AGSO

ARAFURA SEA GEOHISTORY STUDY

BY

AIDAN MOORE

RECORD 1995/65

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Australian Geological Survey Organisation
Canberra, Australia
1996

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Primary Industries and Energy: Hon. J. Anderson, M.P.
Minister for Resources and Energy: Senator the Hon. W.R. Parer
Secretary: Paul Barratt

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Neil Williams

ISSN: 1039-0073
ISBN: 0 642 24951 2

Bibliographic reference
Moore, A., 1995 - Arafura Sea Geohistory Study. Australian Geological Survey Organisation Record 1995/65.

CONTENTS

SUMMARY
Stratigraphic and petroleum related data for eight wells drilled in the Arafura Sea, and four additional, hypothetical locations, were compiled and entered into a basin and well analysis program. The stratigraphic data were based on the age datings, well log and sequence correlations contained in well completion reports, and in the Arafura Prospectivity Evaluation Report of Labutis et al (1992).

The results of the well and basin history analysis are presented here, and some of the implications for hydrocarbon exploration are discussed.

One of the significant findings of this study is that in the Arafura Basin, which contains excellent source rocks of Early Palaeozoic age, the present-day heatflow (and thermal gradient) is lower than commonly believed, but was higher in the distant past. Hydrocarbon generation from common types of kerogen, and migration from the Cambrian and Ordovician source rocks, occurred during the Carboniferous period. Generation from the prolific Early Ordovician oil source *Gleocapsomorpha prisca*, if, as expected, it is present in the basin, would have occurred shortly after. The search for economically viable hydrocarbons requires traps that pre-date migration and survive to the present.

In the Goulburn Graben the major structuring post-dates the time of hydrocarbon generation and migration. Older structuring and stratigraphic trapping should be sought, possibly in the eastern end of the basin, but mainly outside the graben, to the north, where prospective Palaeozoic and Upper Proterozoic successions are thought to exist, and the generation and migration of hydrocarbons probably post-dates the structuring. There is no borehole north of the bounding faults of the Goulburn Graben, and prognosis based on seismic is poorly controlled. Drilling is necessary to confirm the presence of prospective sediments, and to provide basic stratigraphic information in the huge basinal areas outside the graben on its northern and eastern sides.

INTRODUCTION

The petroleum prospectivity of the Arafura Sea was reviewed by Petroconsultants (1989), and Bradshaw et al (1990) published new stratigraphic evidence that indicated the need for an updated assessment of the area. Eight petroleum exploration wells were drilled prior to 1993 (Figure 1). The stratigraphy of seven of the wells was reviewed during an AGSO study (Labutis et al, 1992). In that study, AGSO Record 1992/84, age dating was revised and upgraded from the open file data by Clinton Foster and Robin Helby, and supplemented with zonations contained in the AGSO Oracle-based biostratigraphic database (STRATDAT). A well log and sequence stratigraphic correlation was carried out by Vidas Labutis (Visulab Pty. Ltd.).

The eighth well, Chameleon 1, was drilled in 1991, and data confidential in 1992 are now on open file. In this study, stratigraphic and petroleum related data for the eight wells were compiled and entered into the BURY basin and well analysis program (Paltech, 1993). Hypothetical well sites in areas of particular interest were also analysed. Three of them are located outside the graben, in the northern part of the Arafura Basin. The remaining site is in the deepest part of the graben adjacent to the northern bounding fault near the Arafura 1 well. Plots of well history and related parameters, such as maturity versus depth, and maturity versus time, are presented in this report, and their implications for hydrocarbon generation and trapping are discussed.

Location

The area covered by this study (Fig. 1) is located in the Arafura Sea north of Arnhem Land in the Northern Territory of Australia. It extends from longitude 131°30' East to 138° East, and from the border of the territorial waters of Australia and Indonesia about latitude 9° South, to 12° South. Water depths range from 30 to 200m, but are mostly less than 100m.

Geological Setting

The geology of the northern margin of Australia beneath the Arafura Sea is not well known. It contains the Money Shoal, Arafura and McArthur Basins of Cainozoic-Mesozoic, Palaeozoic and Proterozoic age respectively. These partially overlap to form a sedimentary pile more than 10 kilometres thick in places (Bradshaw et al, 1990). Over most of the area the basinal succession has not been severely tectonised, and geothermal gradients are low. The only oil exploration wells are restricted to the Goulburn Graben, near the southern rim of the Arafura Basin (Figure 1 and Enclosure 1). The stratigraphy derived from the wells is described in Labutis et al (1992).

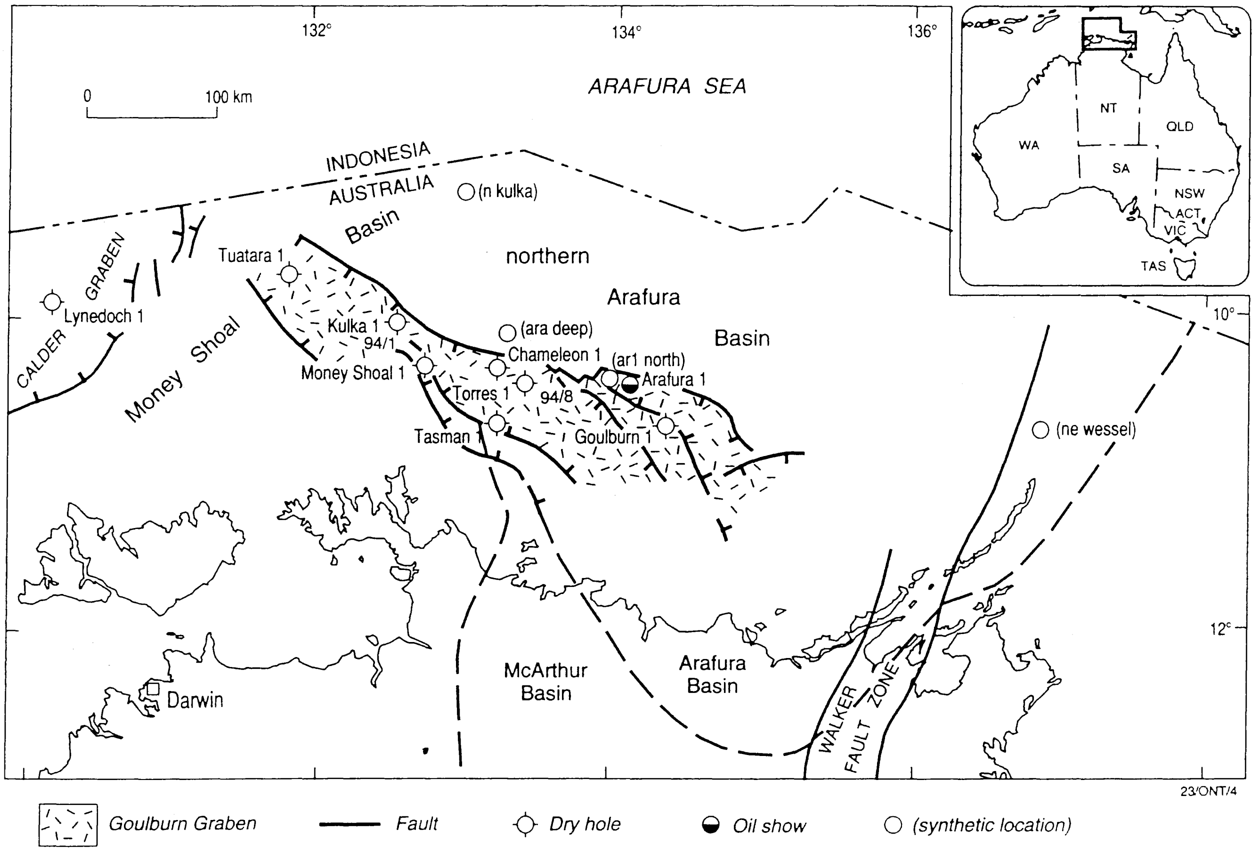
Money Shoal Basin (Cainozoic-Mesozoic)

The Money Shoal Basin occupies the western part of the Arafura Sea. The base is time transgressive, and ranges in age from Late Jurassic in the west, to Late Cretaceous in the east. The Tertiary succession is thin or absent in the eastern parts of the basin, and has not been sampled in the wells. There are up to 400m of Jurassic marine clastics at the base of the sequence in the west. The basin onlaps the angular unconformity at the top of the underlying Arafura Basin, and the shales above the 'base Cenomanian' maximum flooding surface (*D.*

multispinum dinoflagellate zone (Helby, Morgan and Partridge, 1987)) overly the basal unconformity in eastern parts of the area as shown by the dark shading on Enclosure 1.

Arafura Basin (Palaeozoic)
The Arafura Basin extends from onshore outcrops of Cambrian rocks in Arnhem Land and the Wessel Islands to the Australian-Indonesian border and beyond, possibly as far as the mainland of Irian Jaya. The main structural provinces of the basin are shown in Figure 1. In Australian waters it covers an area of more than 130,000 km^2. Its simple synclinal shape is interrupted by the Goulburn Graben which lies on its southern margin and trends west-northwestward. In the Goulburn Graben the basin fill consists of up to 10 km of marine and marginal marine clastics and carbonates ranging in age from the Lower Cambrian to the Permian, with possibly some Triassic in a few restricted locations. The greater part of the basin, the Northern Arafura Sub-basin, east and north of the graben, is undrilled. It is probably composed of Lower Palaeozoic marine clastics and carbonates. It overlies and overlaps the McArthur Basin offshore.

McArthur Basin (Proterozoic)
The McArthur Basin is widely exposed and drilled onshore. It has not been reached offshore. It is a thick and complex basin with (?Upper and) Mid Proterozoic marine and marginal-marine sediments, and it contains at least one major internal angular unconformity, together with five oil source rocks (Crick, 1992; Crick et al, 1988) and a thick dolerite sill. In the central area of the Northern Arafura Sub-basin, the McArthur Basin is likely to be youngest Proterozoic (Roper Group), but toward the Wessel Islands on the eastern flank, and also on the western margin, an angular unconformity separates older Middle Proterozoic, McArthur or Nathan Group sediments from the mildly onlapping Cambrian of the Arafura Basin.



Locality map showing the Arafura Sea, with the Goulburn Graben, the oil exploration wells, and synthetic well locations in the northern Arafura Basin.

METHOD

The BURY Software

BURY is a commercial software program developed in Australia since 1978 for the modelling and analysis of burial and thermal histories of well sequence and basin development in petroleum exploration (Paltech, 1993). It uses industry standard 1-D models for sediment compaction and decompaction, thermal maturity, and kinetic generation of hydrocarbons from source rock, with default values that can in many cases be varied. Multiwell capabilities include cross-section generation and (paleo) contour map generation using Delaunay triangular map interpolation. A discussion of the theoretical foundations and features of BURY and comparisons with other similar packages such as BASINMOD™ can be found in Radlinski (1991), although the software has evolved greatly since then. The Windows™ version 1.4c (WINBURY™) was used in this study

The Input Data

Data from wells for input to the BURY software came from the tables and charts in Labutis et al (1992) and from well completion reports (WCRs) which are referenced in the bibliography under the names of the companies that submitted them.

Well Header data includes well name, latitude and longitude, kelly bushing elevation above sea level (KB), water depth, termination depth (TD), sea bottom (SB) and bottom hole temperature (BHT), estimated basement depth, and an estimated present-day value of heat flow (HF). All depths are related to KB. All of these except SB temperature and HF were obtained from WCRs and logs.

*Unit age and depth.*The age of the top of the first stratigraphic unit in each well is 0 million years (0 My) and the depth to the top is the KB depth of the seafloor. Depth to top of stratigraphic units is taken from Table 1 of Labutis et al (1992) and WCRs. Lithostratigraphic equivalence of Money Shoal Basin and Arafura Basin units to named formations of the same age in the Bonaparte Basin is not assured, hence those names are used as little as possible. Stratigraphic units (palynological zones or well or seismic sequences) have been referred to by their palynological affiliations rather than by formation names, e.g. D.multispinum zone (or stratigraphic sequence, which includes the palynological zone but has a broader time span) rather than Wangarlu Formation. The age equivalence of Bonaparte Basin stratigraphy to the palynological zones and stratigraphic sequences in the Money Shoal and Arafura Basins, and the age ranges of the sequences and zones, are taken from Enclosure 2 of Labutis et al (1992). The absolute ages of geological stages are those used in-house by AGSO. They are close to those of Harland et al (1982) except for the lowermost Permian, the Asselian, now put at 293-298 Ma, and the base of the Cambrian, now put at 545 Ma.

Modelled water depths are lagoonal (0 - 10m) for the Ordovician and Cambrian carbonate formations, inner neritic (20 - 50m) for the sandy clastic sequences, and outer neritic (100 - 200m) for the shaly units.

Lithology for the purpose of geohistory modelling is of interest mainly for calculating the thermal conductivity, density, and compaction factors of units. In this study it is kept very simple, consisting of varying proportions of sand, clay and lime.
Unconformities. Four major unconformities were identified in the data from the wells, as well as four additional major hiatuses. Attempts were made to 'restore' eroded section at the unconformities. This is shown in brackets in the data entry tables (Horizon data), with the prefix 'E' in the second column. The constraint used to control this restoration was the maturity profile, usually based on measured vitrinite reflectance (Ro, or VR), or its equivalents such as Conodont Alteration Index (CAI) in pre-Devonian strata. Deposited section (since eroded) was kept to the minimum required to yield the observed step in Ro maturity, e.g. at the base of the Mesozoic in Kulka 1 (see the relevant section below). This restoration is of necessity a crude first attempt to quantify the major thermal/tectonic events in the very long history of this basinal complex.
Other observed data included *vitrinite reflectance* data (available for most wells) and other types of maturity indicator such as *Rock-Eval* (sparsely available) and Conodont Alteration Index (CAI), especially useful for Lower Palaeozoic successions where vitrinite is not available. For plotting purposes, the observed maturity was converted to its equivalent on the vitrinite reflectance scale, whatever its age or origin. There were *porosity* measurements at a few levels in a few WCRs. *Fission track analysis* was available for two wells (Torres 1 and Tasman 1). *Kerogen data* were available very sparsely in WCRs, e.g. at Kulka 1, and consisted of TOCs determined at a few levels, together with organic matter type.

Heatflow Calculations
Heatflow (HF) modelling was one of the most important parts of this study. It was an iterative process, beginning with a constant HF based on the present-day value quoted in published sources. This resulted in plots of expected value, e.g. of downhole temperature versus depth, of BHT, and of expected maturity. These expected values were then compared with observed values of the same parameters, e.g. temperatures, vitrinite reflectance, and other indications of present and past thermal regimes measured at various depths in the wells, and the heatflow was modelled iteratively to match the observations.

The first task was to verify today's heatflow in the Arafura Sea, beginning with the surface (seabed) temperature, which affects the calculation of the temperature/depth gradient and hence of heatflow. Earlier calculations, e.g. in some WCRs, used an assumed seabed temperature of 18°C, common in warm seas. In the Arafura Sea the water temperature at 10m depth was measured by AGSO's vessel Rig Seismic at 31°C during seismic surveys. An actual record of seabed temperature is available for one well, Arafura 1, where it was measured at 26°C at a depth of 64 m. This value was used, therefore, in the calculation of the present-day thermal gradient and heatflow. The effect of this higher value of surface temperature is to reduce gradients and hence to reduce the calculated present day heatflow. Values of surface temperature that were used in the calculation of past gradients and heatflow, range from the recent 26°C down to a supposed 10° in the early Permian

(Asselian), reflecting the high latitudes of that time, and 20° in the Arenigian/Cambrian, when the Arafura Sea was in equatorial regions.

Observed downhole temperatures were plotted using the Horner method to yield a corrected formation BHT, or an already corrected BHT was taken from the WCR. Where a reliable BHT was not available for a well, e.g. at Kulka 1 or Goulburn 1, an initial assumed value was calculated using an arbitrary geothermal gradient of 30°C/km. This initial value was then checked against other data, e.g. maturity, or uphole measurements of temperature, and adjusted as necessary.

In published maps of heatflow in northern Australia, most of which are based on Cull and Conley (1983), the value in the Arafura Sea is given as about 2 HFU (above 80 mW/m^2). Cull and Conley do not show any data points in the offshore Arafura Sea, and indeed their paper predates almost all of the drilling there. Their value is compatible with shallow basement, which was the assumption of that time. Observed well temperature data that has become available since then, e.g. the BHTs and other downhole temperature measurements at Arafura 1, at Tasman 1 at Tuatara 1, together with the surface temperature data discussed above, indicate that the value is much lower (see below in relevant section), at or less than 1 HFU, especially in the east. This value is compatible with a thick cover of ancient (Lower Palaeozoic and Proterozoic) sediments. It also has major implications for the present day maturity of sediments, and for the timing of generation and migration of hydrocarbons in the past.

RESULTS

The results of the analysis of stratigraphic and other petroleum related information from well completion reports (WCRs) are presented in the following pages. They consist of plots of measured and expected hydrocarbon maturity, temperature and other parameters, plotted against geological time, or depth in the wells, or both. The wells are presented in alphabetical order. There are several plots for each well, beginning with a header containing basic well parameters, a diagram of the stratigraphy encountered, and continuing with diagrams and plots of significant data and the model used to explain the well and basin history. For nearly all wells, one model is clearly superior in explaining the observed temperatures and maturities, though obviously, other models could be devised. The one presented here is considered to be the most realistic. This is followed by a geohistory plot, and a discussion of hydrocarbon maturity. Comments on features of significance are added to the plots themselves, rather than being collected in the textual portion of this report.

The most important wells for the understanding of the Palaeozoic history of the Arafura Basin probably are Arafura 1, Tasman 1 and Torres 1. Arafura 1 has a more complete Early Palaeozoic succession, as well as a large temperature database in the many log runs. Tasman 1 has the most complete later Palaeozoic succession, while Torres 1 has had the most uplift, and has the most highly developed unconformities. The most important wells for understanding the petroleum history are Torres 1, Arafura 1, and Goulburn 1. The most complete Mesozoic succession is found in Tuatara 1.

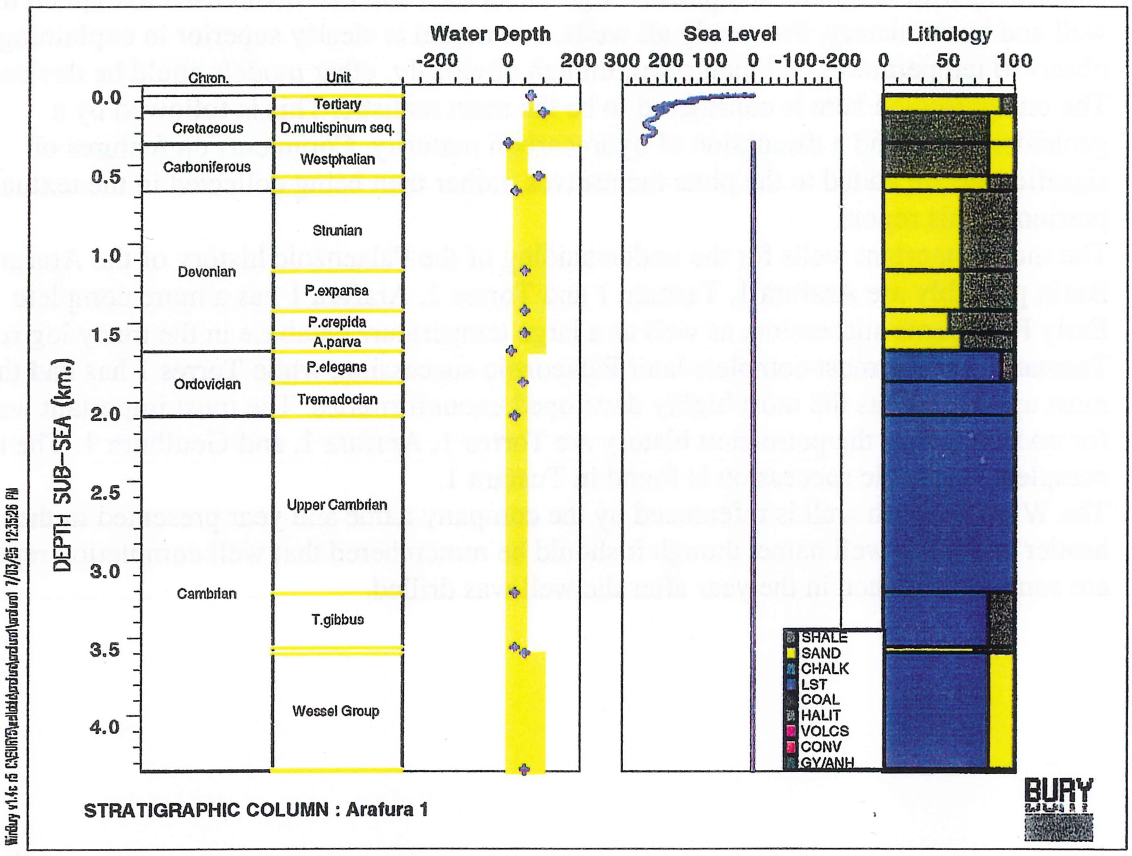
The WCR for each well is referenced by the company name and year presented in the header under the well name, though it should be remembered that well completion reports are sometimes issued in the year after the well was drilled.

ARAFURA 1

PETROFINA EXPLORATION 1983

Latitude: 10º 27' 02.56" S (WGS 84)
KB: 32m asl
Sea Bottom Temperature: 26C
BHT: 96ºC (corrected, Horner plot)

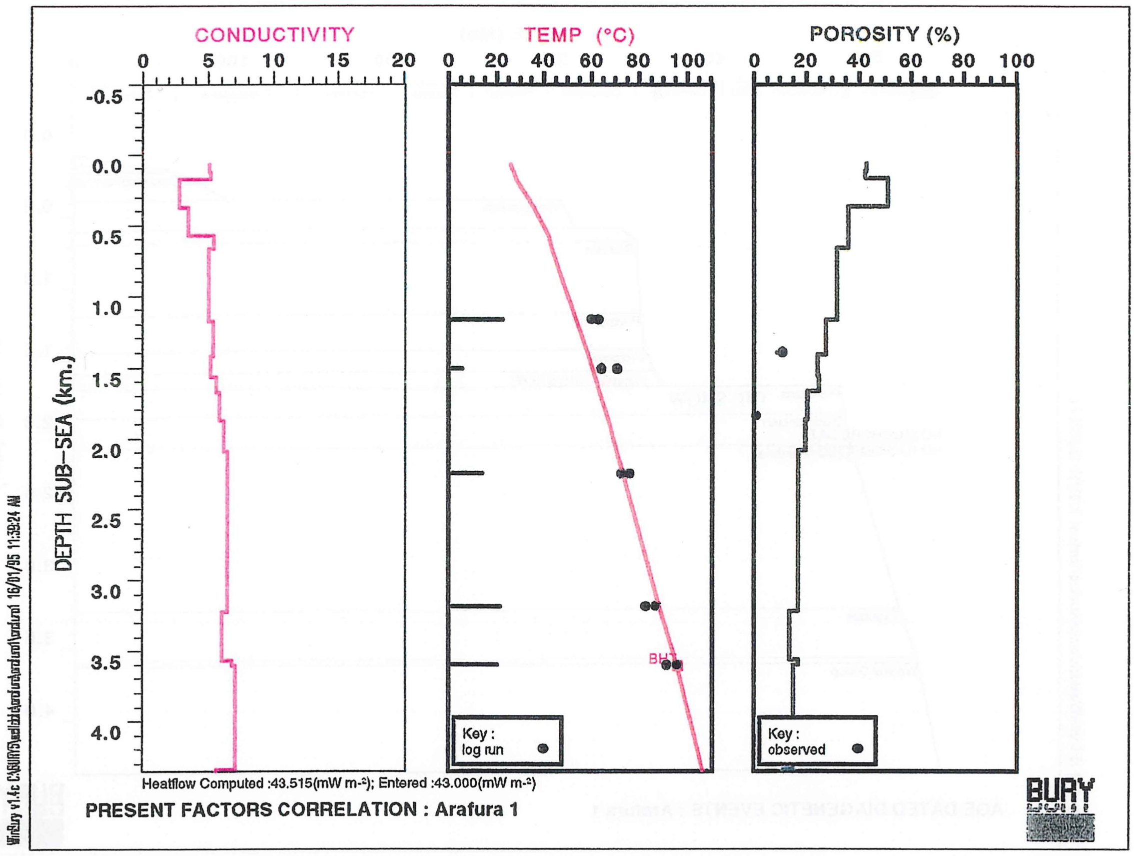
Longitude: 134º 03' 27.22" E (WGS 84)
TD: 3635mKB
Water Depth: 64m
BHT Depth: 3635m



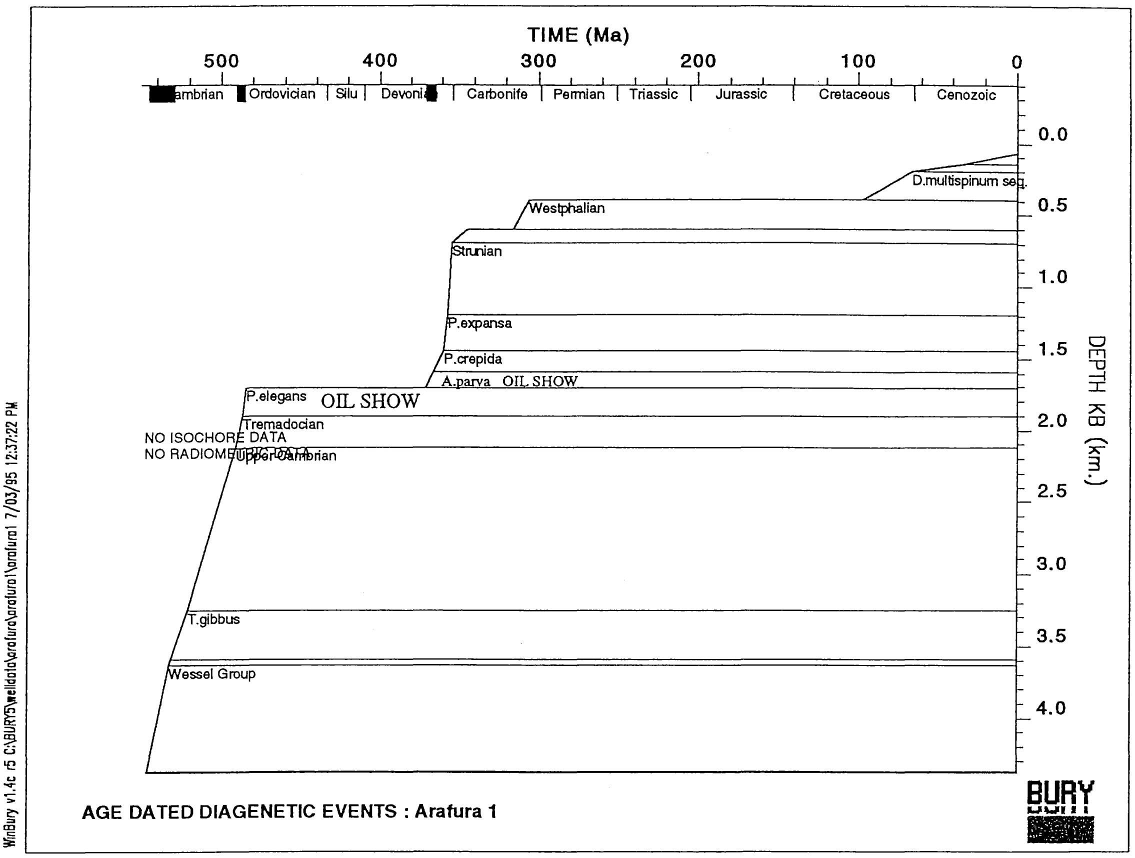
Palynological zones are used where possible in this picture of the stratigraphy of Arafura 1. The uppermost layers were sampled sparsely or not at all, so the Cretaceous is represented by a well stratigraphic sequence (*D. multispinum* sequence) named after the palynological zone found at its base (Labutis et al, 1992).

The well terminated near the top of the Wessel Group. The base of the group, some 1500m below TD, was picked on the seismic at a time compatible with the thickness of the Group estimated from outcrop on the Wessel Islands.

The darkest lithology symbol is carbonate. The next darkest is claystone. The lightest is sandstone.



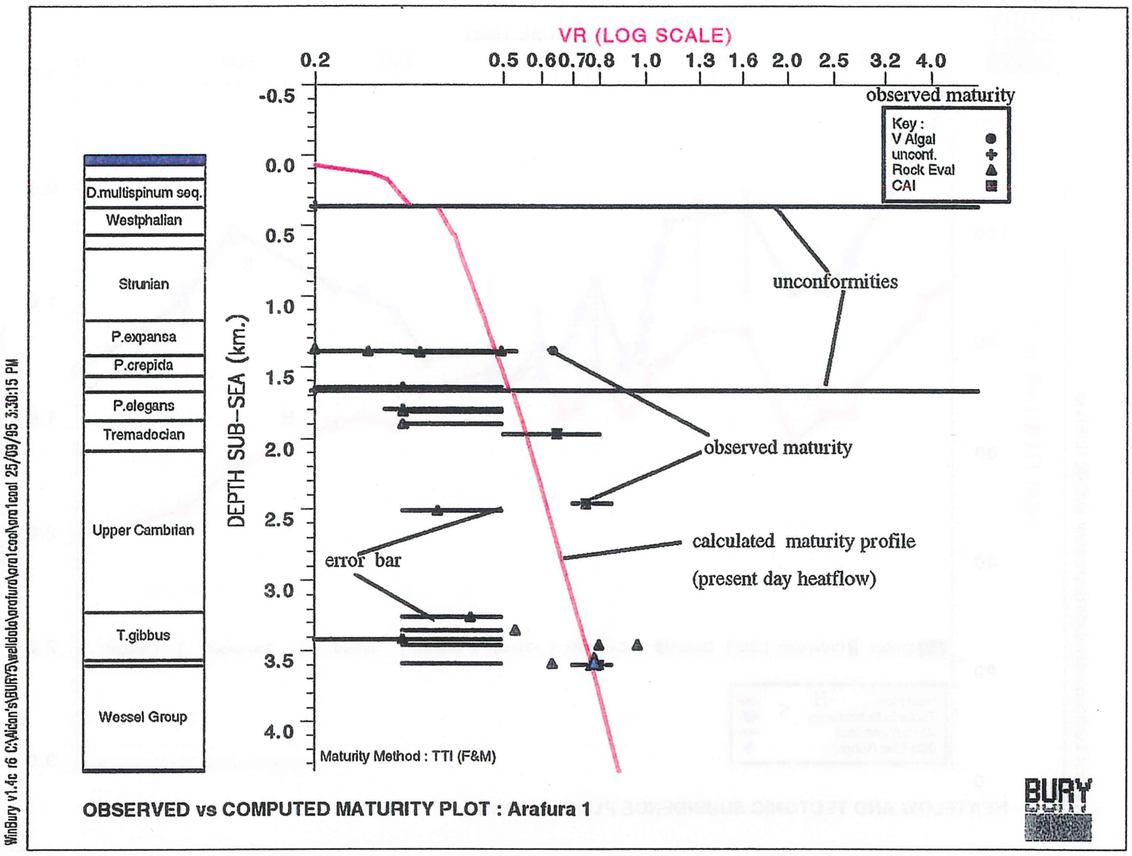
The central panel shows temperatures observed in Arafura-1 well during five log runs at different depths, before and after the application of the Horner correction. The plotted line is the expected temperature for a heatflow of 43 mW/m^2. It agrees with the observed Bottom-hole Temperature (BHT) of 96°C at 3635m KB. This, together with the low BHTs observed in other wells, confirms the low heatflow in the eastern Arafura Basin. The plots are projected below the TD of the well, to include the whole of the Wessel Group down to the base of the Cambrian.



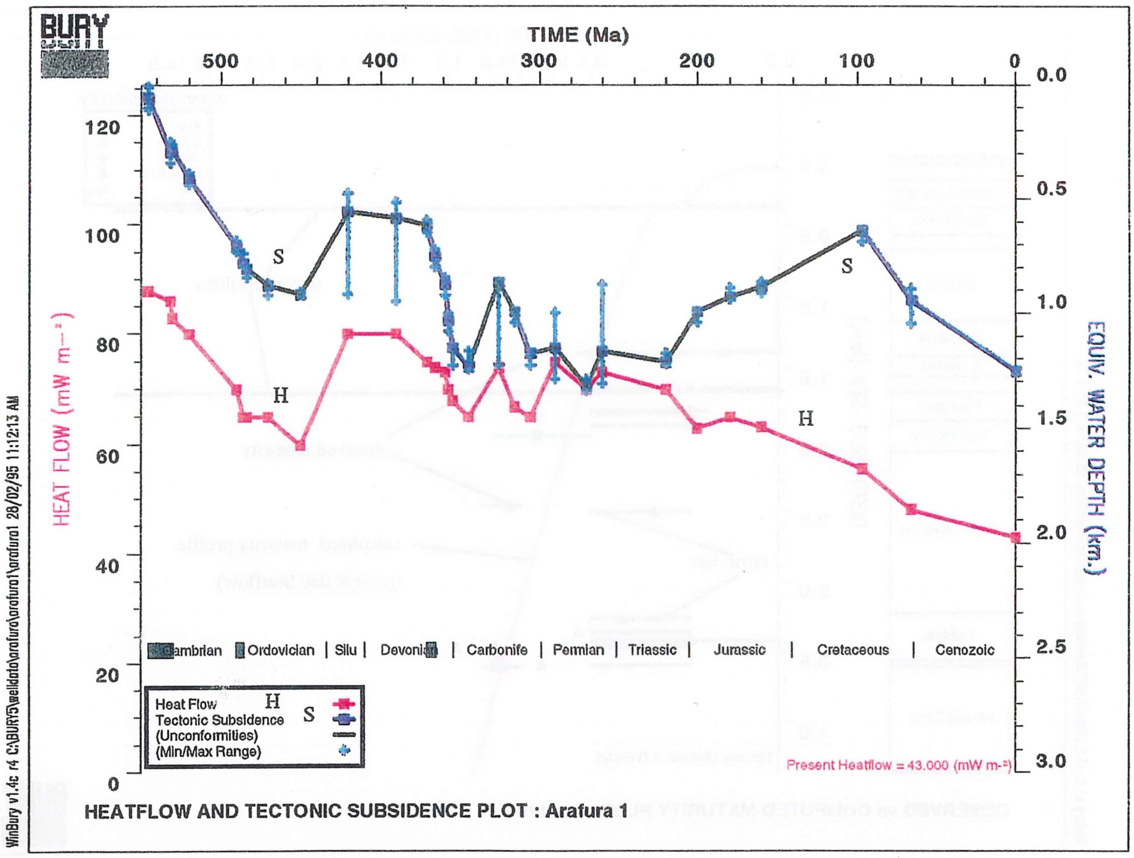
On this time-depth plot of Arafura 1 well stratigraphy, the near-vertical -'quarry-faces' represent depositional sequences, and the horizontal 'benches' represent the unconformities, as determined from palynology. The more nearly vertical the faces, the more rapid the deposition, and the more inclined, the slower. The main periods of deposition are mid Cambrian to early Ordovician, and late Devonian to earliest Carboniferous. Deposition in the late Carboniferous and in the late Cretaceous-Cenozoic was much slower.

The principal unconformities are

- Ordovician-Devonian (485 Ma - 370 Ma)
- Carboniferous (344 Ma - 315 Ma)
- Base of Money Shoal Basin (303 Ma - 98 Ma) This unconformity represents a long time period, which embraces the formation of the Goulburn Graben (late Triassic) and associated events. The unconformities and the tectonic events that gave rise to them are discussed more fully in the section dealing with the Tasman 1 well.

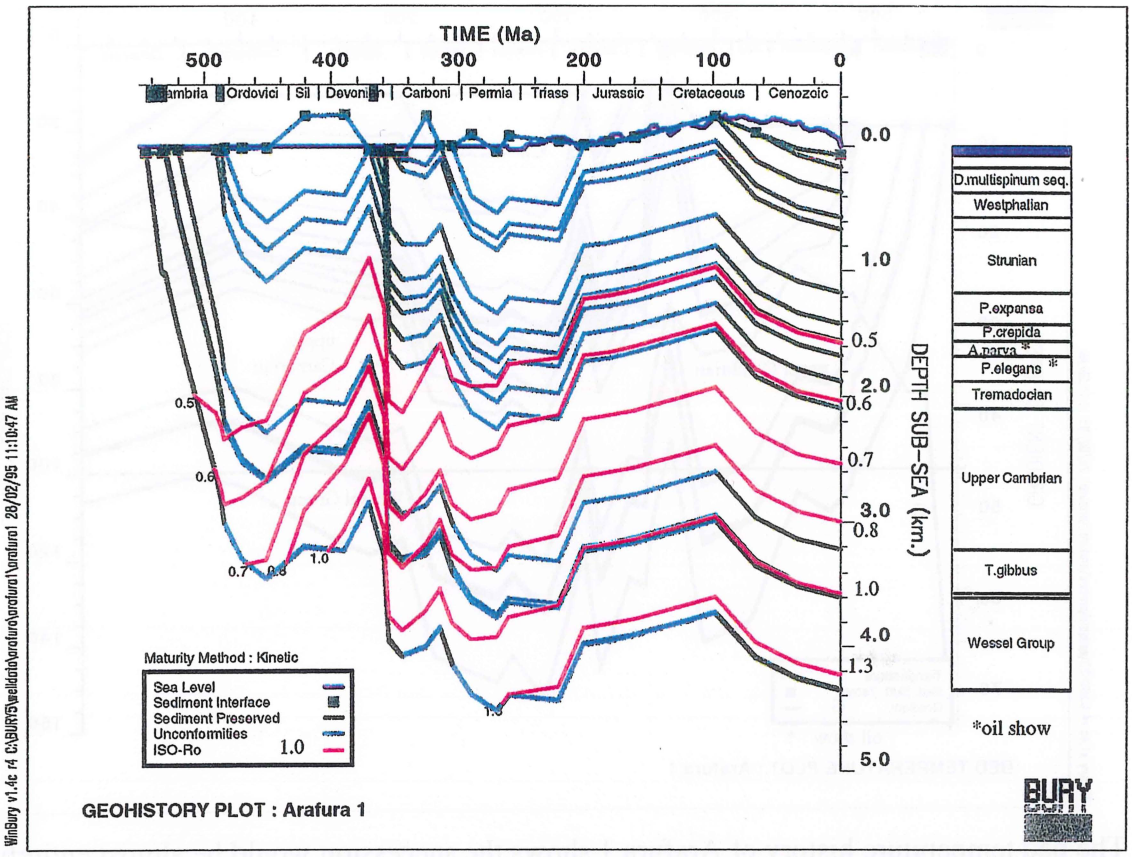


Various methods were used to measure the maturity of the Lower Palaeozoic sediments in Arafura 1, including Rock-Eval and Conodont Alteration Index. There are no measurements of maturity above the base Mesozoic unconformity. The observed maximum maturity in the Palaeozoic succession (triangles, squares, with lines representing error bars) is higher than that calculated from present-day temperature (continuous sloping line). The effect is much greater in wells to the west (see e.g. Chameleon 1, Torres 1). This indicates that the succession was either buried more deeply during the Palaeozoic, or had a higher temperature gradient. The model used below supposes both deeper burial and higher heatflow, with episodes of uplift caused by thermal expansion of the crust.



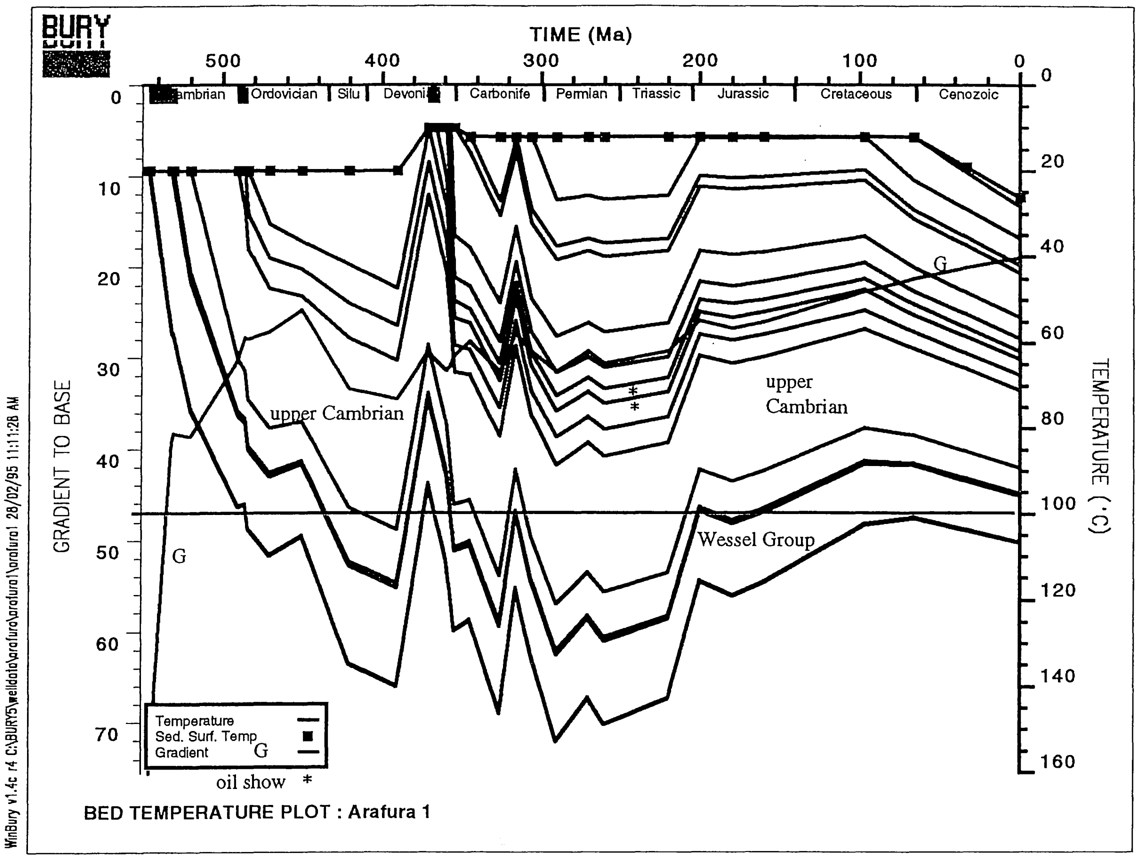
HEATFLOW AND TECTONIC SUBSIDENCE PLOT : Arafura 1

The observed history of subsidence and the model of uplift and of paleo-heatflow at Arafura-1 supposes that the main Palaeozoic episodes of uplift and erosion were caused by crustal response to distant heating\rifting events on the McKenzie (1978) model, followed by subsidence due to contraction of the crust caused by cooling. The thermal anomalies have been kept to a minimum in this model, because the Arafura 1 well was the farthest from the principal sites of the thermal events on the Gondwana margin far to the west. These Palaeozoic events are followed by a long period (Late Carboniferous to Late Cretaceous) of which no record survives at the wellsite, but about which there is evidence elsewhere. The Cretaceous-to-Recent subsidence is attributed to prolonged cooling, resulting in the observed present low heatflow of 43 mW/m^2.



This geohistory plot of Arafura 1 is the result of the heatflow and subsidence history shown in the previous figure. In the right hand panel, the intervals with oil shows are marked with *.

The TD of the well is at the top of the Wessel Group. The succession is very near its maximum depth of burial. It is not, however, anywhere near its maximum temperature.



BED TEMPERATURE PLOT : Arafura 1

The bed temperature history of Arafura 1 shows the succession would be almost entirely immature for hydrocarbons if it were now at maximum temperature. (96°C at TD, 3635m). The Devonian succession is, and always has been, immature for hydrocarbons.
The Ordovician succession, which contains the prolific kerogen *G.prisca,* in northern Australian basins is, and always has been, immature for oil at the Arafura 1 site. It is (barely) mature for oil downdip in the deepest parts of the Graben, adjacent to the northern bounding fault [see geohistory diagrams of synthetic location Arafura 1North (site ar1north on Figure 1)].
The Upper Cambrian is too cool to be generating oil at present, but did so during the interval from Carboniferous to Triassic.

Of the two oil shows in the well (marked with *)

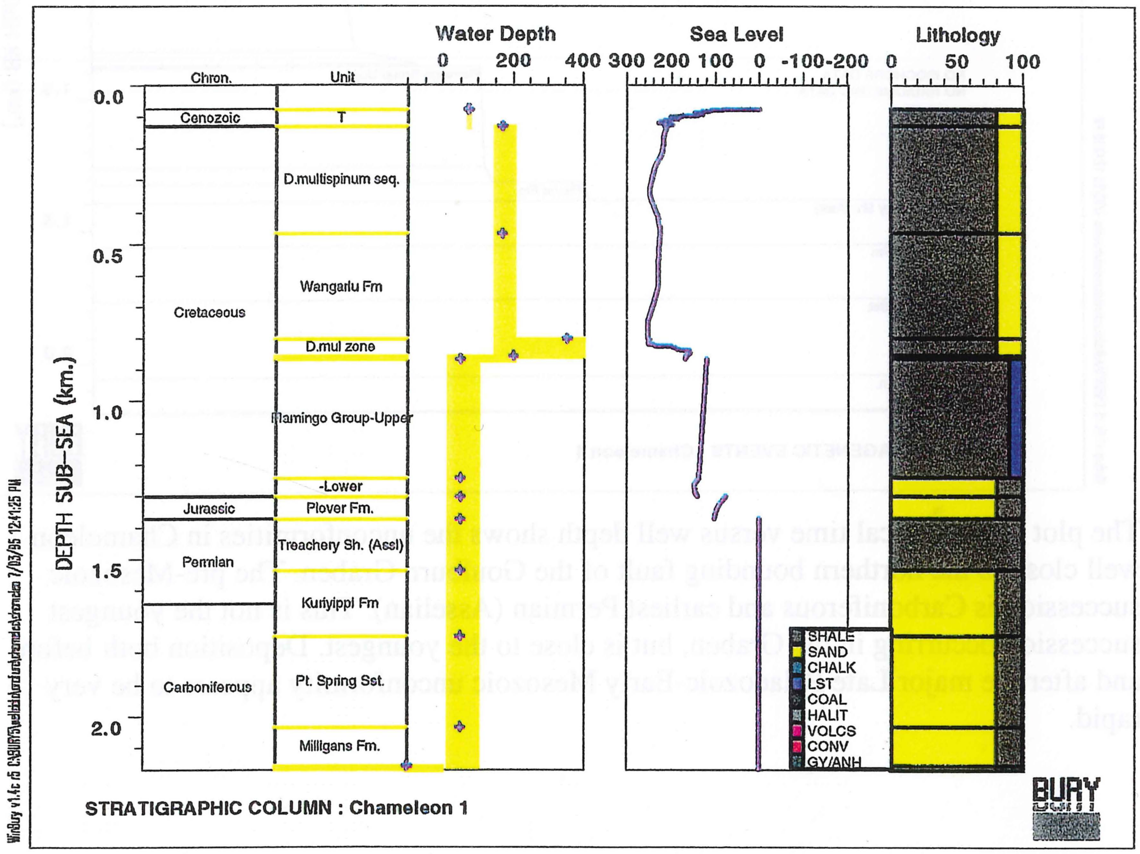
- the upper one in Devonian dolomitic sandstone (A. parva zone), is degraded, and its origin is not clear. It may have re-migrated from the underlying Ordovician or Cambrian carbonates in a downdip location.
- the lower one is in its original reservoir of Ordovician dolomite (*P. elegans* zone), and is of Palaeozoic origin (R. Summons, pers. comm., see Appendix 1)
- the oil was generated during an earlier period of higher heatflow, e.g. the Carboniferous
- possibly it has migrated from below TD, e.g. from the lowermost Cambrian (Wessel Group).

CHAMELEON 1

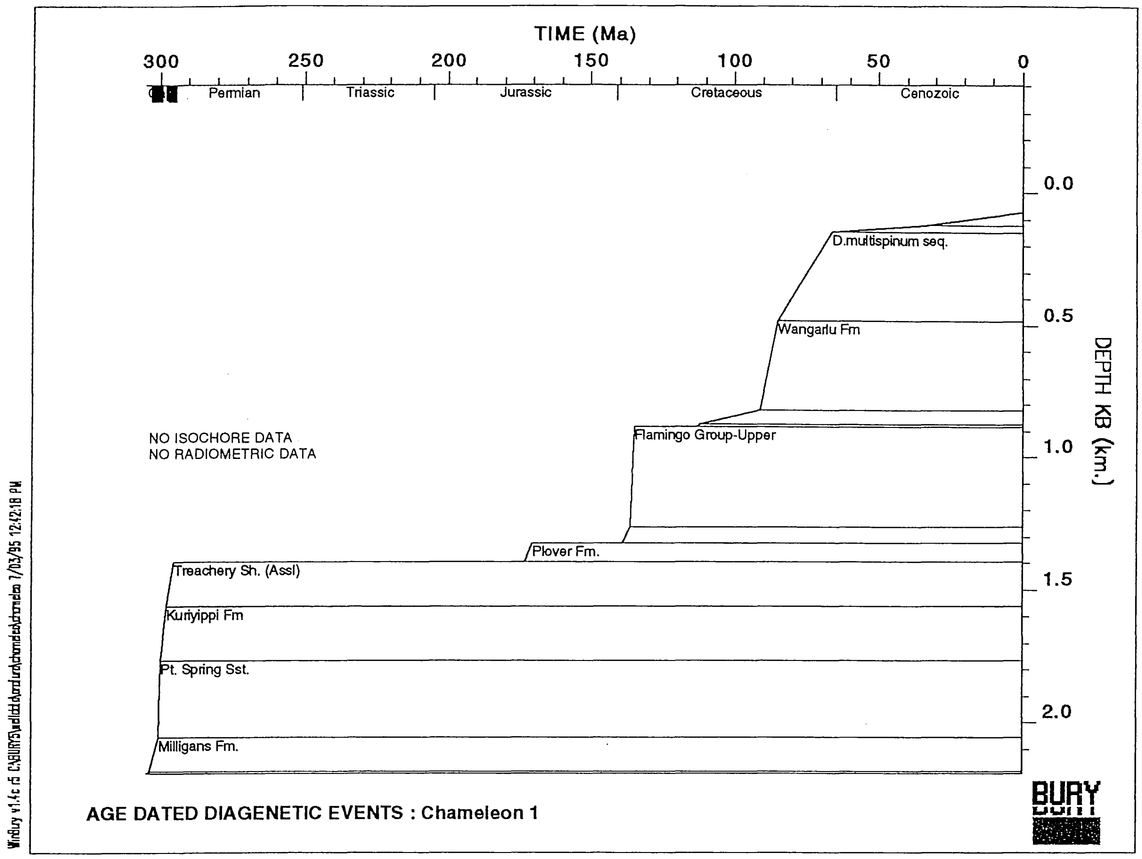
BHP PETROLEUM 1991

Latitude: 10° 18' 21.22" S (WGS 84)
KB: 22m asl
Sea Bottom Temperature: 25°C
BHT: 72°C (Horner plot)

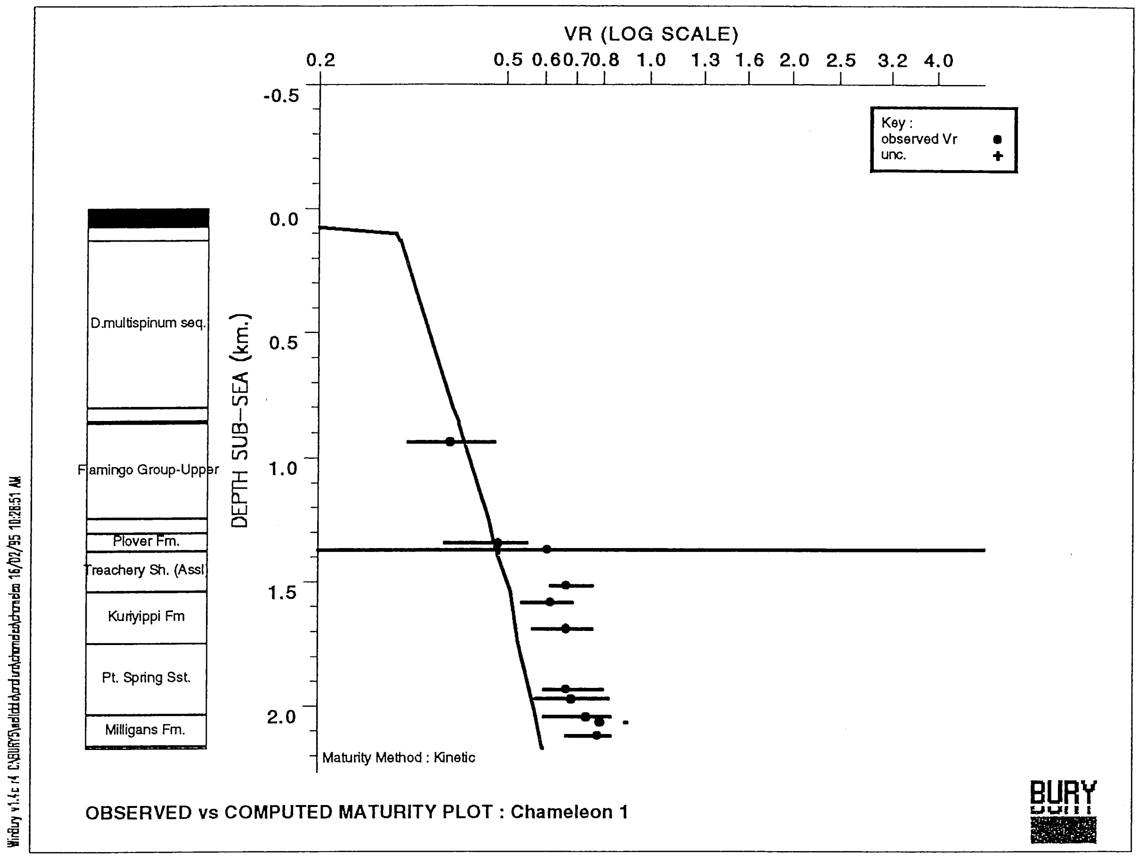
Longitude: 133° 09' 51.22" E (WGS 84)
TD: 2179mKB
Water Depth: 70m
BHT Depth: 2179m



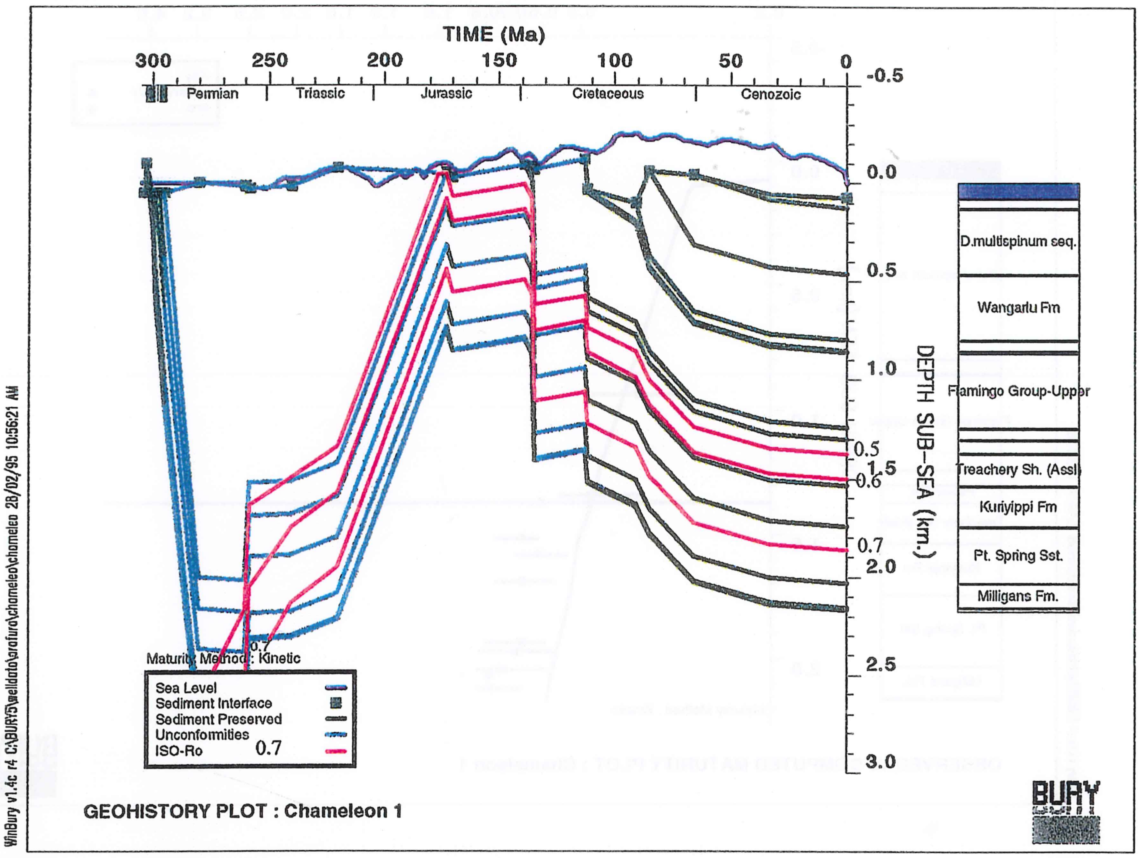
Bonaparte Basin formation names, e.g. Wangarlu Formation, were used in the WCR of Chameleon 1. The *D. multispinum* palynological **zone** is documented here at the base of the Wangarlu Formation. The D. multispinum seismic **sequence** (Labutis et al, 1992) includes all of the succession from the top of the Albian to the base of the Tertiary.
The AGSO sea level curve, which helps to define the basin subsidence, is interrupted at unconformities. It is linear, and set at zero metres, below the Triassic, because it has not been adequately defined there.
The darkest lithology symbol is carbonate. The intermediate shade is claystone. The lightest shade is sandstone.



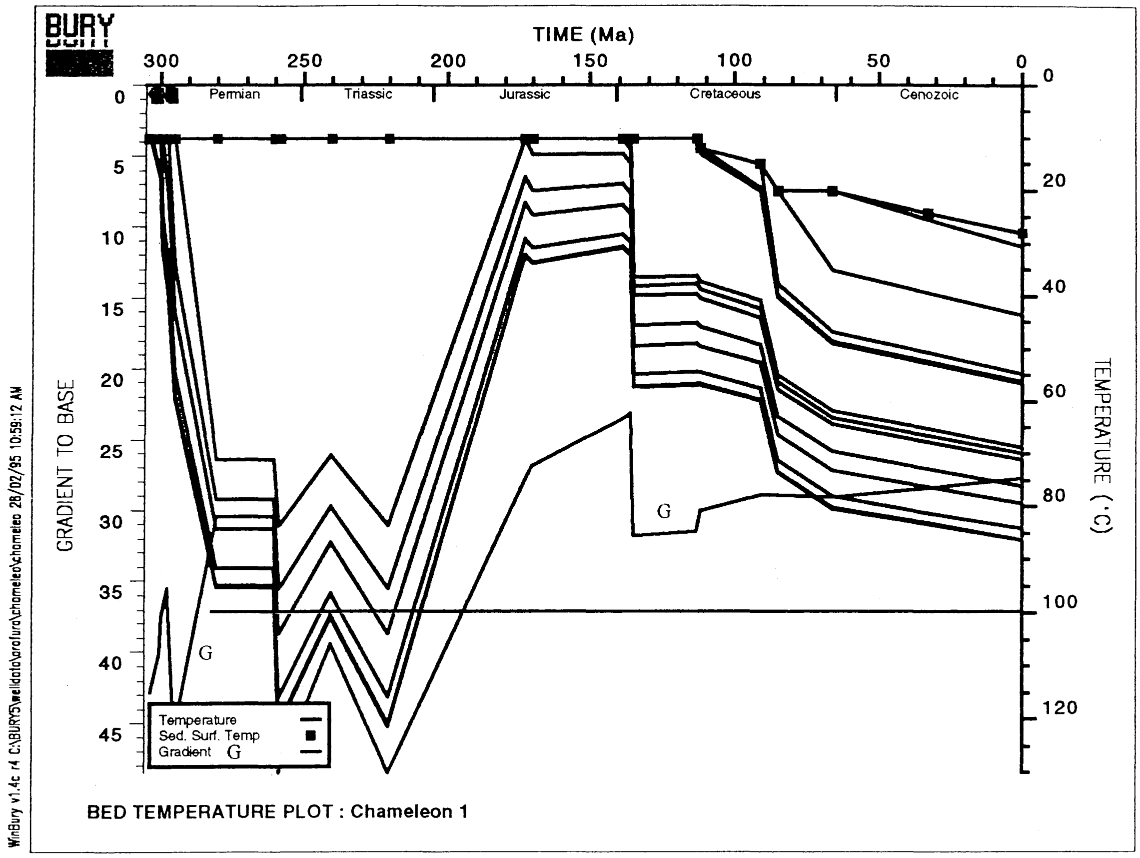
The plot of geological time versus well depth shows the unconformities in Chameleon 1 well close to the northern bounding fault of the Goulburn Graben. The pre-Mesozoic succession is Carboniferous and earliest Permian (Asselian). This is not the youngest succession occurring in the Graben, but is close to the youngest. Deposition both before and after the major Late Palaeozoic-Early Mesozoic unconformity appears to be very rapid.



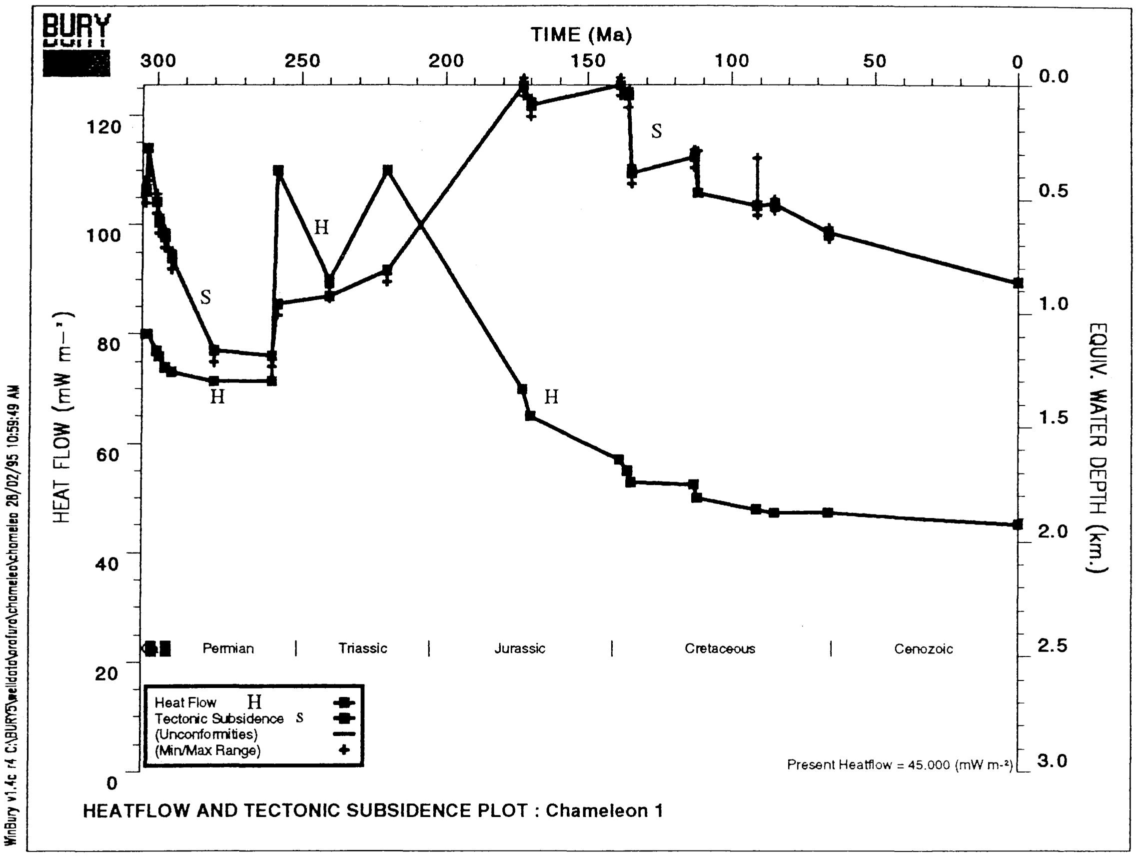
The calculated maturity (curved line) of the well succession based on observed present-day temperatures is in agreement with observed maturity from the surface down to the unconformity (horizontal line) at the base of the Mesozoic succession. However, it shows marked departure from observed maturity below the unconformity. This indicates that the temperature profile in pre-Mesozoic time was quite different from the present day, and a good deal higher. In addition, there has been significant erosion at the unconformity.



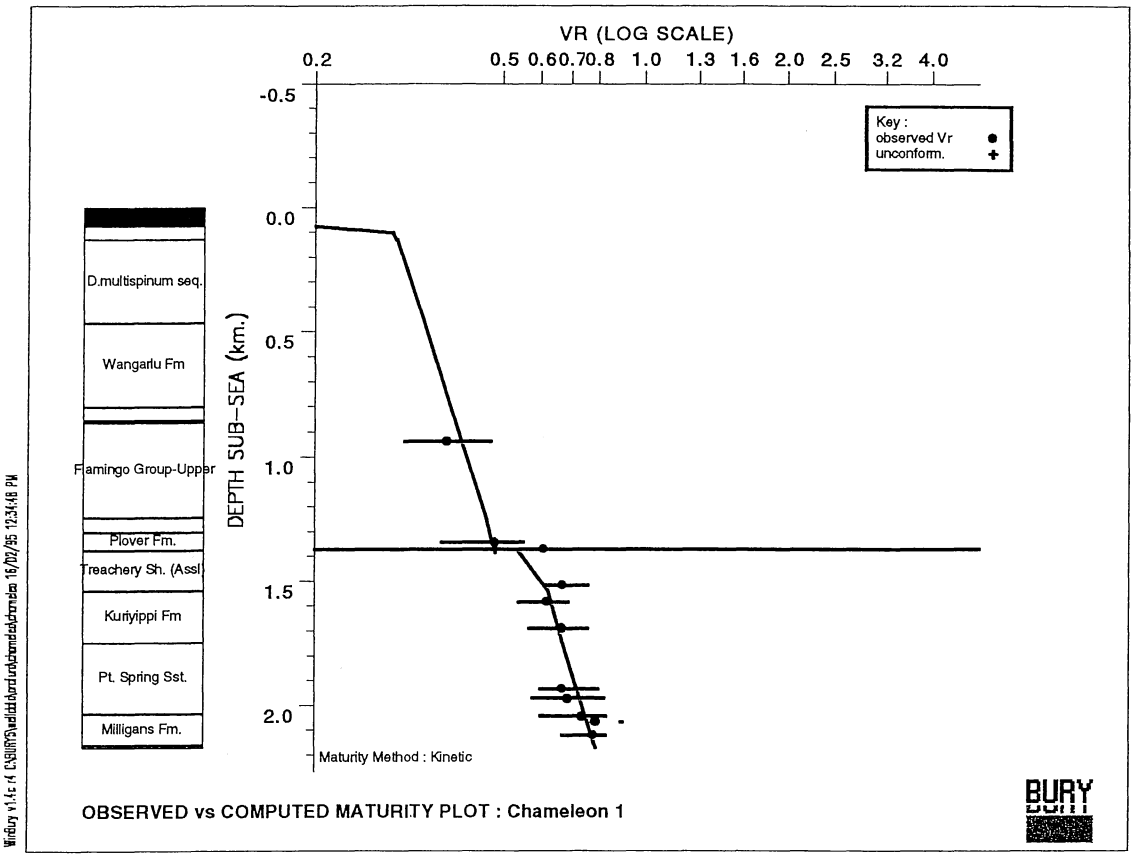
Geohistory plot for Chameleon 1. The Permian and Carboniferous successions are early-mature for hydrocarbons.



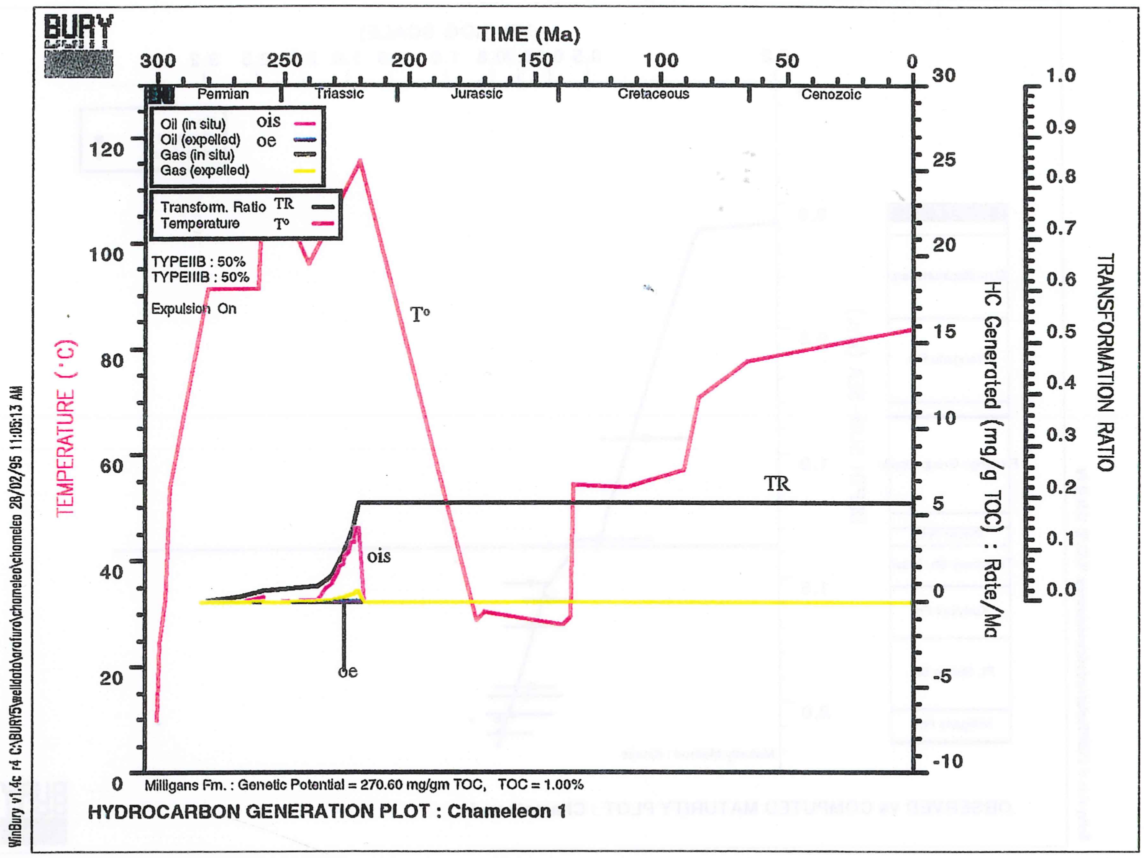
The plot of the thermal history of Chameleon 1 shows that the pre-Mesozoic succession became mature for hydrocarbons during the period of subsidence that began the formation of the Goulburn Graben. The wrenching, uplift and faulting that followed, and that produced the final form of the Graben, terminated the generation of hydrocarbons, and none has been generated in this area since. This would partially account for the lack of success of this well, and others associated with Goulburn Graben structures.



The heatflow and tectonic subsidence plot of Chameleon 1 shows modelled heatflow anomalies in the Late Permian (258 Ma) and Late Triassic (220 Ma) associated with the formation of the Goulburn Graben. They equate with episodes of vulcanism in the offshore Canning Basin. The rapid subsidence that caused the pre-Mesozoic succession to become mature for hydrocarbons before formation of the Graben, may be a remote echo of the continental rifting that accompanied the breakaway of the 'SIBUMASU' blocks from the northeastern Gondwana continent in Permo-Carboniferous time (Metcalfe, 1994).
Note the low present-day heatflow, HF=45mW/m^2.



This plot of observed maturity (symbols and error-bars) versus that calculated from the heatflow-subsidence model (curved line) shows rough agreement. This lends some confidence to the model.



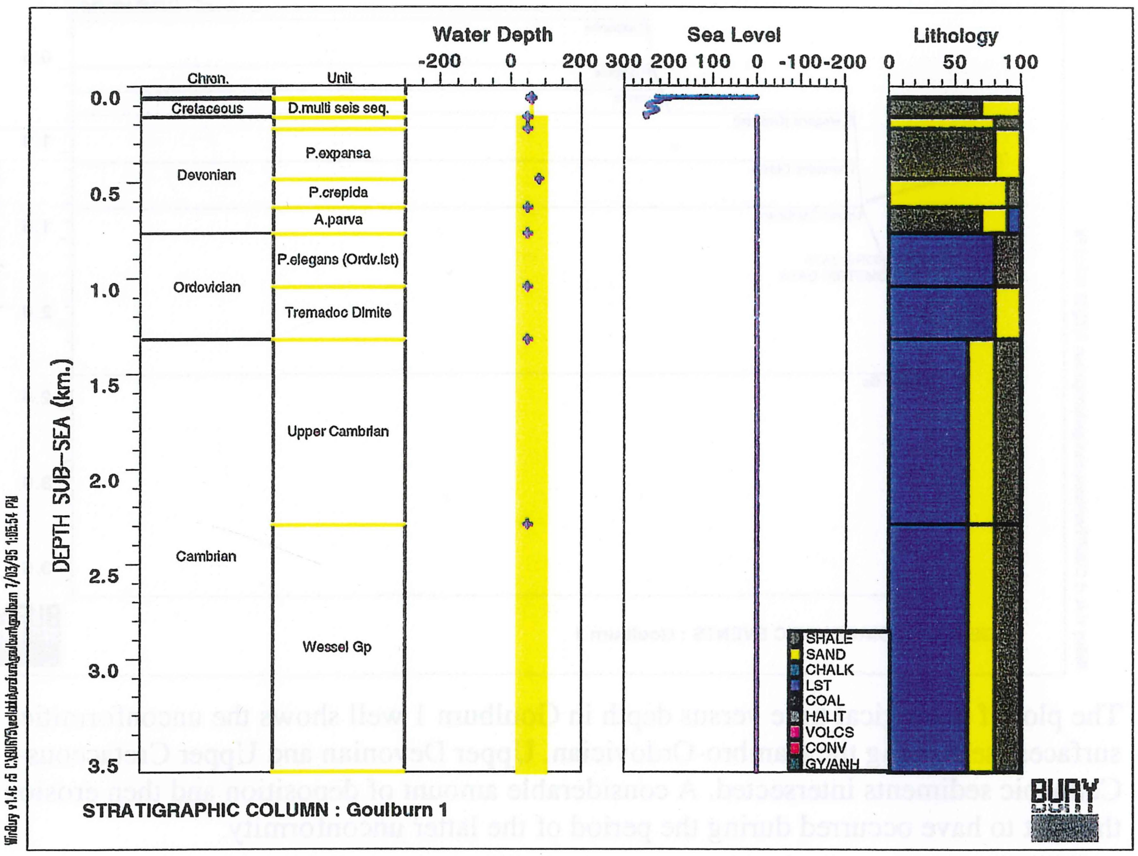
The plot of oil generation from the deepest formation in the well shows the peak of temperature in the Permo Triassic. Some oil is generated, but very little is expelled. The sharp drop in temperature that accompanied the uplift and erosion associated with graben formation, ended generation. Today the low geothermal gradient precludes oil generation from the Carboniferous or the Permian.

GOULBURN 1

PETROFINA EXPLORATION 1986

Latitude: 10° 44' 47.37" S (WGS 84)
KB: 11m asl
Sea Bottom Temperature: 26°C
BHT: 53°C (calculated)

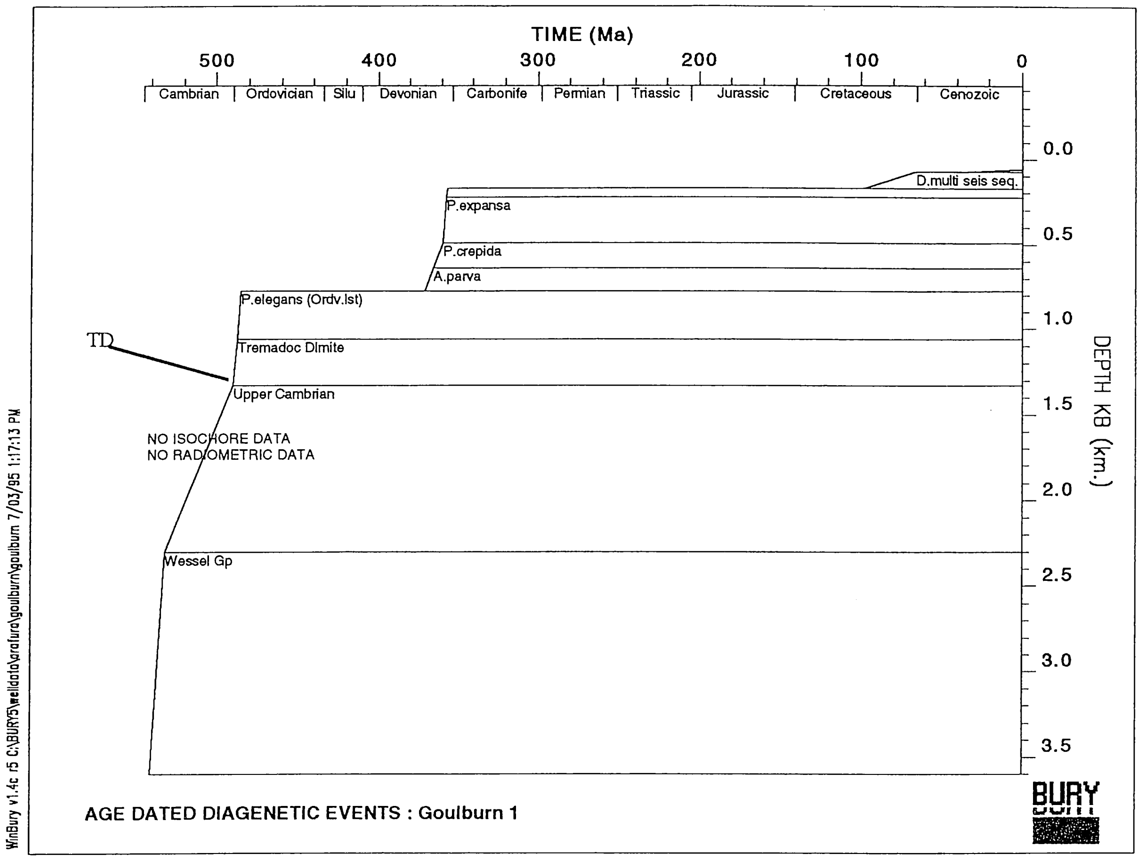
Longitude: 134° 17' 48.71"E (WGS 84)
TD: 1304mKB (logger)
Water Depth: 65m
BHT Depth: 1304m



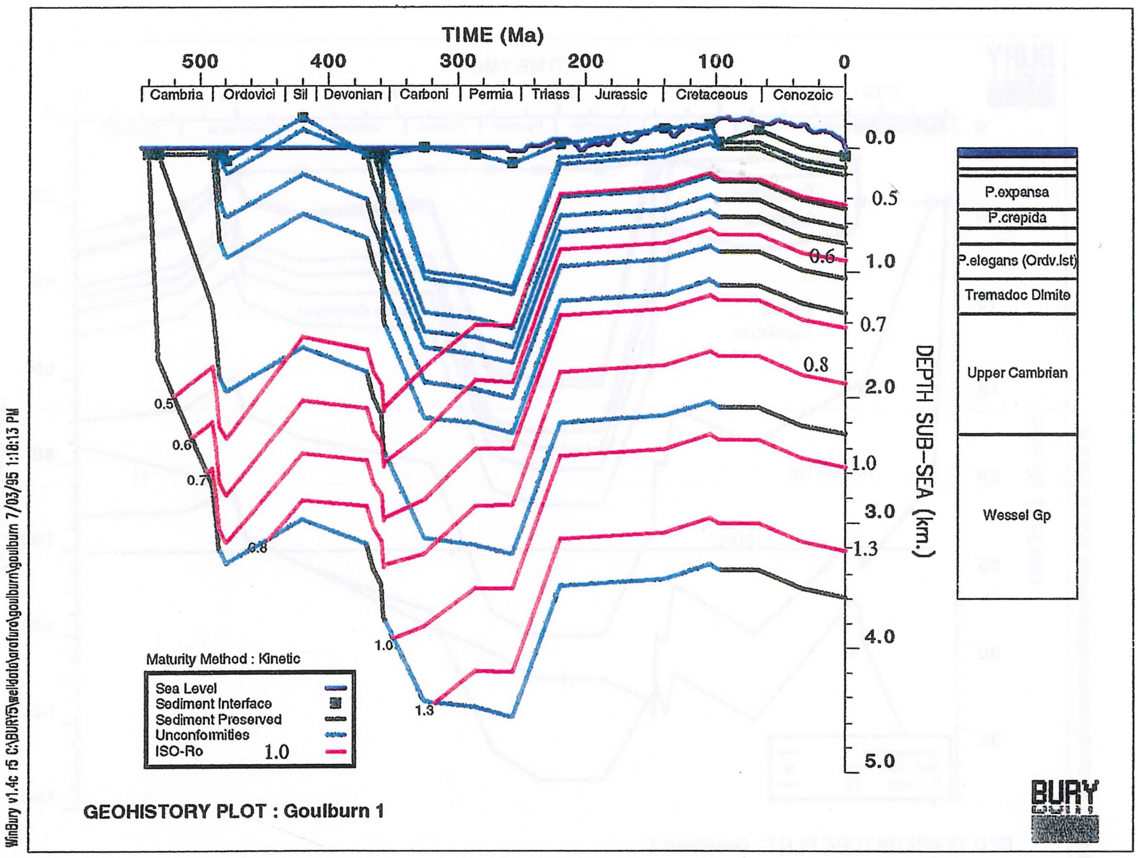
The succession in Goulburn 1 well is mainly Lower Palaeozoic, with some undifferentiated Mesozoic (D. multispinum seismic stratigraphic sequence) claystones above 183 m KB.

The well bottomed in Ordovician (Tremadocian) dolomite. The succession below TD in this diagram is interpreted from seismic to be Cambrian in age, and is underlain by Neoproterozoic sediments presumed similar to the prospective McArthur Basin sediments onshore.

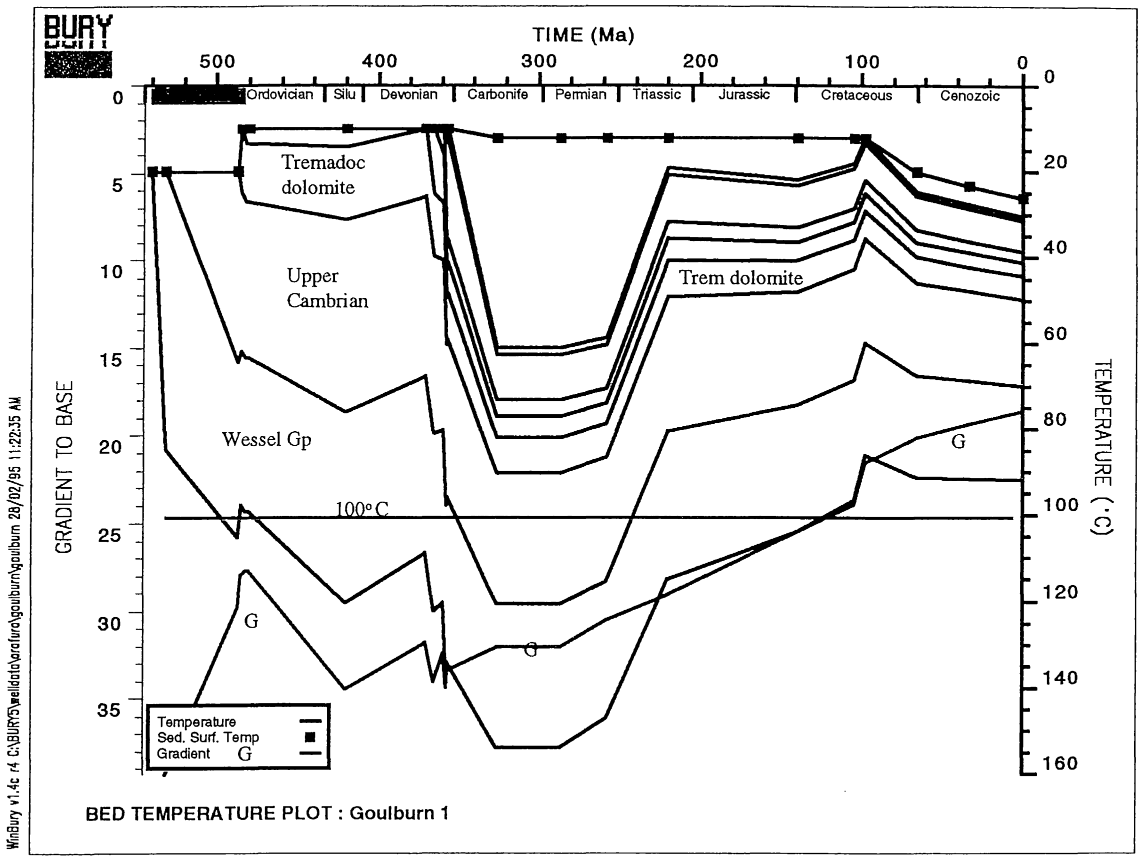
The darkest colour in the lithology column is carbonate. The intermediate shade is claystone. The light shade is sandstone.



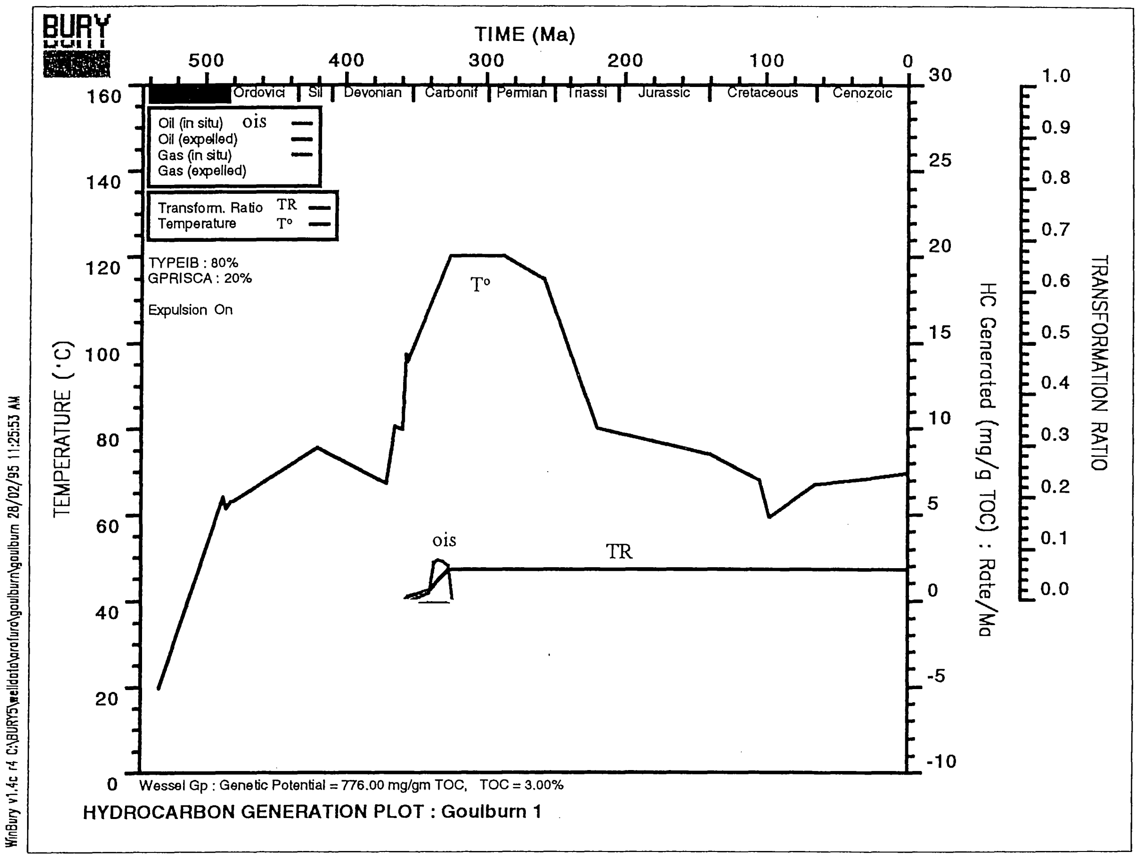
The plot of geological time versus depth in Goulburn 1 well shows the unconformities (flat surfaces) separating the Cambro-Ordovician, Upper Devonian and Upper Cretaceous-Cenozoic sediments intersected. A considerable amount of deposition and then erosion is thought to have occurred during the period of the latter unconformity.



The geohistory plot for Goulburn 1 includes strata below TD at 1304 m. Thicknesses of the Tremadocian dolomitic section and of the Cambrian Wessel Group are estimated from seismic. The Carboniferous and Permian deposits intersected by the Tasman and Chameleon wells on the flanks of the Torres anticline are shown here as having been deposited (although not as thick) and then eroded during the prolonged periods of uplift, and erosion or non-deposition, from early Triassic through Albian.



The bed temperature plot at Goulburn 1 shows that the prospective Neoproterozoic and Cambrian successions, which were buried deeply enough to generate oil in early Carboniferous time, were subjected to uplift, and erosion of the overburden, from the Late Permian to the Late Triassic, though it was not as severe here in the east as it was farther west, e.g. at Torres 1. Deposition was absent through the Jurassic, and Early Cretaceous, and since then it has been insignificant. The Cenozoic warming is almost entirely due to warming of the sea as Australia moves northward. This history of early maturity, followed by tectonism, erosion and prolonged exposure, with only minor late burial, facilitated the re-migration or escape of hydrocarbons from this site.



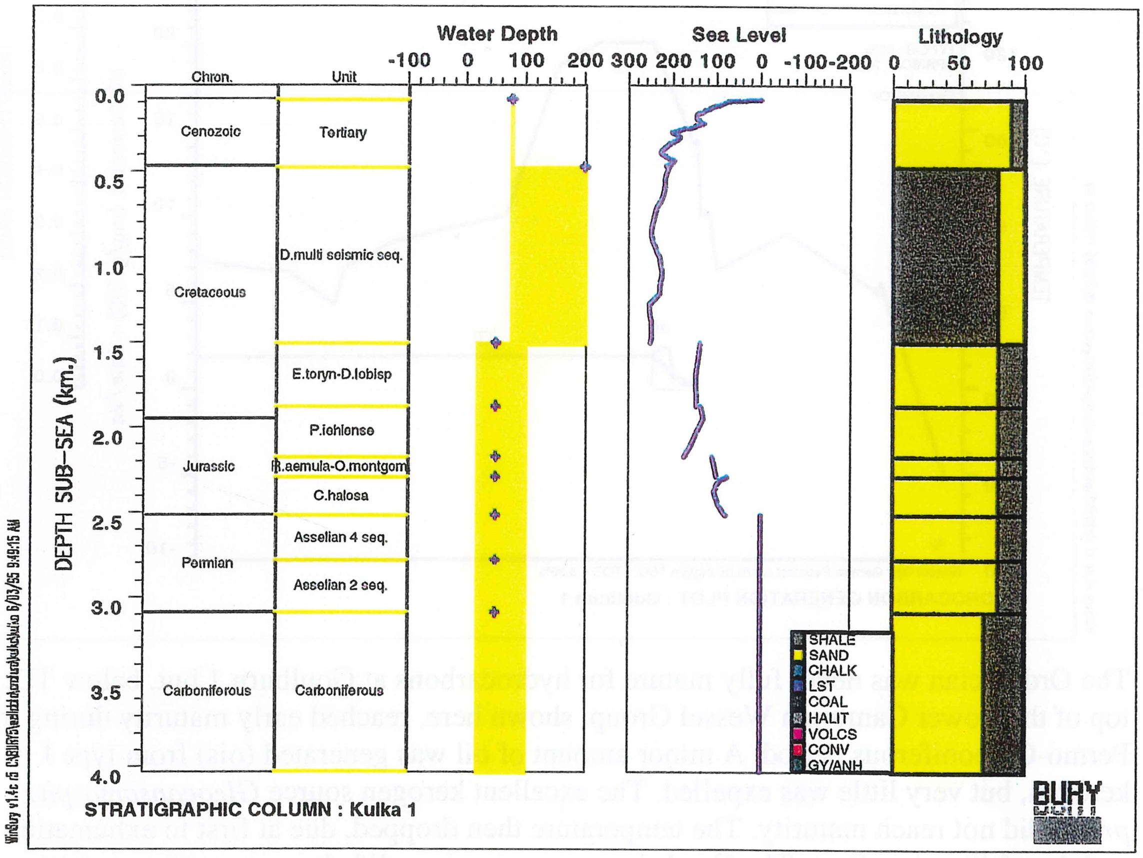
The Ordovician was never fully mature for hydrocarbons at Goulburn 1 but, below TD, the top of the Lower Cambrian Wessel Group, shown here, reached early maturity during the Permo-Carboniferous period. A minor amount of oil was generated (ois) from type I kerogen, but very little was expelled. The excellent kerogen source *Gleocapsomorpha prisca* did not reach maturity. The temperature then dropped, due at first to exhumation and then falling heatflow. The Cambrian succession is well below generation temperatures today, and the underlying Neoproterozoic of the McArthur Basin is within the oil window, though cooler than during the Permo-Carboniferous. Oil should be sought in Palaeozoic-age structures in this area, and to the east and north. The quiet later history of the area favours preservation of early-formed traps. This scenario is compatible with the character of the lower oil show in the nearby Arafura 1 well.

KULKA 1

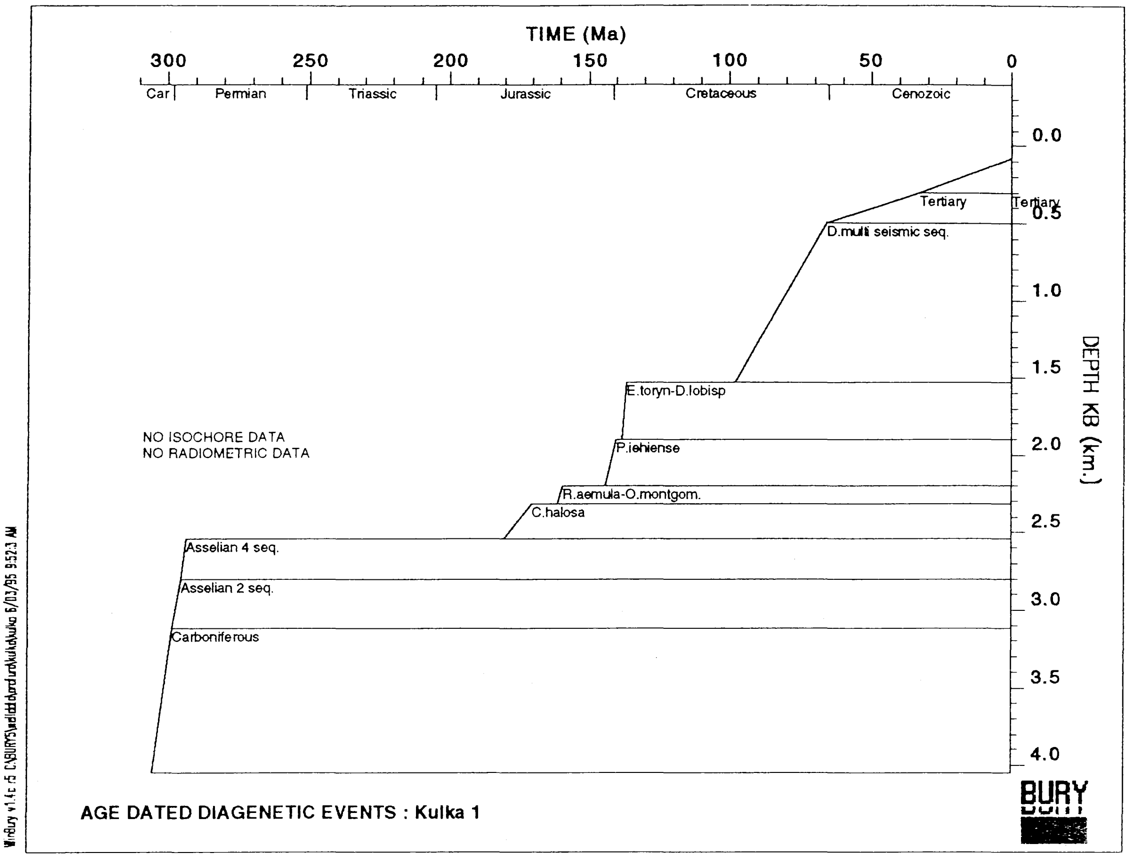
DIAMOND SHAMROCK 1984

Latitude: 10° 03' 41.9" S (WGS 84)
KB: 26m asl
Sea Bottom Temperature: 25°C
BHT: 106°C (estimated)

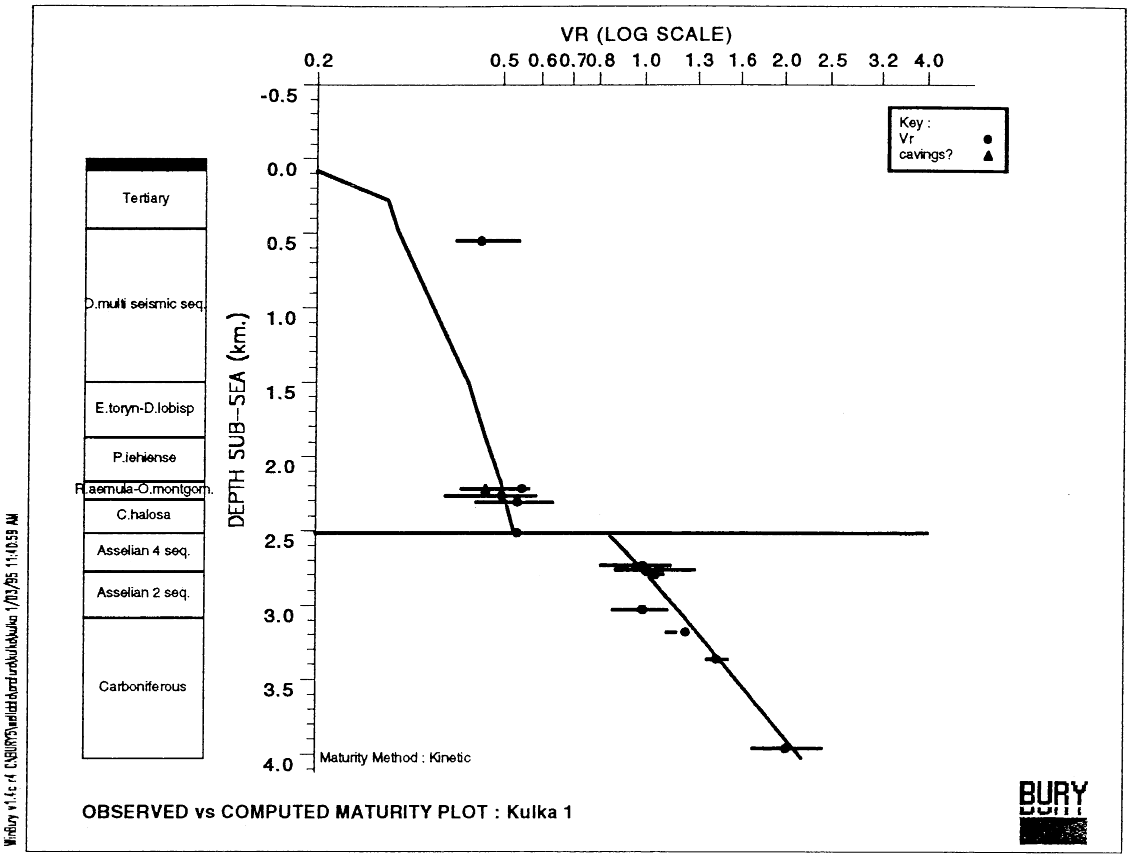
Longitude: 132° 32' 45.30" E (WGS 84)
TD: 3998mKB
Water Depth: 77m
BHT Depth: 3998m



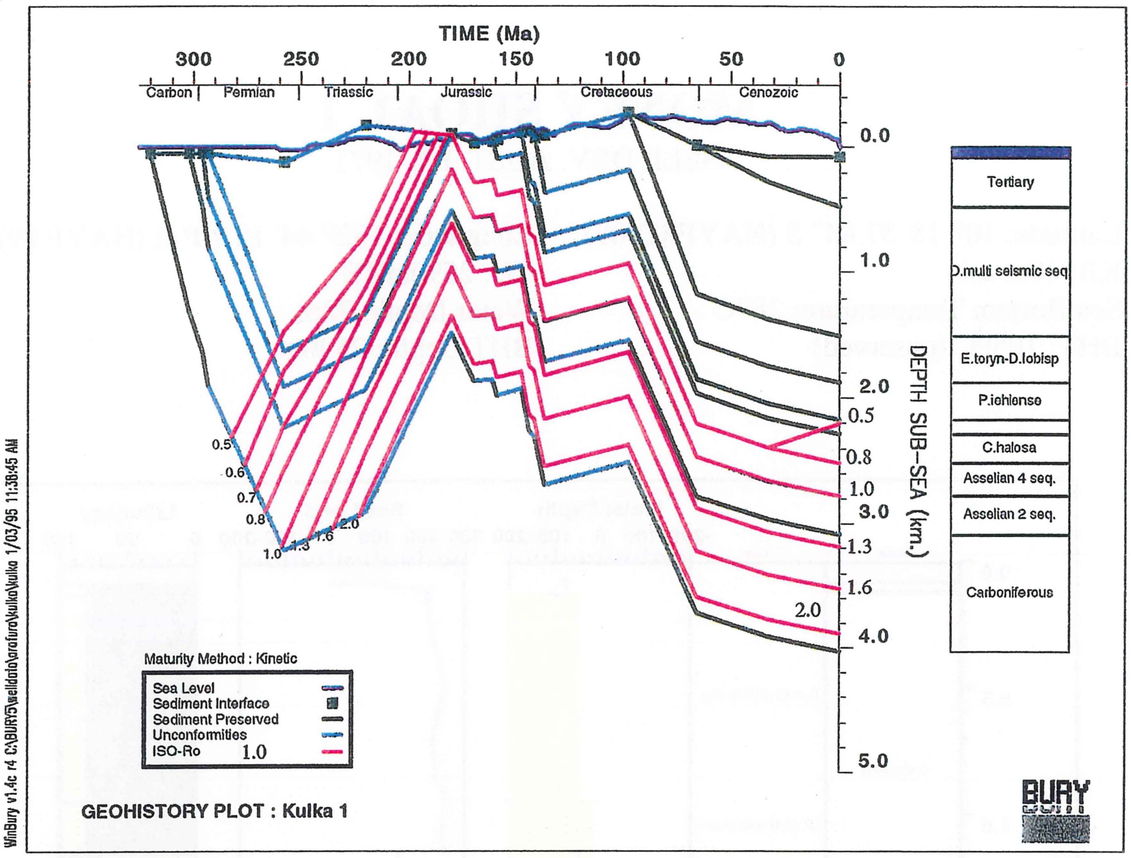
STRATIGRAPHIC COLUMN : Kulka 1



TIME (Ma)
300
250
200
150
100
50
0
Car
Permian
Triassic
Jurassic
Cretaceous
Cenozoic
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
DEPTH KB (km.)
Tertiary
Tertiary
D.multi seismic seq.
E.toryn-D.lobisp
P.iehiense
R.aemula-O.montgom.
C.halosa
Asselian 4 seq.
Asselian 2 seq.
Carboniferous
NO ISOCHORE DATA
NO RADIOMETRIC DATA
AGE DATED DIAGENETIC EVENTS : Kulka 1
BURY



Observed maturity data (vitrinite reflectance) in Kulka 1. Average maturity is represented by dots, minimum and maximum by error bars. Triangles are suspected cavings. The line is the maturity profile predicted by the model. The large stepout on maturity values beneath the base Jurassic unconformity indicates that the different layers of the Permo-Carboniferous succession are not in communication, and that there is little or no vertical convection of formation waters.



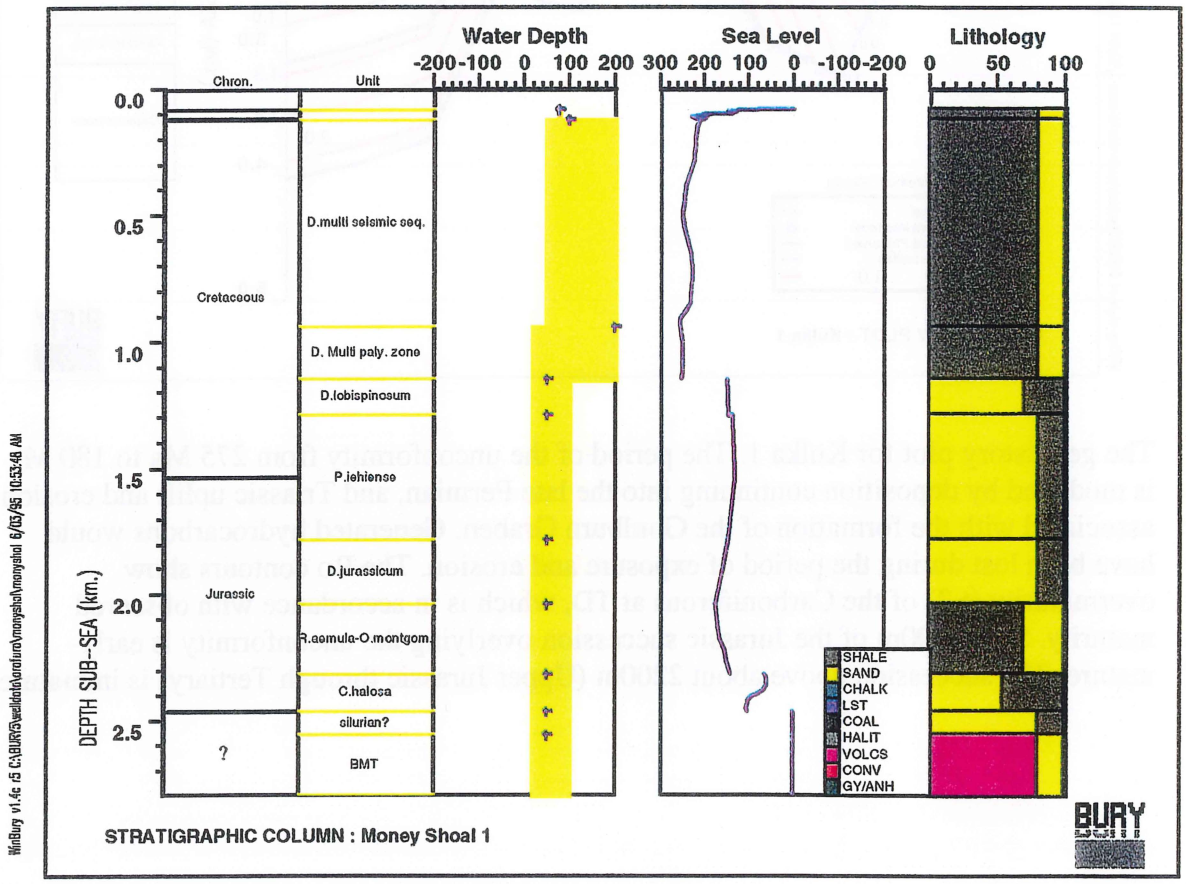
The geohistory plot for Kulka 1. The period of the unconformity from 275 Ma to 180 Ma is modelled by deposition continuing into the late Permian, and Triassic uplift and erosion associated with the formation of the Goulburn Graben. Generated hydrocarbons would have been lost during the period of exposure and erosion. The Ro contours show overmaturity (>2) of the Carboniferous at TD, which is in accordance with observed maturity. Some 300m of the Jurassic succession overlying the unconformity is early-mature. The succession above about 2200m (Upper Jurassic through Tertiary) is immature.

MONEY SHOAL 1

SHELL DEV. AUST. P/L 1971

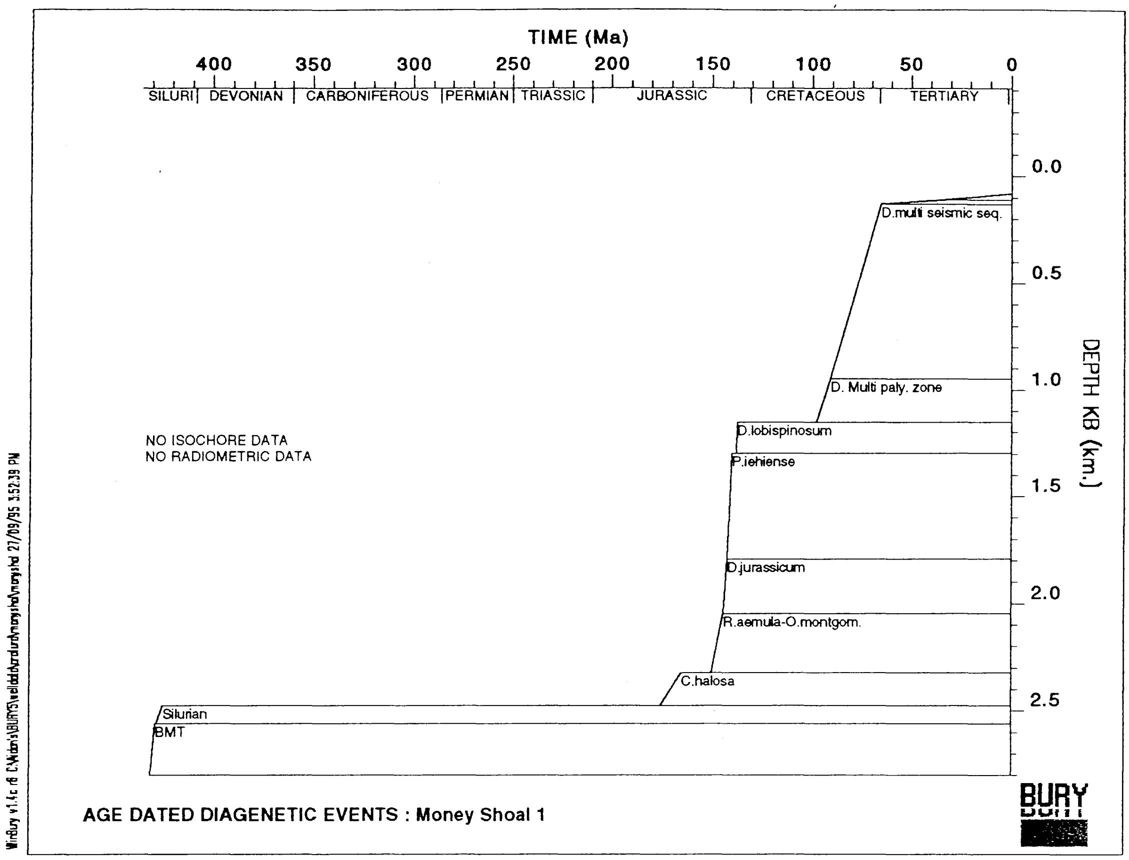
Latitude: 10° 18' 57.84" S (HAYFRD 09)
KB: 10m asl
Sea Bottom Temperature: 28°C
BHT: 105°C (observed)

Longitude: 132° 44' 12.70" E (HAYF 09)
TD: 2590mKB
Water Depth: 78m
BHT Depth: 2590m

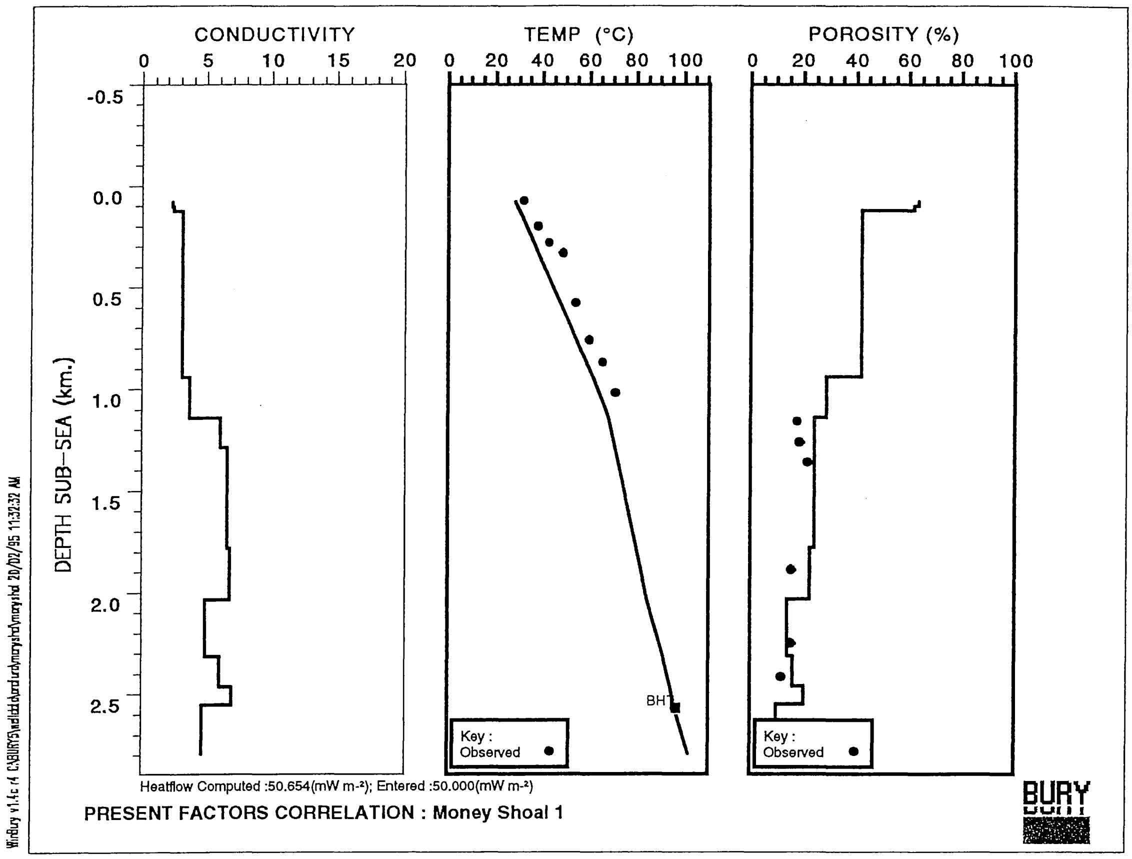


Pre-Cambrian (probably pre-McArthur Basin?) basement clastics (BMT) underly 119 m of poorly dated (?)lower Palaeozoic rocks (labelled Silurian here) in Money Shoal 1.

Follows p. 36

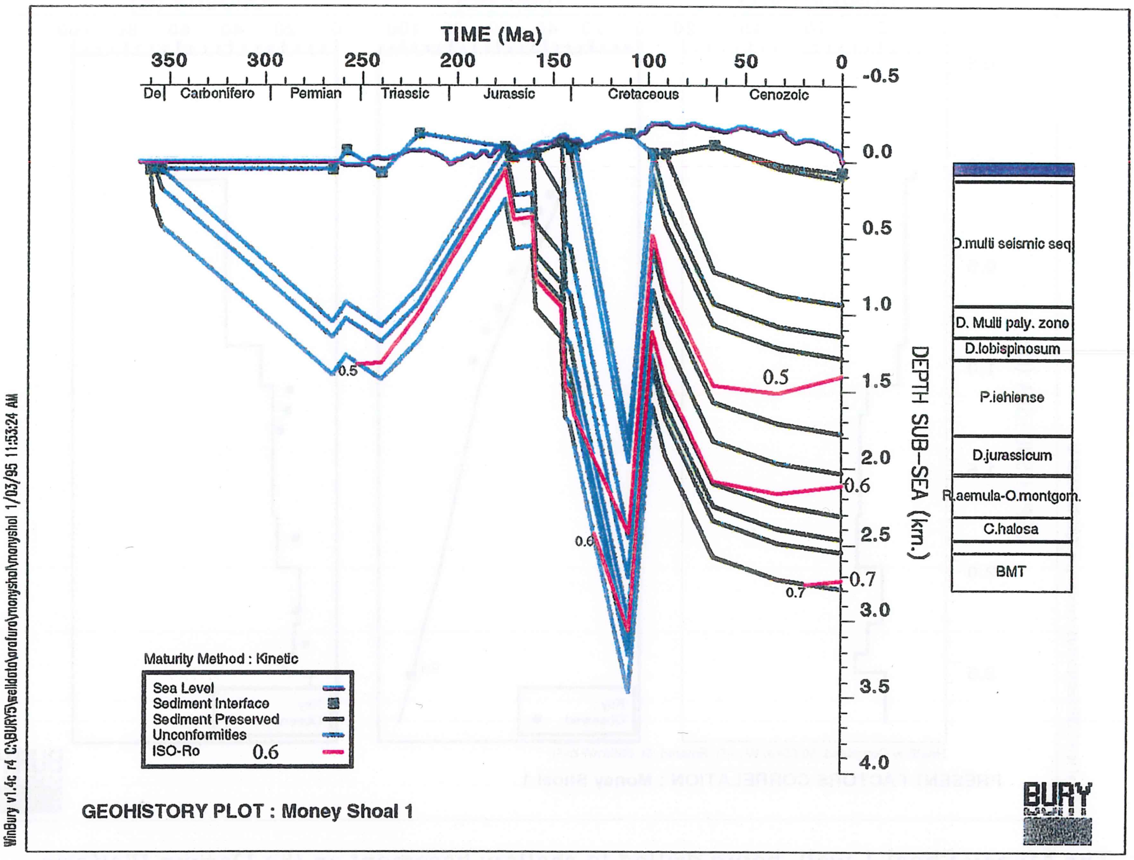


Without the (doubtful) Silurian dating of the succession between Mesozoic and Basement, based on one acritarch, the seismic interpretation alone would suggest that the well is located on a shallow-basement platform outside the Goulburn Graben and the Arafura Basin as well as being outside the McArthur Basin.



The Money Shoal 1 well, being drilled to shallow basement on the Darwin Platform outside the Goulburn Graben and on the very edge of, possibly outside, the Arafura and McArthur basins, has one of the highest heatflows in the Arafura Sea, 50.6 mW/m^2. This was the only well in the area available to Cull and Conley (1983) and led to a perception of higher present-day heatflow that is not applicable to the basins proper.

Temperature measurements in the shallower part of the hole, above 1100 m, lie above the values calculated (the plotted line), from the measured BHT, indicating either that there is vertical fluid circulation (?convection) bringing heat up from the deeper to the shallower levels, or that the measured and corrected BHT is too low.



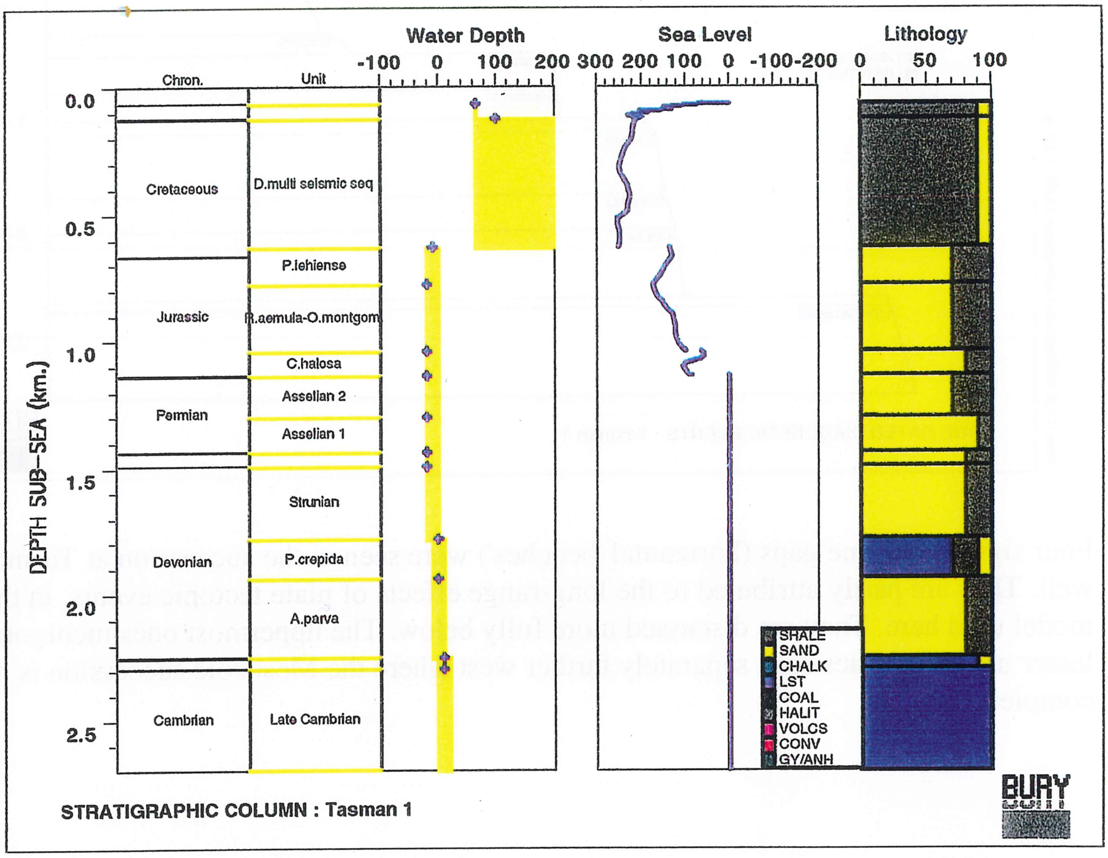
An episode of deposition in the early Cretaceous, followed by pronounced uplift ending at 97 Ma, is incorporated in the geohistory model of Money Shoal 1 well. The seismic interpretation supports this {see Labutis et al, 1992, Enclosure 5, figure (b)} by showing uplift after deposition of the Jurassic and Lower Cretaceous. The model predicts early maturity for the Jurassic in the well, but reservoir quality is degraded by the former deeper burial.

TASMAN 1

ESSO EXPLOR.& PROD. AUST 1983

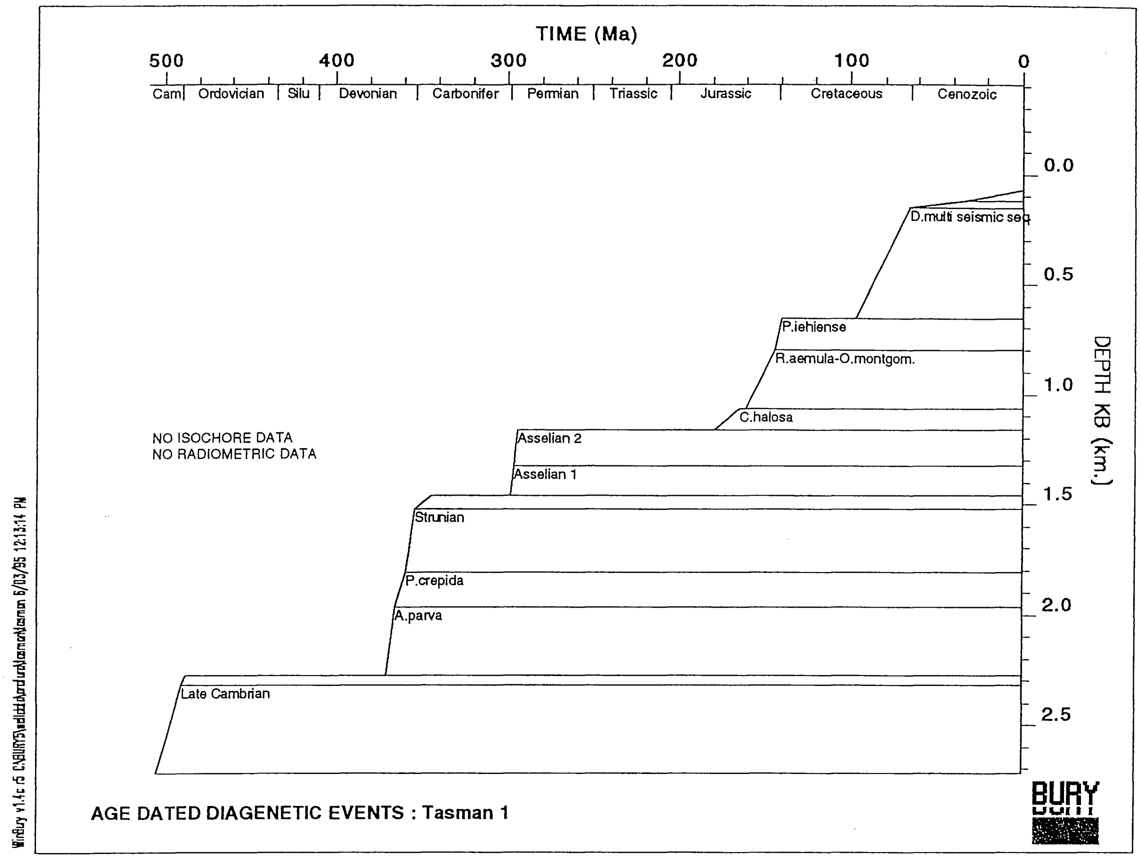
Latitude: 10° 42' 35.22" S (WGS 84)
KB: 25m asl
Sea Bottom Temperature: 26°C
BHT: 89°C (from E-logs)

Longitude: 133° 11' 01.78" E (WGS 84)
TD: 2720mKB
Water Depth: 66m
BHT Depth: 2720m



STRATIGRAPHIC COLUMN : Tasman 1

The Tasman 1 well was drilled with the objective of intersecting the most complete Palaeozoic succession possible in the Arafura Basin. It is located in one of the deepest parts of the Goulburn Graben, adjacent to the southern bounding fault.



Four significant time gaps (horizontal 'benches') were seen in the succession at Tasman 1 well. They are partly attributed to the long-range effects of plate tectonic events, in the model used here. They are discussed more fully below. The uppermost ones incorporate lesser unconformities seen separately farther west where the Mesozoic succession is more complete

Depositional breaks in Tasman 1 well, and unconformities in the Arafura Sea

A. Base Money Shoal Basin unconformity, incorporating some or all of
- Mid-Cretaceous unconformity and
- Top Aptian unconformity and
- Valanginian unconformity and
- Berriasian unconformity and
- Oxfordian unconformity and
- Callovian 'breakup' unconformity 'Argo' event (Symonds et al, 1994)

In general there was no deposition in the eastern Arafura Sea in the intervals between these events.

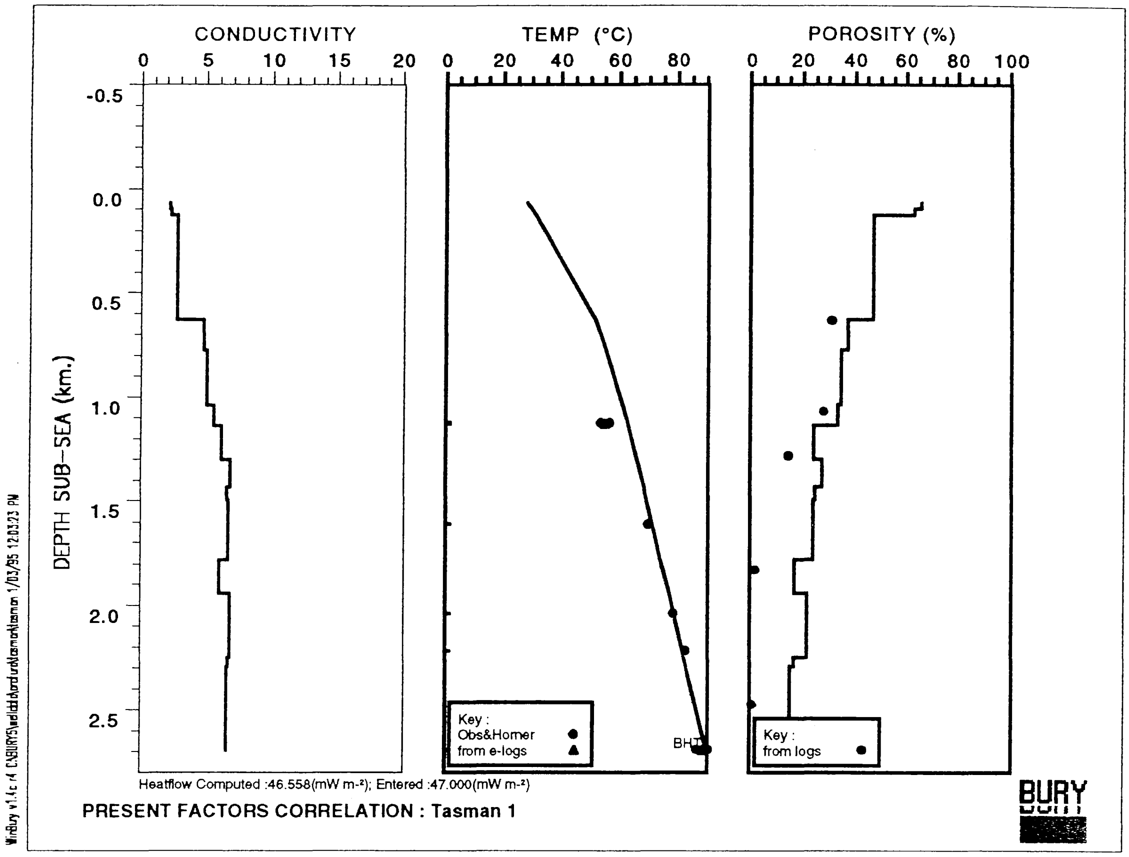
B. Late Palaeozoic-Early Mesozoic unconformity resulting from
- Mid Jurassic West Burma rift (Metcalfe, 1993, 1994)
- Early Jurassic (Hettangian) rift onset (Labutis, 1994)
- Late Triassic (Goulburn Graben) diastrophism and
- Permian heating event (Bradshaw et al, 1990)

C. Carboniferous unconformity resulting from
- Late Carboniferous exposure - Initiation of WA Superbasin, (Symonds et al, 1994) and Sibumasu rifting (Metcalfe, 1993, 1994)
- Visean tectonism (Bradshaw et al, 1990)- Alice Springs orogeny (Symonds et al, 1994)

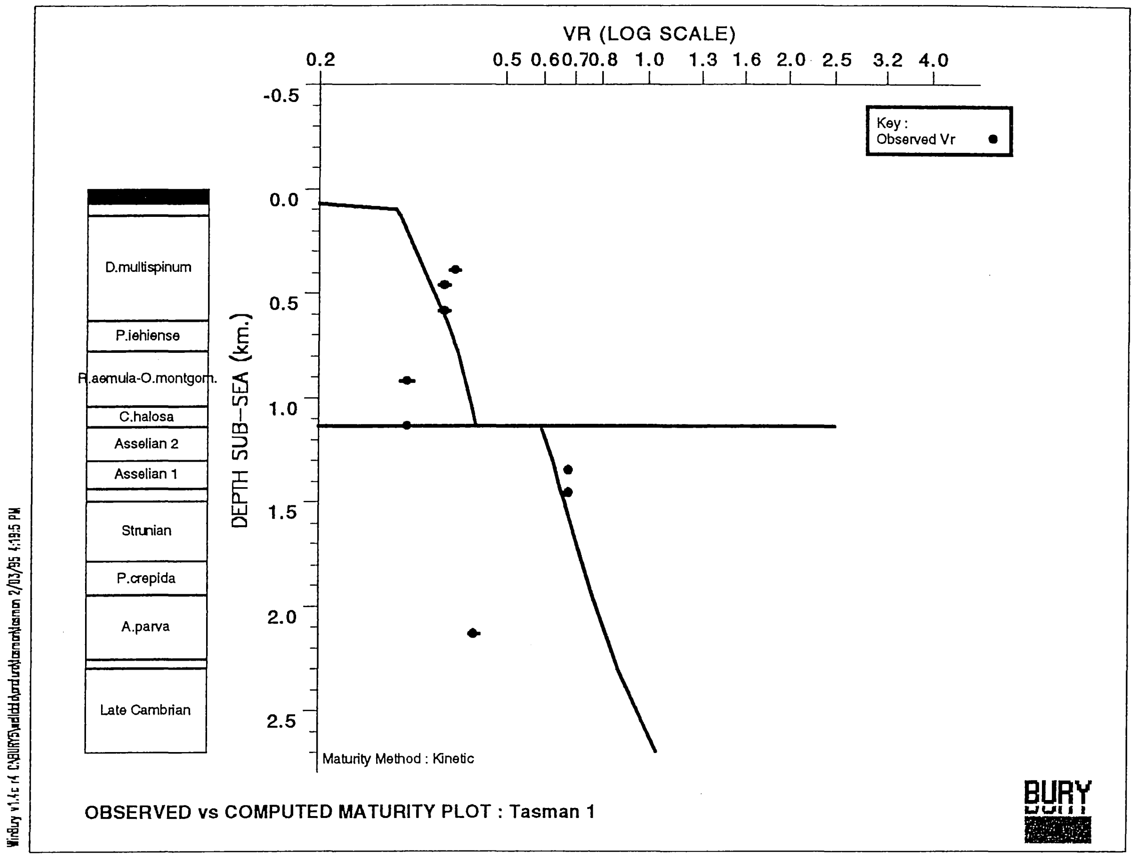
D. Early Palaeozoic unconformity resulting from
- Ordovician-Silurian tectonism - (?) North China (?) Rift (Metcalfe, 1993, 1994)

youngest rocks below		oldest above	erosion begins (estimate)
A.	165 Ma	98 Ma	159\132 and\or 105 Ma
B.	294 Ma	179 Ma	290\258\220 and\or 180 Ma
C.	344 Ma	298 Ma	325 Ma
D.	487 Ma	370 Ma	470 or\and 420 Ma

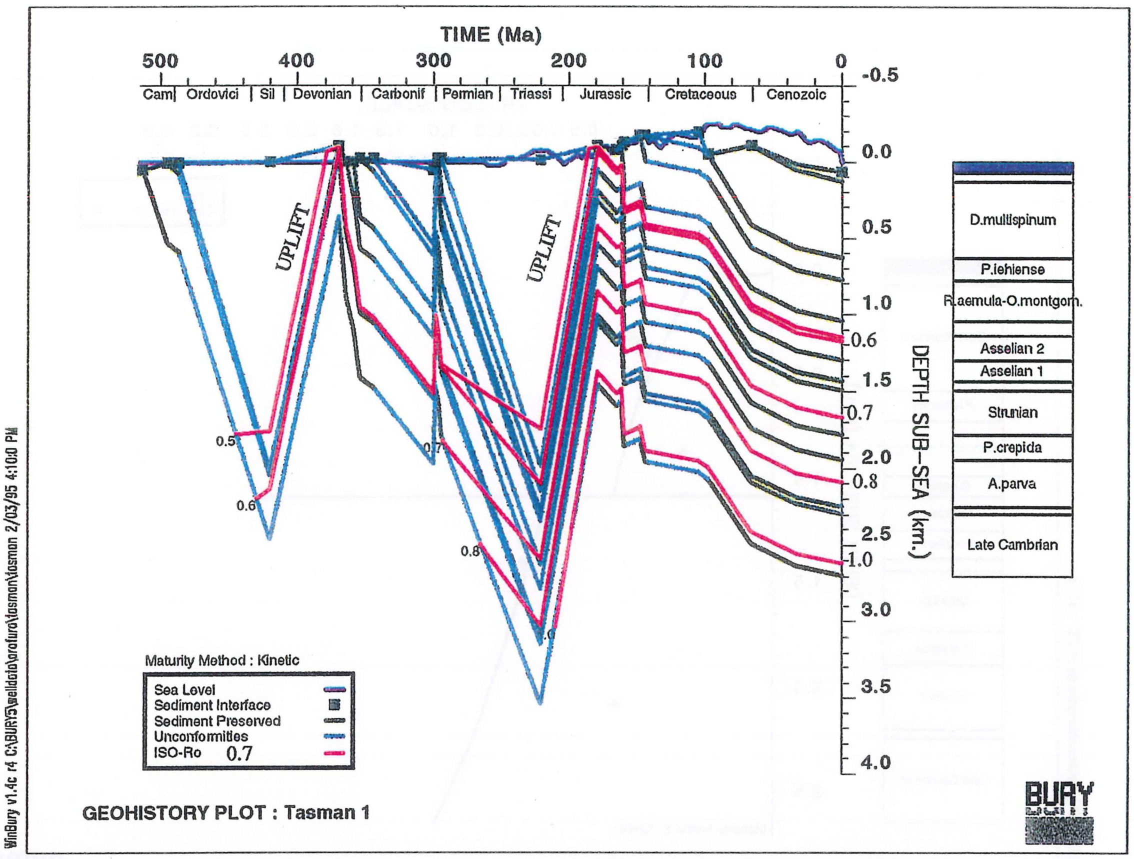
At Tasman 1 wellsite, unconformities D (in the early Palaeozoic)and B (mainly Triassic) show the greatest amount of erosion, the Siluro-Ordovician episode in particular amounting to more than 2 kilometres.



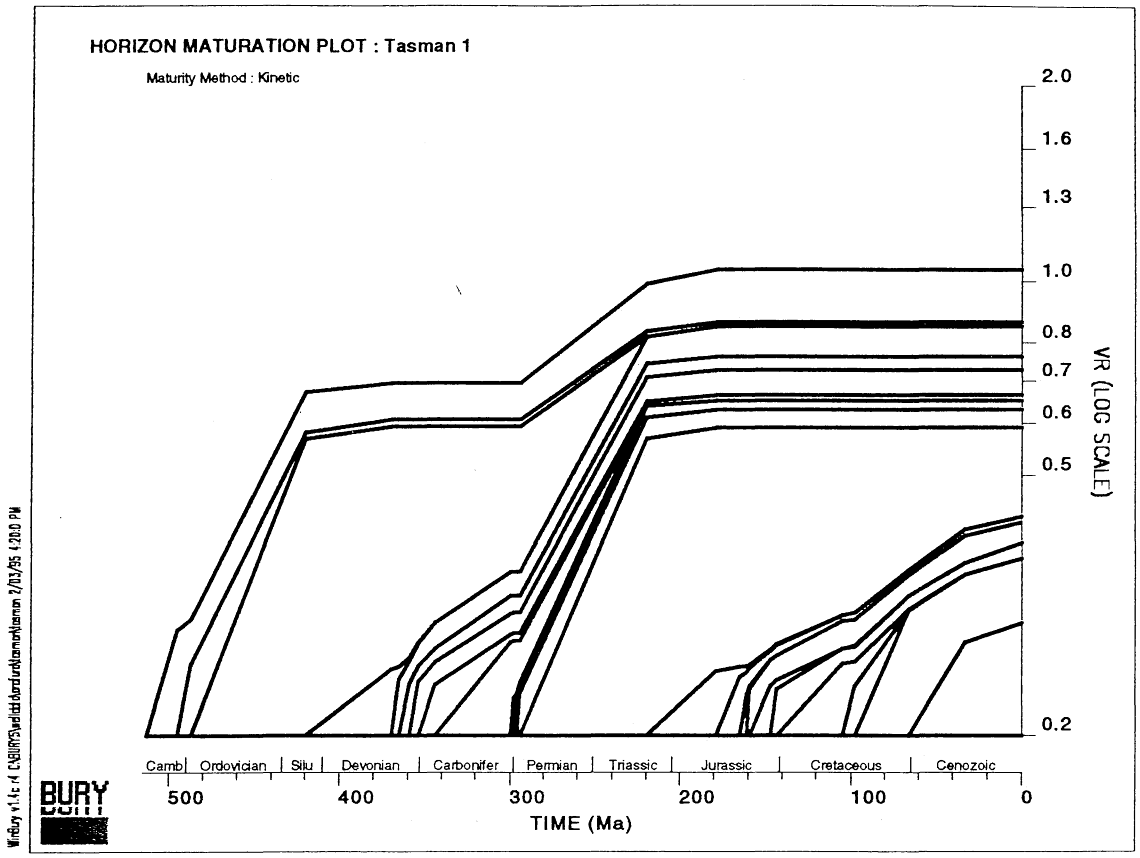
Plot of corrected temperature measurements in Tasman 1 versus calculated temperature based on heatflow of 47 mW/m^2 shows good agreement, again confirming low heatflow in the Arafura Sea. This contradicts previous assumptions widely published (see section on heatflow measurement earlier in text).



Observed maturity (vitrinite reflectance and equivalents) in Tasman 1, with the calculated maturity (curved line) resulting from the model. The rightward step at 1137 m marks an abrupt increase in the maturity. This is an indicator of erosion at the base Jurassic unconformity (the horizontal line).

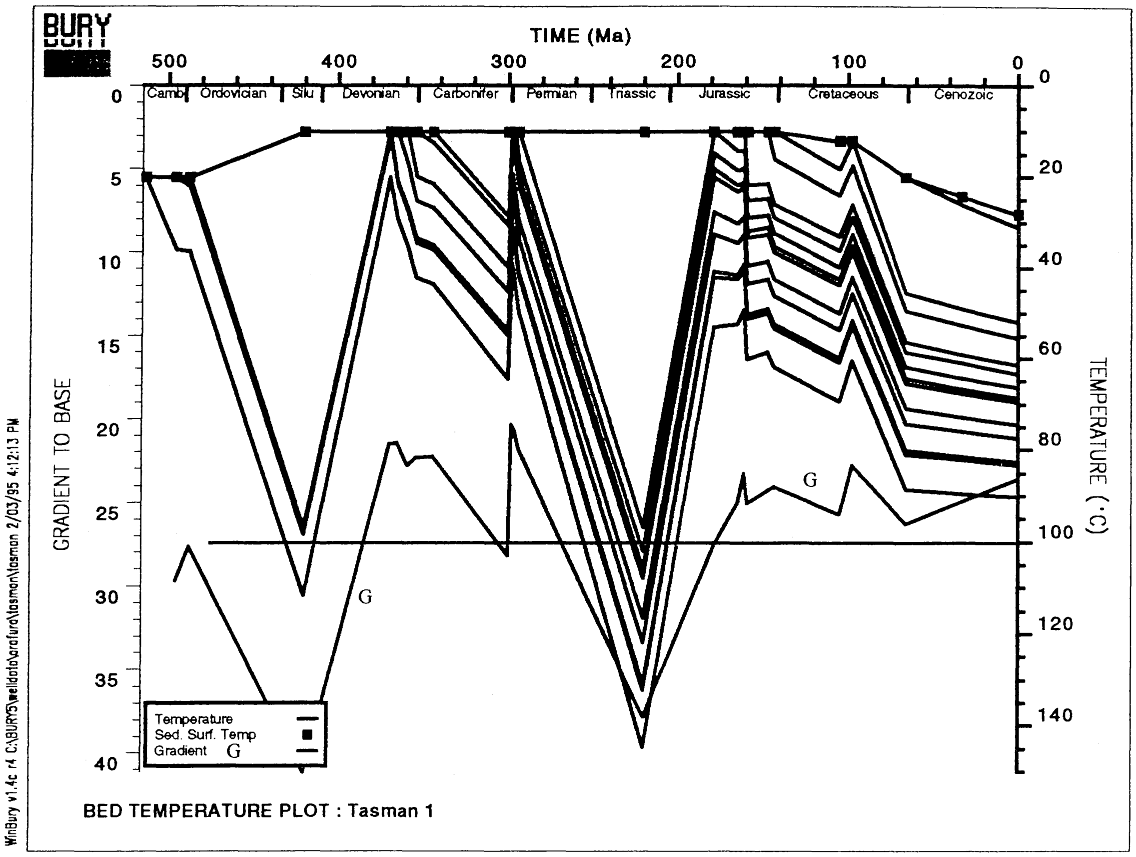


The geohistory diagram of Tasman 1 shows major subsidence and deposition persisting from the Late Cambrian into the Ordovician, and then erosion from Late Silurian time during a major episode of uplift. Subsidence resumed in the Late Devonian and earliest Carboniferous. Further minor erosion in Late Carboniferous time (an echo of the Alice Springs orogeny?) was followed by earliest Permian (Asselian) deposition. This continued until major uplift began again in the Late Triassic, preceding the formation of the Goulburn Graben. Minor episodes of subsidence and uplift continued through the Jurassic and Early Cretaceous, faintly echoing major basin formation further west. Deposition of the Money Shoal Basin resumed here in the Late Cretaceous, continuing into the Cainozoic.



The horizon maturation plot at Tasman 1 shows the early maturation of Palaeozoic source rocks. The Cambro-Ordovician succession became mature as early as the Silurian. The Permo-Carboniferous sediments became mature for oil during the Triassic, largely before the formation of the Goulburn Graben.

There has been little additional maturation since mid Triassic time, and none since the middle Jurassic. The Mesozoic succession is immature for hydrocarbons.



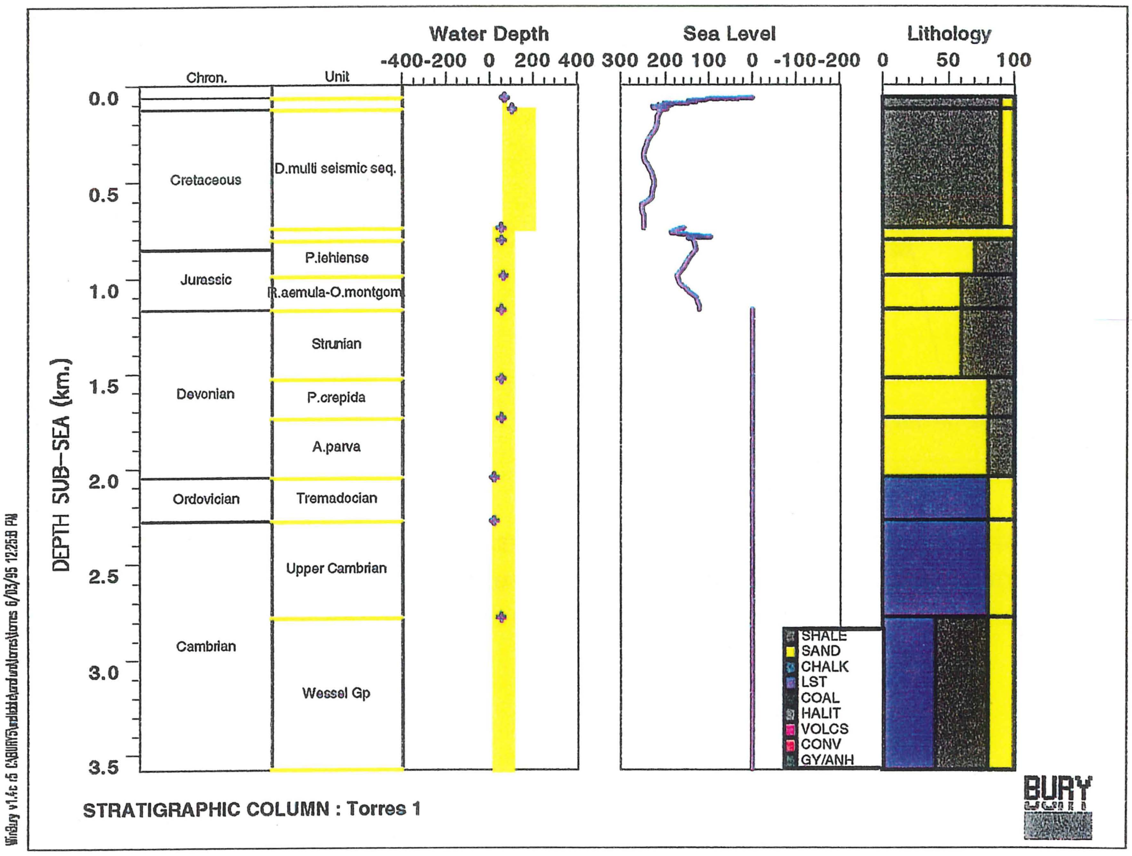
The bed temperature plot for Tasman 1 shows that the prospective Palaeozoic succession from Cambrian through Carboniferous was subjected to its highest temperatures in the Triassic about 220 Ma ago. It was then uplifted in the major diastrophic episode that gave rise to the Goulburn Graben, and has not again reached the same temperatures. The lowermost Mesozoic sediments are now just sub-mature for hydrocarbons. The temperature gradient is proportional to heatflow. It shows maxima at 420 and 220 Ma, plus a number of minor peaks.

TORRES 1

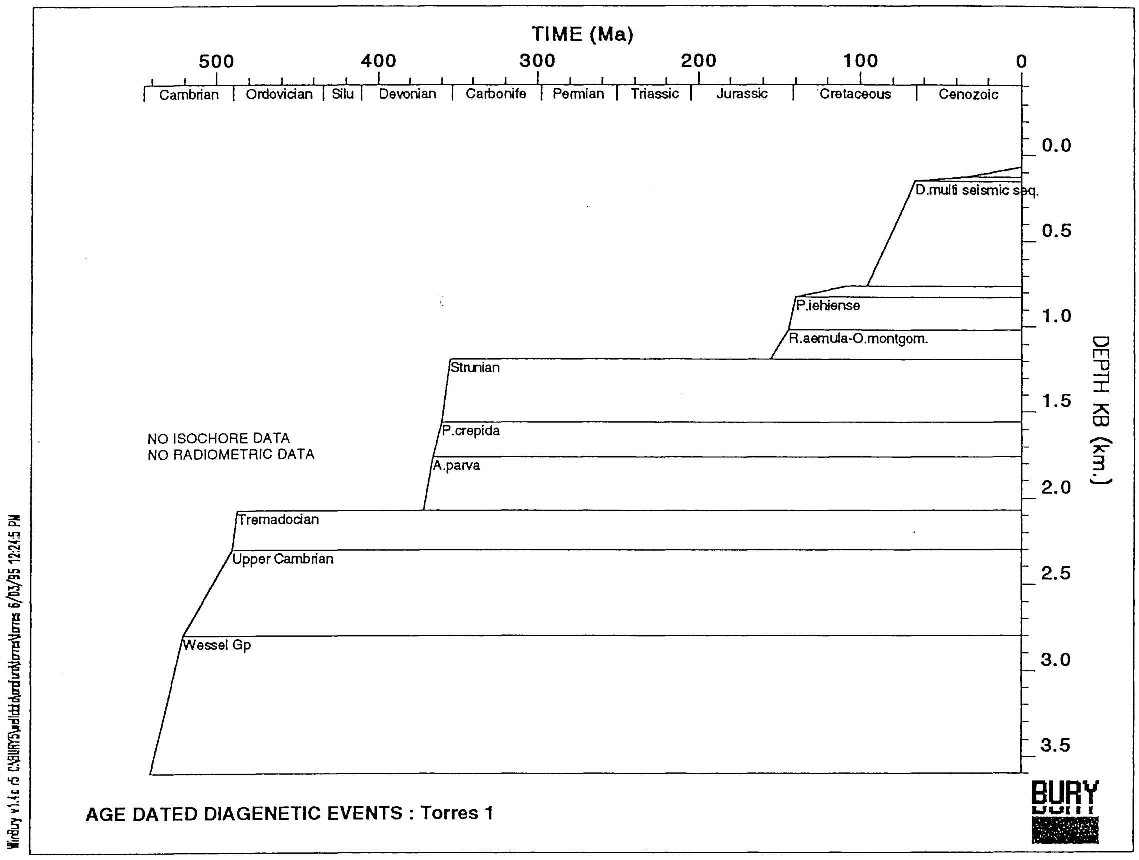
ESSO EXPLOR.& PROD. AUST 1983

Latitude: 10° 28' 01.12" S (WGS 84)
KB: 24m asl
Sea Bottom Temperature: 26°C
BHT: 98°C (corrected)

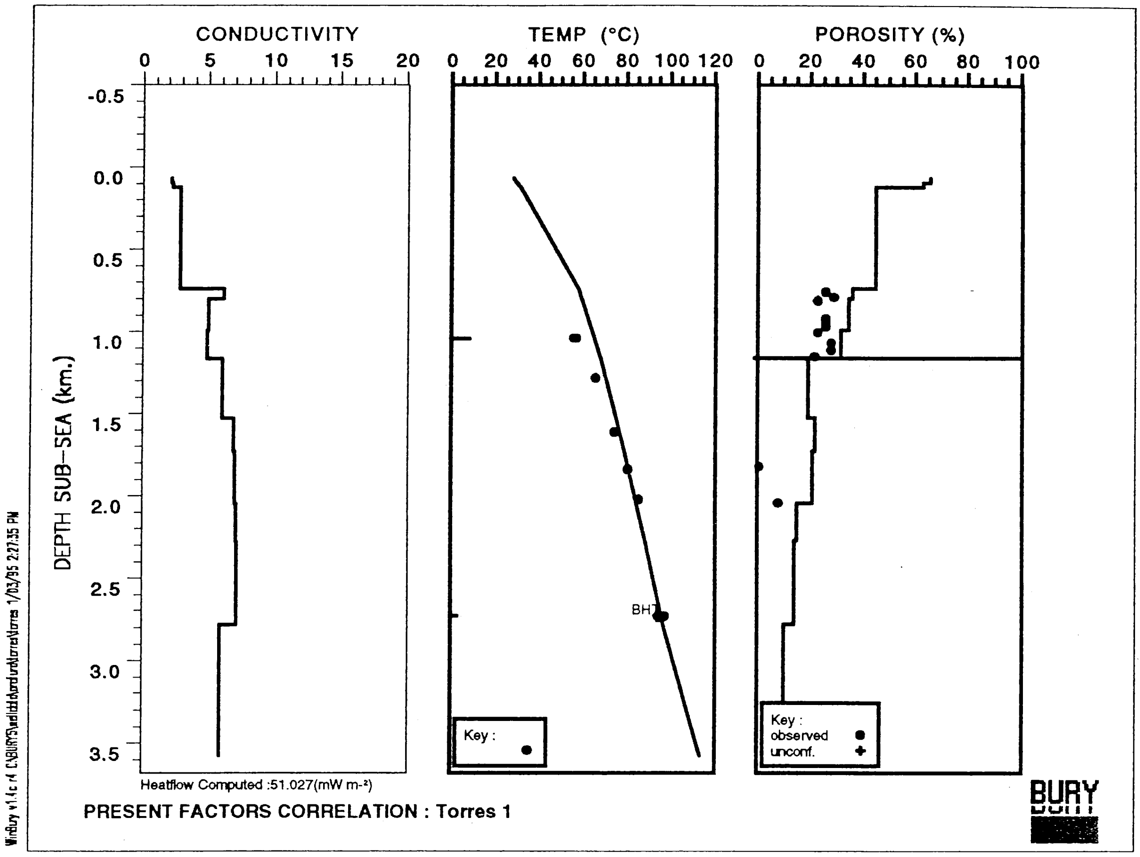
Longitude: 133° 23' 42.18" E (WGS 84)
TD: 2758mKB
Water Depth: 67m
BHT Depth: 2758m



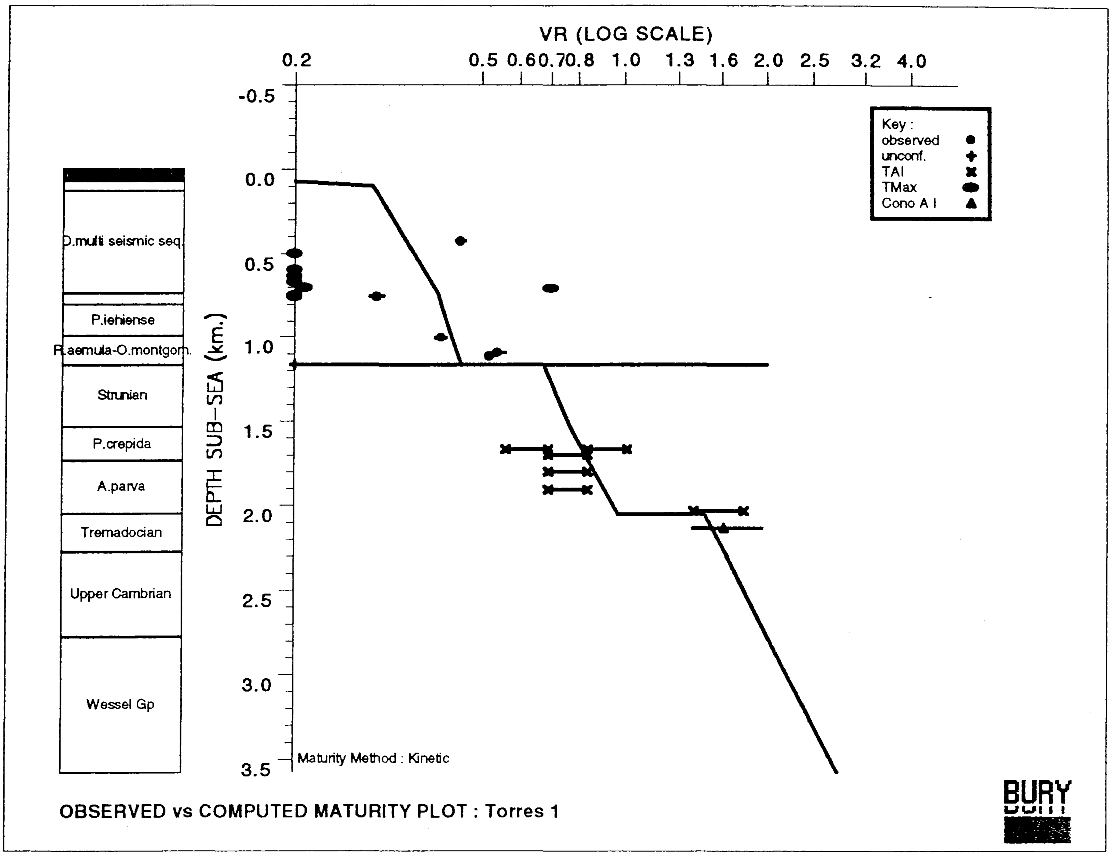
Torres 1 was drilled on the crest of the largest anticline in the Goulburn Graben. There were no hydrocarbon shows.



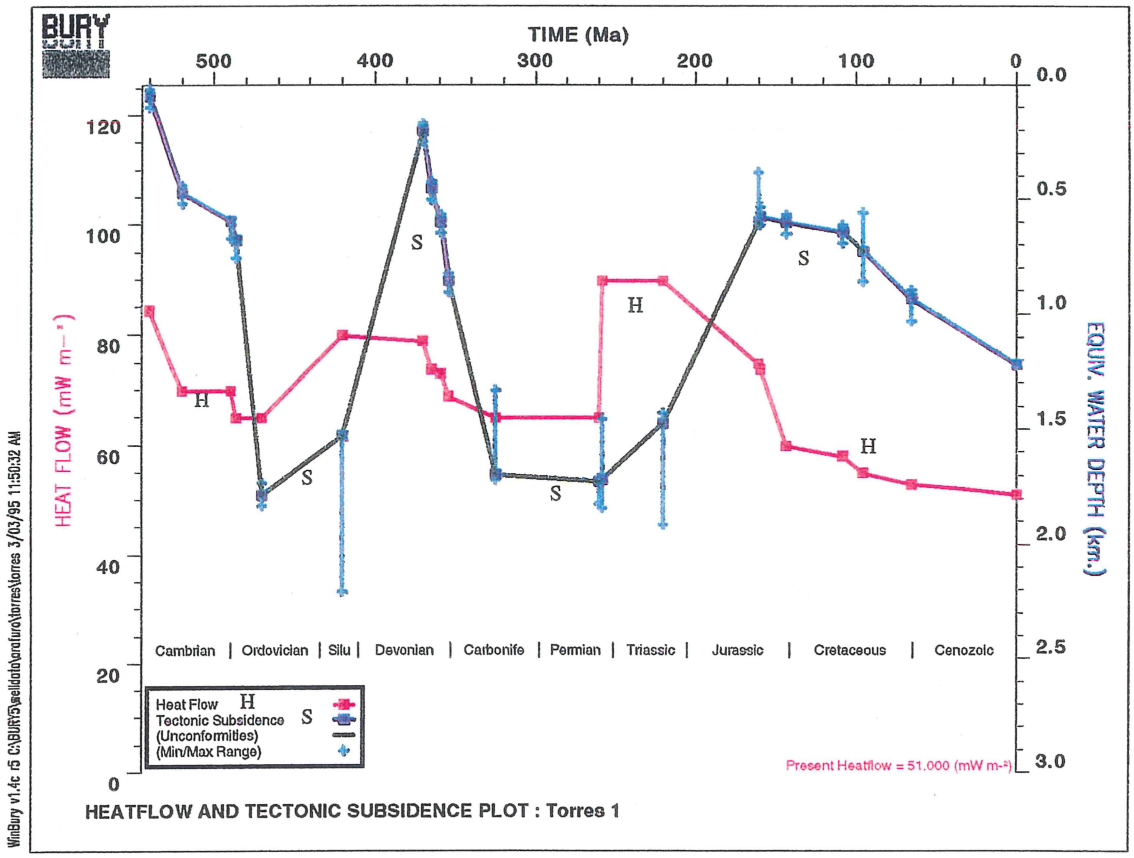
The missing succession from Devonian to Jurassic is an indication of a major unconformity affecting the middle of the Goulburn Graben. An earlier unconformity affects most of the Ordovician, the Silurian and most of the Devonian.



The corrected BHT at Torres 1 indicates heatflow of 51 mW\m^2 at present. Other temperature measurements uphole are in general agreement.

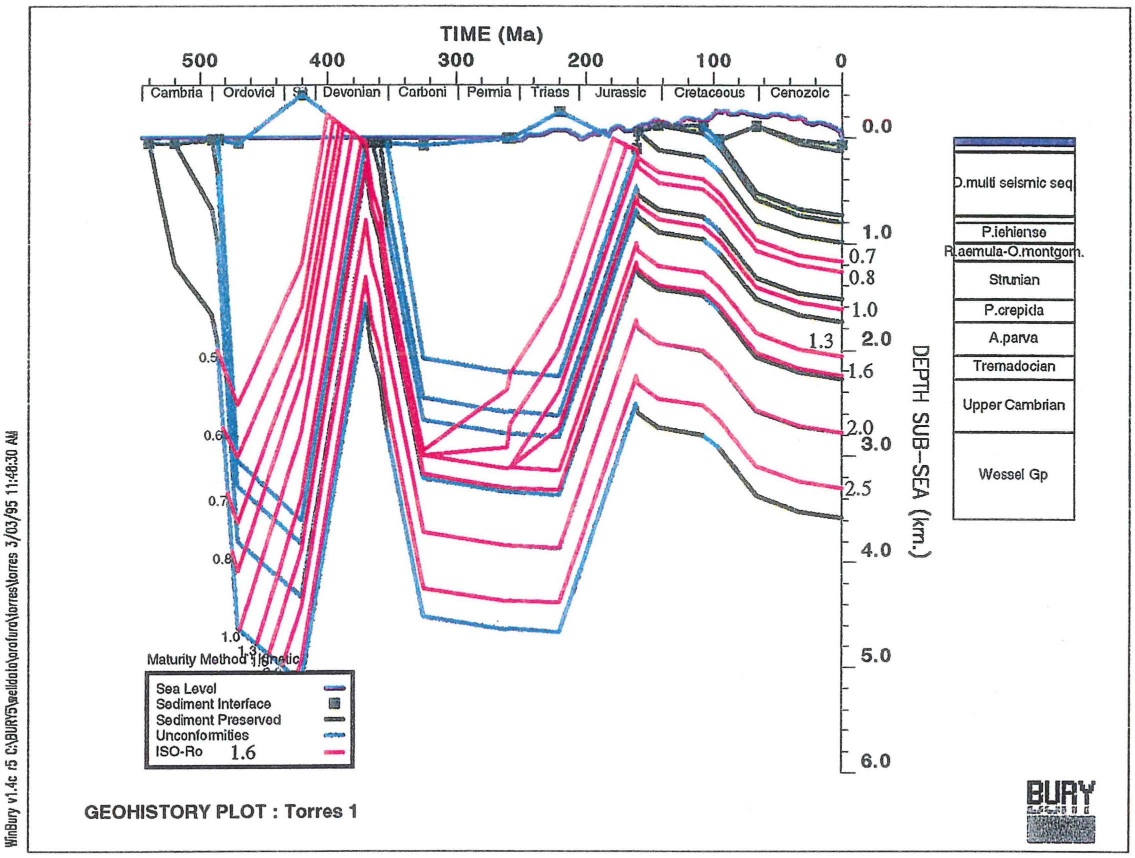


There is a good record of thermal maturity measurements in Torres 1. Various measures are used including TAI, TMAX, and, crucially, CAI in Ordovician sediments (the triangle on the deepest sample). On this plot, they have all been converted to vitrinite reflectance equivalents. These, together with today's temperature, were the main constraints on the development of the geohistory model. The plotted line is the maturity calculated from the complex model of deposition, uplift and heatflow finally arrived at (below). Horizontal steps indicating sudden increases in maturity are seen at the two main unconformities.

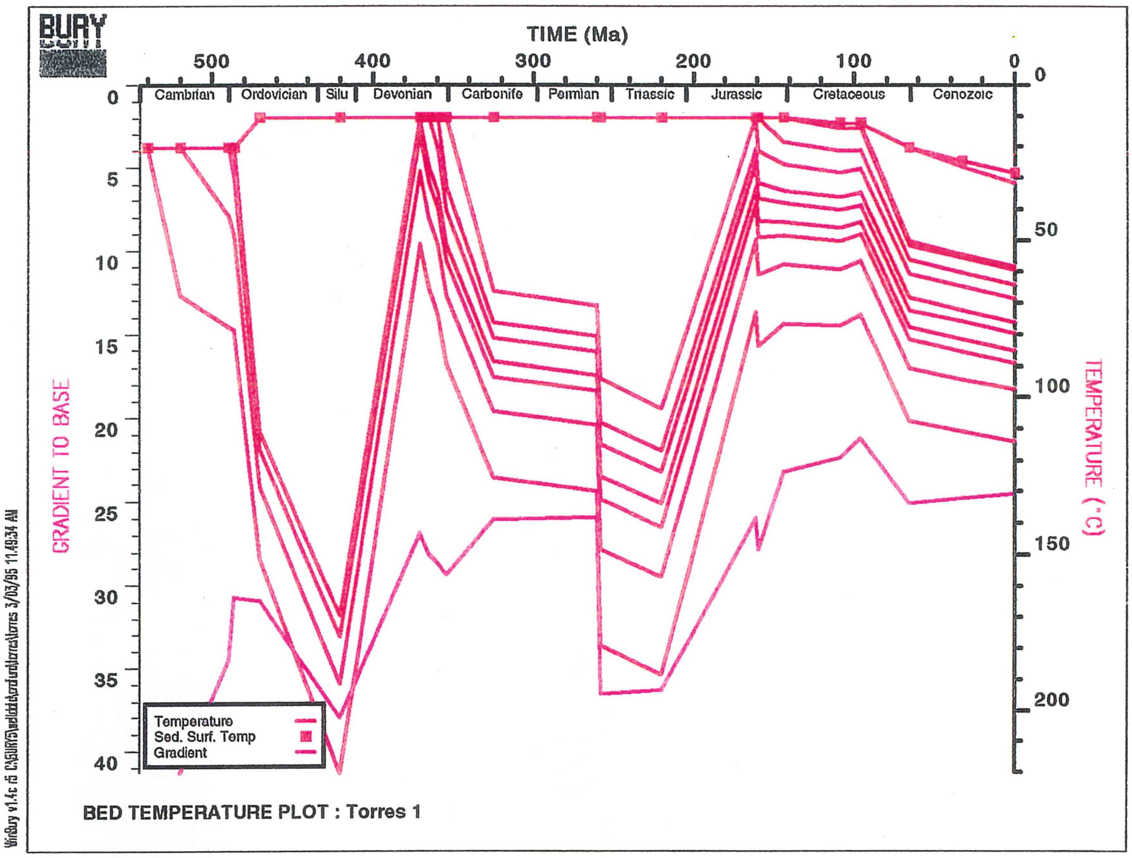


HEATFLOW AND TECTONIC SUBSIDENCE PLOT : Torres 1

The model of subsidence and heatflow at Torres 1 shows two periods of major uplift - beginning at 420 Ma (Silurian) and at 220 Ma (Late Triassic). There is a period of lesser uplift beginning at 470 Ma (Early Ordovician). The associated heatflow events are quite modest, but they are prolonged, thus prolonging the periods of erosion.



Torres 1 shows two major periods of diastrophism. Conditions have been quiet since the Jurassic, with some increased subsidence in the later Cretaceous. Vitrinite reflectance contours begin at 0.7. The early-maturity values of 0.5 and 0.6 per cent are missing because of erosion at the base Jurassic unconformity at 1188m KB.



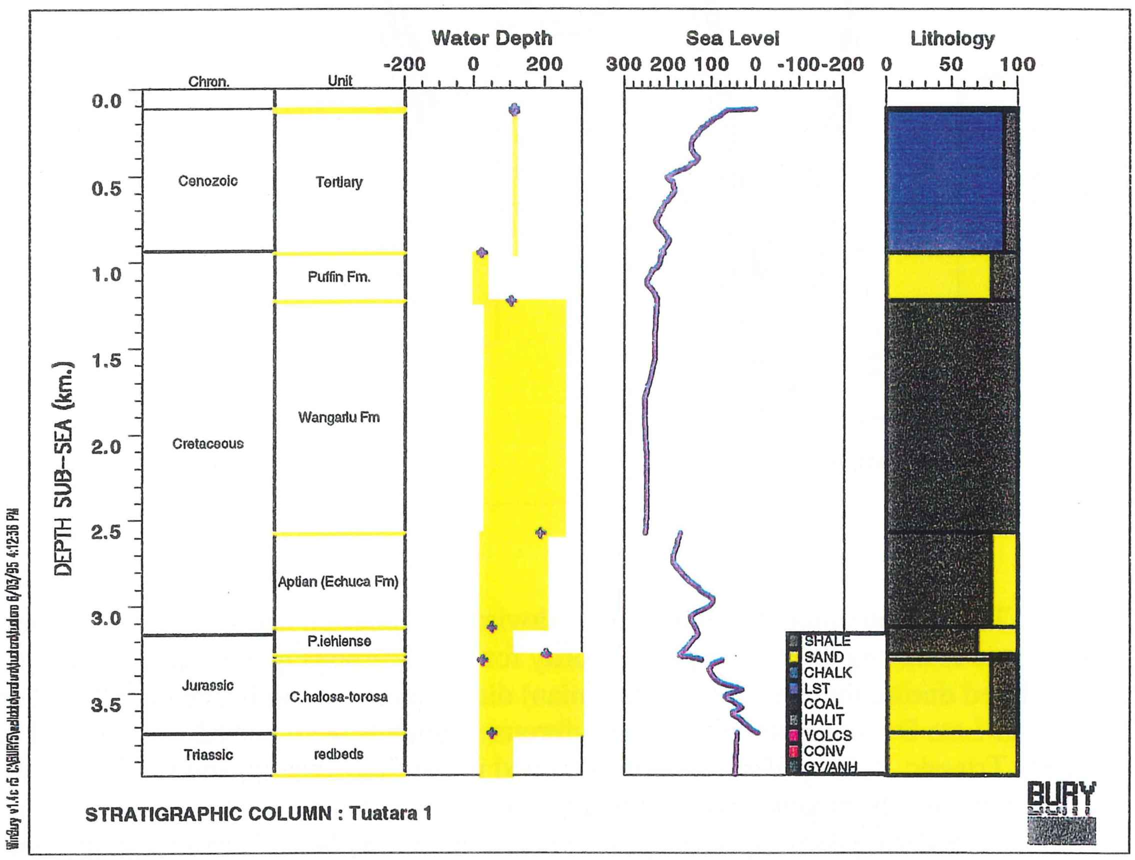
The Bed Temperature plot shows that the Ordovician, Cambrian and earlier source rocks were heated to advanced or even post maturity for hydrocarbons in the Late Ordovician, then uplifted during the first (Siluro-Devonian) diastrophism in the following 50 million years. The Late Devonian to Early Carboniferous sediments were buried and matured in the early Triassic, then uplifted and partly eroded in the Late Triassic and Early Jurassic. Oil that may have been generated in this large anticline had opportunity to remigrate or escape from it during these episodes of tectonic activity. The large Torres anticline, and the Goulburn Graben as a whole, was formed too late to intercept and trap any oil thus generated. Jurassic and later sediments have not yet been heated enough to generate hydrocarbons, and the Palaeozoic sediments are not now at their maximum depth of burial. They are far below their maximum temperature.

TUATARA 1

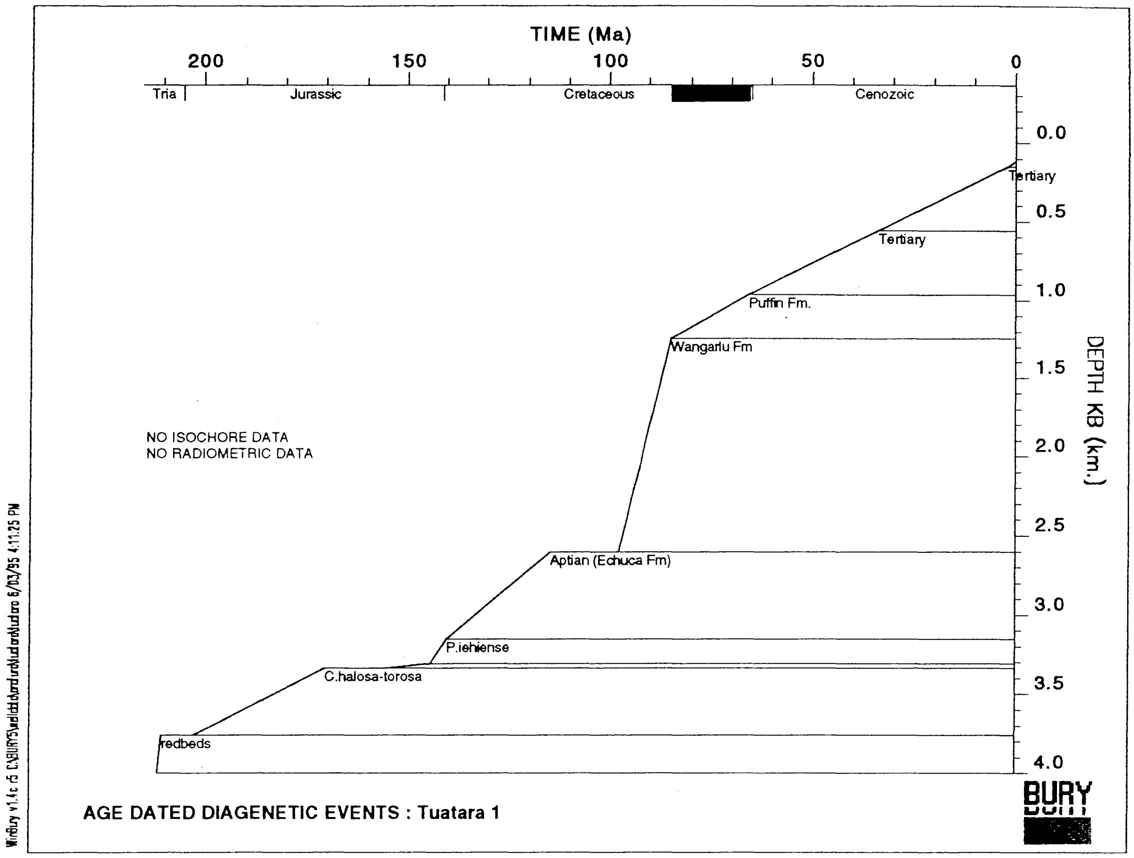
BHP 1990

Latitude: 9° 43' 59.91" S (WGS 84)
KB: 22m asl
Sea Bottom Temperature: 25°C
BHT: 132°C (corrected)

Longitude: 131° 51' 41.00" E (WGS 84)
TD: 3875mKB
Water Depth: 115m
BHT Depth: 3875m

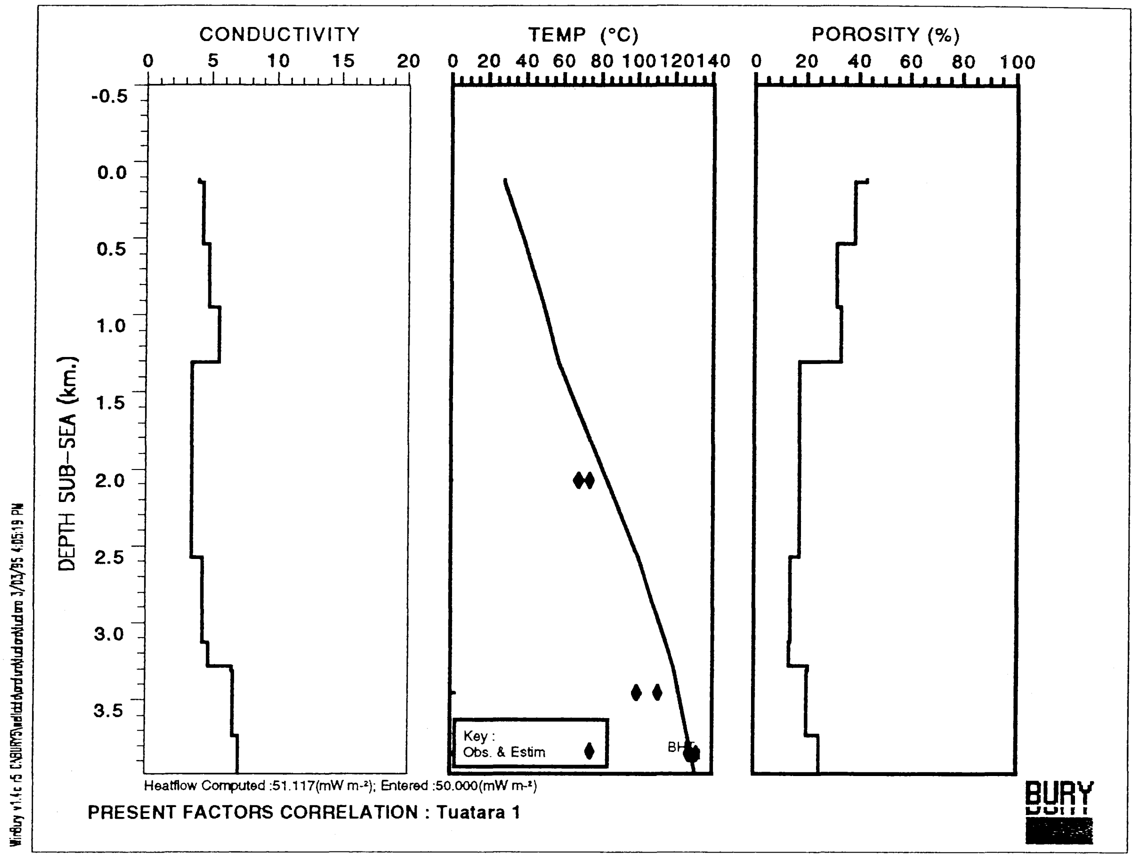


The Tuatara 1 well has had a different history to other wells in the Arafura Sea. It has a much thicker Mesozoic succession, and apparently no intersection of Palaeozoic rocks.

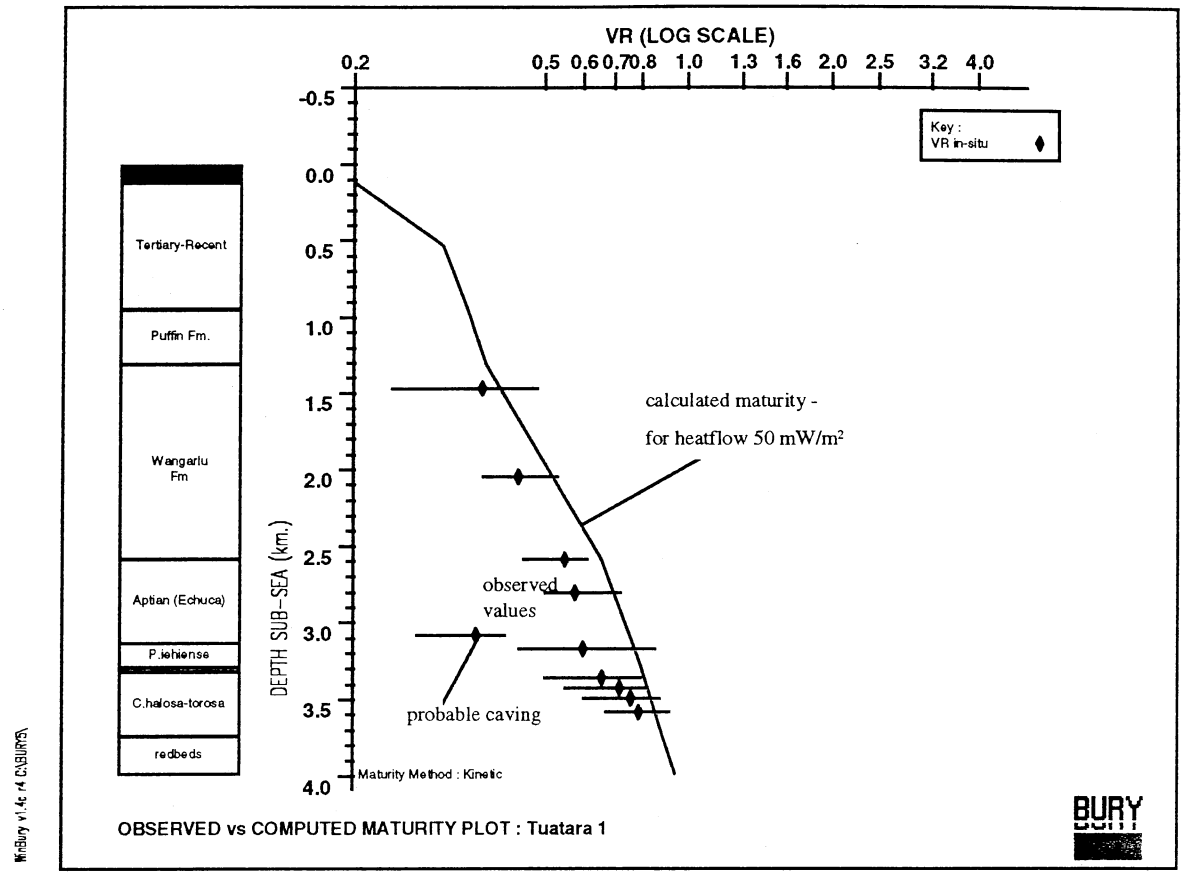


In this, the most westerly well in the study, some Bonaparte Basin formation names have been used.

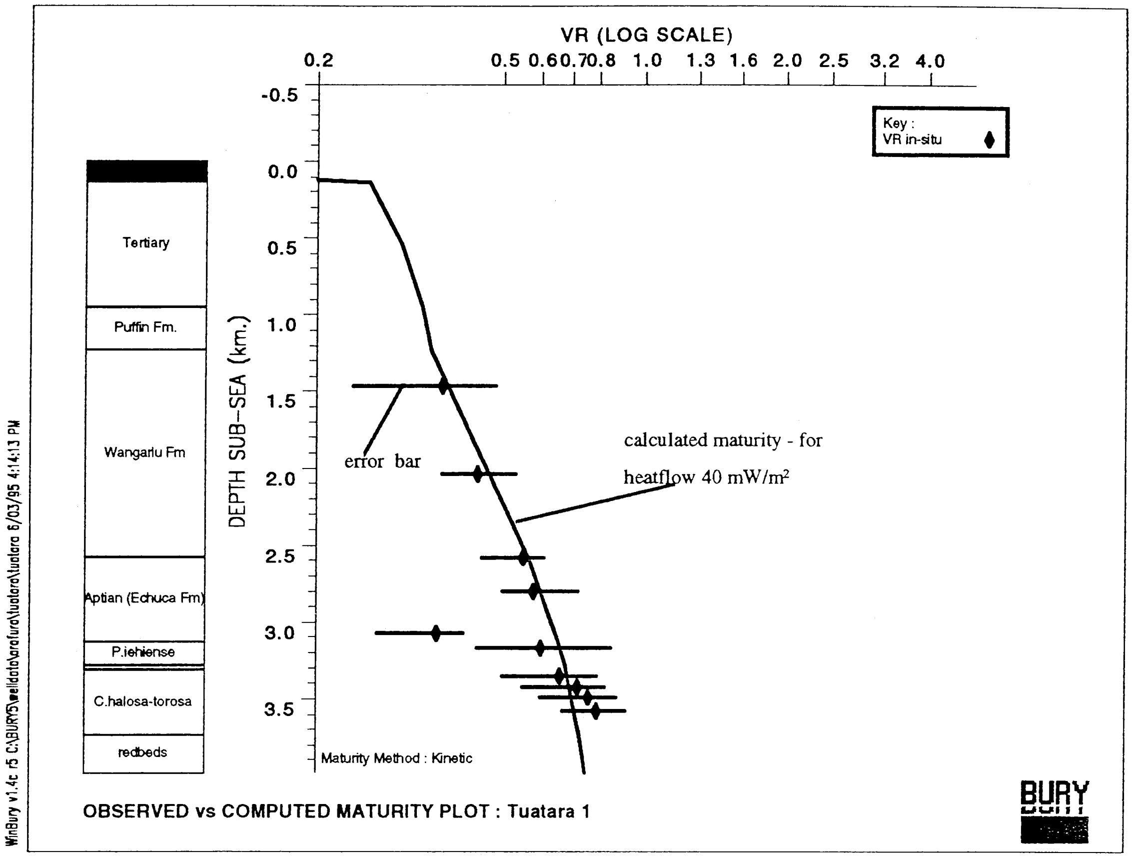
3



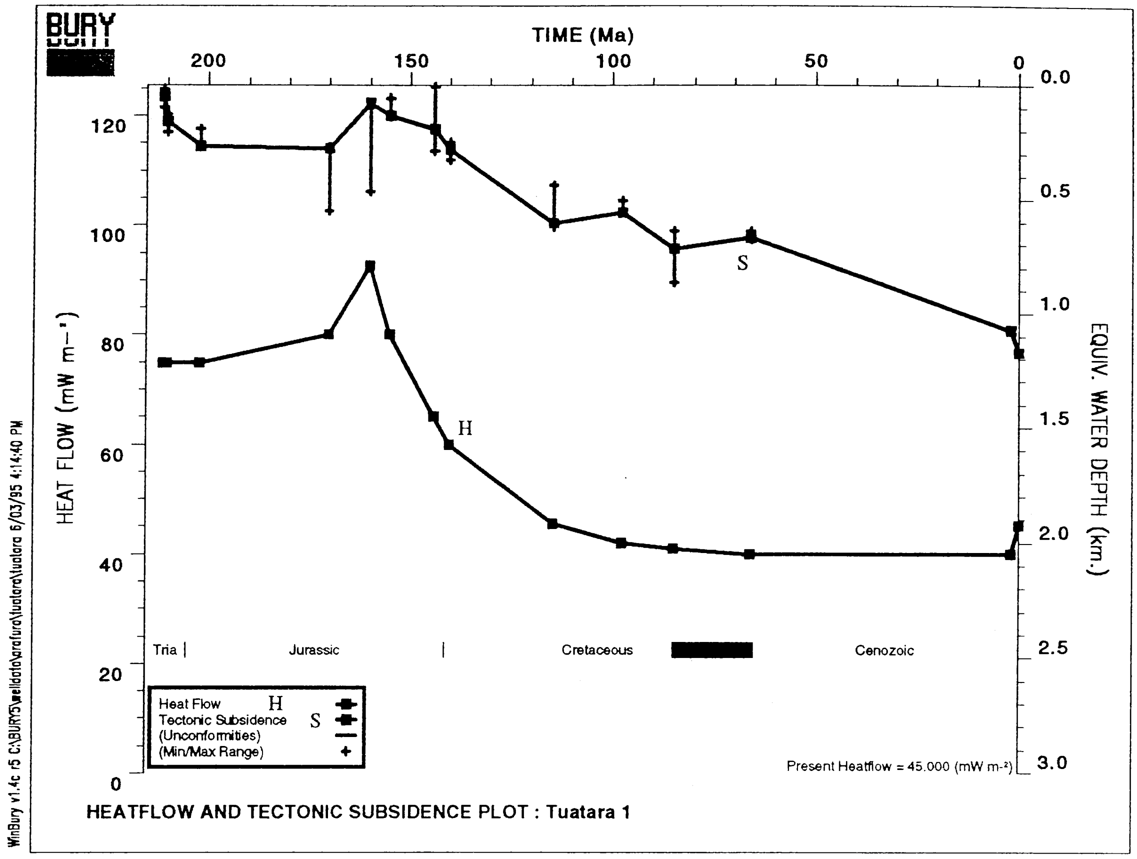
The corrected BHT measured near TD is compatible with a heatflow of 50 mW/m^2 (the curved line), but the Horner-corrected temperatures measured at shallower levels during drilling appear to disagree. They suggest a present-day HF of 40 mW/m^2. The temperature measurement near TD remains an anomaly, but since it is the deepest, it cannot be ignored.



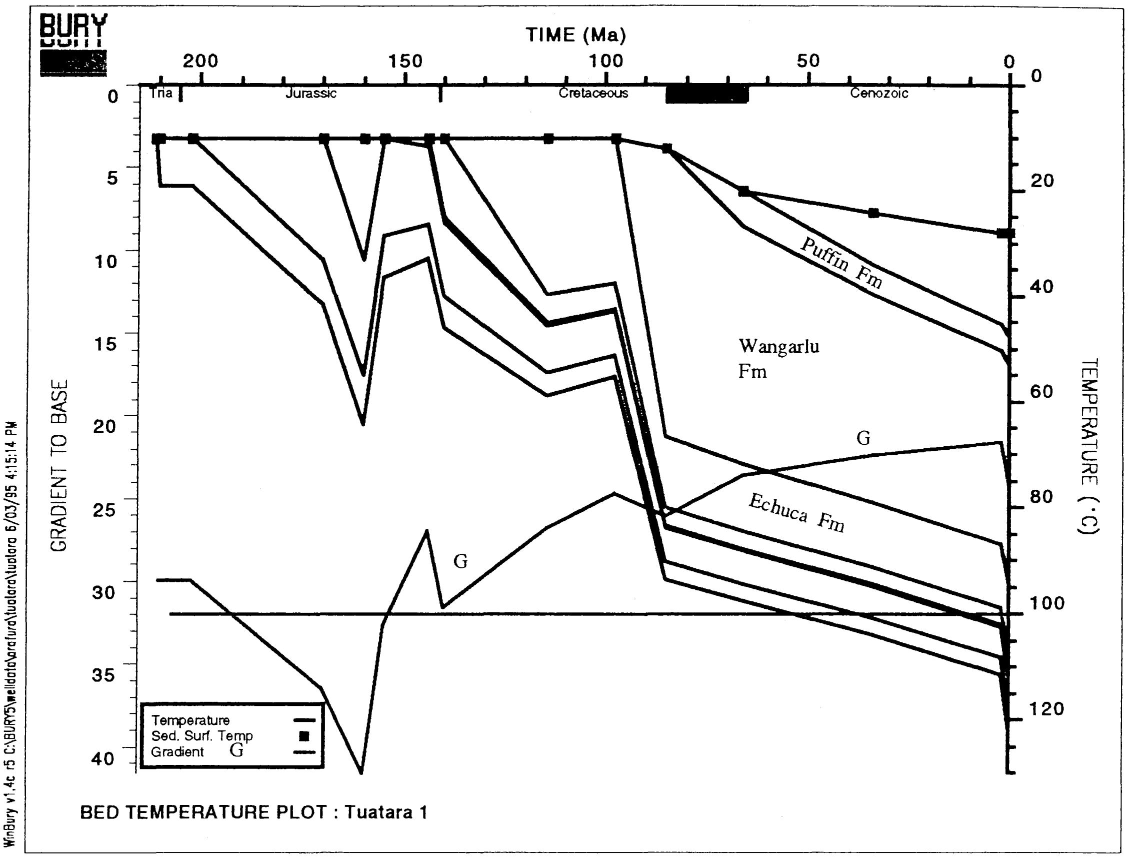
The calculated maturity (curved line) based on heatflow never lower than 50 mW/m^2, appears to disagree with numerous careful observations of maturity in the well. This model, based on one measurement of BHT (the deepest) appears unsatisfactory. It yields a calculated maturity profile higher than that observed in the well. A history of lower heatflow appears necessary (or suppression of vitrinite reflectance).



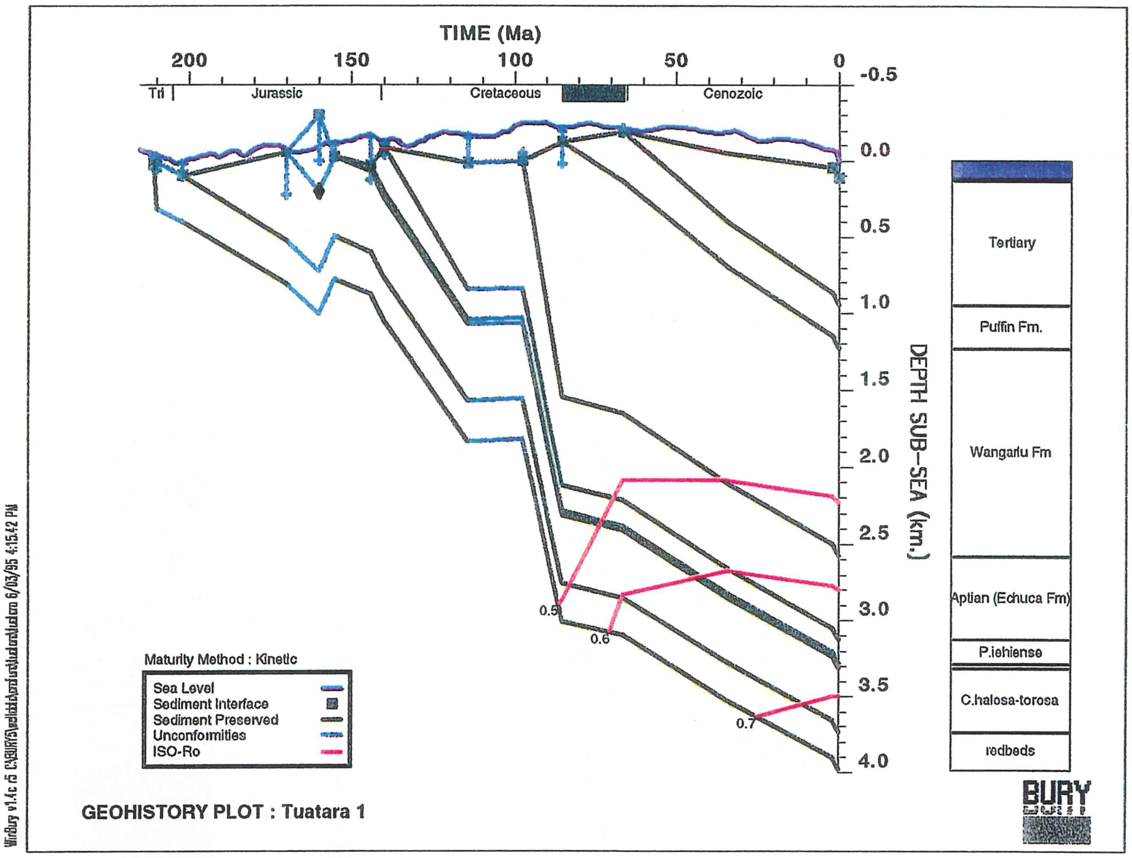
This calculation of maturity appears much more satisfactory than the earlier model which has higher heatflow (50 mW/m^2 and above). This model assumes lower heatflows during most of the well's Cenozoic history (see below).



This model is in agreement with the low heatflow indicated by the maturity measurements at Tuatara 1, but by including a Pleistocene rise in heatflow it also allows near agreement with the anomalously high BHT recorded near TD in the well. The unexplained small rise has no significant effect on the geohistory model or on the calculated maturity profile.
The heatflow/time plot (H) of this, the most westerly well of the study, is much more like a 'normal' NW Shelf profile.
Is the recent (<2Ma) heatflow rise real? If so, is it connected with a change in fluid migration?



The Puffin Formation oil source rock (dark bar on the Time(Ma) scale) has not achieved thermal maturity at Tuatara 1. The Jurassic is at an early mature stage.



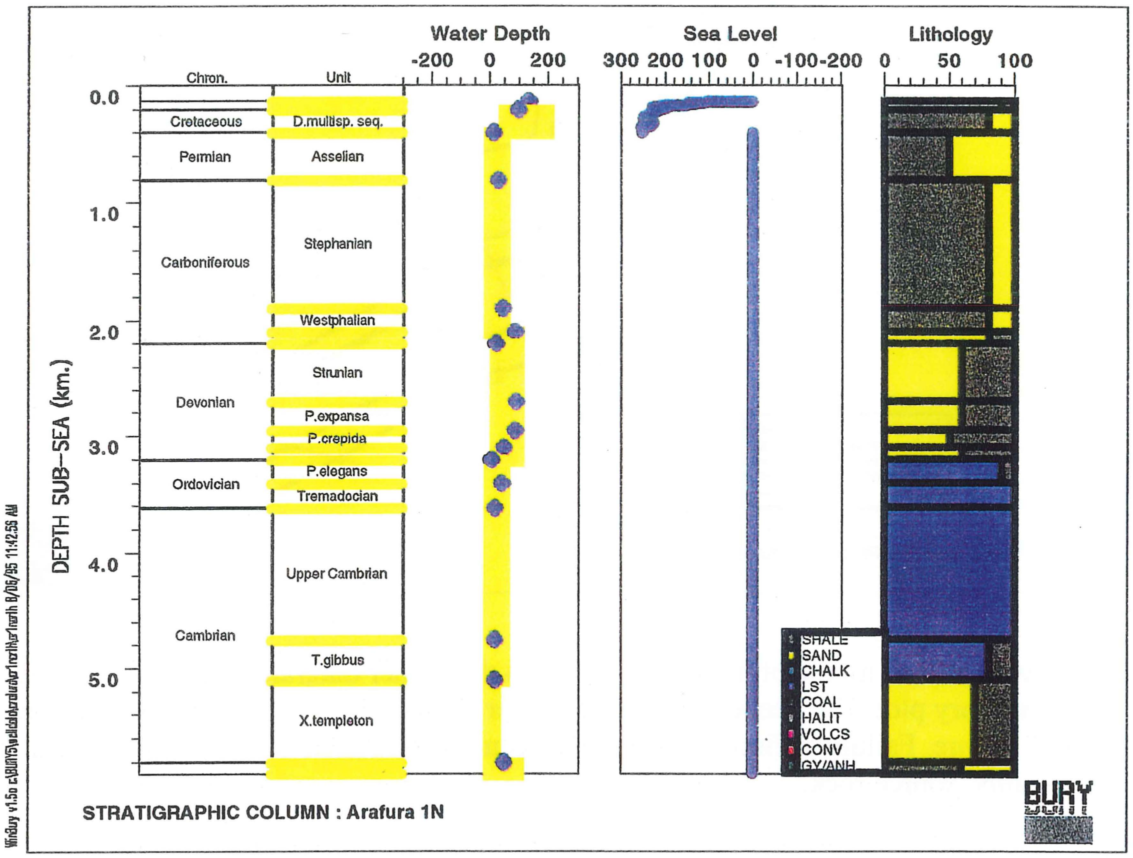
The 'low-heatflow' model of Tuatara 1 shown in the earlier diagram was used to produce this geohistory plot. The deeper part of the Lower Cretaceous and the Jurassic succession is early mature. Failure to find a commercial accumulation is attributed to lack of seal, trap or, possibly, source rock.

ARAFURA 1 North

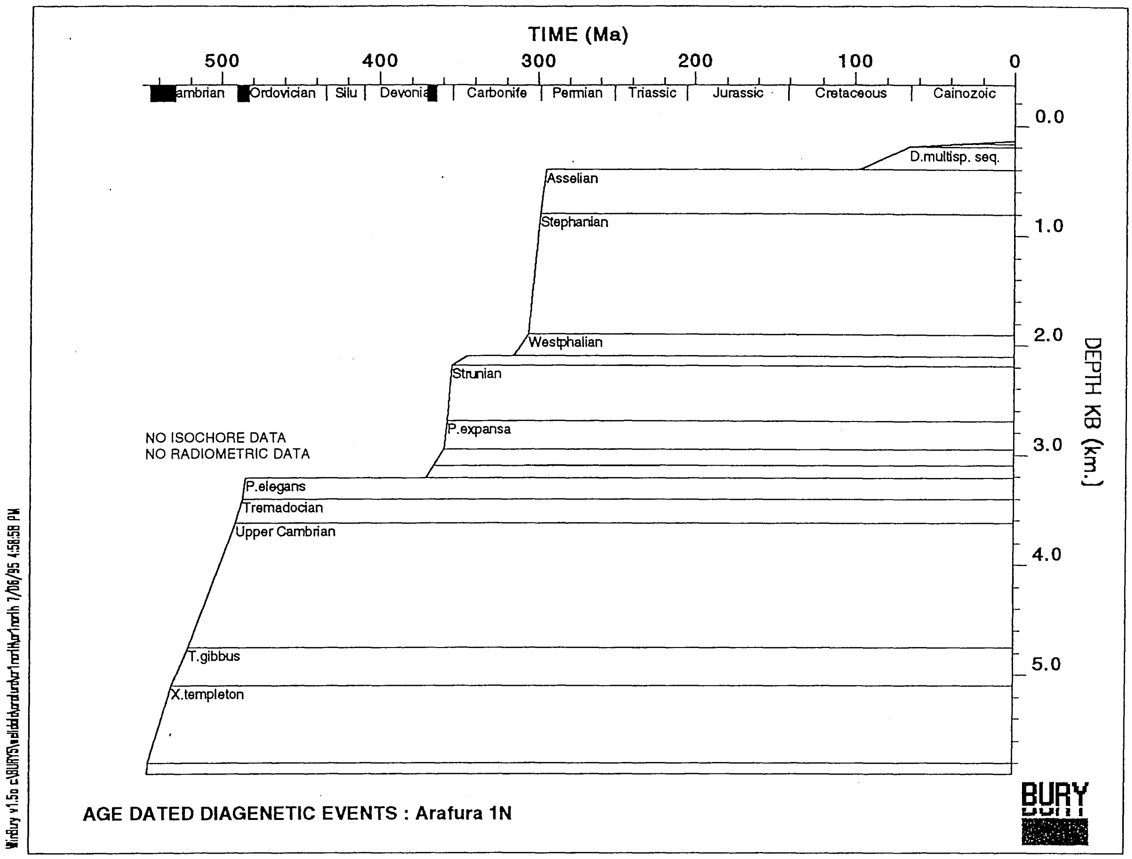
HYPOTHETICAL 1995

Latitude: 10° 20' 42" S (WGS 84)
KB: 00m asl
Sea Bottom Temperature: 26C
BHT: 96°C

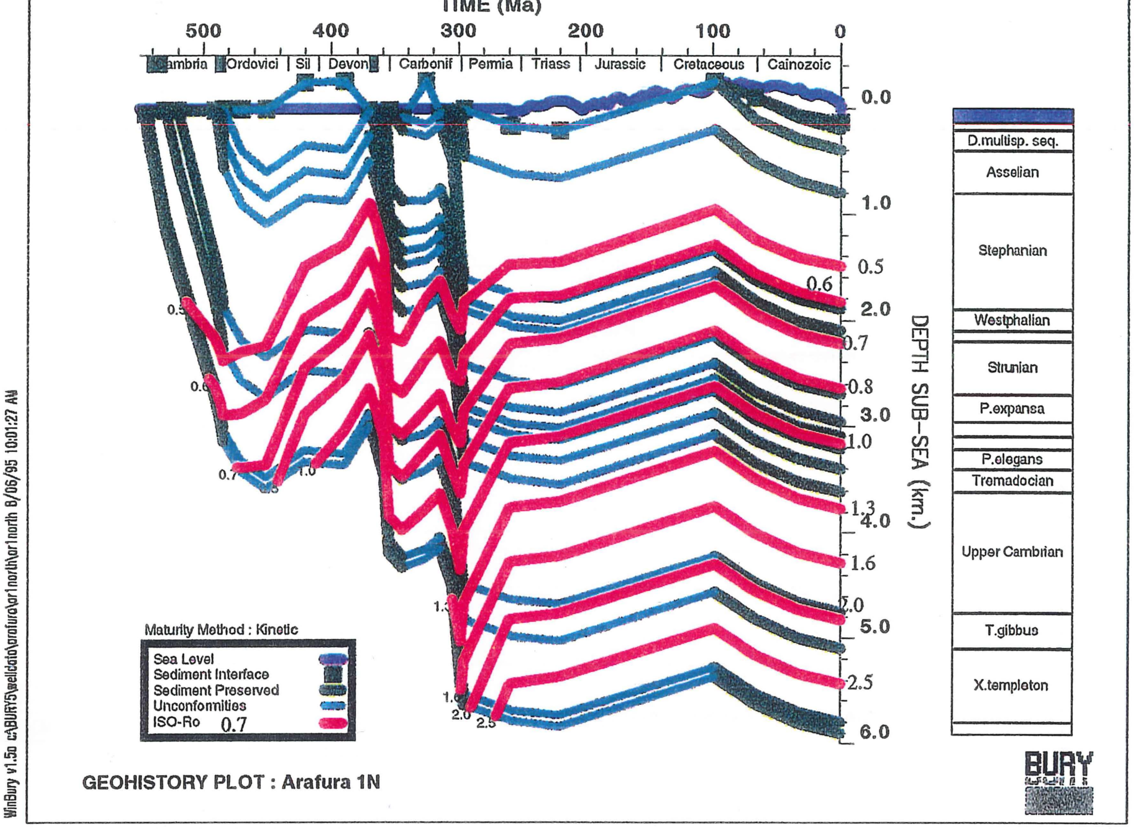
Longitude: 134° 05' E (WGS 84)
TD: 8000mKB
Water Depth: 133M
BHT Depth: 3635m



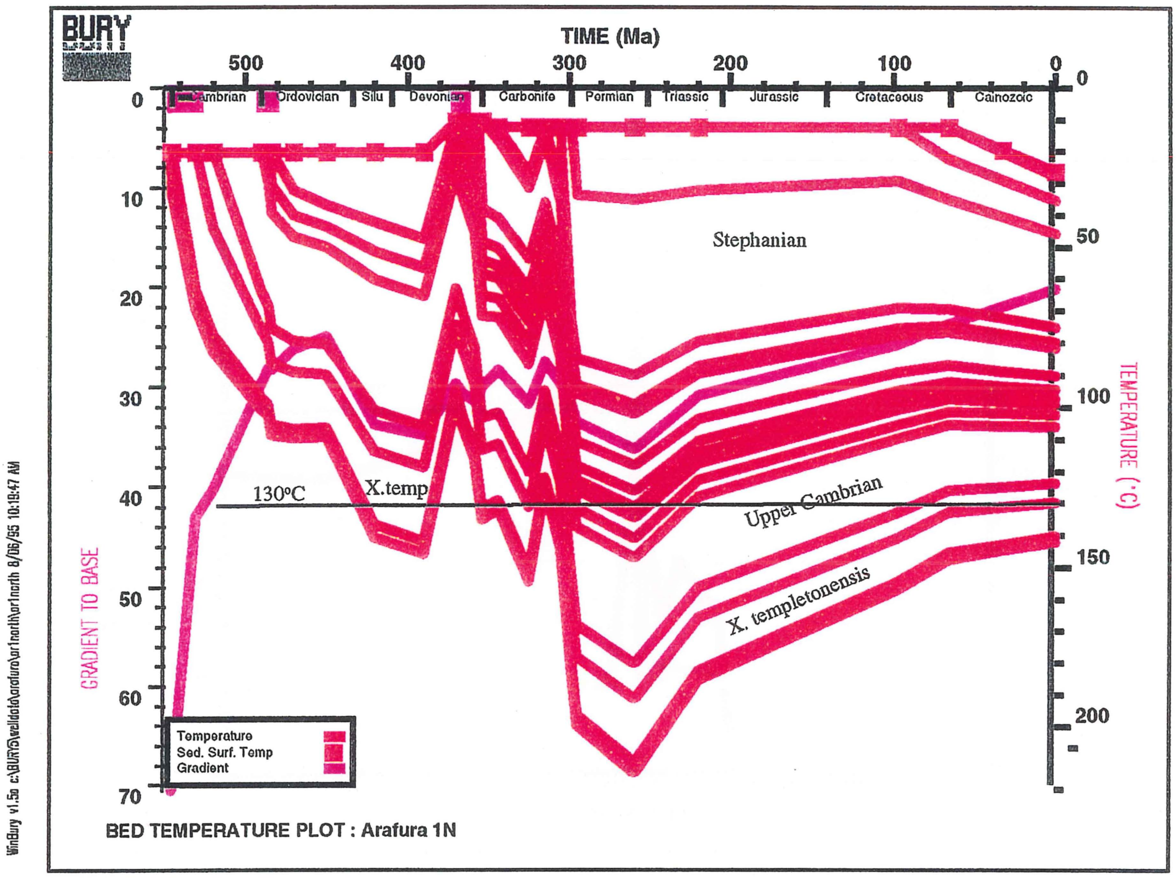
At a hypothetical well site downdip from Arafura 1 well, near the northern boundary of the Goulburn Graben, some 1500 m of Permo-Carboniferous rocks not intersected by the well are present. At this greater depth of burial, the Lower Palaeozoic source rocks probably generated the oil seen updip in the well. The depths shown are derived from seismic.
In the panel at right centre, the relative sea level curve extends from the present back to the base of Mesozoic. Below the unconformity, no relative levels are shown for the Palaeozoic. In the lithology panel, the darkest shade is carbonate. The lightest shade is sandstone. The intermediate shade is shale.



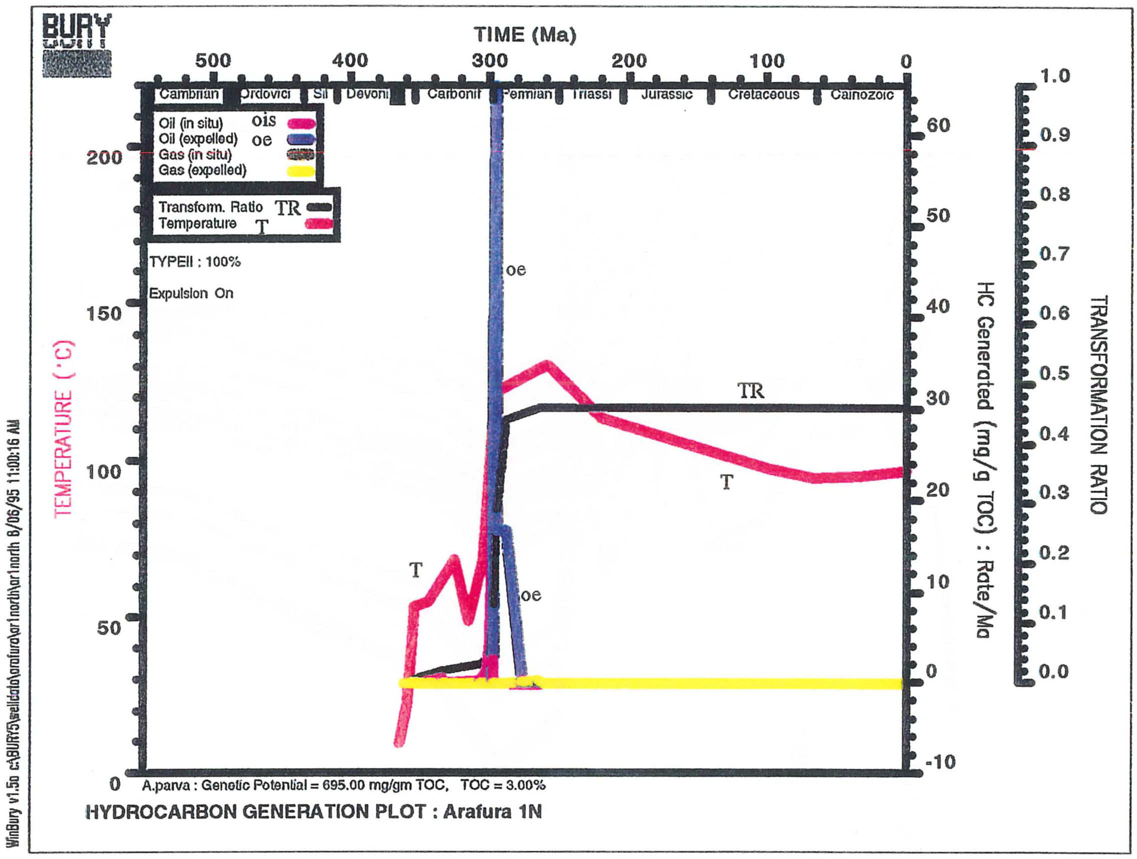
The plot of depth versus geological time, in the hypothetical well site Arafura 1North, shows the unconformities at this location in one of the deeper parts of the Goulburn Graben, eight kilometres downdip from Arafura 1. The oil shows at the well were in the Lower Ordovician carbonates (the *P. elegans* zone), and in the immediately overlying Lower Devonian dolomitic sandstone (*A. parva* zone), but at the well site these were immature for hydrocarbons and could not have generated the shows there.



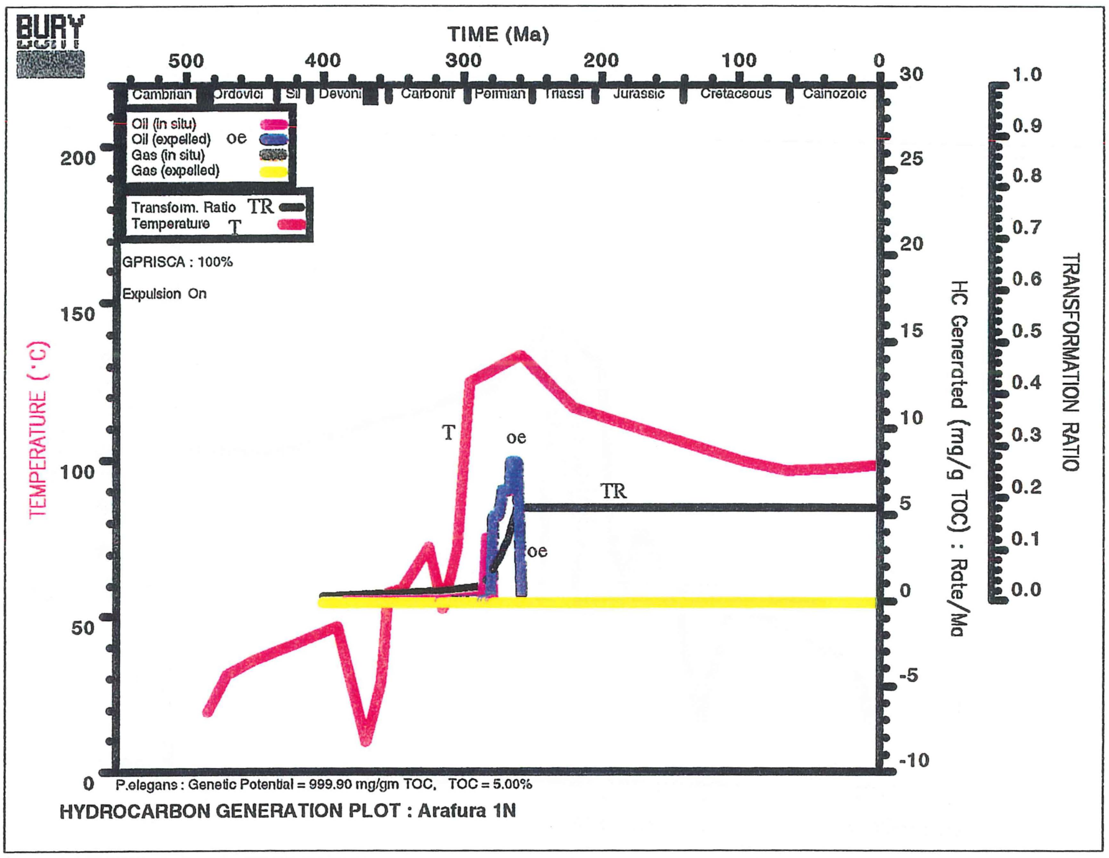
The model for the thermal history of this hypothetical site downdip from Arafura 1 is the same as that derived from the well data, (see the section on the Arafura 1 well) but applied here to a thicker Palaeozoic succession. The Devonian and the Lower Ordovician, which contain oil shows at the well, are mature here for hydrocarbons from type 2 kerogen, and have been so since the Permian. The Cambrian succession reached maturity during the Ordovician period, and today is late mature to post mature. The principal Ordovician kerogen, *Gleocapsomorpha prisca*, behaved differently, as explained in the next diagram.



The Ordovician oil-prone kerogen *G. prisca* generates hydrocarbons at > 130°C. This temperature was reached by the Ordovician succession in the Permian and early Triassic. The succeeding diastrophism that created the Goulburn Graben in its present form lifted this deep area up and out of the generation zone.

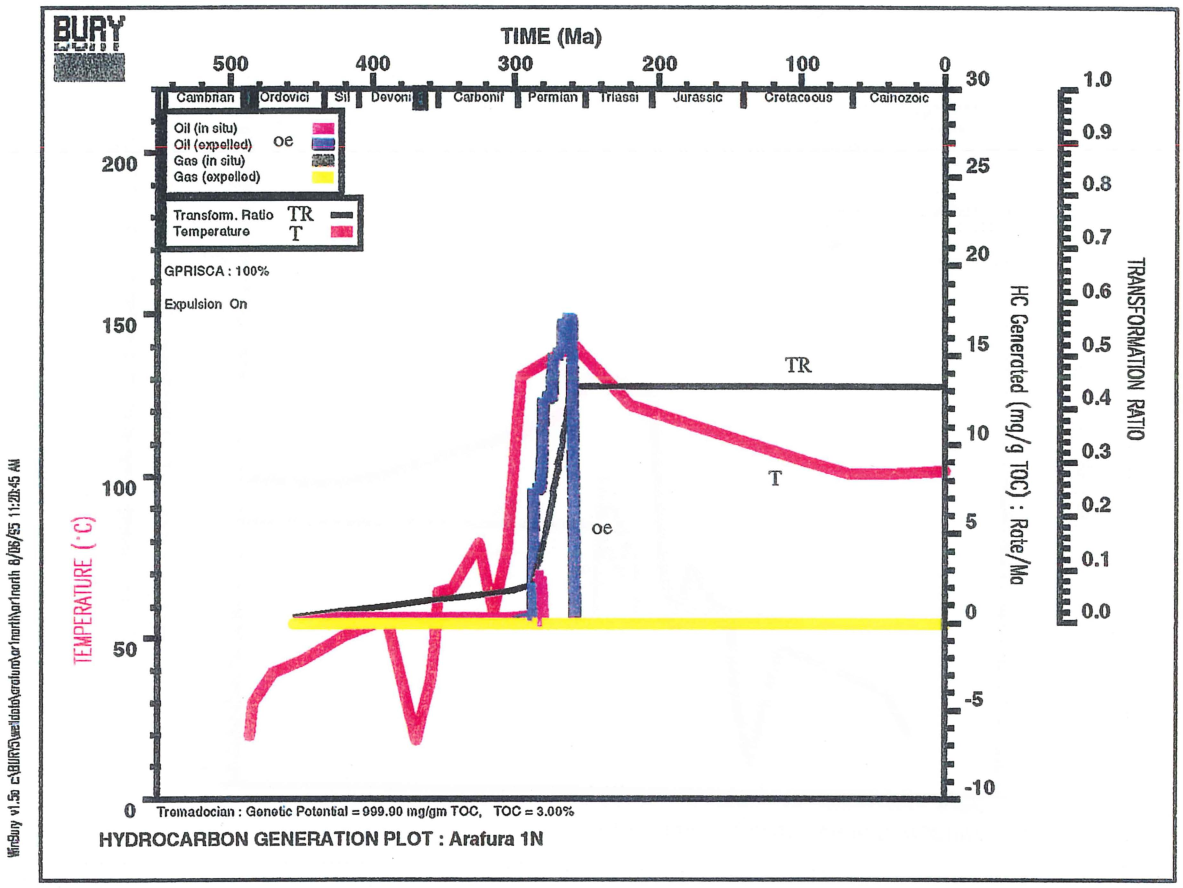


The Lower Devonian zone that contained the upper oil show of Arafura 1 was capable of generating hydrocarbons from type 2 kerogen during only the latest Carboniferous and earliest Permian. The source rock volume involved was very small. Together these time and volume considerations tend to disqualify the Devonian source rock, however promising, as the source of the oil show at this level in Arafura 1. A much larger volume of Ordovician and Cambrian source rocks was mature for hydrocarbons, and therefore they probably are the source of the oil shows at Arafura 1 updip from this site.



WinBury v1.5a c:\BURY5\welldata\arafura\ar1north\ar1north 8/06/95 11:12:23 AM

The behaviour of the *G. prisca* kerogen, an excellent Ordovician oil source, is modelled here at the same stratigraphic level as the best oil show at Arafura 1 well, a few kilometres updip from this site. If present, it would have become marginally mature for hydrocarbons during the earliest Permian, and continued generating until the middle Permian, when generation ceased. Because its depth of burial was marginal, only about one fifth of this kerogen would have been transformed to hydrocarbons. Other types of kerogen, with a lower maturity threshold temperature, were more likely to generate significant volumes of hydrocarbons in the Ordovician succession.



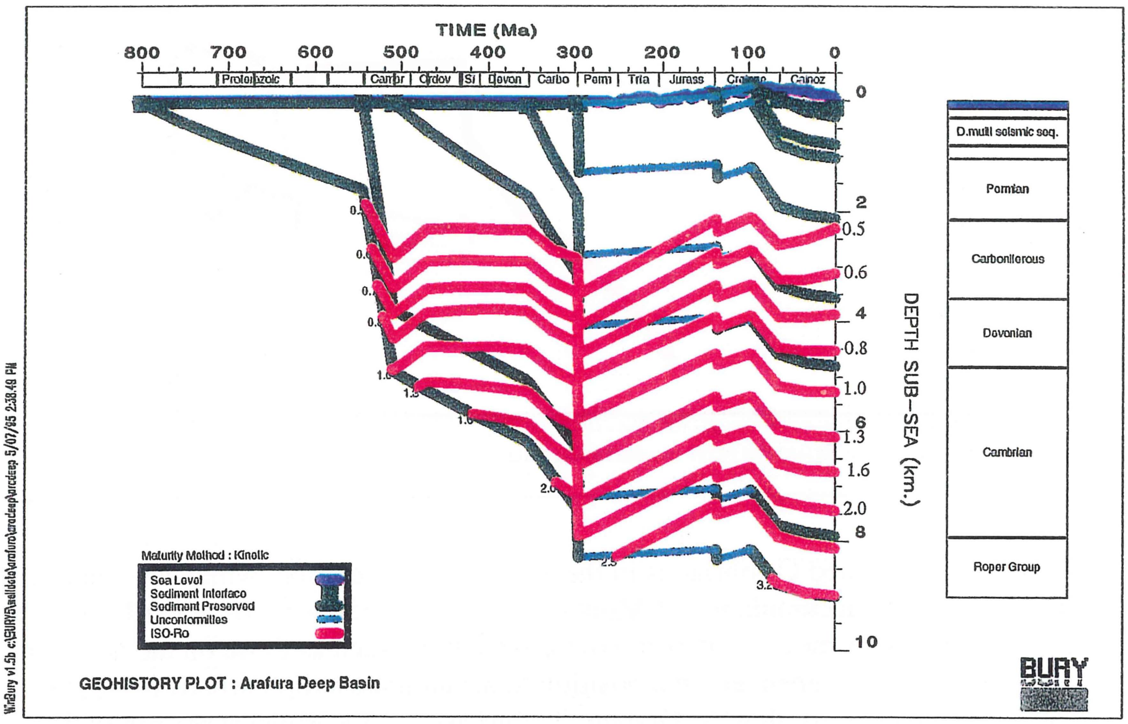
The lowermost Ordovician was moderately mature for a hypothetical *G. prisca* kerogen during the latest Carboniferous and early to mid Permian. Almost half was transformed to hydrocarbons. No significant gas was generated. This and deeper (Cambrian) levels, with whatever variety of kerogens they contained, are the most likely sources and locations for the oil shows seen in the Arafura 1 well. The area involved within the Goulburn Graben is quite small. Was there a bigger area of Ordovician shelf carbonate deposition north of the Graben? Older sources (Cambrian, late Proterozoic) probably were and are present north and east of the Graben, but have not been positively identified yet. Only the drill can do so. A possible oil province north of the Graben waits to be drilled for the first time.

ARADEEP BASIN

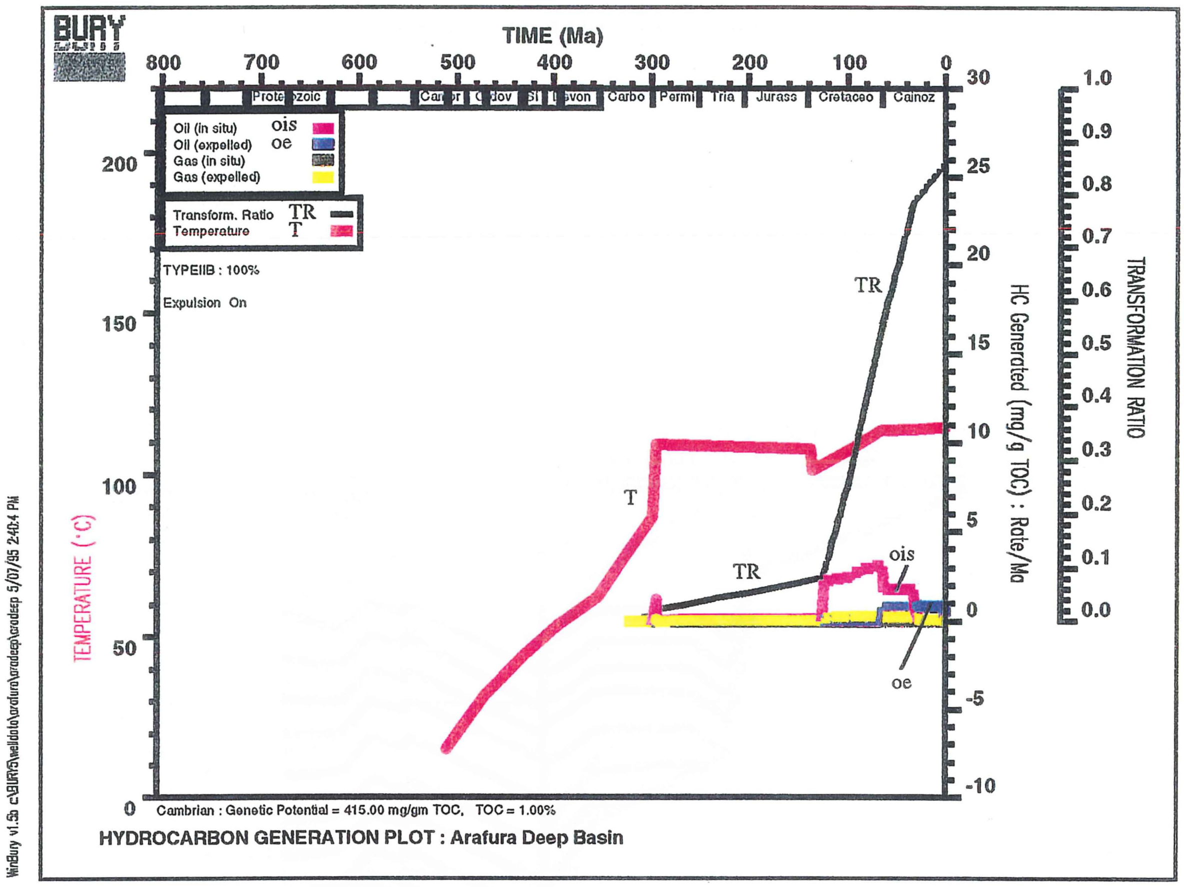
HYPOTHETICAL, 1995

Latitude: 10° 08' 55" S
Seis Loc. AGSO Line 94/09@sp4800
Sea Bottom Temperature: 25°C
BHT: 100°C (assumed)

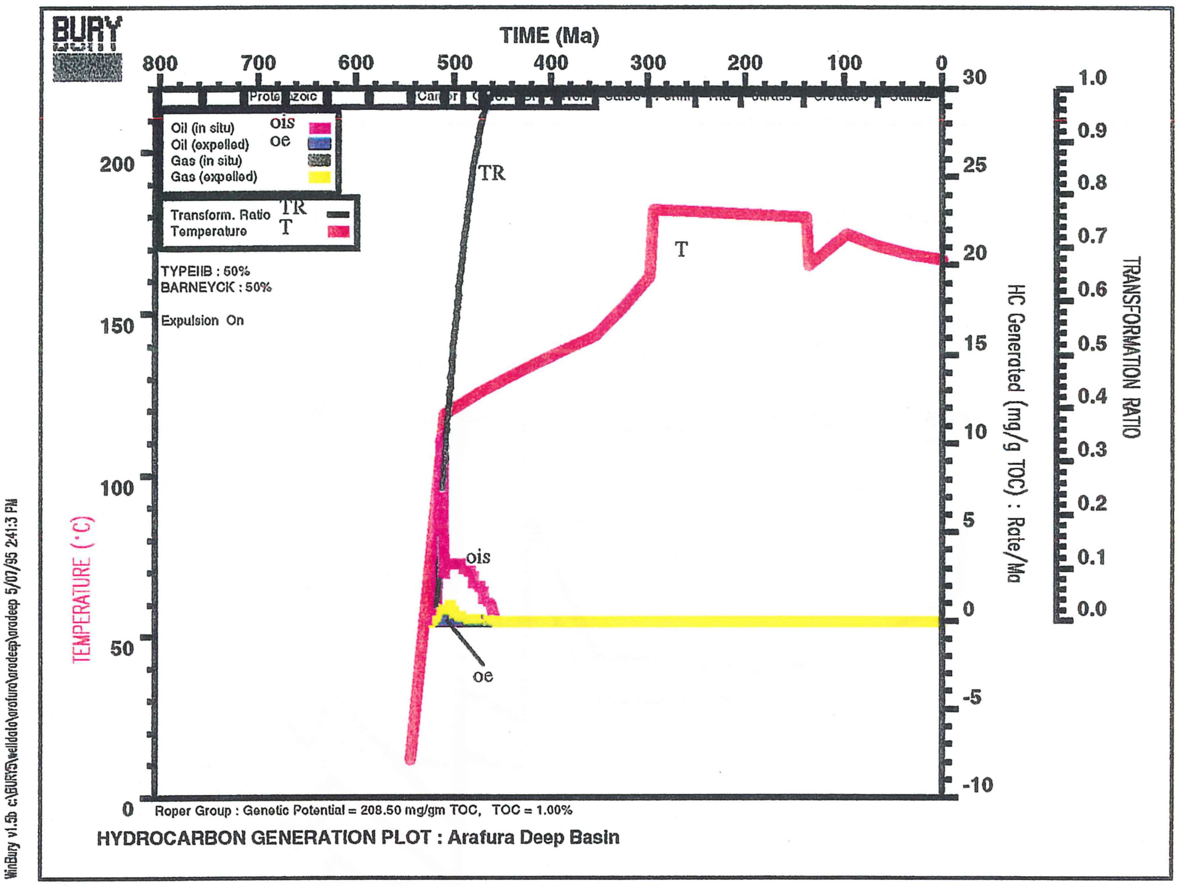
Longitude: 133° 15' 20" E
TD: 9000m (seismic datum)
Water Depth: 112m
BHT Depth: 4000m



At this hypothetical site in the undrilled northern province of the Arafura Basin to the north of and outside the Goulburn Graben, the very thick sedimentary succession is of unknown age, thought to be mainly Palaeozoic. Because of the low geothermal gradient, the oil window is about four kilometres thick. This enhances the chance that it contains hydrocarbon source rocks. Today the oil window lies in the Lower Palaeozoic.



The top of the presumed Cambrian is in the zone of oil generation, which was initiated and is driven by the accumulation of Money Shoal basin sediments from the Jurassic to the present time. This means that even young structures, such as those on the northern rim of the Goulburn Graben, are in a position to accumulate hydrocarbons from the northern basinal areas. Within the Graben, in contrast, hydrocarbons were generated during the early Palaeozoic. Consequently, structures within the feature formed too late to intercept them, and the Graben today is less prospective on this account than the northern basin.



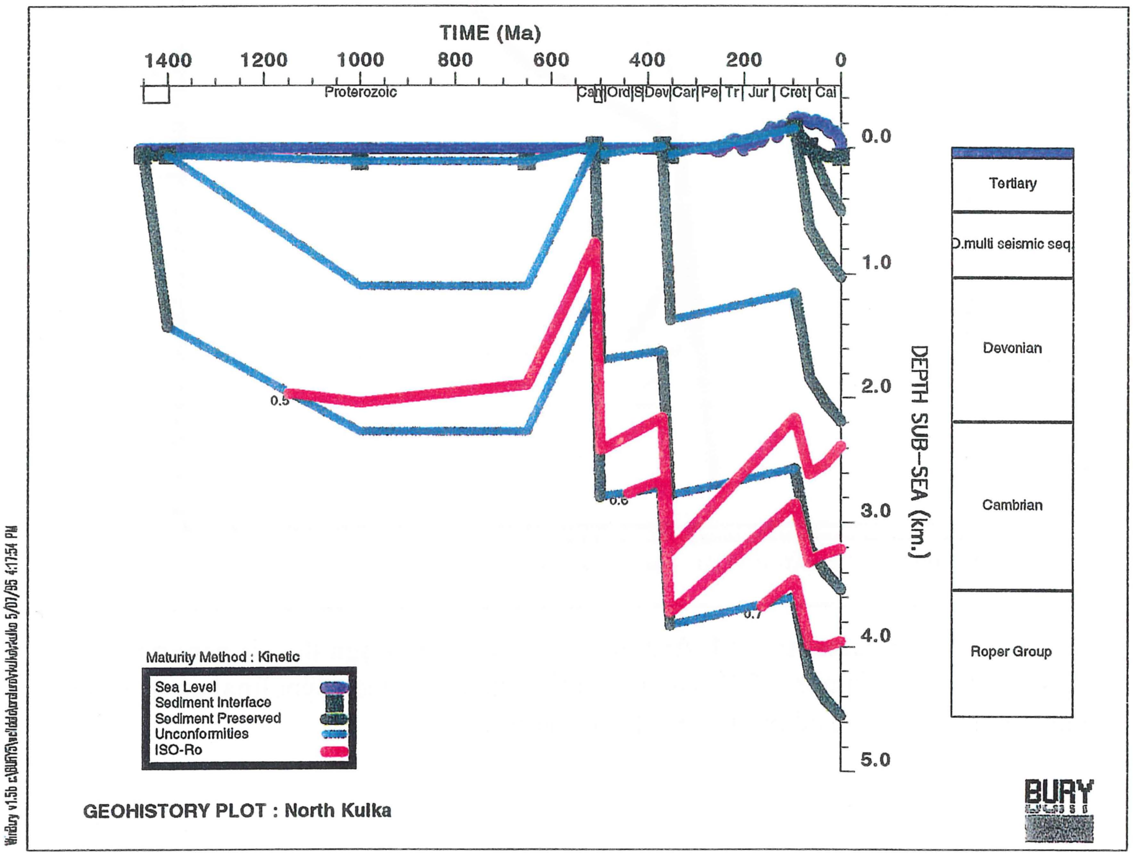
Sediments of the Precambrian McArthur Basin passed through the oil generation window during the Cambro-Ordovician at this site in the deep synclinal areas of the northern Arafura Sea. Today they are post mature.

NKULKA

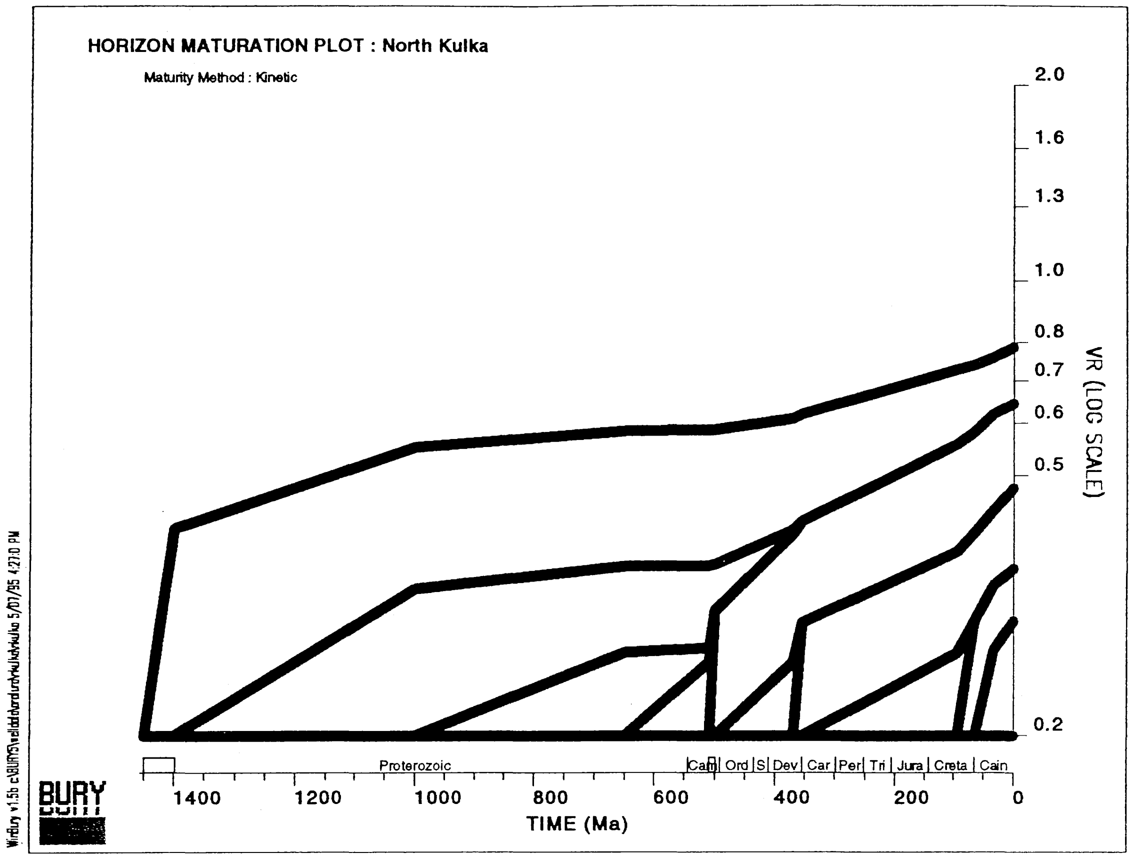
HYPOTHETICAL, 1995

Latitude: 9° 15' 24" S
Seis Loc AGSO line 94/4@sp9400
Sea Bottom Temperature: 25°C
BHT: 100°C (estimated)

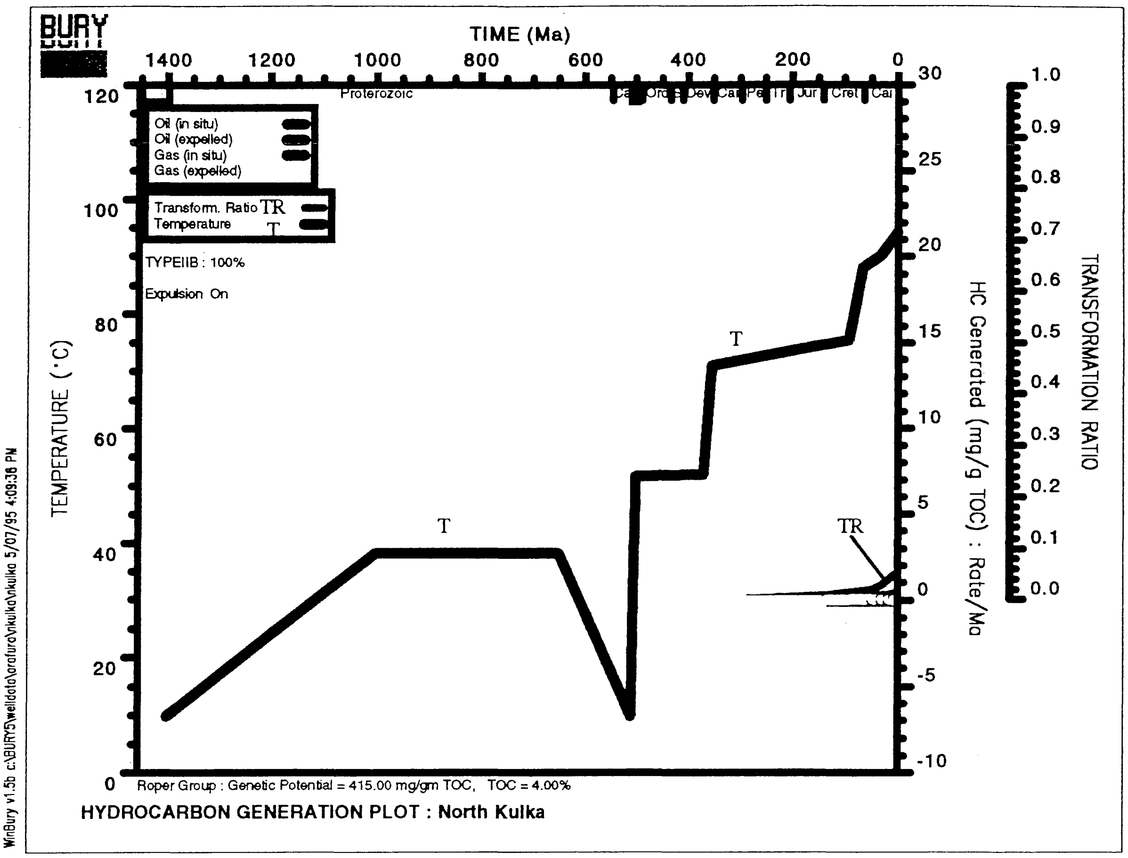
Longitude: 132° 57' 07" E
TD: 5000m (seismic datum)
Water Depth: 70m
BHT Depth: 4000m



The geohistory plot of the hypothetical North Kulka site in the north western Arafura sea shows the Proterozoic Roper Group of the McArthur Basin succession underlying the Palaeozoic Arafura Basin succession. The Proterozoic and the deeper part of the Cambrian are mature for hydrocarbons.



The plot of HC maturity through time shows that the Proterozoic Roper Group matured very slowly at North Kulka, reaching peak oil generation only in the later Mesozoic. Generation in the Proterozoic and Cambrian successions continues to the present day, driven by slow burial under the Money Shoal Basin succession. This means that existing structures of Palaeozoic age predate HC migration in this northwestern area. This prognosis depends on the assumption of a quiet tectonic history of the area, without episodes of great uplift and erosion (see below).



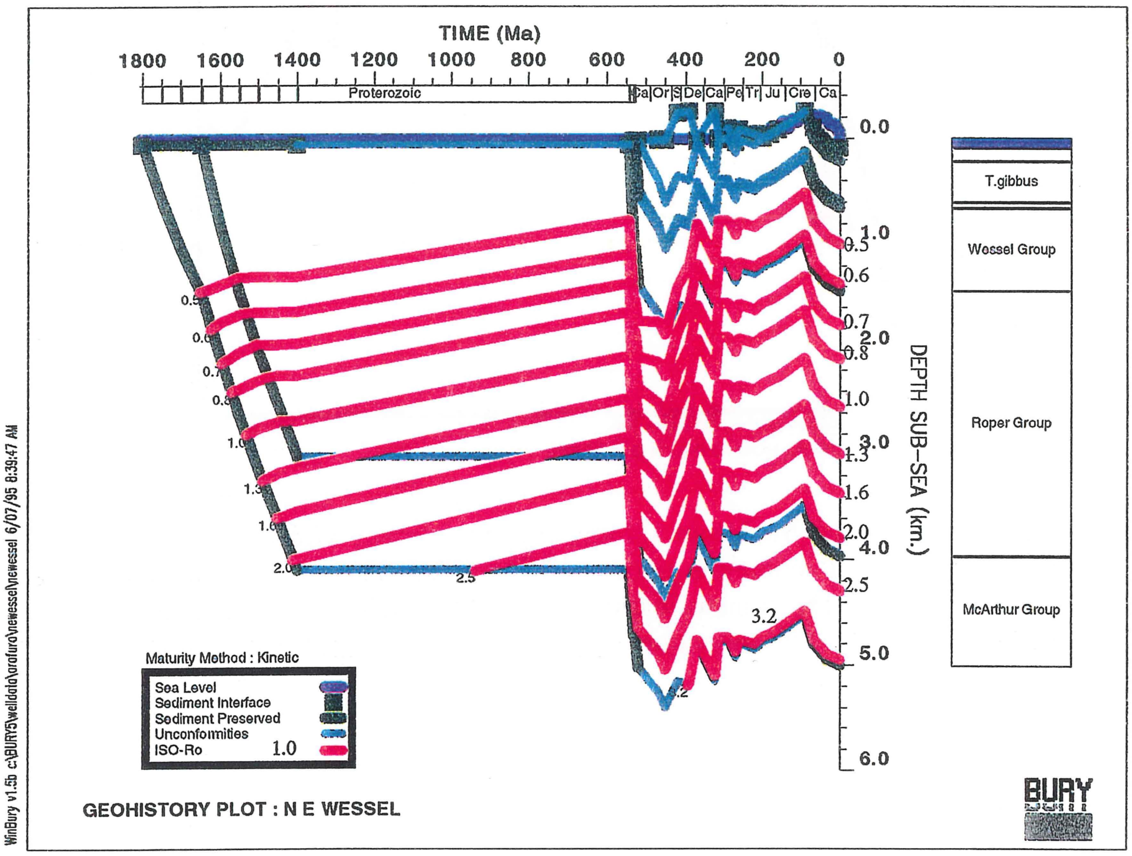
Hydrocarbon generation has only recently begun at the level of the basal Cambrian, top of Roper Group. Maturity is higher than this, and possibly near peak oil generation, at the level of the Velkerri formation oil source rock (Crick et al, 1988) within the Group. There are many unknowns, but in this model, 1000m of sediments younger than the Roper Group have been eroded from the basal Cambrian unconformity. If more was deposited and eroded, then oil generation could have begun earlier, even during the Proterozoic, and the model would require an internal seal to trap early-migrated oil within the Roper Group.

NORTH EAST WESSEL

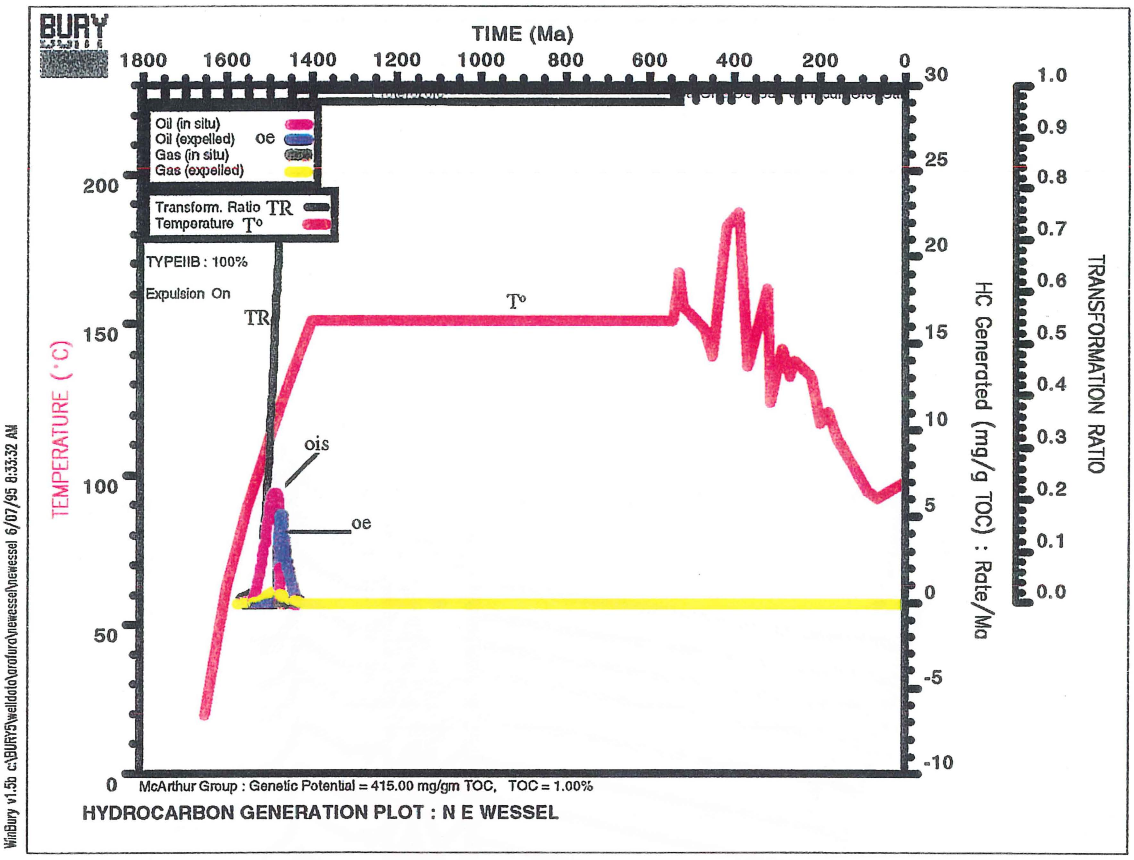
HYPOTHETICAL, 1995

Latitude: 10° 44' 36" S
Seis Loc. AGSO Line 106/06@sp600
Sea Bottom Temperature: 25°C
BHT: 100°C (assumed)

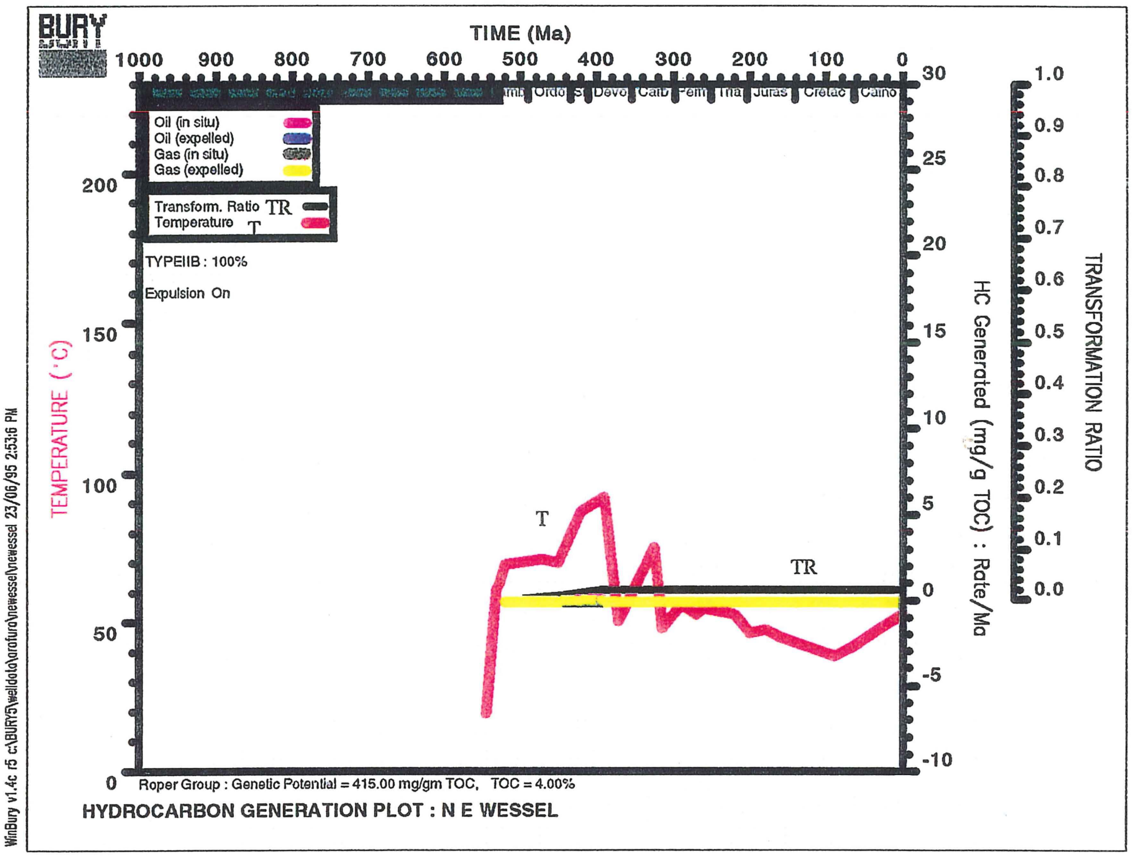
Longitude: 136° 44' 24" E
TD: 5000m (seismic datum)
Water Depth: 81m
BHT Depth: 4000m



At the hypothetical site northeast of the Wessel Islands, the Mesoproterozoic McArthur Group and the lowermost Roper Group are post mature for hydrocarbons. They passed through the 'oil window' during the Proterozoic. The upper Roper Group is within the oil window today, and the lowermost Cambrian is marginally mature.



The source rocks of the McArthur Group, e.g. the Barney Creek Formation, passed through the phase of oil generation prior to 1400 My BP. This plot shows the history of the top of the Group. The transformation ratio (TR) reached 1.0 (all type II kerogen converted) at 1450 Ma. Oil generation (ois) and expulsion (oe) was complete at 1400 Ma.



The top of the Neoproterozoic Roper Group is immature for hydrocarbons.
It did not reach maturity even during the era of maximum heating prior to the Devonian, but the more deeply buried Velkerri Formation oil source probably did. Analysis of this and the older McArthur Group confirms that the area is not now at its maximum geotemperature, and that the oil source rocks of the McArthur Basin probably expelled their hydrocarbons long ago in this part of the Arafura Sea. A play here would require old structuring. There is tentative seismic evidence of such old structuring nearby in what may be a continuation of the Batten Trough.

CONCLUSIONS

The geohistory studies based on well information and the referenced stratigraphic work, combined with the interpretation of AGSO's reconnaissance seismic, have led to the following conclusions -

The Arafura Basin, with its Lower Palaeozoic oil source rocks, probably extends north of the Goulburn Graben all the way to the limits of the Australian territorial seas, covering a very large undrilled area. The Meso- to Neoproterozoic McArthur Basin, which outcrops onshore, and contains oil source rocks, continues underneath the Arafura Basin north of the Goulburn Graben. Large volumes of this Proterozoic basin north of the graben, and older (Cambrian) successions of the predicted Palaeozoic basin, are now in the oil generation and migration zone.

The oil seen in the Lower Ordovician carbonate (the *P. elegans* zone) in Arafura 1 well originated in either that succession or the underlying Cambrian succession, and migrated only a short distance from downdip (from the north, see Arafura 1 North synthetic well location). The oil has been in its present site since about the late Permian period. It survived the Triassic diastrophism that accompanied the formation of the Goulburn Graben, possibly because the disruption of previous structure was gentler in the east than further west.
The oil seen in the calcareous Devonian (the *A. parva* zone) in Arafura 1 did not originate there, because that succession is not, and has not been mature for hydrocarbons. The volume of mature Devonian rock in the vicinity, i.e. in the east end of the graben, is very small. The oil show probably originated in the Ordovician or Cambrian succession and has remigrated a short distance vertically, and also a few kilometres updip, to its present level.

The most prospective section, the Cambrian and the lower Ordovician (Tremadocian), was heated early to maturity for hydrocarbons (HCs). This maturity was the result of both burial and elevated heatflow, and occurred as early as the Silurian in places, but almost everywhere within the future site of the Goulburn Graben before the end of the Permian. Likewise, where the Devonian and the Permo-Carboniferous succession have reached maturity, i.e. in the west, it occurred during the pronounced subsidence that preceded the uplift of the Torres Anticline and the formation of the Goulburn Graben in Triassic time. Most structural traps within the graben appear to post-date the main generative phases of HCs.

The various phases of tectonism and prolonged exposure and erosion that followed the early burial of Palaeozoic source rocks afforded ample opportunity for remigration or escape of the HCs that were generated within the graben. The extensive uplift that ensued brought very deeply buried reservoirs within range of the drill. These reservoirs have been degraded by the consequences of deep burial, such as compaction and the pressure solution of quartz.

The Mesozoic and Cainozoic successions that followed the last phase of tectonism in the mid Cretaceous are almost everywhere immature for HCs.

Hydrocarbon exploration strategy should look for early-formed traps that might have intercepted the possibly prolific HCs expelled during the Palaeozoic, or for areas with late migration. The most likely location for these is outside the Goulburn Graben to the north, where structuring appears to be older, and migration later. The Lower Palaeozoic succession outside the graben was probably not subjected to early deep burial. Therefore it is now more prospective on the grounds of timing, because it remained immature in places until more recent burial by the Money Shoal Basin succession. Within the graben, the Cambro Ordovician and the Devono-Ordovician time-thickness (isotime) maps show thins east of Money Shoal and southwest of Arafura 1 that suggest early structuring there. These areas were extensively remodelled during graben formation, with the risk that hydrocarbon traps may have been disrupted. There is fragmentary evidence of early trap formation in the far eastern end of the graben, and there was less disruption of early structure there.

If, as appears likely, the northern areas of the Arafura Sea were not subjected to the same intensity of subsidence, tectonism and uplift as those within the Goulburn Graben, then the reservoirs may not be as greatly damaged by diagenesis as those in the graben have proven to be. The AGSO seismic indicates that the northern Arafura Sea had an uneventful tectonic history, which is a positive factor for prospectivity in very old basins. There is an analogy here with the Canning Basin, where the Upper Palaeozoic reservoirs commonly are poor in the Fitzroy Graben, but the Lower Palaeozoic ones are often very good, with higher porosity and permeability, on the flanking terrace or platform areas.

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APPENDIX 1

PRELIMINARY ANALYSIS OF ARAFURA-1 ORGANIC MATTER

BMR #	DEPTH m	TYPE	AGE	TOC	Tmax	S1	S2	H1	O1
5091	1429.9	Core#2	Dev	0.18	438	0.01	0.12	60	635
5092	1433.6	Core#2	Dev	0.76	422	5.68	2.97	371	157
5093	1714.8	Core#3	Ord	0.08	428	0.00	0.02	20	760
5094	1722.3	Core#4	Ord	0.11	389	0.00	0.05	50	690
5095	1716.7	Core#3	Ord	0.10	275	0.00	0.02	20	390
5096	1939.9	Core#5	Ord	0.12	275	0.00	0.02	20	610
5097	3294-96	Cuttings	?	0.58	450	0.25	0.88	146	166
5098	3488-92	Cuttings	?	3.64	451	1.59	7.43	206	40
5099	3494-96	Cuttings	?	3.78	450	2.11	7.37	193	44
5100	3574-76	Cuttings	?	1.05	457	0.48	1.29	117	130

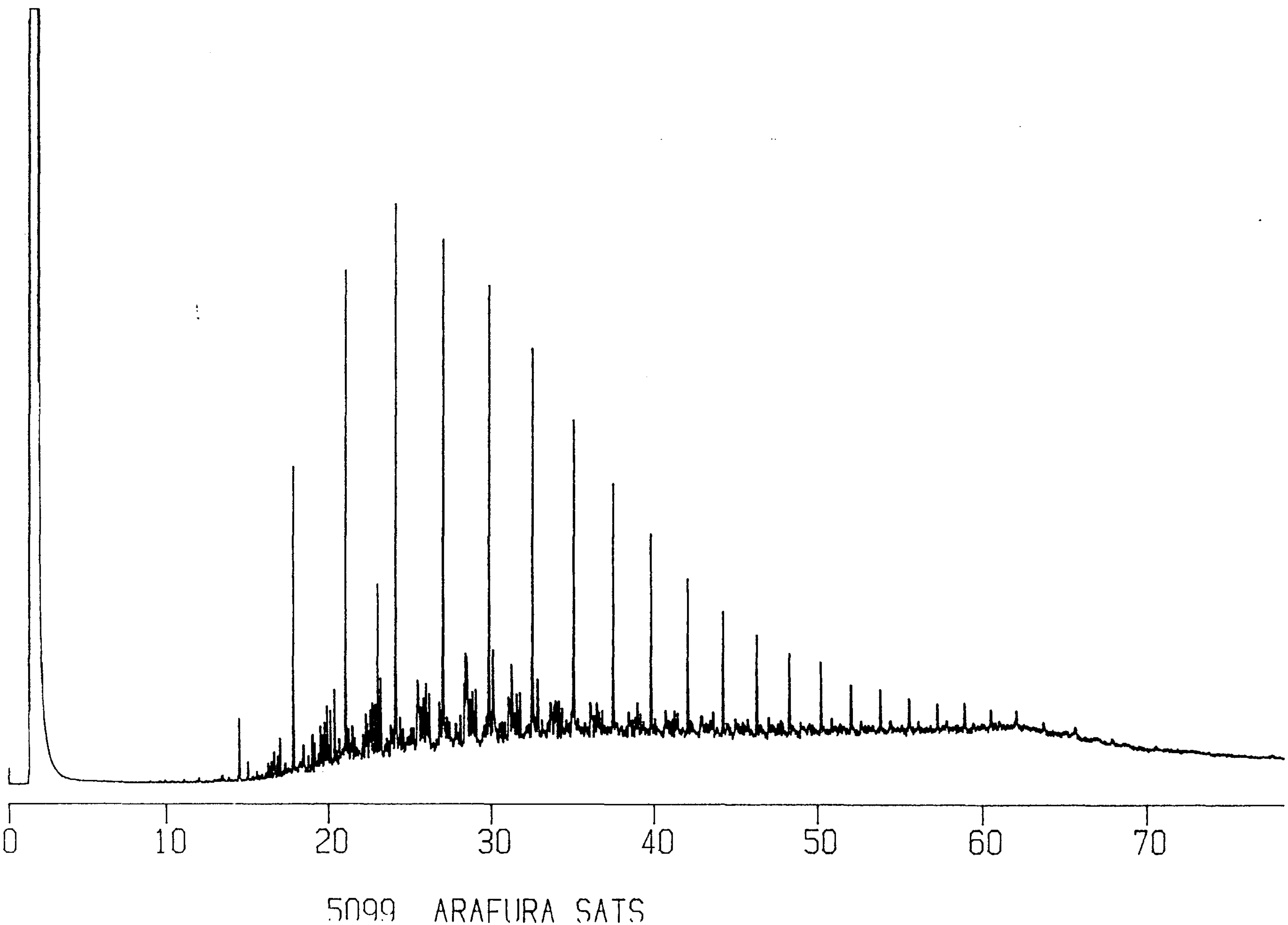
Analysis of the Rock-Eval data, and the composition of hydrocarbons extraacted from these samples, shows that the high TOC Devonian core (#5092) contains a biodegraded oil. There is also a small amount of kerogen present in this core, and this may well be associated with the oil.

The three organic rich cuttings samples from deeper in the hole (#5098, 5099 and 5100) contain mature kerogen and have high production indices of 0.18 and 0.22 and 0.27. The bitumens present here show characteristics often seen in lower Palaeozoic marine shales, though it is clearly not the pattern associated with Middle Ordovician (*G. prisca* - sourced) oils such as those seen in the Canning and Amadeus Basins. These samples are apparently from a Cambrian marine shale sequence and the biomarker patterns are quite consistent with this. The biomarker characteristics also indicate that these deeper bitumens are different to the one present in the Devonian core. This latter sample may have a carbonate or mixed clastic-carbonate source.

All the bitumens present in Arafura-1 are quite distinctly different to the bitumen stranding from Cobourg Peninsula (#442).

Chromatograms of the saturated hydrocarbon fractions are attached. We are currently looking at samples from Goulburn-1 and preliminary examination of Rock-Eval data suggests we have no source here, just a residual bitumen in one of the smples (ca. 910m).

Data and analysis by:
J.M. Hope, G.B. Hieshima and R.E. Summons
7 June 1990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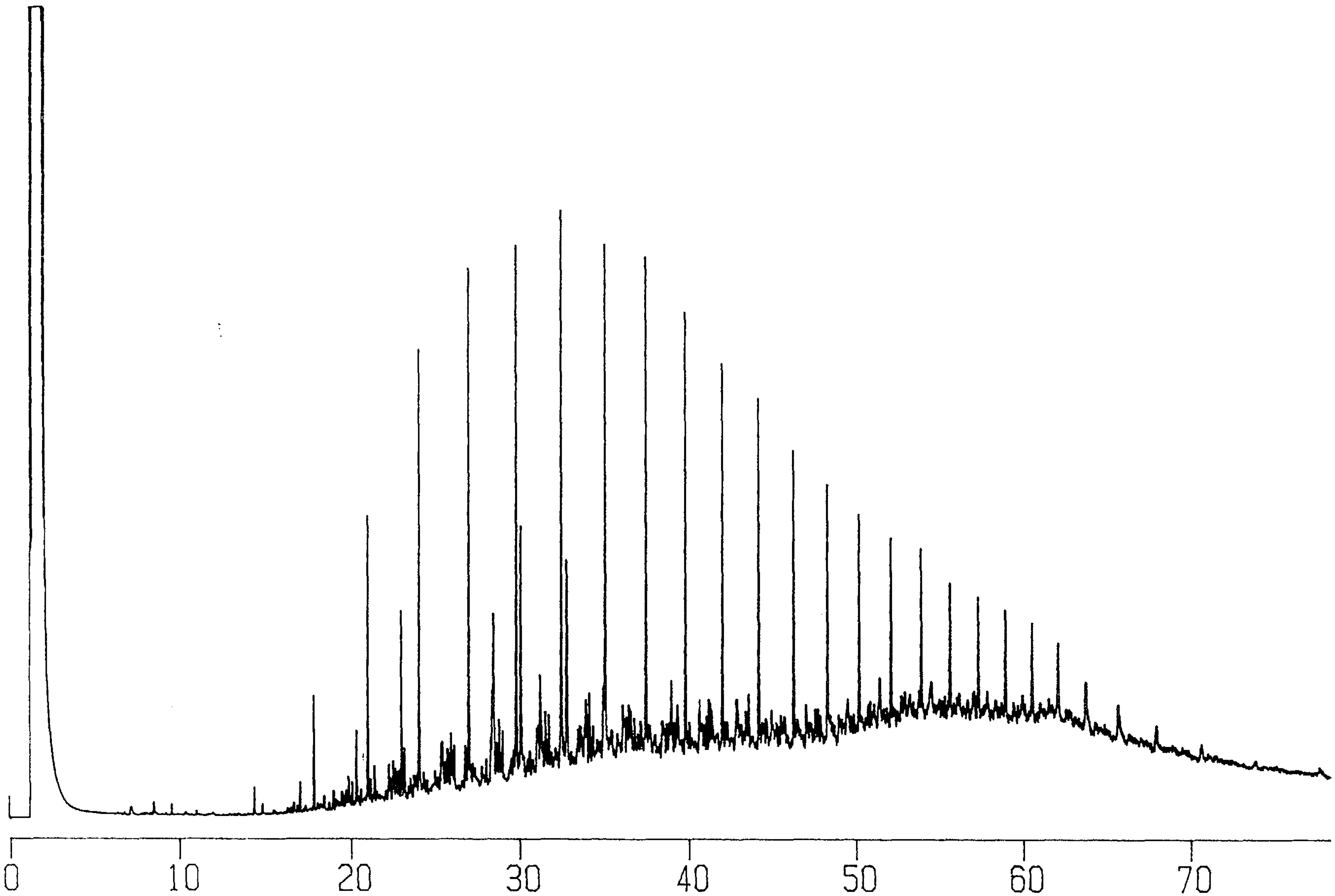
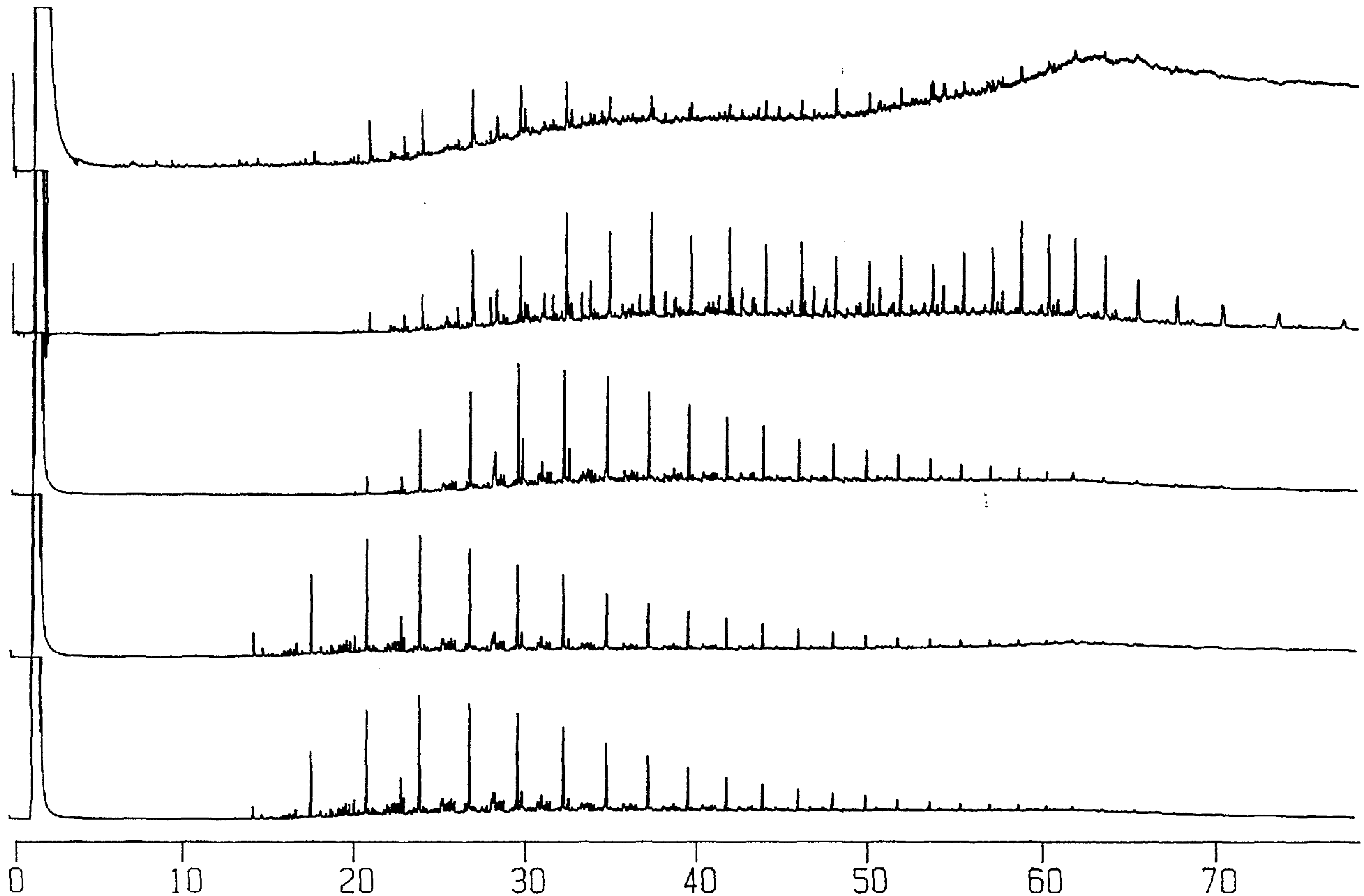
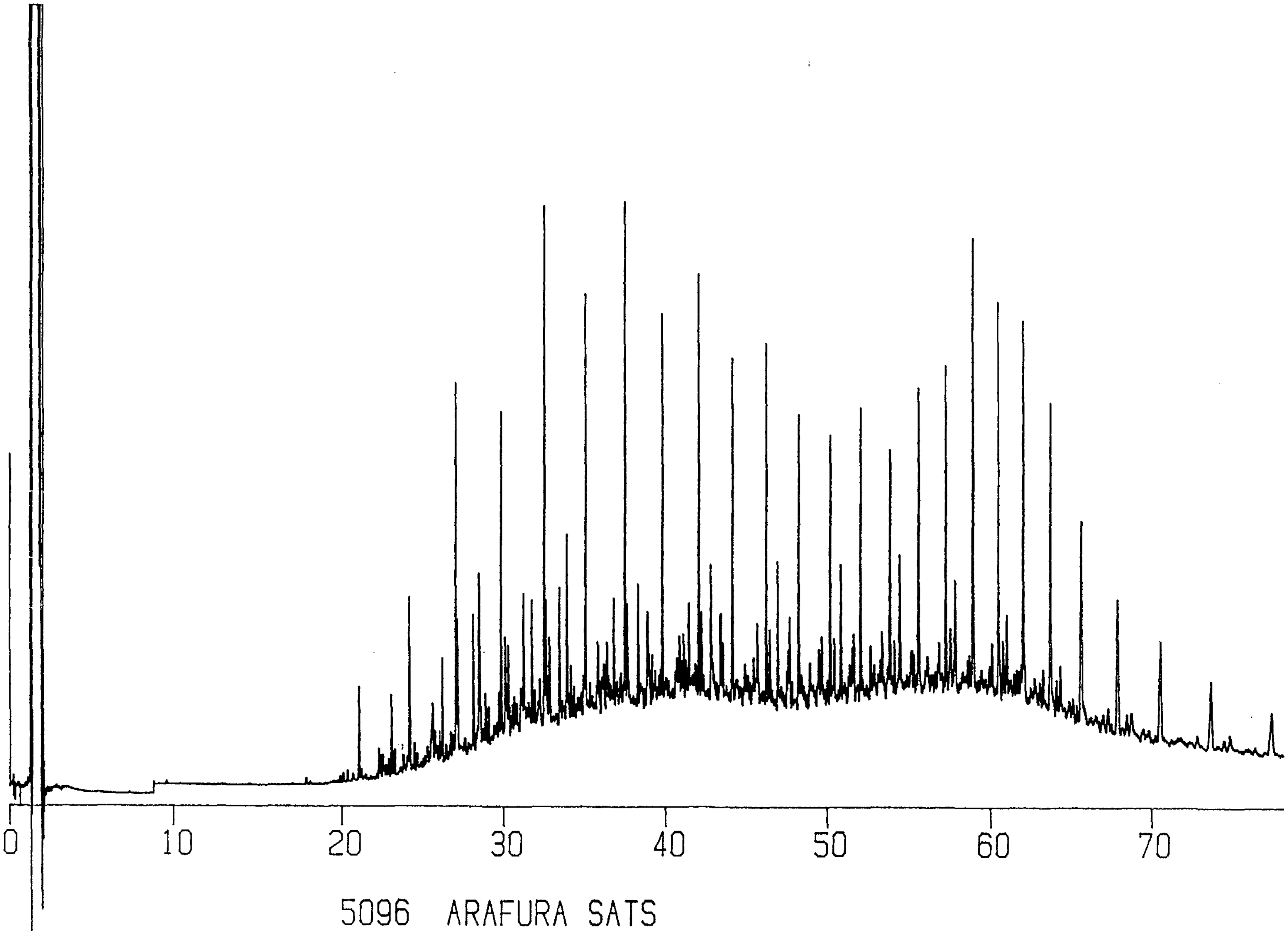


5100 ARAFURA SATS



ARAFURA-5092 5096 5097 5098 5099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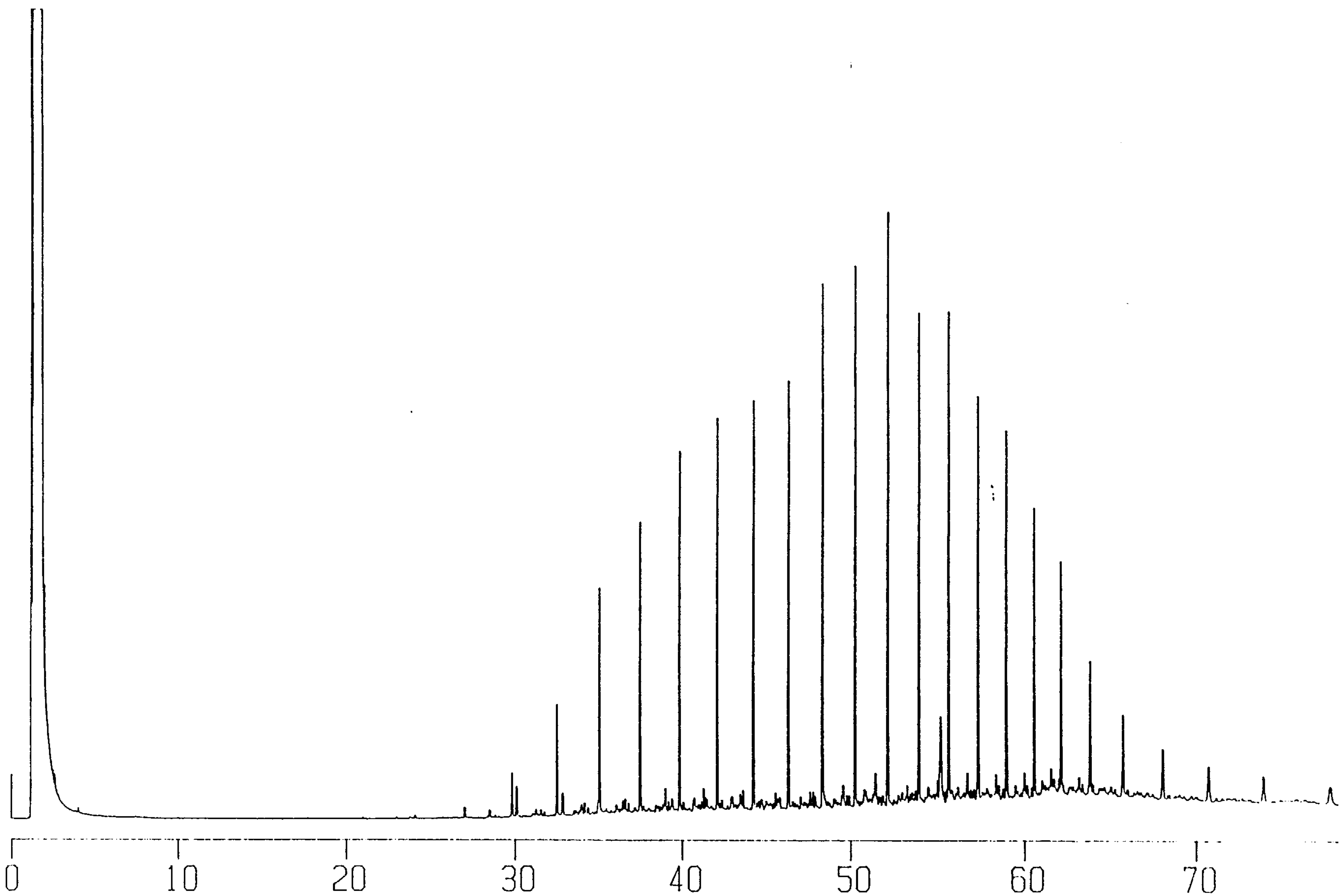
5096 ARAFURA SATS



442 COBOURG PEN SATS