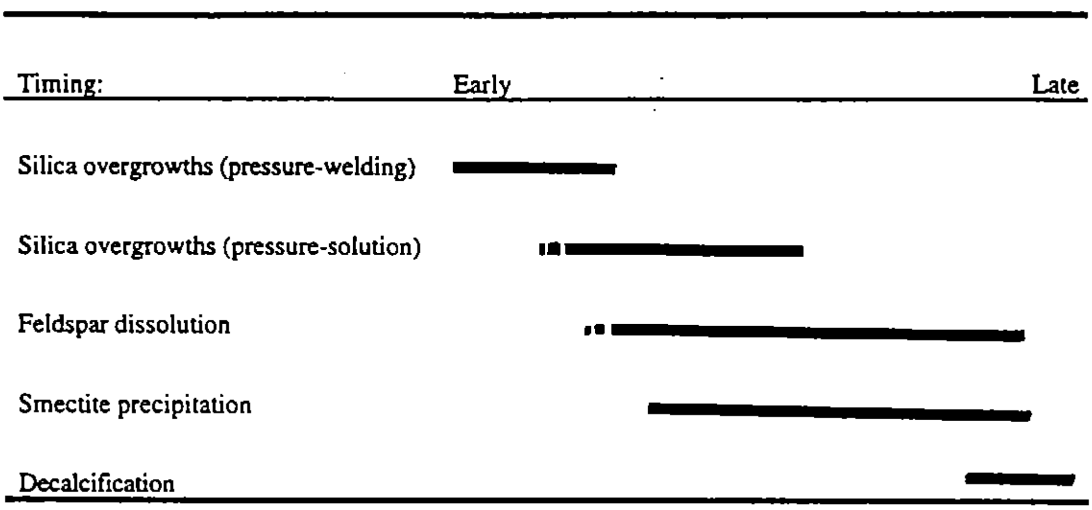

Figure 7.2 The relative timing of diagenetic events affecting porosity and permeability in the Risdon Sandstone.

Minnie Point Formation

Thin section porosity of the Minnie Point Formation is difficult to identify with an optical microscope. Sand-size grains are typically poorly sorted and mineralogy is relatively immature. The sandstone is matrix supported, consisting of very fine, silty, quartz, plagioclase and feldspar. There is minor macroscopic porosity in the form of fossil casts and remnant primary intergranular voids, but most of the latter have been intruded by clay. No intragranular porosity can be identified. Porosity within the Minnie Point Formation is therefore, due predominantly to the preservation of very fine primary intergranular pores between well sorted silt grains.

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Silica overgrowths on quartz grains are rare, this may be due to the presence of clay coatings on grain boundaries, which commonly inhibit the growth of these cements (He and Conaghan, 1994). Many of the quartz grains that do have silica overgrowths are probably reworked, this would explain the sporadic distribution of these features.

Fracture porosity due to microveining is evident in one sample (Plate 3b). Vein-filling minerals have been removed and iron oxide and clay minerals line either side. The infiltration of meteoric water has probably resulted in the dissolution of calcite, the introduction of iron and the weathering of adjacent feldspars and micas to clay. XRD analysis suggests that this is kaolinite and smectite.

The grain coating clay mineral is probably chlorite or smectite. Feldspar and mica dissolution is rare and suggests authigenic clay minerals formed from an influx of K^+ rich water. The diagenetic history of the Minnie Point Formation is relatively limited, a factor that may account for such a poorly sorted, fine grained unit having well preserved primary porosity. The brief diagenetic history of the Minnie Point Formation is summarised below (Figure 7.3).

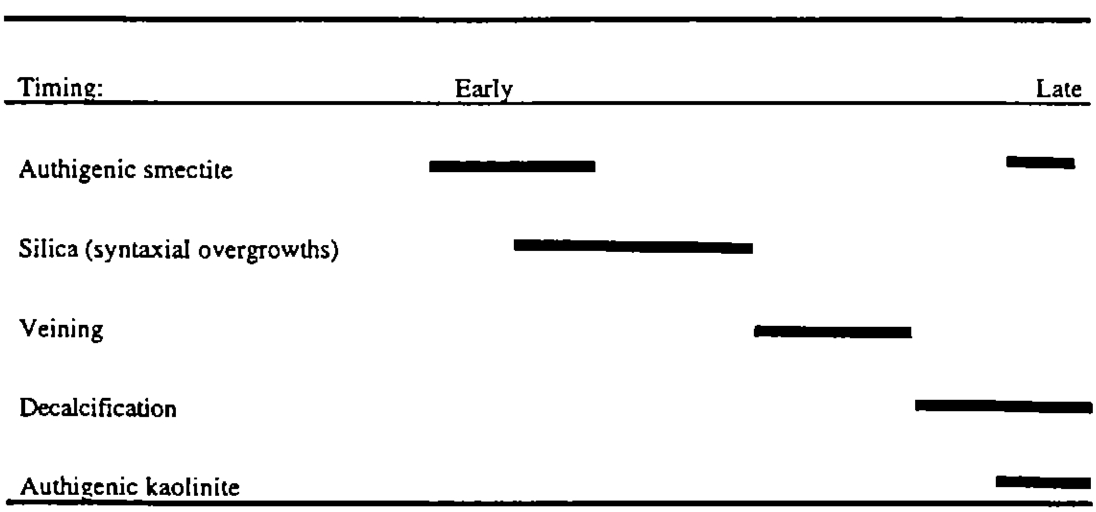

Figure 7.3 Summary of the major diagenetic events affecting the Minnie Point Formation.

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Rayner Sandstone

The very poor porosity determined for the Rayner Sandstone is due predominantly to its poor sorting (Plate 3c). The bioturbation of detrital clay and further compaction, evident by slight preferential alignment of grains, has further precluded any primary porosity. Quartz overgrowths and feldspar dissolution is very rarely observed. Low primary porosity and permeability has inhibited the flow of diagenetic fluids and the formation of authigenic minerals.

Faulkner Group

Most of the void space in the channel sandstone of the Faulkner Group is primary intergranular porosity (Plate 3d). Compaction and welding of quartz grains and silica overgrowths has precluded much of the primary intergranular porosity within this facies. This has resulted in a severe loss of permeability and also inhibited the mechanical intrusion of clay from these boundaries. Quartz-quartz contacts that do not exhibit angular, interlocking cementation are usually coated with thin clay coatings. The grain coating clays have inhibited further syntaxial growth, this is most evident around clays that coat primary pores (Plate 3d). Thus, the precipitation of clay has preserved some of the primary intergranular porosity of the sandstones. All interconnecting pores that have been preserved exhibit clay coating

The fine grained component of this unit is minimal and XRD analysis was therefore not deemed necessary. A diagenetic history is proposed as follows. The angular nature of some pores suggest that they have resulted from the dissolution of minerals. Some feldspar grains are highly weathered and show signs of dissolution. The facies interpretation of this unit as a tidal channel means the unit was subject to flushing by meteoric water and sea water, resulting in the removal of most detrital clays. Early burial and compaction led to pressure-welding of quartz grains. Soon after, an influx of meteoric water caused the dissolution of most feldspar grains and resulted in the precipitation of grain coating clay. The water was also rich in silica ions, but the

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formation of syntaxial silica overgrowths was inhibited to some degree by grain coating clays. Any feldspar that remained after deeper burial underwent some dissolution to form minor intragranular porosity. The paragenesis of this sandstone unit is summarised below (figure 7.4)

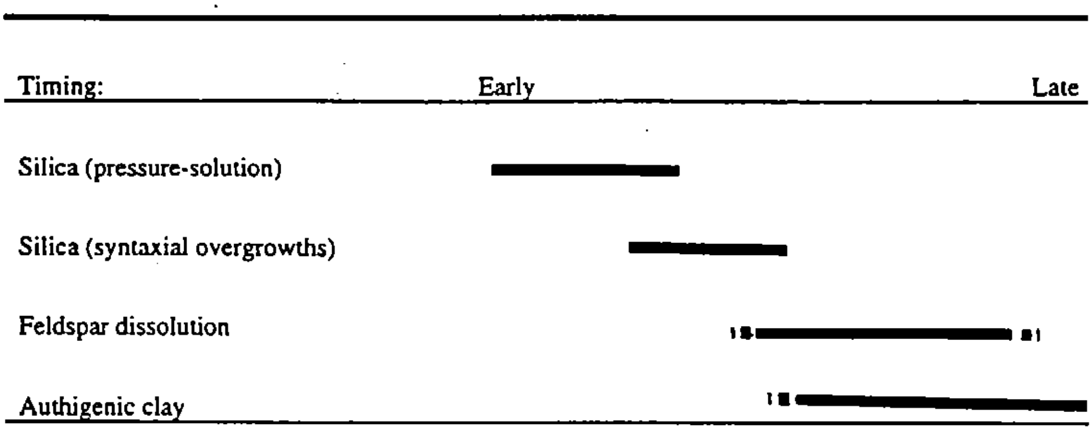

Figure 7.4 Paragenesis of the Faulkner Group channel sand facies.

Bundella Formation

Vuggy porosity is observed in outcrop and in drill core in various units of the Bundella Formation, notably the lowermost sandstone units (Plate 4a). At Mount Nassau, several rosette shaped moulds suggest that some vugs are the result of decalcified glendonites, however they are more commonly fossil moulds. Moulds are generally aligned horizontally, sand grains show some preferential orientation (Plate 4b). Disseminated pyrite is often observed filling a small portion of the mouldic porosity. Horizontal foliation is evident in the silty and clay component of the sediments by the distribution of dark brown clay and opaque minerals.

Clay minerals do not intrude into secondary porosity. Quartz overgrowths are absent or rare and feldspar dissolution is very limited. Grains of mica occasionally exhibit partial dissolution. Glauconite pellets form a small portion of most samples.

Observable porosity is thus, mouldic, with permeability seemingly controlled by foliation associated with bedding.

As previously mentioned (chapter 6.3), the Bundella Formation was deposited on a shallow, low energy marine shelf. The presence of pelletal glauconite, flat-lying bryozoa and horizontal foliation associated with an opaque mineral, probably pyrite, suggests that foliation in these rocks is caused by the laying down of sea-weed fronds which hosted the bryozoa. The precipitation of sulphides occurred by the reduction of organic material during very early burial. In outcrop, these units are apparent as fissile, fenestellid-rich, siltstone and sandstone. Pyrite has done little to affect porosity.

Deeper burial resulted in decarboxylation and the dissolution of remaining organic matter. This occurred only after early cementation, as evidenced by the lack of mechanically intruded clay within the secondary pores. A decarboxylation process is preferential to meteoric decalcification because of the lack of shallow forming diagenetic minerals (for example, kaolinite) found in the deeper core samples, also, calcareous unit conformably overly the vuggy intervals. Outcrop and shallow core samples, have however, had porosity enhanced by late stage decalcification.

Metamorphic induced porosity is also discounted. Porosity is usually considerably reduced by hydrothermal activity (Einsele *et al.*, 1980). The presence of impermeable, interbedded siltstone units, which also exhibit decarbonation, would prevent vertical fluid flow. Also, no evidence of vertical fluid flow was observed in thin section, most sediments of the Bundella Formation appear to have preferential horizontal permeability as indicated by laminated and fissile siltstone.

Quartz overgrowth and feldspar dissolution is rare and has probably been inhibited by the compaction of detrital clay and the silt matrix.

XRD analysis (appendix II) reveals the presence of a small percentage of kaolinite (<5%), this however, was only in a shallow core sample (G33.9), and not observed

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at deeper intervals. In thin section, partial dissolution of mica grains can be observed. Kaolinite is therefore a late diagenetic product resulting from the dissolution of mica by meteoric waters. A summary of the paragenesis of the Bundella Formation is illustrated in figure 7.5.

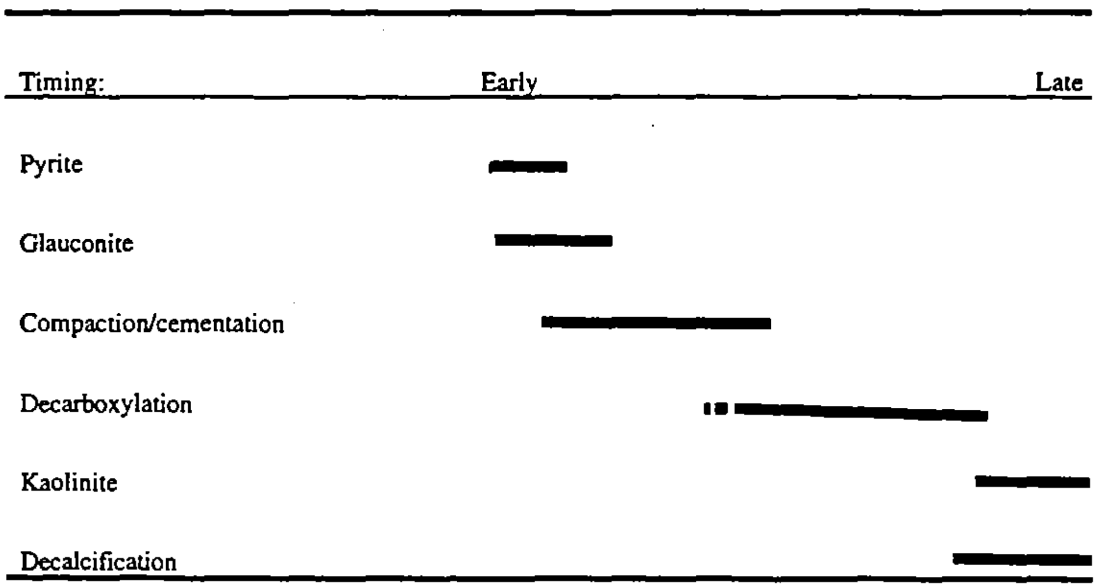

Figure 7.5 Paragenesis of sandstone in the Bundella Formation.

7.6 The effect of metamorphism on potential reservoir characteristics

Diagenesis usually results in a decrease in both porosity and permeability. Burial, due to the effects of time, temperature and compaction, therefore, reduces reservoir quality. Thus, porosity usually decreases markedly with depth. However, a plot of depth against measured core porosity for Shittim 1 show an inverse relationship (Figure 7.6)

This is not what would be expected, taking into account only depositional environment and diagenesis. Within the Shittim 1 and Jericho 1 DDHs, primary textural features are largely obscured by contact metamorphism. Primary and diagenetic minerals are altered to skarn and pyroxene hornfels mineral assemblages. It

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is therefore, the alteration of primary and diagenetic minerals by contact metamorphism that has resulted in the reduction of porosity in relation to proximity to a dolerite sill. Figure 7.6 is best interpreted as a cross-plot of porosity versus distance from thick dolerite sill.

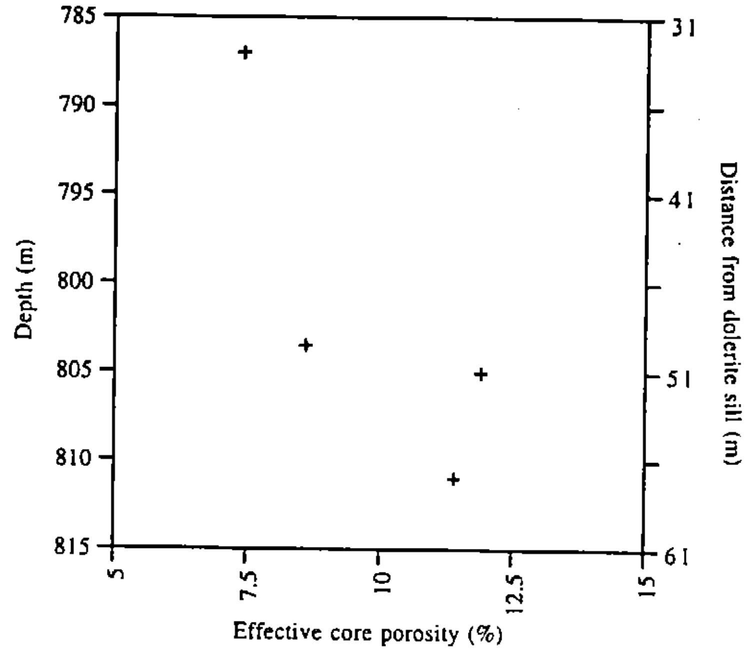

Figure 7.6 Cross-plot of porosity against depth for sandstone units of the Bundella Formation, Shittim 1, Bruny Island

Contact metamorphism has changed primary and diagenetic mineralogy and textures throughout the Lower Parmeener Supergroup. The process of metamorphic recrystallisation generally has the effect of increasing grain size and thereby infilling pores. As the data indicates (figure 7.6), the detrimental effect on porosity is most pronounced in proximity to the intrusion. Metamorphic grain-size generally increases towards the intrusion, this region experiences the highest temperatures over the greatest time and therefore, crystallisation is relatively slow, allowing more pronounced crystal growth.

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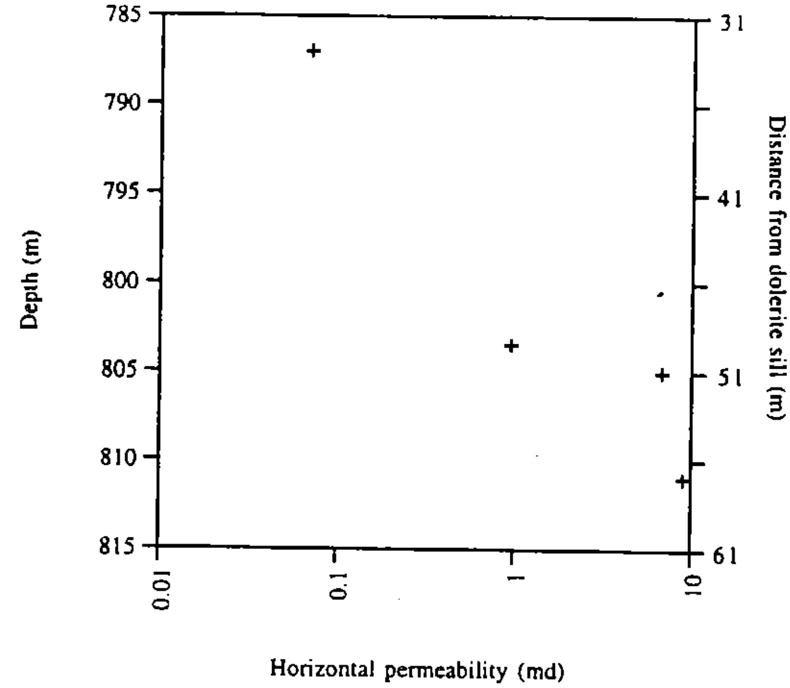

Figure 7.7 Cross-plot of horizontal permeability in sandstone units of the Bundella Formation against distance from a thick dolerite sill. Data from Shittim 1, Bruny Island.

While contact metamorphism has a detrimental effect on porosity, the reduction in permeability is even more severe. A cross-plot of horizontal permeability against distance from the igneous intrusion in Shittim 1 clearly demonstrates an exponential decrease in permeability in proximity to the sill. In thin section, the effect of metamorphic alteration is most evident by the interlocking growth of minerals in secondary pores, for example, the formation of wollastonite 'needles' within fossil moulds has not only reduced porosity, but almost totally destroyed permeability (Plate 4c).

After cooling, metamorphic minerals that rim voids may prevent further reduction in porosity due to compaction or diagenesis (Plate 4c). Permeability is, however, unlikely to be changed, the detrimental effects of metamorphism on reservoir properties can therefore, for all practical purposes, be considered irreversible.

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7.7 *Fracture porosity and permeability*

Fractures, where not filled by hydrothermal or diagenetic minerals may provide significant porosity. Most commonly however, the importance of fractures is associated with permeability (North, 1985). Faults and fractures may provide fluid pathways for petroleum to migrate from source sediments to reservoir rocks, they may also enable hydrocarbons to escape from reservoirs to the surface. Petroleum seeps in the Tasmania Basin have been associated with faults, lineaments and earthquakes (Bendall *et al.*, 1991).

The Woody Island Formation and Truro Tillite are often observed to be highly fractured in outcrop (for example, at Cygnet). It has previously been suggested that these fractured units are potential reservoirs (Bendall, 1990). The Woody Island Formation and Bundella Formation and highly fractured in the Shittim 1 core. Brittle fractures within the Bundella Formation are sub-vertical and typically unsealed, although carbonate and pyrite filling is not uncommon. In the Bruny Island, Shittim 1 core, the Woody Island Formation is highly brecciated in places. Occasionally the breccias are well consolidated, exhibiting a fine siltstone-mudstone matrix with clasts of angular siltstone. More often, brecciated siltstone is poorly consolidated and is readily friable on weathering. Both the consolidated and unconsolidated breccia are probably associated with faulting.

Plate 4d is a photomicrograph of a consolidated breccia within the Woody Island Formation from the Shittim 1 core. A high degree of porosity (>10%) is exhibited by loosely packed clay minerals. Pores are well connected, thus permeability is also good. Fault breccias and fractures may therefore have been the conduit for the gas recorded in the Shittim 1 drill hole.

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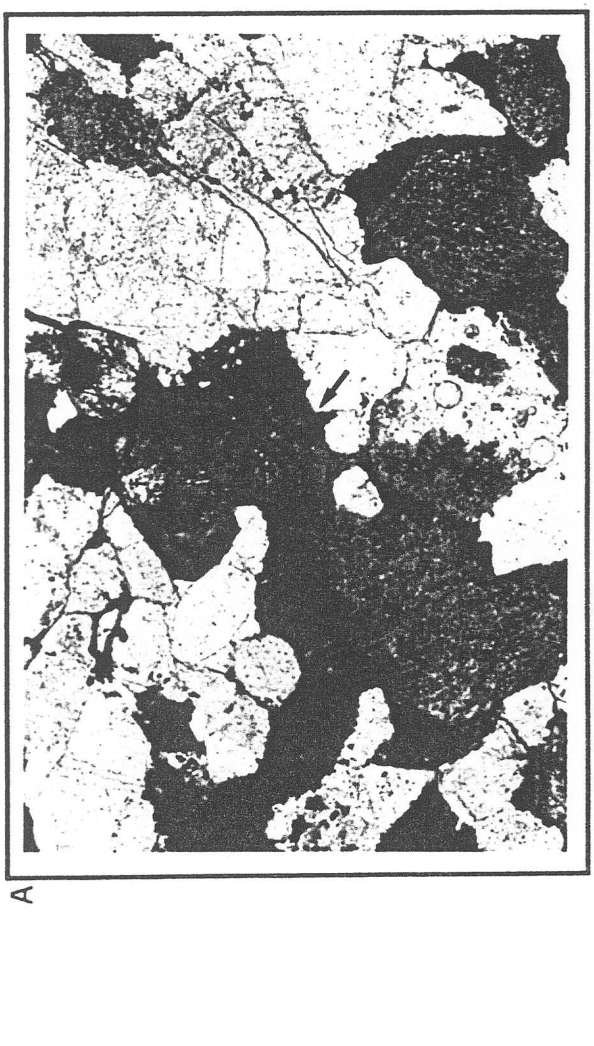
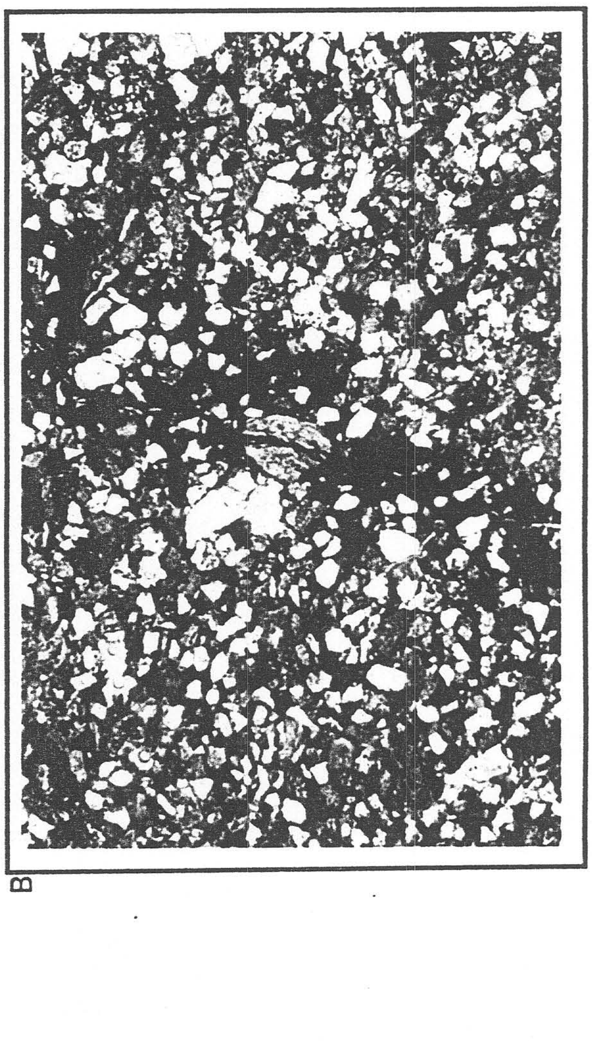
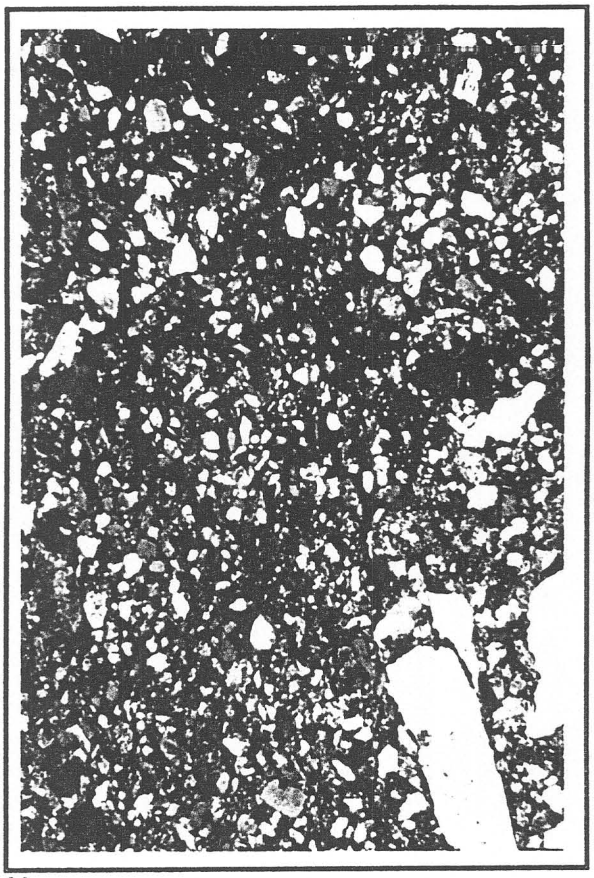


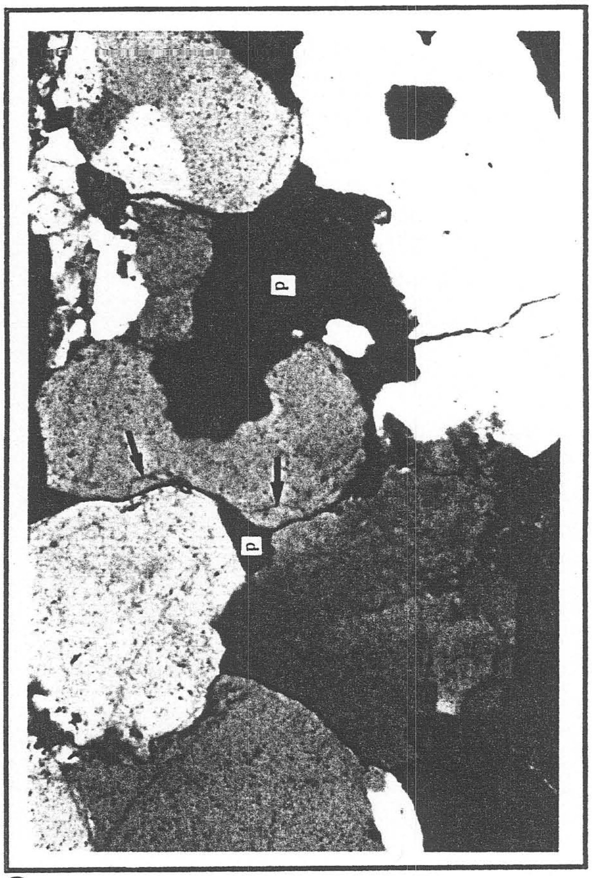
A



B



C



D

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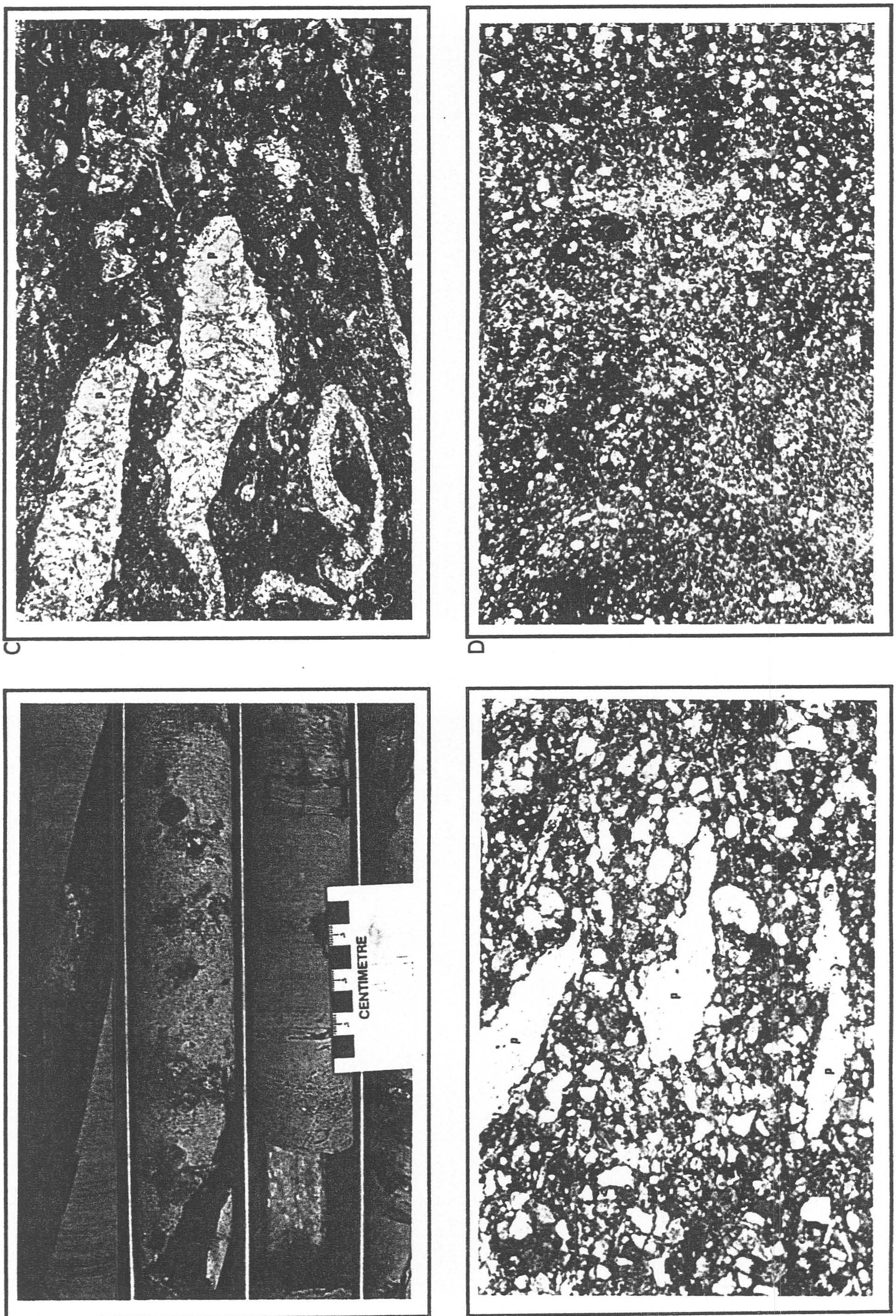

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7.8 Comparison to Australian reservoirs

In order to put the results of reservoir analysis into context with producing petroleum provinces, a brief comparison is required.

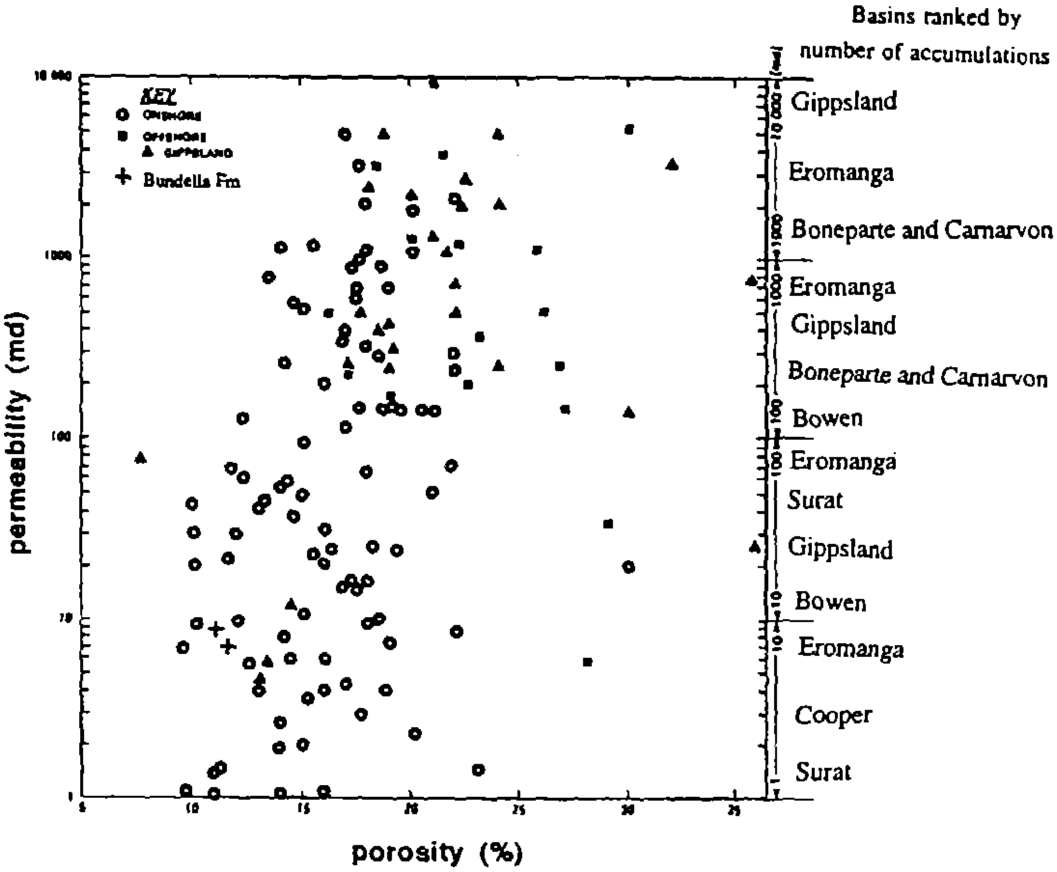

Figure 7.8 Comparison of reservoir characteristics of producing Australian oil and gas fields with potential reservoirs of the Bundella Formation (modified from Miyazaki, 1989).

Porosity and permeability data from the Bundella Formation of Tasmania compares favourably to other onshore Australian oil and gas fields (figure 8.1). Characteristics most closely match reservoirs of the Permian, Cooper Basin in South Australia and the overlying Eromanga Basin of South Australia and Queensland. The Cooper Basin and Tasmania basin share many characteristics, so the similarities in reservoir parameters is not surprising.

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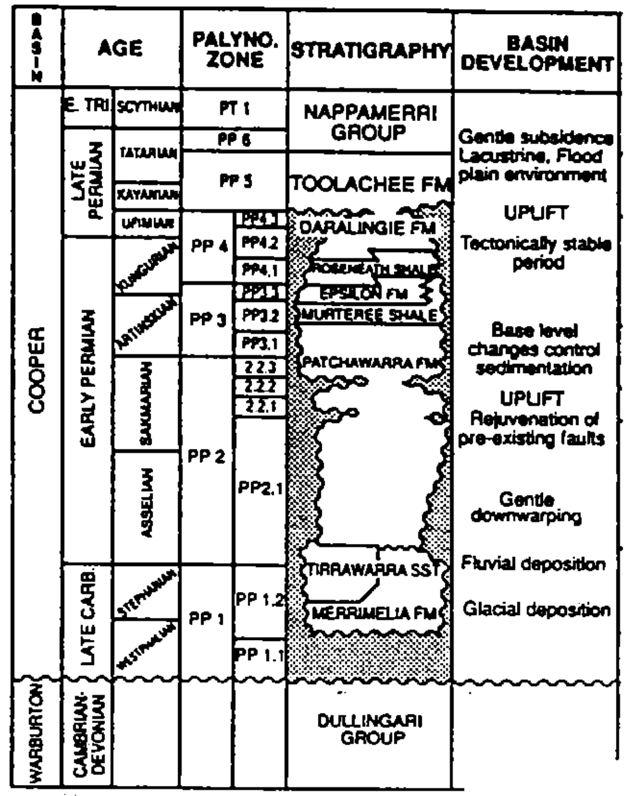

Figure 7.9 Stratigraphic relationships in the Cooper Basin (Apak *et al.*, 1993)

The lowermost units exhibit the most similarities in facies. As in the Tasmania Basin, glacial sediments are overlain by a fluvial sequence. The Tirrawarra Sandstone of the Cooper Basin was deposited in a braided stream environment (Apak *et al.*, 1993). Fine to medium-grained sandstone is interbedded with channel conglomerates, minor shales and coal. It is the primary Permian oil reservoir in the basin. The facies of the Tirrawarra Sandstone is similar to that of the "Lower Freshwater Sequence" of Tasmania, particularly further north from the study area where the intertidal sequences of the Faulkner Group grade into wholly freshwater sediments (Martini and Banks, 1989).

Average porosity in the Tirrawarra Sandstone is 13%, very comparable to 12.8% observed in the channel sandstone of the Faulkner Group. The similarities in porosity are likely to be due to similar depositional environments and diagenesis. The main porosity precluding event in both formations is silica cementing, first by compaction and then further overgrowth due to solution (Wild, 1986). In both formations

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porosity has been enhanced by the dissolution of labile grains. The similarities in depositional environments and porosity demonstrates the importance of environmental setting and diagenesis on reservoir characteristics. The aim of this comparison however, was merely to show that reservoir qualities of the Tasmania Basin sediments are similar to those of developed petroleum provinces.

Discussion and Conclusions 8

The results of thermal modelling indicate that the sediments of the Lower Parmeener Supergroup, particularly those of the Woody Island Formation and the Truro Tillite, are likely to lie within or close to the base of the oil window. Whether these sediments have generated hydrocarbons will depend on the type and amount of organic carbon within the sediments and the depth of burial at various locations. This is a factor of Parmeener Supergroup thickness and post-Triassic cover. The most favourable regions for generation of hydrocarbons from the lowermost units of the Parmeener Supergroup are those that have undergone the deepest burial. That is, the deepest locations of the palaeo-Tasmania Basin, coupled with a maximum thickness of Cenozoic overburden, the later may be found within graben centres. Hydrocarbons are not likely to have been generated from the Lower Parmeener Supergroup until late in the basin history, therefore, potential reservoir and seal rocks of the Permian would have already been emplaced and may have trapped oil or gas.

Considering the Gordon Limestone as a source rock for petroleum, the locations of deepest burial are likely to have resulted in premature maturation and consequently, in the loss of hydrocarbons at the surface. It is very likely that the Gordon Limestone has passed into the oil and gas windows and generated petroleum at some stage, given suitable source rock potential. Within the oil and gas windows, the results of thermal modelling for the base of the Gordon Limestone using maximum and minimum geothermal scenarios gave similar results for the timing of potential hydrocarbon generation. This indicates that burial depth has been more important in determining the thermal maturity of the Gordon Limestone than prevailing geothermal gradients. This is not true of the Woody Island Formation, where geothermal history is the dominant factor due to much shallower burial depths. Rapid burial prior to high mid-Devonian heat flow is not conducive to the preservation of hydrocarbons. Potential Ordovician source rocks are most likely to be generating hydrocarbons where burial has not been extreme. This may include a large area of southern Tasmania as the pre-Parmeener Supergroup geology is relatively unknown. The migration of gas up-dip from the west, or via fractures in siltstone and tillite below, from an Ordovician (or other) source is one explanation for the gas encountered in Shittim 1.

The intrusion of dolerite has a number of implications for petroleum generation. Any hydrocarbons that have been generated and trapped prior to the igneous intrusion will be destroyed to a distance within approximately one third of the sill thickness. Cooling of a large igneous intrusion heats the sediments in which it is hosted. After a period of time, geothermal gradients will decrease, previously immature sediments may be heated for prolonged periods at temperatures within the oil and gas windows. Within the Parmeener Supergroup, this mechanism is most likely to produce gas from organic-rich rocks. This process may have been responsible for the generation of gas discovered in Shittim 1. Heating from igneous intrusions has enhanced hydrocarbon generation in known producing oil and gas fields. The heating of host sediments and additional burial due to thick dolerite intrusions may therefore, be a significant factor in enhancing the thermal maturity in marginally mature potential source rocks of the Lower Parmeener Supergroup.

Several potential reservoirs are available in the Lower Parmeener Supergroup, they include the sandstone units of the Bundella Formation, Faulkner Group, Minnie Point Formation, Risdon Sandstone and possibly the Abels Bay Formation. Porosity for these units varies from fair to good. Depositional environment is the main control on primary porosity. High energy environments are conducive to sorting and therefore offer the prime conditions for primary intergranular porosity. Locally, metamorphism has had severe effects on primary porosity and permeability. Increasing grain size and interlocking textures have resulted in a decrease in porosity and severe loss of permeability.

Diagenesis of potential sandstone reservoirs has also significantly reduced primary porosity. Silica solution and precipitation has had the most detrimental affect. The formation of authigenic clay by the dissolution of feldspar or influx of water has created minimal intragranular porosity. More important than this, is the degree to which authigenic clay has inhibited silica cementing. The process of decarboxylation has significantly increased mouldic porosity in the Bundella Formation. Decalcification by meteoric waters has only recently enhanced the porosity of most potential reservoir units that appear in outcrop. Some fracture porosity is evident in the sandstone units, although it is more significant in the Woody Island Siltstone, which has little primary porosity.

Reservoir characteristics and diagenesis of sandstone units in the Parmeener Supergroup are not unlike that of other known petroleum producing provinces. Permian glacio-marine sandstones have similar porosity and permeability to Permian sandstones of the Coopers Basin, South Australia. Therefore, with potential source rocks identified, potential reservoirs available, and a suitable thermal history, there is every reason to believe that onshore Tasmania is prospective for petroleum.

Identifying structures and traps beneath thick dolerite sills has proved troublesome. Therefore good stratigraphic control is needed to recognise subsurface structure. To further validate thermal models, maturity measurements are needed from various localities and stratigraphic levels. Models may then be further refined in order to identify regions of mature source rocks. Data on porosity and permeability of potential reservoirs could be much expanded so that regional, stratigraphic and diagenetic trends can be distinguished. In summary, the data so far presented is encouraging. Further exploration and study can only add to the geologic database.

References

ACS Laboratories 1995a. Routine core analysis report of Bruny Island cores for Great Southland Minerals. ACS Laboratories Pty. Ltd.

ACS Laboratories 1995b. Routine core analysis report of Faulkner Group sample 11a for Great Southland Minerals. ACS Laboratories Pty. Ltd.

ACS Laboratories 1995c. Routine core analysis report of southern Tasmania samples for Great Southland Minerals. ACS Laboratories Pty. Ltd.

Allison, M. L. & Hulen, J. B. 1990. Oil and igneous intrusions in Nevada. *AAPG Bulletin* **74.**(8) 1313.

Apak, S. N., Stuart, W. J. & Lemon, N. M. 1993. Structural-stratigraphic development of the Gidgealpa-Merrimelia-Inamincka trend with implications for petroleum trap styles, Cooper Basin, Australia. *APEA Journal* **27** 94-103.

Bacon, C. A. 1986. The coal resources of Tasmania. *Newcastle symposium on Advances in the study of the Sydney Basin*, Newcastle, 4-6

Banks, M. R., and Clarke, M.J. 1987. Changes in the geography of the Tasmania Basin in the Late Paleozoic. *In* G. D. McKenzie Ed. *Gondwana six; stratigraphy, sedimentology and palaeontology*, American Geophysical Union.1-14

Banks, M. R. & Hale, G. E. 1957. A type section of the Permian system in the Hobart area, Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* **91** 41-64.

Banks, M. R., Hale, G. E. A. & Yaxley, M. L. 1955. The Permian rocks of Woody Island, Tasmania. *The Papers and Proceedings of the Royal Society of Tasmania* **89** 218-230.

Bendall, M. 1990. Conga Oil, annual report to Tasmania Department of Mines. Tasmania Department of Mines.

Bendall, M. R., Volkman, J.K., Leaman, D.E., Burrett, C.F. 1991. Recent developments in the exploration for oil in Tasmania. *The APEA Journal* 74-84.

Bendall, M. R. 1992. Permian petroleum potential-onshore Tasmania and 1992 drilling proposals. Conga Oil Pty. Ltd.

Berry, R. F. & Banks, M. R. 1985. Striations on minor faults and the structure of the Parmeener Supergroup near Hobart, Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* **119** 23-29.

Bischoff, J. L., Fitzpatrick, J.A., Rosenbauer, R.J. 1993. The solubility and stabilisation of ikaite from 0 degrees to 25 degrees C; environmental and paleoclimate implications for thinolite tufa. *Journal of Geology* **101.**(1) 21-33.

Botrill, R. S. 1995. Unpublished report...Petrographic examination of rocks from the Shittim 1 DDH, Variety Bay, Bruny Island. Tasmania Department of Mines.

Brill, K. G. 1982. Palaeo-environment of the Darlington Limestone (early Permian), Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* **116** 67-84.

Burrett, C. F. 1992. Conodont geothermometry in Palaeozoic carbonate rocks of Tasmania and its economic implications. *Australian Journal of Earth Sciences* .(39) 61-66.

Campbell, D. P. 1992. Environments of deposition of the Quamby Mudstone. Senior Program Thesis,Hamilton College, Clinton, NY

Clarke, M. J., Forsyth, S.M., Bacon, C.A., Banks, M.R., Calver, C.R., Everard, J.L. 1989. Late Carboniferous-Triassic. *In* C. F. M. Burrett, E.L. Ed. *Geology and mineral resources of Tasmania*, Geological Society of Australia.293-338

Council, T. C. & Bennet, P. C. 1993. Geochemistry of ikaite formation at Mono Lake, California; implications for the origin of tufa mounds. *Geology* **21.**(11) 971-974.

Denwer, K. 1986. Geology and geochemistry of the tasmanite oil shale. Honours Thesis,University of Tasmania

Domack, E. W. 1995. Comment on "Hydrocarbon biomarkers, thermal maturity, and depositional setting of tasmanite oil shales from Tasmania, Australia" by Revill, A.T., Volkman, J.K., O'leary, T., Summons, R.E., Boreham, C.J., Banks, M.R., Denwer, K. *Geochimica et Cosmochima Acta* **59.**(11) 2393-2395.

Domack, E. W., Burkley, L. A. & Domack, C. R. 1993. Facies analysis of glacial marine pebbly mudstones in the Tasmania Basin: Implications for regional paleoclimates during the late Paleozoic. *Gondwana Eight; Assembly, evolution and dispersal*, Hobart, Tasmania, Balkema.471-484

Einsele, R., Gieskes, J.M., Curray, J., Moore, D.M., Aguayo, E., Aubry, M-P., Fornari, D., Guerrero, J., Kastner, M., Kelts, K., Lyle, M., Matoba, Y., Molina-Cruz, A., Niemitz, J., Rueda, J., Saunders, A., Schrader, H., Simoneit, B., Vacquier, V., 1980. Intrusion of basaltic sills into highly porous sediments, and resulting hydrothermal activity. *Nature* **283.**(31 January) 441-445.

Ellis, D. 1974. The petrology of the Risdon Sandstone. Honours thesis Thesis,University of Tasmania

Esposito, K. J., Whitney, G 1995. Thermal effects of thin igneous intrusions on diagenetic reactions in a Tertiary Basin of southwestern Washington. U.S. Geological Survey.

Ezat, H., Gary, B., Darrell, H., Barh, D 1994. Enhanced hydrocarbon maturation by igneous intrusions; Smackover Formation, north east Louisiana. *Geological Society of America, 1994 annual meeting*, Seattle, GSA, Boulder, CO.231

Farmer, N. 1985. Kingborough. Tasmania Department of Mines.

Farmer, N. & Clarke, M. J. 1985. A diamond drill hole at Little Peppermint Bay, Woodbridge. Tasmania Department of Mines.

Green, D. C. 1989. Heat flow and heat production in Tasmania. *In* C. F. M. Burrett, E.L. Ed. *Geology and mineral resources of Tasmania*, Geological Society of Australia.461-463

Hand, S. J. 1993. Palaeogeography of Tasmania's Permo-Carboniferous glacigenic sediments. *Gondwana Eight; Assembly, evolution and dispersal*, Hobart, Tasmania, Balkema.459-469

He, F. & Patrick, J. C. 1994. Diagenesis of Jurassic and Lower Cretaceous sandstones of the Eromanga Basin in New South Wales. *Journal of Australian Geology and Geophysics* **15.**(2) 191-215.

Hills 1995. Basin inversion in the Late Cretaceous;results from apatite fission track dating. *Geological Society of London* **in press**

Hunt, J. M. 1979. *Petroleum geochemistry and geology* San Francisco, Freeman.

Jaeger, J. C. 1965. Application of the theory of heat conduction to geothermal measurements. *In Terrestrial heat flow*, 8.American Geophysical-23

Jansen, J. H. F., Woensdregt, C.F., Kooistra, M.J., van der Gaast, S.J. 1987. Ikaite pseudomorphs in the Zaire deep-sea fan: an intermediate between calcite and porous calcite. *Geology* **15** 245-248.

Katz, B. J., Liro, L.M., Lacey, J.E., White, H.W. 1982. Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration. *AAPG Bulletin* **66** 1150-1151.

Leaman, D. E. 1976. Hobart. Tasmania Department of Mines.

Leaman, D. E. 1990. Inferences concerning the distribution and composition of pre-Carboniferous rocks in southeastern Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* **124.**(1) 163-174.

Leaman, D. E., Baillie., P.W., Powell., C.McA 1994. Precambrian Tasmania: a thin-skinned Devil. *Exploration Geophysics* **25** 19-23.

Martin, N. K. 1986. Environment of deposition of the Bundella Mudstone. Honours Thesis,University of Tasmania

Martini, I. P., Banks, M.R. 1989. Sedimentology of cold-climate, coal bearing, Lower Permian "Lower Freshwater Sequence" of Tasmania. *Sedimentary Geology* **64** 25-41.

McDougall, I. 1961. Determination of the age of a basic igneous intrusion by the potassium-argon method. *Nature* **190** 1184-1186.

Miyazaki, S. 1989. Characterisation of Australia's oil fields by fluid and reservoir properties and conditions. 287-297.

Mulready, J. 1992. An evaluation of the oil and gas potential of Tasmania. Questa Australia Pty. Ltd.

North, F. K. 1985. *Petroleum geology* First. London, Allen and Unwin.

O'Leary, T. 1987. Maturity of five early Palaeozoic samples. Amdel Ltd.

O'Sullivan., A. J. 1994. Apatite fission track thermochronology of northeastern Tasmania and the southern Bass Basin. *Contentious issues in Tasmanian geology: a symposium*, University of Tasmania, Geological Society of Australia.109-110

Palacas, J. G. 1984. *Petroleum geochemistry and source rock potential of carbonate rocks* Tulsa, Oklahoma, AAPG.

331107

Pollington, M. 1974. The Berriedale Limestone. Honours Thesis,University of Tasmania

Rao, P. & Green, D. C. 1982. Oxygen and carbon isotopes of Early Permain cold-water carbonates, Tasmania, Australia. *Journal of Sedimentary Petrology* **52.**(4) 1111-1125.

Rejebian, V. A., Harris, A.G., Huebner, J.S. 1987. Conodont color and textural alteration: an index to regional metamorphism, contact metamorphism, and hydrothermal alteration. *Geological Society of America Bulletin* **99** 471-467.

Revill, A. T., Volkman, J.K., O'leary, T., Summons, R.E., Boreham, C.J., Banks, M.R., Denwer, K. 1994. Hydrocarbon biomarkers, thermal maturity, and depositional setting of tasmanite oil shales from Tasmania, Australia. *Geochimica et Cosmochima Acta* **58.**(18) 3803-3822.

Revill, A. T., Volkman, J.K., O'leary, T., Summons, R.E., Boreham, C.J., Banks, M.R., Denwer, K. 1995. Reply to comment by E.W.Domack on "Hydrocarbon biomarkers, thermal maturity, and depositional setting of tasmanite oil shales from Tasmania, Australia". *Geochimica et Cosmochima Acta* **59.**(11) 2397-2399.

Selley, R. C. 1985. *Elements of petroleum geology* First. New York, W.H. Freeman and Company.

Suess, E., Balzer, W., Hesse, K.F., Muller, P.J., Ungerer, C.A., Sefer, G. 1982. Calcium carbonate hexahydrate from organic-rich sediments of the Antarctic shelf: precursors of glendonites. *Science* **216** 1128-1130.

Summons, T. G. 1981. Preliminary report on petroleum potential-onshore Tasmania. The Northwest Bay Co. Pty. Ltd.

Sutherland, F. L. 1977. Zeolite minerals in the Jurassic dolerites of Tasmania: their use as possible depth indicators of burial depth. *Journal of the Geological Society of Australia* **24.**(3) 171-178.

Velde, B. 1992. *Introduction to clay minerals; chemistry, origins, uses and environmental significance* London, Chapman and Hall.

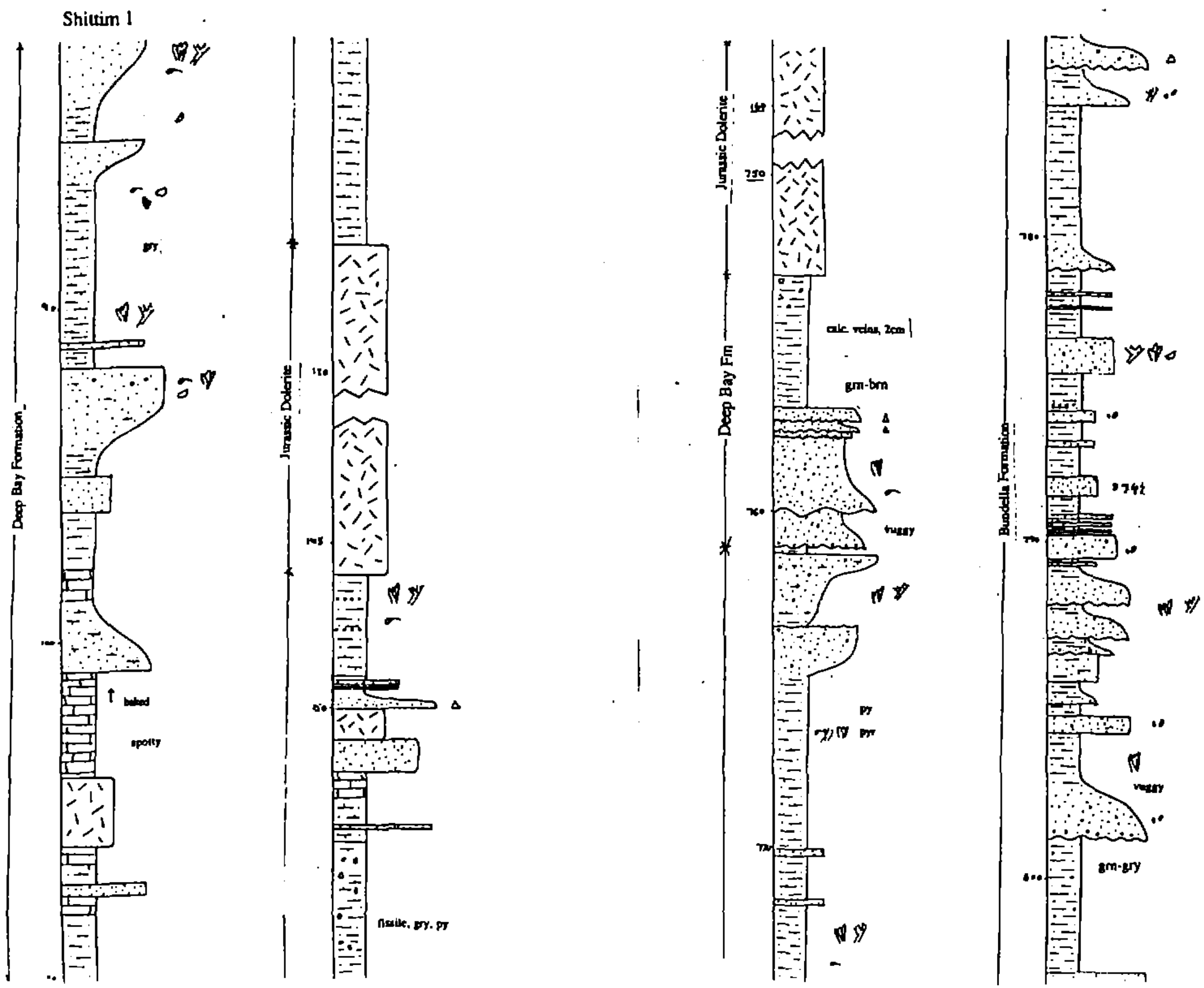
Waples, D. W. 1985. *Geochemistry in petroleum exploration* First. Boston, IHRDC.

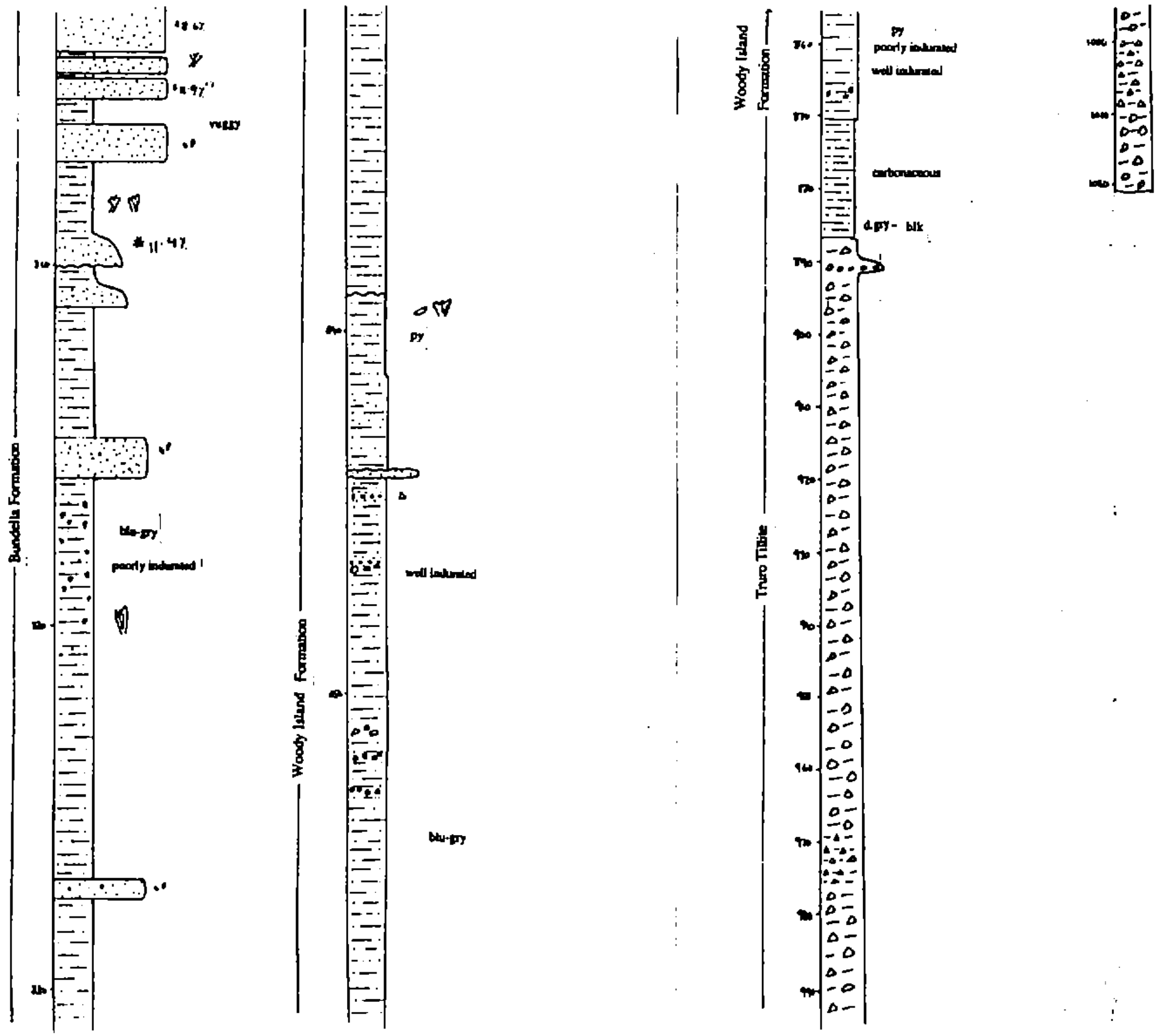
Wellman, P. 1987. Eastern highlands of Australia; their uplift and erosion. *BMR Journal of Australian Geology and Geophysics* **10** 277-286.

Wild, E. K. 1986. Subsurface evaluation of a fluvioglacial sandstone reservoir, Cooper Basin, S.A. *Sediments down-under, 12th international sedimentological congress,* Canberra, BMR.331

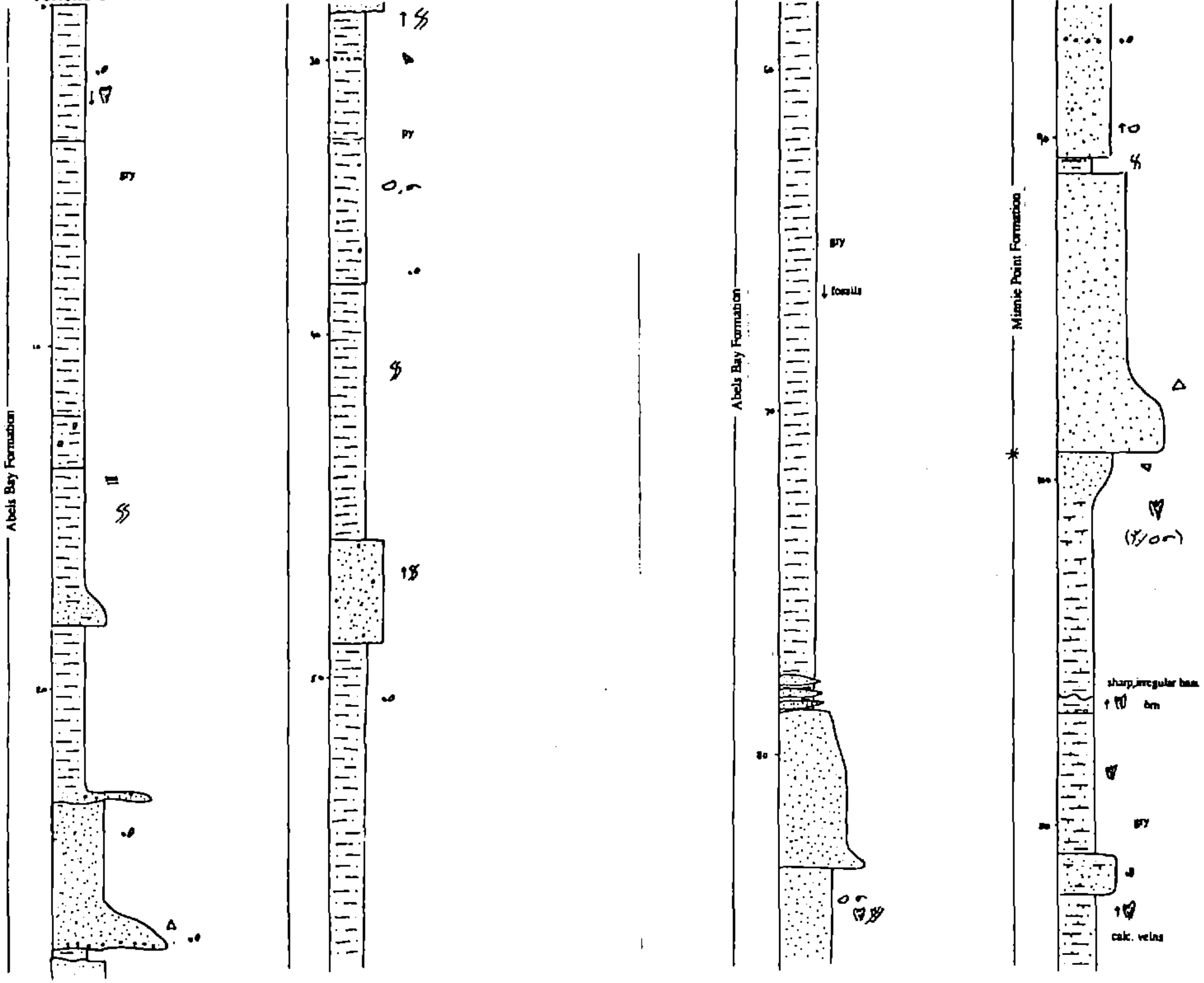
Willink, R. J. 1974. A palaeoecological analysis of the faunas in Member E, Malbina Siltstone and Sandstone, Permian, S.E. Tasmania. Honours Thesis,University of Tasmania

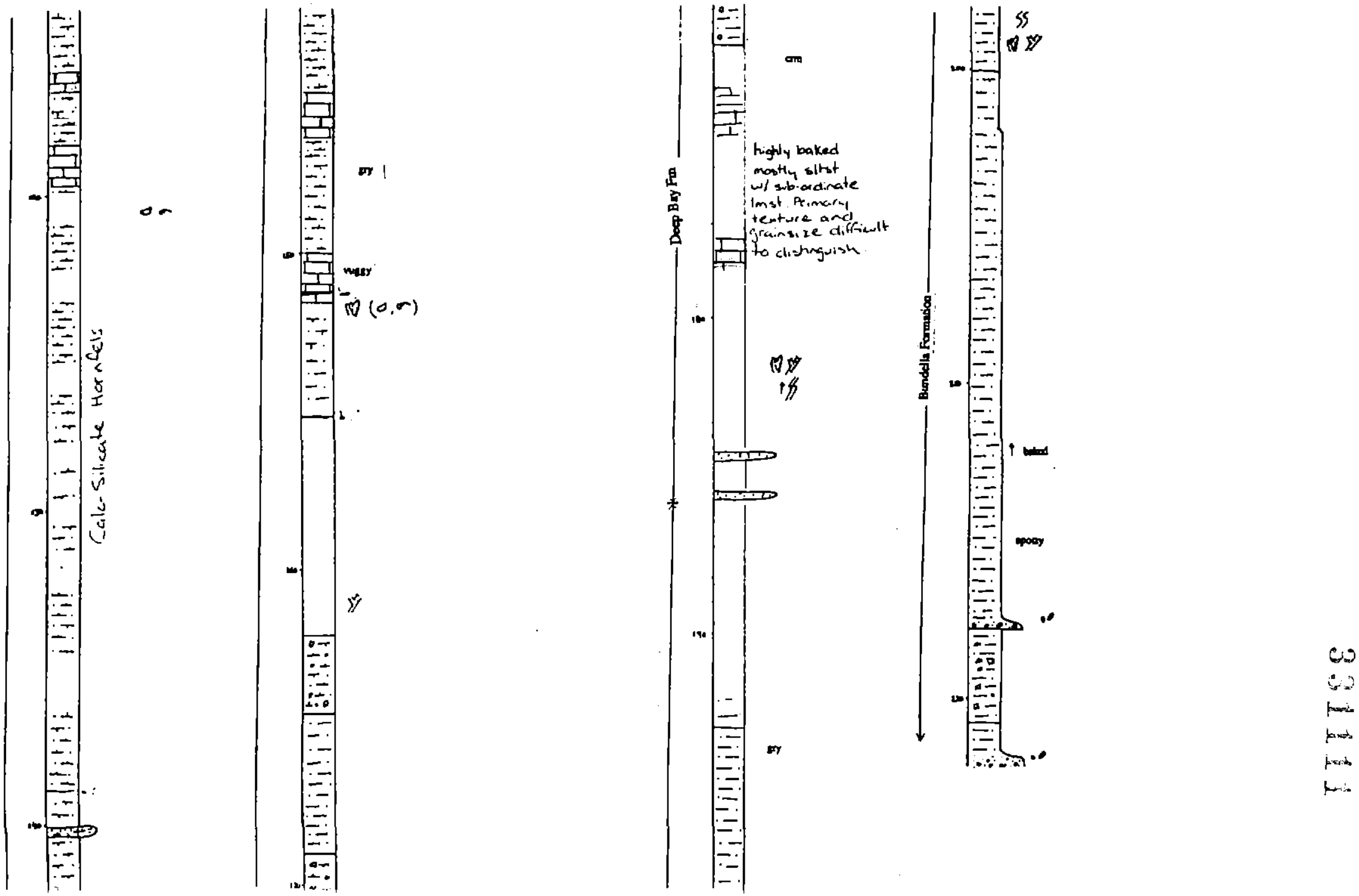
APPENDIX I: Detailed stratigraphic logs

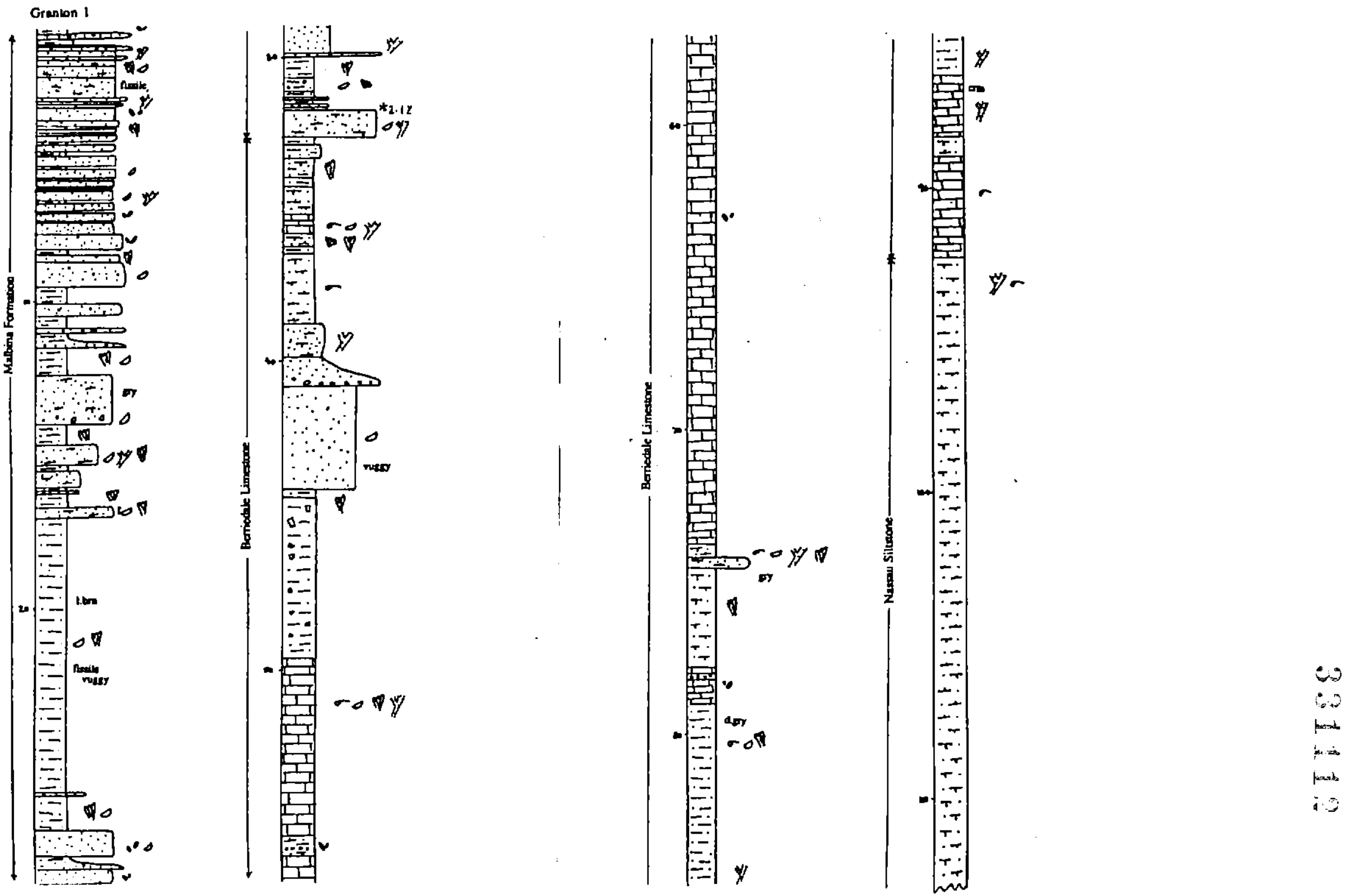



Bundella Formation
vuggy
blu-gry
poorly indurated
Woody Island Formation
py
well indurated
blu-gry
Woody Island Formation
py
poorly indurated
well indurated
carbonaceous
d.gry - blk
Truro Tillite

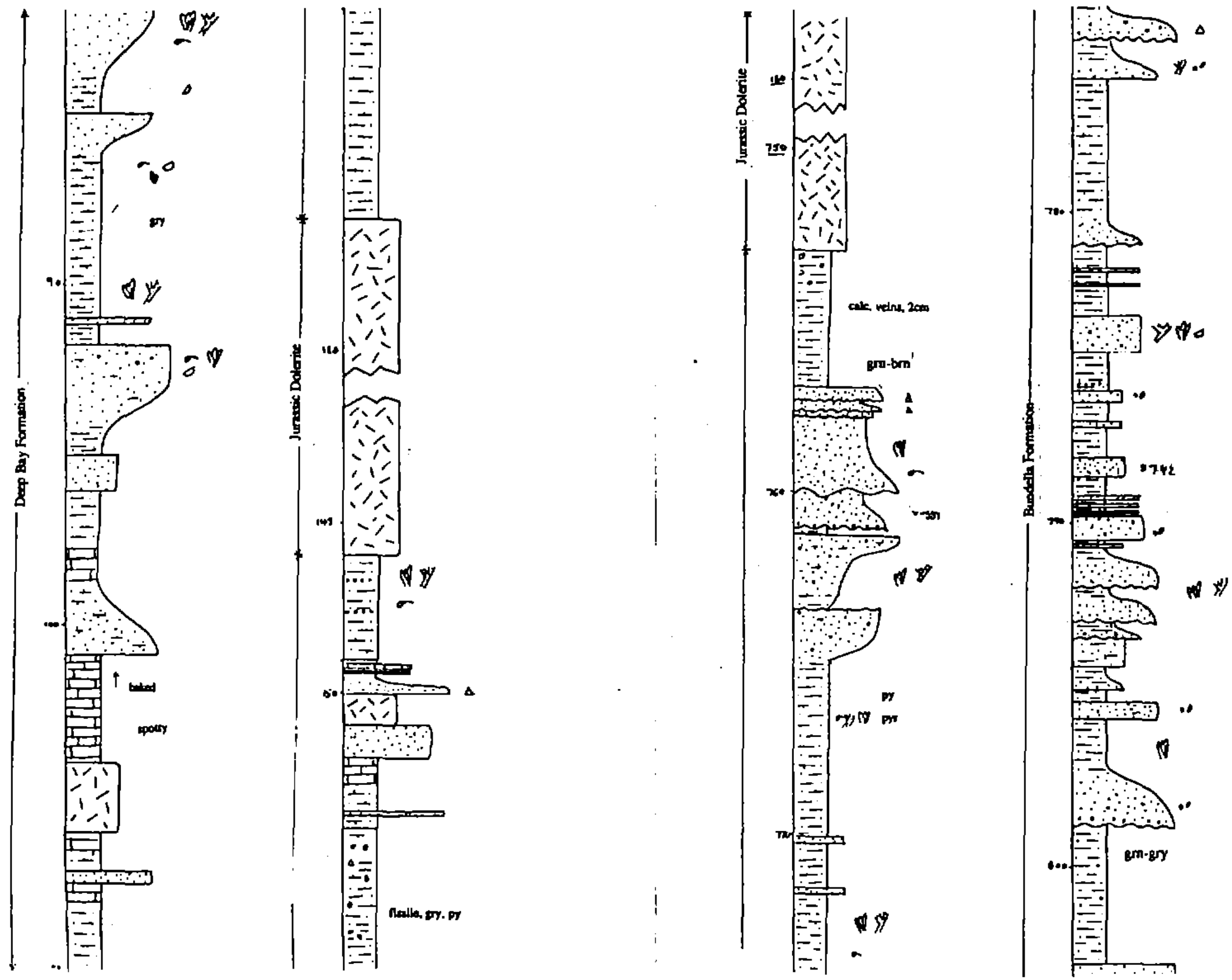
Jericho 1

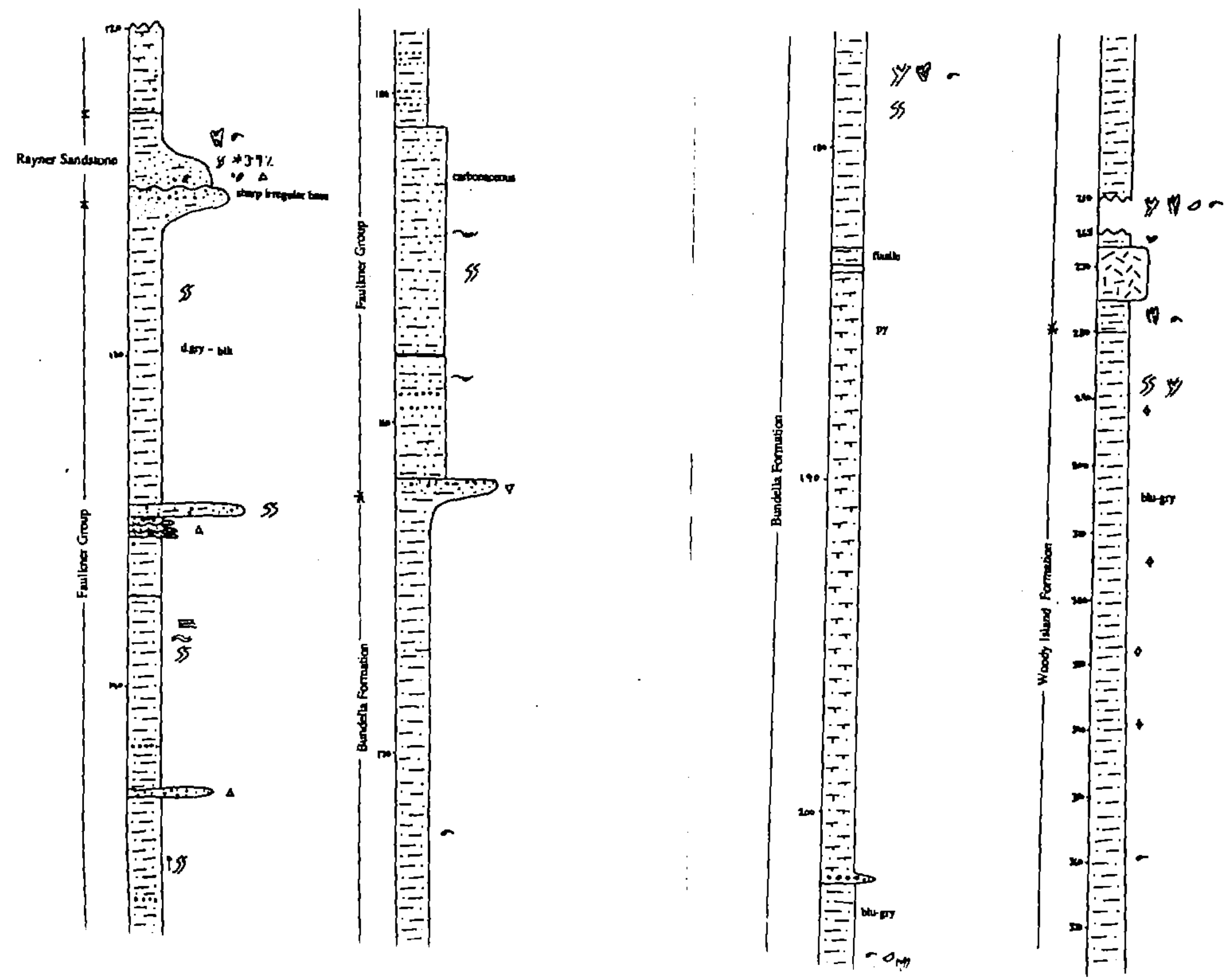

Abels Bay Formation
gry
Abels Bay Formation
gry
fossils
Minnie Point Formation
sharp,irregular base
brn
gry
calc. veins


Calc-Silicate Hornfels
gry
vuggy
cm
highly baked mostly sltst w/ sub-ordinate lmst. Primary texture and grainsize difficult to distinguish.
Deep Bay Fm
gry
Bundella Formation
baked
spotty

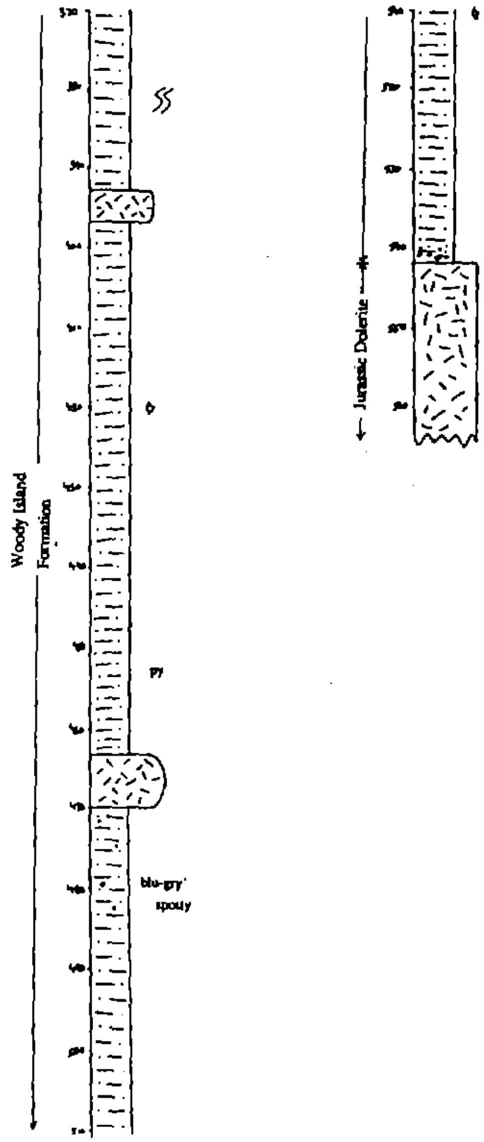


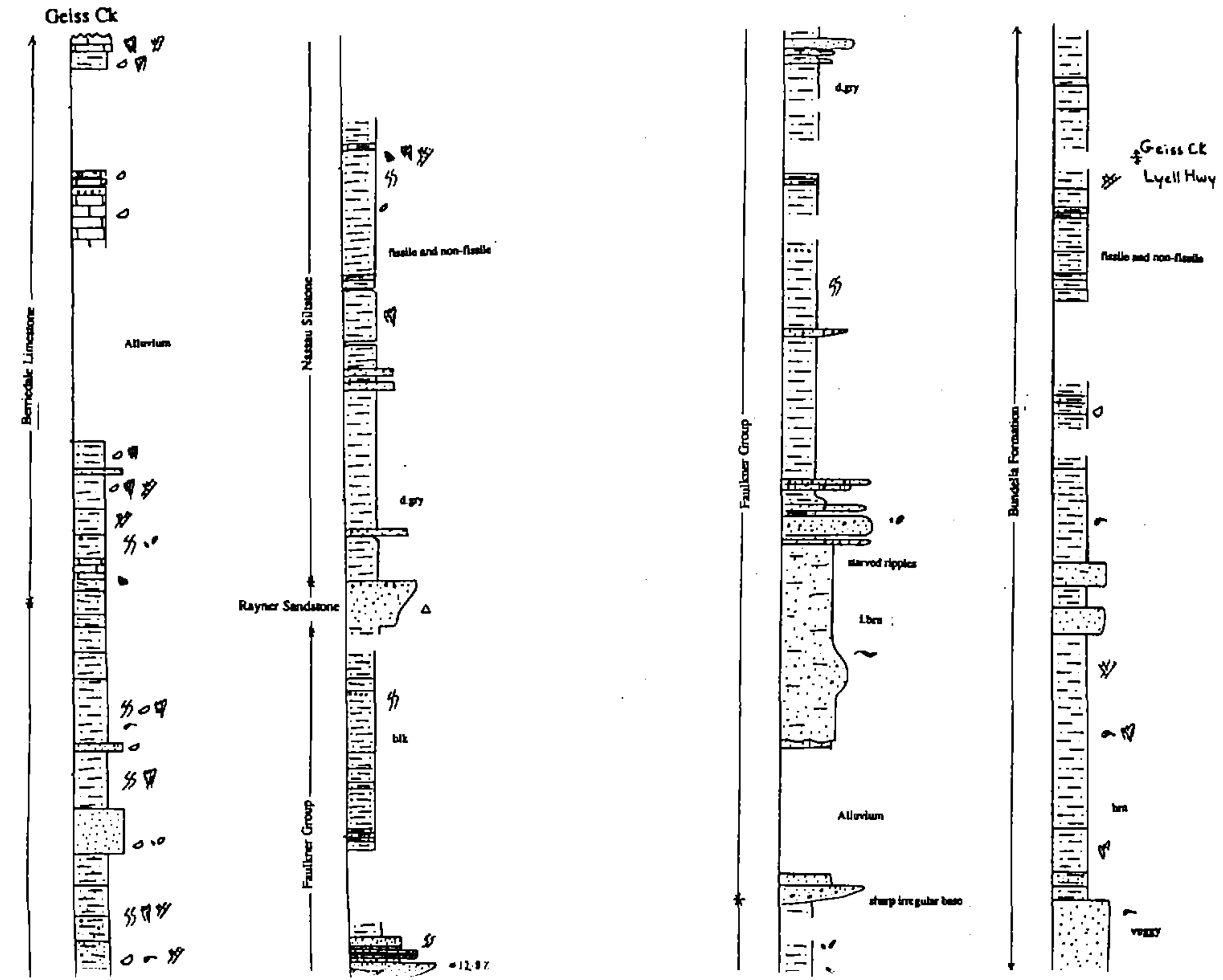
Granton 1
Malbina Formation
fissile
gry
l.brn
fissile
vuggy
Berriedale Limestone
*2.12
vuggy
Berriedale Limestone
gry
d.gry
Nassau Siltstone
brn


Deep Bay Formation
gry
baked
spotty
Jurassic Dolerite
fissile, gry, py
Jurassic Dolerite
calc. veins, 2cm
grn-brn
py
Bundella Formation
grn-gry


Rayner Sandstone
sharp irregular base
dgry - blk
Faulkner Group
carbonaceous
Faulkner Group
Bundella Formation
fissile
py
Bundella Formation
blu-gry
Woody Island Formation
blu-gry

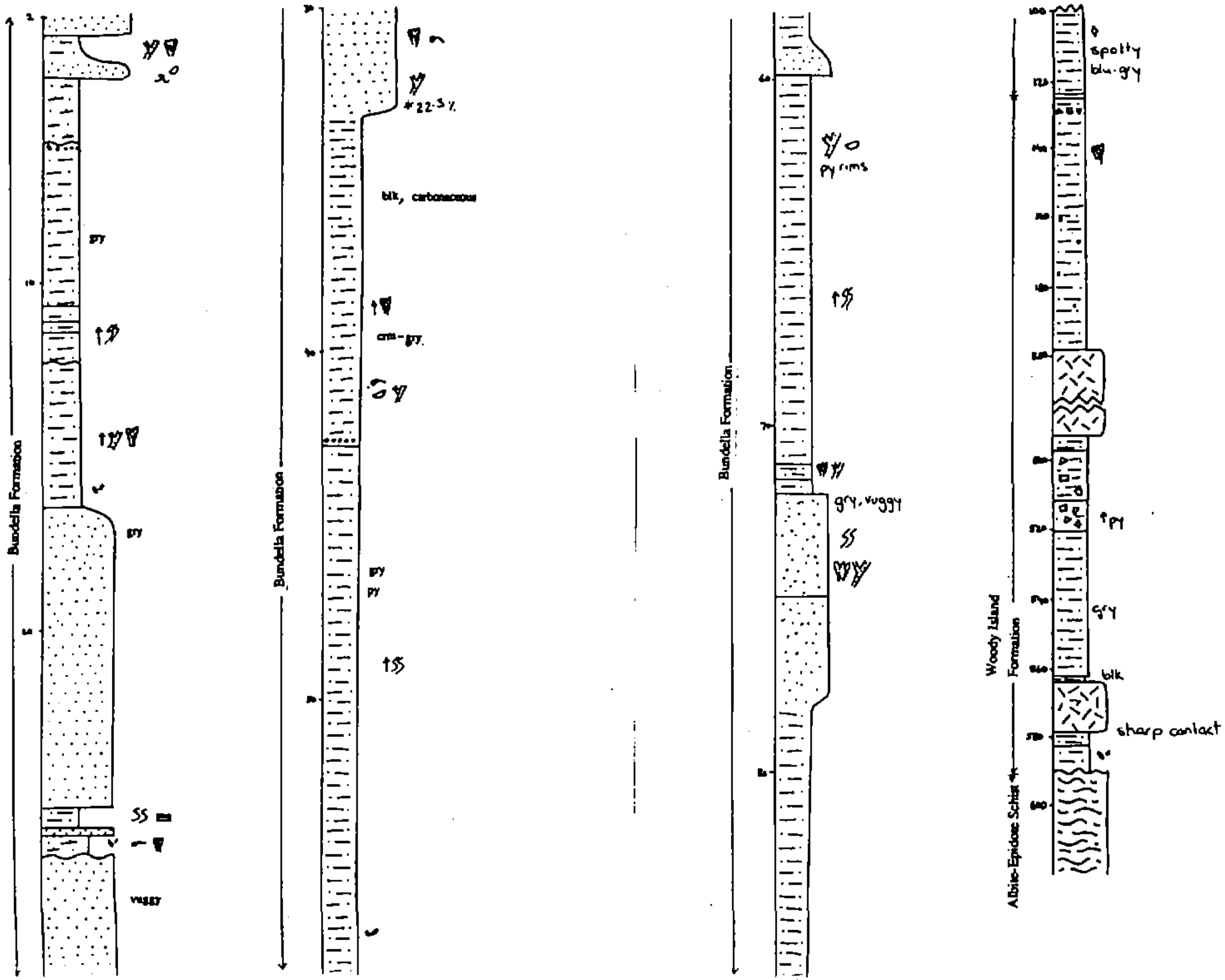
8


Woody Island Formation
py
blu-gry'
spotty
Jurassic Dolerite

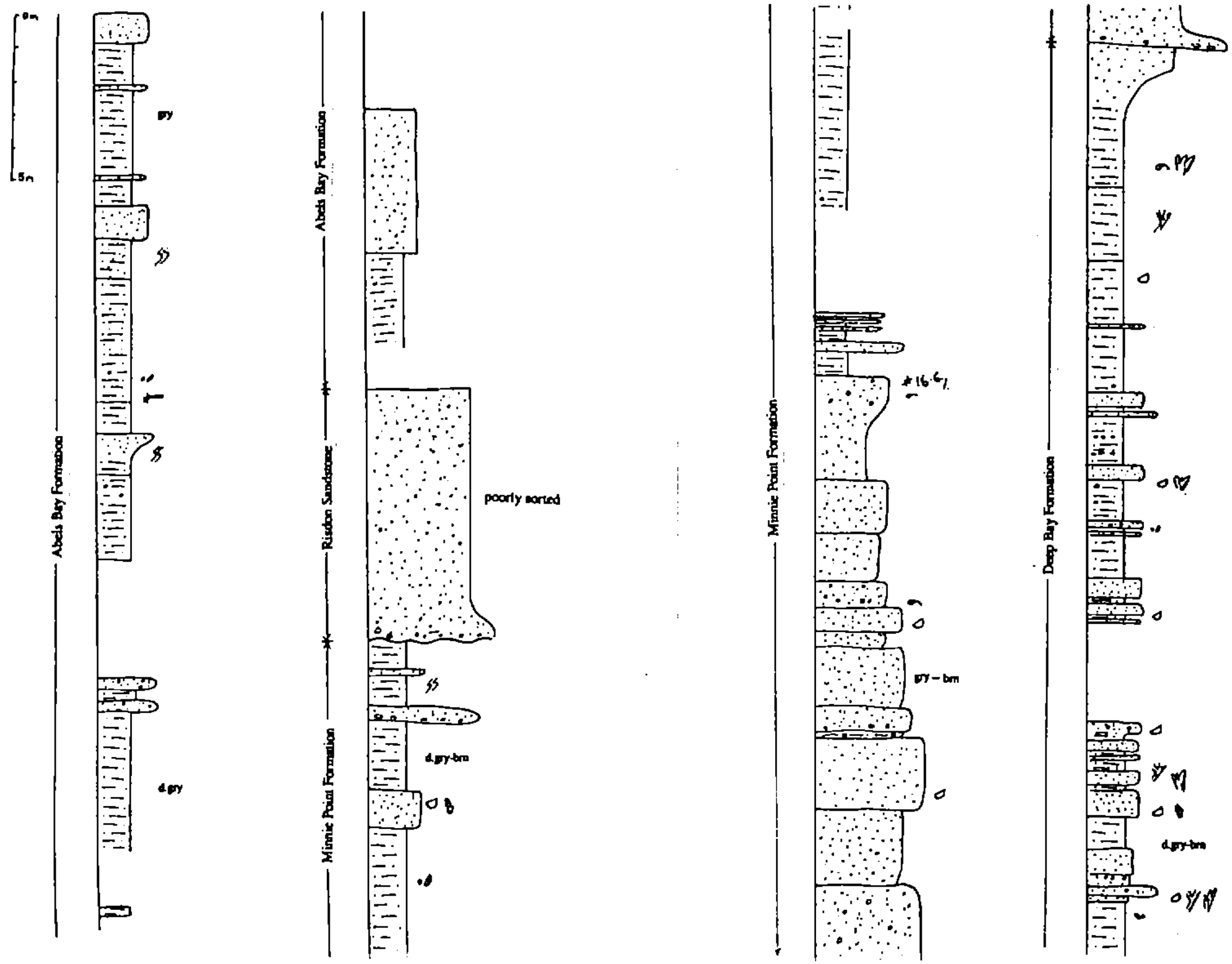


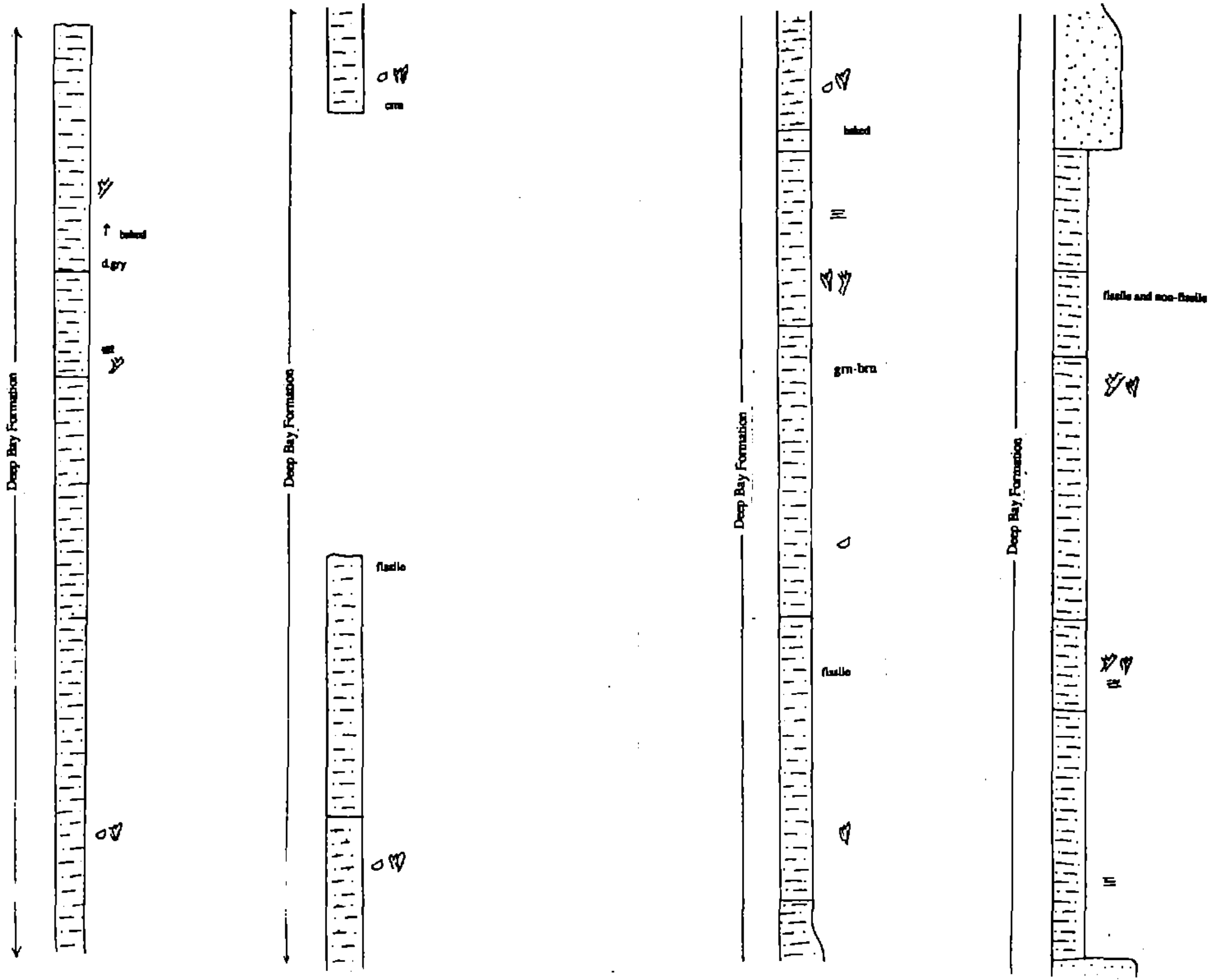
Geiss Ck
Berriedale Limestone
Alluvium
Nassau Siltstone
fissile and non-fissile
d.gry
Rayner Sandstone
Faulkner Group
blk
d.gry
Faulkner Group
starved ripples
Lbrn
Alluvium
sharp irregular base
Bundella Formation
Geiss Ck
Lyell Hwy
fissile and non-fissile
brn
veggy

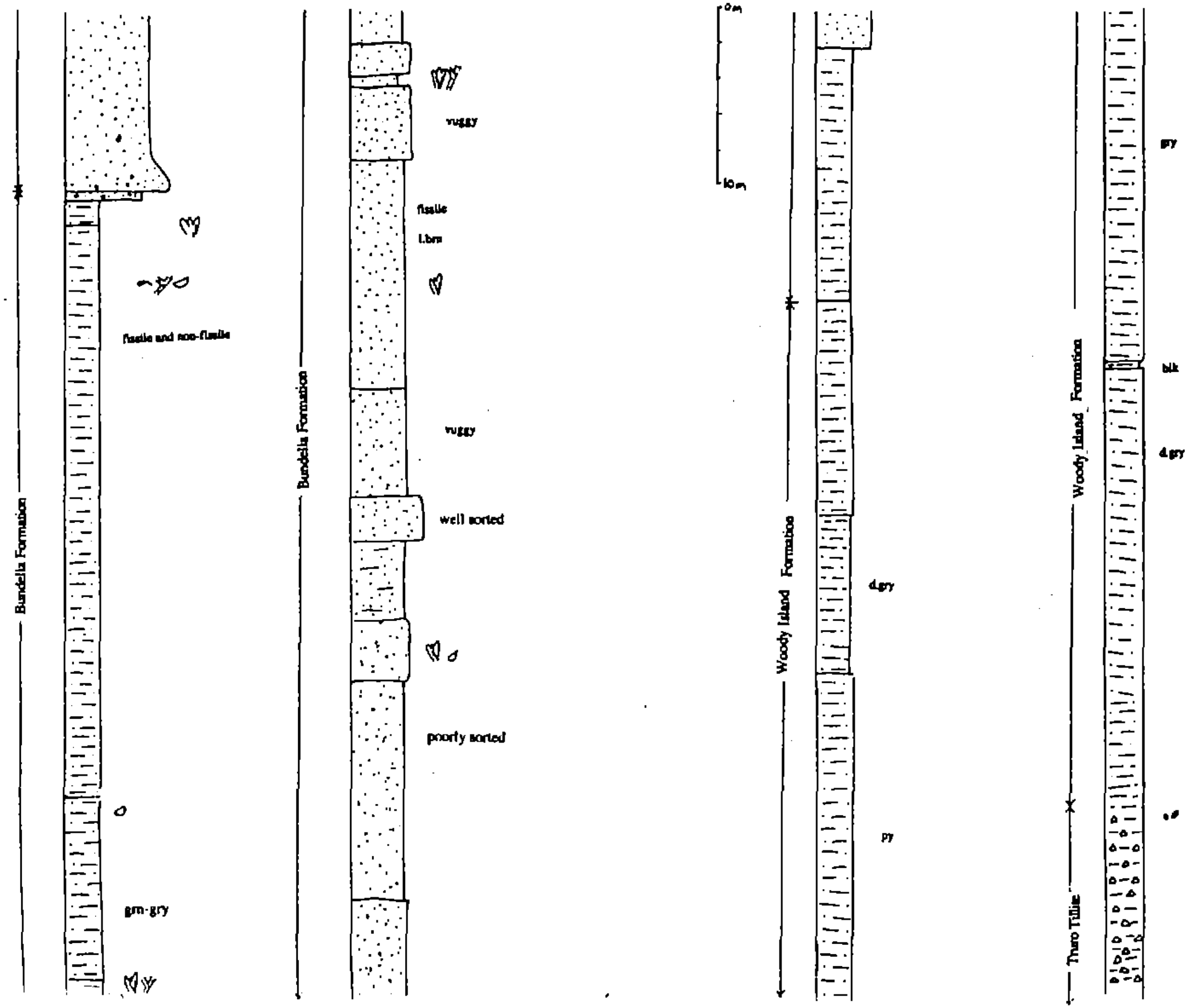
Glenorchy 1


blk, carbonaceous
Bundella Formation
Woody Island Formation
Albite-Epidote Schist
spotty
blu-gry
py rims
gry, vuggy
sharp contact
blk
vuggy

Cygnet


Abels Bay Formation
gry
d.gry
Abels Bay Formation
Risdon Sandstone
poorly sorted
Minnie Point Formation
d.gry-brn
Minnie Point Formation
gry – brn
Deep Bay Formation
d.gry-brn


Deep Bay Formation
baked
d.gry
Deep Bay Formation
fissile
Deep Bay Formation
baked
grn-brn
fissile
Deep Bay Formation
fissile and non-fissile


Bundella Formation
fissile and non-fissile
grn-gry
Bundella Formation
vuggy
fissile
l.brn
vuggy
well sorted
poorly sorted
0m
10m
Woody Island Formation
d.gry
py
gry
blk
d.gry
Woody Island Formation
Thuro Tillite

APPENDIX II: XRD results

TASMANIA DEVELOPMENT AND RESOURCES

Industry Safety and Mines Division

Client: T. Woods
Sample Location: Bruny Island
Analysis: Approximate Mineralogy
Method: X-Ray Diffraction

Results (approx wt %)

Sample	*>60%*	*40-60%*	*25-40%*	*15-25%*	*10-15%*	*5-10%*	*<5%*
3b		Quartz	Pyroxene			Laumontite, Plagioclase, Calcite	Apophyllite
16b	Quartz					Laumontite, Smectite, Chlorite, K-Feldspar	Plagioclase, Calcite, Mica, Stilbite
23a	Quartz					Plagioclase, Laumontite	Smectite, K-Feldspar, Pyrite, Chlorite, Mica, Calcite
26a		Wollastonite			Pyroxene	Plagioclase	Prehnite, Quartz, ?
32a		Quartz		Calcite	Prehnite	Smectite	Epidote
34b		Quartz		Smectite	Prehnite, Calcite		K-Feldspar/Pyroxene, ?Epidote
37a		Quartz		Chlorite	Plagioclase	K-Feldspar, Smectite	Mica
43a		Quartz			Mica, Plagioclase, Chlorite	Smectite	K-Feldspar, Stilbite, ?Pyrite, ?Prehnite
48a		Quartz		Mica, Chlorite		Plagioclase	Calcite
G33 9	Quartz				Plagioclase, K-Feldspar	Kaolinite	Mica, Pyrite, ?Gypsum
VB004	Quartz			Smectite		K-Feldspar	
VB006	Quartz				Plagioclase	K-Feldspar	Smectite, Kaolinite
W1011 8		*Chlorite*	*Mica*	*Quartz*			*Plagioclase*

Minerals present in trace amounts may not be detected.
Peak overlap may interfere with identifications (e.g. in low concentrations, Pyroxene and K-Feldspar are hard to distinguish).

Analyst: R.N. Woolley
Date: 29 November 1995

APPENDIX III: Method of porosity and permeability determination

SAMPLING

Due to the size (47 mm diameter) of the core, it was sampled as follows:

A. Whole core sections were trimmed and run in the whole core apparatus to determine helium injection porosity and vertical permeability.

B. One inch (1") core plugs were then cut (with water) to run horizontal permeability measurements.

C. All core and plugs were trimmed and offcuts retained. The offcuts are held in the Brisbane laboratory for viewing and possible selection of petrology/palaeontology samples.

The core was sampled and analysed as follows:

1. SAMPLE EXTRACTION AND DRYING

Under UV light there was no visible fluorescence and therefore no extraction.

All plugs were dried in a controlled humidity environment at 60°C and 40% relative humidity. The plugs were stored in an airtight plastic container and allowed to cool to room temperature before analysis.

2. AIR PERMEABILITY

Air permeability was determined on the 1" plugs (horizontal) and whole core (vertical). The plugs are placed in a Hassler cell at a confining pressure of 250 psig (1720 kpa). This pressure is used to prevent bypassing of air around the sample when the measurement is made.

During the measurement a known air pressure is applied to the upstream face of the sample, creating a flow of air through the sample. Permeability for each sample is then calculated using Darcy's Law through knowledge of the upstream pressure and flow rate during the test, the viscosity of air and the plug dimensions.

3. HELIUM INJECTION POROSITY

The helium injection porosity of the whole core sections was determined as follows. The samples were sealed in a matrix cup and a known volume of Helium at 100 psi reference pressure introduced to the cup. From the resultant pressure the unknown volume i.e. the grain volume was calculated using Boyles law, where $P_1V_1 = P_2V_2$

The bulk volume of the samples was determined by mercury immersion. The difference between the grain volume and the bulk volume is the pore volume and from this the porosity is calculated as the volume percentage of pore space with respect to the bulk volume. The porosity calculated using this technique is an effective porosity.

4. APPARENT GRAIN DENSITY

The apparent grain density is determined by dividing the weight of the sample by the grain volume determined from the helium injection porosity measurement.

The core plugs used in routine core analysis are currently stored with ACS Laboratories Pty Ltd in our Brisbane laboratory. The whole core remnants and offcuts are held pending further instructions.

We have enjoyed working for Great Southland Minerals on this project and look forward to working with you in the near future.

END OF REPORT

331124

APPENDIX 3

OIL AND GAS PROSPECTIVITY OF THE TASMANIA BASIN: A PROGRESS REPORT

SEPTEMBER 1995

331125

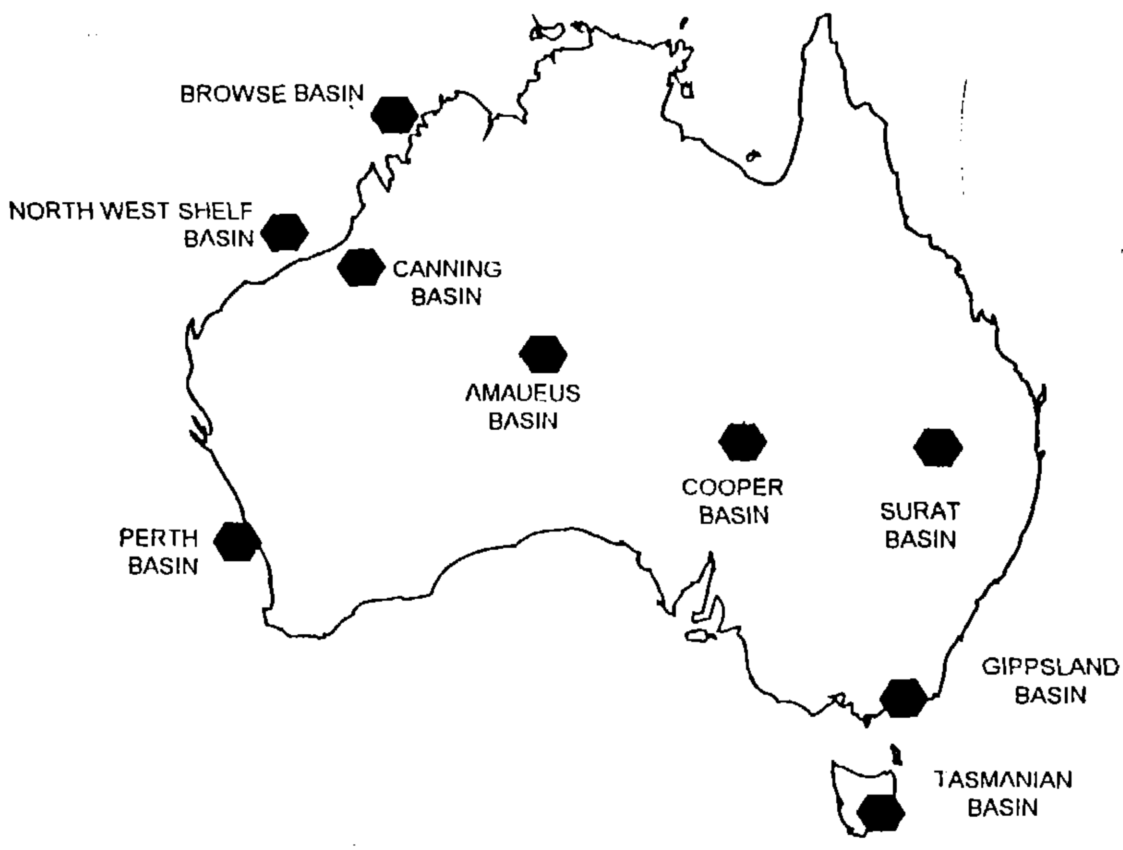
Great Southland Minerals Pty Ltd
ACN 068 650 386

Oil and Gas Prospectivity of the Tasmanian Basin

A Progress Report

Hydrocarbon Prospectivity

Great Southland Minerals' 1995 stratigraphic drilling program on North Bruny Island has confirmed that the Tasmanian Basin is a valid and prospective province for the exploration of commercial oil and gas.



Corporate Directory

Directors

Dr Gordon Michael Wise	Director Chairman
Mr Ian McNeil McCormick	Director Deputy Chairman
Dr Clive Francis Burrett	Director Chief Geologist
Mr Malcolm Roy Bendall	Director Special Projects
Mr David Bendall	Director
Mr Jason Slot	Managing Director
Mr David Michael Wise	Director

Company Secretary	Jason Slot
Business & Postal Address **Registered Office**	24 Jackson St Glenorchy PO Box 101, Glenorchy Tasmania 7010 Tel (6102) 723 044 Fax (6102) 730 284
Accountants	Garity Hurd & Partners, 110 Hampden Road Battery Point Tasmania 7004
Independent Consultant Geologist	Mulready Consultants Level 25 Challenge Tower, 459 Collins Street Melbourne, Victoria 3000
Independent Solicitor	Jennings & Elliott 1 Brooke Street Hobart, Tasmania 7000

Letter from the Chairman

I am pleased to advise you of developments and progress of the Company during 1995 and in particular the results from recent drilling in our tenement EL 1/88 on North Bruny Island. The following report is further, an introduction to the structure and objectives of Great Southland Minerals Pty Ltd which is actively exploring for commercial oil and gas in south eastern Tasmania.

The inaugural meeting of the Company was held at Faulkner House, Wentworth Street South Hobart on 1st July 1995. A board strong in commercial, administrative and technical experience was appointed at the meeting.

The table below lists the issued share capital of the Company at the time of writing this report.

As it is our objective to become a successful oil and gas exploration and development Company we are, accordingly, committed to funding and promoting hydrocarbon exploration in the State.

Currently Great Southland Minerals Pty Ltd is the operator of EL1/88, EL9/95 and EL21/95, manages a drilling program in these tenements and has an exploration team to support a wider basin study program in the State.

Yours faithfully,
Great Southland Minerals Pty Ltd

Gordon Wise
Chairman Director

Location of the Tenements

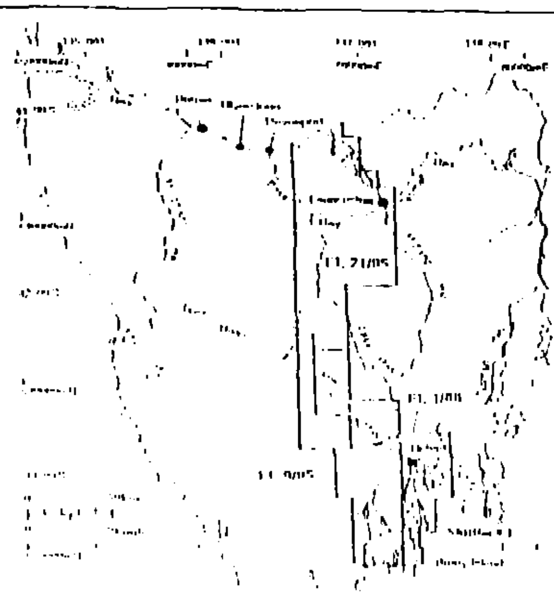
The company holds 100% of EL 1/88 comprising 3500 km² which is located in the Derwent Valley. The Company has applied for an extension to the term of this licence, which is due to expire in December 1995.

Two further tenement applications, also held 100% by the Company, are EL 9/95 and EL 21/95. The Tasmanian Department of Mines has recommended these applications be granted to Great Southland Minerals Pty Ltd. These exploration licences cover about 60% of the Tasmanian Basin.

The schedule below lists the status and the Company's interest in these tenements at the date of printing this report.

Schedule of Tenements

	Area km²	Equity	Anniv. Date	Status
Granted				
EL/188	3500	100%	31/12/95	Extension applied for.
Recommended for Approval				
9/95	3700	100%		Granted for 6 years
21/95	6000	100%		Granted for 6 years



Map of Tasmania showing Exploration Licences and major population centres and highways.

1995 Drilling Program Bruny Island

A stratigraphic hole was planned in EL 1/88 during November of 1994. The well plan contained a contingency to be used in the event hydrocarbons or abnormal pressure were encountered downhole.

HQ core drilling below a precollar set at 80m commenced in March and proceeded to 181m. NQ coring followed to 888m and finally a BQ core string run inside the NQ rods drilled to a depth of 1021.4m before drilling operations were suspended on 14 July 1995.

The Company has now installed Blow Out Prevention safety equipment to control increasing levels of hydrocarbon gases that have been entering the hole.

Drilling to date has provided encouraging results for the Company.

A lithology description and a stratigraphy for this area of the basin has been prepared by our Company geologist. Hydrocarbon gases recorded while drilling have also been sampled and described by two laboratories.

Porosity and permeability analysis, maturation and source rock studies carried out on core obtained at Shittim #1 have enhanced substantially the prospectivity of the tenements bow operated by or under application to Great Southland Minerals Pty Ltd.

Lithology Log

Core has been moved off location to a storage area and logged by the Company geologist. A lithology log and interpreted stratigraphy for this section is included on page 6 of this progress report.

History of Hydrocarbon Exploration in Tasmania

The Government geologist W.H. Twelvetrees reported unconfirmed hydrocarbon seeps and bituminous residues in the Mines Department Circular No. 2 of 1917 titled The Search for Petroleum in Tasmania.

There has been sporadic exploration for oil and gas in the state since 1915. Some samples collected during this time were held in collections at the Hobart and Launceston Museums. Past contributors to the history of the search are listed below.

Tasmanian Oil Wells Company	1915
Port Davey Mineral and Oil Prospecting Syndicate	1915
The Asphaltum Glance and Oil Syndicate	1915
The Bruni Oil Company	1916
The Tasman Oil Company	1921
The Mersey Valley Oil Company	1922
The Adelaide Oil Exploration Company	1922
The Tasmanian Oil Company	1929
The Austral Oil Drilling Syndiicate	1936
Producers Oilwell Supplies	1939
Nudec Pty Ltd	1965
EZ Company Pty Ltd	1965
BHP Limted	1980
Conga Oil Pty Ltd	1984
Great Southland Minerals Pty Ltd	1995

Continuing exploration in the Tasmanian Basin, after BHP Ltd in 1980, has been, to a great extent, the result of a persistance on the part of Mr Malcolm Bendall who has promoted and reported all operations carried out since 1984.

A full and recent account of the Geology of Tasmania may be found in C.F. Burrett & E. Martin, *Geology and Mineral Resources of Tasmania*. GSA (1989) and in *Recent Developments in Exploration for Oil in Tasmania*, M.R. Bendall, J.K. Volkman, D.E. Leaman, C.F. Burrett, APEA Journal 1991.

Maturation Studies

Vitrinite reflectance and fosil pollen studies (palynology) have shown core sampled between 855 to 883m in the Woody Island Formation to indicate the shale has been heated above 300¡C. This heating event precludes the possibility of hydrocarbons having originated locally from shales of this formation.

Porosity and Permeability Core Analysis

Although heat has meta-morphosed the sands and shales at this location in the basin four samples taken between 787m and 811m were forwarded for porosity as well as horizontal permeability analysis.

The porosities ranged from 7.4 to 11.9% while horizontal permeabilities ranged from 6.8 to 9.0 millidarcies. These readings are considered fair in oil reservoirs. The Cooper Basin fluvial sandstone reservoir poro-sities, for example, range from 5 to 12% with corresponding production rates of 100 to 600 bbls of oil per day.

Manifestations of Combustible Hydrocarbon Gases

Combustible gas vapours were first detected while drilling in open hole above the dolerite. The first gas show recorded at the location occured shortly after a hot wire was installed while coring below 904m. At 907m the chart recorder drove to a peak reading of 58 gas units which was 22 units above a steady gas background in the interval.

Two following cores to 910 and 913m recorded 20 units background generated as cuttings gas and it was not until 944m that a further show above 100 units was noted.

The most recent report on the basin is *Permian Petroleum Potential Onshore Tasmania*, 1992, which was also compiled by M.R. Bendall.

Some past seismic data has revealed structures beneath the pre-Permian unconformity and there is a need of a wider seismic surveying program in the basin to support further stratigraphic drilling.

Source for Hydrocarbons

Over 200 historical hydrocarbon seeps and shows have been recorded in the Tasmanian Mines Department archives and include tar, "bitumens", oil and gas. Seepages have been reported mainly after earthquakes. Tars stored in the Launceston Museum have been studied geochemically along with samples collected from the field. These studies have identified at least four mature oils. There are several probable hydrocarbon sources in the Tasmania Basin. Geochemical comparisons of seeps show that the most prolific source has been the Ordovician Gordon Limestone. Ratios of C27:C28:C29 steranes are identical between seeps on Bruny Island and the Gordon Limestone and the predominance of C27 steranes and the abundant diasteranes in Tasmanian bitumens suggests a widesperead alga and clay-rich source rock.

Conodonts colour indicates that much of the Gordon Limestone, particularly in central and southern Tasmania, is in the oil and gas windows. This limestone is expected to underly Permian and Triassic sediments in much of the Tasmanian basin.

Other sources include the Permian Quamby Mudstone, "Freshwater Sequence" and the Preolenna Coal Measures. In all three rock units the total organic carbon may reach 25%. Vitrinite reflectance data and fossil pollen colours show that these source rocks are within the oil window over large areas of the basin.

Reservoirs

Potential reservoirs are within the Siluro-Devonian sandstones of the Eldon and Tiger Range Groups, with palaeokarst and reefs of the Gordon Limestone and within sandstones of the Permian Bundella Formation, Faulkner Group and Liffey Sandstone. Measured porosities in the Faulkner and Liffey are 13% and 12% respectively, whilst other Permian sandstones in EL 21/95 have porosities average 16% and ranging up to 386 millidarcies horizontal permeability.

The hole continued to produce high swab and bottoms up gas after each rig shut down while drilling to 1021m. At this depth a 100 show was recorded while the resultant swab gas generated recovering this core reached 250 units. The recorded shows are believed to emanate from high angle fracture porosity noted in the core.

Cuttings Gas

Cuttings gas is released from rock cuttings as they are displaced from the bit to the surface. The discharged gas produced a background record of 5 to 30 gas units during drilling.

Gas Shows

The first gas show recorded at the location occurred after the hotwire was installed while coring below 904m. At 907m the chart recorder drove to a peak reading of 58 gas units which was 22 units above a steady gas background being recorded in the interval.

Eight subsequent shows are recorded in the mud log. The highest show was 254 units at 988m.

The recorded gas shows are believed to emanate from high-angle fracture porosity noted in the core.

Swab Gas

Swab gas is produced retrieving the inner core barrel after a coring run. The wireline retrieves the core tube to surface inside the drill rod and swabs the bottom hole like a pump piston. The procedure (after every 3 or 6m of coring) swabs-in formation gas from the bottom of the hole. When the barrel is pumped back to bottom the mud with swab gas returns to and discharges at the surface.

Seals

Good seal sequences are found throughout the Permian-Triassic sedimentary sequence. The Jurassic dolerite sills also make effective cap rocks.

Traps

Conventional anticlinal and fault traps will be expected in the pre-Permian Palaeozoic while gentle warping of the Permian sediments has produced domal structures. Both pre- and post-Permian faulting was extensive and may be expected to have produced many suitable structural traps.

The highest swab gas recorded peaked at 360 units while recovering core from 1021.4m.

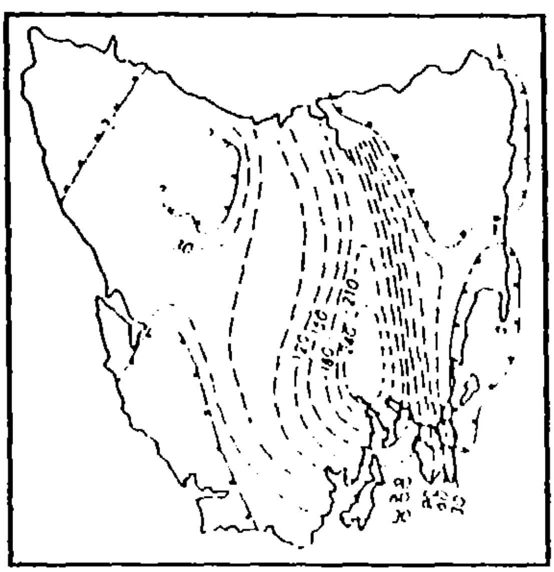
Bottoms Up Gas

Mud down the hole is frequently charged with gas from the formation if the hole is left uncirculated for any length of time. Circulating after the hole has been left overnight produced peaks up to 390 gas units at 1021m

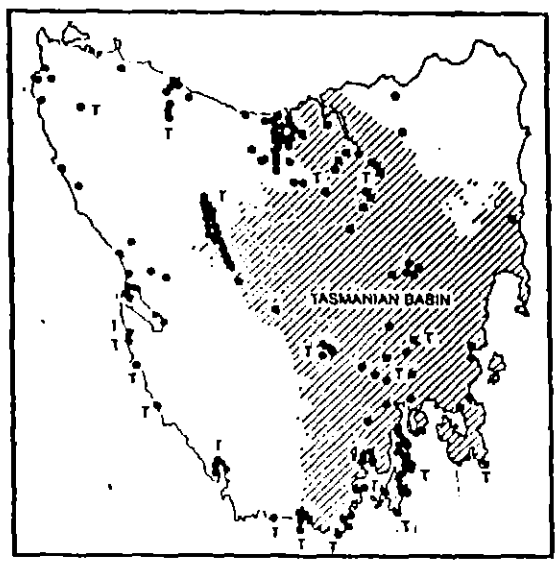
Gas Analysis

Samples of peak gas collected in glass containers or syringes were forwarded to Amdel and the Central Science Laboratory at the University of Tasmania for GCMS analysis.

The gas samples contain methane and ethane in an approximate ratio of 4:1. Significant concentrations of the saturated hydrocarbons Propane (C3) to hexane (C6) have also been detected in these samples.



Isopach map (in metres) of early Permian strata

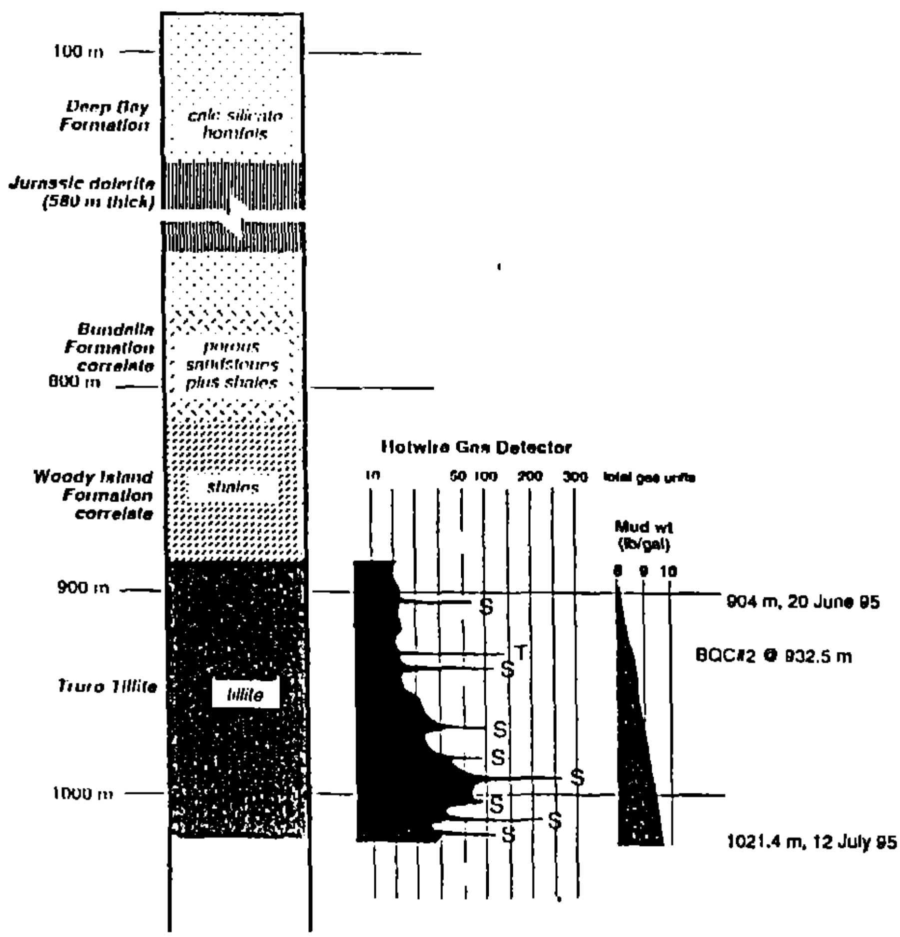


Seeps and coastal tars in the Tasmanian Basin
T = Tars

Shittim #1, North Bruny Island, Well Log			
Well name	Shittim #1	Lat	220 000N
Location	Nth Bruny Is	Long	533 000E
State	Tasmania	Elevation	25 m ASL
Operator	Great Southland Minerals	Rig	Longyear 44
Supervisor	-	Spud Date	November 94
		Projected Depth	1250 m

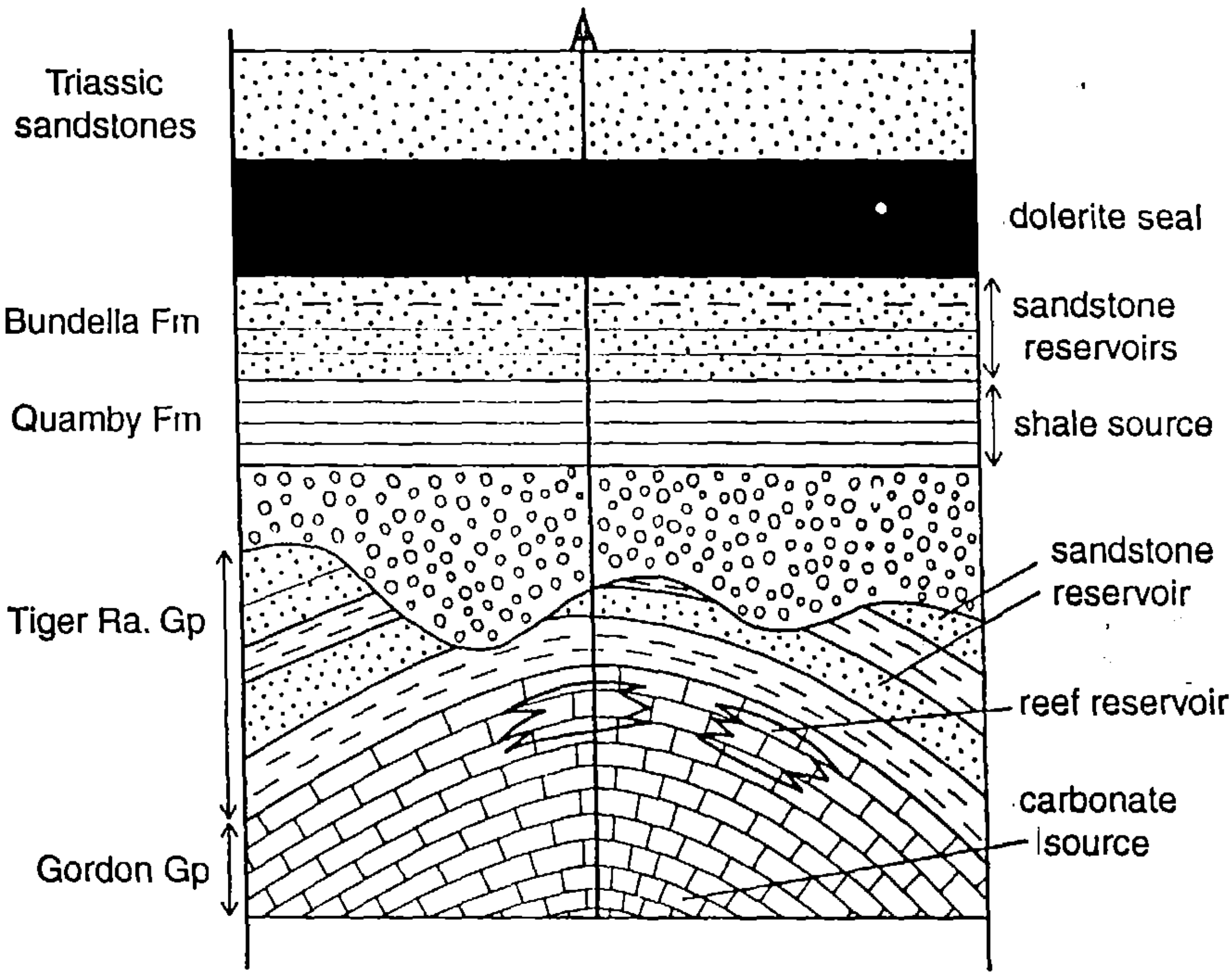
Hole Data

Interval	Depth m	Rod	OD mm	ID mm	Wt kg/m	Hole L/m	Rod L/m
Conductor	6	air	150	polypipe			
Conductor	80	air	100	polypipe			
Surface casing	181	HQ	89.0	77.8	11.45	7.248	4.754
Intermediate	888	NQ	70.0	60.3	7.58	4.500	2.959



Exploration Strategy

Thick sedimentary sequences containing several sources and with several sealed and stacked reservoir targets are anticipated in all three licence areas. The Company is to review all existing geophysical data including aeromagnetics, marine and land seismics and gravity. A stratigraphic drilling program is planned that will include both shallow (to 1200m) and deep (to 2500m) holes.



Stratigraphic reservoirs plus, seals and sources in central part of Tasmanian Basin with simplified structure.

331133

APPENDIX 4

REPORT ON THE SIGNIFICANCE OF THE SHITTIM NO 1 STRATIGRAPHIC CORE HOLE E/L 1/88 NORTH BRUNY TASMANIA AS AT SEPTEMBER 5TH 1995.

BY JACK MULREADY.

SEPTEMBER 1995

(INDEPENDENT CONSULTANT)

MULREADY CONSULTING SERVICES PTY LTD

A.C.N. 007 049 989 Incorporated in Victoria

MCS

The Atrium, Level 5, 459 Collins Street Melbourne Victoria 3000
Postal GPO Box 427 G Melbourne 3001
Phone (03) 629 1575 Facsimile (03) 629 1624 A/H (03) 840 2760 Mobile 018 032678

September 14, 1995

The Directors
Great Southern Minerals Pty Limited
24 Jackson Street
Glenorchy
Tasmania 7010

Dear Sirs,

At your request I have prepared the following report regarding the significance of recent drilling at Great Southern Minerals' Shittim#1 well, North Bruny Island.

On Monday September 4th I met with Dr Clive Burrett, Chief Geologist for Great Southern Minerals in Hobart. Extensive discussions regarding the results of the well and recent developments with respect to the ongoing exploration of EL1/88 followed.

On the morning of Tuesday September 5th I inspected the Shittim#1 core at Dr. Burrett's home before leaving to inspect the rig site at Bruny Island in the company of Malcolm Bendall. I returned to Melbourne on Wednesday September 6th.

Dr. Burrett has kindly made available the references listed at the end of the accompanying report. In preparing this report I have drawn on my own knowledge of the history of exploration in EL1/88 and its predecessor EL29/84, the references cited herein, and discussions with GSM staff and contractors.

Yours truly

Jack N. Mulready
B.Sc., Fell. Dip. Management RMIT
MGSA MPESA
AAPG Certified Petroleum Geologist #5321

331135

REPORT ON THE SIGNIFICANCE OF THE SHITTIM NO 1 STRATIGRAPHIC COREHOLE, EL1/88 NORTH BRUNY ISLAND, TASMANIA

AS AT SEPTEMBER 5TH 1995.

PREPARED FOR GREAT SOUTHERN MINERALS N.L.
BY
MULREADY CONSULTING SERVICES PTY LTD
September 14, 1995.

M C S

CONTENTS

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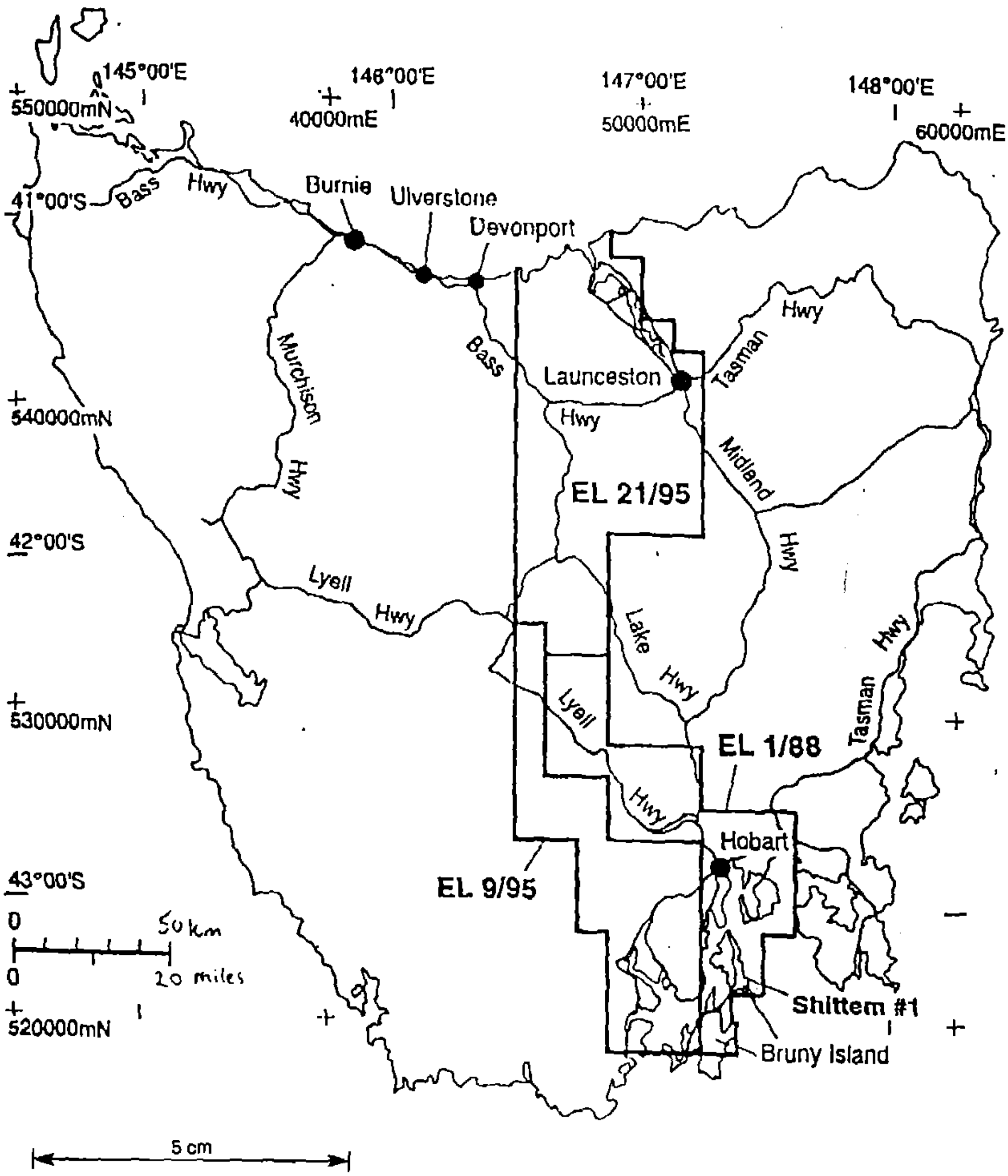

Figure 1

331138

SUMMARY OF THE SIGNIFICANCE OF THE RESULTS OF SHITTIM#1

The results of drilling thus far at Shittim#1 are significant in the following respects.

1. It has established the effectiveness of the dolerite seal in this portion of the Tasmania Basin..

2. It has established the presence of fair quality reservoir sandstones at Bruny Island.

3. It has established the presence of gaseous hydrocarbons in this reservoir, thus indirectly confirming the significance of the Johnson's well seep results of the 1930's.

4. It has raised the possibility of a hydrocarbon-trap at Bruny, possibly stratigraphic in nature, and the results of Johnson's well and the presence of C4+ gas fractions suggest that an oil leg may not be an impossibility.

5. Just as importantly it provides further encouragement for continuing the exploration effort on the Main Island, and raises the possibility of attracting additional risk funds for expenditure on Tasmanian onshore plays.

It is certainly true that GSM have adopted an innovative approach in attempting to further their exploration endeavours in EL1/88. In the circumstances this has been almost unavoidable. In this context the surprising results of Shittim#1 thus far provide encouragement for further exploration on Bruny Isl., and hopefully, (particularly if supported by quantitative well test data), will provide the technical and financial incentive required to fund the more expensive drilling required to evaluate the main plays located within the depocentre of the Tasmania basin.

MCS

INTRODUCTION

Great Southern Minerals Pty Limited ("GSM") now hold three petroleum exploration licences within the Tasmania Basin. The oldest of these is EL1/88, which includes much of the depositional centre of the basin, (generally defined by the valley of the Derwent River), as well as the estuary of the Derwent River, parts of Storm Bay and Frederick Bay, North Bruny Island and parts of South Bruny Island, (refer Figure 1).

Exploration activity early this century was focused on shallow plays dictated largely by the distribution of seeps. A notable result was the recovery of oil and gas in a shallow sandstone reservoir at Johnson's well on North Bruny Island in the 1930's. Whilst in retrospect much of this activity can be seen to have been misguided, due to lack of understanding of the requirements for petroleum generation and entrapment, exploration was, (and continues to be), severely hampered by the wide distribution of substantial dolerite sills throughout the Tasmania Basin.

EXPLORATION STRATEGY

Modern exploration in Tasmania has been concentrated largely within the offshore Bass Basin with minor activity in the offshore Sorrell Basin. Onshore exploration within Tasmania has largely languished for two dominant reasons.

1. **A perceived lack of mature source rocks**, based largely on samples of Parmeener Supergroup samples, in particular the Tasmanite oil shale which although very rich in algal material has lacked sufficient maturity for oil or gas generation where sampled. (Note, however, the absence of samples from the Basin depocentre due to the absence of well control at the depths required. Also note that a recent paper on analysis of samples of the Tasmanite oil shale at Douglas River indicates that it is near the oil window at that location - see Revill et al. in reference).

2. **The formidable problem of attempting to image horizons below the dolerite cover.**

   After being granted petroleum exploration licences in the Tasmania Basin in the mid 1980's Conga Oil attempted to address both these problems as follows

   (a) Lack of mature source rocks
   Studies of conodont colour maturation indices (Burrett) had suggested that the widely distributed Ordovician carbonates (Gordon Limestone) could provide a viable alternative oil source rock which in many parts of Tasmania would be within the oil &/or gas generation window. Conga Oil expended considerable effort sampling both the Gordon River Limestone and the widespread oil seeps recorded in Tasmania.

MCS

Some success in relating Gordon Limestone source to seeps has been achieved, but the separate issue of whether Gordon Limestone karst or fracturing could provide adequate reservoir remains to be resolved. Similarly the question of the ultimate potential of the Tasmanite oil shale section awaits appraisal by drilling to depths of >2500 m. in the vicinity of the Tasmania basin depocentre.

(b) Seismic imaging of structure beneath the dolerite
Recognising the need to be able to map sub-dolerite structure Conga firstly attempted to extend the gravity and magnetics data bases in the Tasman Basin. Whilst this has helped in defining regional trends and lineations, the lack of subsurface control and the limitations of the method itself have limited the usefulness of these techniques for the purpose of identifying potential hydrocarbon traps.

Despite earlier discouraging results onshore Tasmania, Conga elected to attempt acquisition of additional data both on the Main Island and North Bruny Island in the vicinity of Johnson's seep. Additional data was acquired offshore in Storm Bay utilising AGSO's Rig Seismic vessel. In general it may be said that the results have proved deeply disappointing. Certainly the poor quality of these records means that none of the sections would be regarded as adequate for the purpose of identifying and mapping a petroleum trap.

The problem faced by the current permit holders (GSM) is how to advance their exploration programme in the absence of useful seismic, this being the most commonly accepted criterion for prospect definition.

As foreshadowed in my report of 1987 and Questa's report of 1991 there is an alternative, high risk option available, namely stratigraphic drilling designed to answer questions related to stratigraphy, reservoir quality and structure. This is essentially the logic behind the drilling of the Shittim#1 well.

Shittim #1, North Bruny Island, Well Log

Well name	Shittim #1	Lat	220 000N
Location	Nth Bruny Is	Long	533 000E
State	Tasmania	Elevation	25 m ASL
Operator	Great Southland Minerals	Rig	Longyear 44
Supervisor	-	Spud Date	November 94
		Projected Depth	1250 m

Hole data

Interval	Depth m	Rod	OD mm	ID mm	Wt kg/m	Hole L/m	Rod L/m
Conductor	6	air	150	polypipe			
Conductor	80	air	100	polypipe			
Surface casing	181	HQ	89.0	77.8	11.45	7.248	4.754
Intermediate	888	NQ	70.0	60.3	7.58	4.500	2.959

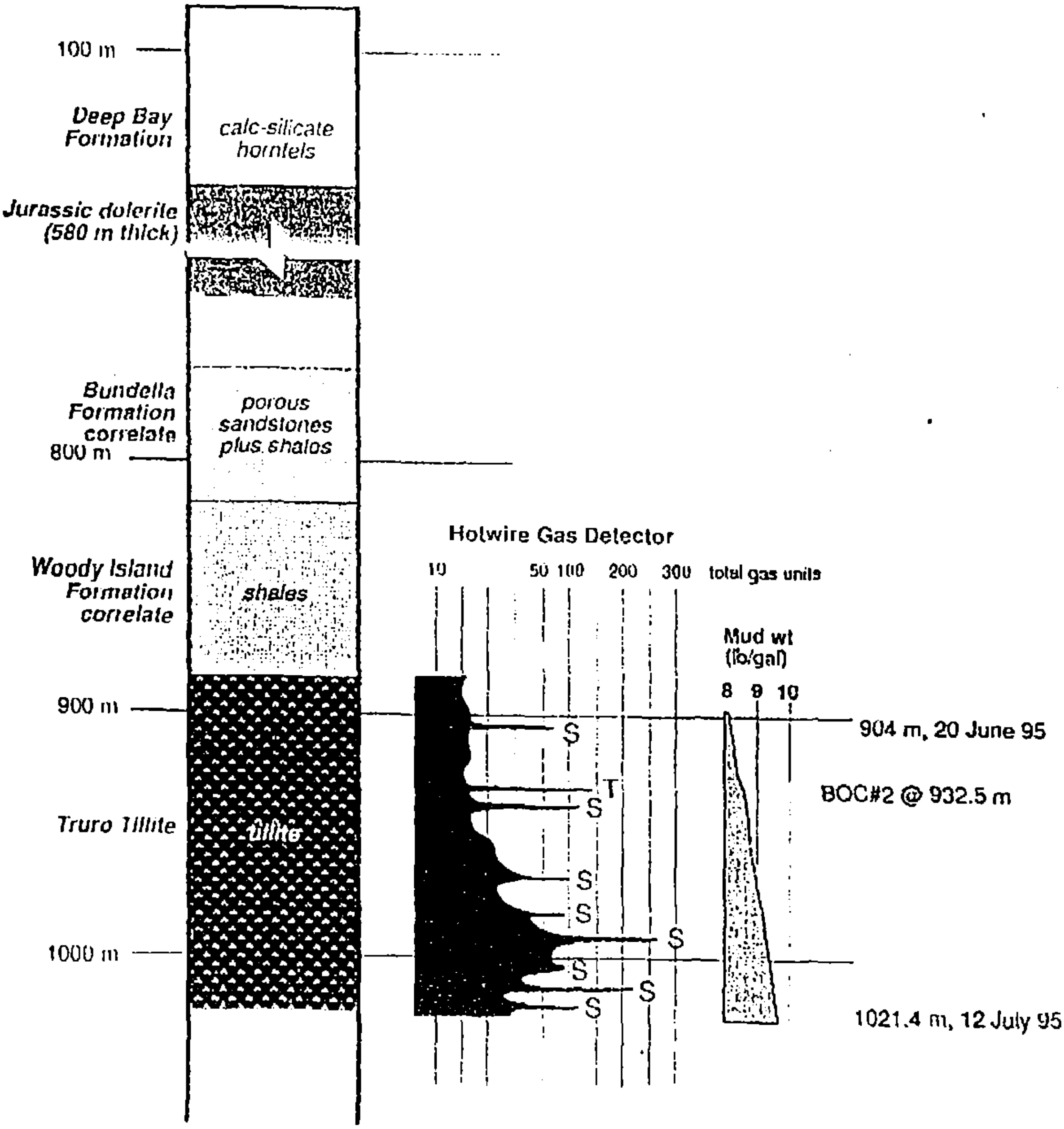

Figure 2

Shittim#1 Well

I have reviewed the results of the well to date with Dr Clive Burrett, and also briefly examined the core from this well. The drilling results are summarised in figure 2.

Shittim#1 well is located on North Bruny Island, several hundred metres to the east of Johnson's well. The well was designed to resolve the question of the nature of basement at Bruny Island, in particular whether the Gordon Limestone section is present at depth, as well as providing stratigraphic/petrophysical information on possible migration paths, reservoirs and seals, (refer Leaman, D. "Prognosis for a well, North Bruny Isl.")

The well spudded in November 1994, and at the time of my visit (5/9/95) was shut in waiting on cement, having reached a depth of 1021.4 m. The operator, Great Southland Minerals, were in the process of checking out equipment prior to installing a BOP stack, following flows of gas encountered in the well.

The important results to date are as follows:

1. The dolerite thickness is greater than expected (580m.), suggesting the possibility that the location is close to a feeder.

2. The Bundella Fm equivalent sandstones possess porosity and permeability of reservoir quality for production of gas and possibly also for oil (marginal). Results of core analysis from Shittim#1 cores were as follows:

   787 m, porosity 7.4%, horizontal permeability 0.07 mdarcy.
   803.5 m, porosity 8.6%, horizontal permeability 0.96 mdarcy.
   805 m, porosity 11.9%, horizontal permeability 6.8 mdarcy.
   811 m, porosity 11.4%, horizontal permeability 9.0 mdarcy.

   From my inspection of the core I suspect that this porosity may be secondary, but this matter should shortly be resolved as I understand GSM are submitting samples for petrological analysis.

3. The Woody Island equivalent shales exhibit high vitrinite reflectance (of order 3.7) showing they are over mature for sourcing of both oil & gas.

4. Sands of the Bundella Fm equivalent and the Truro Tillite have both yielded significant gas shows. A gas detector was installed at a depth of ca. 880 m. The continuing flows of gas into the borehole have necessitated weighting up of the drilling fluid and finally cessation of drilling to enable BOP's to be installed. I am also informed that gas shows were encountered near the base of the dolerite, presumably associated with fractures. No quantitative data is available for these shows.

The gas detector equipment on site does not include a chromatograph at this stage, but analysis of samples has been undertaken at AMDEL. Considerable air contamination is noted, presumably due to the inadequacy of on site sampling facilities, but the analysis does indicate the gas has fractions up to C_4 and higher.

5. Pressure data is qualitative at this stage, but I am informed that drilling fluid weights in excess of 9.5 lb/gal. have been required to contain gas production from the well. This is suggestive of over-pressuring

CONCLUSIONS:

Several conclusions can be drawn from the drilling results thus far.

1. **Reservoir** quality sands exist within the Bundella equivalent sandstones at Bruny Island North. Sampling of outcrop of time equivalents of these sands elsewhere in Tasmania has yielded porosity values of 12.8% (Mt Nassau Faulkner Gp.) and up to 19.9% porosity and 386 mdarcy (Poatine & vicinity, Nth tasmania). If this porosity proves to be secondary it opens up the possibility of a widespread but unpredictable distribution of reservoir in sediments which may have been ignored as potential targets to date.

2. **Seal.**
It has been demonstrated that the dolerite is capable of acting as an effective seal. Variations in its thickness would appear to be difficult to predict with any degree of accuracy.

3. **Generation & Migration of Hydrocarbons .**
The Woody Fm correlate at Bruny is over- mature for sourcing. It can therefore be concluded that the hydrocarbons encountered in the Bundella equivalent sands are hosting hydrocarbons which have migrated into the formation, presumably from down-dip to the west. The source of these hydrocarbons is yet to be established. The most likely migration path at this stage is the pre-Permian unconformity.

4. **Pressure data**, although qualitative, suggests that the gas reservoir/s are over pressured. This is significant in that it raises the possibility of a sizeable column of gas, possibly located in a stratigraphic trap.

COMMENTS:

Shittim#1 has raised as many questions as it has answered, but must certainly be viewed as a most encouraging result so far. Unfortunately GSM are now faced with the problem of attempting to drill and evaluate a well originally designed as a stratigraphic core-hole. The well has first to be drilled to basement, (assuming casing integrity is established), and it would be most desirable if at all possible to firstly run electric logs and then drill-stem test at least the Bundella equivalent sands at around 810 m. The availablity of logging tools for such small diameter hole within Australia may present an insurmountable problem, especially as it will also be necessary to first remove stuck rods from this part of the hole. The value of a sustained drill stem test should not be underestimated, however. The choking effect of such a small hole may restrict the size of the flow but the pressure and fluid recovery which may be anticipated would be of immense value in attempting to assess the importance of the results of Shittim#1.

BIBLIOGRAPHY

ACS Laboratories Core Analysis Reports
(a) Bruny Island Cores July 1995.
(b) Northern Tasmania Samples
(c) Mt Nassau Faulkner Gp Sample 11A

AMDEL "Analysis of Gas Samples ex Bruny Island" June 1995.

Bendall et al. "Recent Developments in Exploration for Oil in Tasmania" APEA Journal 1991.

Burrett & Martin (Eds) "Geology & Mineral Resources of Tasmania" GSA Special Publication 15, 1989.

Great Southern Minerals Pty Limited "Draft Progress Report on Hydrocarbon prospectivity of Tasmania Basin", August 1995.

Leaman D. Conga Oil "Exploration Status Project d'Entrecasteaux SE Tasmania, March 1990.

Mineral Resources Tasmania & AGSO "Tasmania NGMA Project 'TASGO' Draft Proposal for a new national geoscience Mapping Accord (NGMA) Project 1994-1997", July 1997.

Mulready J.N. "Review of Exploration in EL29/84 Onshore Tasmania", February, 1987.

Questa Pty Ltd "An Evaluation of the Oil & Gas Potential of Tasmania" Report for Conga Oil, October 1992.

Revill et al "Hydrocarbon Biomarkers, thermal maturity, and depositional setting of the tasmanite oil shales from Tasmania, Australia" in Geochemica et Cosmochimica Acta Vol. 58 No.18, 1994.

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APPENDIX 5

CONODONT GEOTHERMOMETRY IN PALEOZOIC CARBONATE ROCKS OF TASMANIA AND ITS ECONOMIC IMPLICATIONS

BY DR CLIVE BURRETT

1992

Appendix 4.

Australian Journal of Earth Sciences (1992) 39, 61–66

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Conodont geothermometry in Palaeozoic carbonate rocks of Tasmania and its economic implications

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Conodont colour alteration index (CAI) values from Early to Middle Palaeozoic marine carbonate rocks of the West Tasmania Terrane range from 1.5 to 8. Highest CAI values are found in hornfels adjacent to a Jurassic dolerite intrusion. CAI of 5 indicate temperatures of 300–480°C and are found either adjacent to Jurassic dolerite intrusions or in an arcuate belt around the west and northwest of the island rimming the Precambrian rocks of the Tyennan and Rocky Cape regions. CAI values of 1.5 are found in the southwest of the state and values of 2 are common in central southern Tasmania.

Low vitrinite reflectance values from the unconformably overlying Late Carboniferous–Late Triassic Parmeener Supergroup, suggest that the major heat input into the conodonts was in the Late Devonian–Early Carboniferous associated with regional metamorphism and the widespread intrusions of granitoids.

High CAI values are not due to thick overburden as these are very unlikely in many parts of Tasmania. It is probable that high heat flow occurred in many areas of northwest Tasmania in the Late Devonian and that these areas are prospective for hydrothermal ore deposits.

Low CAI (1.5–3) in southwest and central Tasmania suggest that, if Gordon Group carbonate rocks are present at depth, they are in the oil and gas windows and may have, or may be, generating oil and gas.

Key words: conodonts, Devonian, gas, metamorphism, Ordovician, ores, petroleum, Tabberabberan Orogeny, Tasmania.

INTRODUCTION

During the 1970s Harris and others found that the colour variation in conodonts could be related primarily to metamorphic temperature (Epstein *et al.* 1977; Harris 1979). Conodonts from unmetamorphosed carbonate rocks are amber in colour with white matter in the denticles, whereas conodonts from metamorphosed carbonate sequences are darker and often black. The colour change is progressive and irreversible. Epstein *et al.* (1977) established a 'Colour Alteration Index' (CAI) scale from 1 to 5, which was later extended to 8 (Harris 1979; Rejebian *et al.* 1987). They experimentally reproduced the colours found in field samples and suggested the following values for each CAI: 1 = 50–80°C; 1.5 = 50–90°C; 2 = 60–140°C; 3 = 110–200°C; 4 = 190–300°C; 5 = 300–480°C, 6 = 360–550°C; 6.5 = 440–610°C; 7 = 490–720°C and 8 > 600°C. This is a useful geothermometer that overlaps with the well established palynomorph thermal alteration index at low temperatures, and the well known mineral indices of metamorphism at high temperatures (Ovnatanova & Petrosyants 1984). The temperature assignments have been verified in several studies (Armstrong & Strens 1987; Kovacs & Arkai 1987) and the method applied to basinal studies on several continents (Bergstrom 1980; Legall *et al.* 1981; Aldridge 1984, 1986; Bao & Wang 1984; Nicoll & Gorter 1984; Nowlan & Barnes 1987; Orndorff *et al.* 1988).

METHODS

Conodonts have been obtained from almost all major outcrops of Ordovician (Gordon Group) to Early Devonian (Eldon Group) marine carbonate sequences in the West Tasmania Terrane. Specimens were compared with standard samples prepared, using the technique of Epstein *et al.* (1977) from CAI 1 conodonts obtained from unmetamorphosed Australian and American Palaeozoic carbonate rocks.

RESULTS

Since no appreciable differences in CAI values (Table 1, Fig. 1) were found between the tops and the bases of the thick (up to 1800 m) limestone piles only one CAI value has been used for each location. Only three samples from Devonian carbonate units yielded conodonts and these have been plotted. Their inclusion makes no difference to the contouring. The CAI value of 8 is found in a wollastonite-diopside-epidote hornfels adjacent to a Jurassic dolerite at Lake Sydney (Correy 1983) in

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Table 1 Localities referred to in the text with conodont colour alteration indices (CAI) ages and grid references.

Locality	No. on Fig. 1	Grid ref.	CAI	Age and unit
Andrew River	1	CP 940131	5	M.Ord., Gordon Gp
Bubs Hill	2	CP 985361	5	M.-L.Ord., Gordon Gp
Claude Creek	3	DQ 293068	5	M.Ord., Gordon Gp
Duck Creek	4	CP 381749	5	M.-L.Ord., Gordon Gp
Eugenana	5	DQ 422349	5	M.Ord., Gordon Gp
Everlasting Hills	6	DP 200154	4	M.-L.Ord., Gordon Gp
Florentine Valley	7	DN 560820	3	M.-L.Ord., Gordon Gp
Flowery Gully	8	DQ 848312	5	M.Ord., Gordon Gp
Franklin River	9	CN 990910	5	M.Ord., Gordon Gp
Gunns Plains	10	DQ 190297	5	M.-L.Ord., Gordon Gp
Huskisson Syncline	11	CP 658743	5	M.-L.Ord., Gordon Gp
Isle Du Golfe	12	DM 615755	4	M.-L.Ord., Gordon Gp
Judds Cavern	13	DN 662107	4	M.Ord., Gordon Gp
Lake Sydney	14	DN 682069	6	L.Ord.-E.Sil., Eldon?Gordon Gps
Liena	15	DP 359996	5	M.-L.Ord., Gordon Gp
Loongana	16	DQ 120150	5	M.-L.Ord., Gordon Gp
Lower Gordon River	17	CN 911865	5	L.Sil.-E.Dev. Eldon Gp
Lower Gordon River	18	CN 990740	5	M.-L.Ord., Gordon Gp
Lune River/Ida Bay	19	DM 891921	3	M.-L.Ord., Gordon Gp
Melrose/Paloona	20	DQ 401339	5	M.Ord., Gordon Gp
Moina	21	DG 223067	5	M.Ord., Gordon Gp
Mole Creek Area	22	DP 505990	5	M.-L.Ord., Gordon Gp
Olga River	23	CN 000701	5	M.-L.Ord., Gordon Gp
Picton River	24	DN 739140	3	M.-L.Ord., Gordon Gp
Point Cecil	25	DM 673738	3	M.-L.Ord., Gordon Gp
Point Hibbs	26	CN 575804	1-5	M.Ord.-M.Devonian
Precipitous Bluff	27	DM 677880	5	M.-L.Ord., Gordon Gp
Queenstown	28	CP 800400	5	M.-L.Ord., Gordon Gp
Railton	29	DQ 516225	5	M.Ord., Gordon Gp
Salisbury River	30	DM 680969	5	M.-L.Ord., Gordon Gp
Sophia River	31	CP 900744	5	M.-L.Ord., Gordon Gp
Surprise Bay	32	DM 716736	3	M.-L.Ord., Gordon Gp
Vale of Belvoir	33	DQ 076010	5	M.-L.Ord., Gordon Gp
Vanishing Falls	34	DM 704954	1.5-2	M.-L.Ord., Gordon Gp
Wilson River	35	CP 646763	5	M.-L.Ord., Gordon Gp
Zeehan	36	CP 617614	5	M.-L.Ord., Gordon Gp

southwest Tasmania. CAI 5 values are common in western and northwestern Tasmania and form an arcuate belt following the outcrop of the Early Palaeozoic rocks around the Precambrian metamorphic units in the Tyennan region. CAI values decrease to the east with values of 2 to 3 in central southern Tasmania and the lowest values (1.5–2) are found in the south at Vanishing Falls. High values (5) are found at Precipitous Bluff.

INTERPRETATION

CAI values are the result of the total heat input into the conodont element. A brief pulse of high heat input may have the same effect as lower heat input over much longer periods of time. As Tasmania has been subjected to many heating events that varied in intensity, longevity and geographic distribution (Williams 1989), caution is clearly necessary in the interpretation of the CAI isograds.

In the Appalachians, Epstein *et al.* (1977) suggested that 'depth of burial and the attendant increase in temperature is the dominant factor' in controlling CAI. If this is true in Tasmania, then post-Middle Devonian overburdens of 10 km would have to be postulated in areas such as western Tasmania where CAI of 5 are common in Late Ordovician–Early Devonian limestone deposits. This appears highly unlikely, as the unconformably overlying Late Carboniferous to Late Triassic Parmeener Supergroup rarely exceeds 1 km in thick-

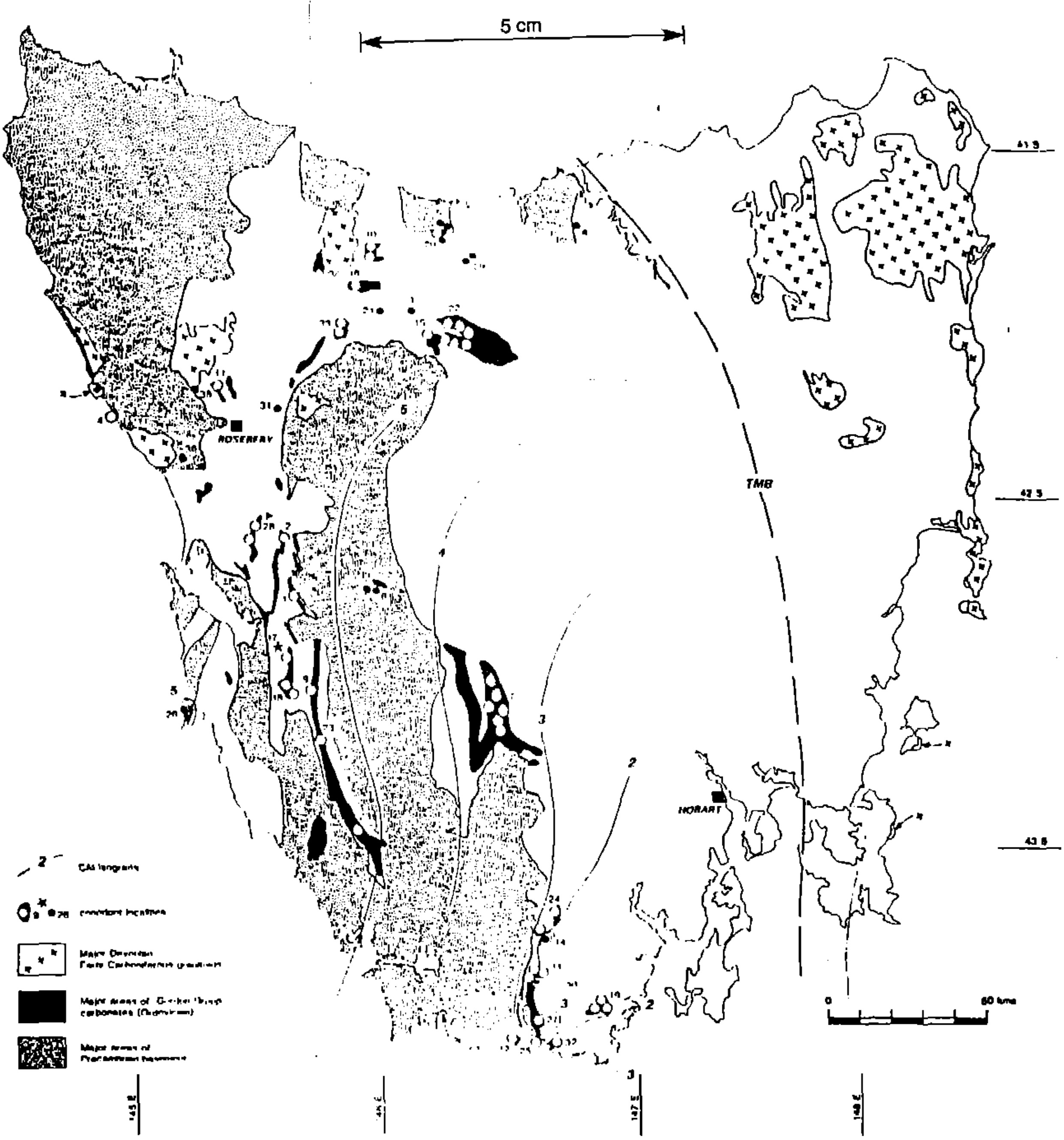

Fig. 1 Contours drawn on CAI values obtained from conodonts from the Gordon Group (Ordovician; O) and from Eldon Group and correlative Siluro-Devonian carbonate units (×). TMB is the eastern limit of the Tamar Mobile Belt of Leaman and Richardson (1990) which defines the margin of the West Tasmania Terrane and includes the Tamar Fracture System of Williams (1989). The northwestern area of Precambrian rocks is the Rocky Cape Region and the central area is the Tyennan Region. Conodont localities are listed in Table 1.

ness and is usually much thinner (Clarke & Forsyth 1989) and the younger rocks such as the Jurassic dolerite and Tertiary sedimentary deposits are most unlikely to have exceeded another 3 km (Everard *in* Turner & Calver 1987). This conclusion is supported by the low Ro values from the Permo-Triassic sequence.

Therefore, if depth of burial is insufficient to account for the high CAI values, then high heat flow has to be postulated for Tasmania in post-Early Devonian times. The conodonts may have been heated in the Devonian–Early Carboniferous by regional metamorphism and granitoid intrusions (McClenaghan 1989); in the Jurassic by the intrusion of large volumes of doleritic magma (Carey 1976); in the Cretaceous by continental rifting and local syenitic intrusions (Sharples & Klootwijk 1981) and in the Tertiary by widespread rifting and basaltic volcanism (Sutherland 1989).

Although there was sufficient heatflow during the Cretaceous to reset the 'soft' magnetism in Palaeozoic sequences (Sharples & Klootwijk 1981), this could have been of relatively low intensity if distributed over 10 Ma. Except very close to dolerite, vitrinite reflectance values from the Parmeener Supergroup (Banks *et al.* 1989) are commonly in the range 0.5–0.6 (i.e. CAI 1) and suggest that post-Middle Carboniferous heating was of low intensity.

It is therefore probable that the major heat input into the conodonts was in the Devonian and associated with the widespread regional metamorphism and intrusion of granitoid from the Eifelian to the Early Carboniferous. There is good correlation of low CAI values with the deepest levels of granite as determined from gravity data (cf. Richardson 1989). Other estimates of the intensity of Devonian regional metamorphism in western Tasmania are in good agreement with the CAI values in this study. For instance, Hall (1990), using the six component chlorite geothermometer-geobarometer of Walshe (1986), estimated temperatures of 310–340°C with an average of 328°C, and Green (1983) estimated temperatures from 350–400°C. These data agree well with the nearby black (CAI = 5) conodonts that suggest temperatures between 300°–480°C. CAI values of 3 from Surprise Bay on the south coast are not supported by vitrinite reflectance equivalents of 1.15 (CAI = 2) calculated from the organic geochemistry of carbonate samples (Volkman 1988) but are supported by reflectance values on graptolites (A. C. Cook pers. comm. 1990) from the same locality average 2.17 or a CAI of 3 (Bertrand 1990).

Channel samples from the Early Devonian Point Hibbs Limestone (on the remote west coast of Tasmania, collected by J. Conkin in the early 1960s) yielded a mixture of low CAI Devonian conodonts and high CAI Ordovician conodonts. Burrett (1984) processed Conkin's samples and interpreted this mixing as indicating metamorphism, uplift and redeposition of the conodonts as clasts within the Point Hibbs Limestone in the Pragian. However, follow-up work by Carey and Berry (1988) showed that the channel samples had been collected across a series of low angle thrust faults that brought together Ordovician (Gordon Group) and Devonian (Point Hibbs) carbonate units. Both carbonate units contain a variety of high (5) and low (2) CAI values. Conodonts from the dolomite that fills the thrust planes have the characteristic pitted texture indicative of hydrothermal alteration (Rejebian *et al.* 1987).

The data from western Tasmania suggest that metamorphic temperatures of over 300°C were common in the Ordovician limestone and that later Devonian thrusting brought slices of varied metamorphic grade into contact. This later Devonian thrusting is important through all of Tasmania (Bendall *et al.* 1991). Subsequently, hydrothermal alteration occurred along thrust planes.

An important conclusion is that very high heat flow was developed during the Tabberabberan Orogeny. The palaeogeothermal gradient at the time of the Devonian granitoid intrusion is difficult to assess because the amount of overburden is hard to estimate and the duration of high heat flow associated with the intrusions may have been between 10–100 Ma. CAI of 5 (the most common value in western Tasmania) may be achieved at 370°C in 1000 years or at 300°C in 50 Ma (Rejebian *et al.* 1987). This latter temperature, if present at a depth of 4 km, suggests a geothermal gradient of 7.5°C per 100 m during the Tabberabberan Orogeny, or double that of normal modern continental gradients ($<$ 3°C per 100 m according to van Orstrand 1951).

ECONOMIC IMPLICATIONS

The zone of maximum generation of oil in a sediment lies between CAI 1.5 and CAI 2. Thus, outcropping Ordovician limestone in south and central Tasmania has reached the oil window and in the subsurface, may be expected to be generating oil, assuming sufficient total organic carbon content. Areas with CAI 2–3 are in the gas window. Work by M. Bendall of Conga Oil Ltd and J. Volkman of CSIRO has shown that some of the numerous hydrocarbon seeps and shows ($>$ 260) that have been recorded in the last 100 years in Tasmania have geochemical signatures remarkably similar to those of the Ordovician Gordon Group carbonate (Volkman 1988). It is possible that, if suitable reservoirs, such as palaeokarst, exist at depth either in or adjacent to Gordon Group limestone with low CAI values, then oil and gas may be present in commercial quantities.

The extension of areas with high CAI values beyond the known extent of granite intrusions may suggest areas of hydrothermal activity and indicate regional prospectivity for mineral deposits, which may be useful, not only economically, but in regional land use assessments (Baillie & Burrett 1990). A search for hydrothermally altered cono-

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donts should be useful in detecting ore deposits in areas of both high and low CAI values. Their distribution might even be used to reconstruct palaeoconvection cells in mineralized terrains.

CONCLUSIONS

Conodont CAI isograds from Early to Middle Palaeozoic carbonate units provide a good indication of variations in palaeoheat flow in Tasmania. The major heat input is interpreted as being Devonian, associated with the intrusion of granite and with regional metamorphism during the Tabberabberan Orogeny. Regional metamorphism in western and northwestern Tasmania was just above 300°C and was due to high heat flow rather than to depth of burial. Thrusting during the Tabberabberan Orogeny has brought together thrust slices with very different CAI.

Hydrothermally altered conodonts should be searched for and may provide evidence of palaeohydrothermal systems.

Areas with low CAI (1.5–2.5) in central and southern Tasmania are in the oil and gas windows, are associated with hydrocarbon seeps and are prospective for oil and gas.

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REFERENCES

ALDRIDGE R. J. 1984. Thermal metamorphism of the Silurian strata of the Oslo region, assessed by conodont colour. *Geological Magazine* 121, 347–349.

ALDRIDGE R. J. 1986. Conodont paleobiogeography and thermal maturation in the Caledonides. *Journal of the Geological Society* 143, 177–184.

ARMSTRONG H. A. & STRENS M. R. 1987. Contact metamorphism of conodonts as a test of colour alteration index temperatures. *In* Austin R. L. ed. *Conodonts: Investigative Techniques and Applications*, pp. 203–208. Ellis Horwood, Chichester.

BAILLIE P. & BURRETT C. 1990. Conodont geothermometry and land use planning in Tasmania. *Mines Department of Tasmania Report* (unpubl.)

BANKS M. R., BACON C. A. & CLARKE M. J. 1989. Economic Geology. *In* Burrett C. F. and Martin E. L. eds. Geology and Mineral Resources of Tasmania. *Geological Society of Australia Special Publication*, 15, 335–338.

BAO D. & WANG Y. 1984. Huabei diqu aotaoji yaxingshi sebian he youji wuzhi chengshudu fenqu chubu yanjiu (A preliminary study of conodont colour alteration and organic maturity zones in the Ordovician system of north China). *Shiyou Shiyan Dizhi (Experimental Petroleum Geology)* 6, 311–317.

BENDALL M. R., VOLKMAN J. K., LEAMAN D. E. & BURRETT C. F. 1991. Recent developments in exploration for oil in Tasmania. *Australian Petroleum Exploration Association Journal* 30.

BERGSTROM S. M. Conodonts as paleotemperature tools in Ordovician rocks of the Caledonides and adjacent areas in Scandinavia and the British Isles. *Geologiska Foreningens i Stockholm Forhandlingar* 102, 377–392.

BERTRAND R. 1990. Correlations among the reflectances of vitrinite, chitinozoans, graptolites and scolecodonts. *Organic Geochemistry* 15, 565–574.

BURRETT C. F. 1984. Early Devonian deformation and metamorphism of conodonts in western Tasmania — economic, theoretical and nomenclatural implications. *In* Baillie P. W. and Collins P. L. F. eds. *Mineral Exploration and Tectonic Processes in Tasmania*, pp. 14–16. Geological Society of Australia, Hobart.

CAREY S. P. & BERRY R. F. 1988. Thrust sheets at Point Hibbs, Tasmania: Palaeontology, sedimentology and structure. *Australian Journal of Earth Sciences* 35, 169–180.

CAREY S. W. 1976. *The Expanding Earth*, pp. 567. Elsevier, Amsterdam.

CLARKE M. J. & FORSYTH S. M. 1989. Late Carboniferous-Triassic. *In* Burrett C. F. and Martin E. L. eds. Geology and Mineral Resources of Tasmania. *Geological Society of Australia Special Publication* 15, 293–338.

CORREY J. J. 1983. The geology of the Gordon and Eldon Group correlates and the Parmeener Supergroup in the Mt Bobs–The Boomerang area, southern Tasmania. BSc(Hons) thesis, University of Tasmania, Hobart (unpubl.).

EPSTEIN A. G., EPSTEIN J. B. & HARRIS L. D. 1977. Conodont colour alteration — an index to organic metamorphism. *United States Geological Survey Professional Paper* 995, 1–27.

GREEN G. R. 1983. The geological setting and formation of the Rosebery volcanic-hosted massive sulphide orebody, Tasmania. PhD thesis, University of Tasmania, Hobart (unpubl.)

HALL S. 1990. The Koonya prospect, Roseberry, Tasmania. BSc(Hons) thesis, University of Tasmania, Hobart (unpubl.)

HARRIS A. G. 1979. Conodont color alteration, an organic-mineral metamorphic index, and its application to Appalachian basin geology. *Society of Economic Paleontologists and Mineralogists Special Publication* 26, 3–16.

KOVACS S. & ARKAI P. 1987. Conodont alteration in metamorphosed limestones from northern Hungary, and its relationship to carbonate texture, illite crystallinity and vitrinite reflectance. *In* Austin R. L. ed. *Conodonts: Investigative Techniques and Applications*, pp. 209–229. Ellis Horwood, Chichester.

LEAMAN D. E. & RICHARDSON R. G. 1990. Tasmania crustal features. *Geological Society of Australia Abstracts* 25, 100–101.

LEGALL F. D., BARNES C. R. & MACQUEEN R. W. 1981. The thermal maturation, burial history and hotspot development of Paleozoic strata of southern Ontario-Quebec, from conodont and acritarch color alteration studies. *Bulletin of Canadian Petroleum Geology* 29, 492–539.

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McClenaghan M. P. 1989. Mid-Palaeozoic granitoids. *In* Burrett C. F. and Martin E. L. eds. Geology and Mineral Resources of Tasmania. *Geological Society of Australia Special Publication* 15, 253–270.

Nicoll R. S. & Gorter J. D. 1984. Conodont colour alteration, thermal maturation and the geothermal history of the Canning Basin, Western Australia. *Australian Petroleum Exploration Association Journal* 24, 243–258.

Nowlan G. S. & Barnes C. R. 1987. Application of conodont colour alteration indices to regional and economic geology. *In* Austin R. L. ed. *Conodonts: Investigative Techniques and Applications*, pp. 188–202. Ellis Horwood, Chichester.

Orndorff R. C., Harris A. G. & Schultz A. P. 1988. Reevaluation of conodont color alteration patterns in Ordovician rocks, eastern-central valley and ridge and western Blue Ridge provinces, Tennessee. *United States Geological Survey Bulletin* 1893, 1–10.

Ovnatanova N. S. & Petrosyants M. A. 1984. Paleothermometrirovaniye po okraske konodotov i spor (paleothermometry based on conodont and spore colors) *Doklady Akademii Nauk SSSR* 276, 1446–1449.

Rejebian V. A., Harris A. G. & Huebner J. S. 1987. Conodont color and textural alteration: an index to regional metamorphism, contact metamorphism, and hydrothermal alteration. *Geological Society of America Bulletin* 99, 471–479.

Richardson R. G. 1989. Crustal Structure. *In* Burrett C. F. and Martin E. L. eds. Geology and Mineral Resources of Tasmania. *Geological Society of Australia Special Publication* 15, 465–467.

Sharples C. & Klootwijk C. T. 1981. Palaeomagnetic results from the Gordon Subgroup of Tasmania: further evidence for a Late Cretaceous magnetic overprint in southeastern Australia. *Papers and Proceedings of the Royal Society of Tasmania* 115, 85–91.

Sutherland F. L. 1989. Tertiary volcanism. *In* Burrett C. F. and Martin E. L. eds. Geology and Mineral Resources of Tasmania. *Geological Society of Australia Special Publication* 15, 383–398.

Turner N. J. & Calver C. R. 1987. St Marys. *Geological Survey Explanatory Report*. Tasmanian Department of Mines, Hobart.

Van Orstrand C. E. 1951. Observed temperatures in the Earth's crust. *In* Gutenberg B. ed. *Internal Constitution of the Earth*, pp. 107–149. Dove, New York.

Volkman J. K. 1988. Hydrocarbons in Ordovician limestones from Queenstown and Lune River, Tasmania. *CSIRO Marine Laboratories, Hobart, Report* 88HCL, 1–22.

Walshe J. L. 1986. A six component chlorite solid solution model and the conditions of chlorite formation in hydrothermal and geothermal systems. *Economic Geology* 81, 681–703.

Williams, E. 1989. Summary and Synthesis. *In* Burrett C. F. and Martin E. L. eds. Geology and Mineral Resources of Tasmania. *Geological Society of Australia Special Publication* 15, 468–499.

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APPENDIX 6

HYDROCARBON BIOMARKERS , THERMAL MATURITY, AND DEPOSITIONAL SETTING OF TASMANITE OIL SHALES FROM TASMANIA , AUSTRALIA

BY A.T.REVILL ET AL

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Hydrocarbon biomarkers, thermal maturity, and depositional setting of tasmanite oil shales from Tasmania, Australia

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Abstract—This study represents the first geological and organic geochemical investigation of samples of tasmanite oil shale representing different thermal maturities from three separate locations in Tasmania, Australia. The most abundant aliphatic hydrocarbon in the immature oil shale from Latrobe is a C_{19} tricyclic alkane, whereas in the more mature samples from Oonah and Douglas River low molecular weight *n*-alkanes dominate the extractable hydrocarbon distribution. The aromatic hydrocarbons are predominantly derivatives of tricyclic compounds, with 1,2,8-trimethylphenanthrene increasing in relative abundance with increasing maturity. Geological and geochemical evidence suggests that the sediments were deposited in a marine environment of high latitude with associated cold waters and seasonal sea-ice. It is proposed that the organism contributing the bulk of the kerogen, *Tasmanites*, occupied an environmental niche similar to that of modern sea-ice diatoms and that bloom conditions coupled with physical isolation from atmospheric CO_2 led to the distinctive "isotopically heavy" $\delta^{13}C$ values (−13.5‰ to −11.7‰) for the kerogen. $\delta^{13}C$ data from modern sea-ice diatoms (−7‰) supports this hypothesis. Isotopic analysis of *n*-alkanes in the bitumen (−13.5 to −31‰) suggest a multiple source from bacteria and algae. On the other hand, the *n*-alkanes generated from closed-system pyrolysis of the kerogen (−15‰) are mainly derived from the preserved *Tasmanites* biopolymer algaenan. The tricyclic compounds (mean −8‰) both in the bitumen and pyrolysate, have a common precursor. They are consistently enriched in ^{13}C compared with the kerogen and probably have a different source from the *n*-alkanes. The identification of a location where the maturity of the tasmanite oil shale approaches the "oil window" raises the possibility that it may be a viable petroleum source rock.

INTRODUCTION

THE OIL PROSPECTIVITY of onshore Tasmania has long been problematical. Interest in the possibility of finding oil has been stimulated by repeated reports of bitumen strandings on western and southern beaches since the late 19th century (TWELVETREES, 1917). This interest has continued, despite the fact that these coastal bitumens are now thought to arise from Mesozoic or Cainozoic offshore sediments that are poorly represented onshore (VOLKMAN et al., 1992). There have been, however, numerous reports over the last century of oil-seeps onshore (BENDALL et al., 1991), suggesting the possibility that older onshore rocks may also be a source of petroleum. Central to much of this interest has been the organic-rich tasmanite oil shale (subsequently referred to simply as "tasmanite" or "oil shale") which occurs particularly in the north-west of the state (Fig. 1). JAMES et al. (1932) reported that the oil shale was retorted to liberate hydrocarbons as early as 1910, and this carried on until the 1930s, producing about 1.13 megalitres of shale oil.

The tasmanite occurs as a distinctive band low in the Quamby Mudstone. The stratigraphy of Late Palaeozoic sediments in Tasmania has been the centre of much research interest (see CLARKE and FARMER, 1976; CLARKE, 1989) due to the difficulty of applying the (warm water based) internationally accepted biostratigraphic divisions to the cold water environment of Tasmania at this time. Because of this difficulty, the more appropriate Rekunian Series has been proposed (CLARKE and BANKS, 1975; CLARKE and FARMER, 1976) with a subdivision, the Tamarian stage, within which is the Quamby Mudstone (Fig. 2). That part of the Quamby Mudstone containing the oil shale has consistently yielded stage 2 microfloras (TRUSWELL, 1978) and a Faunal Zone 1 macrofauna (Fig. 2; CLARKE and BANKS, 1975). The age has been given as either Early Permian (FOSTER and WATERHOUSE, 1988) or Late Carboniferous (CLARKE, 1992; i.e., a little older or a little younger than 290 my BP, taken as the age of the beginning of the Permian by HARLAND et al., 1990).

The only lithological distinction between the oil shale and surrounding mudstone is that the former contains abundant algal remains. These are dominated by the unicellular alga *Tasmanites punctatus* [NEWTON (1875)] whose biological affinities have been suggested to lie with the extant green alga *Pachysphaera pelagica* [OSTENFELD (1899)] (WALL, 1962). Initially, the tasmanite was thought to have been deposited in an extensive lake (MILLIGAN, 1852), but the discovery of marine fossils (GOULD, 1861) precluded this. Recent work has suggested a nearshore marine origin (BANKS, 1962; CALVER et al., 1984) with the oil shale representing a period of algal blooms (CALVER et al., 1984; CLARKE, 1989). This hypothesis is further supported by comparison of the known occurrence of tasmanite with the inferred palaeogeography of Tasmania during the early Tamarian (BANKS and CLARKE, 1987; Fig. 3).

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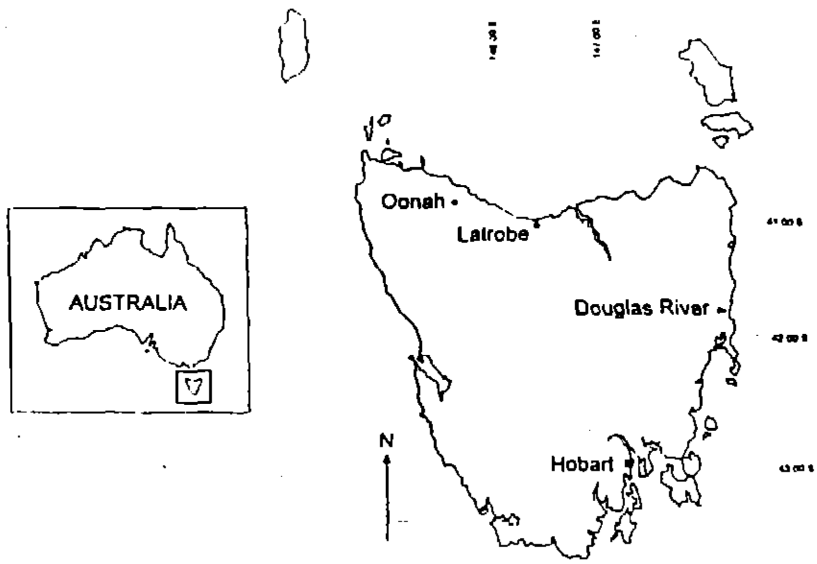

FIG. 1. Sample locations.

There has been much discussion about the correct nomenclature for the abundant microfossils found in the tasmanite (see WALL, 1962). The term spore has been used (SIMONEIT and BURLINGAME, 1973), while studies of some modern prasinophycean genera (*Pachysphaera*, *Halosphaera*, and *Pterosperma*) have shown that the asexual reproductive cycle consists of a phycoma (cyst) and a motile stage (PARKE and HARTOG-ADAMS, 1965; PARKE, 1966; PARKE et al., 1978). GUY-OHLSON (1988) identified various developmental stages of *Tasmanites* in the Jurassic of Sweden and concluded that the fossil cysts were phycomata. Recent studies (BOALCH and GUY-OHLSON, 1992; GUY-OHLSON and BOALCH, 1992) have indicated that the morphology of fossil *Tasmanites* are sufficiently close to some rarely found living specimens of *Pachysphaera* that the genus *Tasmanites* suffices for both. TAPPAN (1980) indicates that the term phycoma describes the non-motile stage specific to prasinophytes and therefore,

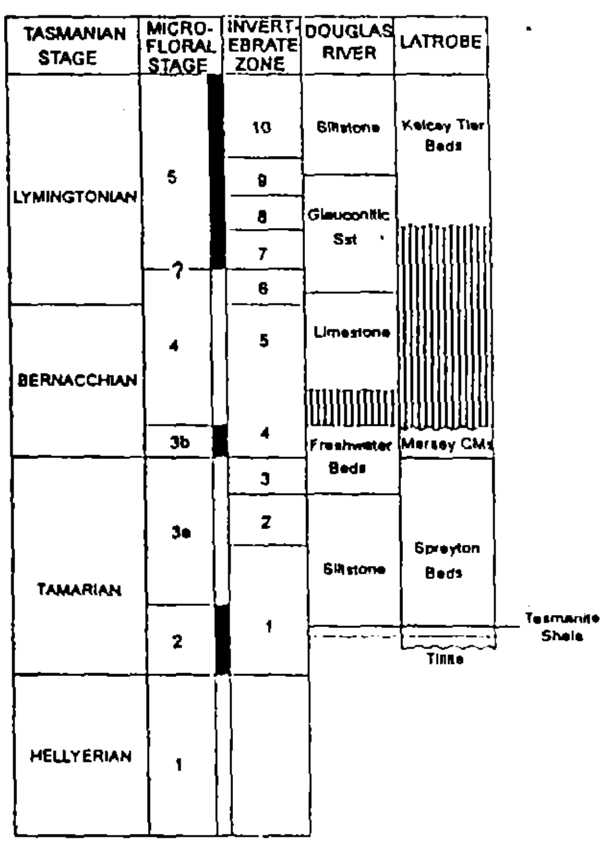

FIG. 2. Correlation chart for the lower (Carboniferous and Permian) sections of the Parmeener Supergroup for Latrobe and Douglas River (adapted from BANKS and CLARKE, 1987). Sst = Sandstone, CMs = Coal Measure Formation.

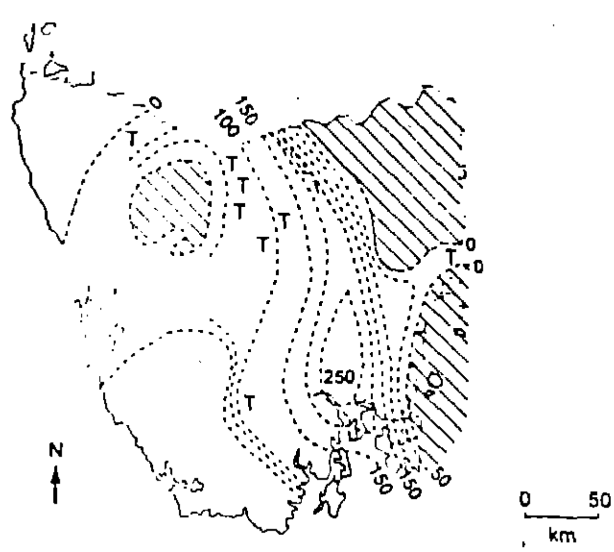

FIG. 3. Suggested paleogeography of Tasmania during the Early Tamarian stage. Dashed lines = isopachs, numbers = thicknesses in metres. T = occurrence of tasmanite oil shale. ☐ = land areas, ☐ = areas of unknown geography. (Adapted from BANKS and CLARKE, 1987).

5 cm

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Table 1. Examples of oil shale characteristics at Oonah.

	Lower bed-lower seam	Lower bed - Upper seam	Middle bed - Upper seam	Upper bed - Lower seam
Thickness of oil shale (m)	0.28-0.42	0.3-0.7	0.38-0.59	0.24-0.28
Thin walled : thick walled fossils	16:1	6.5:1	10.5:1	5.6:1
% Matrix	48.9	71.4	48.8	74.8
% Fossils	36.5	10.1	32.2	5.4
% Spherical fossils	<0.2	0.4	0.2	0.6
% Pyrite framboids	3.5	2.0	4.3	3.7
% Non-framboidal pyrite	1.3	<0.2	<0.2	<0.2
% Vitrinite	0.5	0.2	0.4	n/d
% Elongate burrows	1.2	0.6	1.4	0.6
% Other*	7.9	15.5	12.5	15.3

* Predominantly clay and silt
n/d = not detected
Percentages are from point counts using approximately 500 data points

In the sample from Latrobe, silica-filled burrows are less prevalent and smaller than in the sediments from Oonah. The oil shale at this site exhibits large-scale lensing as well as the small-scale lensing noted above. This suggests a fluctuating environment, and the oil shale maintains a constant thickness possibly indicating an almost flat sea floor.

Within the core taken from Douglas River, two beds of oil shale can be recognised between 320 and 321.5 m (CALVER et al., 1984). The lower bed exhibits a fossil morphology very similar to that from Latrobe. The upper bed has a thin (20 cm thick) basal conglomerate which fines upwards into the oil shale. Similar small-scale structures to those in the sample from Latrobe can be observed and the top of the shale is characterised by flame structures. The oil shale is overlain by a thin fining upwards sequence (ca. 50 cm thick) commencing with conglomerate. Dispersed *Tasmanites* are observed in the silt at the top of this sequence.

Bulk Parameters

Bulk parameters are given in Table 2. The samples from Oonah represent a span from the upper tasmanite seam to below the lower seam.

Total organic carbon (TOC) concentrations are consistently greater in the immature sample from Latrobe and the more mature Douglas River sample than in that of intermediate thermal maturity from Oonah (Table 2). There appears to be no direct correlation between organic carbon content and sulphur concentration in the Oonah sediments, except possibly in the upper seam (Fig. 5). The majority of sulphur is framboidal (Table 1) with the greatest concentration coinciding with the fossil-rich sediments. In the sample from Latrobe, pyrite is present in lower concentrations than at Oonah and appears to be proportional to the TOC content (Fig. 5). Despite having the lowest maturity, the relative amount of extractable organic matter in the Latrobe material is ca. three times that of the other samples. This probably reflects a generally higher fossil concentration in these samples, with some being almost 74% *Tasmanites*.

Total extractable organic matter contained from 56% hydrocarbons in the Latrobe sample to 95% hydrocarbons in the lower shale seam at Oonah; the remainder being attributed to polar material (Table 2).

The high Hydrogen Index (HI) of the Latrobe, Oonah, upper seam and Douglas River samples (Table 2) classify the kerogen as containing hydrogen-rich Type I organic matter (TISSOT and WELTE, 1984) wherein over 70% of the organic

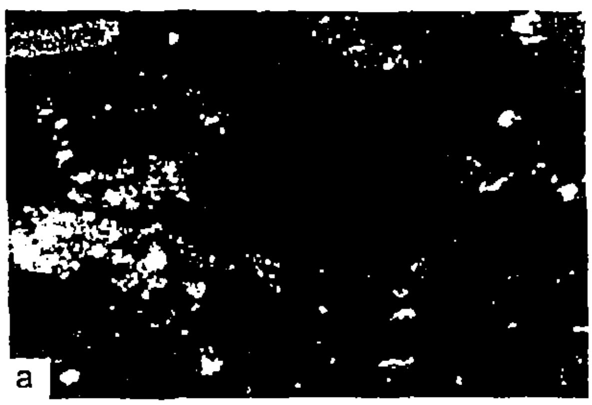

FIG. 4. (a) Fossil *Tasmanites* filled with pyrite from Oonah (diameter = ca. 0.5 mm). (b) Dropstone in tasmanite shale from Oonah. Note how the stone breaks the bedding of the shale. (magnification = ×10).

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to use this description would indicate an acceptance that *Tasmanites punctatus*, found in Tasmanian tasmanite, is the equivalent of a modern prasinophyte. To avoid any taxonomic inference, the abundant microfossils in these samples will be referred to as *Tasmanites* or simply fossils. Although known to range from the Cambrian (540 Ma) to present, *Tasmanites* and related forms occur in high concentrations only in the tasmanite deposits of Tasmania (Permian) and Alaska (Jurassic) with other less abundant occurrences in the Sahara and Brazil (AQUINO NETO et al., 1992).

The fossils were spheroidal, but become disc shaped with sediment compaction, ranging in size from <0.1 to >0.6 mm in diameter. The wall of the fossil is formed of two to three layers, with the outer layer rarely preserved. The middle layer forms the bulk of the wall, the inner layer being thin and fibrous (KANTSLER, 1980).

The algal origin for the tasmanite and its organic richness has led to a wide range of geochemical studies of the kerogen. Data have been presented on carboxylic acids (BURLINGAME et al., 1969; SIMONEIT and BURLINGAME, 1973), and more recently the hydrocarbon content (PHILP et al., 1982; AZEVEDO et al., 1990; SIMONEIT et al., 1990; AZEVEDO et al., 1992). These studies have identified novel aliphatic and aromatic compounds, but all have been based on samples from the one site at Latrobe (Fig. 1), where the oil shale is relatively immature. In this paper we report a comprehensive organic geochemical study of the tasmanite oil shale, including a comparison of immature and mature samples from different locations in Tasmania.

EXPERIMENTAL

Samples

Samples were collected from rock outcrops at Oonah, Latrobe, in the Mersey Valley and from a core taken at Douglas River (Fig. 1; for stratigraphy see Fig. 2). The rock sample from Latrobe shared many of the characteristics of that from Oonah, except that it came from a continuous 1.8 m seam, 21.4 m above the basal conglomerate within the Spreyton beds (Fig. 2). A spore concentrate was obtained from a sample collected at Oonah by density separation of the fossils from the crushed rock using ferric chloride.

Extraction

Total solvent-extractable compounds were obtained by sonication of the crushed rock samples (ca. 50 g) with chloroform/methanol (2:1, 3 × 50 mL). The composition of a portion of the total extracts was determined either by gravimetry after fractionation or by Iatroscan thin-layer chromatography-flame ionisation detection, using hexane as the developing solvent (VOLKMAN et al., 1986). Saturated and aromatic hydrocarbons were isolated by applying 30 mg of extract to a glass column containing 3 g of silicic acid (100–200 mesh) capped with 1 g of activated alumina (BDH). Aliphatic hydrocarbons were eluted with hexane (20 mL) and a second fraction containing aromatic hydrocarbons was obtained by eluting with hexane:toluene (1:1; 20 mL). Resins and asphaltenes were eluted with chloroform (20 mL) and methanol (10 mL).

Analyses

Hydrocarbon fractions were analysed by capillary gas chromatography on a 50 m nonpolar methyl silicone fused silica capillary column (HP-1, 0.32 mm i.d., 0.25 μm film) with on-column injection and hydrogen as the carrier gas. The temperature program was 45°C for 1 min, followed by a ramp to 120°C at 30°C min^{-1} then a ramp to 310°C at 4°C min^{-1}. The oven was then maintained isothermally for 15 min.

Biomarker information was obtained by gas chromatography-quadrupole mass spectrometry (Hewlett Packard 5790 MSD with HP 5890 GC and 59970A computer workstation) in selected ion monitoring (SIM) mode. Typical conditions were: electron multiplier 2200 V, transfer line 310°C, electron impact energy 70 eV. GC conditions were as above except that helium was used as carrier gas. Samples were also analysed using metastable reaction monitoring GC-MS using a VG 70E instrument fitted with an HP 5790 GC and controlled by a VG 11-250 data system. The GC was equipped with a HP Ultra-1 capillary column (50 m × 0.2 mm i.d.) connected to a OCI-3 cooled on-column injector (SGE) with a retention gap of uncoated fused silica (0.5 m × 0.33 mm i.d.). The oven was programmed from 50 to 150°C at 10°C min^{-1} and then to 300°C at 3°C min^{-1} with a final hold time of 30 min. The carrier gas was hydrogen with a linear flow of 30 cm s^{-1}. The mass spectrometer was operated with a source temperature of 240°C, ionisation energy of 70 eV and interface and re-entrant at 310°C. In full scan mode the MS was operated from m/z 650 to m/z 50 at 1.8 s per decade and an inter-scan delay of 0.2 s. In MRM mode, the magnet current and ESA voltage were switched to sequentially sample 26 selected parent-daughter pairs. The sampling time was 40 ms per reaction with a 10 ms delay giving a total cycle time of 1.3 s.

Gas chromatography-isotope ratio mass spectrometry (GC-IRMS) was carried out as described by HAYES et al. (1990) using a Finnigan-MAT 252 isotope ratio mass spectrometer linked to a Varian 3400 GC via a cupric oxide combustion furnace operated at 900°C. Isotopic calibration was made using an external primary CO_2 standard introduced via a sample bellows and change-over valve and checked using deuterium labelled *n*-alkanes as internal standards. The latter, in hexane, were co-injected with the sample onto a J&W DB-5 capillary column (30 m × 0.25 mm i.d.) using a Varian SPI injector. The oven was programmed from 50–300°C at 6°C min^{-1}.

Closed-System Pyrolysis

Kerogen was isolated from the tasmanite shale by standard acid digestion techniques and pyrolysed in evacuated quartz tubes for 72 h at 300, 330, and 350°C, in the presence of water. Only liquid products were isolated and these were treated in the same way as other extracts. Rock-Eval derived kinetic parameters on whole rock samples of Latrobe tasmanite (AGSO #1995) were determined by Daniel Jarvie, Humble Instruments, Humble, Texas.

RESULTS AND DISCUSSION

Geological Setting of the Tasmanite Oil Shale

The tasmanite at Oonah consists of two seams, separated by up to 6.7 m of siltstone. The lower and upper seams contain two and three *Tasmanites*-rich beds, respectively. These beds consist of a multiplicity of lenses, each up to about a millimetre thick and a few centimetres long, separated by silt layers. The beds generally show a gradually increasing concentration of algal remains upwards. The fossil content decreases rapidly at the top of each bed. The oil shale contains fossils in spherical or flattened forms, the latter being much more common. Spherical *Tasmanites* are observed in fossil-poor sediment, but are absent or rare in fossil-rich sediment (Table 1), and tend to be filled with framboidal pyrite with or without collophane. The flattened disks are probably produced by compaction of the spheroidal form. The fossils exist as thin- and thick-walled specimens, the latter having two distinct walls (Fig. 4). The samples from Oonah contain relatively high levels of clay and silt (quartz) grade sediments. The fossil-rich sediments also contain a greater abundance of elongate, horizontal, silica-filled burrows (Table 1).

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Table 2. Bulk parameters for tasmanite samples

Sample	Sample No.†	TOC (% whole sample)	EOM (mg/g TOC)	Iatroscan TLC-FID: Hydrocarbons (%, (mg/g TOC))	Polars (%)	Rock-Eval: T_{max} (°C)	S_1 (kg/Tonne)	S_2 (kg/Tonne)	S_3 (kg/Tonne)	PI	HI	OI
Latrobe	1	31.3	52	56* (29)	44	444	12.5	304.2	5.6	0.039	972	18
Oonah												
Upper Seam												
Total	2	6.9	66	94 (62)	6	443	3.6	65.2	0.3	0.052	937	4
fossil Concentrate	3	63.0	23	85 (19)	15	446	30.8	590.8	2.3	0.050	937	3
Siltstone above seam	9	1.01	n.m.	n.m.	n.m.	437	0.04	0.89	0.73	0.04	88	72
Siltstone between seams	7	0.78	n.m.	n.m.	n.m.	440	0.07	1.30	0.34	0.05	166	43
Lower Seam												
Total	6	8.1	32	95 (30)	5	440	1.4	54.4	2.2	0.025	675	27
fossil Concentrate	4	61.3	n.m.	n.m.	n.m.	444	22.82	534.94	3.23	0.04	87[illegible]	5
Siltstone below seam	8	1.1	35	73 (25)	27	436	0.1	1.8	0.6	0.052	163	51
Douglas River	5	17	34	90 (31)	10	446	6.3	147.5	0.2	0.041	868	1

† Sample number refers to Fig. 13
n.m. = not measured
* determined by gravimetry
PI = Production Index = $S_1 / S_1 + S_2$

matter is convertible to hydrocarbons. The slightly reduced HI value from the Oonah lower seam may be a result of more oxidation/reworking consistent with the elevated Oxygen Index (OI) value.

Hydrocarbon Distributions and Source Characteristics

The GC-FID traces (Fig. 6) of the saturated hydrocarbons from the tasmanite extracts show *n*-alkane distributions dominated by lower molecular weight components with distributions maximising between *n*-C_{11} and *n*-C_{13}, with little odd or even predominance (Table 3). Samples also contained significant amounts of the acyclic isoprenoids pristane and phytane, though in different relative proportions (Table 3). The siltstone sample has a Pr/Ph ratio higher than the oil shales (Table 3), consistent with deposition under more oxic conditions.

For the purposes of this study, detailed analyses were only conducted on three of the samples: a thermally immature rock sample from Latrobe, the *Tasmanites* fossil concentrate from Oonah, and the core sample from Douglas River. All the samples contain steranes and diasteranes as shown by the *m/z* 217 mass chromatograms (Fig. 7), which is in contrast to their presence as only "trace components" in a sample from Latrobe (Fig. 1) analysed by SIMONEIT et al. (1990).

The relative proportions of C_{27}, C_{28}, and C_{29} steranes show some variation between the samples (Table 3) with C_{29} dominant in the Latrobe sample, C_{27} in Oonah and no preference at Douglas River. Although this may reflect subtle differences in source inputs, maturity will also have an influence. C_{30} 24-*n*-propylcholestanes which are generally accepted to be indicative of a marine source (MOLDOWAN et al., 1990) could not be easily detected in the *m/z* 217 mass chromatogram, but were readily identified (though less so in the Douglas River sample) using MRM together with 2α-methyl and 3β-methyl sterane isomers (Figs. 8–10). The samples also contain relatively high proportions of diasteranes (Fig. 7; Table 3) which were not reported in samples previously analysed (SIMONEIT et al., 1990).

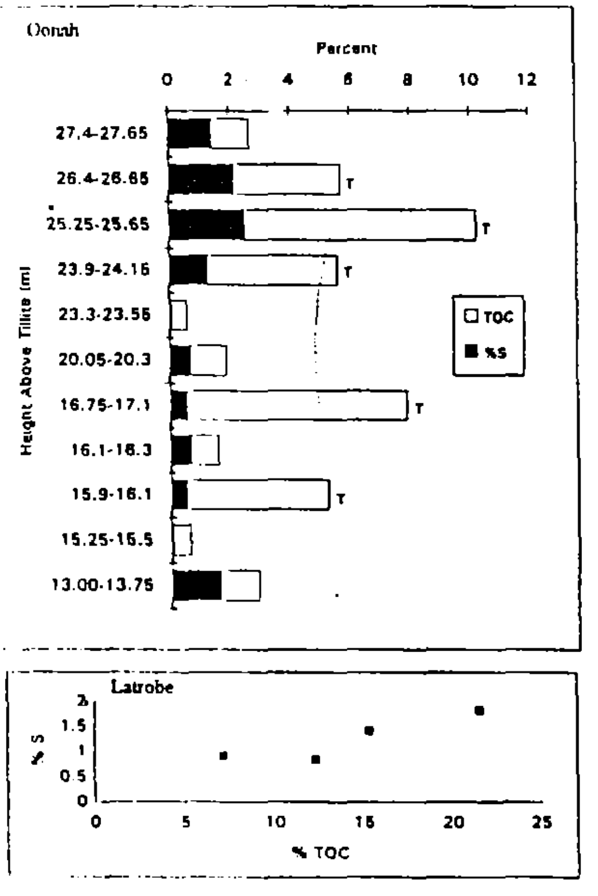

FIG. 5. Relationship between TOC and sulphur content in tasmanite samples. The upper graph shows the relationship with height above the Wynard tillite in a sample from Oonah. T indicates the oil shale seams. The lower graph shows the general relationship in samples taken from Latrobe.

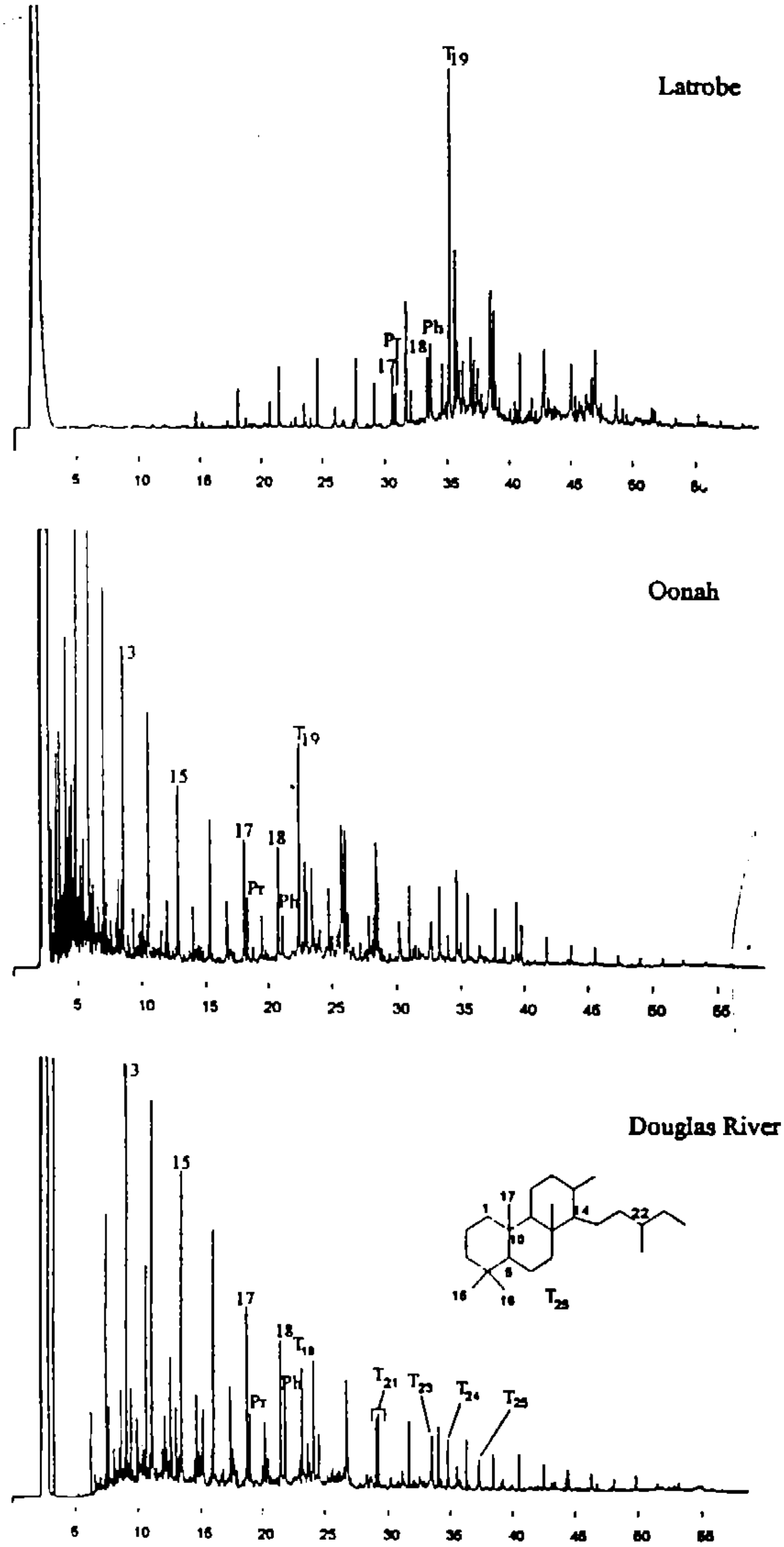

FIG. 6. Gas chromatograms of the aliphatic fractions of extracts from samples taken from Latrobe, Oonah, and Douglas River and an example tricyclic (cheilanthane) structure. Numbers refer to carbon number; Pr = pristane; Ph = phytane; T = tricyclic alkane. Note that the Latrobe fraction was analysed using a different temperature program.

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Table 3: Molecular data for tasmanite samples

Sample	Parameter 1 Pr/Ph	2 Pr/C_{17}	3 CPI	4* steranes $C_{27:28:29}$	5* Diasteranes	6* 20S/S + R	7* αββ/αββ + ααα	8 MPI
Latrobe	0.35	0.62	n.d.	1.3:1:2.6	0.12	0.11	n.d.†	n.d.‡
Oonah								
Upper Seam								
Total	1.6	0.69	0.92	n.m.	n.m.	0.30	0.15	n.m.
fossil concentrate	1.5	0.60	1.03	2.2:1:1.9	0.35	0.35	0.15	0.46
Lower Seam								
Total	1.3	0.48	0.83	n.m.	n.m.	0.31	n.m.	n.m.
Siloasme	3.3	0.91	1.40	n.m.	n.m.	n.m.	n.m.	n.m.
Douglas River	0.7	0.45	0.98	2:1:2	0.64	0.54	0.5	0.36

* calculated from MRM data. † αββ probably absent, isomer is 20R 5β,14α,17α(H). ‡ MPI not applicable at this maturity
n.d. = Not detected; n.m. = Not measured

Parameters:

1. Pristane / Phytane
2. Pristane / n C_{17}
3. Carbon Preference Index $= \frac{(\Sigma C_{25}-C_{33}\text{ odd}) + (\Sigma C_{27}-C_{35}\text{ odd})}{2(\Sigma C_{26}-C_{34}\text{ even})}$
4. 5α,14α,17α(H) 20R steranes
5. C_{29} Diasteranes (βα 20S + 20R) / (ααα + αββ 20S & 20R)
6. C_{29} ααα sterane 20S / (20S + 20R)
7. C_{29} αββ 20R steranes / C_{29} 20R (ααα + αββ) steranes
8. Methyl Phenanthrene Index $= \frac{1.5(2\text{-}MP + 3\text{-}MP)}{P + 1\text{-}MP + 9\text{-}MP}$

The GC-FID chromatograms and extended m/z 191 mass chromatograms for each sample show a high abundance of tricyclic compounds (Figs. 6, 11) and these extend to at least C_{35}. In the m/z 191 chromatograms hopanes occur in trace amounts while C_{23}, C_{24} and C_{25} tricyclic compounds show the greatest intensity. However, the FID chromatogram reveals the predominant tricyclic terpane is a C_{19} compound. In the C_{19} pseudo homologue, the abundance of the m/z 191 ion is minor compared with the base peak at m/z 123 (AQUINO NETO et al., 1982). In the MRM reactions used to detect hopanes (Figs. 8–10; e.g., 412 → 191 for the C_{30} hopane), tricyclic terpanes appear as nonquantitative artefacts as a consequence of their high relative abundance and the limitations of the linked scan technique used for the analysis. Only the C_{30} tricyclic is specifically detected using the 416 → 191 reaction. Measurement of the C_{27} Ts/Tm hopane ratios was not possible due to interference from an unknown compound co-eluting with Ts.

Examination of the aromatic fraction of samples from Oonah and Douglas River show they are dominated by a single compound (Fig. 12) which was identified by GC-MS as a C_3-phenanthrene. This was positively identified by co-injection with an authentic standard as 1,2,8-trimethylphenanthrene. This compound is seen as one endmember of an identifiable aromatisation sequence as indicated by the presence of partially aromatized intermediates in the less mature samples from Latrobe (Fig. 12; Scheme 1).

Maturity

The samples from Latrobe and the *Tasmanites* concentrate from Oonah exhibit a predominance of the thermodynamically less stable 5α,14α,17α(H) (cf. 5α,14β,17β(H)) sterane isomers (Table 3) indicating that they are thermally immature. This is further emphasised by the greater proportion of the 5α,14α,17α(H) 20R epimer compared with the 20S epimer and the presence of small amounts of 5β(H)-steranes (as determined by metastable reaction monitoring, MRM). A value of 0.54 for the 20 S/S + R sterane ratio (Table 3) suggests the Douglas River sample is within the oil window (PETERS and MOLDOWAN, 1993). An αββ-ααα ratio of 0.5 is consistent with this, the onset of the oil window occurring at about 0.25 (PETERS and MOLDOWAN, 1993).

Maturity estimates based on phenanthrenes (namely the methylphenanthrene index, MPI; Table 3) showed little discrimination. The uniformity in the MPI has been observed previously for low maturity and hydrogen-rich marine organic matter (RADKE et al., 1986; BOREHAM et al., 1988). The presence of aromatic compounds which appear to be derived from the tricyclic precursors in such immature samples (both this study, AZEVEDO et al., 1992, and REVILL et al., 1993) suggests that aromatisation has occurred early in the maturation process. This possibly reflects the unusual nature of the organic matter or microbial influences on the aromatisation processes (TRENDEL, 1985; LOHMANN, 1988; TRENDEL et al., 1989; WOLFF et al., 1989).

There is little evidence to suggest which tricyclic compound is being preferentially converted to the aromatic compounds. The only noticeable correlation being a relative decrease in the complexity of the m/z 191 mass chromatogram in the C_{30} region in the Douglas River sample compared with the Oonah *Tasmanites* concentrate (Fig. 11), which is assumed to be a maturity driven decrease in the three stereoisomers relative to the 13β(H),14α(H) compound (CHICARELLI et al., 1988).

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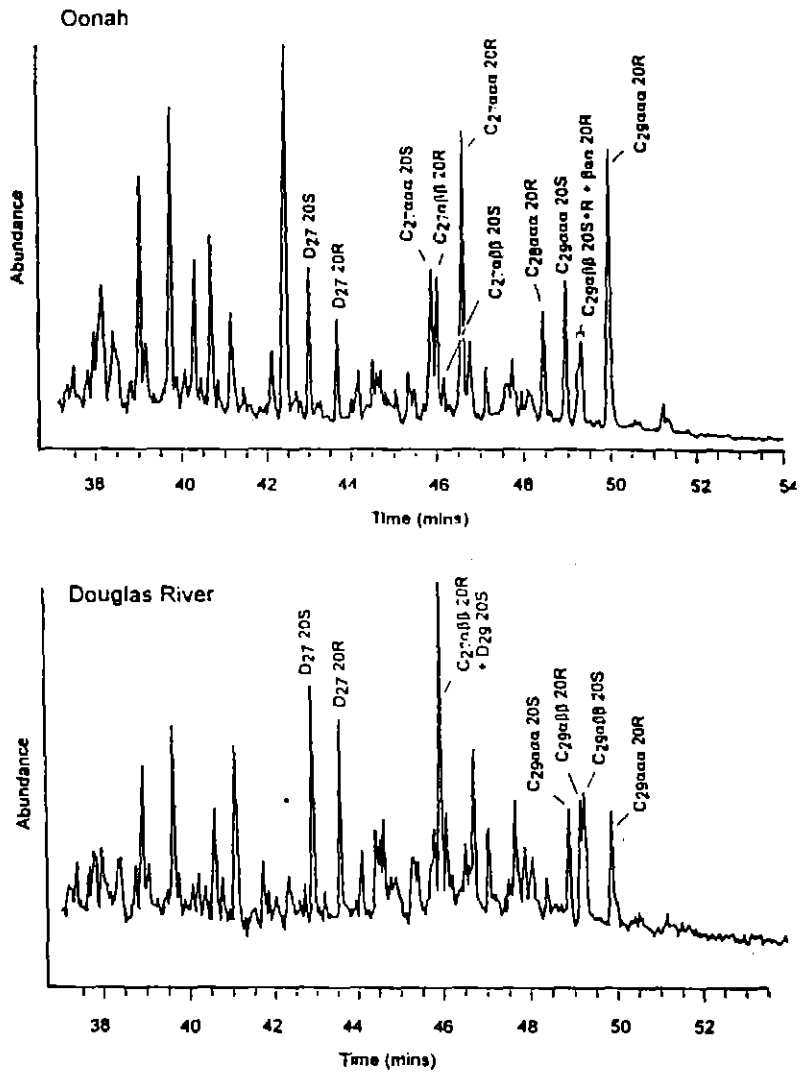

FIG. 7. Extended m/z 217 mass chromatograms for samples from Oonah and Douglas River. Numbers refer to carbon number; D = diasteranes; 20S and 20R refer to stereochemistry at carbon 20. Those denoted ααα 20R have the biological stereochemistry, i.e., 5α,14α,17α(H)-20R with the other signals arising from "geological" isomers.

The plot of T_{max} vs. HI (Fig. 13) shows very similar T_{max} (443–446°C) values for the Latrobe, Oonah fossil concentrate and Douglas River samples. However, the siltstone from above and below the oil shale has a similar maturity but shows a much lower T_{max} (436°C), equivalent to a vitrinite reflectance of 0.5% for Type III kerogen (Fig. 13). This emphasises the limited use of the T_{max} parameter in assessing the thermal maturity of Type I kerogens (TISSOT et al., 1987).

The Production Index (PI) for the most thermally mature sample (Douglas River) is only 0.04 (4%; Table 2), which indicates an immature kerogen (BORDENAVE et al., 1993). This suggests that the biomarker data (steranes) are overestimating the thermal maturity of the samples, which is consistent with recent results. MARZI and RULLKÖTTER (1992) calculated an activation energy for sterane isomerization at C_{20} of 169 kJ/mol, while kinetic data derived for the tasmanite indicates a typical Type I distribution (TISSOT et al., 1987). There is a very narrow distribution of activation energies for kerogen transformation (Fig. 14) which, in combination with the frequency factor of 8.9×10^{13} s^{-1}, indicates a relatively labile kerogen once generation commences. When these data are used to model maturity it becomes clear that the 20 S/20 R isomerisation is complete before the onset of significant hydrocarbon generation (Fig. 15). In contrast, the kinetic data for sterane isomerisation calculated by MACKENZIE and MCKENZIE (1983) predicts over 50% kerogen conversion for the Douglas River sample (Fig. 15), clearly inconsistent with its high HI value.

Calculation of the Transformation Ratio (TR), according to hydrogen index (HI) values

$$TR = \frac{HI_0 - HI_t}{HI_0}$$

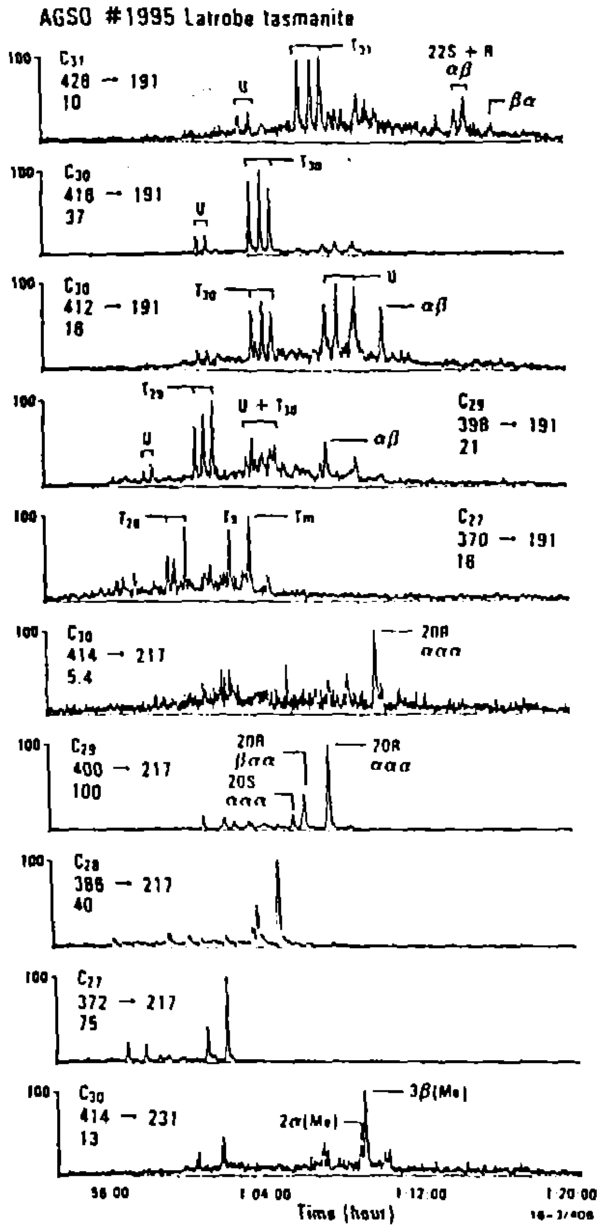

FIG. 8. Distribution of sterane and terpane biomarkers in the saturated hydrocarbon fraction isolated from the Latrobe sample. The data were acquired by gas chromatography-mass spectrometry using metastable reaction monitoring (MRM). Each trace is identified with the carbon number, the reaction as determined by the masses of the parent and daughter ions, and a normalised relative abundance. The last peak to elute in each sterane trace (i.e., those denoted ααα-20R) have 5α,14α,17α(H)-20R stereochemistry with the other signals arising from "geological" isomers. The desmethyl steranes are 24-*n*-propylcholestane (C_{30}), 24-ethylcholestane (C_{29}), 24-methylcholestane (C_{28}), and cholestane (C_{27}). The C_{30} methylsteranes are 24-ethylcholestanes with an additional methyl group in ring-A, i.e., 2α-methyl and 3β-methyl which are denoted 2α(Me), 3β(Me), respectively. Hopanes are denoted H, tricyclics T, and unknown compounds U. Tricyclic terpenoids appear in each hopane reaction as artefacts of the MRM analysis using the linked scan technique. For example, T_{30} is specifically detected in the 416 → 191 reaction. It also appears as an artefact, along with T_{31}, in the 412 → 191 reaction.

(where HI_0 and HI_z are the initial HI value and the HI at a depth z, respectively, and HI_0 is taken as the value for Latrobe: Table 2), shows the Douglas River sample to have a TR value of 0.1, considered to define the onset of petroleum generation. Thus, from the kinetic data curve (Fig. 14) it is clear that this sample has only just started hydrocarbon production, but significantly, an increase of only 10–15°C to exceed the activation energy would see a rapid increase in the amount of petroleum production. The production curve (Fig. 15) shows that some hydrocarbons have been produced quite early in the maturation sequence, and this is probably

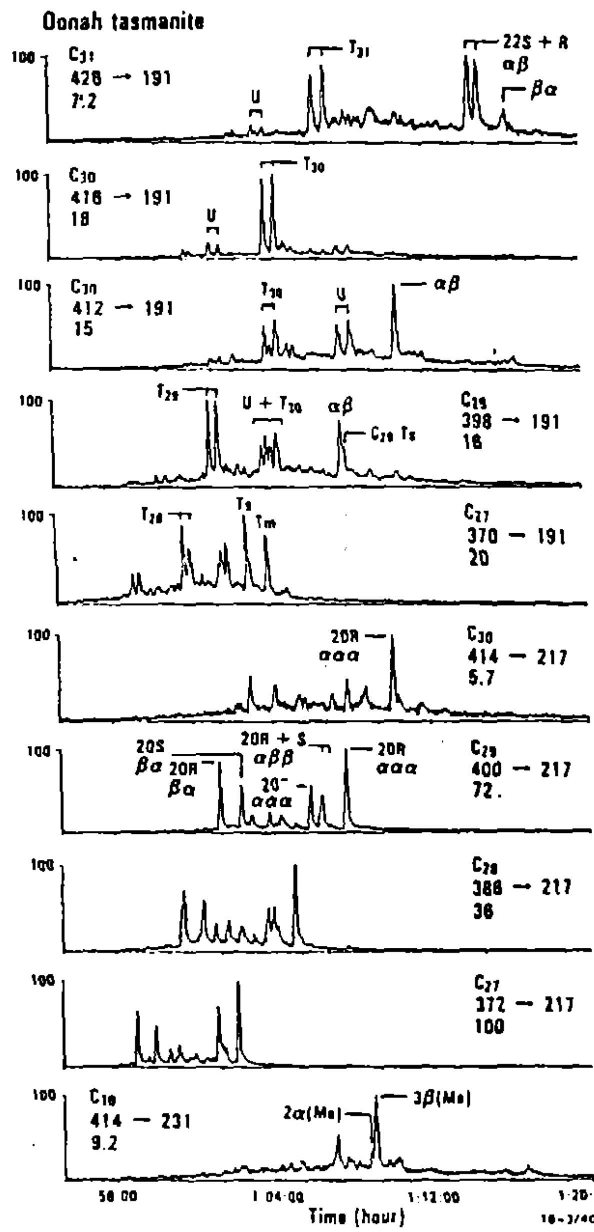

FIG. 9. Distribution of sterane and terpane biomarkers in the saturated hydrocarbon fraction isolated from the Oonah sample, from GC-MS analysis with MRM (see Fig. 8 legend for an explanation of symbols).

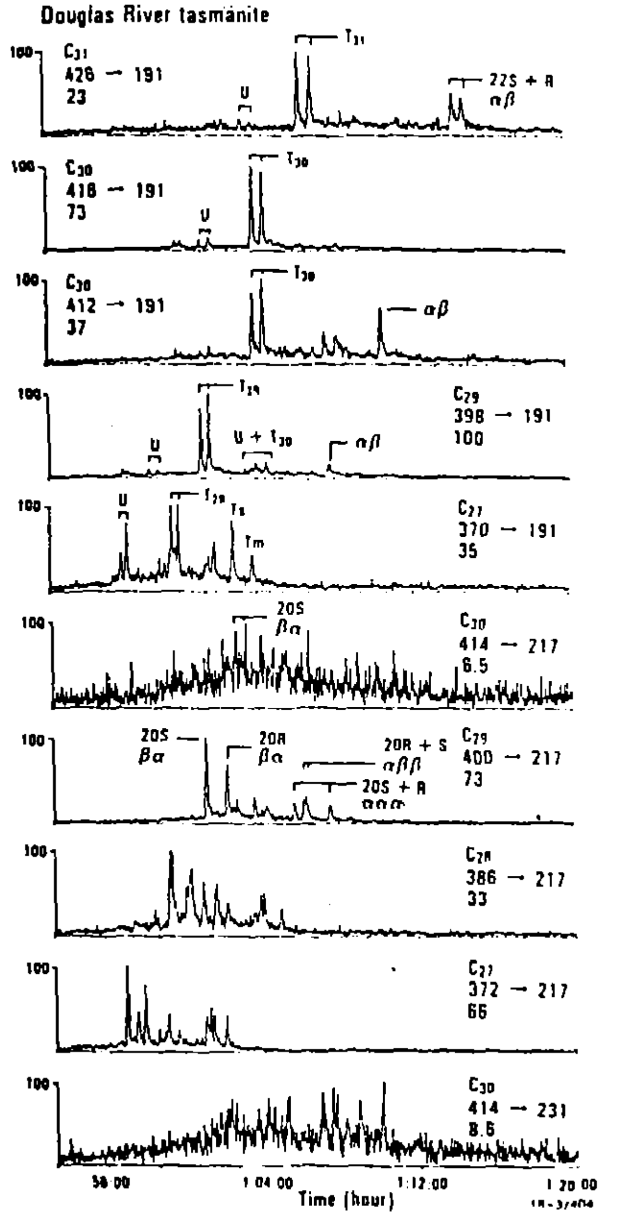

FIG. 10. Distribution of sterane and terpane biomarkers in the saturated hydrocarbon fraction isolated from the Douglas River sample, from GC-MS analysis with MRM (see Fig. 8 legend for an explanation of symbols).

due to the presence of weaker bonds within the kerogen. These are represented by the lower activation energies (205 and 209 kJ/mol; Fig. 14) and probably reflect the sulphur content of the kerogen. Clearly, the depth of the oil shale at Douglas River (320 m) is insufficient to produce this level of thermal maturity, even given a high geothermal gradient for this area of around 30°C/km (GREEN, 1989). This could reflect significant erosion of Tertiary material or be due to past and localised heating of the organic matter. Too little is currently known about the geology of this region of Tasmania to assess which is the more likely of these two alternatives.

The high TOC and HI values confirm that the tasmanite has the potential to generate large amounts of hydrocarbons but importantly, in the east of Tasmania, as shown by the data from Douglas River, its thermal maturity is near the oil window. This result contradicts previous assumptions that the oil shale in Tasmania is too immature to represent a possible petroleum source, although the present day areal extent of mature strata is unknown.

Inferred Environment of Deposition

BANKS (1962), KANSTLER (1980), and CALVER et al. (1984) suggested that *Tasmanites* represents the "cysts" of a planktonic organism living in a restricted environment, generally littoral and associated with reduced salinity due to a high freshwater input. It has been suggested that much of present-day Tasmania was covered during the Late Carboniferous by an ice sheet flowing from the west (BANKS and CLARKE, 1987). At that time Tasmania was positioned in high southern latitudes (ca. 75–80°S; SMITH et al., 1981). As the glaciers retreated, black muds were deposited on the sea floor in front of the ice, and it was in these muds that beds of tasmanite were formed. The occasional presence of fossil brachiopods and starfish in the tasmanite shale indicates a marine setting. Deposition in quiescent shallow to very shallow water is indicated by fine-scale cross lamination, scouring, and lensing-out over very short distances of both the siltstone and *Tasmanites*-rich layers in oil shale from Oonah and by the close association with lenticular sand and well-sorted granule bodies in the Douglas River core. It is suggested that deposition occurred in water depths of 100 m or less (Fig. 3); a nearshore deposition is further suggested by the presence of desmocollinite at Oonah and collinite at Latrobe. The overall fine-grain size of the oil shale–bearing sequence shows that very low current strengths existed at the site of deposition. Lonestones, some of which are demonstrably dropstones (Fig. 4b), may have been transported to the site by shore ice as their shapes are characteristic of fluvial and beach environments with little evidence for transport by glacial ice (DOMACK et al., 1993).

Estimates of sea surface temperature for early Permian Tasmania of −1.8°C (RAO and GREEN, 1982) are close to the present average near the Antarctic ice shelf of −1.9°C. DOMACK et al. (1993) propose that the tasmanite beds record a period of enhanced primary productivity coupled with polar to subpolar glacial marine conditions characterised by very cold waters, seasonal sea ice, and shore-ice rafting. Cold water deposition is consistent with the low diversity of the invertebrate fauna and strongly indicated by the presence of glendonites, pseudomorphs after ikaite (calcium carbonate hexahydrate; $CaCO_3 \cdot 6H_2O$). This mineral is suggested to be an authigenic precipitate, forming at low temperatures from interstitial waters of organic-rich sediments, undergoing microbial degradation and accumulated rapidly in cold bottom-waters (SUESS et al., 1982; SHEARMAN and SMITH, 1985; JANSEN et al., 1987).

It is notable that the sediments where *Tasmanites* is abundant, in the Late Ordovician-Early Silurian of the Sahara, the Devonian of Brazil, the Late Carboniferous-Early Permian

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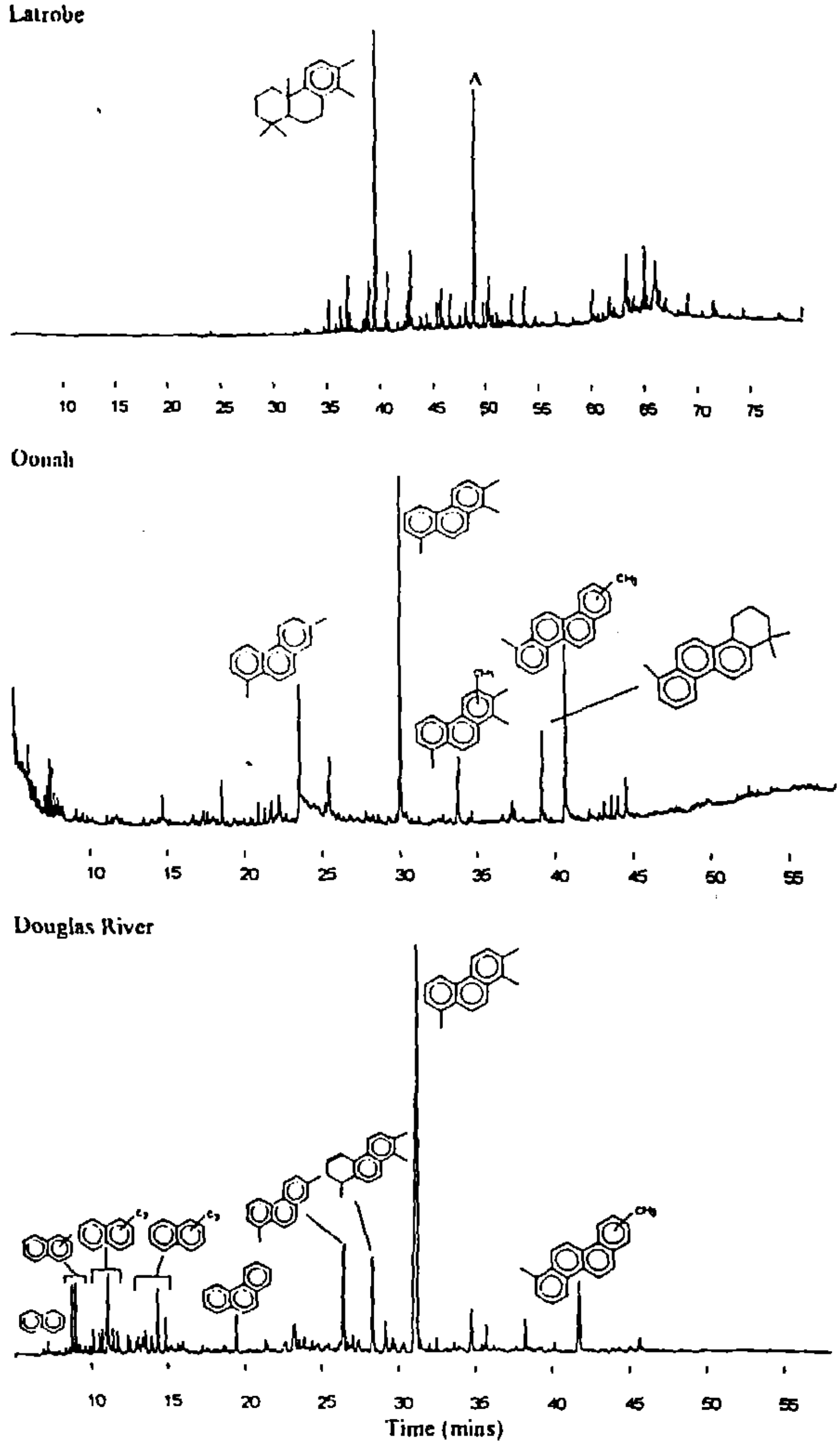

FIG. 12. Gas chromatograms of the aromatic fractions isolated from samples collected at Latrobe, Oonah, and Douglas River. Peak assignments are indicated by structures. Peak A is discussed in the text.

important (TEN HAVEN et al., 1987). In contrast, the siltstone above and below the tasmanite shale which represents deposition in an oxic environment exhibits a relatively high pristane/phytane ratio of 3.1. Our data is consistent with earlier models of tasmanite deposition, suggesting that the sum of the physical properties indicates deposition in a dysaerobic environment with a dissolved oxygen content less than 0.5 ml L^{-1} at the sediment-water interface (ARTHUR et al., 1984).

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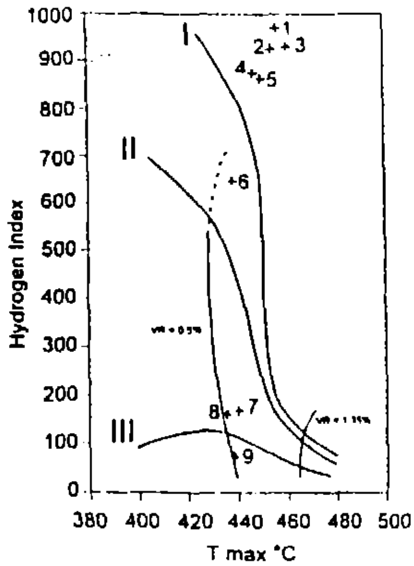

FIG. 13. HI/Tmax plot showing the relative positions of the samples. Note the difference in maturity shown by the algal kerogen and the associated siltstone. The standard 0.5% Vitrinite reflectance contour is shown. 1 = Latrobe, 2 = Oonah upper seam whole rock, 3 = Oonah *Tasmanites* concentrate, 4 = Oonah lower seam *Tasmanites* concentrate, 5 = Oonah lower seam whole rock, 6 = Douglas River whole shale, 7, 8, 9 = Siltstone samples from above and below the oil shale at Oonah.

SIMONEIT et al. (1992, 1993) reported high ^{13}C enrichment for the tricyclic compounds ($\delta^{13}C$ values of −9.9 to −12.2‰) extracted from an immature sample from Latrobe (Fig. 1) which was attributed to bloom conditions prevailing at the time of deposition. Phytoplankton from cold, high latitude waters are typically depleted in ^{13}C due to the elevated P_{CO_2} caused by increased CO_2 solubility at these temperatures (reviewed by SACKETT, 1991). Low atmospheric P_{CO_2} associated with global glaciation (RAU et al., 1991a) in the Early Permian, possibly combined with additional P_{CO_2} drawdown during algal blooms provides a possible explanation for the ^{13}C enrichments of tasmanite kerogen reported here and by SIMONEIT et al. (1993). However RAU et al. (1991b) showed that particulate organic matter associated with sea ice could also be significantly enriched in ^{13}C ($\delta^{13}C$ −16 to −28‰) relative to the seawater. Within the sea-ice the physical isolation from reequilibration with the atmosphere may reduce CO_2 availability and therefore significantly reduce isotopic fractionation. SIMONEIT et al. (1993) reported a tasmanite kerogen with a $\delta^{13}C$ value of −16.6‰ and our samples have $\delta^{13}C$ values of −13 to −11‰ (Fig. 16). Thus, in view of the depositional setting implied by geological evidence we propose that *Tasmanites* in this instance may have occupied an environment very similar to that of present-day sea-ice algae. Thus, by analogy with present-day sea-ice diatom communities, the *Tasmanites* bloomed within the ice as the light intensity increased during the spring. As the ice melted, algae from the bloom were released into the water column and subsequently sedimented. The fine scale laminations and rarity of bioturbation are consistent with a quiescent water column, which may be assisted by persistent ice cover. To test this hypothesis we measured the $\delta^{13}C$ for sea-ice diatoms collected from ice cores taken in Antarctica, during November 1991. These gave a $\delta^{13}C$ value of −7‰ (Fig. 16) which supports this interpretation. Further studies of sea-ice algae from several Antarctic locations have confirmed their ^{13}C enrichment compared to algae isolated from the associated water column (R. E. Summons and P. D. Nichols, unpubl. data). The taxonomic assignment of *Tasmanites* with the Prasinophyceae (Chlorophyta) (WALL, 1962; PARKE, 1966) and the observations of TAPPAN (1980), who suggested that the fossil prasinophytes are a "disaster species," somehow surviving the widespread extinctions of the middle Palaeozoic and, perhaps most importantly, thriving in the absence of other phytoplankton, are all consistent with our model.

Origins of Biomarkers in the Tasmanite Oil Shale

Recently COLLISTER et al. (1992) reported isotopic values for tricyclic compounds in the Green River oil shale which

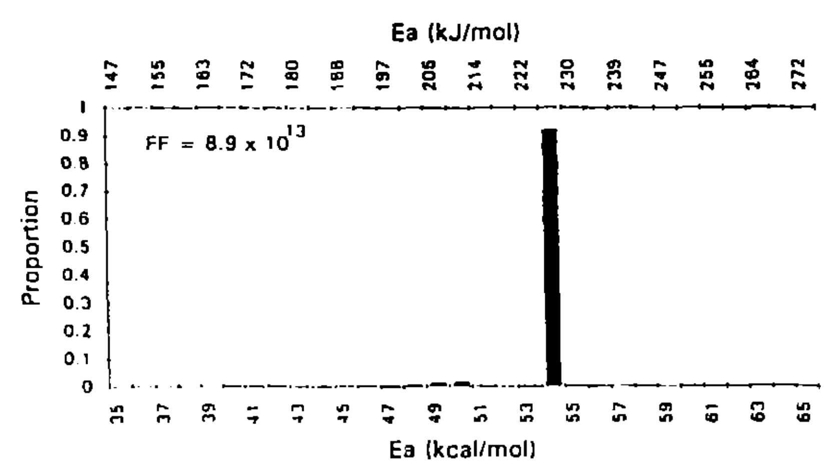

FIG. 14. Plot showing the distribution of activation energies in the Latrobe tasmanite kerogen. FF = Frequency Factor (s^{-1}).

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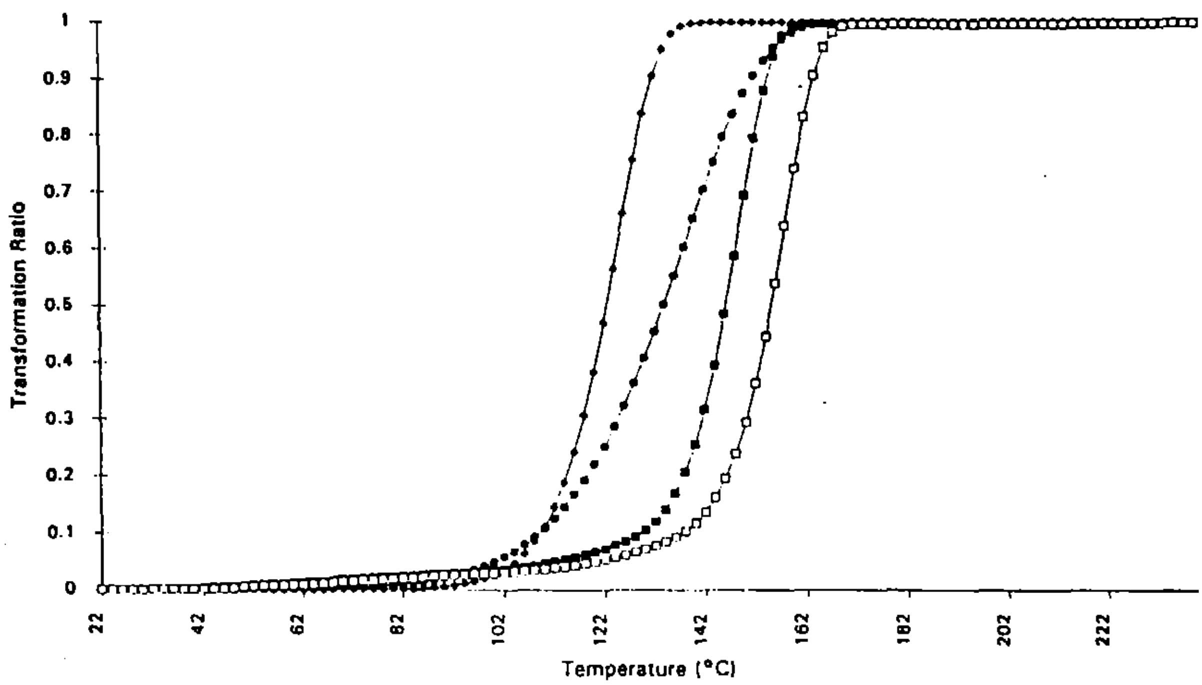

FIG. 15. Simulated maturation of the Latrobe tasmanite kerogen, compared with sterane isomerisation at C_{29}. Sterane activation energies used are those of MACKENZIE and MCKENZIE (1983) — ● — and MARZI and RULLKOTTER (1992) — ♦ —, at 8°C per million years. Tasmanite maturation is shown at 8°C (— □ —) and 2°C (— ■ —) per million years.

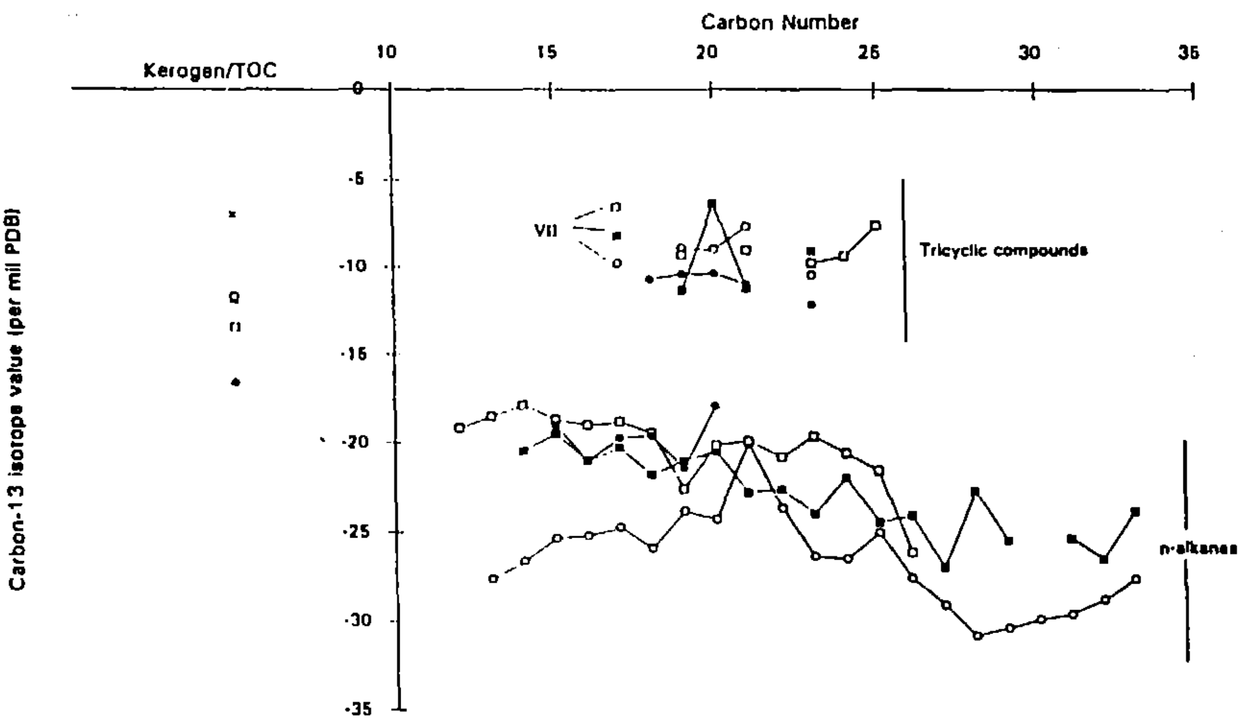

FIG. 16. Plot showing the variation in $\delta^{13}C$ values for kerogen and for *n*-alkanes, tricyclic compounds and aromatic derivatives vs. carbon number. Data from this study are represented as: — ■ — Latrobe; — O — Oonah; — □ — Douglas River; and — × — Sea-ice diatoms. Data previously reported by SIMONEIT et al. (1993) are represented as — ● —. Groups of compounds are indicated as *n*-alkanes and cyclic compounds (tricyclic alkanes and aromatic derivatives). Numerals refer to structures in scheme 1, tricyclic alkanes are all of type I. Note that the $\delta^{13}C$ values of kerogen from Latrobe and Oonah are almost identical.

ranged from −33.7 to −27.3‰. This range corresponds to the values generally associated with photoautotrophs, but there was no correlation with the values for β-carotane or steranes in the same samples, indicating different source organisms. The difference between the isotopic values of COLLISTER et al. (1992) and those reported here and by SIMONEIT et al. (1993) may be due to the source organism occupying a different niche in the very different environments of deposition.

The high proportion of preserved organic remains in the tasmanite oil shale, and the dominance of tricyclic compounds in the hydrocarbon fractions, has often led to *Tasmanites* to be proposed as the likely source for these compounds (e.g., VOLKMAN et al., 1989; SIMONEIT et al., 1992, 1993). However, tricyclic compounds have been identified in a wide range of sediments and petroleum from a range of geological ages, and do not appear to be limited to areas of high *Tasmanites* content (see AQUINO NETO et al., 1983), so other sources must be examined. A consideration of $\delta^{13}C$ values of tricyclic compounds in the extracts and pyrolysates of the tasmanite oil shale provides evidence for a source distinct from the accompanying algaenan.

GC-IRMS analysis of tricyclics in previous studies (SIMONEIT et al., 1993) and the present study yielded $\delta^{13}C$ values of −9.9 to −12.2‰ and −6.4 to −11.3‰, respectively, which shows that these compounds are enriched in ^{13}C compared with the corresponding kerogen (Fig. 16). The light and variable isotopic composition for the *n*-alkanes ($\delta^{13}C$ values −18 to −30‰) suggests multiple sources. There is a general trend for ^{13}C depletion in higher *n*-alkane homologues, suggesting a possible contribution from allochthonous bacterial or plant waxes. For the lower *n*-alkane homologues, algal and cyanobacterial sources may become increasingly important.

Closed-system pyrolysis of tasmanite kerogen for 72 h at increasingly higher temperatures showed a number of interesting trends (Table 4). Recovery of bitumen maximised at 68% at 330°C and decreased to 59% at 350°C, probably as a result of the generation of a larger proportion of gas resulting from cracking of liquid hydrocarbons. The composition of the bitumen also changed markedly. At 350°C almost 96% of the bitumen could be recovered from the chromatographic column, as saturates, aromatics, and weakly polar materials. At 300°C and 330°C the recoveries from column chromatography were only 52 and 57%, respectively, indicating that the pyrolysate comprised a major proportion of asphaltic or strongly polar material which bound irreversibly to the silica gel. The proportions of saturates, aromatics, and weakly polar fractions in the material recovered from column chromatography did not change significantly as the pyrolysis temperature increased.

A comparison of GC traces for the C_{10+} saturated hydrocarbons (Fig. 17) shows a low abundance of *n*-alkanes compared to tricyclanes in the extract and the 300°C pyrolysate. At the higher temperatures, *n*-alkanes dominate the GC-FID chromatogram, consistent with flash pyrolysis-GC results which revealed the aliphatic nature of the tasmanite kerogen (C. J. Boreham, unpubl. data). There is also a progression in *n*-alkane generation leading to reduced waxy *n*-alkane contents and lower molecular weight predominance as the temperature increases to 350°C. In the 300°C pyrolysate, the *n*-alkane envelope maximises at C_{18} compared with C_{14} in the 350°C pyrolysate. Evidence for this evolution is also shown by $\delta^{13}C$ analysis of the alkanes (Fig. 18) and comparison with those in the extract. The *n*-alkanes produced at 300°C exhibit an isotopic composition closest to those of the extract with a progression to "heavier" compounds with an increase in pyrolysis temperature. Note that at 350°C the $\delta^{13}C$ values of C_{16}–C_{21} *n*-alkanes are in the range −12 to −15‰, compared with the kerogen at −12‰. The C_{13} and C_{14} *n*-alkanes are now prominent (Fig. 16) and are slightly "heavier" than the starting kerogen at −10 to −11.5‰, although this could be due, in part, to isotopic fractionation on evaporative loss of some of the volatile *n*-alkanes.

The observations from the pyrolysis experiments are consistent with the concept of generation of an asphaltene- and polar-rich material during the initial stages of kerogen conversion (EVANS and FELBECK, 1983), and subsequent cracking of this to lower molecular weight components, including gaseous products. The main information conveyed by the isotope data is, however, that the $\delta^{13}C$ values of the *n*-alkanes produced by kerogen pyrolysis are significantly different from those in the extract of immature tasmanite. Pyrolytically generated *n*-alkanes and *n*-alkylcyclohexanes (data not shown) are isotopically similar to the kerogen consistent with earlier observations (BURWOOD et al., 1988) of a close correlation between ^{13}C contents of sapropellic kerogens and their pyrolysates. Based on experience with other algal-derived kerogens (e.g., GOTH et al., 1988; TEGELAAR et al., 1989; DERENNE et al., 1992; BOREHAM et al., 1994), these compounds are probably derived from an *n*-alkyl based biopolymer, algaenan,

Table 4. Comparison of whole rock extract and kerogen pyrolysate of tasmanite from Latrobe, Tasmania

72 hr Pyrolysis Temp. (°C)	EOM (mg/g TOC)[#]	C_{12} + Saturates* (%)	Aromatics* (%)	Polars* (%)	Asphaltenes‡ (%)
unheated	51.4	19.0	30.5	38.8	11.7
300	190.8	7.0	13.3	31.3	48.4
330	1019.2	8.5	13.9	39.3	38.3
350	879.1	14.9	42.1	39.7	3.3

TOC (kerogen) = 67.1 %

* Based on pre-chromatography weight

‡ Taken as that fraction not eluting from the chromatographic column

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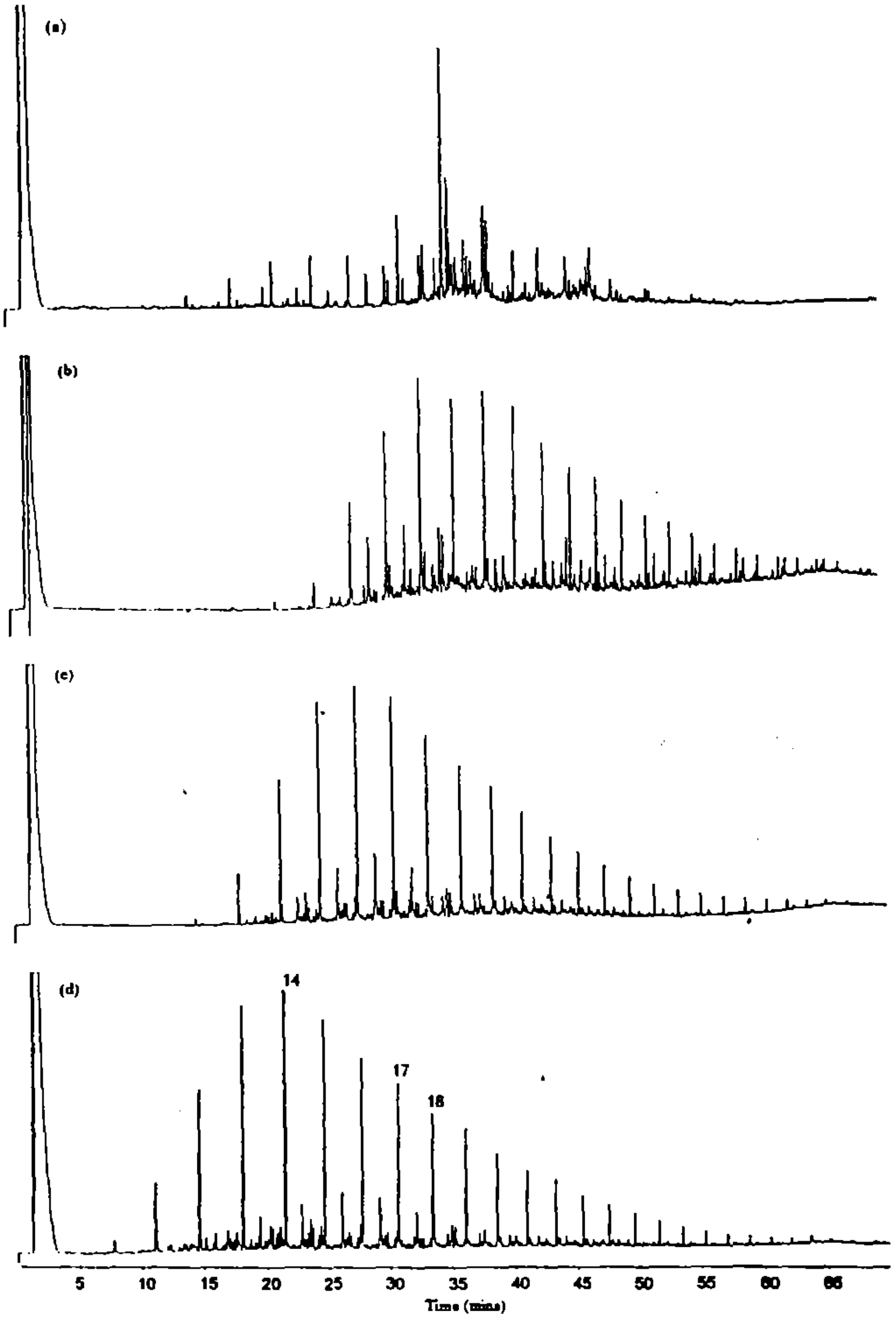

FIG. 17. Gas chromatograms showing the aliphatic hydrocarbons from (a) the original extract and from closed-system pyrolysis of tasmanite kerogen, isolated from a simple collected at Latrobe, at (b) 300°C, (c) 330°C, and (d) 350°C. Note the progressive increase in low molecular weight *n*-alkanes and the relative decrease in tricyclic compounds.

which forms part of the structure of the tasmanite fossils. Indeed, the $\delta^{13}C$ values are constant for the C_{17}–C_{27} *n*-alkanes from the 330°C pyrolysate. Here, yields are high, secondary cracking is minimal and the isotopic value is considered to represent that of the *Tasmanites* algaenan. This is also consistent with the reported aliphatic nature of the preserved organic matter (KJELLSTRÖM, 1968).

Saturated tricyclic alkanes did not appear to be generated during the 330 and 350°C pyrolyses where the *n*-alkanes were mostly produced. Their abundance relative to the *n*-alkanes

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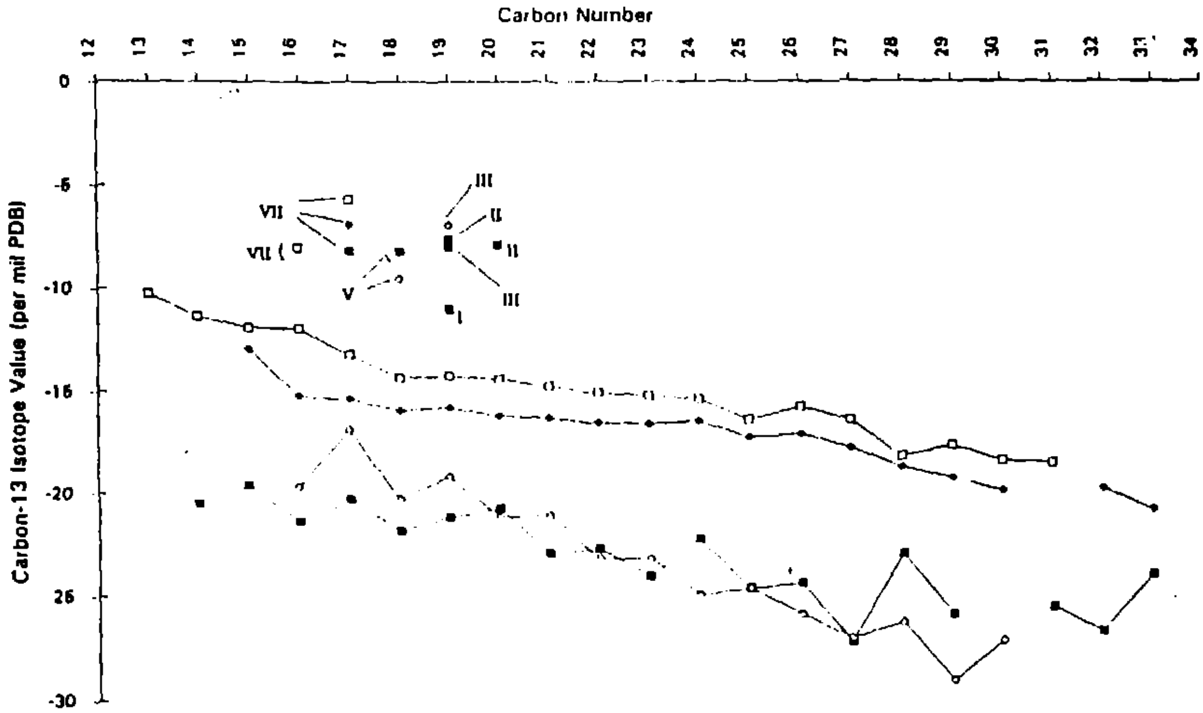

FIG. 18. Chart showing the $\delta^{13}C$ values of (a) *n*-alkanes liberated by pyrolysis at 300°C — ○ —, 330°C — ♦ — and 350°C — □ — of tasmanite kerogen from Latrobe (AGSO sample # 1995), compared with the original extract — ■ — (b) tricyclic hydrocarbons (structures I–VII in scheme 1) from Latrobe (extract and pyrolysate, symbols as in (a)).

decreased as the temperature increased. Caution should be exercised however. Tricyclic hydrocarbons may have been converted to aromatics at higher pyrolysis temperatures. Furthermore, the composition of the aromatic fractions generated in the pyrolysis experiments became much simpler with increasing temperature and at 350°C was dominated by 1,7-dimethylphenanthrene and 1,2,8-trimethylphenanthrene with $\delta^{13}C$ values of −7.9 and −5.7‰, respectively, which are within the range for tricyclic compounds in the tasmanite extracts of different maturities (Fig. 16). The isotopic similarity in the tricyclic hydrocarbons from pyrolysis and tasmanite extracts (Scheme 1 and Fig. 18) suggest that they are almost certainly derived from the same precursors. A proposed genetic relationship between the tricyclic hydrocarbons is shown in Scheme 1. It is uncertain at present whether this process is mediated by bacteria or by heating in the natural environment (LOHMANN, 1988; FREEMAN, 1991; FREEMAN et al., 1994). Certainly, the latter process is indicated by the bias towards the fully aromatised tricyclics in both the pyrolysates and the higher maturity Oonah and Douglas River extracts. Peak A in Fig. 12 has previously been assigned to a tetracyclic monoaromatic des-A-gammacerane (SIMONEIT et al., 1993). However, preliminary NMR data on this compound suggests that it is not a des-A-oleanane or des-A-gammacerane (BORTHAM and WILKINS, 1994) and the isotopic similarity between it (−8.5‰) and the tricyclic compounds suggests a common source.

The isotopic dissimilarity of the tricyclic hydrocarbons (mean −8‰) to the kerogen and kerogen-derived *n*-alkanes suggests a source distinct from the *Tasmanites* themselves. Interestingly, the difference in kerogen $\delta^{13}C$ data in this study with that of SIMONEIT et al. (1993) is matched by differences of a similar magnitude in the tricyclic compounds, aromatic derivatives, and *n*-alkanes in the extracts. This, in conjunction with the previously noted differences in sterane and hopane observations, suggests that there were fluctuations in the source and depositional environment of organic matter within the oil shale seam which affected both biomarker distributions and their ^{13}C isotopic values.

CONCLUSIONS

This study represents the first organic geochemical comparison of thermally mature and immature tasmanite oil shale samples in conjunction with a detailed geological evaluation of the sedimentary setting.

1) This study has shown, for the first time, that at least some deposits of the tasmanite shale in Tasmania are near the "oil window."
2) Geological, isotopic, and biomarker analysis indicates that *Tasmanites* thrived in an environment of ice cover and bloomed in conditions analogous to those experienced by present-day sea-ice diatoms. The algal cells were subsequently deposited in sediments overlain with oxygen-depleted waters, induced by restricted water movement.
3) Closed-system pyrolysis suggests that there is little correlation between the temperature profiles for production of *n*-alkanes and the tricyclic compounds from the kerogen precursors. The *n*-alkanes are mainly derived from thermal cracking of algal aliphatic biopolymer whereas the tricyclic

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alkanes and aromatic hydrocarbons are generated earlier, possibly from a different source.

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REFERENCES

Aquino Neto F. R., Restle A., Connan J., Albrecht P., and Ourisson G. (1982) Novel tricyclic terpanes (C_{19}, C_{20}) in sediments and petroleums. *Tetrahedron Lett.* 23, 2027–2030.

Aquino Neto F. R., Trendel J. M., Restle A., Connan J., and Albrecht P. (1983) Occurrence and formation of tricyclic and tetracyclic terpanes in sediments and petroleums. In *Advances in Organic Geochemistry 1981* (ed. M. Bjorøy et al.), pp. 659–667. Wiley.

Aquino Neto F. R., Triguis D. A., Azevedo D. A., Rodrigues R., and Simoneit B. R. T. (1992) Organic geochemistry of geographically unrelated *Tasmanites*. *Org. Geochem.* 18, 791–803.

Arthur M. A., Dean W. E., and Stow D. A. V. (1984) Models for the deposition of Mesozoic-Cenezoic fine-grained organic-rich sediment in the deep sea. In *Fine-Grained Sediments: Deep-Water Processes and Facies* (ed. D. A. V. Stow and D. J. W. Piper); *Geol. Soc. Special Publication*, pp. 527–560.

Azevedo D. A., Aquino Neto F. R., and Simoneit B. R. T. (1990) Mass spectrometric characteristics of a novel series of ring-C monoaromatic tricyclic terpanes found in Tasmanian tasmanite. *Org. Mass Spectrom.* 25, 475–480.

Azevedo D. A., Aquino Neto F. R., Simoneit B. R. T., and Pinto A. C. (1992) Novel series of tricyclic aromatic terpanes characterized in Tasmanian tasmanite. *Org. Geochem.* 18, 9–16.

Banks M. R. (1962) Permian (Tasmania). *J. Geol. Soc. Australia* 9, 189–216.

Banks M. R. and Clarke M. J. (1987) Changes in the geography of the Tasmania Basin in the late Paleozoic. In *Gondwana Six: Stratigraphy, Sedimentology and Paleontology* (ed. G. D. McKenzie); *Amer. Geophys. Union Geophys. Monograph 41*, pp. 1–14.

Bendall M. R., Volkman J. K., Leaman D. E., and Burrett C. F. (1991) Recent developments in exploration for oil in Tasmania. *APEA J.* part 1, 31, 74–84.

Boalch G. T. and Guy-Ohlson D. (1992) *Tasmanites*, the correct name for *Pachysphaera* (Prasinophyceae, *Pterospermataceae*). *Taxon* 41, 529–531.

Bordenave M. L., Espitalié J., Leplat P., Oudin J. L., and Vandenbroucke M. (1993) Screening Techniques for Source Rock Evaluation. In *Applied Petroleum Geochemistry* (ed. M. L. Bordenave), Chap. II-2, pp. 217–278. Editions Tecnip.

Boreham C. J. and Wilkins, A. L. (1994) Structure and origin of the two major monoaromatic hydrocarbons in a tasmanite oil shale from Tasmania, Australia. *Tetrahedron* (submitted).

Boreham C. J., Crick I. H., and Powell T. G. (1988) Alternative calibration of the Methylphenanthrene Index against vitrinite reflectance: Application to maturity measurements on oils and sediments. *Org. Geochem.* 12, 289–294.

Boreham C. J., Summons R. E., Roksandic Z., Dowling L. M., and Hutton A. C. (1994) Chemical, molecular and isotopic differentiation of organic facies in the tertiary lacustrine Duaringa oil shale deposit, Queensland, Australia. *Org. Geochem.* 21, 685–712.

Burlingame A. L., Wszolek P. C., and Simoneit B. R. T. (1969) The fatty acid content of tasmanites. In *Advances in Organic Geochemistry 1968* (ed. P. A. Schenck and I. Havenaar), pp. 131–155. Pergamon-Vieweg.

Burwood R., Drozd R. J., Halpern H. I., and Sedivy R. A. (1988) Carbon isotopic variations of kerogen pyrolysates. *Org. Geochem.* 12, 195–205.

Calver C. R., Clarke M. J., and Truswell E. M. (1984) The stratigraphy of a late Palaeozoic bore hole section at Douglas River, eastern Tasmania: a synthesis of marine macro-invertebrate and palynological data. *Pap. Proc. R. Soc. Tasm.* 118, 137–161.

Chicarelli M. I., Aquino Neto F. R., and Albrecht P. (1988) Occurrence of four stereoisomeric tricyclic terpane series in immature Brazilian shales. *Geochim. Cosmochim. Acta* 52, 1955–1959.

Clarke M. J. (1989) Lower Parmeener Supergroup. In *Geology and Mineral Resources of Tasmania* (ed. C. F. Burrett and E. L. Martin); *Geol. Soc. Australia, Special Publication 15*, Chap. 8, pp. 295–309.

Clarke M. J. (1992) *Hellyerian and Tamarian (Late Carboniferous-Lower Permian) Invertebrate Faunas from Tasmania. Tasm. Geol. Surv. Bull. 69.*

Clarke M. J. and Banks M. R. (1975) The stratigraphy of the Lower (Permo-Carboniferous) parts of the Parmeener super-group, Tasmania. In *Gondwana Geology* (ed. K. S. W. Campbell), pp. 453–467. A.N.U. Press.

Clarke M. J. and Farmer N. (1976) Biostratigraphic nomenclature for late Palaeozoic rocks in Tasmania. *Pap. Proc. R. Soc. Tasm.* 110, 91–109.

Collister J. W., Summons R. E., Lichtfouse E., and Hayes J. M. (1992) An isotopic biogeochemical study of the Green River oil shale. *Org. Geochem.* 19, 265–276.

Derenne S., Le Berre F., Largeau C., Hatcher P., Connan J., and Raynaud J. F. (1992) Formation of ultralaminae in marine kerogens via selective preservation of thin resistant outer walls of microalgae. *Org. Geochem.* 19, 345–350.

Didyk B. M., Simoneit B. R. T., Brassell S. C., and Eglinton G. (1978) Organic geochemical indicators of palaeoenvironmental conditions of sedimentation. *Nature* (London) 272, 216–222.

Domack E. W., Burkley L. A., Domack C. R., and Banks M. R. (1993) Facies analysis of glacial marine pebbly mudstones in the Tasmania Basin: Implications for regional paleoclimates during the late Paleozoic. In *Gondwana Eight: Proceedings of the Eighth Gondwana Symposium* (ed. R. H. Findlay et al.), pp. 471–484. Balkema.

Evans R. J. and Felbeck G. T., Jr. (1983) High temperature simulation of petroleum formation—I. The pyrolysis of Green River shale. *Org. Geochem.* 4, 135–144.

Foster C. B. and Waterhouse J. B. (1988) The Granulatisporites confluens Oppel-zone and Early Permian marine faunas from the Grant Formation on the Barbwire Terrace, Canning Basin, Western Australia. *Australian J. Earth Sci.* 35, 135–157.

Freeman K. H. (1991) The carbon isotopic composition of individual compounds from ancient and modern depositional environments. Ph.D. thesis, Indiana University.

Freeman K. H., Boreham C. J., Summons R. E., and Hayes J. M. (1994) The effect of aromatisation on the isotopic compositions of hydrocarbons during early diagenesis. *Org. Geochem.* (in press).

Goth K., De Leeuw J. W., Püttmann W., and Tegelaar E. W. (1988) Origin of Messel Oil Shale kerogen. *Nature* (London) 336, 759–761.

Gould C. (1861) Resinous shales (Dysodile at Latrobe). *Tasm. House of Assembly Pap.* 8.

Green D. C. (1989) Heat flow and heat production in Tasmania. In *Geology and Mineral Resources of Tasmania* (ed. C. F. Burrett and E. L. Martin); *Geol. Soc. Australia, Special Publication 15*, Chap. 13, pp. 461–463.

Guy-Ohlson D. (1988) Developmental stages in the life cycle of Mesozoic *Tasmanites*. *Bot. Mar.* 31, 447–456.

Guy-Ohlson D. and Boalch G. T. (1992) Comparative morphology of the genus *Tasmanites* (Pterospermales, Chlorophyta). *Phycologia* 31, 523–528.

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HARLAND W. B., ARMSTRONG R. L., COX A. V., CRAIG L. E., SMITH A. G., and SMITH D. G. (1990) *A Geological Timescale 1989*. Cambridge Univ. Press.

HAYES J. M., FREEMAN K. H., POPP B. N., and HOHAM C. H. (1990) Compound-specific isotope analysis: a novel tool for reconstruction of ancient biogeochemical processes. In *Advances in Organic Geochemistry 1989* (ed. B. DURAND and F. BEHAR), pp. 1115–1128. Pergamon Press.

JAMES C., GEPP H. W., AIKENHEAD A., SCOTT J. B., NYE P. B., PURVES S. S. B., CHAMBERS C. O., JUDE E. M., and REES H. W. (1932) *Report of the Tasmanian Shale Oil Investigation Committee*. Tasmania Department of Mines, Geological Survey, Mineral Resources, No. 8, vol. II. (Reprinted 1950).

JANSEN J. H. F., WOENSDREGT C. F., KOOISTRA M. J., and VAN DER GAAST S. J. (1987) Ikaite pseudomorphs in the Zaire deep-sea fan: an intermediate between calcite and porous calcite. *Geology* 15, 245–248.

KANTSLER A. J. (1980) Aspects of organic petrology with particular reference to the exinite group of macerals. In *Oil Shale Petrology Workshop, Wollongong, 1980* (ed. A. C. COOK and A. J. KANTSLER), pp. 16–41. Keiraville Kopiers.

KJELLSTROM G. (1968) Remarks on the chemistry and ultrastructure of the cell wall of some Palaeozoic Leiospheres. *Geolog. Fören. Stockh. Förhandlin.* 90, 221–228.

LOHMANN F. (1988) Aromatisations microbiennes de triterpenes vegetaux. Ph.D. dissertation, L'Université Louis Pasteur de Strasbourg.

MACKENZIE A. S. and MCKENZIE D. P. (1983) Aromatization and isomerization of hydrocarbons in sedimentary basins formed by extension. *Geol. Mag.* 120, 417–470.

MARZI R. and RULLKÖTTER J. (1992) Qualitative and quantitative evolution and kinetics of biological marker transformations—laboratory experiments and application to the Michigan Basin. In *Biological Markers in Sediments and Petroleum* (ed. J. M. MOLDOWAN et al.), pp. 18–41. Prentice-Hall.

MILLIGAN J. (1852) Report on the coal said to have been found at the Don River, and upon the west bank of the Tamar River, in Tasmania. *Pap. Proc. R. Soc. V.D.L.* II, 90–106.

MOLDOWAN J. M., FAGO F. J., LEE C. Y., JACOBSON S. R., WATT D. S., SLOUGUI N. E., JEGANATHAN A., and YOUNG D. C. (1990) Sedimentary 24-*n*-propylcholestanes, molecular fossils diagnostic of marine algae. *Science* 247, 309–312.

NEWTON E. T. (1875) On 'tasmanite' and Australian 'white coal'. *Geol. Mag.* 12, 337–342.

OSTENFELD C. H. (1899) Pachysphaera. In *Iagttagelser over overfladevandets temperatur, saltholdighed og plankton pa islandske og gronlandske skibsrouteri 1898*. Bianco Lunos Hof-Bogtrykkeri.

PARKE M. (1966) The genus *Pachysphaera* (Prasinophyceae). In *Some Contemporary Studies in Marine Science* (ed. H. BARNES), pp. 555–563. Allen and Unwin.

PARKE M. and HARTOG-ADAMS I. (1965) Three species of *Halosphaera*. *J. Mar. Biol. Ass. U.K.* 45, 537–557.

PARKE M., BOALCH G. T., JOWETT R., and HARBOUR D. S. (1978) The genus *Pterosperma* (Prasinophyceae): Species with a single equatorial ala. *J. Mar. Biol. Ass. U.K.* 58, 239–276.

PETERS K. E. and MOLDOWAN J. M. (1993) *The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments*. Prentice-Hall.

PHILP R. P., GILBERT T. D., and RUSSELL N. J. (1982) Characterization by pyrolysis gas chromatography-mass spectrometry of the insoluble organic residues derived from the hydrogenation of *Tasmanites* sp. oil shale. *Fuel* 61, 221–226.

RADKE M., WELTE D. H., and WILLSCH H. (1986) Maturity parameters based on aromatic hydrocarbons: influence of organic matter type. In *Advances in Organic Geochemistry 1985. Part I. Petroleum Geochemistry* (ed. D. LEYTHAEUSER and J. RULLKÖTTER), pp. 51–64. Pergamon Press.

RAO C. P. and GREEN D. C. (1982) Oxygen and carbon isotopes of Early Permian cold-water carbonates, Tasmania, Australia. *J. Sediment. Petrol.* 52, 1111–1125.

RAU G. H., FROELICH P. N., TAKAHASHI T., and DES MARAIS D. J. (1991a) Does sedimentary organic $\delta^{13}C$ record variations in Quaternary ocean $[CO_2(aq)]$? *Paleoceanogr.* 6, 335–347.

RAU G. H., SULLIVAN C. W., and GORDON L. I. (1991b) $\delta^{13}C$ and $\delta^{15}N$ variations in Weddell Sea particulate organic matter. *Mar. Chem.* 35, 355–369.

REVILL A. T., VOLKMAN J. K., O'LEARY T., and SUMMONS R. E. (1993) Aromatic hydrocarbon biomarkers in tasmanite oil shales from Tasmania, Australia. In *Organic Geochemistry: Poster Sessions from the 16th Intl. Mtg. on Organic Geochemistry, Stavanger 1993* (ed. K. ØYGARD), pp. 3–6. Falch Hurtigtrykk.

SACKETT W. M. (1991) A history of the $\delta^{13}C$ composition of oceanic plankton. *Mar. Chem.* 34, 153–156.

SHEARMAN D. and SMITH A. J. (1985) Ikaite, the parent material of jarrowite-type pseudomorphs. *Proc. Geol. Assoc.* 96, 305–314.

SIMONEIT B. R. T. and BURLINGAME A. L. (1973) Carboxylic acids derived from Tasmanian tasmanite by extractions and kerogen oxidations. *Geochim. Cosmochim. Acta* 37, 595–610.

SIMONEIT B. R. T., LEIF R. N., AQUINO NETO F. R., AZEVEDO A. D., PINTO A. C., and ALBRECHT P. (1990) On the presence of tricyclic terpane hydrocarbons in Permian tasmanite algae. *Naturwissenschaften* 77, 380–383.

SIMONEIT B. R. T., SCHOELL M., and AQUINO NETO F. R. (1992) Sources of biomarkers in Permian tasmanite based on carbon isotope compositions of individual compounds. Abstract of a presentation at Amer. Chem. Soc. mtg., San Francisco.

SIMONEIT B. R. T., SCHOELL M., DIAS R. F., and AQUINO NETO F. R. (1993) Unusual carbon isotope compositions of biomarker hydrocarbons in a Permian tasmanite. *Geochim. Cosmochim. Acta* 57, 4205–4211.

SMITH A. G., HURLEY A. M., and BRIDEN J. C. (1981) *Phanerozoic Palaeocontinental World Maps*. Cambridge Univ. Press.

SUESS E., BALZER W., HESSE K.-F., MÜLLER P. J., UNGERER C. A., and WEFER G. (1982) Calcium carbonate hexahydrate from organic-rich sediments of the Antarctic shelf: precursors of glendonites. *Science* 216, 1128–1131.

TAPPAN H. (1980) *The Paleobiology of Plant Protists*. Freeman.

TEGELAAR E. W., DE LEEUW J. W., DERENNE S., and LARGEAU C. (1989) A reappraisal of kerogen formation. *Geochim. Cosmochim. Acta* 53, 3103–3106.

TEN HAVEN H. L., DE LEEUW J. W., RULLKÖTTER J., and SINNINGHE DAMSTÉ J. S. (1987) Restricted use of the pristane/phytane ratio as a palaeoenvironmental indicator. *Nature* (London) 330, 641–643.

TISSOT B. P. and WELTE D. H. (1984) *Petroleum Formation and Occurrence*. Springer-Verlag.

TISSOT B. P., PELET R., and UNGERER P. (1987) Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation. *AAPG Bull.* 71, 1445–1466.

TRENDEL J.-M. (1985) Degradation de triterpenes dans les sediments: aspects photochemique et microbiologiques. Ph.D. dissertation, L'Université Louis Pasteur de Strasbourg.

TRENDEL J.-M., LOHMANN F., KINTZINGER J. P., and ALBRECHT P. (1989) Identification of des-A-triterpenoid hydrocarbons occurring in surface sediments. *Tetrahedron* 45, 4457–4470.

TRUSWELL E. M. (1978) *Palynology of the Permo-Carboniferous in Tasmania: An Interim Report*. *Tas. Geol. Survey Bull. No. 56*. Dept. Mines, Hobart, Tasmania.

TWELVETREES W. H. (1917) The search for petroleum in Tasmania. *Tasm. Mines Dept. Circ.* 2, 1–18.

VOLKMAN J. K., EVERITT D. A., and ALLEN D. I. (1986) Some analyses of lipid classes in marine organisms, sediments and seawater using thin-layer chromatography-flame ionisation detection. *J. Chromatogr.* 356, 147–162.

VOLKMAN J. K., BANKS M. R., DENWER K., and AQUINO NETO F. R. (1989) Biomarker composition and depositional setting of tasmanite oil shale. Poster presentation, 14th Intl. Mtg. on Organic Geochemistry, Paris, France.

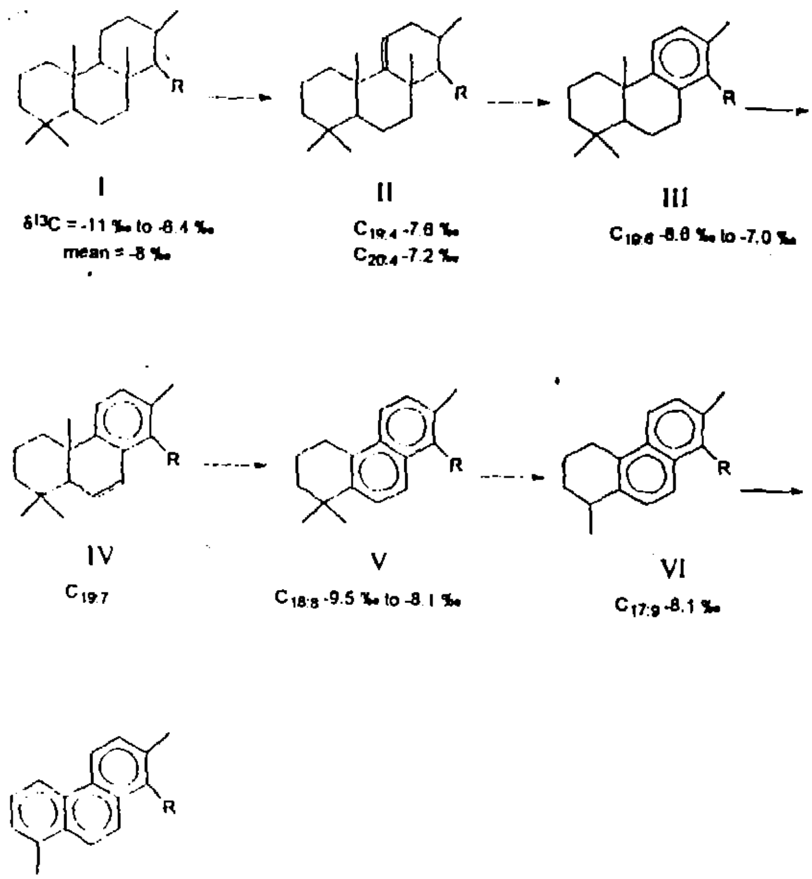
VOLKMAN J. K., O'LEARY T., SUMMONS R. E., and BENDALL M. R. (1992) Biomarker composition of some asphaltic coastal bitumens from Tasmania, Australia. *Org. Geochem.* 18, 669–682.

WALL D. (1962) Evidence from recent plankton regarding the biological affinities of *Tasmanites* Newton 1875 and *Leiosphaeridia* Eisenack 1958. *Geol. Mag.* 94, 353–362.

WOLFF G. A., TRENDEL J.-M., and ALBRECHT P. (1989) Novel monoaromatic triterpenoid hydrocarbons occurring in sediments. *Tetrahedron* 45, 6721–6728.

APPENDIX

Scheme 1



I: $\delta^{13}C$ = -11 ‰ to -8.4 ‰, mean = -8 ‰

II: $C_{19:4}$ -7.6 ‰, $C_{20:4}$ -7.2 ‰

III: $C_{19:6}$ -8.8 ‰ to -7.0 ‰

IV: $C_{19:7}$

V: $C_{18:8}$ -9.5 ‰ to -8.1 ‰

VI: $C_{17:9}$ -8.1 ‰

VII: $C_{16:10}$ -8.3 ‰ to -7.6 ‰, $C_{17:10}$ -9.8 ‰ to -6.0 ‰

Proposed general scheme for tricyclic compound aromatisation, R = H or alkyl chain, Cn:x, n = carbon number, x = rings + double bonds. Compound IV could be identified but no isotopic data could be obtained. Compounds I, III and V-VII had mass spectra comparable to published data. For type II ($C_{19:4}$) M^+ 260 (27 %), 245 (100), 189 (8), 175 (29), 163 (15), 149 (67), 119 (21); type IV ($C_{19:7}$) M^+ 254 (35), 239 (45), 183 (42), 169 (100).

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APPENDIX 7

CONGA OIL CURRENT EXPLORATION STATUS PROJECT DENTRECASTEAUX SOUTH EAST TASMANIA.

BY DR DAVID LEAMAN

1987

CONGA OIL PTY. LTD.

Oil Exploration and Drilling Company

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391174

CONGA OIL

CURRENT EXPLORATION STATUS

PROJECT D'ENTRECASTEAUX
SOUTH EAST TASMANIA

Notes prepared by

Dr. D.E. Leaman

Nov 1987

CONGA-10

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SUMMARY STATEMENT

Conga Oil Pty Ltd first claimed part of the D'Entrecasteaux Region of Southern Tasmania in June 1984 in order to verify old hydrocarbon reports. Since then, and especially since November 1986, it has acquired exploration rights to a large part of Southern Tasmania and has established:

1. Oil has definitely been generated. Reported seepages have been located. Material analysed demonstrates that the source is not Permian oil shale as all earlier workers have presumed. An Ordovician carbonate source has been suggested. This has become Conga's presumption.

2. Although seepage studies are incomplete there is evidence that very low volume seepage is still occurring over a large area.

3. Source rock studies of vitrinite reflectance and conodont alteration index confirm that Ordovician carbonates exposed around the region are within the oil window (mature).

4. Permian and younger rocks blanket most of the region and obscure distribution, structure and stratigraphic relationships. Permian rocks unconformably overlie a range of Palaeozoic and Precambrian units. The young rocks, including massive Jurassic dolerite intrusions, create an array of exploration problems but gravity-magnetic analysis has defined a major Palaeozoic basin beneath them.

5. Basin development began in the Late Precambrian, was most active during the Cambrian, but continued up to Middle Devonian times. By the Early Ordovician a relatively stable environment was established and a sequence of Ordovician carbonates and Silurian sandstones and shales was deposited. Deposition was terminated by a Middle Devonian folding event and uplift not accompanied by granite intrusion.

6. Possible reservoirs include the Ordovician limestone or Silurian sandstone.

7. Silurian shales or, more likely, Lower Permian mudstones and dolerite at the unconformity offer seal conditions. Exploration has not yet resolved any specific targets but an array of stratigraphic and structural traps can be conceived.

8. Massive disruption was associated with intrusion o. the Jurassic dolerites into the post-unconformity sequence but the region was not significantly affected by Tertiary disruption.

9. Escaping hydrocarbons were probably generated following a Cretaceous thermal event. Heat flows remain abnormal.

10. Seepages in the Bruny region may represent migration up dip, along the unconformity to Jurassic faults disturbed during the Tertiary, from the eastern margin of the basin some 10 to 20 kilometres to the west.

11. Exploration to date has emphasized gravity and magnetic methods. This partly reflects stage of exploration, budgetary issues and the crucial impact of Jurassic dolerite within the moderate to high relief terrain. Extended use of such methods allows cost effective evaluation of basin orientation, content and post unconformity structuring. Definition of the thin, folded, wedge remnants of the Ordovician-Silurian rocks was poor in first pass interpretation. These materials occur patchily and are not universal beneath the unconformity.

12. Gravity and magnetic data have defined how to effectively orient specific seismic surveys and will also be required to interlock seismic surveys. Advanced but proven technology is required and the geophysical method mix for target definition can never be current industry balance. Although the seismic method will never have predominance in this region its application and requirements have now been established. Usage will involve high acquisition costs and some delicate land use negotiations. Variable but usable seismic data can be obtained in difficult conditions.

Conga Oil has elevated a region previously considered quite unprospective into a province with established source rocks, escaping fluids, good seal conditions and a geological history to support generation and preservation. Some confirmatory work is still required but the exploration problems related to prospect definition have been assessed and a methodology established for dealing with them.

1

SUPPORTING EXPLANATION

INTRODUCTION

Although the D'Entrecasteaux Channel Region south of Hobart in Tasmania has some history of hydrocarbon occurrence and failed exploration it is not known as a province with hydrocarbon potential. Indeed, no basin with an appropriate structural history is obvious or exposed. In this respect the region is similar to many other complex provinces before the crucial insights were made.

Conga Oil has accepted that old records might be valid and sought to confirm them. Having done so, and reviewed the implications, it has now established that the region may have considerable potential where none was previously credited.

This document reviews previous exploration history, crucial discoveries to date, and the objectives of present and future programmes. The nature of the geological and geophysical problems facing the explorer are discussed in length.

Because Tasmania lacks an onshore Petroleum Act (no perceived oil potential) tenements have been acquired under the terms of the Mining Act. These involve smaller areas and higher acreage costs. Attempts are being made to consolidate the licences under more realistic terms. The distribution of the 4535 sq km held is shown in Figure 1.

The region is of moderate to high relief generally and a large part is crown forest. Much of the remainder is privately owned farmland divided into relatively small lots. The climate is temperate with a moderate annual rainfall (1000 mm).

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HISTORY

Many of the geographic names reflect the French discovery and mapping of this region in the late 18th Century by Admiral D'Entrecasteaux. His ships and crew members are honoured by names such as Recherche, Huon, Cygnet, Esperance, Bruny Island etc.

Between 1800 and the present there have been many reports of hydrocarbon occurrences in the Channel region and along the Storm Bay and southern coastlines. Few have been seen by acceptable observers (Twelvetrees in 1909, Wade (1915), McIntosh Reid (1929)) but none had been confirmed to universal satisfaction. Modern chemical techniques offer the means to resolve the issues. Reports have often been encouraging and companies were floated to drill on Bruny Island on two occasions (1915, 1929-30). Very limited depths were drilled (max 130m) due to limited budgets and unsatisfactory equipment.

Failure of these projects led to a loss in interest.

A search of records has shown that the area has never been held for any regional or specific exploration although a general reconnaissance of surface geology was undertaken some years ago.

It has always been presumed that any oil seepage reported, or oil generated, would be derived from the Permian oil shales. Appraisal of Tasmania's hydrocarbon potential on this basis has always been poor; the rocks are exposed, not sealed and reservoir conditions are virtually non existent. The basic assumption has never previously been challenged and in absence of any satisfactory alternatives the province (known as the Tasmania Basin overall) has been downrated. Coupled with this assumption and the general difficulty of exploration (see "Source rock studies" and "Geology") no deep geological assessment has ever been attempted.

General geological mapping has continued, including Leaman (1972) and Farmer (1981), as has development of technology to evaluate dolerite structures (Leaman (1972b, 1975) which compound problems of structural assessment and research into pre Permian rocks fringing the D'Entrecasteaux region (e.g. Burrett et al 1981, 1984).

Conga Oil was founded in 1984 to seek out the reported Bruny Island sites and assess their origin if located (EL 29/84 - see Figure 1).

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SEEP AND SOURCE ROCK STUDIES

Until late 1986 the prevailing view concerning any possible hydrocarbon generation (seepages) in Tasmania was that it must be related to Permian oil shales. Since this unit is patchily developed and often exposed its potential as a source rock is limited. Reservoir conditions are most unlikely and this has often been stressed. These realities and this assumption has led to neglect of the province.

Neither Conga Oil nor those who have observed bitumens and tars in Ordovician limestone exposed in western Tasmania, including Drs Banks and Burrett of the University of Tasmania and the author, were convinced that the oil shales represented the only possible source since the same limestone is occasionally exposed beneath Permian cover west of the Huon River (Figure 3B).

Dr. Burrett reported to Conga Oil that the conodont colour alteration index for Ordovician carbonates in the region of the Picton River, Lune River and south coast was within the mature oil window (1.5 to 2.0, see Figure 3B). Subsequent vitrinite reflectance determinations of Upper Cambrian and Ordovician carbonates from the periphery of the region have yielded values of 0.7 to 1.12 with total organic carbon levels consistent with weathered surface samples.

Relocation of reported seepage sites in the Bruny region has produced some confirmatory analyses (by Dr. J. Volkman, CSIRO, Hobart). Although no confirmed seep site yet sampled is associated with residual tars - these have been reported in the past - or obvious flows, the chemical signature of the released hydrocarbons is distinctive (Figures 2A to 2E). It is considered indicative of an Ordovician source rock which may be proven when residual tars from the limestones are analysed. The hydrocarbons are not derived from Tasmanites oil shale of Permian age. Samples from as far apart as Tinderbox, Dennes Point, Johnsons Well, Miles Creek and the Isthmus present the same signature. Pollution or contamination may be excluded and the results give some credibility to other reported sightings (see Figure 3C) and other sites are now being sought.
A mud sampling programme is underway around both parts of Bruny Island and the Huon estuary. The first phase of sampling, north of Kettering, supports the land-based results. All analysis and marine sampling has been contracted to the CSIRO Division of Oceanography.

Recovery of oil in an ephemeral stream (Miles Creek) shows that low volume release is still occurring. Hydrocarbon concentrations in the confirmed samples have been very low. Volumes of oil released are clearly much lower than reported in 1929 when oil was seen escaping from rock fissures at Johnsons Well (McIntosh Reid, 1929) and encountered at 27 m during drilling. Eyewitness reports describe storage of the fluid light oil in drums. Release may be controlled by periods of seismic activity. Bacterial activity coupled with low release volumes probably explains the absence of residual products although these have been described in the past at Variety Bay and Little Fancy Bay (Figure 3C). A possible occurrence from Barnes Bay is now being analysed.

The analyses reported in Table 1 (Figure 2A) from North Bruny Island (Dennes Point to the Isthmus), and apparently supported by the channel mud samples (Volkman, pers com), indicate a mature crude with distinctive chemistry. A full signature has not yet been obtained due to the very low concentrations in the recovered samples.

It must, however, be stressed that until the recovered hydrocarbon signature is matched to a particular source unit the Ordovician source origin implied by chemical indicators and current knowledge of the limestone can only be a presumption. While the Tasmanites oil shale has been excluded as a source possibility other Lower Permian mudstones, or Siluro-Devonian shales could be source rocks.
Current exploration by Conga Oil presumes a pre Devonian, probably Ordovician, source rock.

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GEOLOGY

Before scenarios for generation, storage, sealing and migration can be presented it is necessary to consider the geological peculiarities of the D'Entrecasteaux Region. Figure 3A presents a simplified version of the exposed geology. Jurassic dolerite dominates the map, the upper parts of the section and the topography. Various Permian and Triassic formations complete the map. Permian oil shales are not known in the region even though formation correlates are well exposed. In any event current studies suggest that Ordovician rocks may be significant sources. The known distribution of Ordovician rocks is shown in Figure 3B.

Figure 3C presents knowledge of the pre Permian geology prior to commencement of Conga's exploration programme. Coreholes at Glenorchy and Woodbridge demonstrate that Lower Palaeozoic units of west Tasmania affinity extend as far east as the Derwent River at least.

The base of the Fermo-Triassic cover, with its stockwork of massive dolerite intrusions, is probably never less than 500m deep and, depending on topography and stratigraphic position, may exceed 1500m.

The base of the Permian succession is marked by a major unconformity which may be locally irregular and possess relief of more than 300m. Depressions are often filled with tillite marking late Carboniferous glaciation.

Figure 3D presents the current understanding of the distribution of Lower Palaeozoic and Precambrian rocks as projected onto the unconformity and was derived from a primary gravity-magnetics interpretation. Formation properties and the first order techniques used to date have not permitted resolution of post Cambrian rocks, although some inferences are possible.

The interpretation coupled with analogies based on exposures west of the tenements indicates that siliceous Precambrian (Tyennan) basement is deeply buried by younger Precambrian dolomite and argillite sequences and an early Palaeozoic trough. The most active trough developments were Cambrian in age. The dominant Cambrian components include mafic and felsic volcanics and some ultramafics. All aspects are comparable to the Dundas Trough of Western Tasmania.

Several periods of deformation are likely; in the Early Cambrian, Middle-Late Cambrian and Early Ordovician. The last was followed by gentle sag deposition within, or near the margins of the main trough. The limestones providing the probable source rocks were deposited at this time. Deposition may not have been universal but Ordovician- Silurian units may have been up to 4 km thick locally. A relatively gentle orogeny in the Middle Devonian folded and uplifted the basin without accompanying granitic intrusion.

The scale of the residual basin is suggested in Figures 3G and 3H but the volume and nature of the material between the Upper Cambrian and the Permian unconformity has not yet been resolved.

Figure 3D suggests a possible distribution for the truncated folded volumes of Ordovician-Devonian rocks. Exploration is not yet sufficiently advanced to be able to assess the reliability of the inferences shown in respect of these materials. The distribution SW of Dover, is reasonable but the map otherwise can be accepted only near Glenorchy, Clifton, Leslie Rd., Woodbridge and North Bruny Island. The definition of the style and type of pre-Palaeozoic rocks and indications of the content and form of the Cambrian basin is much more satisfactory at this stage.

The style of the relationships likely is suggested in Figure 3E. Figure 3E reproduces an actual section from NW Tasmania while Figure 3F presents a fragment of Conga's interpretation within its tenements. The upper part of Figure 3E illustrates the structural complications introduced by the dolerite.

Figures 3G and 3H suggest the primary structural orientations and significant block boundaries which should be viewed in association with Figure 3I. The present understanding indicates considerable rejuvenation of structural elements and implies that the modern coastline reflects Jurassic and Tertiary incarnations of Late Precambrian structures. There is, however, no evidence of continued uplift over basement highs and isostatic stability was probably achieved before deposition of the Permian formations. Figure 3D summarises the present understanding in the absence of seismic data (see below) of fold systems. No closures have been established yet.

After the Pre Carboniferous glaciation the area was subject to gentle subsidence until Middle Jurassic intrusion of massive dolerite sheets. The post Carboniferous section was completely disrupted but the older rocks were probably not greatly affected. This was a significant thermal event. The area was uplifted and eroded throughout the Cretaceous. In the late Cretaceous the rocks near the unconformity were intruded by a syenite laccolith centred on Cygnet. This has domed the Permian rocks and inserted a fracture fill dyke swarm, and some sheets in the roof.

Gravity-magnetic analysis suggests the syenite mass has a diameter of about 20 km with a possible extension toward Kettering (see dotted area, Figure 3D). The discovery of this body accounts for the enigmas discussed by Leaman and Naqvi (1967), and resolves many of the apparent conflicts outlined by Farmer (1985). This was also a significant thermal event since many sedimentary palaeomagnetic indicators were reset (Sharples and Klootwijk, 1981).

Within the exposed rocks Jurassic faulting is predominant but not always obvious and the region largely escaped Tertiary extensional faulting. Most Tertiary disruption occurred east of Hobart, Dennes Point and Adventure Bay although some offsets

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were translated through North West Bay. Tertiary deposition, once more general, is restricted to valley fill accumulations (see Farmer, 1985).

The geological and geophysical problems presented are peculiar to Eastern Tasmania and their solution requires much experience and local knowledge. An ability to assess dolerite forms, strip the post-Carboniferous cover and thereby increase resolution of Jurassic faulting and the pre-unconformity rocks is critical to the present exploration.

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GENERATION AND PRESERVATION

Given the geological history of the region, and the Ordovician limestones in particular (presuming these to be the source rocks), it is unlikely that any hydrocarbons generated prior to the Devonian orogeny would be preserved. The depth of burial may have been inadequate in any case in light of the alteration indices. It is, however, possible to conceive situations in which hydrocarbons generated after the Permian could migrate into anticlines sealed by Silurian shales or Permian mudstones above the unconformity.

The Jurassic and Cretaceous thermal events are likely to have been critical. While the entire post unconformity succession was disrupted during the Jurassic event all breaks were sealed by the cooling intrusions (Leaman, 1975). The disruptive influence of the Cretaceous event was spatially restricted geographically to the Cygnet area and stratigraphically to the rocks immediately above and below (?) the unconformity. Thus either or both events could have led to generation without significant loss of hydrocarbons (see also trap conditions).

It has been suggested that seepages might be related to dolerite feeder systems. These may have generated small volumes of hydrocarbons from suitable materials. The widespread release or distribution of hydrocarbons suggested by the old reports and Conga's own findings tends against this possibility unless the source rocks are basal Permian mudstones. The Lower Palaeozoic potential source rocks are unlikely to be sufficiently widespread when matched to the seventy feeders, large and small, identified in primary interpretation. And, Lower Palaeozoic rocks do not appear to be present in the North Bruny region where the hydrocarbon traces have been established to date. This issue must remain open until more is known of the source and the sub-unconformity section. The volumes released or observed may be crucial; while currently very small, significant flows were observed in 1929.

A more plausible explanation of the seepages east of the syenite intrusion and the eastern margin of the basin is that oil generated by the Cretaceous event, from Lower Palaeozoic sources, has migrated up dip along the unconformity and is escaping along the primarily Jurassic faults of the region. These structures, which lie close to the limits of Tertiary activity, have probably been disturbed. Even so, leakage volumes are very small. A clearer view may emerge when the distribution of seepages is more precisely known.

There is no evidence at the present time for any occurrence of the probable source rocks on the shelf of Late Precambrian rocks which underlie the unconformity at North Bruny Island.

Heat flows in the region remain elevated and thermal springs occur on the SW perimeter of the syenite intrusion.

RESERVOIR AND TRAP CONDITIONS

A number of possible reservoir rocks can be conceived. The Silurian formations, if present, offer paired reservoir and seal units; thick sandstones and shales. The Ordovician limestones, whether present as reefal accumulations or not, offer many storage possibilities. Reef and shelf limestones are known to exist in the southern part of the region. Thick sections of the limestone at Lune River have been recrystallized and have high porosity. Where the limestone was exposed prior to the onset of Permian sedimentation karsts and deep weathering porosity have also been developed.

The Lower Permian formations - tillite and Woody Island Siltstone (and correlates) - are unlikely to offer reservoir conditions. These rocks, with a total thickness never less than about 200 metres, are either very fine grained or possess a very fine grained matrix. They could be expected to form an excellent seal on the unconformity. Their efficiency as seals, given Jurassic dislocation and breakage, may account for the trace seepages.

Other Permian formations are passable aquifers with strong bedding heterogeneity. These may offer local reservoir potential, especially if sealed by dolerite intrusions or traps formed by faulting or dolerite dykes.

Optimum reservoir - trap conditions probably lie below, or at, the unconformity and involve the limestone itself.

331186

GEOPHYSICS AND PROSPECT EVALUATION

The geology of the D'Entrecasteaux region, its historical development and the nature and properties of some of the rock units present make an unusual bias to the exploration programme essential when compared with normal industry practice. This is unlikely to change, as discussed below, due to the combination of geological considerations, costs, access, data quality and political factors.

The approach employed is capable of yielding equivalent results but at a much lower final cost and has already provided the regional setting and geological history noted above.

The twin pillars upon which all exploration in the D'Entrecasteaux Region must rest are the gravity and magnetics data bases (Figures 4A, 4B). Comprehensive surveys have been completed and primary analysis completed (previous section and Figures 3F to 3I). The analysis is not yet exhaustive and, as seismic traverses or survey segments become available, the evaluation can and must be expanded. Both methods are able to assess the impact of Jurassic structuring and intrusions in the post unconformity sequences and provide a basis for linking seismic surveys after stripping the covering materials. This implies extended application of these methods and state-of-art 3D whole geology techniques.

But why is this necessary (essential)? There are several reasons. The seismic method can not be relied upon to yield high quality data in Tasmania but adequate results can be often achieved. Due to terrain, access, environmental and political issues a very high acquisition cost is inevitable and the method can only be employed selectively. There is no possibility of acquiring a first order regional grid and the gravity-magnetic coupling has already attained most of the objectives of such a coverage.

The waterways offer an opportunity for some regional coverage and marine survey would provide an indication of structural relationships and unit onlap or termination characteristics.

The extant interpretation already suggests where seismic surveys should be concentrated and what line orientation will be most effective. This approach is efficient and will reduce future exploration costs.

Three survey fragments from the region are presented in Figures 4C, 4D. All are pre-processing and were recorded with no input filters. Displays in Figure 4C present various playback filter options. These sections demonstrate that in parts of the area high quality data and many reflectors are present to at least 4 seconds. In others, the data is poorer and such reflectors are absent (Figure 4D). These fragments suggest that important pre-Permian sections may be present at Clifton and Leslie Rd. but not at North Bruny. This is consistent with the gravity-magnetics view as presented in Figures 3D and 3F. The base of the Permian is considered to lie at about 1.3 secs (Clifton), 0.6 secs (upper Leslie Road at Southern Outlet intersection and Nth. Bruny).

The significant problems for onshore seismic surveys relate to very high surface velocities, especially on dolerite, coupled with irregular three dimensional terrain and complex intrusion forms including a mix of subvertical and subhorizontal limbs. The test sites of Figure 4C avoid such problems while that at Murrayfield (Figure 4D) carries only moderate 2D terrain effects. For original discussion concerning sites presented in Figure 4C refer to Leaman (1978).

These estimates have been based on limited velocity information, used conservatively for near vertical incidence, and stratigraphic control near surface. Approximately 0.5 secs of the Clifton example is due to Tertiary sediments on the Permian rocks which include at least one dolerite sheet. The North Bruny traverse was fired in Permian rocks above a dolerite sheet while the Leslie Road test was fired within the upper part of a dolerite sheet. With respect to the various sections, although widely separated, the dolerite sheets are stratigraphically equivalent but not the same sheet system.

In all cases the unconformity reflection is multiple (compare Tertiary to Permian effect; 1700 to 3500 + m/s).

The reflector patterns at Clifton and Leslie Road indicate strongly heterogeneous sections as would be expected within the Ordovician-Devonian succession. The bland Murrayfield (North Bruny) effect has often been observed in tests around Hobart and suggests that structural homogeneity has been impressed on Precambrian basement (type 2) as suggested by the Woodbridge core.

331188

CURRENT AND FUTURE PROGRAMMES

Although Conga Oil Pty. Ltd. began work in 1984 most of the results presented here were obtained in 1987 after a reported seepage was relocated and analysed. This is considerable progress in a difficult, virgin province. It also accounts for the bias toward the more universal and less costly gravity and magnetic methods and the limited amount of seismic data available to date. The groundwork for seismic application has been laid since research programmes have established that the method can yield usable results, albeit variable in quality and at high cost.

Consequently, marine seismic traverses followed by limited land-based surveys of the eastern margin of the Palaeozoic basin have been proposed since materials in this region are presumably sourcing seeps along the channel and Bruny Island. Such traverses may also provide prospect indications.

No seepages are known from the western side of the basin but this may reflect lack of observation. Identification of seepage patterns may be important for ultimate targetting and further sampling programmes are in train. Magnetic identification of Jurassic structures, which may be intersecting migration paths, is also proposed. Possible source rocks are being sampled in order to match the oil signature.

The first stage interpretation was unable to resolve in detail the remnants of the Ordovician and Silurian section beneath the unconformity. While the proposed seismic coverage will aid this process locally the gravity-magnetics data base can be used to provide areal description of forms. In the case of part of North Bruny Island this has already been achieved. These techniques will be supported by a programme studying pyroclastics. The region contains a number of extinct Tertiary volcanoes and the ejecta offer a means of inspecting the actual rocks beneath the volcano. Two volcanoes already examined have collected much younger Precambrian material (type 2). Both lie east of line A-A in Figure 31 and the method appears a workable way of supporting uncontrolled interpretation. This approach, coupled with gravity-magnetic--seismic analysis, may allow some specific identifications well in advance of any drilling.

The present and future programme has been designed to provide information about folding, closure styles and stratigraphic wedges, and a prospect list at minimum cost in order to allow drilling at the earliest feasible date (Conga Oil owns a petroleum rig of 3000m capacity).

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CONCLUSIONS

The D'Entrecasteaux Region possesses all the hallmarks of a potentially productive petroleum province. There are possible source rocks, hydrocarbons have been generated, either generation is continuing (improbable) or reservoirs are leaking since seeps remain active, and likely relationships between structures, basins, source rocks, reservoirs and traps are well understood and known to occur. An Ordovician source for the oil, though probable, has yet to be proven.

The region would appear to have potential at least equivalent to the Amadeus and Canning Basins. The sealing unconformity, and the rocks above it, provides an insurance of this potential as well as posing difficult exploration conditions.

Target definition in the prevailing conditions will not be a simple process and will require a judged balance between gravity, magnetic and seismic methods. No single method will prove adequate or cost effective.

331190

REFERENCES

Burrett, C., Stait, B., Laurie, J. 1981. Gordon Subgroup (Ordovician) Carbonates at Precipitous Bluff and Point Cecil, Southern Tasmania, Australia. Proc. Roy. Soc. Tasm., 115.

Burrett, C., Stait, B., Sharples, C., and Laurie, J., 1984. Middle-Upper Ordovician Shallow Platform to Deep Basin Transect, Southern Tasmania, Australia. In "Aspects of the Ordovician System", edited by D.L. Bruton Universitetforlaget.

Farmer, N. 1981. Geological Atlas 1:50000 series. Sheet 88 (8311N). Kingborough. Geol. Surv. Tasm.

Farmer, N. 1985. Geological Atlas 1:50000 series. Sheet 88 (8311N). Kingborough. Explan. Rep. Geol. Surv.Tasm.

Leaman, D.E., 1972a. Geological Atlas 1:50000 Series. Sheet 82 (8312S). Hobart. Geol. Surv. Tasm.

Leaman, D.E., 1972b. Gravity Survey of the Hobart District. Bull. geol. Surv. Tasm. 52.

Leaman, D.E., 1975. Form, mechanism and control of dolerite intrusion near Hobart, Tasmania. J. Geol. Soc.Aust., 22(2), 175-186.

Leaman, D.E., 1978. Use of the reflection method in Tasmania. Geophysics special report 7, Mines Dept. Tasm.

Leaman, D.E., and Naqvi, I.H., 1967. Geology and Geophysics of the Cygnet District. Bull. geol. Surv. Tasm.,49.

McIntosh Reid, A., 1929. North Bruny Oil Prospects. Unpub. Rept. Dep. Mines Tasm.

Sharples, C., and Klootwijk, C.T., 1981. Palaeomagnetic results from the Gordon Subgroup of Tasmania: further evidence for a Late Cretaceous magnetic overprint in southeastern Australia. Pap. Roy. Soc. Tasm., 115, p.85

Wade, A., 1915. Report on the Prospects of Discovering Petroleum on North Bruny Island, Tasmania. Parliamentary Paper.60.

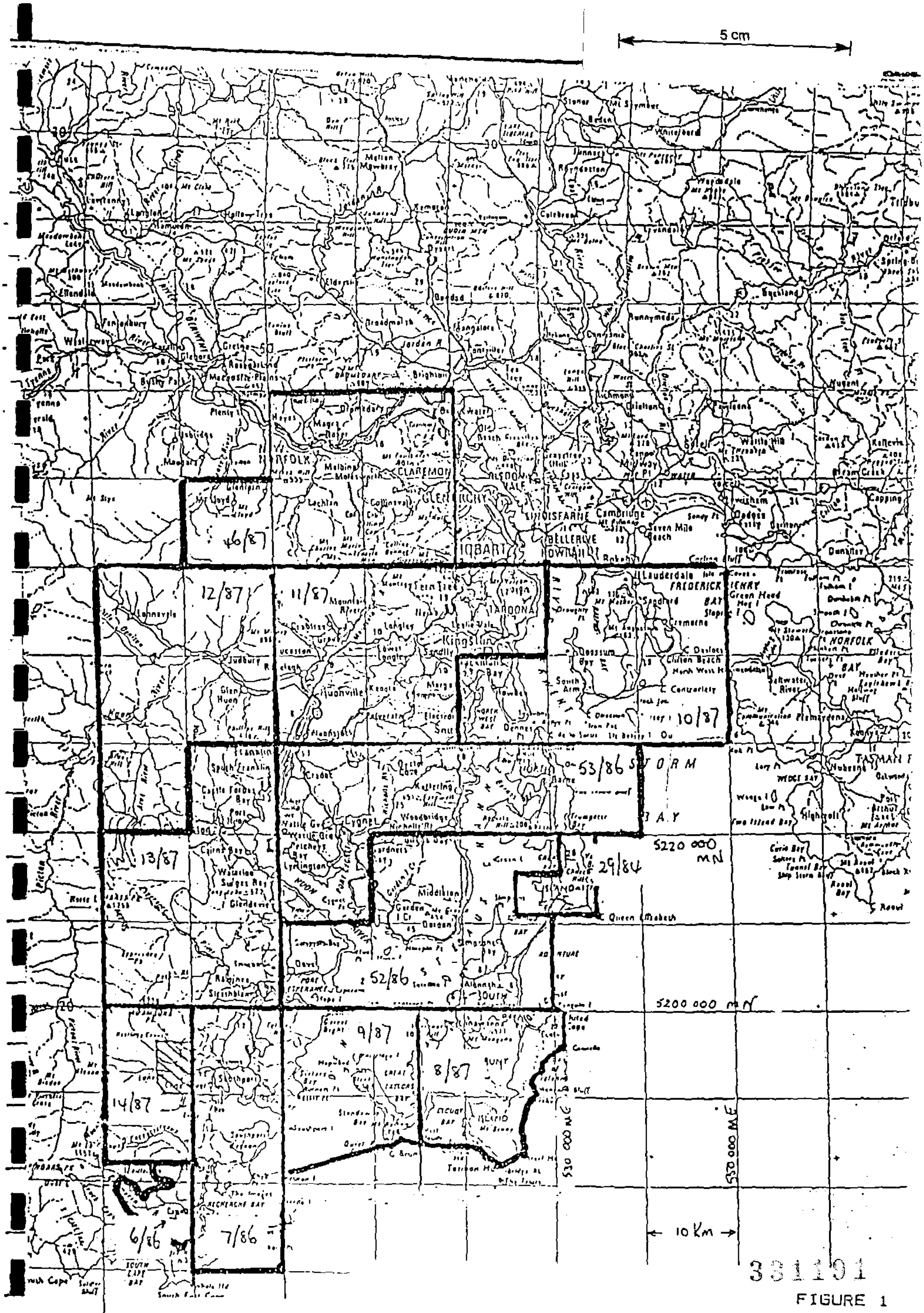

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FIGURE 1

SURVEY AREA AND LOCATION OF EXPLORATION LICENCES

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TABLE 1

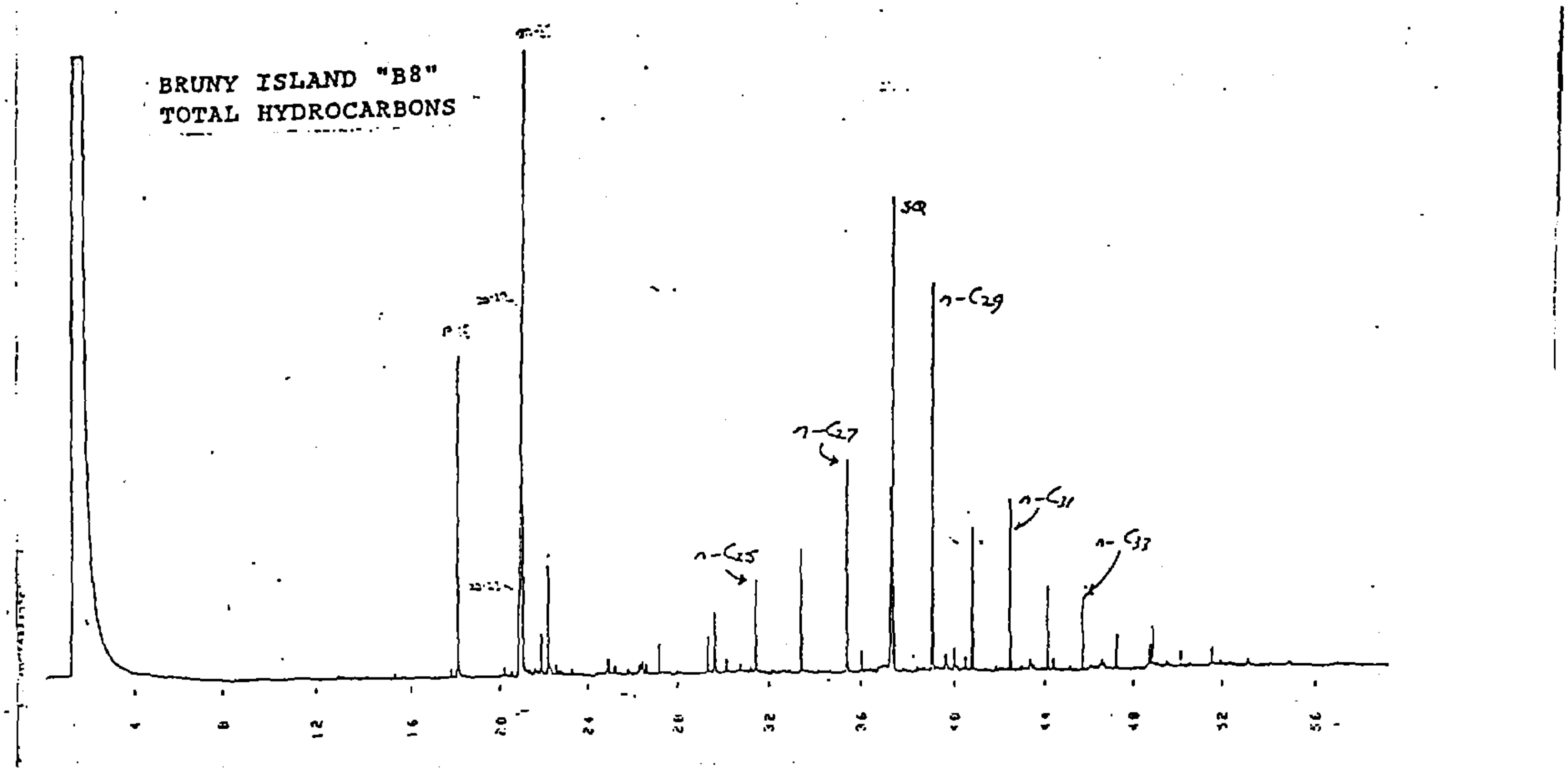
SELECTED BIOMARKER PARAMETERS FROM GC-MS ANALYSIS

SAMPLES: Sediment and water samples from Bruny Island supplied by Mr. K. C. Morrison.

MATURITY PARAMETERS	SP2	B5	B6	B7	B8
1. C_{27} hopanes: T_s/T_m	0.63	nd	0.70	0.38	0.79
2. C_{30} hopane/C_{30} moretane	4.8	nd	7.4	3.1	6.0
3. C_{31} 22S hopane/(C_{31} 22R + 22S hopanes) X 100	6%	nd	37%	21%	28%
4. C_{32} 22S hopane/(C_{32} 22R + 22S hopanes) X 100	56%	nd	58%	55%	60%
5. C_{29} $\alpha\alpha\alpha$-steranes: 20S/20R	0.81	0.79	0.71	0.72	0.73
6. C_{29} 20R steranes: $\alpha\beta\beta/\alpha\alpha\alpha$.	1.02	0.95	0.94	0.90	0.82
SOURCE PARAMETERS					
7. C_{27}/C_{29} steranes	0.93	0.71	0.78	0.98	0.73
8. C_{27}/C_{29} diasteranes	1.7	1.5	nd	1.0	0.77
9. Pristane/phytane	0.20	1.3	1.3	1.1	1.3

Parameters 1-4 calculated from m/z 191 mass fragmentograms
Parameters 5-7 calculated from m/z 217 and 218 mass fragmentograms
Parameter 8 calculated from m/z 259 mass fragmentograms
Parameter 9 calculated from m/z 113 mass fragmentograms.
nd: not dteremined due to co-elution with other compounds or too weak.

FIGURE 2A



CAPILLARY GAS CHROMATOGRAM OF TOTAL HYDROCARBONS IN BRUNY ISLAND SAMPLE "B8".

FIGURE 2B

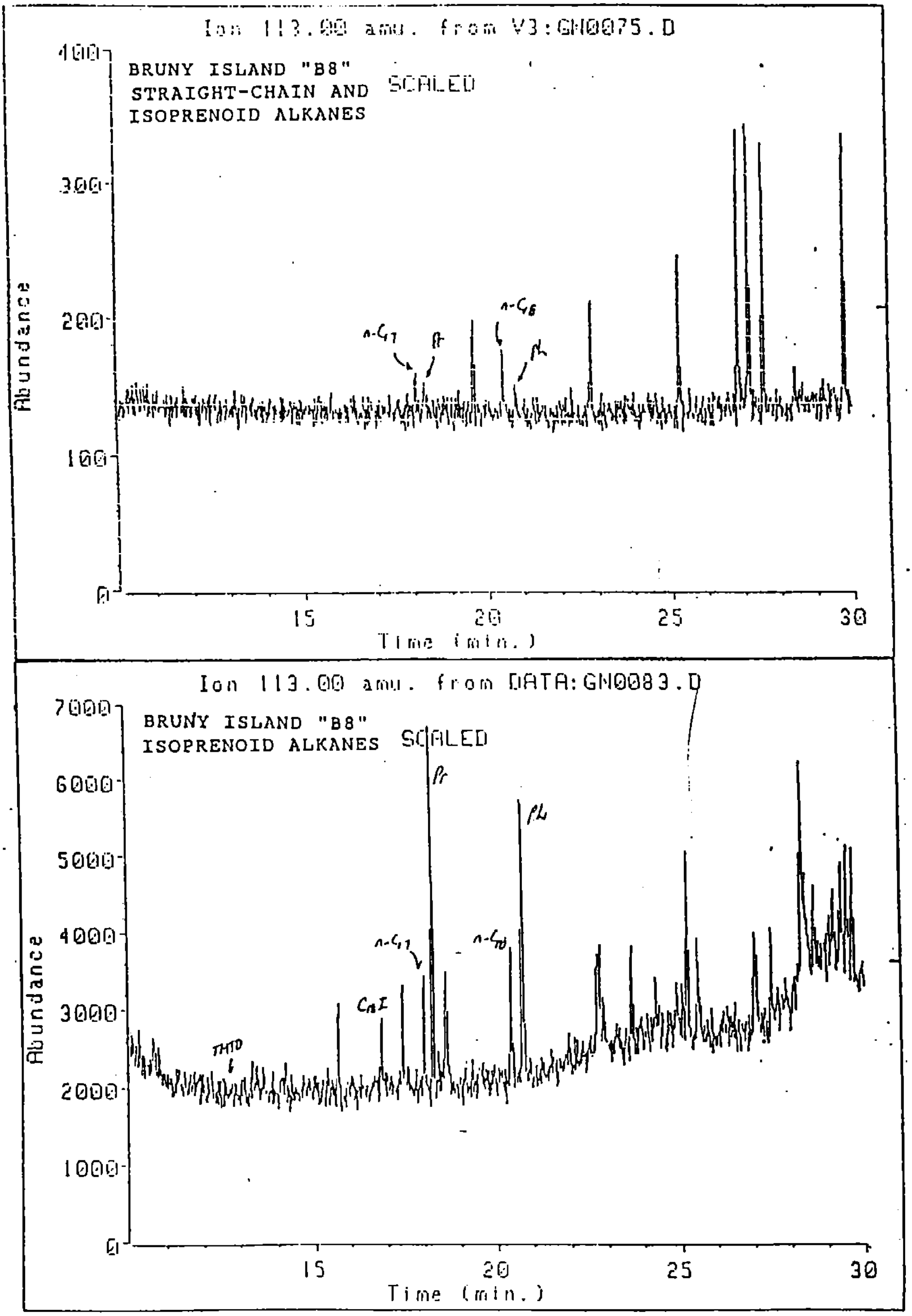


FIGURE 2c(i) STRAIGHT-CHAIN AND ISOPRENOID ALKANES FROM TOTAL HYDROCARBONS IN BRUNY ISLAND SAMPLE "B8".

FIGURE 2c(ii) ISOPRENOID ALKANES FROM BRANCHED/CYCLIC ALKANE FRACTION FROM BRUNY ISLAND SAMPLE "B8".

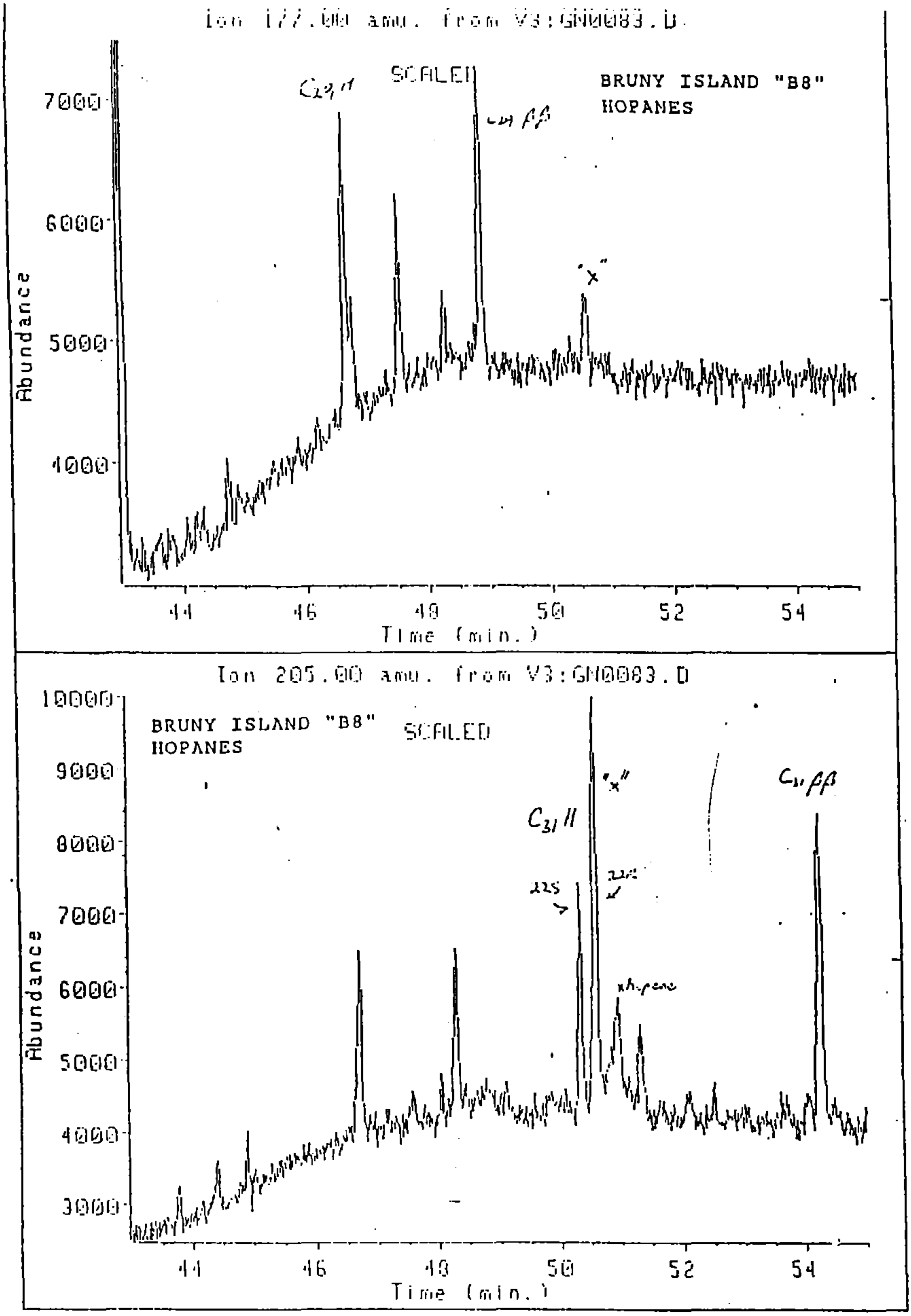


FIGURE 2D MASS FRAGMENTOGRAMS FOR M/Z 191 (HOPANES PLUS OTHER TRITERPANES) IN BRUNY ISLAND SAMPLE "B8".

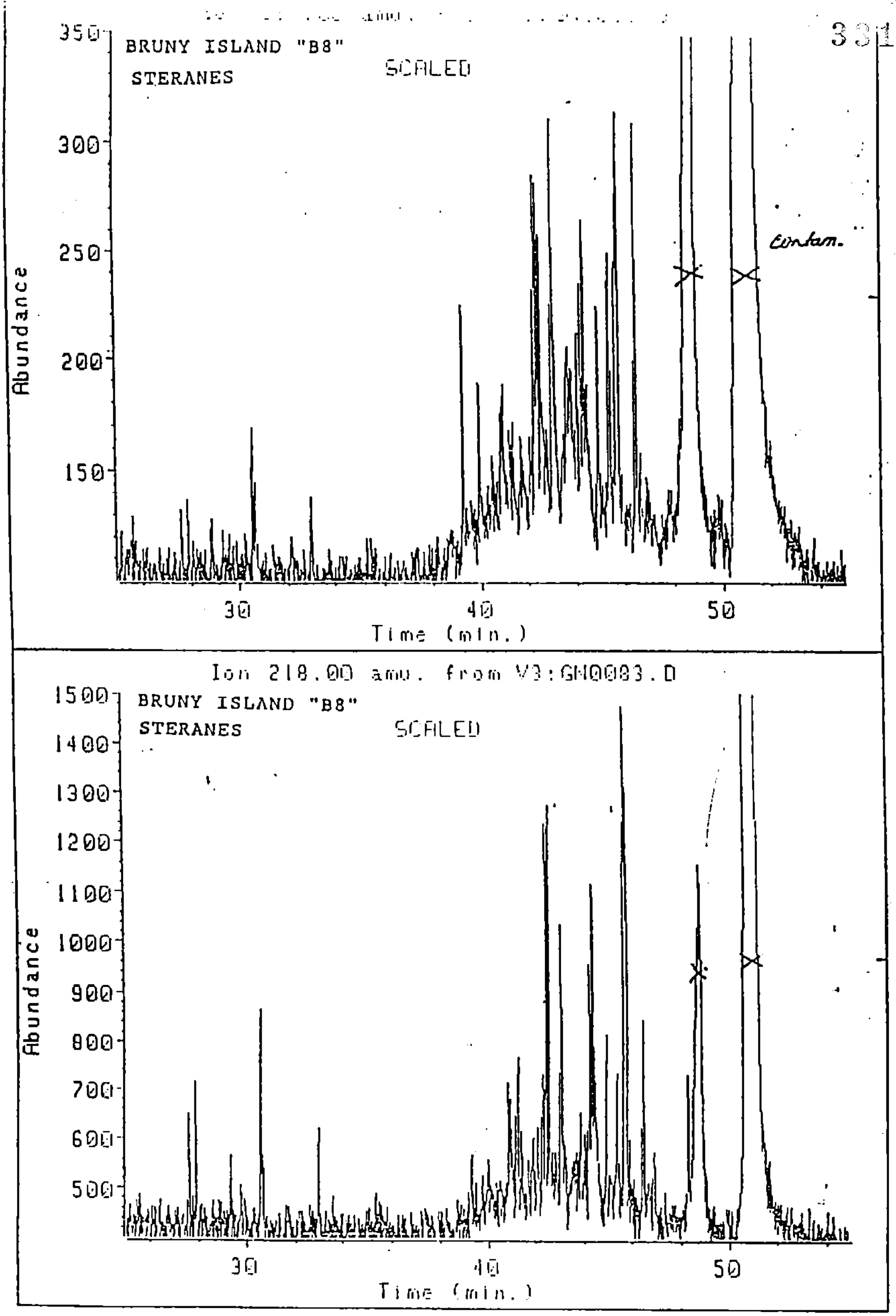
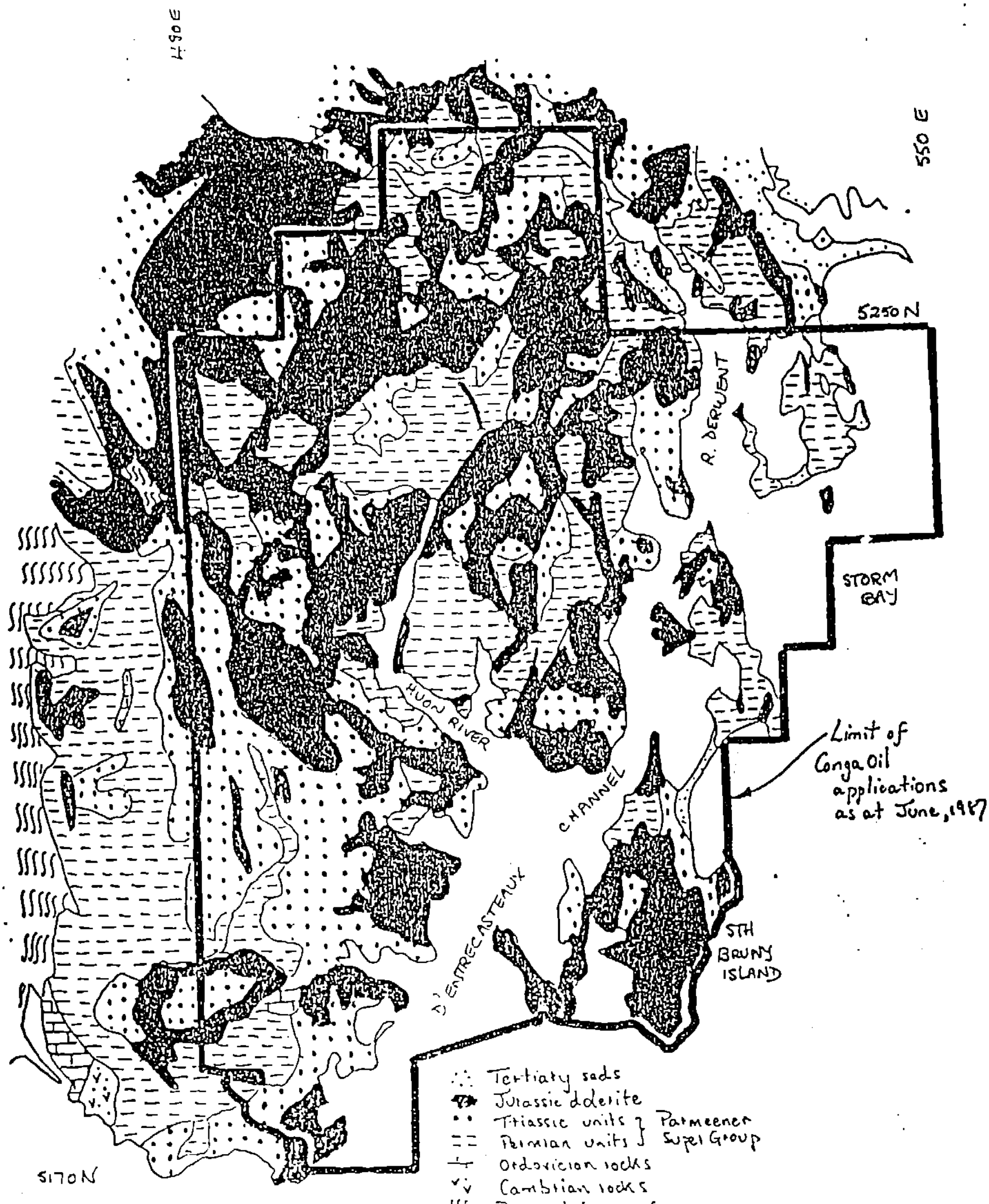


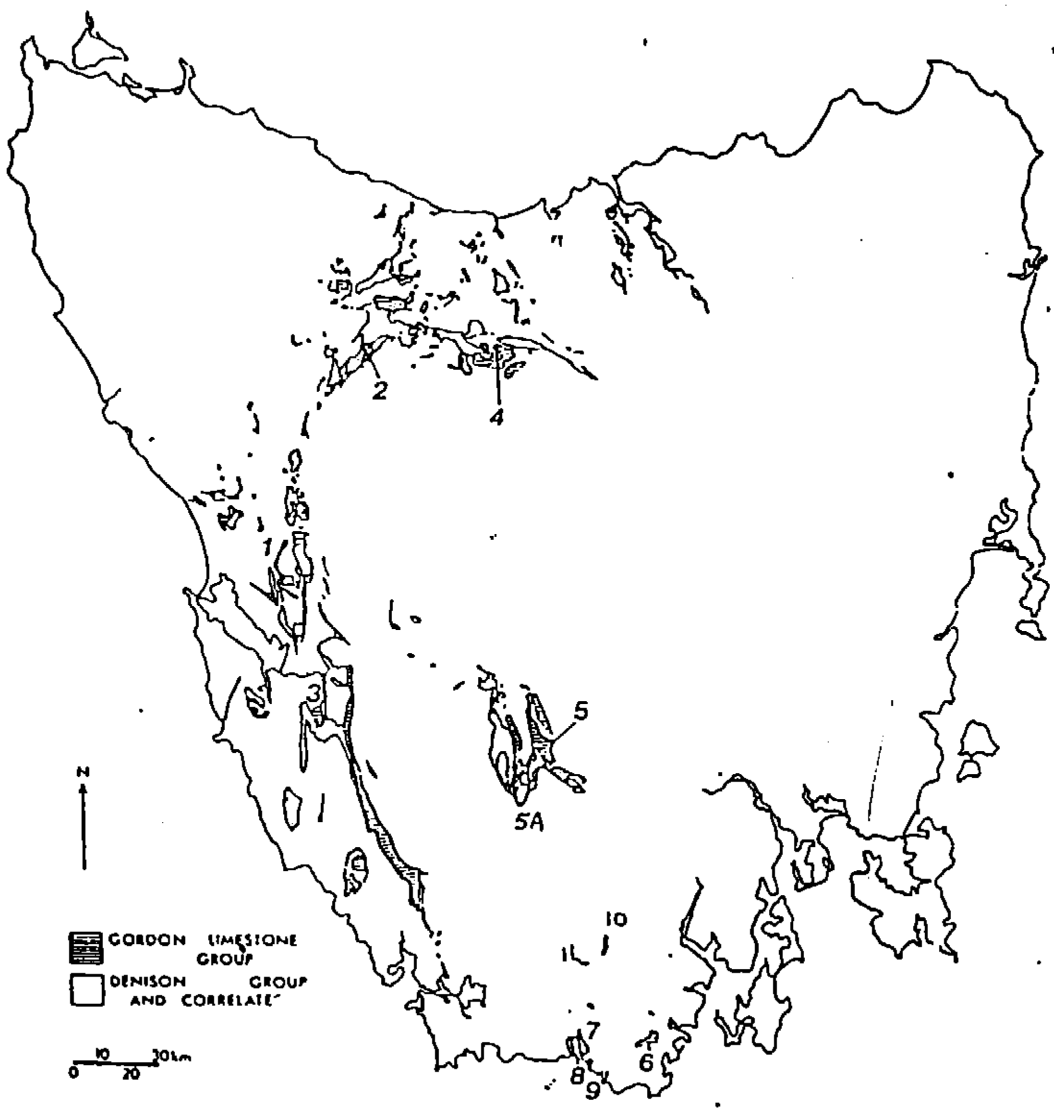
FIGURE 25 MASS FRAGMENTOGRAMS FOR M/Z 217 AND 218 (C_{20} - C_{30} STERANES) IN BRUNY ISLAND SAMPLE "B8".



Geology simplified from "Geological Map of Tasmania"

FIGURE 3A

PRINCIPAL GEOLOGICAL ELEMENTS OF THE REGION



5 cm

EXPOSURE OF ORDOVICIAN ROCKS
(map after Burrett)
Table: Conodont alteration index for sites 5 to 11

site	index
5	2
5A	4
6	1.5
7	2
8	1.5
10	1.5
11	5

FIGURE 3B

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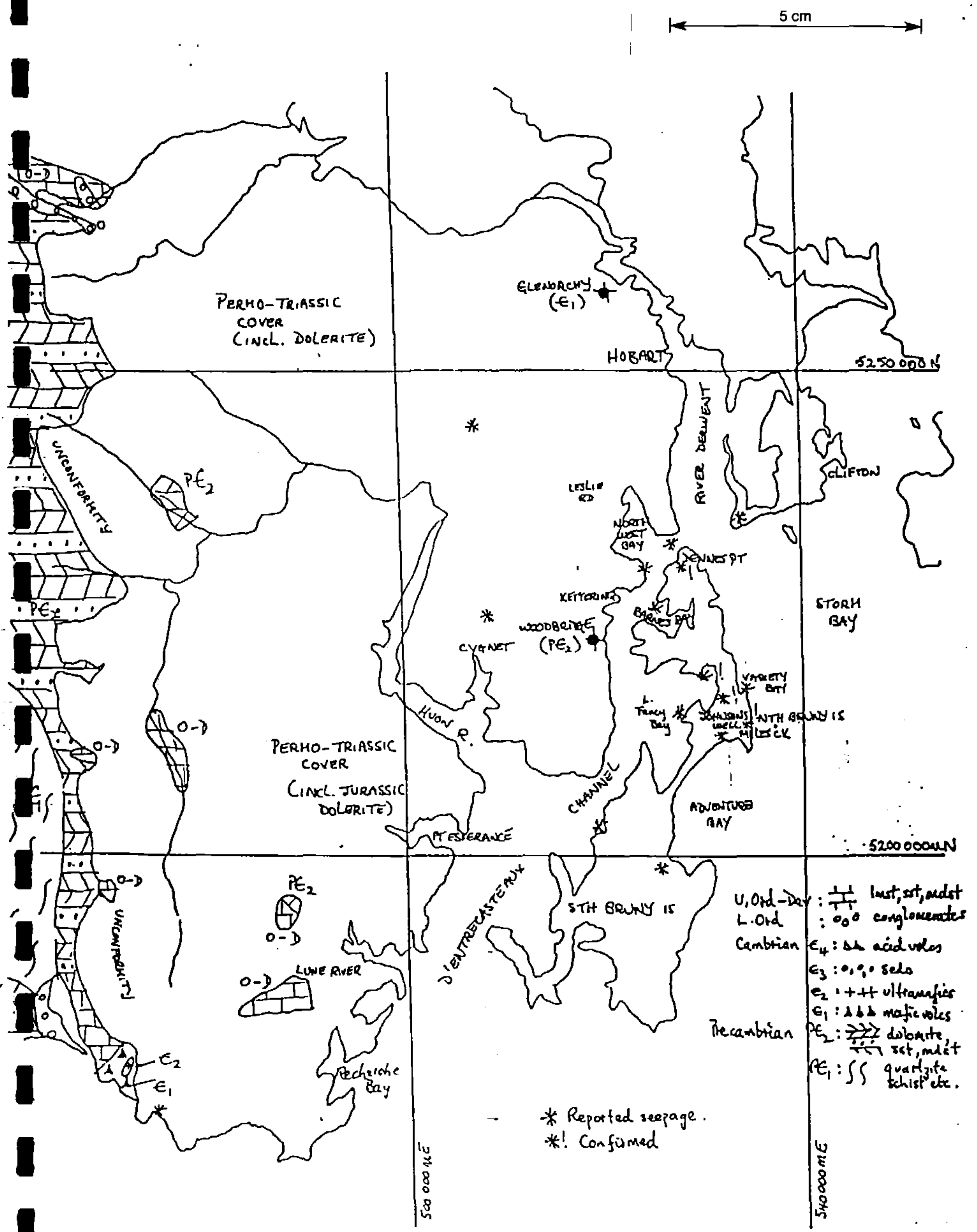

KNOWLEDGE OF PRE CARBONIFEROUS GEOLOGY PRIOR TO CONGA OIL
(based on Geological Survey map, 1975)
Some reported seepages are also indicated.

5 cm

301200

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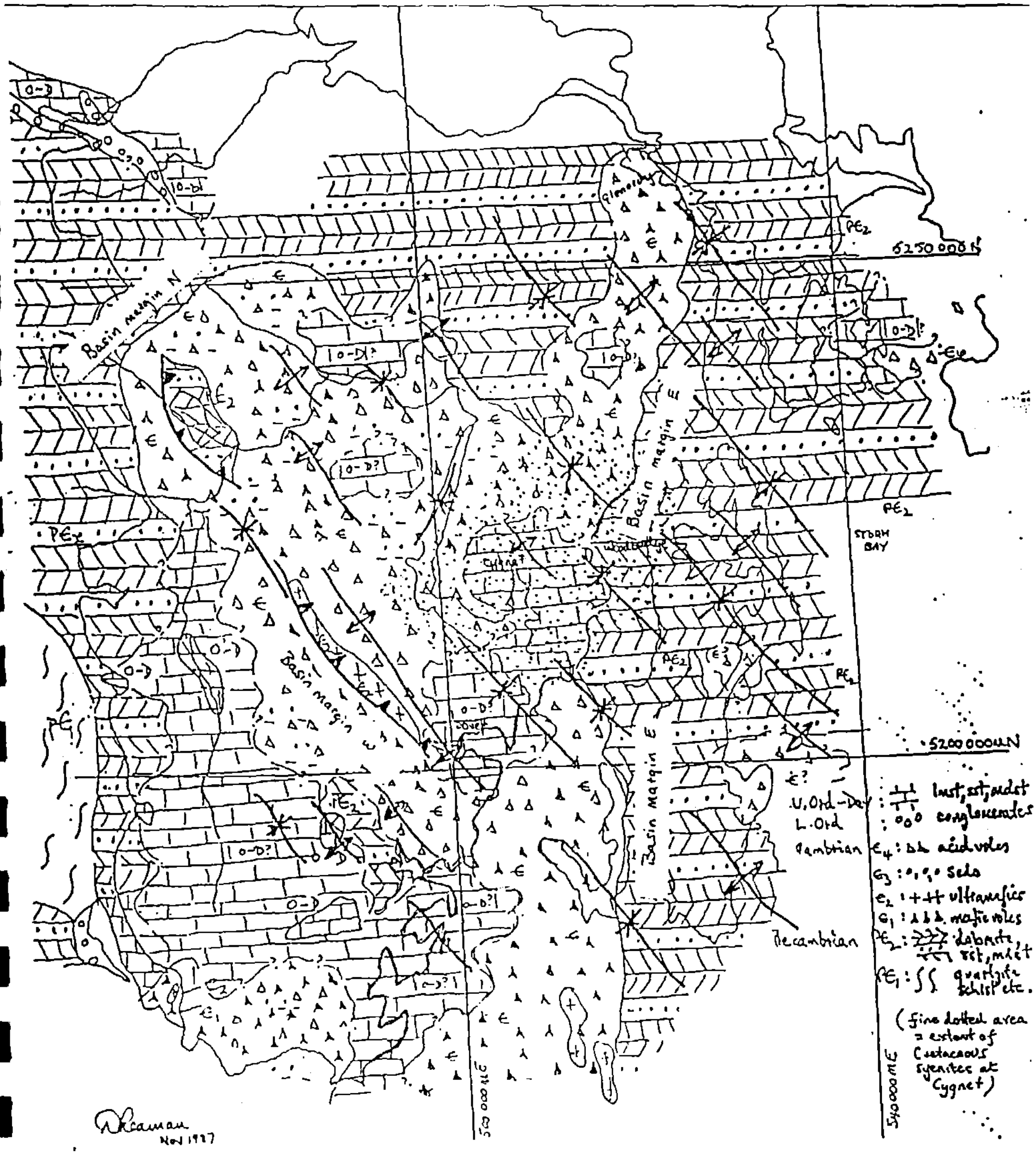


D Leaman
Nov 1987

CURRENT UNDERSTANDING OF PRE CARBONIFEROUS GEOLOGY (NOV 1987)
(based on initial geophysical interpretations. Provisional)
Note that distribution of Ordovician-Devonian rocks is not yet well defined and will be the subject of second order refined analysis. The indicated fold systems are likewise sketchy at this stage.

FIGURE D

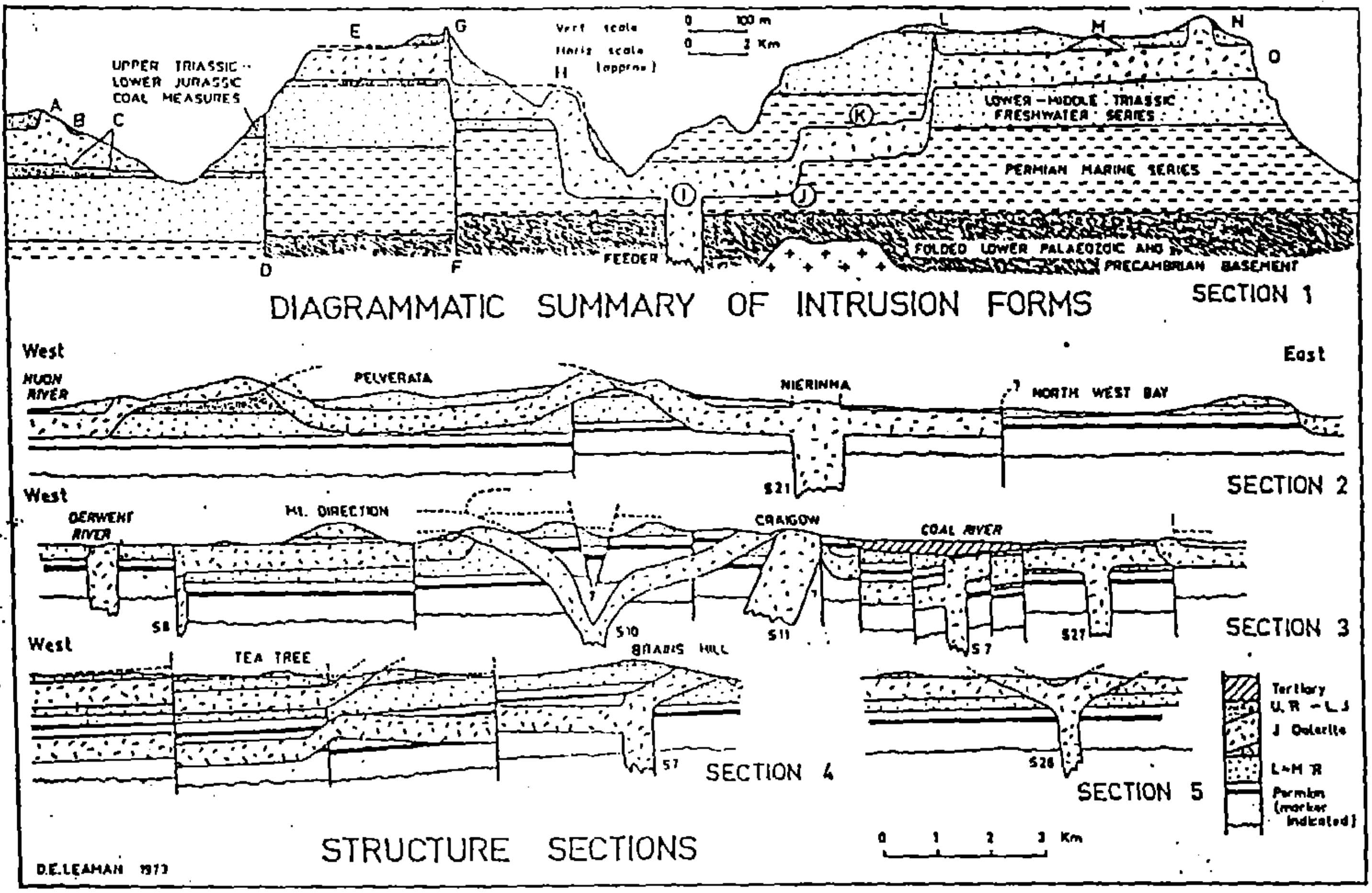
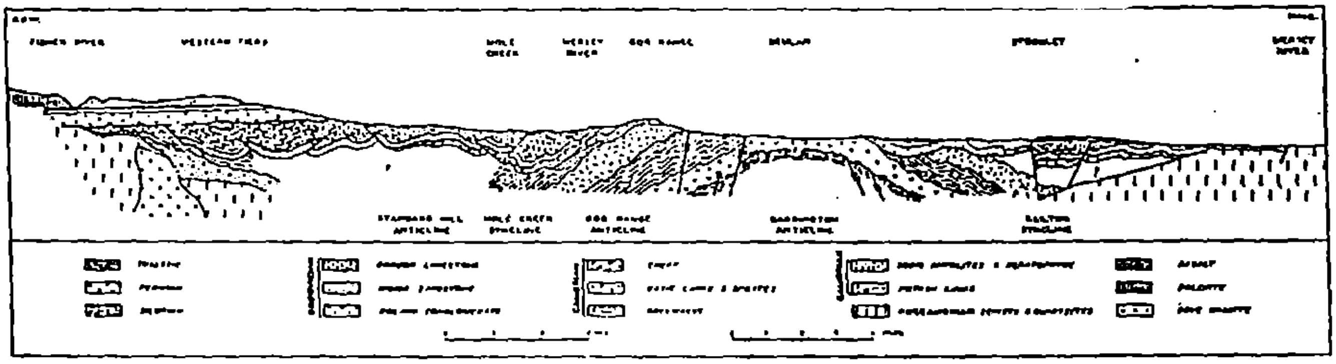


Fig. 2. Vertical sections of dolerite intrusion forms. 1: Diagrammatic summary of intrusion forms. Capital letters indicate features discussed in t 2, 3, 4, and 5: East to west geological sections located by reference to Fig. 1 and Fig. 3. S7, S11, etc., refer dolerite sheets to tl appropriate feeding sources in Fig. 3.

POST CARBONIFEROUS SECTION: SUMMARY OF RELATIONSHIPS
(after Leaman, 1975)

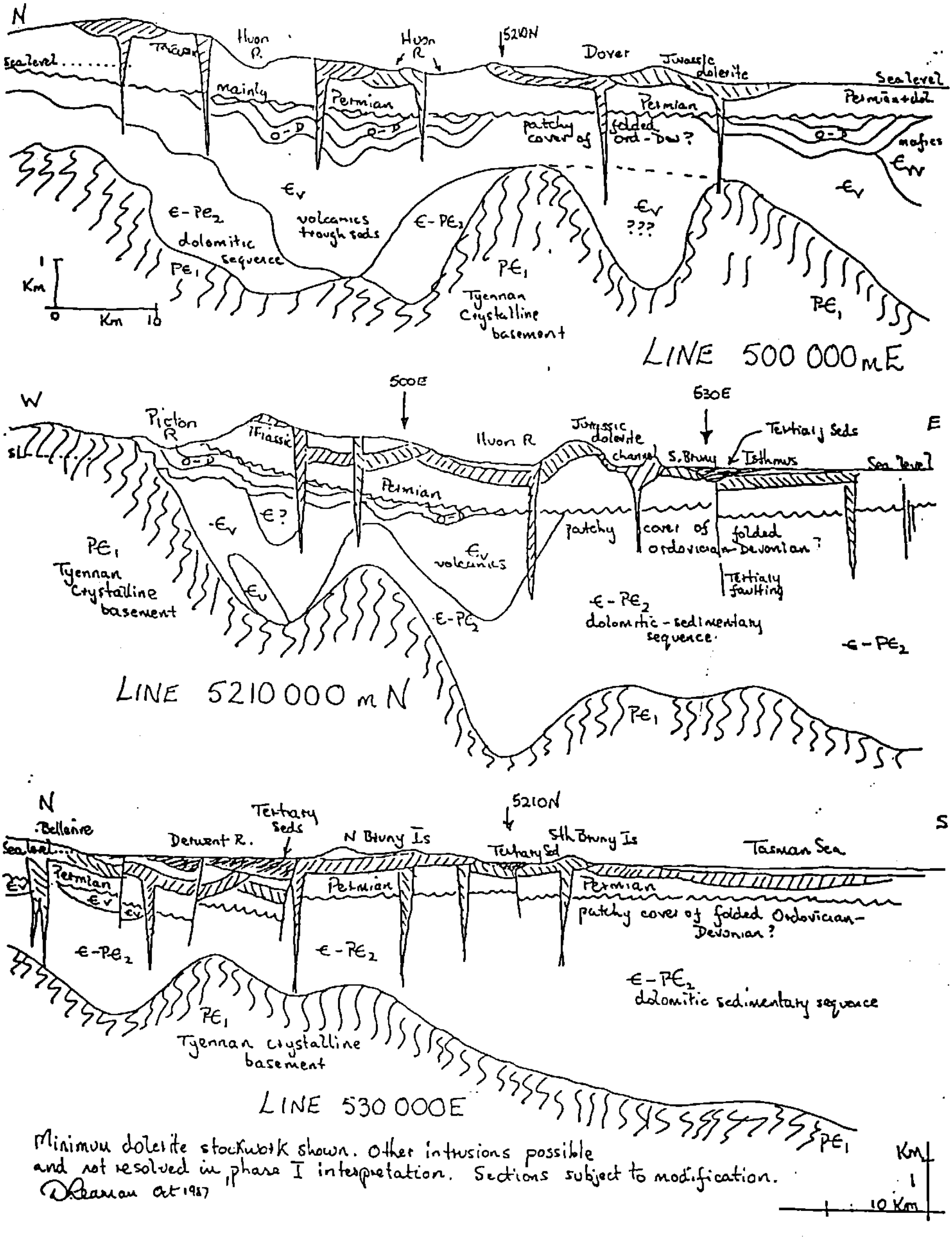
5 cm



Section through the North-West Coast (I. B. Jennings).

PRE CARBONIFEROUS SECTION: SUMMARY OF RELATIONSHIPS
(from Geology of Tasmania, J.geol.Soc.Aust., 9, 1962)

FIGURE 3E



SUMMARY OF INFERRED STRUCTURAL STYLES INDICATED BY INITIAL INTERPRETATION

5 cm

FIGURE 3F

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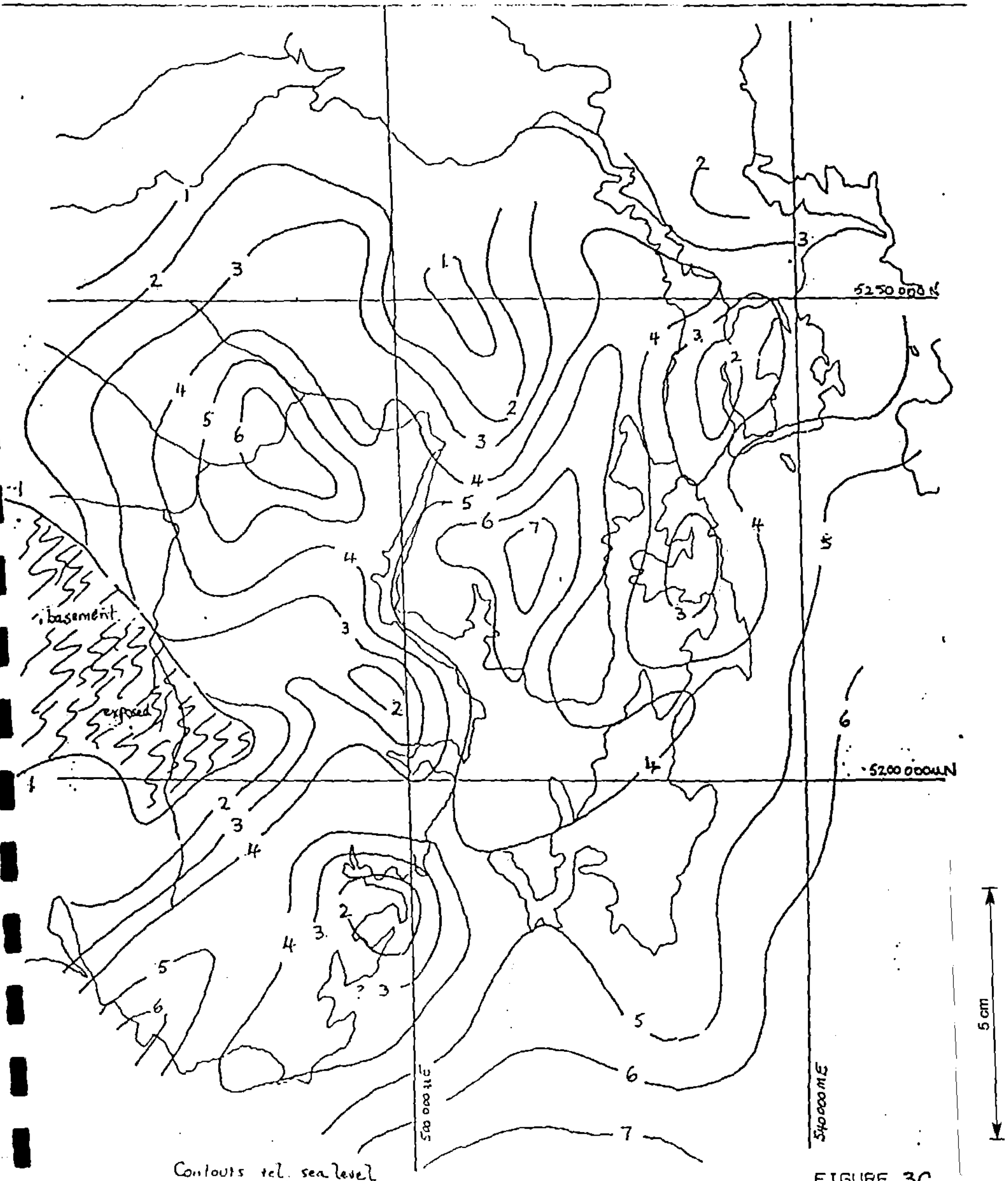

FIGURE 3G

DEPTH MAP: CRYSTALLINE BASEMENT (Tyennan Precambrian)

Derived from initial gravity-magnetic interpretation and not confirmed by 3D or second phase modell

331204

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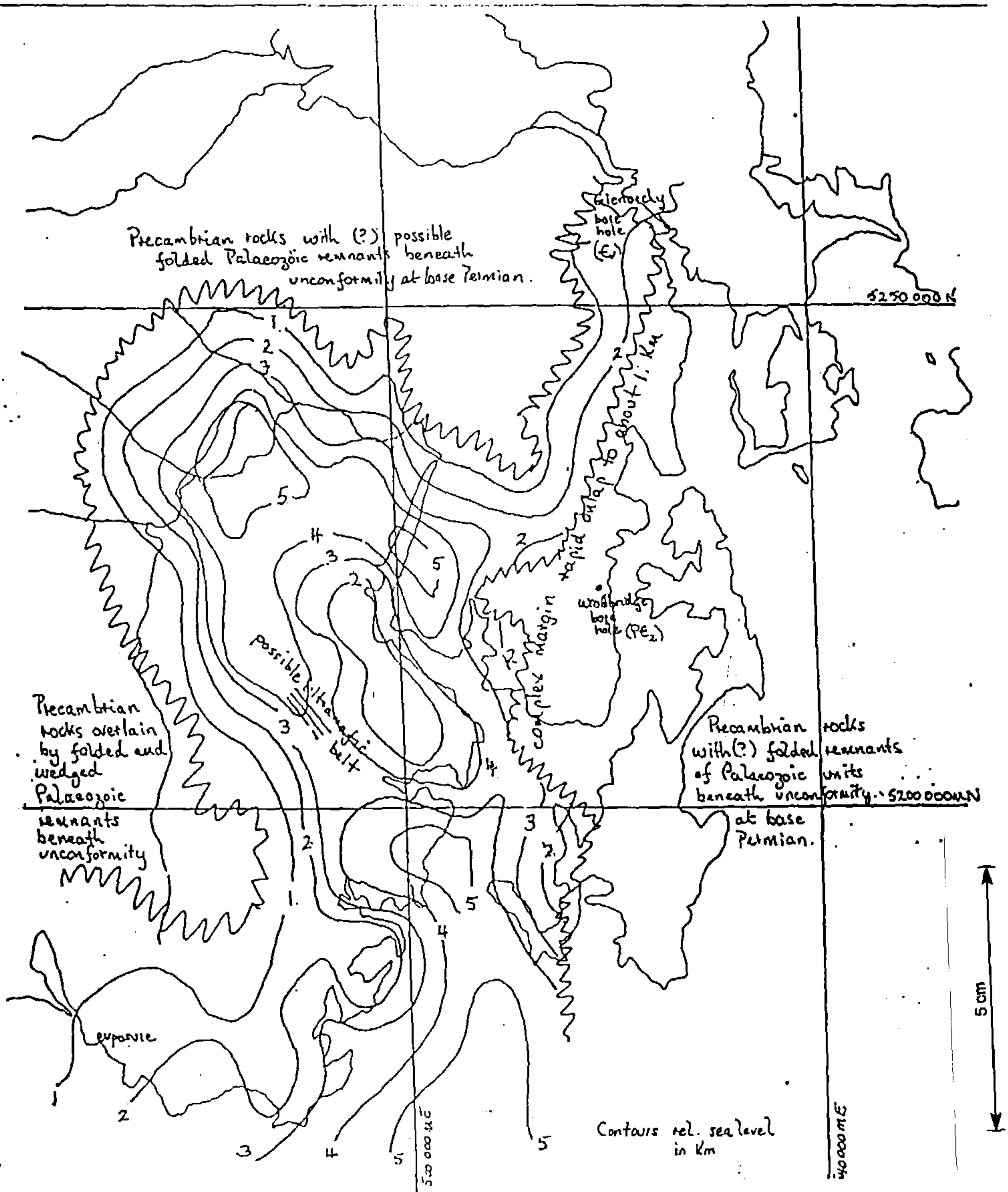

FIGURE 3H

DEPTH MAP: BASE OF CAMBRIAN VOLCANIC (MAGNETIC) SEQUENCES.

Derived from initial gravity-magnetic interpretation and not confirmed by 3D or second phase modelling (no control). Considered minimum volume. Upper surface rarely shallower than 1000-1500 m.

331205

LEAMAN GEOPHYSICS

Survey Review, Specification, Reduction, Interpretation
Wide Experience Most Methods
Specialties:- Gravity, Magnetics, Seismic Methods

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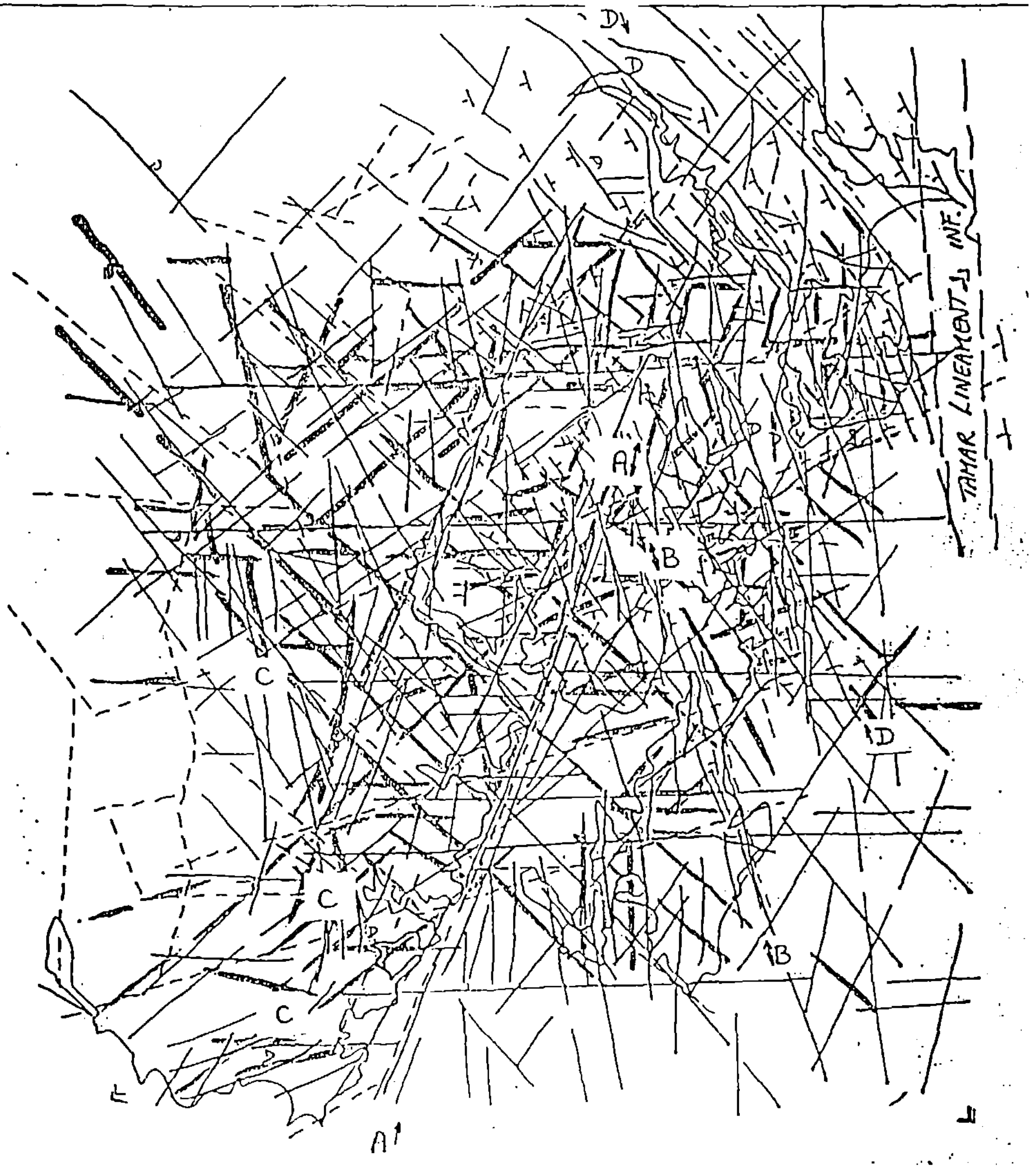
TELEPHONE: (002) 47 8849



--- topographic
—— geological
—— magnetics (1000 m)
▬▬ gravity

FIGURE 31

TREND SUMMARY MAP - COMPILATION OF ALL INFERRED TRENDS

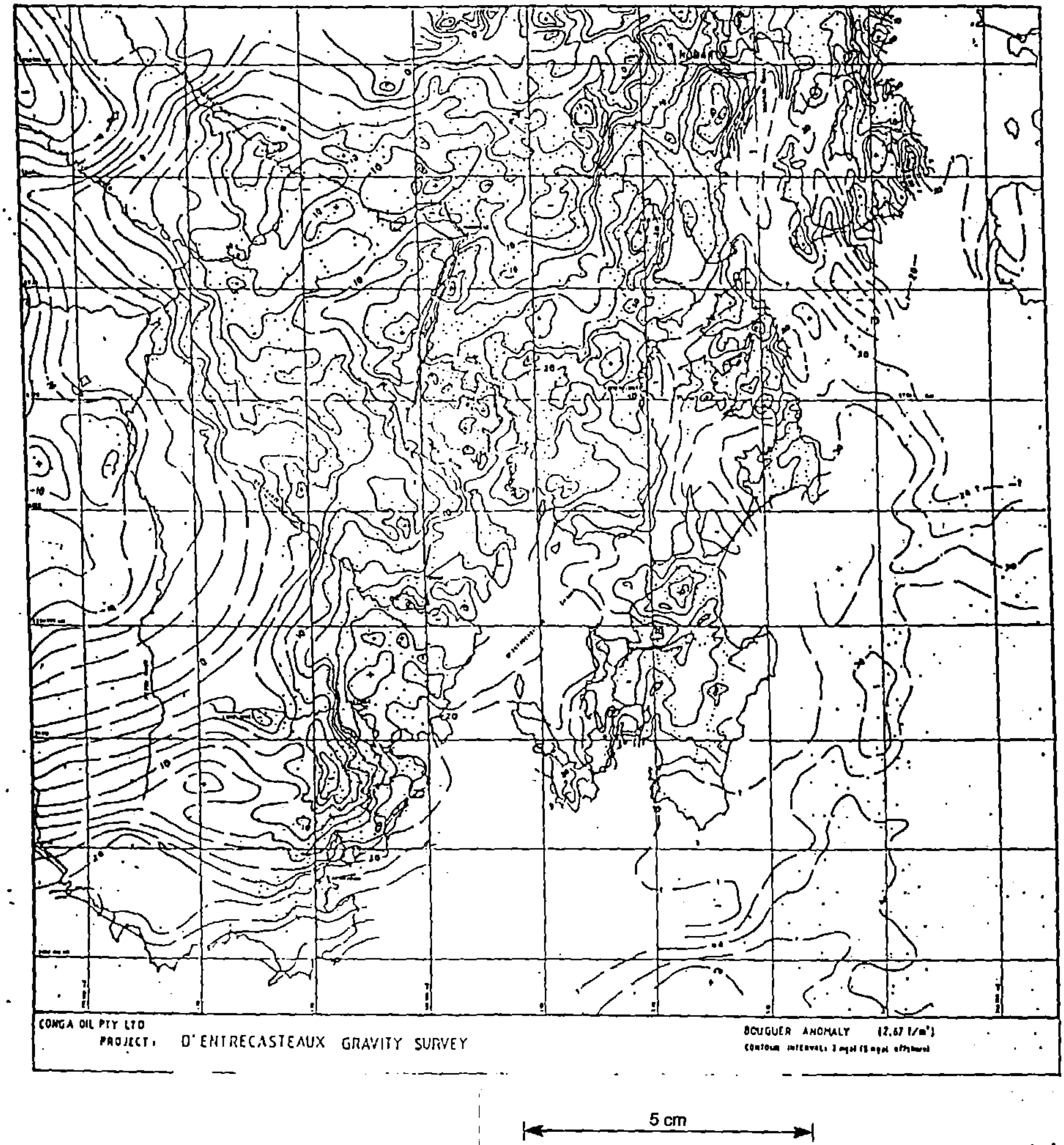
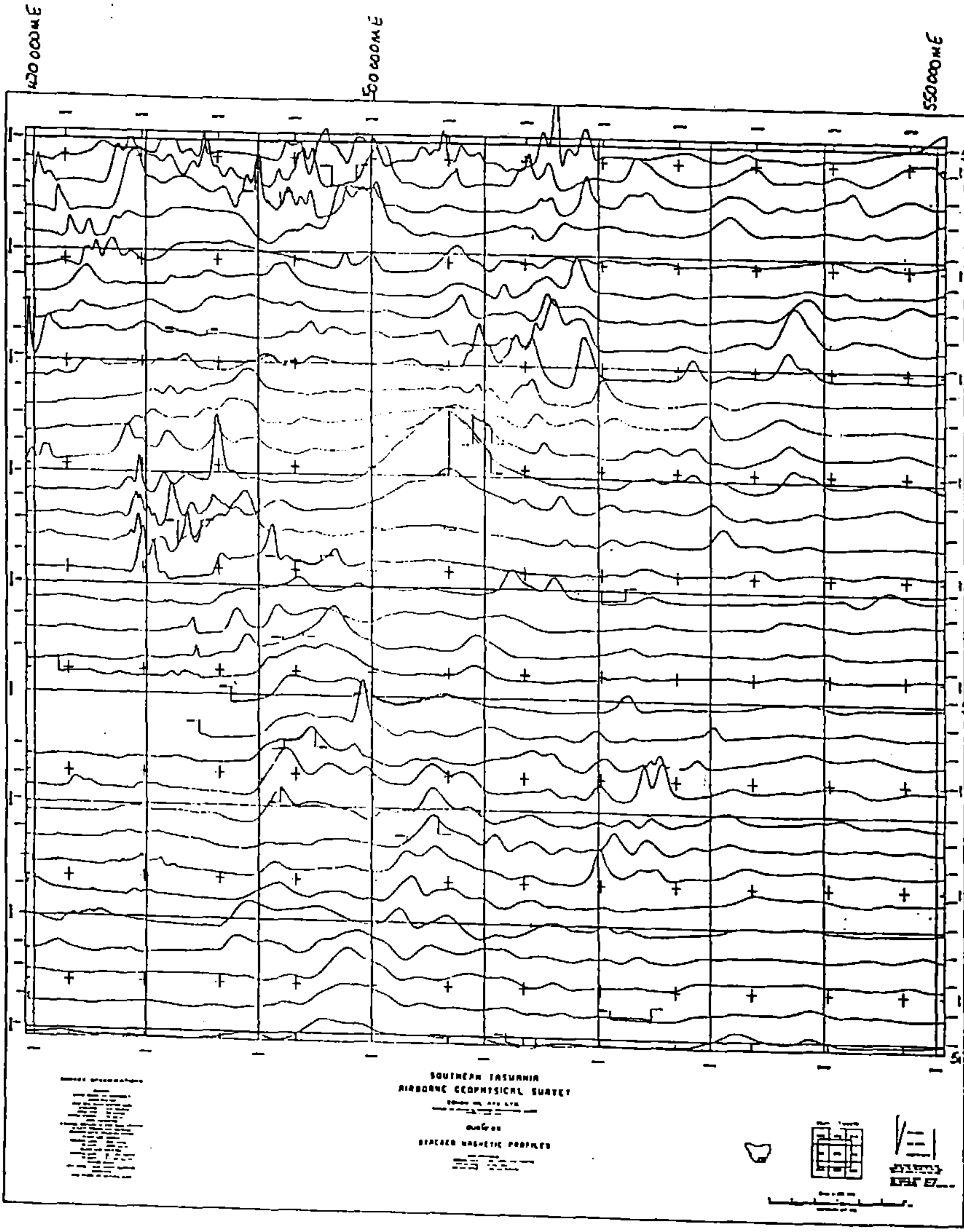


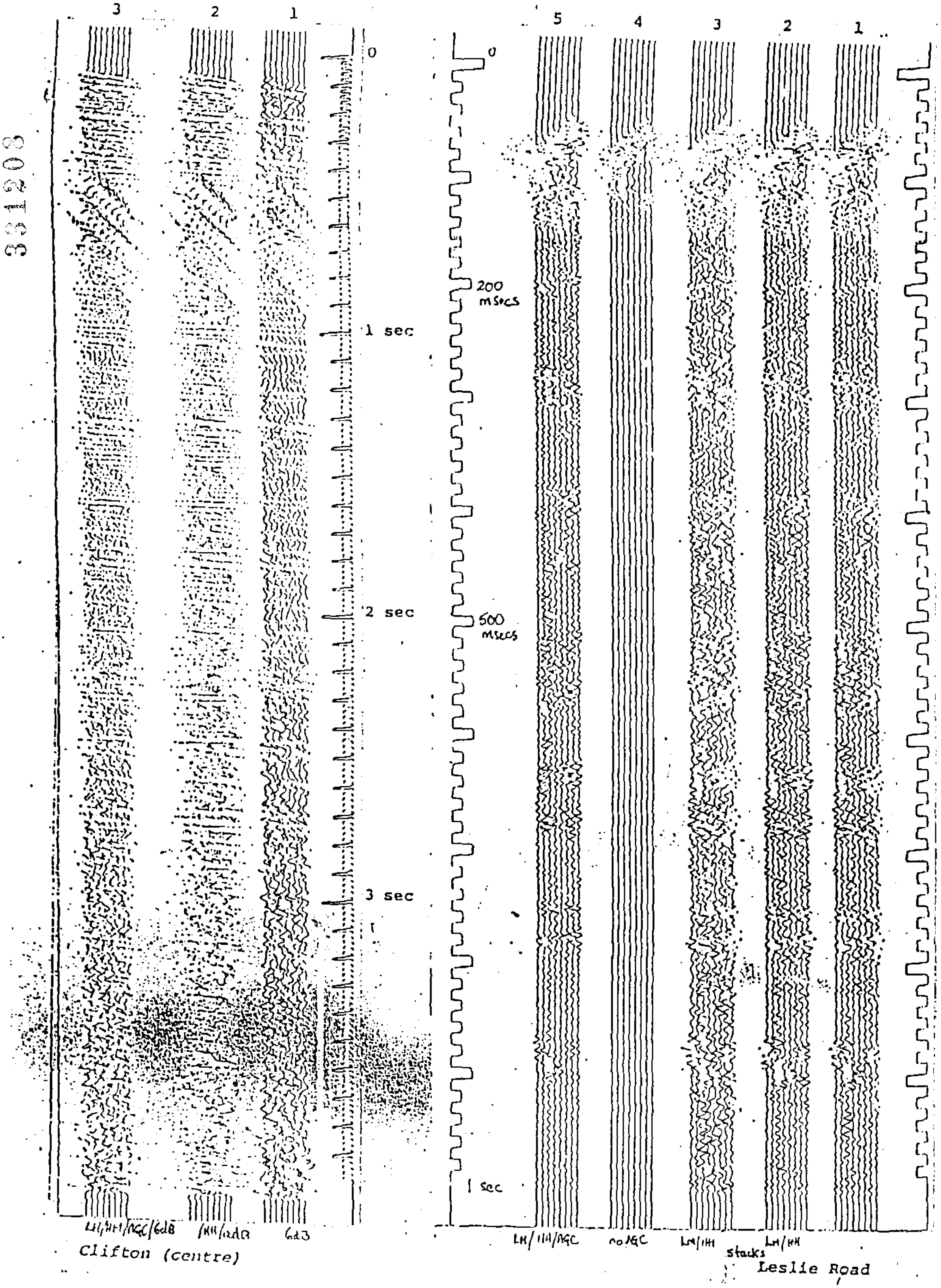
FIGURE 4A

COMPILATION MAP: BOUGUER ANOMALY MAP, DENSITY 2.67 T/CU M



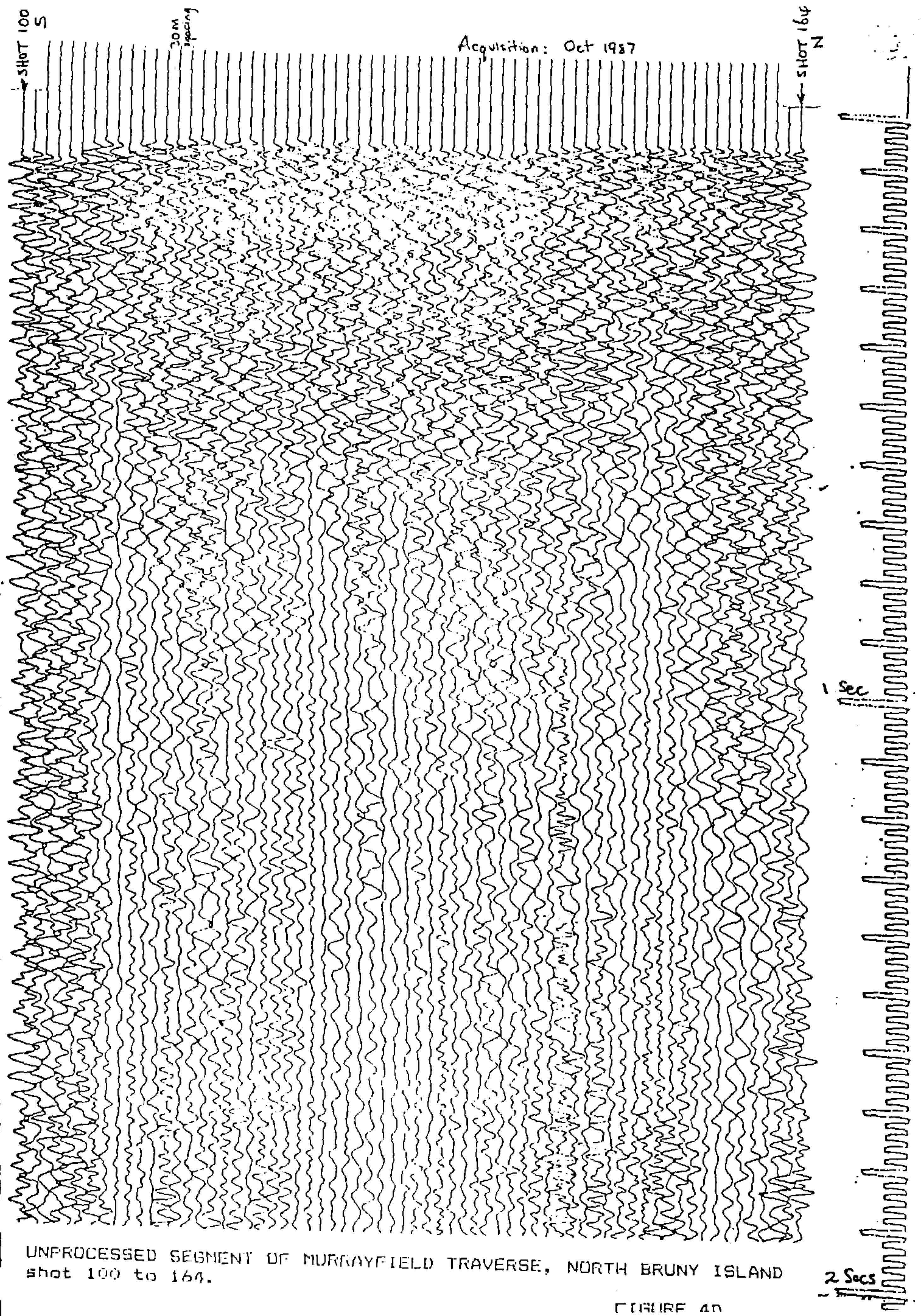
5 cm

FIGURE 4B



SEISMIC REFLECTION RESEARCH TRIALS : CLIFTON AND LESLIE RD
FIGURE 4C

331209



UNPROCESSED SEGMENT OF MURRAYFIELD TRAVERSE, NORTH BRUNY ISLAND shot 100 to 164.

FIGURE 4D

APPENDIX 8

ACS LABORATORIES PTY LTD

BY WARREN FARLEY

1995

ACS Laboratories Pty Ltd

ACN: 008 273 005

PO Box 396, Chermside
BRISBANE QLD 4032, AUSTRALIA
Telephone: 61 7 350 1222
Fax: 61 7 359 0666

30 BOOTHBY ST
KEDRON
QUEENSLAND
4031

Date:	30 June, 1995		
To:	Dr Clive Barrett	**Company:**	Great Southland Minerals
Fax:	(002) 232 547	**cc:**	
Subject:	Bruny Island Core Samples		
Our Ref:	P: 2-218.fx2	**Your Ref.**	
Sender:	Warren Farley	**Total Pages:**	2

This facsimile is intended only for the use of the person or company named above and may contain information that is confidential. If you are not the intended recipient, you are notified that any dissemination, distribution or copying of this facsimile is strictly prohibited. If you have received this facsimile in error, please notify us immediately by telephone and destroy the original facsimile.

Clive,

Please find attached the porosity and permeability (horizontal and vertical) determinations on the four core samples referenced above. Should you have any queries regarding this analysis, please do not hesitate to contact me.

We will hold the samples in our Brisbane laboratory pending any further analysis you may request.

Best regards,

W Farley

WARREN W FARLEY
Group General Manager

CS LABORATORIES PTY. LTD.
008 273 005
Petroleum Reservoir Engineering Data

CORE ANALYSIS FINAL REPORT

mpany	: GREAT SOUTHLAND MINERALS	Date	: 24/06/95
ll	: Bruny Island Samples *from Shittem #1*	File	: 2-218
ield	: unknown	Location	: TASMANIA
ore Int.	:	ACS Lab.	: 002
re Int.	:	Analyst	: WJD
re Int.	:		

mple Number	Depth From	To	Porosity Helni	Density GD	ND	Kair MAX	Kair 45	Kair 90	KaV Vert	Fluid Saturations Oil%	H2O%
1	787.00m	787.00m	7.4	2.72	2.52	0.07			0.03		
2	803.50m	803.50	8.6	2.76	2.52	0.96			1.01		
3	805.00m	805.00	11.9	2.76	2.44	6.8			6.5		
4	811.00m	811.00	11.4	2.78	2.46	9.0			4.87		

fair (handwritten beside porosity of samples 3–4 and KaV Vert of samples 2–4)

= Vertical Fracture; HF = Horizontal Fracture; MP = Mounted Plug; SP= Short Plug
F = Top of Core; B# = Bottom of Core; OWC = Probable Oil/Water Contact
= Probable Transition Zone; GC = Probable Gas Cap; NS = Not suitable for SCAL

Using terminology of Levorsen
samples 2-4
have fair porosity and fair permeability

ACS LABORATORIES PTY. LTD.
ACN: 008 273 005
Petroleum Reservoir Engineering Data

331213

CORE ANALYSIS FINAL REPORT

Company : GREAT SOUTHLAND MINERALS
Well : Northern Tasmania Samples
Field : Unknown
Core Int. :
Core Int. :
Core Int. :

Date : 22/08/95
File : 2-223
Location : TASMANIA
ACS Lab. : 002
Analyst : BJS

Sample Number	Depth	Dir	Porosity % Helium	Roll Ø	Density ND	GD	Permeability (md) Ka	Roll Ka *	Summation of Fluids Ø	Oil%	H2O%
1000		R	15.3	good		2.63	34.7	good			
1000		V	15.8	good		2.63	81.6	good			
1001		R	18.5	good		2.62	386	very good			
1001		V	19.9	very good		2.63	143	very good			
1002		R	17.5	good		2.63	7.7	fair			
1002		V	17.0	good		2.64	5.9	fair			
4001		V	17.7	good		2.64	32.2	good			
4004		R	13.3	fair		2.66	4.34	fair			
4004		V	12.7	fair		2.65	2.22	fair			

VF = Vertical Fracture; HF = Horizontal Fracture; MP = Mounted Plug; SP= Short Plu
C# = Top of Core; B# = Bottom of Core; OWC = Probable Oil/Water Contact
Tr = Probable Transition Zone; GC = Probable Gas Cap; NS = Not suitable for SCAL

* permeability appraisal from Levorsen "Geology of Petroleum" 2nd Ed. p. 105.

porosity ibid p. 102

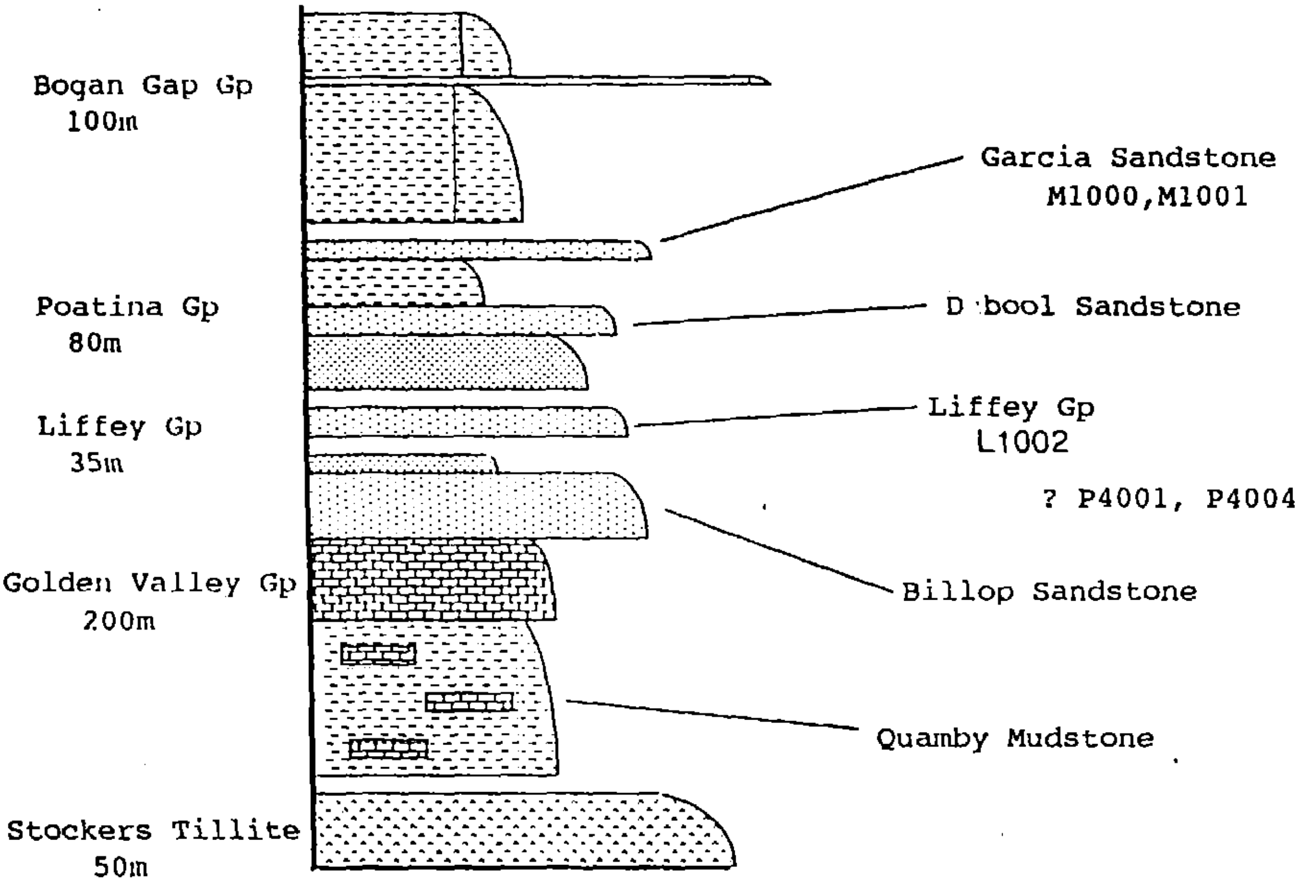
stratigraphic localities shown over

MAINLY POATINA Section

North Central Tasmania.

331214

Generalised Log of Section in the Quamby Area



logged by Ben Maynard 1995

Sample	Depth Dir	Density	Porosity	Permeability
P4001	V	2.64	17.7	32.2
P4004	R	2.66	13.3	4.34
	V	2.65	12.7	2.22
L1002	R	2.63	17.5	7.7
	V	2.64	17	5.9
M1000	R	2.63	15.3	34.7
	V	2.63	15.8	81.6
M1001	R	2.62	18.5	386
	V	2.63	19.9	143

ACS LABORATORIES PTY. LTD.
ACN: 008 [illegible]
Petroleum Reservoir Engineering Data

CORE ANALYSIS PRELIMINARY REPORT

Company : GREAT SOUTHLAND MINERALS
Well : Northern Tasmania Samples
Field : Unknown
Core Int. :
Core Int. :
Core Int. :

Date : 13/08/96
File : 2-225
Location : NORTHERN TASMANIA
ACS Lab. : 002
Analyst : IJM

	Sample Number	Depth	Dir	Porosity % He Inj	Porosity % Roll Ø	Density ND	Density GD	Permeability (md) Ka	Permeability (md) Roll Ka	Summation of Fluids Ø	Summation of Fluids Oil%	Summation of Fluids H2O%	Remarks
Bundella Fm. Glenorchy BH1	1	33.90	R	22.3			2.57						Glauc.
Malbina Fm. Granton BH1	2	32.50	R	2.1			2.61						
Rayner sst, Granton BH1	3	124.20	R	3.9			2.66						
Risdon sst. Variety Bay	4		R	12.5			2.62						
Risdon sst. Davey St.	5		R	13.7			2.65						
Minnie pt Fm. Variety Bay	6		R	14.1			2.63						
Minnie pt. Fm, Cygnet	7		R	16.6			2.66						
Risdon sst. Kettering	8		R	14.7			2.66						

VF = Vertical Fracture; HF = Horizontal Fracture; MP = Mounted Plug; SP= Short Plug
C# = Top of Core. B# = Bottom of Core; OWC = Probable Oil/Water Contact
Tr = Probable Transition Zone; GC = Probable Gas Cap; NS = Not suitable for SCAL

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UNIVERSITY OF TASMANIA

Central Science Laboratory
GPO Box 252C
Hobart
Tasmania 7001
Australia

Preliminary Report - Gas Samples from Bruny Island

A sample of headspace above approximately 1 litre of water sealed in a plastic Coca-cola bottle labelled 'Shittim trip gas, 930 m' was analysed by GC-MS for the presence of C1-C6 hydrocarbons.

Qualitative analyses revealed the presence of methane, ethylene, ethane, propylene, propane, isobutane, 1-butene, cis- and trans- 2-butene, n-butane and trace amounts of pentanes and hexanes.

As standards for calibration were not immediately available at the time these analyses were done, and the sample was not in an ideal container, true quantitative data are not as yet available. Semiquantitative estimations of proportions of gases, based on percent by volume relative to methane, were as follows;

methane	= major hydrocarbon
ethylene	trace - (much less than ethane)
ethane	~10% relative to methane
propylene	~3% relative to methane
propane	~6% relative to methane
isobutane	<1% relative to methane
1-butene	~2% relative to methane
n-butane	~1.5% relative to methane
2-butenes	trace
isopentane	trace
n-pentane	trace
isohexane	trace
n-hexane	trace

Work on current samples taken is teflon-stoppered gas sampling containers is proceeding, and standards of target gases are now available enabling more accurate absolute and relative quantitation.

No hydrogen sulfide was detected in this preliminary analysis, although this gas was not specifically targetted to enable low or sub parts per million detection.

(Dr) Noel Davies
Officer-in-Charge, Organic Mass Spectrometry

APPENDIX 9

AMDEL , GEOCHEMICAL EVALUATION OF AN OIL SEEP SAMPLE FROM LONNAVALE , TASMANIA

BY SCOTT WHYTHE AND BRIAN WATSON

JANUARY 1996

amdel

331218

GEOCHEMICAL EVALUATION OF AN OIL SEEP SAMPLE FROM

LONNAVALE, TASMANIA

REPORT LQ4496 FOR

GREAT SOUTHLAND MINERALS PTY LTD

BY

SCOTT WYTHE

BRIAN WATSON

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1. INTRODUCTION

One oil seep sample was received from Lonnavale, Tasmania for physical testing and petroleum geochemical analyses. This report is a formal presentation of results forwarded by facsimile on 15 January 1996.

2. ANALYTICAL PROCEDURES

The analytical procedures used in this study are provided in Appendix 1.

3. RESULTS

Analytical data is presented in this report as follows:

Analysis	Table	Figure
Bulk Composition and GC of Whole Oils and Saturates	1	1 - 4
GC-MS of aromatic hydrocarbons	2	5 - 6
GC-MS of branched/cyclic hydrocarbons	3	7 - 9 Appendix 2

Due to the bituminous nature of the sample and its close association with an unidentified solid material no physical testing of the sample was possible. However sulphur analysis was performed on both a portion of the whole sample (including the solid material) and on the solid material alone following extraction of the oil. Both were found to contain 0.1% sulphur. This suggests a low sulphur content for the oil (ie.<0.1%).

4. GEOCHEMICAL INTERPRETATION OF SEEP SAMPLE

4.1 Maturity

Aromatic maturity indicators for the Lonnavale seep indicate that the sample was generated and expulsed from an early mature to mature source interval (Parameters A, C, E and F, Table 2). Parameter A indicates a maturity of VR_{equiv}=0.85%.

Maturities indicated for this sample by saturated biomarker maturity parameters are less precise than the aromatic derived biomarker ratios. These parameters (ie, C_{29} steranes and isosteranes - Biomarker Parameters 4 & 6, C_{27} diasteranes - Biomarker

Parameter 5, C_{27}, C_{30} & C_{32} hopanes - Biomarker Parameter 11, Table 2) all indicate that the sample has a moderate maturity.

The isoprenoid/n-alkane ratios (Figure 4) is unreliable for assessment of maturity due to pristane, phytane, n-C_{17} and n-C_{18} being affected by biodegradation and light end loss.

4.2 Source Affinity

The Lonnavale seep sample is aromatic-naphthenic in composition (Figure 2).

The pristane/phytane ratio (Table 1, Figures 1 & 7) is likely to be affected by biodegradation and light end loss. However despite these effects the ratio is still considered to indicate generation from sources deposited in anoxic conditions typical of a marine environment.

GC-MS of branched/cyclic alkanes for the sample has sterane and diasterane distributions (m/z 217, 218, 259; Table 3, Figures 7 & 9, Appendix 2) which contain significant C_{29} homologues of higher plant origin (Biomarker parameters 1, 2 & 3, Table 3) suggesting some terrestrial input into the precursor organic matter.

Tricyclic terpane distributions (m/z 191, Appendix 2) show that C_{19} - C_{31} tricyclics are the dominant compounds present in the sample. Such a distribution is characteristic of precursor organic matter rich in *Tasmanites* alga. Tasmanite is thought to have been deposited in a low energy, nearshore marine environment.

Hopane signatures (m/z 191, Appendix 2) are unreliable due to the dominance of tricyclic compounds. However the C_{29} norhopane is likely to be more abundant than the C_{30} hopane suggesting a likely carbonate source. The presence of significant amounts of diasteranes usually associated with clay-rich environments though suggests otherwise.

No significant amount of botryococcane was detected (m/z 183, Appendix 2).

This data suggests that the precursor organic matter of the Lonnavale oil seep sample has been derived from a somewhat mixed algal/terrestrial source containing abundant *Tasmanites* alga deposited in an anoxic, probably nearshore, marine environment.

The ratios of 1-methylphenanthrene/9-methylphenanthrene and 1,2,5-trimethylnaphthalene/1,3,6-trimethylnaphthalene (Figure 7) has been used to indicate source input from Araucariacean derived plant resins (trees from the Kauri pine group) which were most prominent in Early to Middle Jurassic times. The low relative abundance of 1-methylphenanthrene and 1,2,5-trimethylnaphthalene implies that these resins were not significant components of the precursor organic matter. However, this does not preclude the possibility that this oil was generated from a source of Jurassic/Cretaceous age.

4.3 Post Pooling Alteration and Migration

The abundance of cycloalkanes and corresponding lack of n-alkanes in the sample (Figures 1 & 3) suggests that this condensate may have been subjected to light biodegradation. No evidence of significant biodegradation was observed in any of the biomarker compounds.

Figure 8 suggests that the sample is likely to have undergone a degree of migration since generation from its source interval.

5. CONCLUSIONS

5.1 Aromatic maturity indicators for the Lonnavale oil seep indicate that it was generated and expulsed from a moderately mature source interval ($VR_{equiv}\approx0.80\%$). Saturated biomarker maturity indicators ratios support this level of maturity.

5.2 Various aspects of the molecular composition of the sample indicates that the precursor organic matter of the oil seep is likely to have been derived from a mixed algal/terrestrial source containing abundant *Tasmanites* alga deposited in an anoxic, possibly nearshore, marine environment.

5.3 The sample appears to have been subjected to light biodegradation.

5.4 The extract is likely to have undergone some migration since generation from its source interval.

TABLE 1

C_{12+} BULK COMPOSITION AND ALKANE RATIOS, LONNAVALE SEEP

	Composition (%)				Alkane Ratios			
EOM (%)	n+iso	Naph	Arom	NSO	Np/Pr	Pr/Ph	Pr/n-C_{17}	Ph/n-C_{18}
20.32	4.1	36.5	26.2	9.7	-	0.44	0.36	0.64

EOM = extractable organic matter
n+iso = normal + iso-alkanes
Naph = naphthenes (branched and cyclic alkanes)
Arom = aromatic hydrocarbons
NSO = compounds containing nitrogen, sulphur and oxygen

Np = norpristane
Pr = pristane
Ph = phytane
n-C_{17} = n-heptadecane
n-C_{18} = n-octadecane

TABLE 2

AROMATIC MATURITY DATA, LONNAVALE SEEP

MPI	MPR	DNR	MPDF	VR CALC (%)					
				A	B	C	D	E	F
0.756	1.306	14.58	0.454	0.85	1.85	1.05	7.60	0.75	0.85

KEY TO AROMATIC MATURITY INDICATORS

Methylphenanthrene index (MPI), methylphenanthrene ratio (MPR), dimethylnaphthalene ratio (DNR) and calculated vitrinite reflectance (VR_{calc}) are derived from the following equations (after Radke and Welte, 1983; Radke *et al*, (1984):

$$MPI = \frac{1.5(2\text{-}MP + 3\text{-}MP)}{P + 1\text{-}MP + 9\text{-}MP}$$

$$VR_{calc}\ (a) = 0.6\ MPI + 0.4\ (\text{for } VR < 1.35\%)$$

$$VR_{calc}\ (b) = -0.6\ MPI + 2.3\ (\text{for } VR > 1.35\%)$$

$$MPR = \frac{2\text{-}MP}{1\text{-}MP}$$

$$VR_{calc}\ (c) = 0.99\ \log_{10} MPR + 0.94 (VR = 0.5\text{-}1.7\%)$$

$$DNR = \frac{2,6\text{-}DMN + 2,7\text{-}DMN}{1,5\text{-}DMN}$$

$$VR_{calc}\ (d) \quad 0.46\ DNR + 0.89\ (\text{for } VR = 0.9\text{-}1.5\%)$$

Where
P = phenanthrene
1-MP = 1-methylphenanthrene
2-MP = 2-methylphenanthrene
3-MP = 3-methylphenanthrene
9-MP = 9-methylphenanthrene
1,5-DMN = 1,5-dimethylnaphthalene
2,6-DMN = 2,6-dimethylnaphthalene
2,7-DMN = 2,7-dimethylnaphthalene

Peak areas measured from m/z 156 (dimethylnaphthalene), m/z 178 (phenanthrene) and m/z 192 (methylphenanthrene) mass fragmentograms of diaromatic and triaromatic hydrocarbon fraction isolated by thin layer chromatography.

Recalibration of the methylphenanthrene index using data from a suite of Australian coals has given rise to another equation for calculated vitrinite reflectance (after Boreham *et al*, 1988):

$$VR_{calc}\ (e) = 0.7\ MPI + 0.22\ (\text{for } VR < 1.7\%)$$

The methylphenanthrene distribution ratio (MPDF) and calculated vitrinite reflectance VR_{calc} (f) is derived from the following equation (after Kvalheim *et al*, 1987):

$$MPDF = \frac{(2\text{-}MP + 3\text{-}MP)}{(2\text{-}MP + 3\text{-}MP + 1\text{-}MP + 9\text{-}MP)}$$

$$VR_{calc}\ (f) = -0.166 + 2.242\ MPDF$$

TABLE 3

BIOMARKER PARAMETERS OF SOURCE, MATURITY, MIGRATION AND BIODEGRADATION, LONNAVALE SEEP

Steranes							**Terpanes**						**Acyclic Alkanes**		
Parameter															
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
29:30:41	1.38	1.14	1.41	1.25	1.72	0.91	-	-	-	6.37	-	-	0.44	0.36	0.64

- = not determined

KEY TO BIOMARKER PARAMETERS OF SOURCE, MIGRATION AND BIODEGRADATION

Parameter	Derivation*	Specificity
1	C_{27}:C_{28}:C_{29} 5α(H)14α(H)17α(H) 20S steranes	Source
2	C_{29} 5α(H)14α(H)17α(H) 20S sterane/C_{27} 5α(H)14α(H)17α(H) 20S sterane	Source
3	C_{29} 13β(H)17α(H) 20R diasterane/C_{27} 13β(H)17α(H) 20R diasterane	Source
4	C_{29} 5α(H)14α(H)17α(H) 20S sterane/C_{29} 5α(H)14α(H)17α(H) 20R sterane	Maturity, Biodegradation
5	C_{27} 13β(H)17α(H) 20S diasterane/C_{27} 13β(H)17α(H) 20R diasterane	Maturity
6	C_{29} 5α(H)14β(H)17β(H) 20R sterane/C_{29} 5α(H)14α(H)17α(H) 20R sterane	Maturity, Migration
7	C_{29} 13β(H)17α(H) 20R+20S diasteranes/C_{29} 5α(H) steranes	Migration, Source
8	18α(H)-30-norneohopane (C_{29}Ts)/C_{29} 17α(H) hopane + C_{29}Ts	Maturity, Source
9	17α(H) diahopane/18α(H)-30-norneohopane (C_{30}*/C_{29}TS)	Source, Maturity
10	C_{27} 18α(H)-22,29,30-trisnorhopane (Ts)/C_{27} 17α(H)-22,29,30-trisnorhopane (Tm)+ Ts	Maturity, Source
11	T_s/C_{30} 17α(H)21β(H) hopane	Maturity
12	C_{32} 17α(H)21β(H) 22S homohopane/C_{32} 17α(H)21β(H) 22R homohopane	Maturity
13	C_{30} 17β(H)21α(H) moretane/C_{30} 17α(H)21β(H) hopane	Maturity
14	pristane/phytane	Source
15	pristane/n-heptadecane	Source, Biodegradation, Maturity
16	phytane/n-octadecane	Source, Biodegradation, Maturity

* Ratios calculated from peak areas as follows:

Parameters	1-7	m/z = 217, 218, 259 mass fragmentograms
Parameters	8 - 13	m/z = 191 mass fragmentogram
Parameters	14 - 16	capillary gas chromatogram of alkanes or whole oil/extract

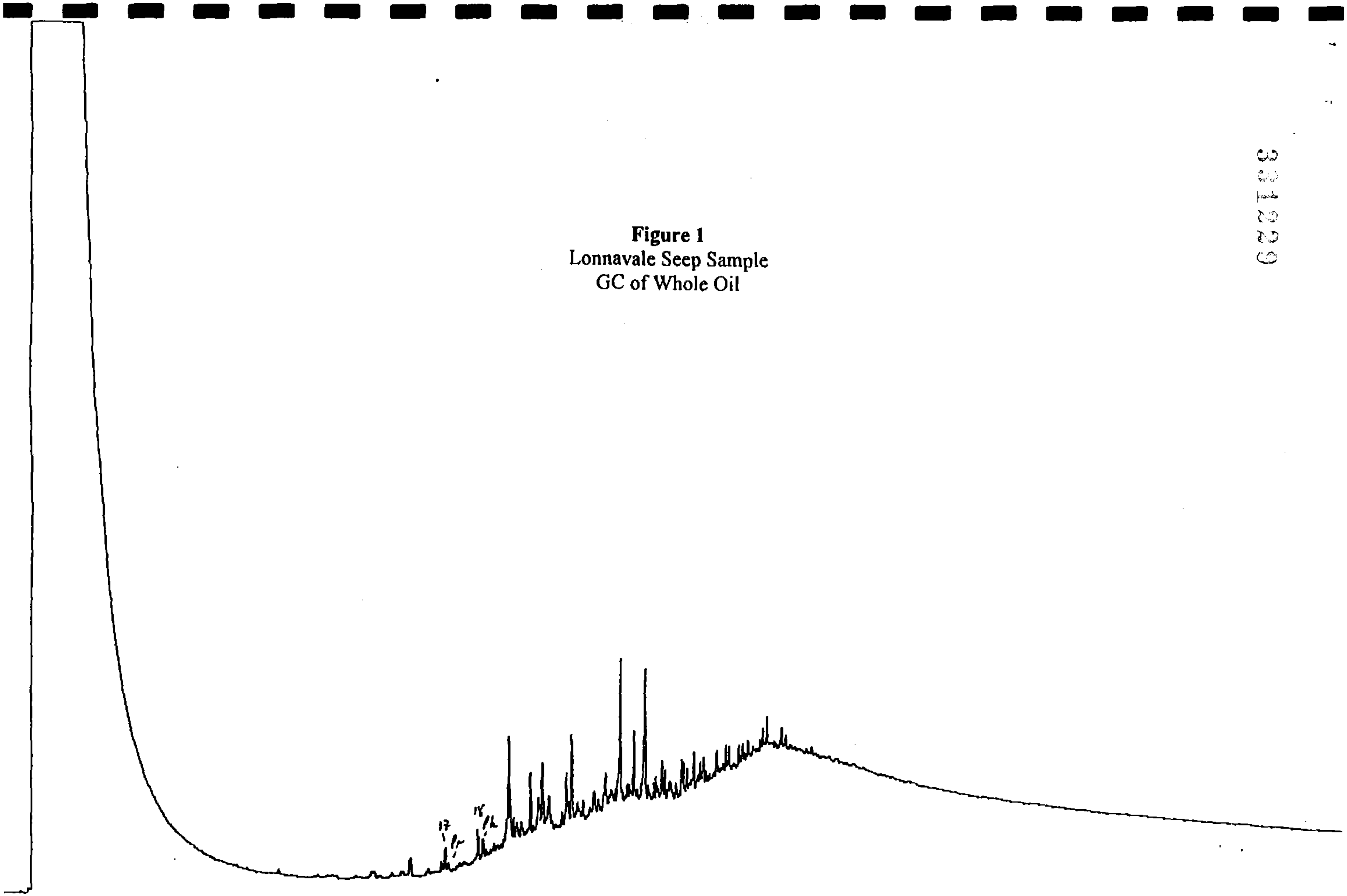


Figure 1
Lonnavale Seep Sample
GC of Whole Oil

3312629

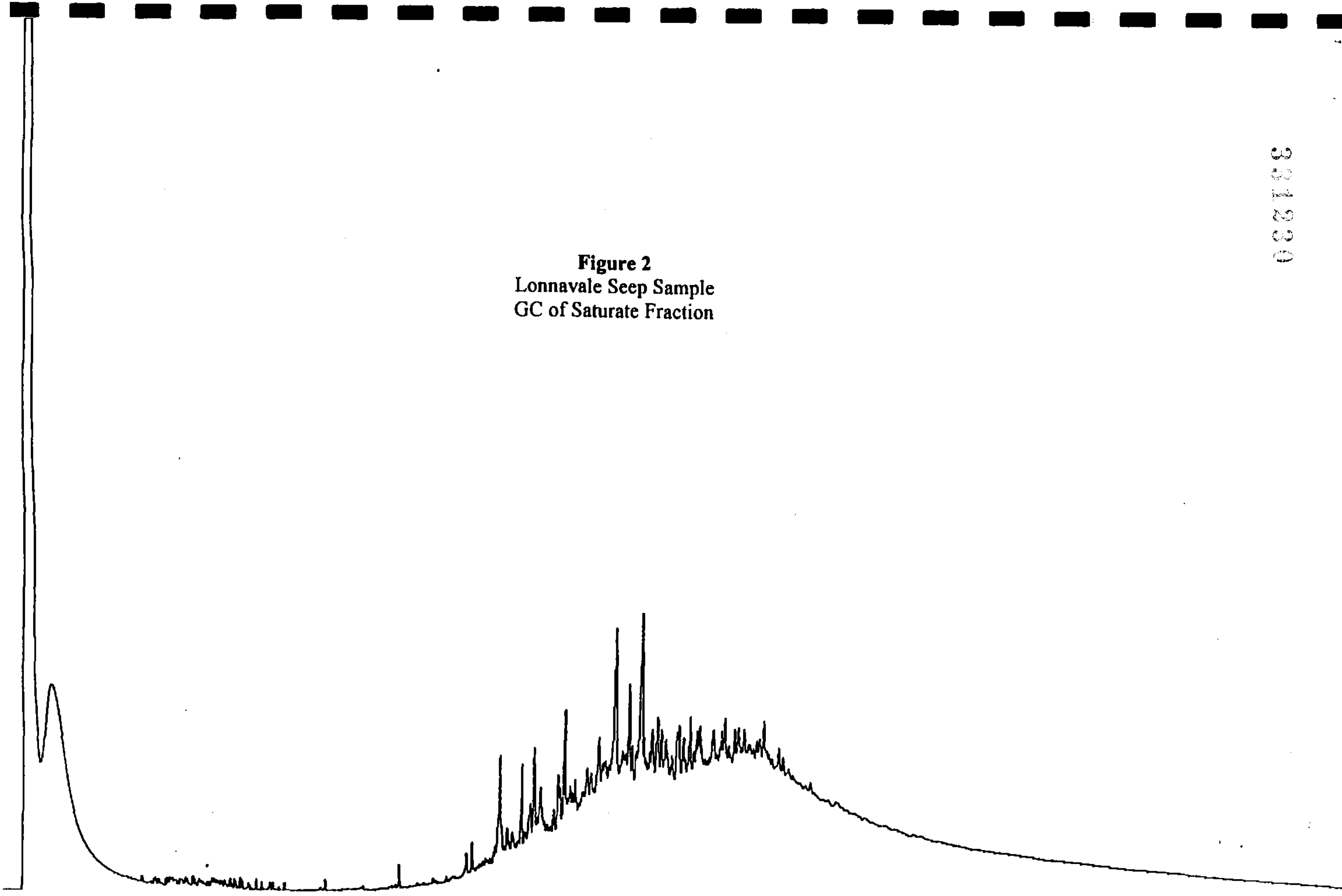


Figure 2
Lonnavale Seep Sample
GC of Saturate Fraction

FIGURE 3

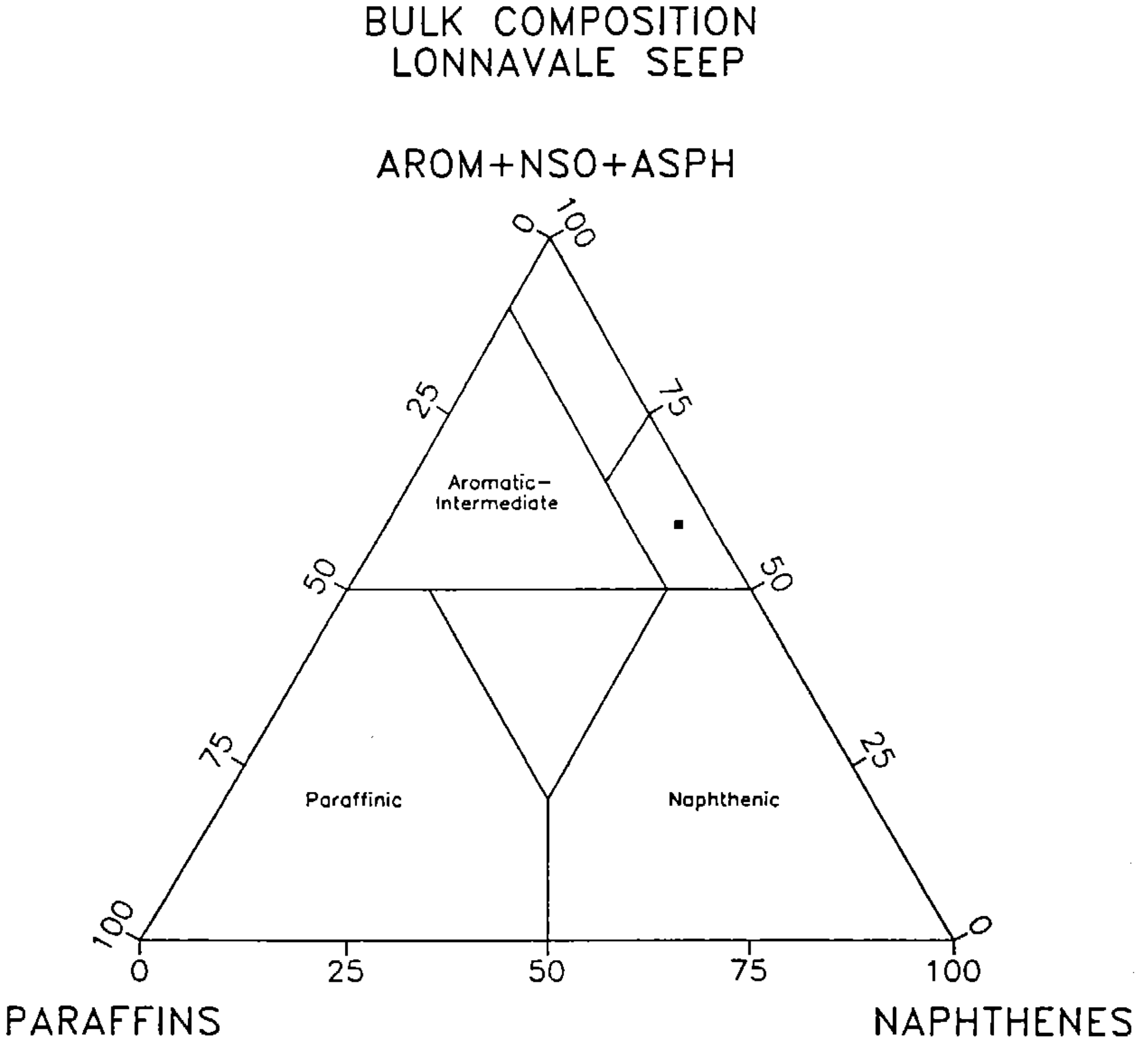

BULK COMPOSITION
LONNAVALE SEEP
AROM+NSO+ASPH
0
100
25
75
50
50
75
25
100
0
0
25
50
75
100
Aromatic-
Intermediate
Paraffinic
Naphthenic
PARAFFINS
NAPHTHENES

FIGURE 4

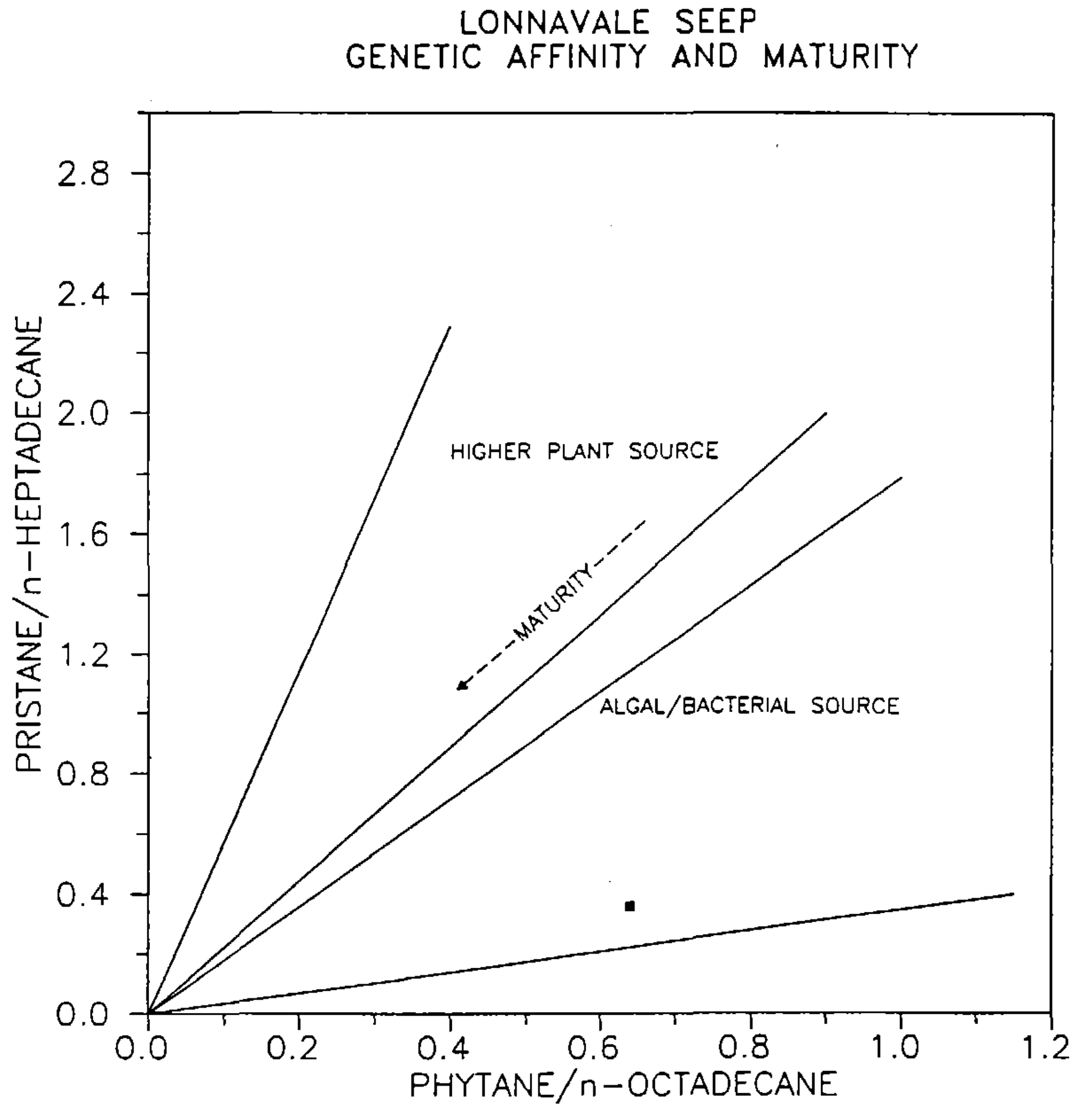

LONNAVALE SEEP
GENETIC AFFINITY AND MATURITY
PRISTANE/n-HEPTADECANE
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
HIGHER PLANT SOURCE
MATURITY
ALGAL/BACTERIAL SOURCE
0.0
0.2
0.4
0.6
0.8
1.0
1.2
PHYTANE/n-OCTADECANE

FIGURE 5a

File : C:\HPCHEM\1\DATA\UOFA\4496AROM.D
Operator : WYTHE
Acquired : 12 Jan 96 11:16 am using AcqMethod 60MAROM
Instrument : AMDEL-597
Sample Name: LONAVALE SEEP
Misc Info :
Vial Number: 1

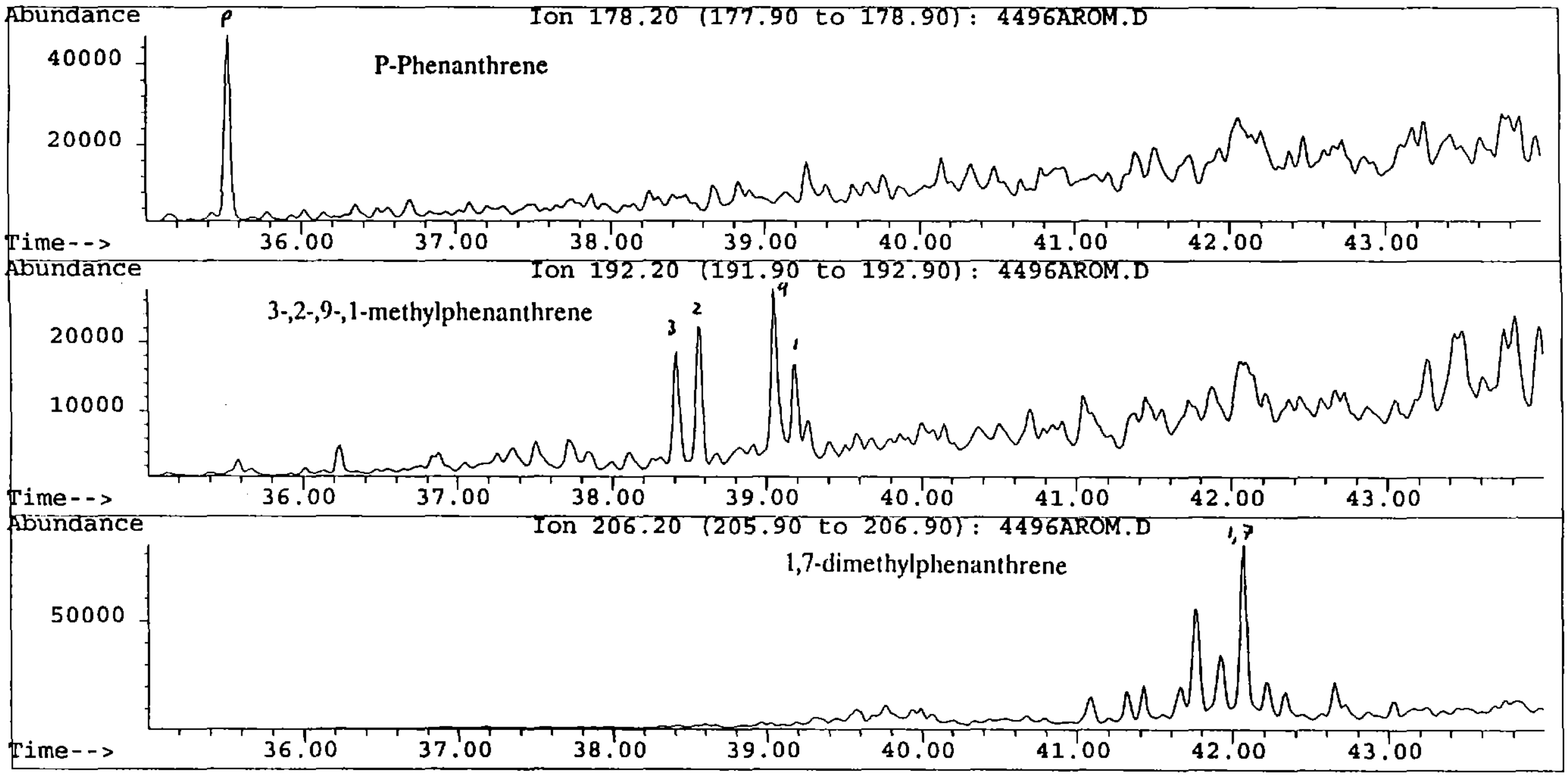


FIGURE 5b

File : C:\HPCHEM\1\DATA\UOFA\4496AROM.D
Operator : WYTHE
Acquired : 12 Jan 96 11:16 am using AcqMethod 60MAROM
Instrument : AMDEL-597
Sample Name: LONAVALE SEEP
Misc Info :
Vial Number: 1

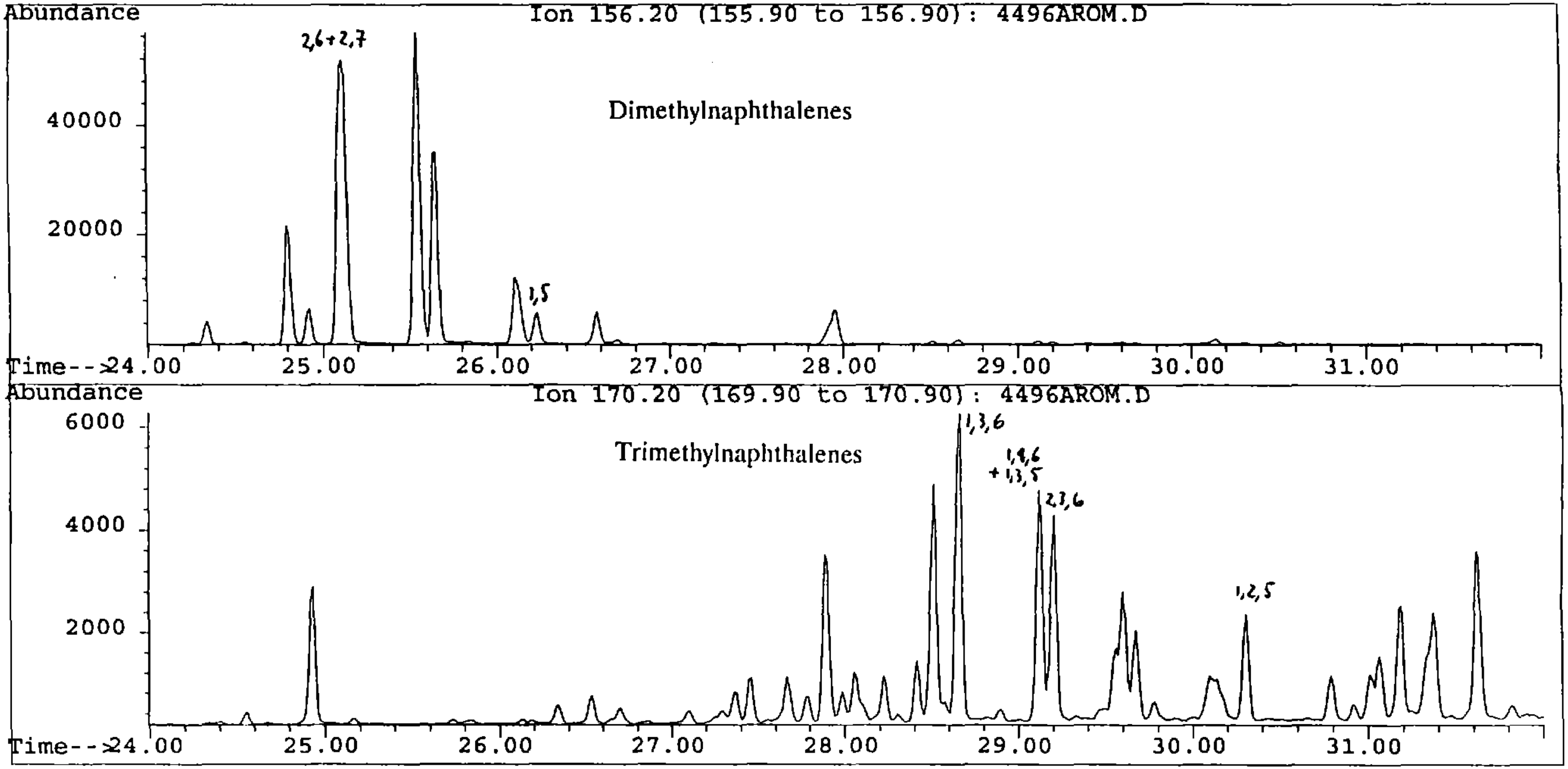
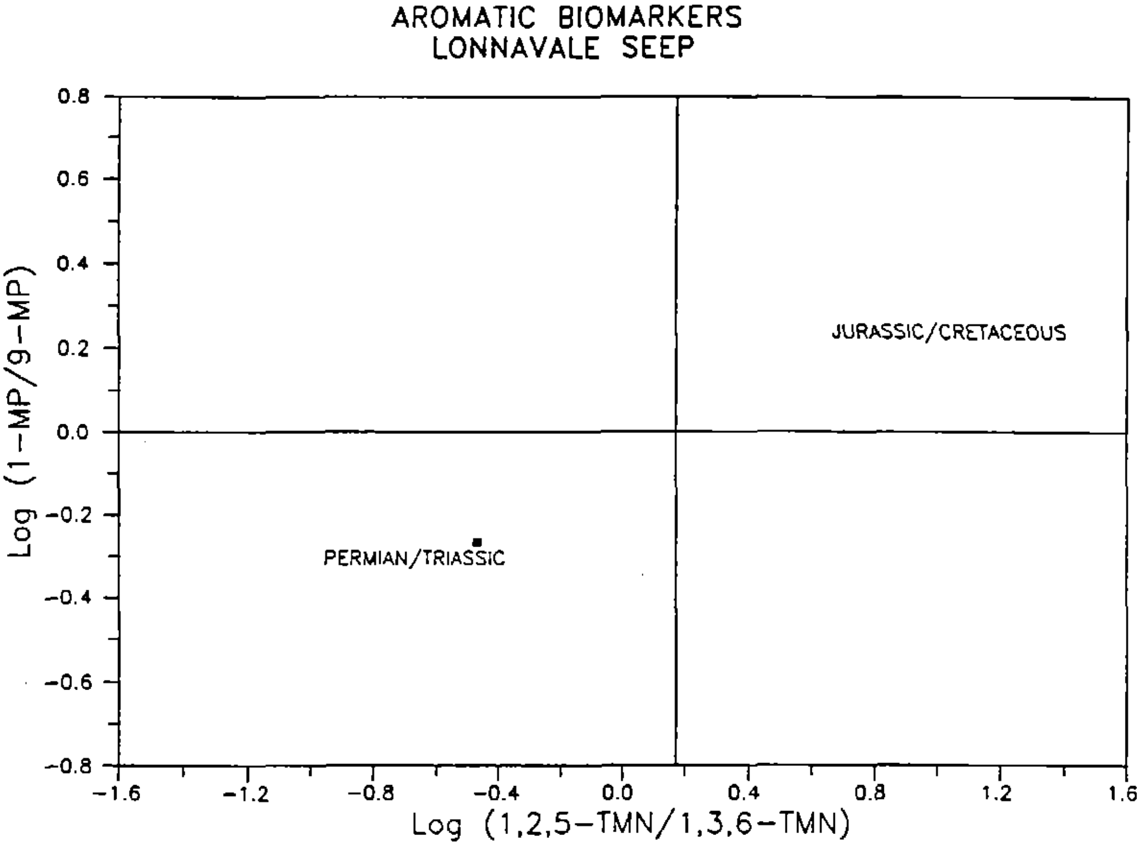


FIGURE 6



AROMATIC BIOMARKERS
LONNAVALE SEEP
Log (1-MP/9-MP)
Log (1,2,5-TMN/1,3,6-TMN)
JURASSIC/CRETACEOUS
PERMIAN/TRIASSIC
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.6
-1.2
-0.8
-0.4
0.0
0.4
0.8
1.2
1.6

FIGURE 7

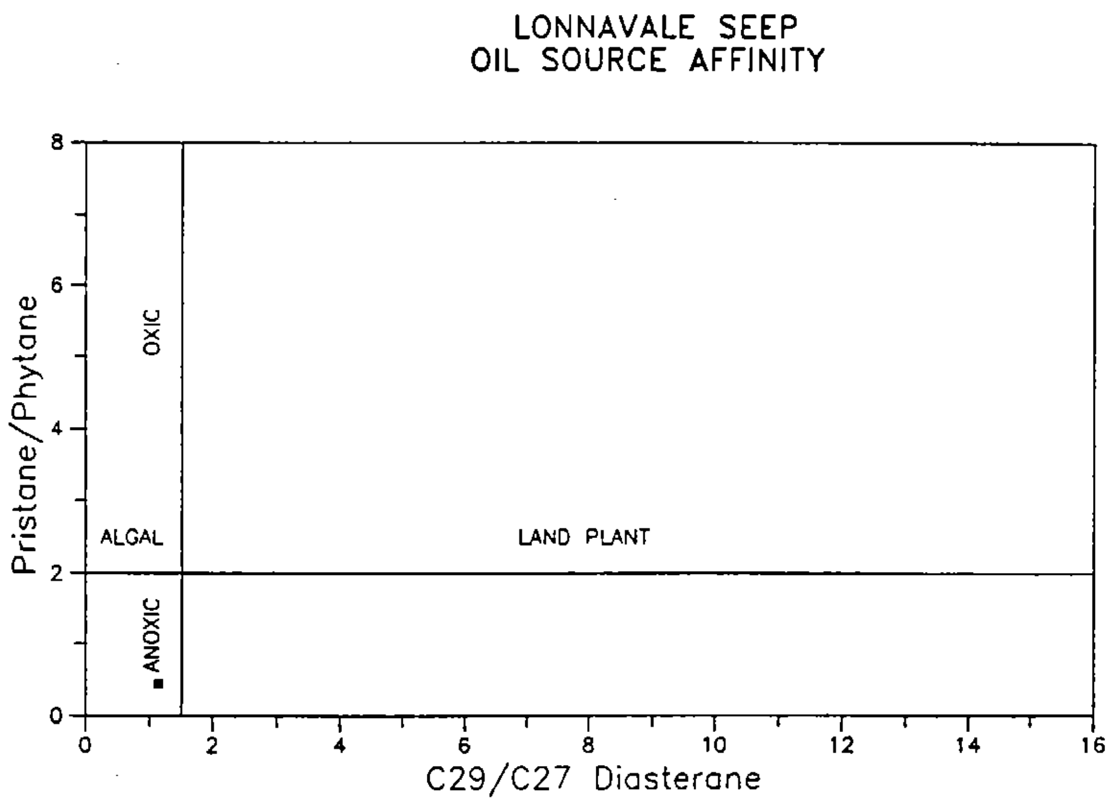

LONNAVALE SEEP
OIL SOURCE AFFINITY
Pristane/Phytane
C29/C27 Diasterane
OXIC
ALGAL
LAND PLANT
ANOXIC
0
2
4
6
8
10
12
14
16

FIGURE 8

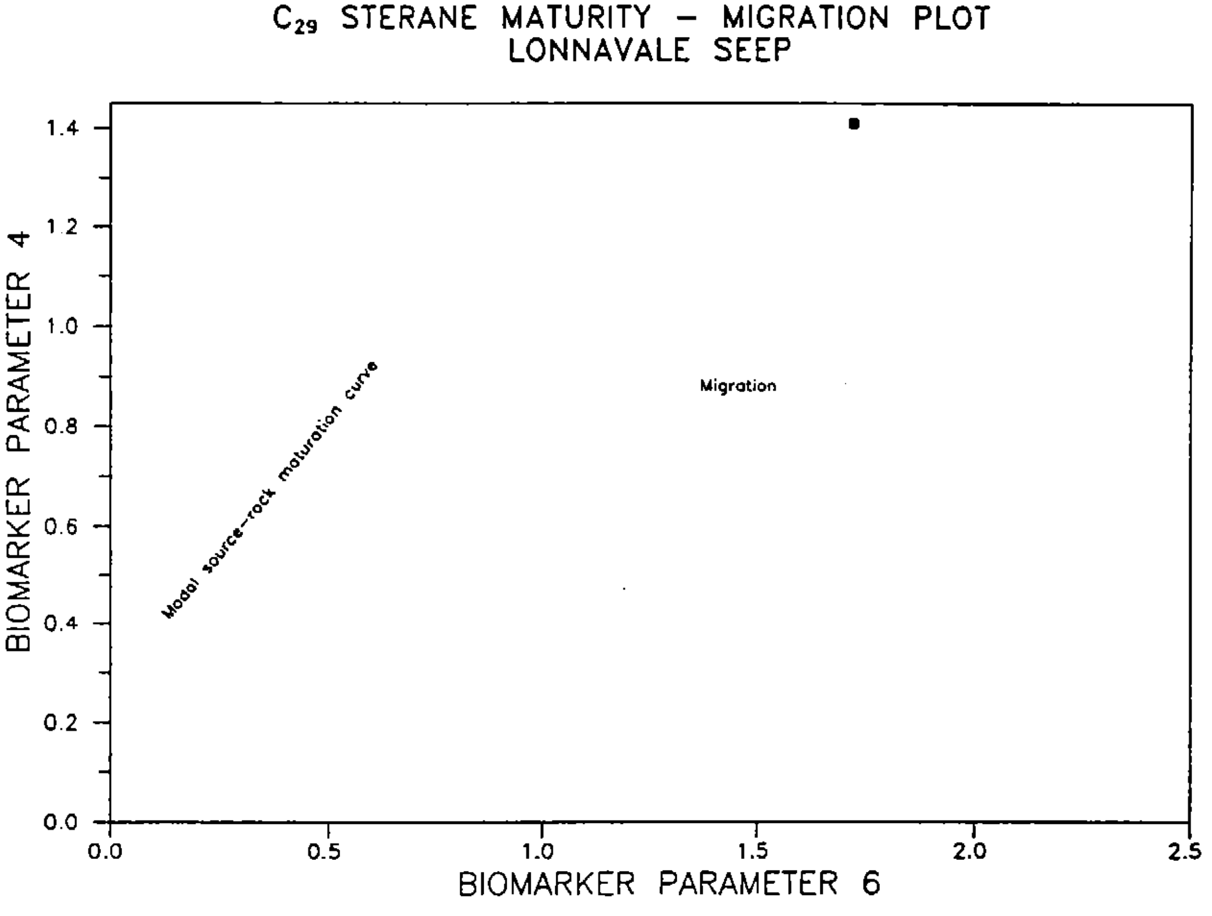
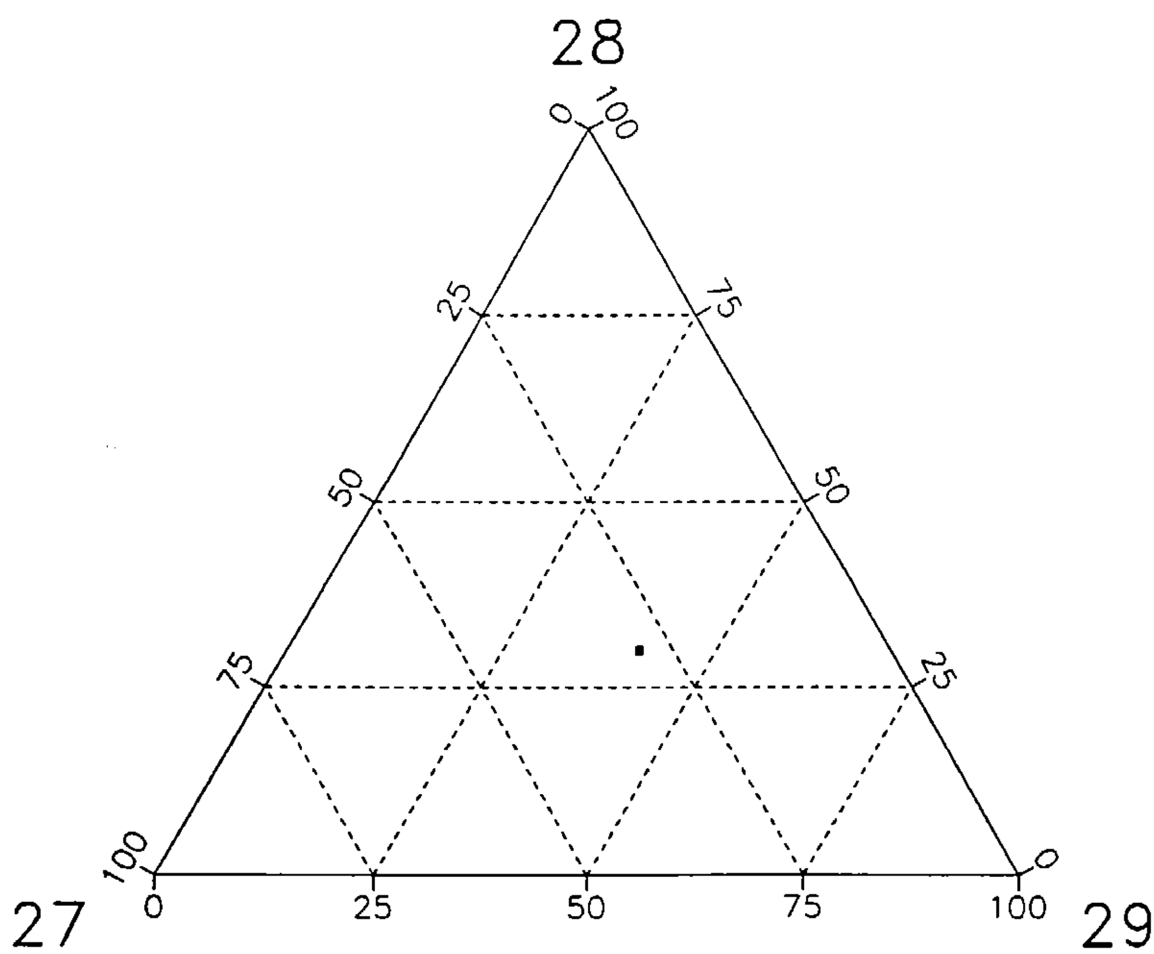

C29 STERANE MATURITY – MIGRATION PLOT
LONNAVALE SEEP
BIOMARKER PARAMETER 4
BIOMARKER PARAMETER 6
Modal source-rock maturation curve
Migration
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5

FIGURE 9

STERANE DISTRIBUTIONS
LONNAVALE SEEP



APPENDIX 1

ANALYTICAL PROCEDURES

1. **Isolation of Residual Oil**

The seep sample was extracted with dichloromethane in a soxhlet apparatus until the solvent was clear. Removal of the solvent by careful rotary evaporation gave the oil (nominal C_{12+} fraction).

2. **Liquid Chromatography**

Asphaltenes were not precipitated from the condensate prior to liquid chromatography. The samples were separated into hydrocarbons (saturates and aromatics) and polar compounds (resins) by liquid chromatography on activated alumina and silica (sample:adsorbent ratio = 1:100). Saturated hydrocarbons were eluted with petroleum ether, aromatic hydrocarbons with petroleum ether/dichloromethane (50:50) and polar compounds with dichloromethane/methanol (35:65).

3. **Gas Chromatography**

Whole oils and saturated hydrocarbons (alkanes) were examined by gas chromatography using the following instrumental parameters:

Gas Chromatograph:	Perkin Elmer 8500 operated in the split injection mode
Column:	25 m x 0.3 mm fused silica, SGE QC3/BP1
Detector Temperature:	300°C
Column Temperature:	40°C for 1 minute, then 8° per minute to 300°C and held isothermal at 300°C until all peaks eluted
Quantification:	Relative concentrations of individual hydrocarbons were obtained by measurement of peak areas with a Perkin-Elmer LCI 100 integrator. The areas of peaks responding to aromatic hydrocarbons were multiplied by appropriate response factors

4. Thin Layer Chromatography (TLC)

Aromatic hydrocarbons were isolated from the extracted oil by preparative TLC using Merck GF_{254} silica plates and distilled AR grade n-pentane as eluent. Naphthalene and anthracene were employed as reference standards for the diaromatic and triaromatic hydrocarbons, respectively. These two bands, visualised under UV light, were scraped from the plate and the aromatic hydrocarbons redissolved in dichloromethane.

5. Gas Chromatography-Mass Spectrometry (GC-MS)

GC-MS analysis of the aromatic and naphthenic hydrocarbons was undertaken in the selected ion detection (SID) mode. The instrument and its operating parameters were as follows:

System:	HP 5890 Series II Plus GC coupled to HP 5972 MSD
Column:	60m x 0.25 mm i.d., DB-1 cross-linked methylsilicone phase fused silica, interfaced directly to source of mass spectrometer
Injector:	Splitless 2μL
Carrier Gas:	Helium at a linear velocity of 30cm/minute
Column Temperature:	50°C for 2 minutes then 50-290°C @ 7°/minute
Mass Spectrometer Conditions:	70 eV EI; 9-ion selected ion monitoring, 70 millisec dwell time for each ion

The di- and triaromatic hydrocarbons isolated from the extracted oil by thin layer chromatography were analysed by GC-MS.

The following mass fragmentograms were recorded:

m/z	Compound Type
156	dimethylnaphthalenes
170	trimethylnaphthalenes
178	phenanthrene
192	methylphenanthrene
206	dimethylphenanthrenes

The area of the phenanthrene peak was multiplied by a response factor of 0.667 when calculating the methylphenanthrene index (MPI).

Naphthenes (branched/cyclic alkanes) were isolated from the oil by molecular sieve separation of the saturates fraction.

GC-MS analysis of the naphthenes was undertaken in the multiple ion detection (MID) mode. Instrumental conditions are given below.

The following mass fragmentograms were recorded:

m/z	Compound Type
83	alkylcyclohexanes
123	drimanes, diterpanes
177	demethylated triterpanes
183	acyclic alkanes (incl isoprenoids, botryococcanes)
191	triterpanes (incl hopanes, moretanes)
205	methyltriterpanes
217	steranes
218	steranes
231	4-methylsteranes
259	diasteranes

APPENDIX 2

GC-MS OF BRANCHED/CYCLIC ALKANES

File : C:\HPCHEM\1\DATA\UOFA\4496NB.D
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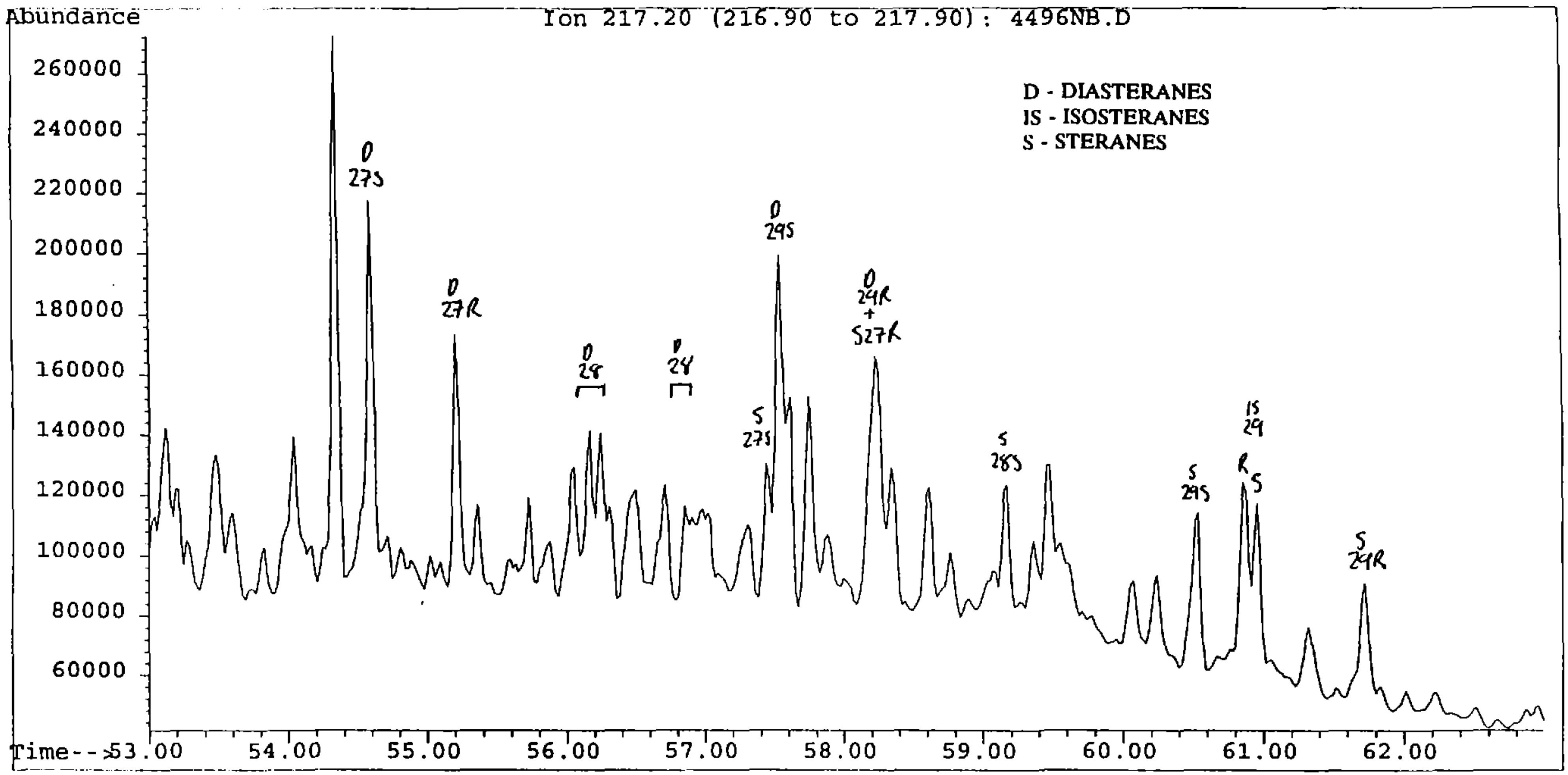
Acquired : 11 Jan 96 6:57 pm using AcqMethod 60MAMDEL
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1



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Operator     : WYTHE
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Instrument :   AMDEL-597
Sample Name: Lonavale Seep
Misc Info  :
Vial Number: 1
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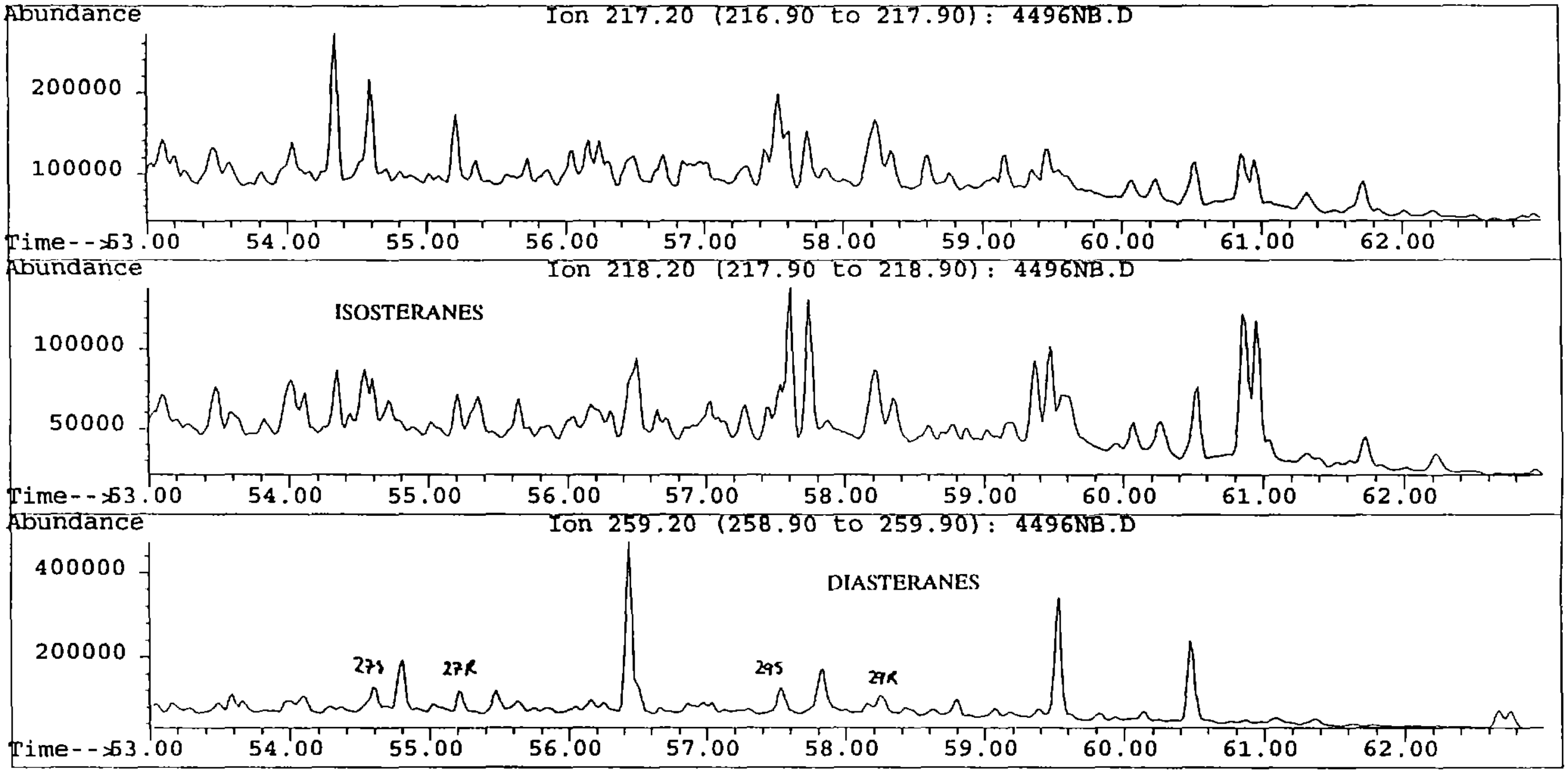

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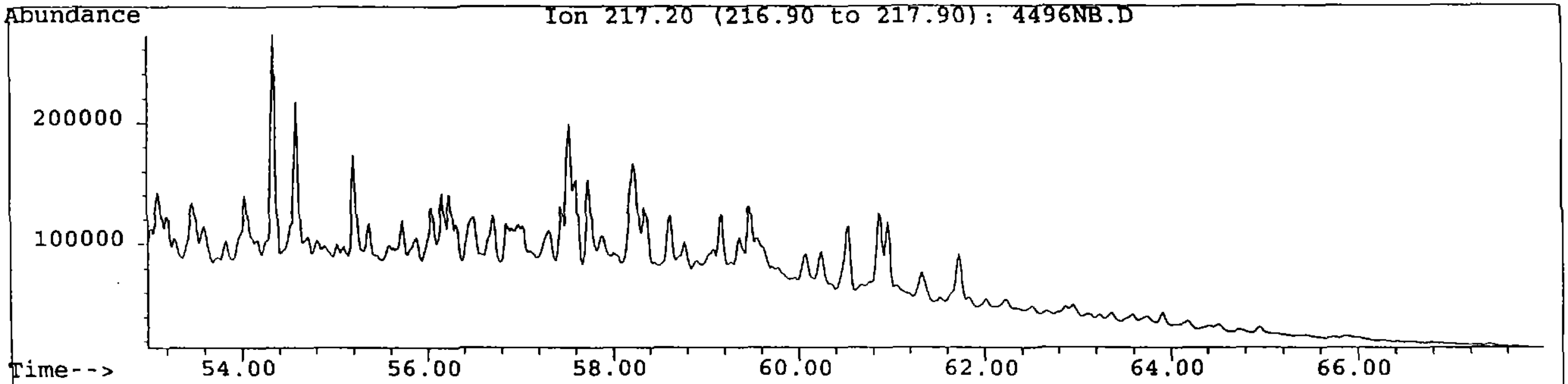
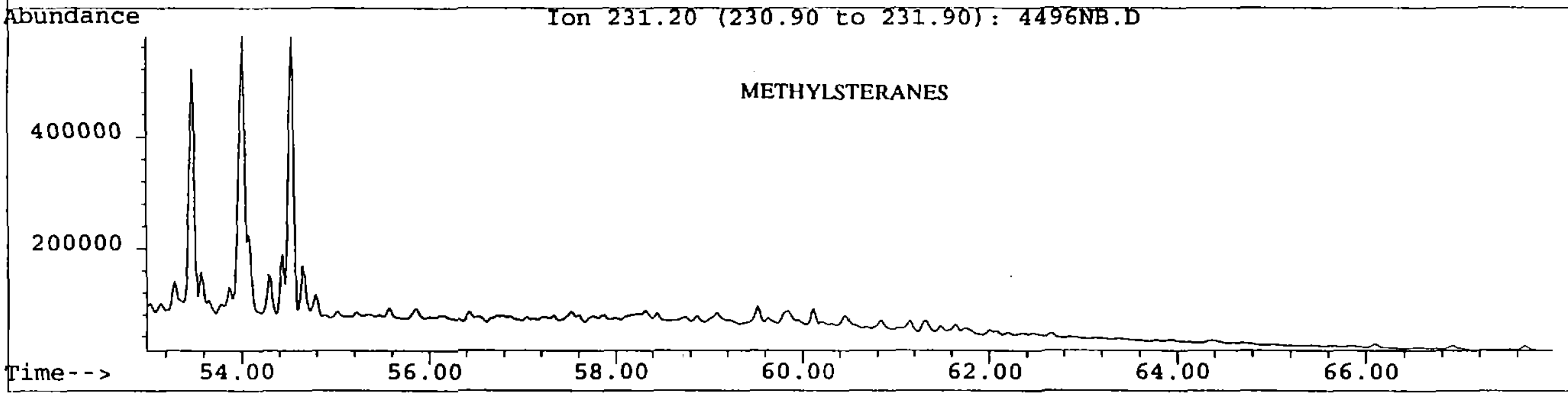
Operator : WYTHE
Acquired : 11 Jan 96 6:57 pm using AcqMethod 60MAMDEL
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1





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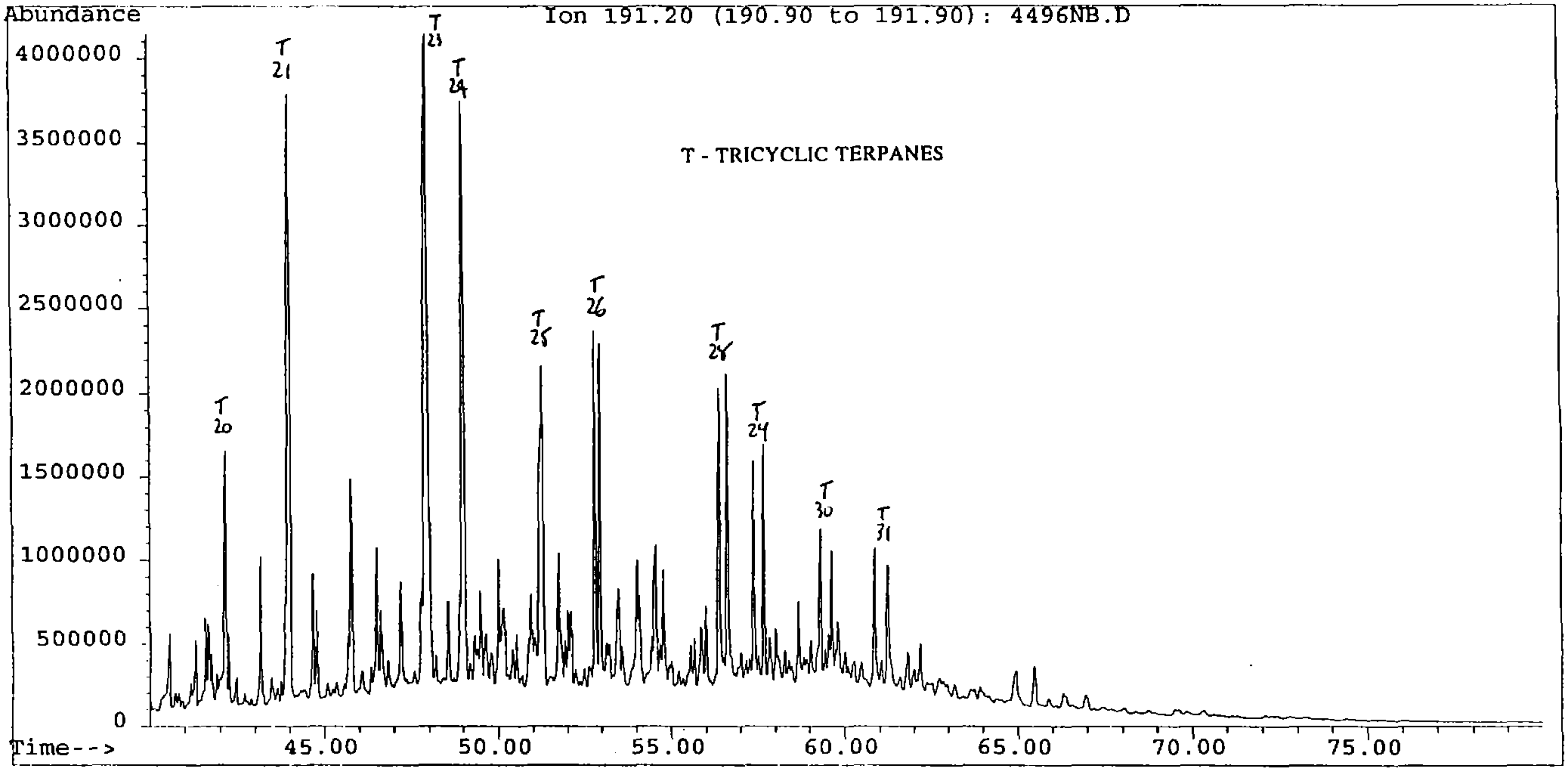
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1



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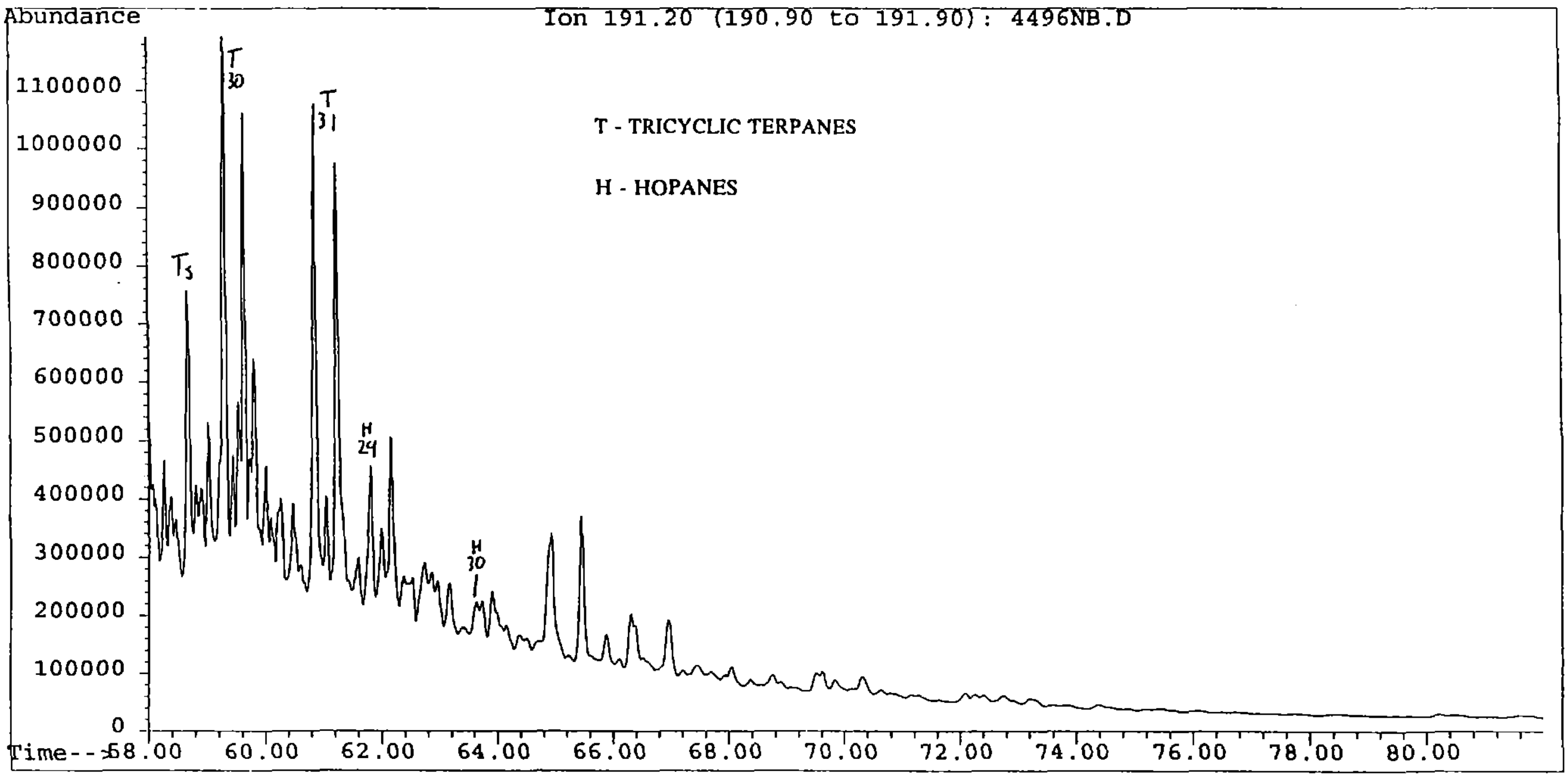
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1



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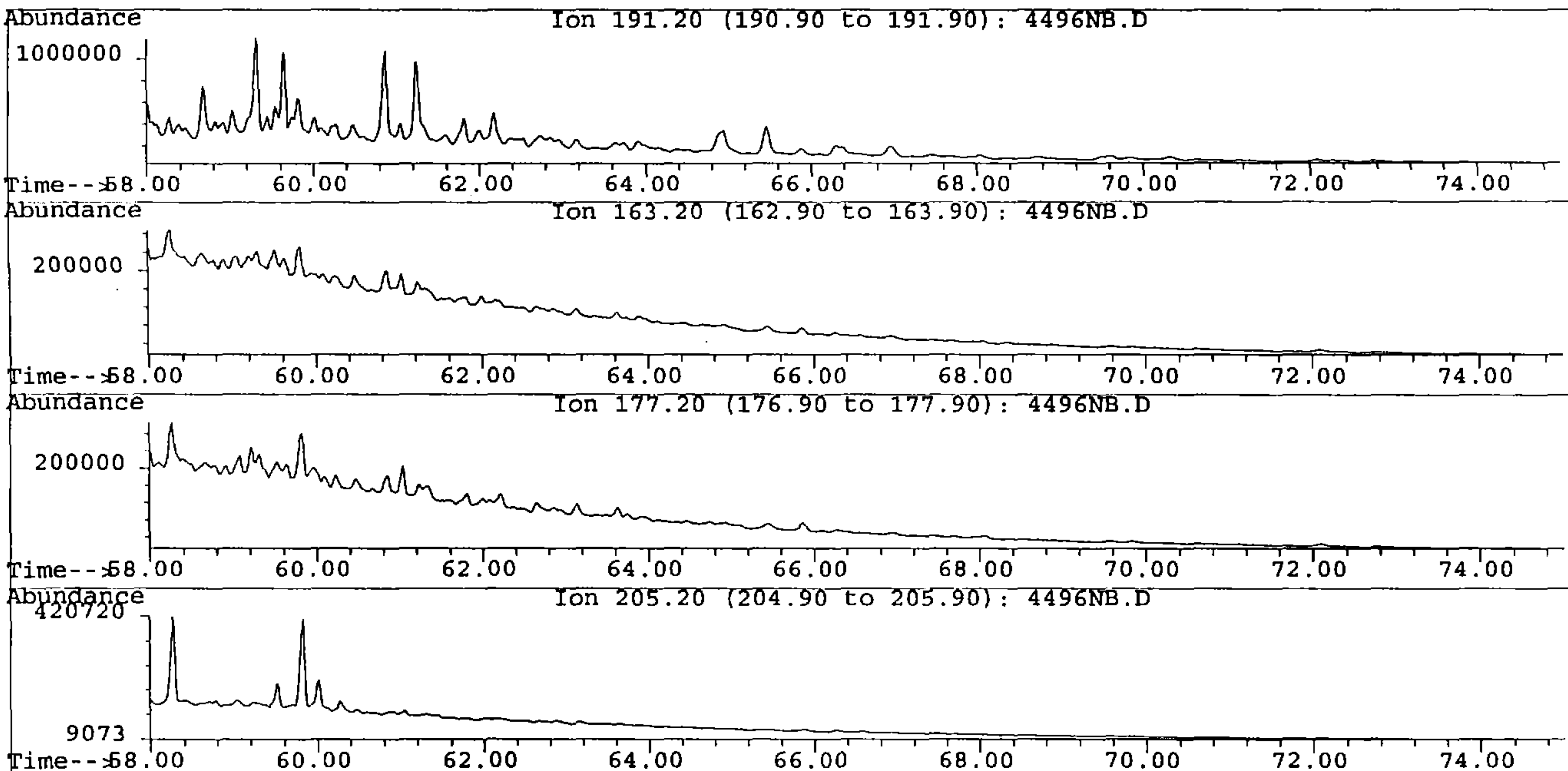
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1



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Operator : WYTHE
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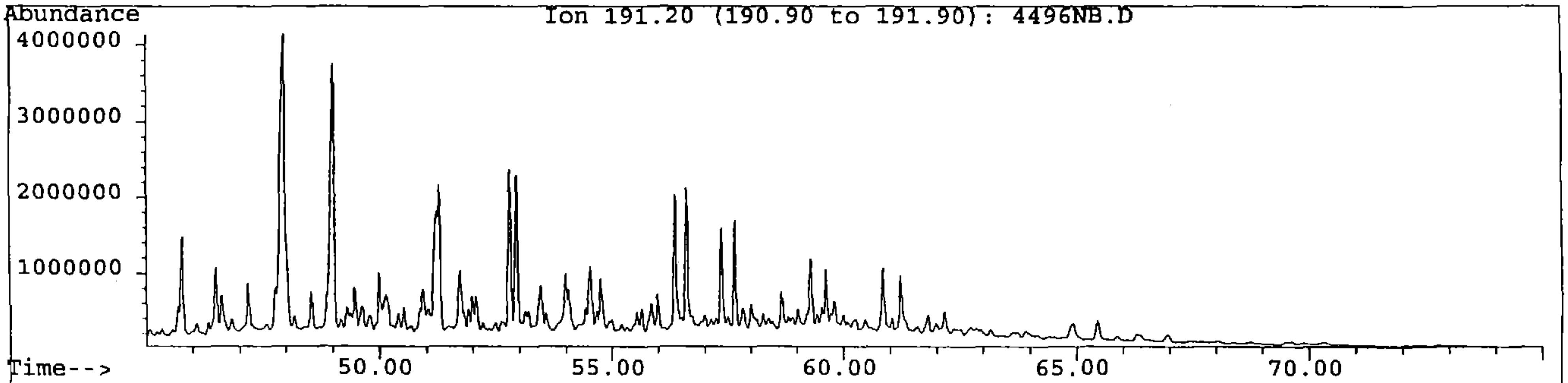
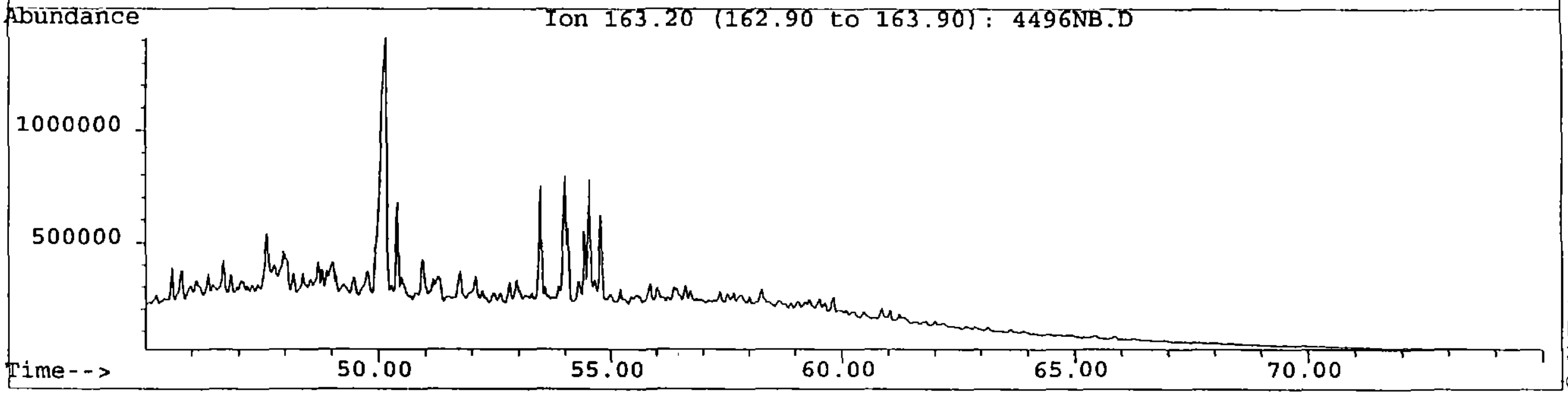
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1





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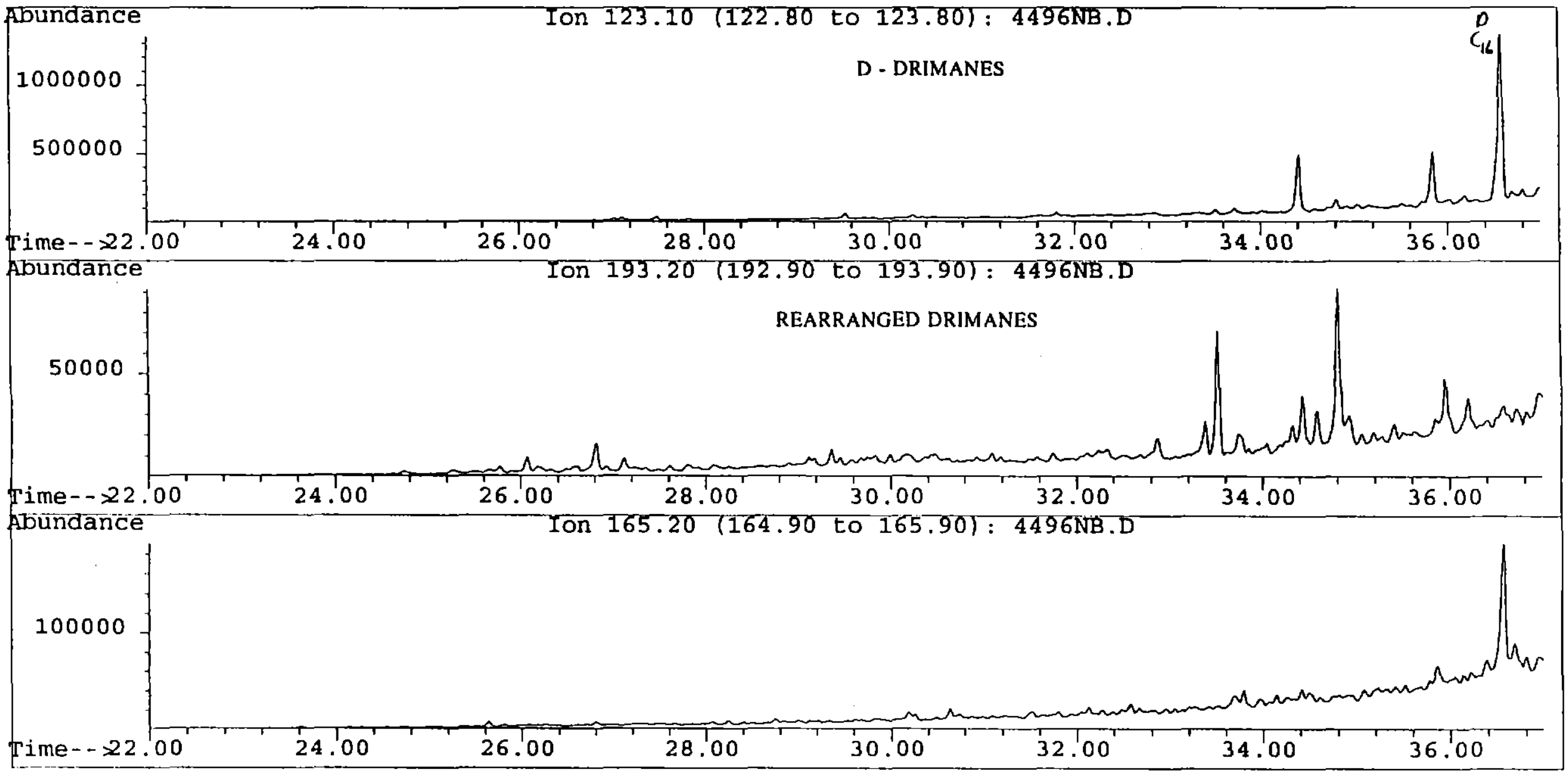
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1



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Operator : WYTHE
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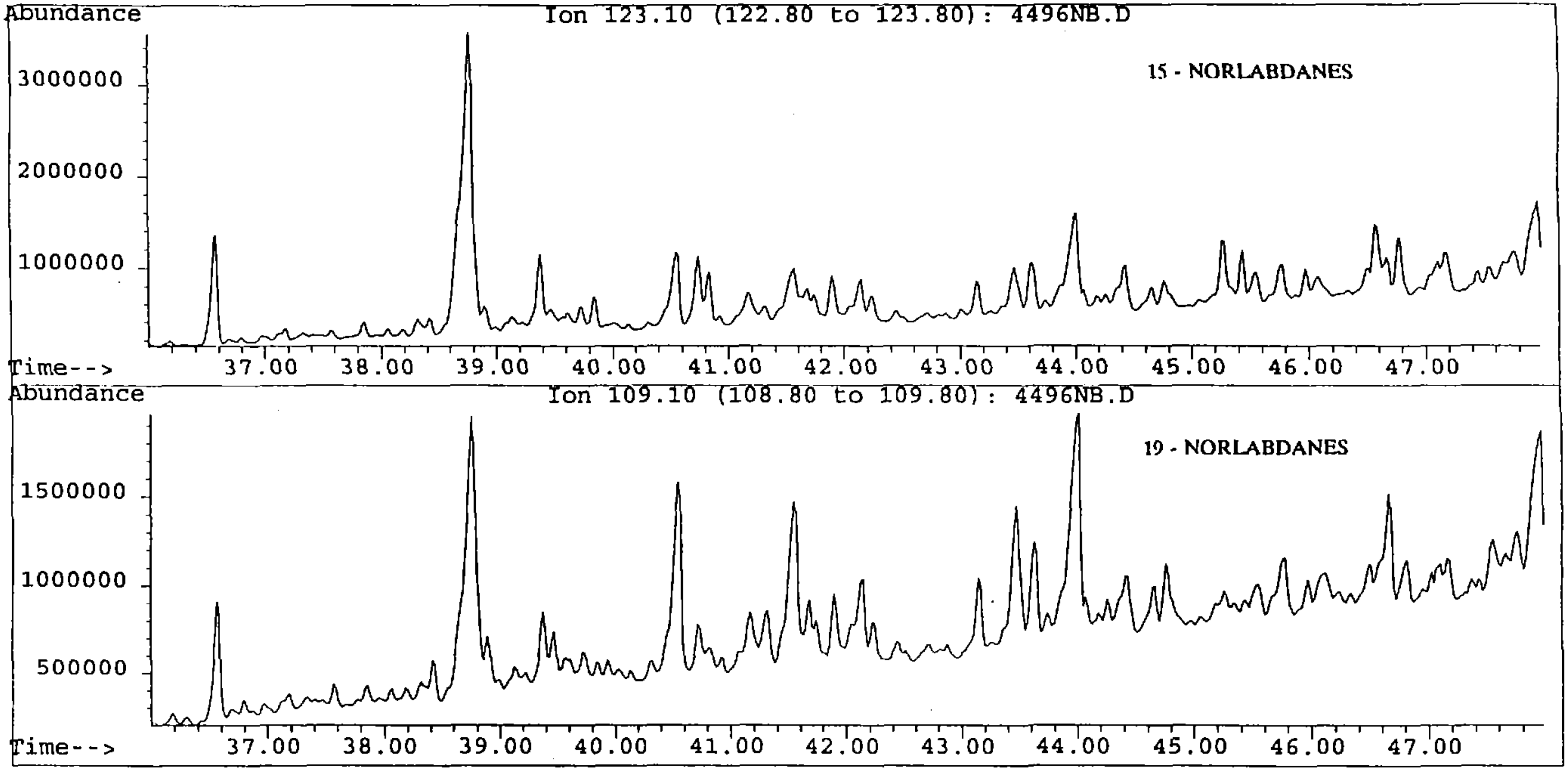
Instrument : AMDEL-597
Sample Name: Lonavale Seep
Misc Info :
Vial Number: 1



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Instrument  :   AMDEL-597
Sample Name: Lonavale Seep
Misc Info   :
Vial Number: 1
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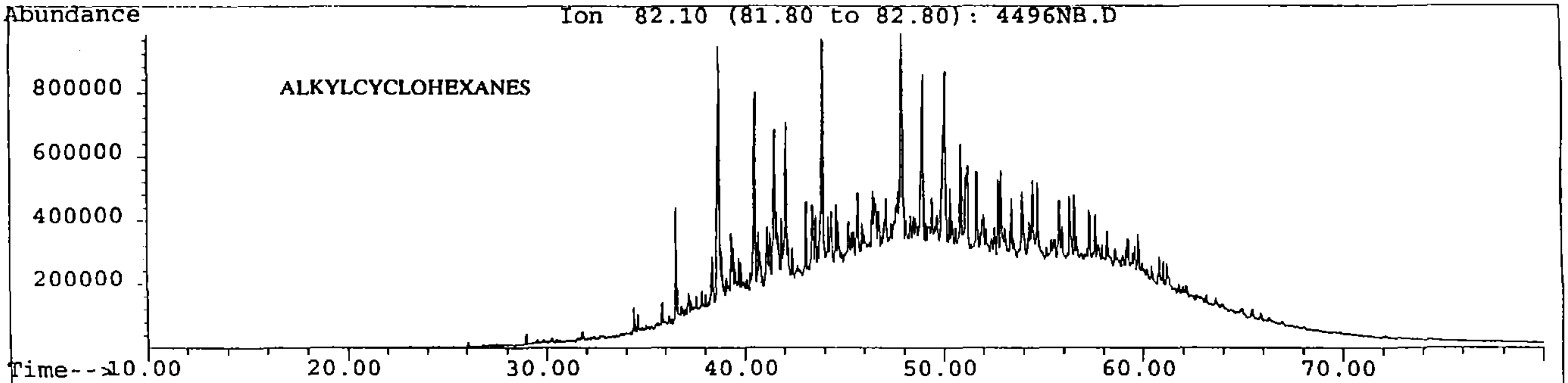
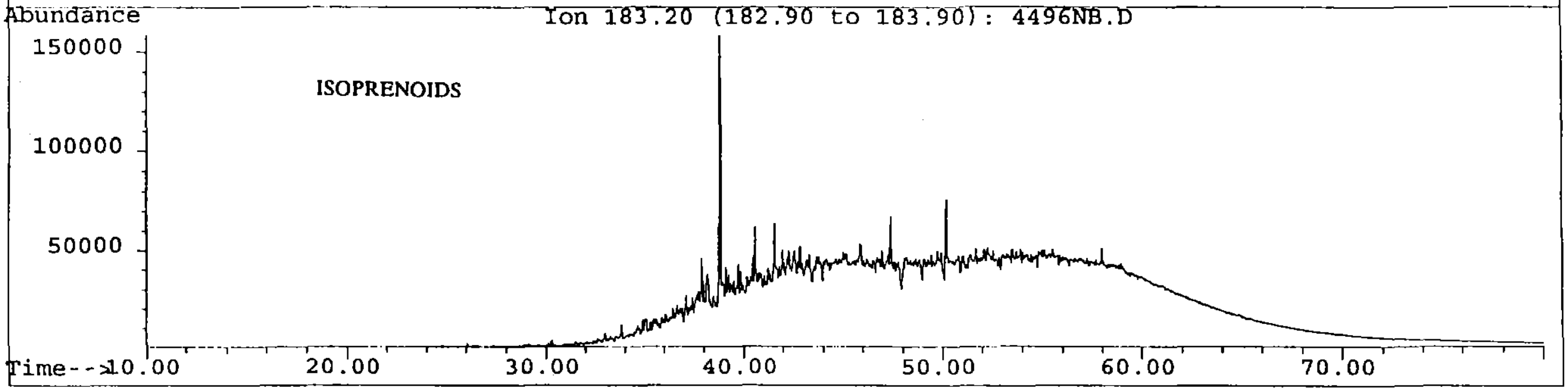


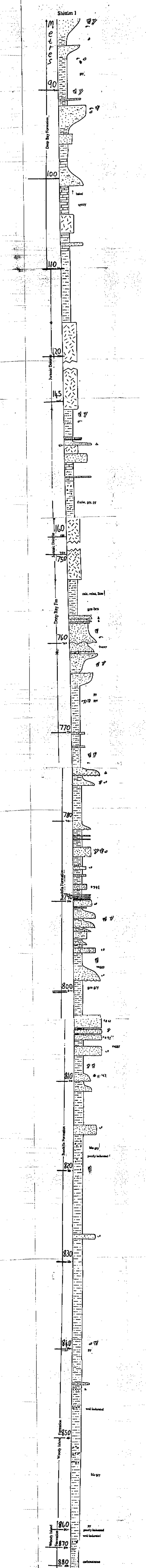


APPENDIX 10

STRATIGRAPHIC LOGS OF SHITTIM#1 AND JERICHO#1

BY TRENT.J.WOODS

DECEMBER 1995


Bilston 1
1021 metres END


Jericho 1