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An interpretation of the geothermal history of the Otway Basin based on vitrinite reflectance and fission track analyses

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AN INTERPRETATION OF THE GEOTHERMAL HISTORY OF THE OTWAY BASIN BASED ON VITRINITE REFLECTANCE AND FISSION TRACK ANALYSES.

Submitted as Part of the Requirements
for the degree of M. Sc., (Coal Geology)
UNIVERSITY OF WOLLONGONG, N.S.W.
by
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INDEX

1. ABSTRACT

The study of the maturation of organic matter is of interest to the Petroleum Exploration Industry.

Liquid hydrocarbons are generated over a restricted maturation interval, and are related to a time, temperature function.

Techniques now available for determining the location of the hydro-carbon -generating interval in a sedimentary basin; are "fission track" a time-consuming quasi-academic technique, and vitrinite reflectance - a fully commercial technique, that takes a fraction of the time.

The Regional and Local tectonic setting of the Otway Basin is discussed.

The wells discussed are:

Onshore	Offshore
Tullich 1	Voluta 1
Casterton 1	
Eumeralla 1	
Flaxman 1	
Ferguson's Hill 1	
Olangolah 1	
Krumbruk 13	

The relevance of these wells in relation to the tectonic setting is as follows:-

Wells Tullich 1 to Ferguson Hill 1 are located onshore in a relatively undisturbed block, Olangolah 1 and Krumbruk 13 are located on the uplifted overthrust Otway Range Block, while Voluta 1 is representative of the offshore post Australia-Antarctic separation basin.

The Fission Track - where available - and Vitrinite Reflectance data are discussed for each well and it seems that the two systems are complementary, in that a small amount of expensive fission track information can lead to the reinterpretation of a large amount of

cheaper vitrinite reflectance data, and yield a better understanding of the relevant basin's thermal history.

2. INTRODUCTION

The maturity or rank of organic matter in sedimentary basins is one of several factors which establish the suitability of that basin for petroleum exploration.

Oil source rocks and sedimentary basins are commonly classified as immature, if they have not yet begun to generate oil, mature when they are currently generating oil, or overmature when they are generating condensate or dry gas only. Vitrinite, a constituent of coal and present in many sediments, is very sensitive to changes in temperature over a long period of time. Its' reflectance is a most discriminating indicator of coal rank and hence of source rock maturity. Vitrinite reflectance data are also the basis of a number of coalification models which relate time to the temperature of organic metamorphism. (Kantsler, A. J. & Cook , A.C. 1978(a), Stach, E. 1982, Tissot, B.P. & Welte, D.H. 1978).

The generation of liquid hydrocarbons in sedimentary rocks is largely a function of the extent to which suitable source beds have been heated into the 60°C to 130°C temperature window.

Fission track dating of detrital apatites in sedimentary rocks provides a relatively new and alternative method for directly interpreting the thermal evolution of sedimentary basins. Fission tracks in apatite, caused by radiation damage from the spontaneous nuclear fission of U238, are stable over geological time only at relatively low temperatures. As temperatures are increased the tracks begin to fade, and these tracks are eventually lost, effectively resetting the age. This process, called track annealing is a most useful aspect of fission track dating, making apatite a natural recording geothermometer.

Annealing of fission tracks occurs progressively over a temperature range which is called the track annealing range. For apatite this range is from 70°C to 125°C, which is within the hydrocarbon generating window of 60° to 130° (Gleadow et al 1983)

The present study of 7 deep wells in the onshore Otway Basin and 1 representative offshore well is an attempt to compare the results of the two methods and determine their relative advantages in the location and recognition of the hydrocarbon generating window.

3. THE VITRINITE REFLECTANCE TECHNIQUE

3. (a) Reflectance Measurement (Rank)

Since oil and gas are released during the alteration of organic matter in sedimentary rocks by geothermal heating over long periods of time, the study of rank via vitrinite reflectance data is an indication of the likely release of oil and gas products, which may then be exploited. [Kantsler et al, 1978 (a)]. Data world wide tend to indicate that petroleum generation and entrapment are enhanced in basins of high heat flow, and therefore of rank increase. (Kantsler et al 1978 (b) and Fig. 1)

The alteration of hydrocarbons with increasing maturity and their later destruction can also be correlated with rank. Therefore, rank data are of immediate use to hydrocarbon explorers in relatively new and untested areas, as they establish the nature and depth of possible pay zones and help delineate the most prospective horizons. In well-drilled producing and non-producing basins such data can be used to establish the history of hydrocarbon generation, and are also of use in evaluating possible new prospective horizons. [Kantsler et al 1978 (b),].

The vitrinite reflectance data are only completely reliable with samples from drill core, since only then can the samples be correctly orientated and their depths known accurately.

Cuttings may or may not give reliable results - though cavings and other extraneous material can commonly be detected if the samples are studied systematically down a single drillhole, at one time. Samples also lack orientation, and the settling characteristics mean that coal fragments may be lost or gained, in the block preparation, relative to the amount present at the depth from which the bulk of the sample has been derived. However, reflectance techniques are relatively insensitive to non-representivity of samples and to organic matter type.

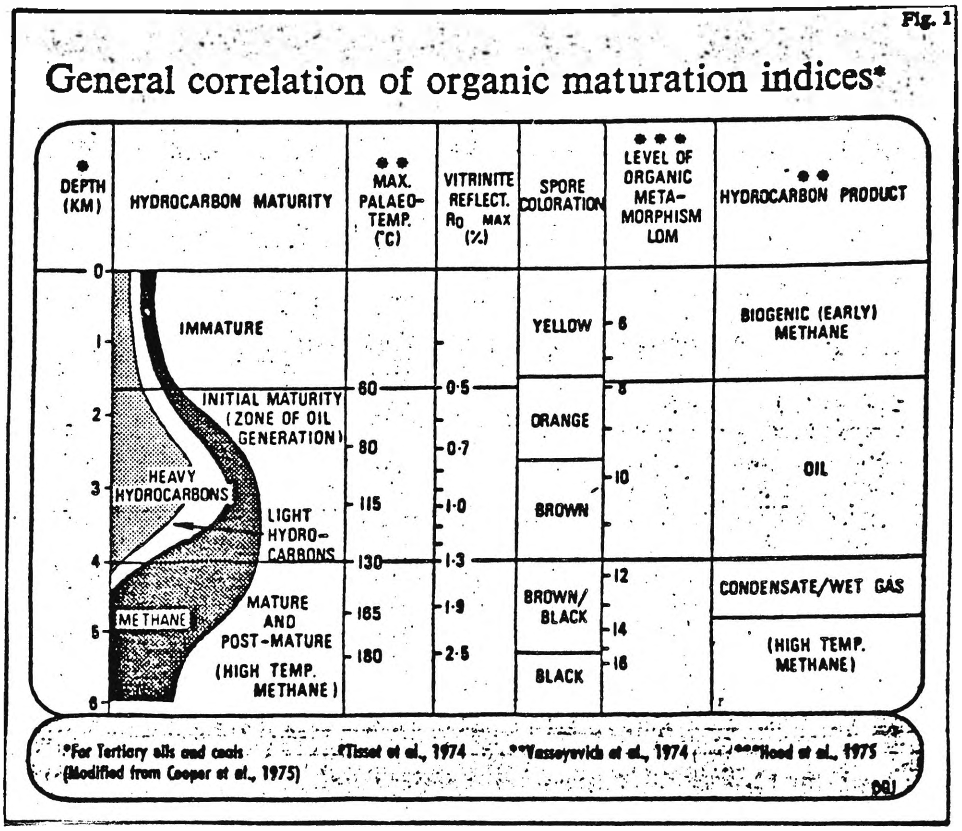


Fig. 1 From: Kantsler et al., The Oil and Gas Journal, 1978.

KARWEIL DIAGRAM (AFTER BOSTICK)

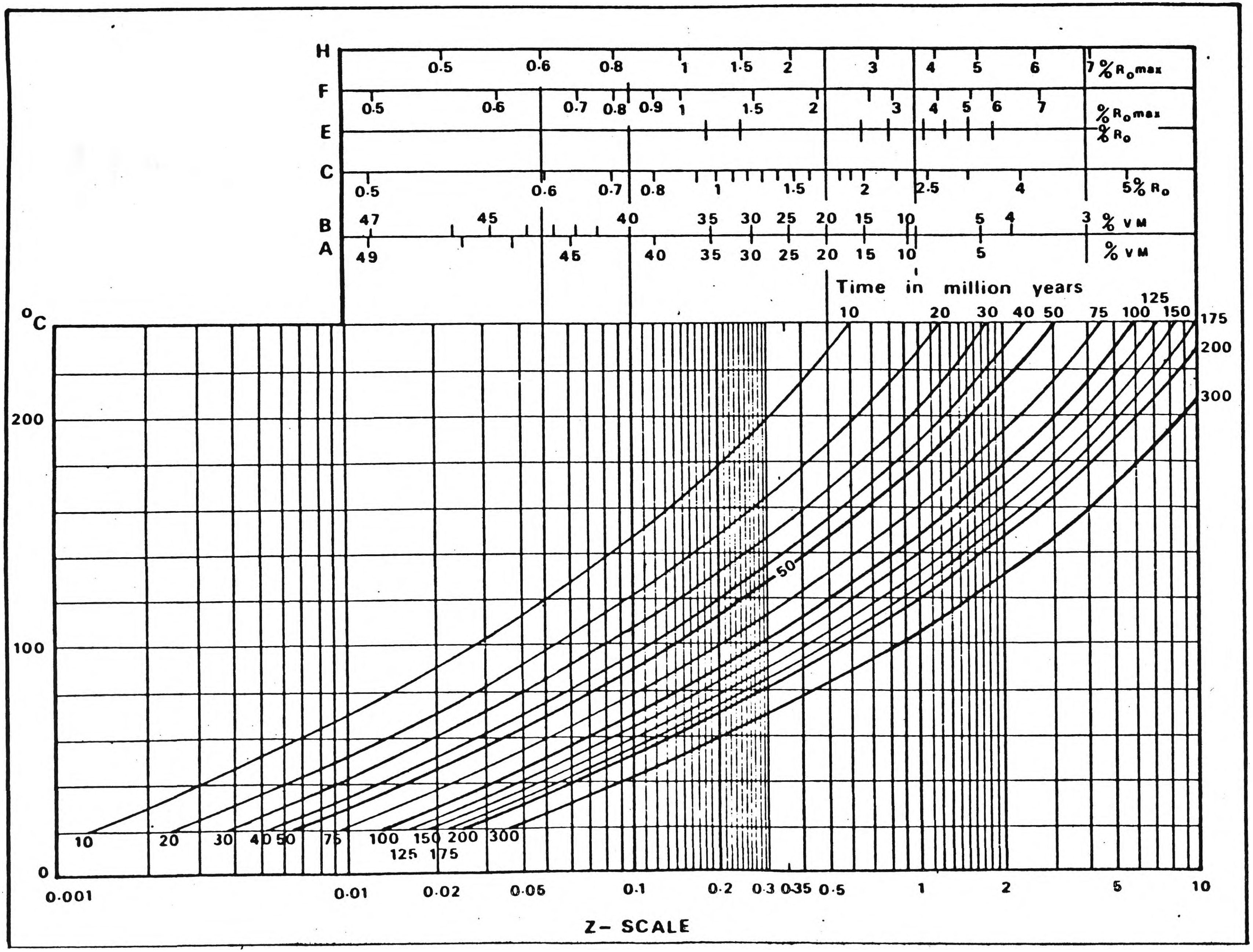


FIGURE 2 - From Cook, 1982(a)

3. (b) Palaeotemperature

The Karweil/Bostock Nomograph [Kantsler et al 1978 (a)]

A transformation has been developed which converts the mean maximum vitrinite reflectance to give the isothermal temperature via the Karweil/Bostock nomograph. In turn the final, or gradthermal temperature, can be calculated. This temperature would produce the same amount of coalification, if the temperature had risen uniformly since time of deposition of the sediment. However, calculated palaeotemperatures are heavily dependent on a number of input assumptions as well as being subject to inaccuracies in the models. Ordering of the data from individual wells according to how well they fit the various models minimum systematic errors and allows inferences to be made regarding relative aspects of thermal history of a sedimentary basin. [Kantsler et al 1978 (a)].

The Lopatin Method [Waples 1981]

High temperature acting for a short time can have the same effect on oil generation and destruction as a lower temperature acting over a longer period of time. Lopatin therefore concluded that doubling the reaction rate with each increase in temperature of 10°C provides a suitable model of the relative effects of temperature and time in organic metamorphism. In addition Lopatin described a temperature and time period index (T.T.I.) Using this index the onset of oil generation is 15 (R_o = 0.65%) the peak at 75 (R_o = 1.0%) and the end of oil generation at 160 (R_o = 1.30%). This is a cumulative maturity index and it is calculated using a reconstruction of the subsidence curve and either the present geothermal gradient or a series of assumed gradients.

The L.O.M. Method [Hood et al 1975]

This is an approximately linear scale of the level of organic maturity (L.O.M.). This scale is based on a combination of maximum temperature with an effective heating time. This is used to determine subsurface depths at which oil and gas are generated from the kerogens of those rocks.The scale goes from 0 to 20, starting with low rank lignite through to high rank anthracite with the oil generation zone being in the interval from L.O.M. 7.0-11. The L.O.M. is therefore a derived scale based on vitrinite reflectance or on max.temperature, as well as effective heating time.

4. FISSION TRACK DATING TECHNIQUE

(Refer to figures 3 to 6).

Fission track dating is a relatively new approach to the interpretation and quantitative modelling of thermal histories of sedimentary basins for hydrocarbon resource evaluation. This technique depends on the observation that annealing of fission tracks in minerals, like the generation and maturation of hydrocarbons, is a function of temperature and time. The temperature interval over which track annealing occurs in the mineral apatite for example, a common detrital mineral in sedimentary rocks is, virtually the same (50°C to 125°C) as that required for the maximum generation of liquid hydrocarbons. Fission tracks formed in apatite which has been separated from a rock sample, thus contain a record of its heating in the oil generation window. The pattern of apatite fission track ages, together with detailed analyses of the distribution of track lengths, thus yield information on thermal history unobtainable by other methods. The unique advantage of the fission track method is that it can give quantitative information not only on maximum palaeotemperatures, but also their variation through time.

Fission tracks formed in detrital zircon and sphene are stable at higher temperatures (200°-300°) than is the case with apatite, enabling limits to be placed on maximum temperatures reached in sedimentary basins, as well as giving important information on sedimentary provenance, via heavy mineral age and type.

For the Otway Basin fission track ages and lengths determined on apatites and ages determined on sphenes and zircons, have been used by Messrs. Gleadow and Duddy to reconstruct the thermal histories of different portions of the basin Ages and track lengths of apatites from deep wells in the Otway Basin show the expected down hole decrease reaching zero apparent age where present well temperatures are about 125°C. The shape of the track length distribution curve is characteristic of the position of a sample within the track annealing zone, and hence the oil generation window.

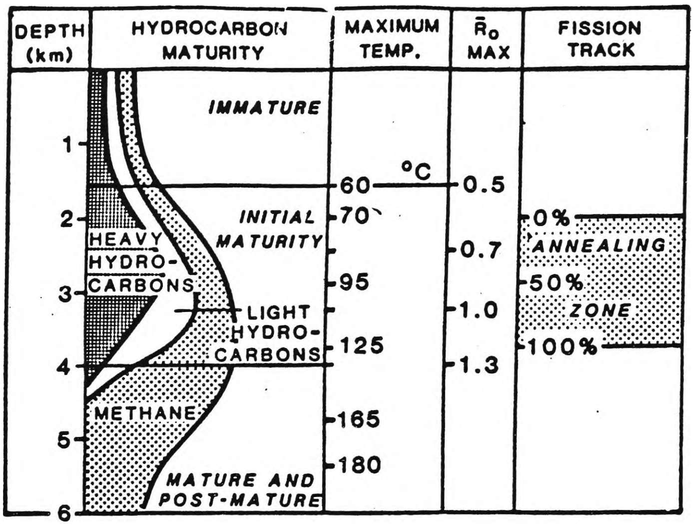


Fig.3 The Relationship between the fission track annealing zone in apatite, temperature and hydrocarbon maturity (From: Gleadow et al., 1983)

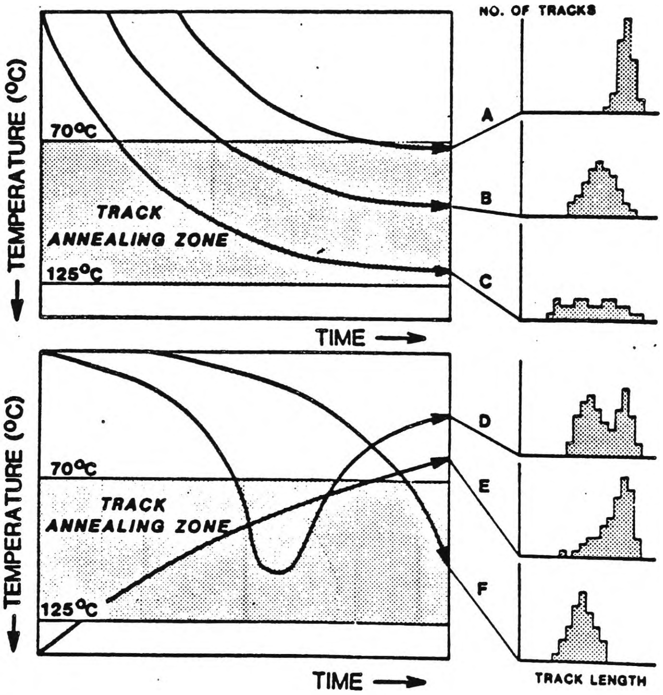


Fig. 4 Temperature-time paths and the resulting apatite track length distributions for rocks of varying thermal history. The upper three (A, B and C) show the evolution of the temperatures for progressive burial to different levels in the track annealing zone. The lower three distributions show the patterns for a past thermal event (D), slow cooling (E) and a recent heating event (F). [From Gleadow et al 1983.]

Fission track analysis thus has the potential within the constraints of present models, of giving a new, quantitative perspective on the temperature history of rocks.

Interpretation of Track Length Distributions

The length reduction patterns discussed in the paper by Gleadow et al 1983 provide a basis for interpreting length distributions in various geological environments. Figure 4 shows a number of hypothetical temperature-time plots and the resulting apatite length distributions. The upper three examples show a simple burial history like that interpreted for Flaxman 1 giving apatite length patterns essentially in equilibrium with the present day annealing zone. The lower three show the characteristic bimodal length distribution typical of slow cooling through the annealing zone, and the entirely shortened distribution produced by a recent temperature increase.

Bimodal distributions consist of two major length components: those that were annealed together during the heating event and those that have formed since cooling to lower temperatures. In such cases the time of heating can be obtained by statistically separating the two components and estimating the contribution of the longer group to the total age. A bimodal distribution is comparable to that from a partial laboratory annealing to which a new generation of long tracks has been added. Skewed distributions, characteristic of slow-cooling histories, are essentially the summation of the three length distributions shown in the case of simple burial. A recent increase in temperature will produce a length pattern similar to that found in the laboratory annealing experiment where all previous tracks are shortened together. In this way it is recognized that thermal pulses, particularly late in a basin's history, will have a major effect on hydrocarbon generation. [Gleadow et al 1983].

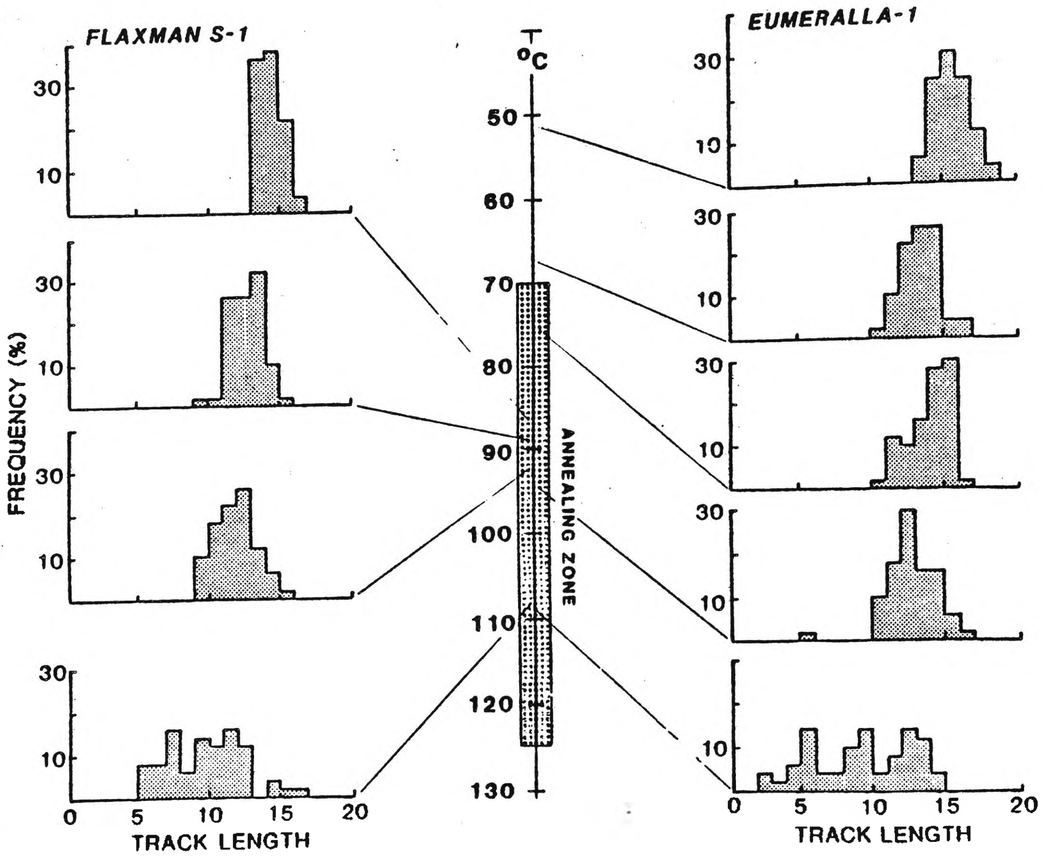


Fig. 5. A comparison of the fission track lengths for various apatite samples from Flaxmans 1 and Eumeralla 1. Present day downhole temperatures for the samples are indicated against the centre scale, together with the track annealing zone. Those from Flaxmans 1 compare favourably with laboratory annealing experiments, whereas those from Eumeralla suggest that the upper samples were once at a higher temperature.

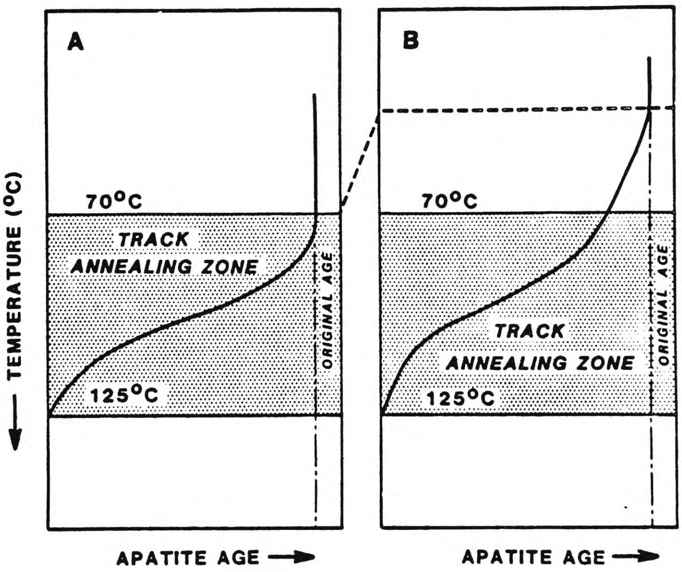


Fig.6 Hypothetical profiles of apatite age with downhole temperature for two deep wells. (A) shows a well where temperatures are now at their maximum and (B) a well where the temperatures have decreased from an earlier peak. In (B) reduced ages are preserved at shallower levels than the present day annealing zone. The broken line in (B) shows the level of the peak position of the top of the annealing zone. (From: Gleadow et al., 1983)

INDEX OF WELL NAME ABBREVIATIONS

T=Tullich No1,C=Casterton No1, E=Eumeralla No1,F-Flaxmans No1,F.H.= Fergusons Hill No1, O=Olangolah No1, K-Krumbruck No13,V=Voluta No.1.

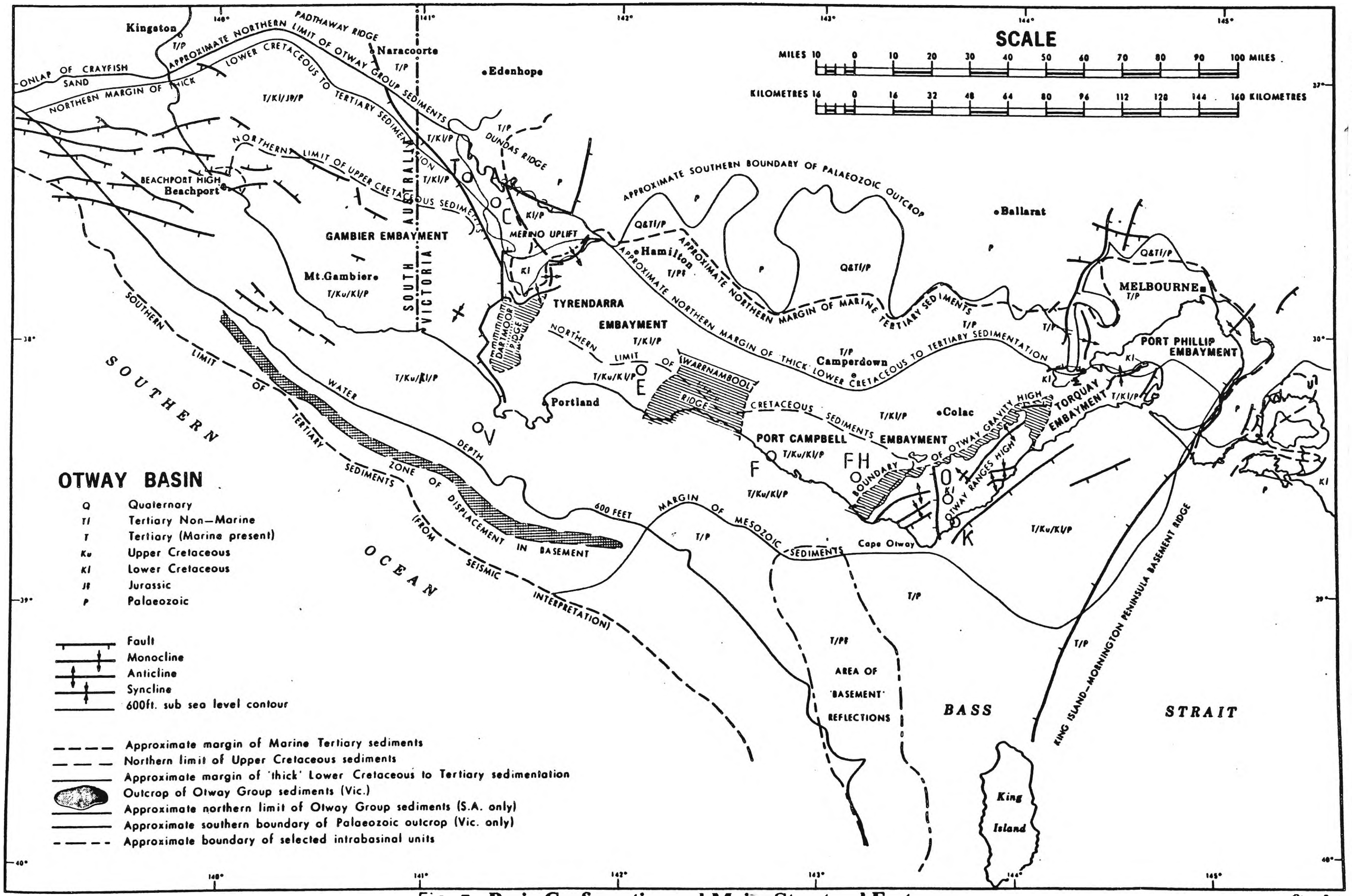


Fig. 7 **Basin Configuration and Major Structural Features** oF Well Location [From: THE OTWAY BASIN OF SOUTHEASTERN AUSTRALIA - Special Volume.] Wopfner and Douglas (1971)

5. STRUCTURAL SETTING

5. (a) Regional Structure

The Otway Basin is located on the former junction between Australia and Antarctica and the theoretical tectonic consequences are as follows for this type of situation.

The tectonic model has two stages:

Rift Stage A rift valley sedimentary basin system formed by crustal thinning and resulting subsidence of continental crust along incipient rift lines. High heat flow, associated alkaline vulcanism, and rapid vertical foundering of large fault blocks occurs along the rift system with the rapid accumulation of immature volcanoclastics. Commonly, major rift basins are located at rift line triple junctions. A major erosion surface occurs at the base of the rift sequence which may result from a pre-rift period of extensive crustal uplift due to the effects of initial lithospheric heating.

Drift Stage From 25-100 Myr after initial rifting a spreading ridge emerges along the axis of the rift basin. This causes a basinwide decrease in subsidence, relative uplift along the ridge margins and probable reverse-faulting of some earlier formed rift fault blocks causing uplift in the main rift basins. A more restricted second cycle terrestrial sequence then accumulates composed of immature clastics or a shallow sea incursion may occur.

The Strzelecki-Otway and Tasman Sea Rift phases are notable for tensional stress with rapid subsidence and deposition at rates in excess of 150m/M.a. [G.G. Smith, 1982]. The rift-controlled structural trends in the Strzelecki-Otway Rift phase were orientated west north-west but were overprinted by northeast structural trends of the Tasman Sea Rift Phase. The sediments were deposited in alluvial, fluvial and restricted paludal environments in steep-sided fault controlled basins. Two intracratonic rift valley clastic suites developed; the volcano clastic Otway Group, followed by an overlying marine succession and finally a non-marine capping to complete the depositional cycle [Ref. G.C.Smith, 1982]

5. (b) Local Structure

The more local structural setting summarised as follows:

Tectonic Framework

The Otway Basin was initiated in Late Jurassic (?) Early Cretaceous time as a major east trending trough, formed by numerous faults subparallel to the basin's axis. By the end of Early Cretaceous possible overthrusting (Bruce Thompson personal communication) and block faulting superimposed upon this essentially single depositional trough a series of north-east trending highs (Dartmoor Ridge, Warrnambool High, Otway Ranges High). During the Late Cretaceous-Tertiary, these highs effectively divided the area into four sub-basins which from west to east are: the Gambier Embayment the Tyrendarra Embayment, the Port Campbell Embayment,and the Torquay Embayment. Seismic and gravity data suggest that the Otway Ranges High continues off-shore, and during Late Cretaceous-Paleocene time divided the Otway Basin into two different sedimentary provinces. The Dartmoor and Warrnambool highs appear to be essentially on-shore features, with no offshore extensions.

6. THE STRATIGRAPHIC SUCCESSION

6. (a) Outline - Stratigraphy and Sedimentation

The sedimentary fill of the Otway Basin (Fig.7) consists of Upper Jurassic (?)- Lower Cretaceous continental lithic (volcanic derived) sandstones and intercalated shales (Otway Group), Upper Cretaceous-Paleocene transgressive-regressive sands/shales (Sherbrook and Wangerrip Groups) west of the Otway Ranges, and a suite of younger cover rocks.

Upper Jurassic (/)- Lower Cretaceous.

Otway Group

The known maximum thickness of the Otway Group is over 3500m penetrated in Crayfish-1 without encountering basement. Seismic data indicates that the group may exceed 4 500 m in thickness in the deepest part of the basin.

Basal Unit. Lower Otway Group sedimentation in the Otway Basin began in isolated locations along the northern basin margin with black fissile shales, weathered olivine basalts and some feldspathic quartz sandstones of probable Late Jurassic age being deposited. The shales are believed to be margnal sorce rocks for gas and light oil in some areas and are now interpreted as paludal deposits that accumulated in locally low lying areas while the rare sandstone interbeds are lensoidal fluviatile deposits. The volcanic rocks are believed to be contemporaneous flows. (Ref. Ellenor 1975)

More recent fission track and petrological studies by Gleadow and Duddy in the eastern Otway Basin suggest a higher proportion of basement material in the oldest section of the unit. A large number of zircons and apatites have been separated out and also have been dated, and garnet compositions are found to be identical to those found in the equivalent age basement-derived Pretty Hill Sandstone.

The Pretty Hill Sandstone known from the central and north-western parts of the basin, forms the principal Lower Cretaceous target and consists of medium-thick bedded quartzose sandstones, with some interbedded carbonaceous shales, siltstones and coals. Pink and brown garnet grains are a characteristic accessory mineral. The unit is extremely variable in thickness (1,590-135 m) and also has a variable sand/shale content. In Pretty Hill-1 central Otway Basin, for example the unit is 570 m thick consisting of 94 per cent quartz sand with porosities up to 25 per cent and permeabilities to a few darcies. The unit contains a good floral assemblage but it is devoid of marine fauna indicating that deposition has probably occurred under terrestrial conditions. Abundant large scale cross bedding, carbonaceous shales, coaly laminations and occasional ripple marks further suggest a fluviatile sedimentary environment. The brackish to salt water found in some wells may indicate a restricted marine influence during deposition or alternatively the salt water may have displaced the original connate waters. All available data suggests, however, that the Pretty Hill Sandstone is only locally developed on or near the flanks of basement paleohighs. (Ref. Ellenor 1975)

Eumeralla Formation. This unit has a wide distribution and consists mainly of a monotonous sequence of first cycle fluviatile siltstones, carbonaceous claystones, fine grained sandstones containing abundant volcanic detritus, and minor coal. The bulk of the formation was derived from contemporaneous intermediate to acid volcanics. Extensive diagenetic alteration of this volcanic detritus, imparting a characteristic greenish colour to these rocks, has destroyed all reservoir potential within the formation. It is however a thick seal for the relatively clean Pretty Hill Sandstone. (Ref. Ellenor 1975)

GEOLOGICAL HISTORY OF THE OTWAY BASIN

The Basement of Western Victoria varies in age from Pre-Cambrian to Upper Palaeozoic. As the structural elements of these basement strata generally trend north-south, they can be expected to underlie the Otway Basin. Some of the exploratory wells have intersected basement strata and Cambrian to Ordovician rocks have been encountered.

The oldest known sediments in the Otway Basin are probably of Jurassic Age, based on evidence from age dating. The Otway Basin in Upper Jurassic/Lower Cretaceous times was a down warped basin or trough straddling the boundary between Australia and Antarctica, prior to separation, and trending generally east-west. (Ref.Falvey et al 1981).

This trough was first infilled with sideritic mudstone and shale, together with thin dolerite layers. This was followed by

LITHOSTRATIGRAPHIC UNITS OF THE LOWER OTWAY BASIN SUCCESSION

Formation	BMR Unit	Lithology
Waarre Formation	J-H	Upper orthoquartzite, lower chloritic protoquartzite, with carbonaceous mudstone and coaly horizons; calcite cement in lower part; significant absence of volcanic detritus.
		unconformity 97,5 million years
Eumeralla Formation	M	Chloritic mudstone and shale with coaly lenses; subordinate grey-wacke to subgreywacke and volcanic sandstone; diagenetic calcite, siderite and zeolite, and clay cement.
Geltwood Beach Formation "Pretty Hill sandstone"	P-R	P-Lithic garnetiferous sandstone interfingering with fine sediments of Unit M affinities; volcanic and metamorphic detritus; R-lithic garnetiferous sandstone with kaolinite and siderite cement.
Unnamed	T	Conglomerate, lithic sandstone (phyllite fragments mainly) with thin interbeds of mudstone, sideritic in lower part, and shale
		unconformity 146 million years

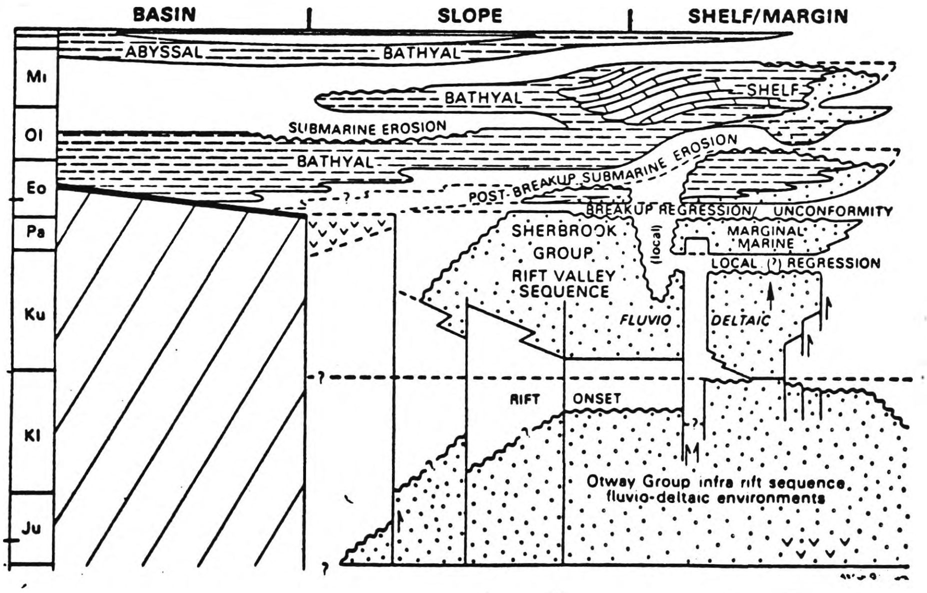


Fig. 8. Generalised time stratigraphic cross-section of the Otway Basin area.

Dots - marginal to nonmarine

Dashes - marine

Bricking - prograding carbonate
V's - volcanic
(Ref. BMR Journal, 1981)

conglomerates, lithic sandstones and shales along with carbonaceous material in a paralic environment, adjacent to an area of high relief. The age dating metamorphic studies of Gleadow and Duddy (Gleadow et al 1981) suggest a higher proportion of basement material in this the oldest part of the Otway Basin succession.

The principal oil exploration target formed during this stage of the Otway Basin depositional cycle was the Pretty Hill Sandstone (unit R), which is found exclusively on or adjacent to local basement highs.

The lowermost Unit, known as the Casterton Beds where the sediments are conglomeratic and obviously locally derived, and with Unit R form part of a larger unit, known as the Geltwood Beach Formation (Unit P).

The remainder of the succession of the Lower Cretaceous Otway Group is known as the Eumeralla Formation (Unit M), this in turn has been subdivided into two sub-units M1 (the upper part) and M2 (the lower part) mainly on the basis of composition. This thick succession is up to 2740m thick (Ferguson Hill No.1), and is largely of volcanogenic origin. It is variously described as chloritic mudstone and shale with thin interbeds of sandstone and coal; M1 has less chloritic mudstone than M2. The studies of Gleadow and Duddy (1981) further show deposition was essentially in two pulses, lower Aptian times for the first down to late Neocomian or about 126 M.a. , for the second pulse. The source of the volcanic detritus is thought to be from volcanism along the continental rift system which was beginning to form at this stage. This whole succession was apparently deposited under shallow water conditions.

The Eumeralla Formation generally has a very low porosity due to chloritic cement but one discontinuous, volcanic detritus free unit is the "Heathfield Sandstone". This is of interest in oil exploration.

The deposition in the sinking Otway Basin Trough was violently disrupted between about 93 and 98 M.a. when Antarctica commenced separating from Australia. The rift formed was then subject to a major marine incursion and Upper Cretaceous sediments were largely deposited in a marine environment when the post-breakup non-marine phase set in. The most notable feature of the remainder of the Tertiary period was the outpouring of the Newer flood basalts which cover a large portion of the exposed onshore Otway Basin at the present time.

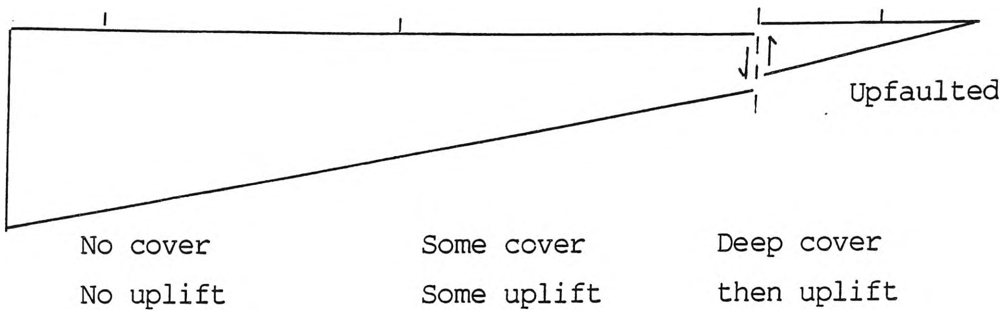
Earth movements have taken place in a right-lateral sense along the northern margin of the Otway Basin, forming overthrusts on the north-western sides of large fault blocks such as the Otway Ranges. Similar overthrusts have, however, been more closely studied in the adjoining and related Gippsland Basin, by B. Thompson et al. (Personal Communication).

7. THE BASIS FOR WELL SELECTION

1. The Department of Minerals and Energy, Victoria wished to have comparative vitrinite reflectance data to compare with the promised fission track data, due to be obtained from the University of Melbourne, Department of Earth Sciences.

2. Fission track data from the Otway Basin, viz. Flaxman's 1, Eumeralla 1, and Olangolah 1, were together with abundant vitrinite reflectance data, already available and free to be used in this study.

3. Casterton 1 Ferguson's Hill 1 Eumeralla 1 Olangolah 1
Tullich 1 Krumbruk 13



This diagram shows the broad tectonic basis, for the selection of the wells, to cover a range of settings. The above were supplemented by Flaxmans 1, because of the availability of fission track data, and by Voluta 1, an offshore well, with high vitrinite reflectance.

4. Wells selected were those for which information was readily available, or were oil wells for which data were available in the D.M.E. core library and some work on the zeolites had already been done by Duddy. (Personal communication).

8. DETAILED STUDY OF THE WELLS

1. Samples were collected for Tullich 1, Casterton 1, Ferguson Hill 1 and Krumbruk 13, from the D.M.E. core store. Core with coal or dispersed organic matter was selected, for preference, and where there was insufficient sample or a gap in the sequence, coal or dispersed organic matter-bearing cuttings were collected instead. The actual depths and coal content is given in Annexure 2.

2. Reflectance values were determined on both S.E.C. Melbourne coal laboratory and Wollongong University

equipment. The equipment is described in Annexure 1, along with sample preparation methods.

3. The ages of the samples were determined as follows:-

   (a) The litholog giving the palynological units was referred to, to give the geological age.
   (b) Reference was then made to the geologic time scale (1982), in Annexure 2, for the ages in millions of years.

4. The T iso model temperatures were read off using the age as found above, and the percentage vitrinite reflectance data for each sample, by referring to the Karweil Diagram. The H-scale was used throughout, as only on this scale can Casterton 1 and Olangolah 1 both be accommodated.

   T grad is then calculated from Tiso by multiplying the latter by a factor of 1.6.

5. The bottom of hole temperatures are uncorrected.

6. Tiso has been plotted against depth to give the palaeo-geothermal gradient.

8.1 THE ONSHORE WELLS

TULLICH NO.1

1. This well is located in the Gambier Embayment on the edge of a high known as the Merino Uplift.

2. The present day geothermal gradient is believed to be comparable with the palaeo-gradient for Casterton 1, located nearby, of 22°C/km. The values in Tullich 1 well are too low for the interpretation of Tiso and Tgrad via the Karweil diagram. [Fig.9].

3. The near surface samples show very little evidence of burial metamorphism, with textinite being recognisable at a depth of 186m.

4. Thin Tertiary to Upper Cretaceous cover is present on the Lower Cretaceous. The well stopped in Pretty Hill Sandstone. The age range without palynological control is largely estimated by reference to Casterton 1 and by taking into account the presence and thickness of the sandstone horizons - that are present in both wells.

5. Tullich 1 well essentially provides a lower temperature complement to the Casterton 1 well nearby.

TABLE NO. 1

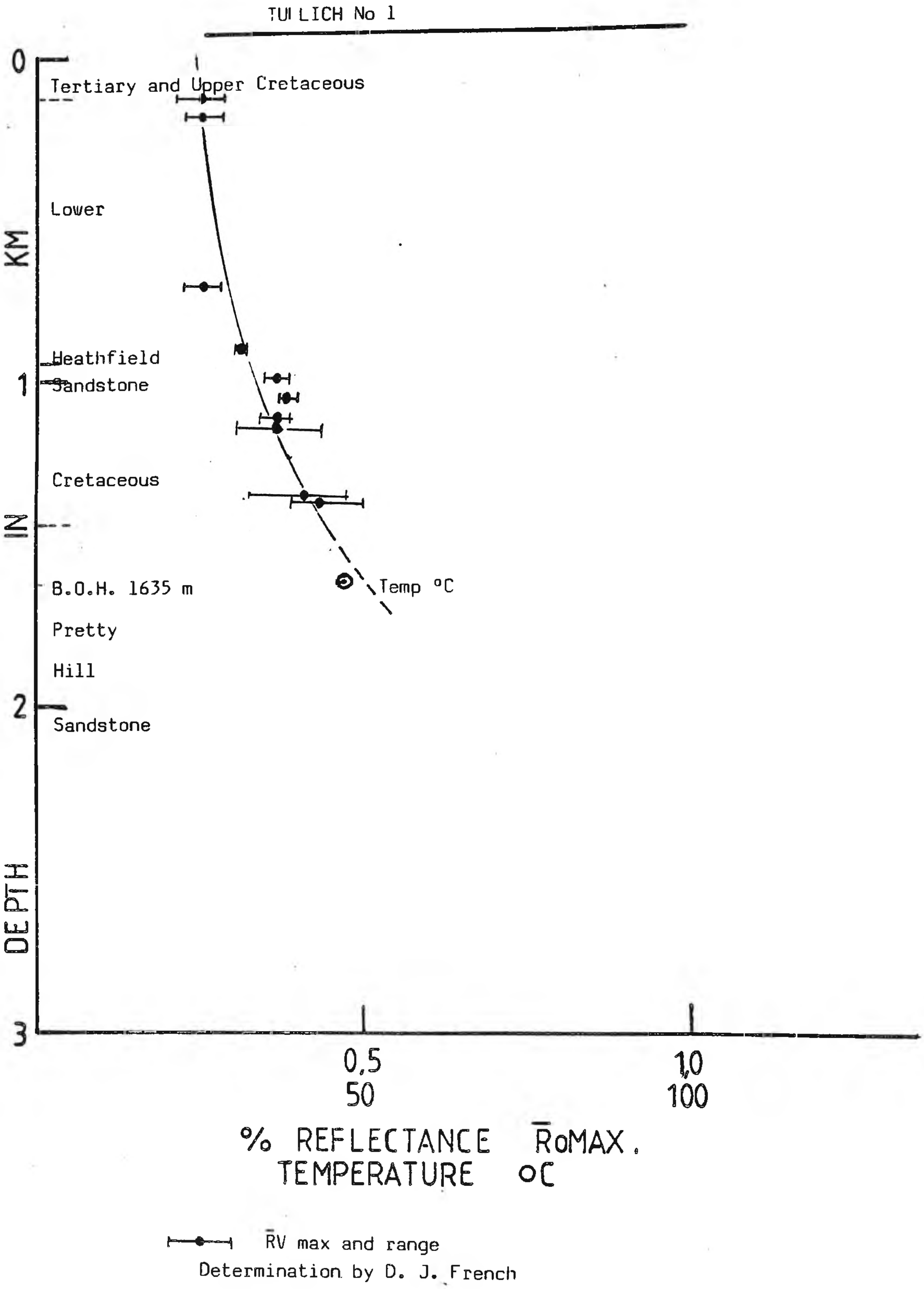
TULLICH No 1

LAB. NO.	DEPTH (M)	AGE	MEAN	STD. DEV.	RANGE	NO. OF READINGS	COMMENTS	TISO	TGRAD
17963	129.5	98	0.26	0.03	(.220-.298)	5	volcanic rich		
17964	186	98.5	0.26	0.02	(.238-.291)	10	volcanic rich		
17965	705	106	0.26	0.02	(.234-.287)	10	greywacke and volcanics		
17966C7A	912C	109	0.32	0.01	(.309- .330)	3	Heathfield sandstone		
17967	1004	111.5	0.38	0.02	(.360-.399)	5	dip change		
17968C8A	1060C	113.5	0.39	0.01	(.385- .420)	6	greywacke and mudstone		
17969	1126	116	0.36	0.02	(.331-.380)	8	arkose		
17970	1147	117	0.36	0.05	(.303-.440)	7			
17971C12A	1372C	125	0.42	0.04	(.340-.490)	14	greywacke		
17972C13A	1384C	125	0.45	0.04	(.390-.505)	16	subgreywacke		

BOTTOM OF HOLE 1635 m

TEMPERATURE 46.7°C

FIG. 9.


TULLICH No 1
0
1
2
3
DEPTH IN KM
Tertiary and Upper Cretaceous
Lower
Heathfield
Sandstone
Cretaceous
B.O.H. 1635 m
Pretty
Hill
Sandstone
Temp °C
0,5
50
1,0
100
% REFLECTANCE $\bar{R}$oMAX.
TEMPERATURE °C
$\bar{R}$V max and range
Determination by D. J. French

CASTERTON NO. 1

1. The well is located ln the Merino Uplift and the immediately surrounding strata have never been covered by any significant development of younger rocks.

2. Erosion of the uppermost unit probably occured at the end of the Lower Cretaceous.

3. The present day geothermal gradient is 26.7°C/km, and does not compare too badly with a palaeo-gradient of 29.9°C/km between 1141 + 2211 m (calculated). The palaeo-gradient as determined from the graph is, however, much lower at 22° C/km. [Fig. 10, Fig.11].

4. The bottom of hole temperature (uncorrected) approaches the possible palaeo-geothermal (gradthermal) value of 85°C.

5. There is no clear evidence for a higher temperature in the past, in fact the palaeo-gradient appears to show that the well has attained its maximum temperature at the present time.

6. The age range is well documented from the dating of lavas just above the basement contact.

CASTERTON No. 1

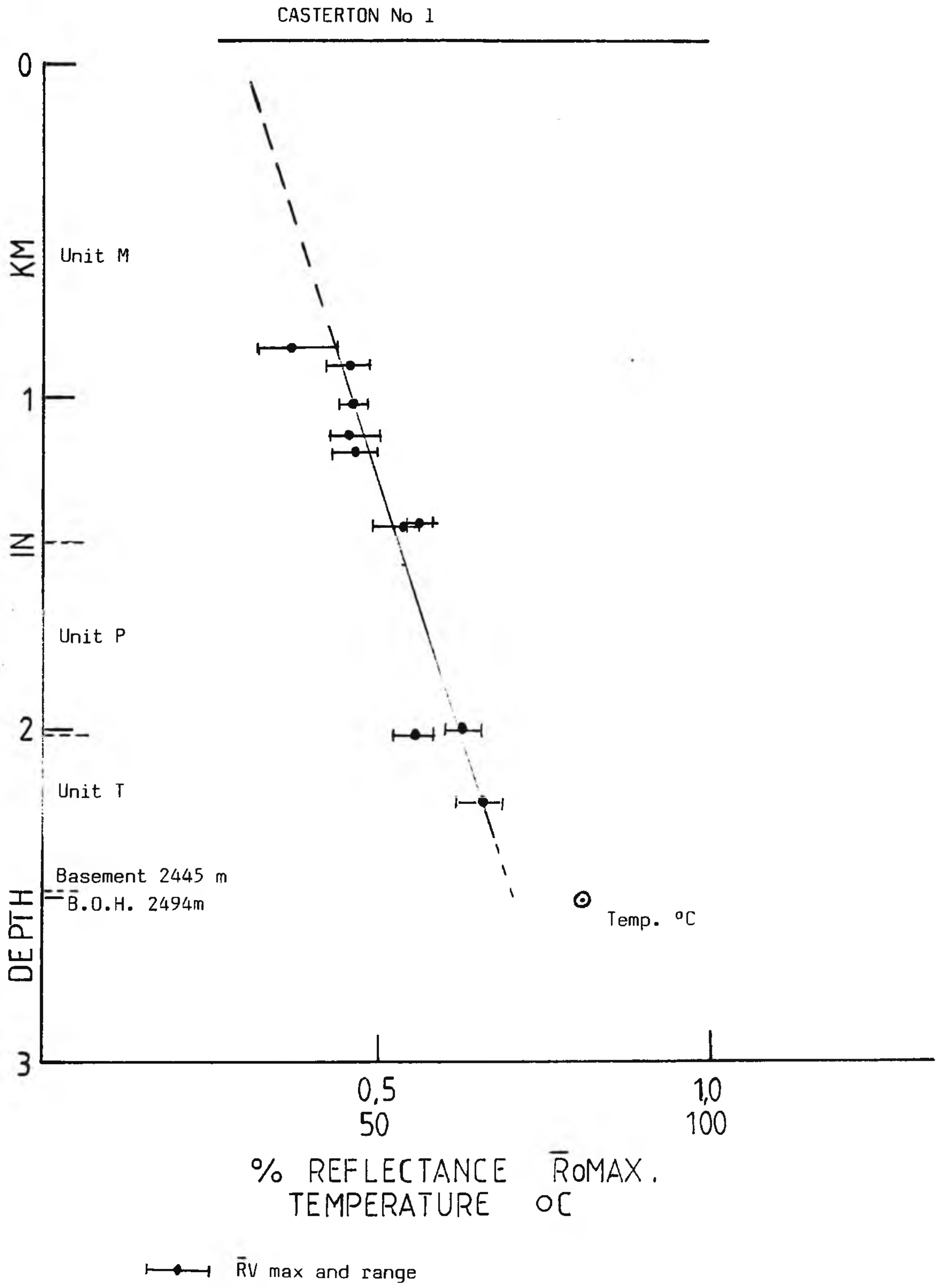
LAB NO.	DEPTH (M)	AGE	MEAN	STD. DEV.
17924	843	114	0.37	0.4
17925	888	116.5	0.46	0.3
17926	995	119.0	0.46	0.1
17927C4	1096	121.0	0.46	0.03
17928	1141	123.5	0.47	0.02
17929B	1373	128.5	0.54	0.03
17930	1374	129.0	0.56	0.1
17931	1983	141.0	0.63	0.02
17932	2011	144.0	0.56	0.03
17933	2211	150.00	0.66	0.02

LOWERMOST UNIT to 2445 m

BOTTOM OF HOLE IS AT 2494 m TEMPERATURE 81.7°C

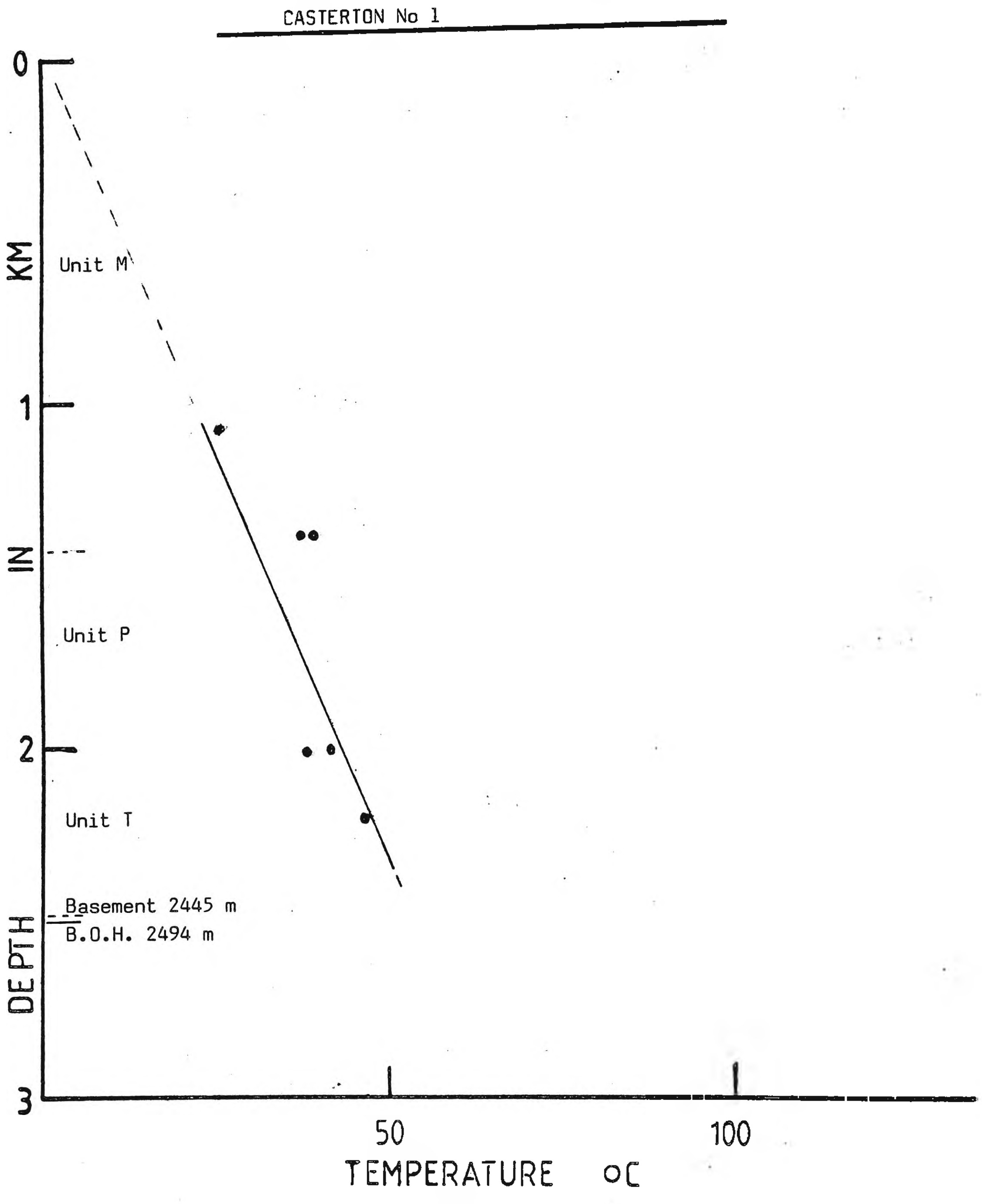
RANGE	NO. OF READINGS	COMMENTS	TISO	TGRAD
(.320 - .440)	16			
(.425 - .495)	11			
(.442 - .478)	5			
(.425 - .498)	4	M		
(.43 - .495)	10		16°C	26°C
(.502 - .590)	10		38	61
(.548 - .570)	6	------------------------	40	63
(.600 - .660)	6	P	42	67
(.525 - .590)	6		38	61
(.625 - .700)	6	------------------------	48	77

FIG. 10.



Determination by D. J. French

FIG. 11.



Palaeotemperatures from Karweil Diagram

Tiso vs Depth

Gradient 22°C/KM

A. Fission Track

The well samples demonstrate that well temperatures have decreased from an earlier peak, with temperatures having been 10-20 ° C hotter in the past. Eumeralla has had very little post-Early Cretaceous cover, and this decrease in temperature may be due to reduced heat flow since the sediments were first laid down, or may be due to tectonic uplift. (fig. 12).

B. Vitrinite Reflectance

(1) The well was situated on the Warrnambool Ridge and the immediately surrounding area has been the subject of very limited younger cover.

(2) The average present day geothermal gradient for the Otway Basin is 30°C/km, while the palaeo-gradient is 41°C/km between 1785 m and 2757 m (calculated) or 36°C/km from the graph, this would confirm the fission track interpretation that there has been tectonic uplift and that the bottom of hole well temperature (uncorrected) has fallen. [Fig. 13, Fig. 14].

3) The age range of 38 M.a.to 130 M.a. has been documented by palynological dating methods, for the strata intersected.

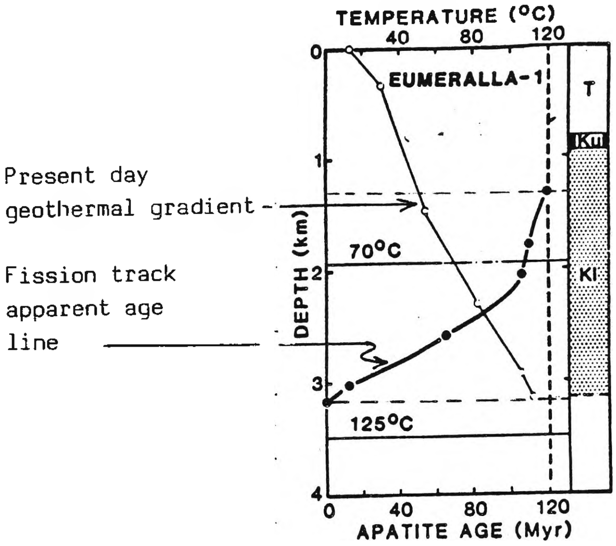


Fig.12 The apatite age profile is shown, along with the present day annealing zone. The reduced ages are preserved at shallower levels, than the present day annealing zone.
Thin line - present day well temperature curve.
Thick line - fission track apparent age line.
(From: Gleadow et al., 1983)

TABLE NO. 3

LAB.NO.	AGE	DEPTH(M)	MEAN	STD.DEV.
	42	471	0.36	
	45	541	0.42	
	97.5	952	o.46	
	102.5	1160	0.41	
	106.5	1340	0.48	
	113	1742	0.49	
	114	1785	0.48	
	116.5	2047	0.61	
	118.5	2204	0.61	
	122	2440	0.67	
	126	2610	0.74	
	129	2738	0.80	
	130	2757	0.79	

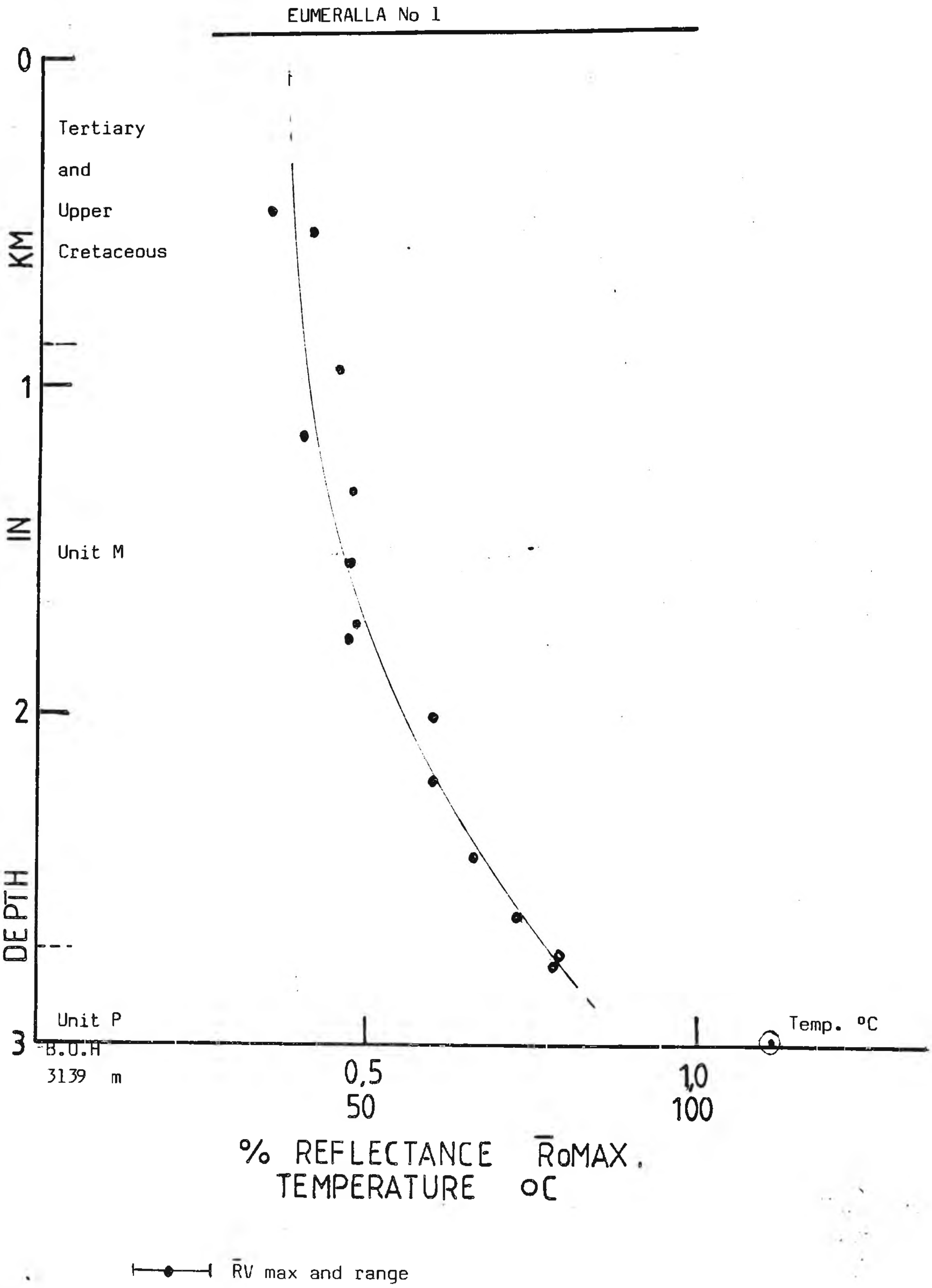
BOTTOM OF HOLE 313.9 m TEMPERATURE 112°C

DETERMINATIONS BY A.C.COOK.

EUMERALLA No 1

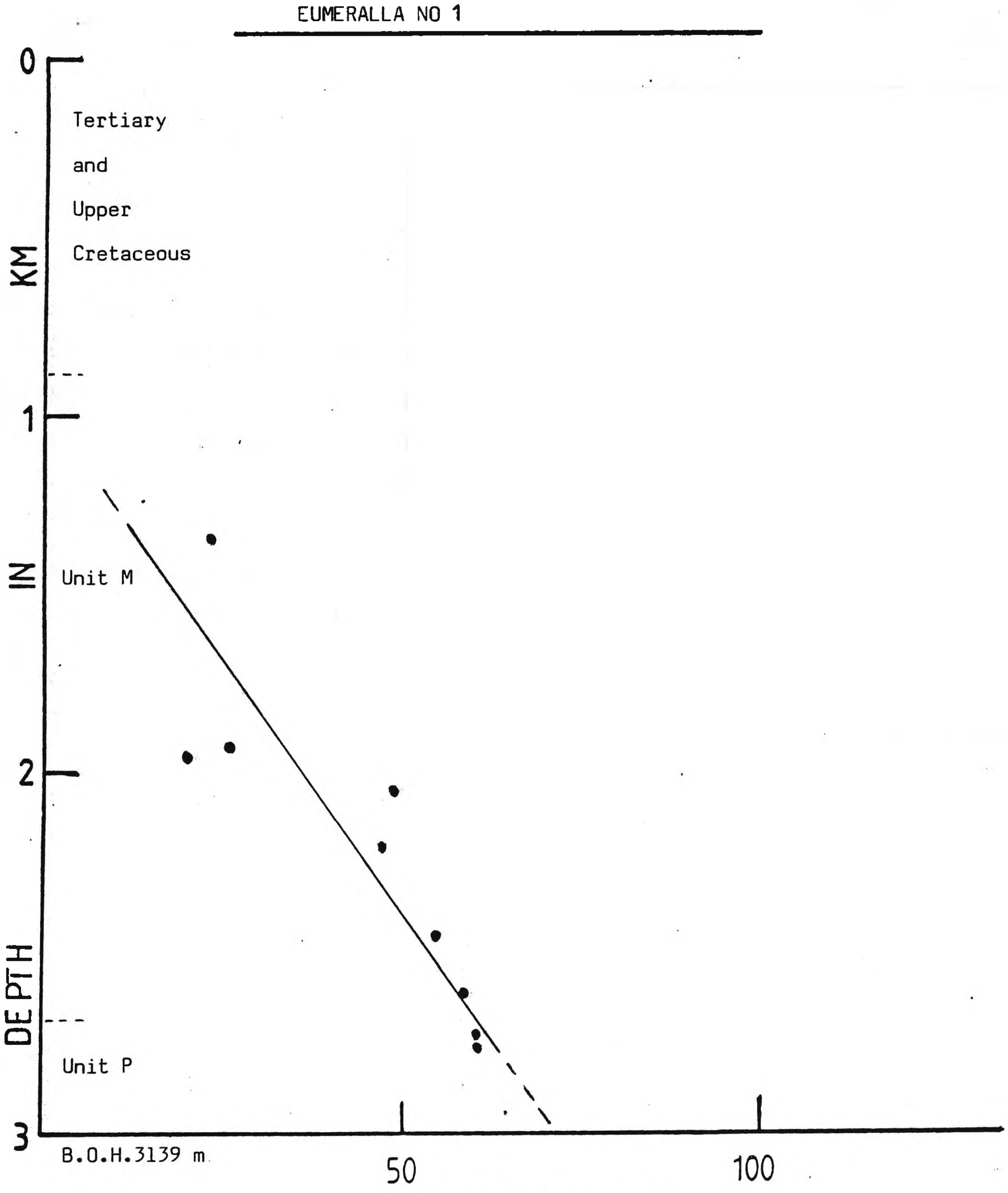
RANGE	NO.OF READINGS	COMMENTS	TISO	TGRAD
			23°C	37°C
			26	42
			20	32
			48	77
			47	75
			54	86
			58	93
			60	96
			60	96

FIG. 13.



Determinations by A. C. Cook

FIG. 14.



Palaeotemperatures from Karweil Diagram

Tiso vs Depth

Gradient 36°C/KM

FLAXMAN'S NO 1

A. Fission Track

The apatite age profile shows, by analogy with experimentally determined laboratory curves, that the well is essentially in equilibrium at the present time, and that well temperatures are at their maximum [Fig. 15].

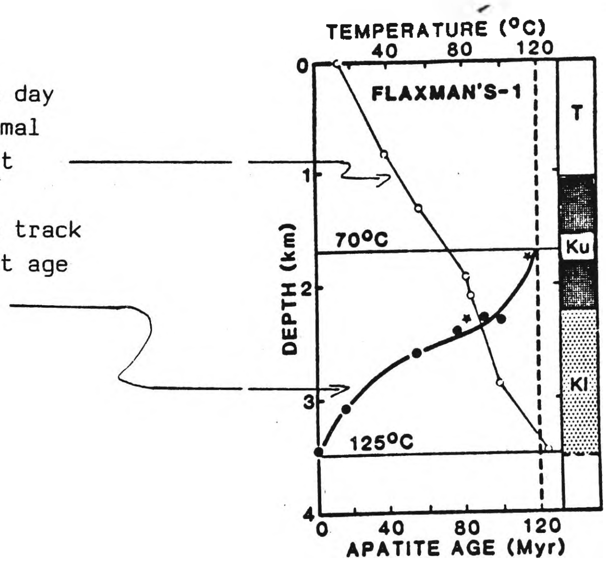
B. Vitrinite Reflectance

(1) The well was located in the Port Campbell Embayment.

(2) An erosional event probably occurred at the top of the Lower Cretaceous, at around 97.5 M.a.

(3) The present day geothermal gradient for the Otway Basin is about 30°C/km, while below 2200 m the palaeo-gradient is 30.5°C/km (calculated) or 30°C/km from the graph-figure 16. This suggests no tectonic uplift or any significant change in the geothermal gradient. [Fig. 16, Fig. 17].

(4) The age range is well documented by palynological dating methods, giving results showing that the strata cover is in the range of 38 M.a. to 115 M.a. - to the depth drilled.



Present day geothermal gradient

Fission track apparent age line

Fig.15. The apatite age profile is shown, along with the present day track annealing zone. This bore is essentially in equilibrium at the present time, and well temperatures are now at their maximum. Thin line - present day well temperature curve. Thick line - fission track apparent age line. (From: Gleadow et al., 1983)

TABLE NO. 4

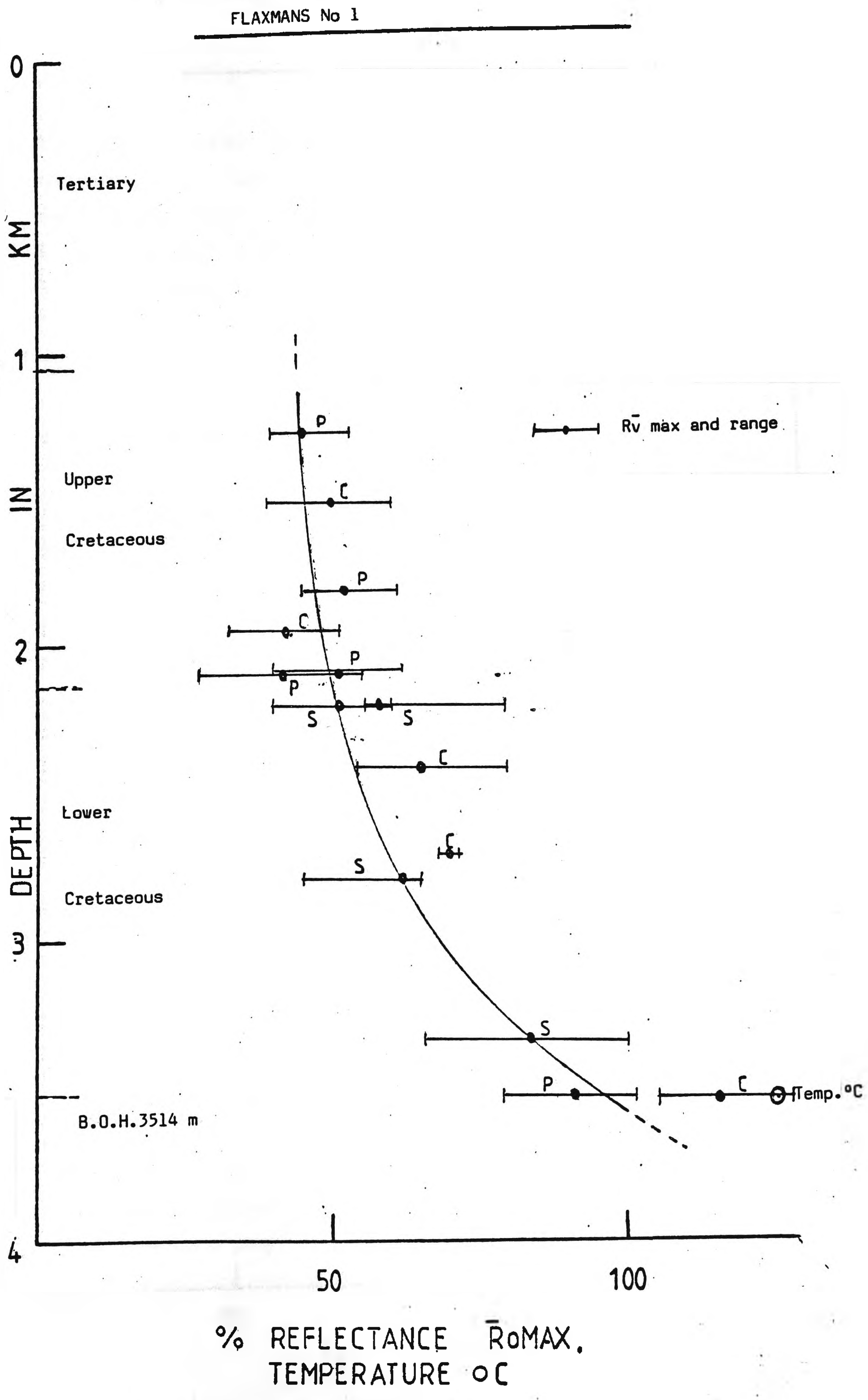
LAB. NO.	DEPTH(M)	AGE	MEAN	STD.DEV.
15352	1258C	69	0.45	
9800	1519	75	0.50	
15353	1815C	89	0.52	
9801	1945	90	0.42	
15354	2095C	91	0.51	
15355	2105C	91	0.43	
15356	2199C	95	0.51	
	2200	95	0.58	
9802	2397	99	0.65	
9803	2709	102.5	0.70	
	2782	103	0.62	
	3295	109	0.84	
15357	3513C	115	0.92	
9804	3513	115	1.17	

BOTTOM OF HOLE 3514 m TEMPERATURE 125°C

FLAXMAN'S No 1

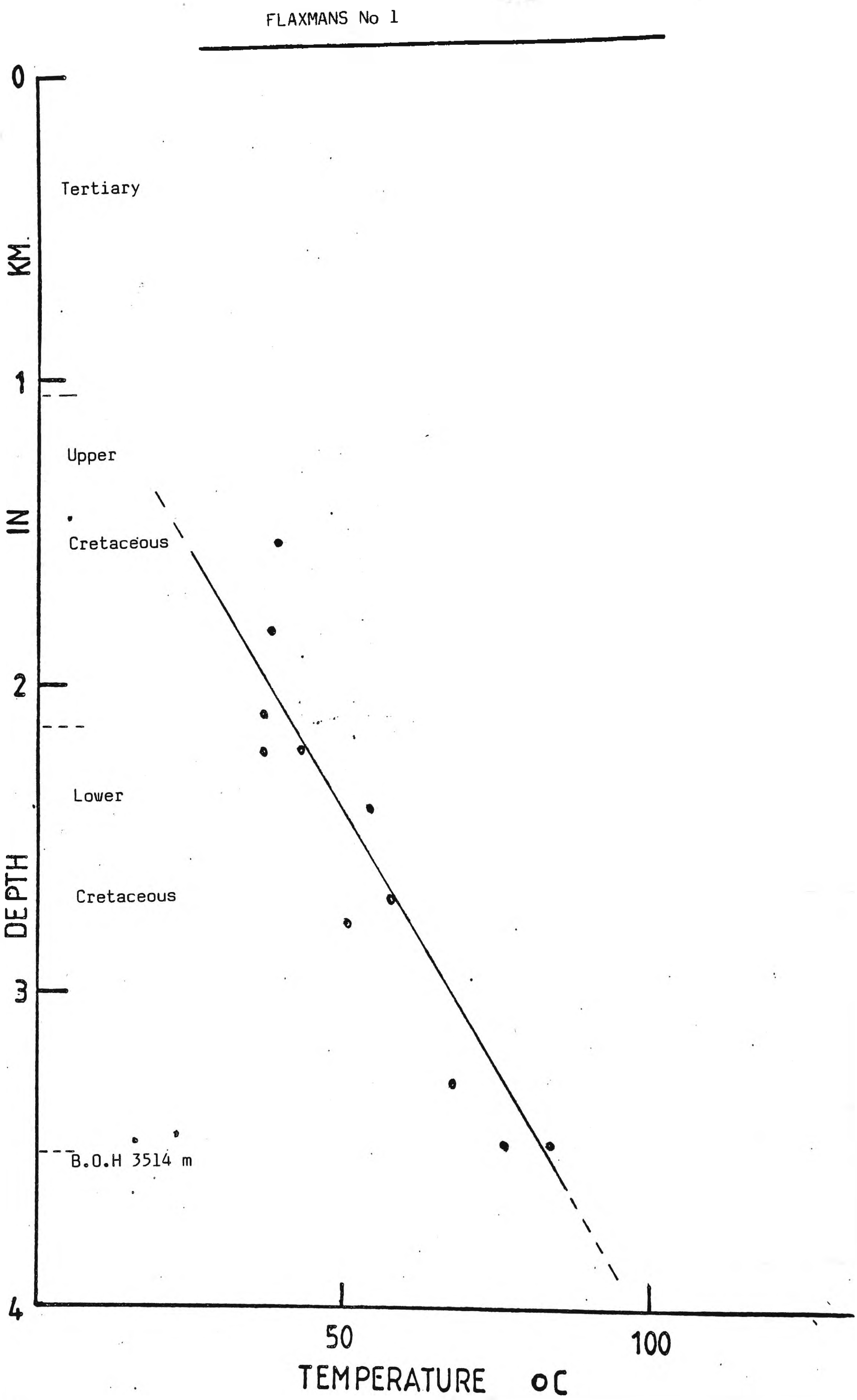
RANGE	NO. OF READINGS	COMMENTS	TISO	TGRAD
(0.39- 0.53)	3	PALTECH		
(0.39-0.60)	4	A.C.COOK	40°C	64°C
(.45-.61)	3	PALTECH	39	62
(0.32-0.51)	2	A.C.COOK		
(0.40-0.62)	7	PALTECH	38	61
(0.26-0.55)	9	PALTECH		
(0.40-0.59)	20	PALTECH	38	61
	30	SAXBY ET AL.	44	70
(0.54-0.80)	7	A.C.COOK	56	90
(0.68-0.71)	2	A.C.COOK	59	94
	30	SAXBY ET AL.	52	83
	26	SAXBY ET AL.	68	109
(0.79-1.02)	14	PALTECH	76	122
(1.0-1.25)	10	A.C.COOK	84	134

FIG.16



• P PALTECH, • C COOK, • S SAXBY ET AL. DETERMINATIONS.

FIG. 17



Palaeo temperatures from Karweil Diagram

Tiso vs Depth

Gradient 30°C/KM

A. Fission Track

The Temperatures appear to have decreased slightly from an earlier peak, with temperatures about 10°C hotter than present well temperatures. This decrease in temperature may be due to slight uplift, i.e. possibly related by the uplift in the adjoining Otway Range area. [Fig.18].

B. Vitrinite Reflectance

(1) This well was located just to the west of the Otway High in the Port Campbell Embayment.

(2) The present day average geothermal gradient is 32.5°C/km, which is higher than the palaeo-geothermal gradient of 24.5°C/km obtained from the graph. [Fig.19,Fig.20].

(3) The temperature calculated from isothermal model values is just over 100°C at the bottom of the well, while Tgrad is 165°C. Tiso, therefore most closely approximates the bottom hole temperature of 118.8°C.

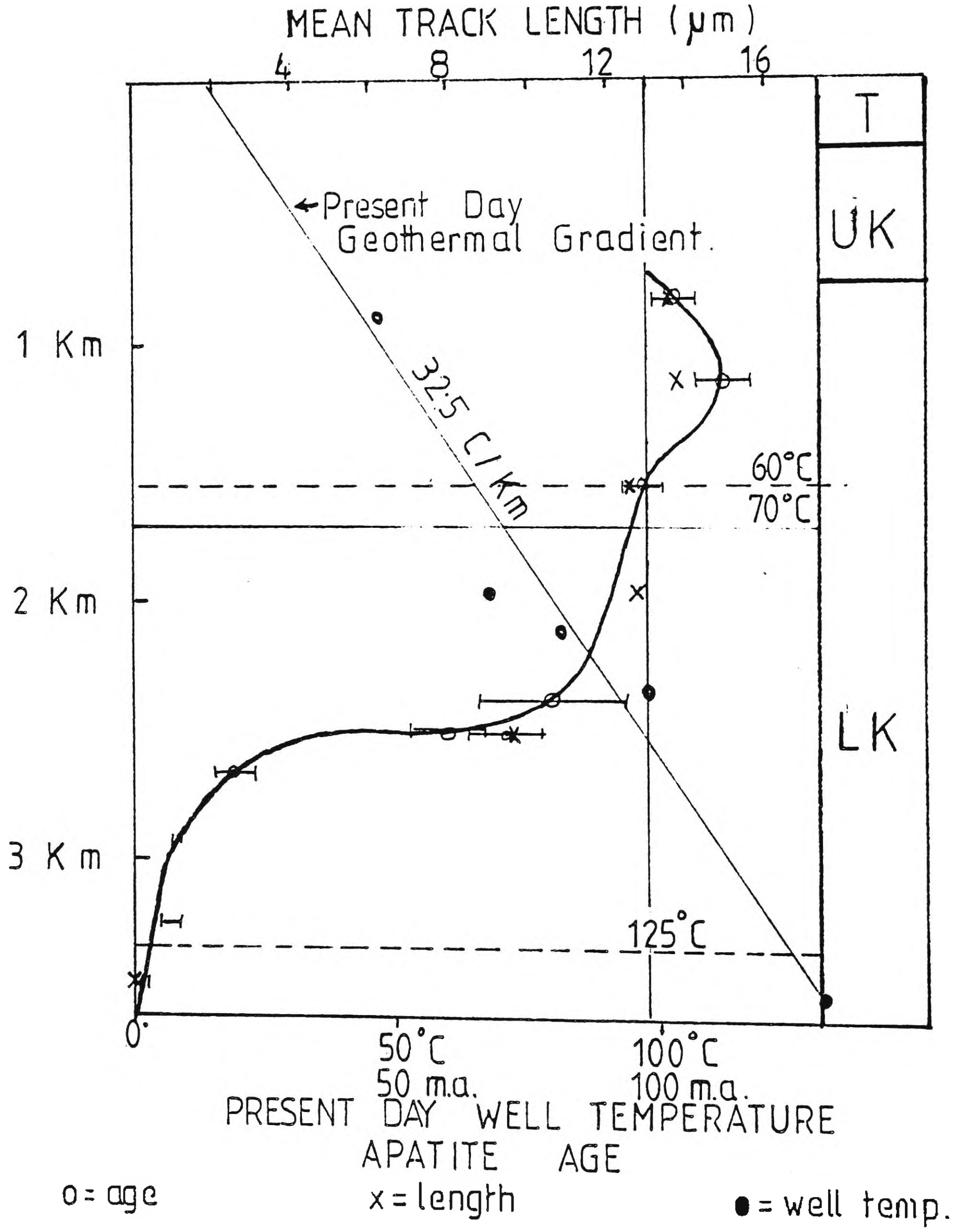
(4) Coking of the coaly material at the 3484m depth level (see A. Cook Open file Report 1979 (a)) suggests igneous emplacement at or near the basement contact.

(5) The age range of the strata encountered in the well is well documented by palynological methods.

C. Lopatin Diagram

Using the technique of plotting age against depth and relating this to the present day geothermal gradient; the temperature intervals have been drawn in as shown in figure 21. Using these temperature intervals the Total Thermal Maturity (T.T.I.) has

FERGUSON HILL NO 1 FIG. 18.



(Source - Gleadow
Personal Communication)

TABLE NO. 5

LAB.NO.	DEPTH(M)	AGE	MEAN	STD.DEV.
9836	471	73.5	0.30	
9837	478	74	0.43	
9838	743	96.5	0.49	
17934C7	836	98.5	0.33	0.03
17935C11	1143	102	0.37	0.01
17936C12	1253	103		
17937C14	1548	107	0.44	0.2
17938C16	1809	111	0.54	0.04
17939C18	1999	112	0.80	0.02
17940C20	2206	114.5	0.84	0.10
9840	2237	115	0.65	
17941C23	2518	118.5	0.72	0.04
17942C25	2803	121.5	0.75	0.02
17943C29	3249	127	1.02	0.05
9841	3484	130	1.57	

BASEMENT AT 3509 m

BOTTOM OF HOLE AT 3964.5 m TEMPERATURE 118.8°C

FERGUSON'S HILL No 1

RANGE	NO. OF READINGS	COMMENTS	TISO	TGRAD
	1	A.C.COOK		
(0.38-0.46)	6	A.C.COOK		
(0.44-0.58)	19	A.C.COOK	30°C	48°C
(.305-.360)	6			
(.355-.380)	11			
		no vitrinite		
(.420-.460)	7	M1		
(.480-.622)	12		35	56
(.780-.835)	11		65	104
(.820-.855)	10	M2	68	109
(0.47- 0.77)	15	A.C.COOK	54	86
(.650-.740)	4		58	93
(.732- .795)	12		60	96
(.972-1.098)	6		84	134
(1.20-2.02)	14	A.C.COOK	92	147

FIG. 19

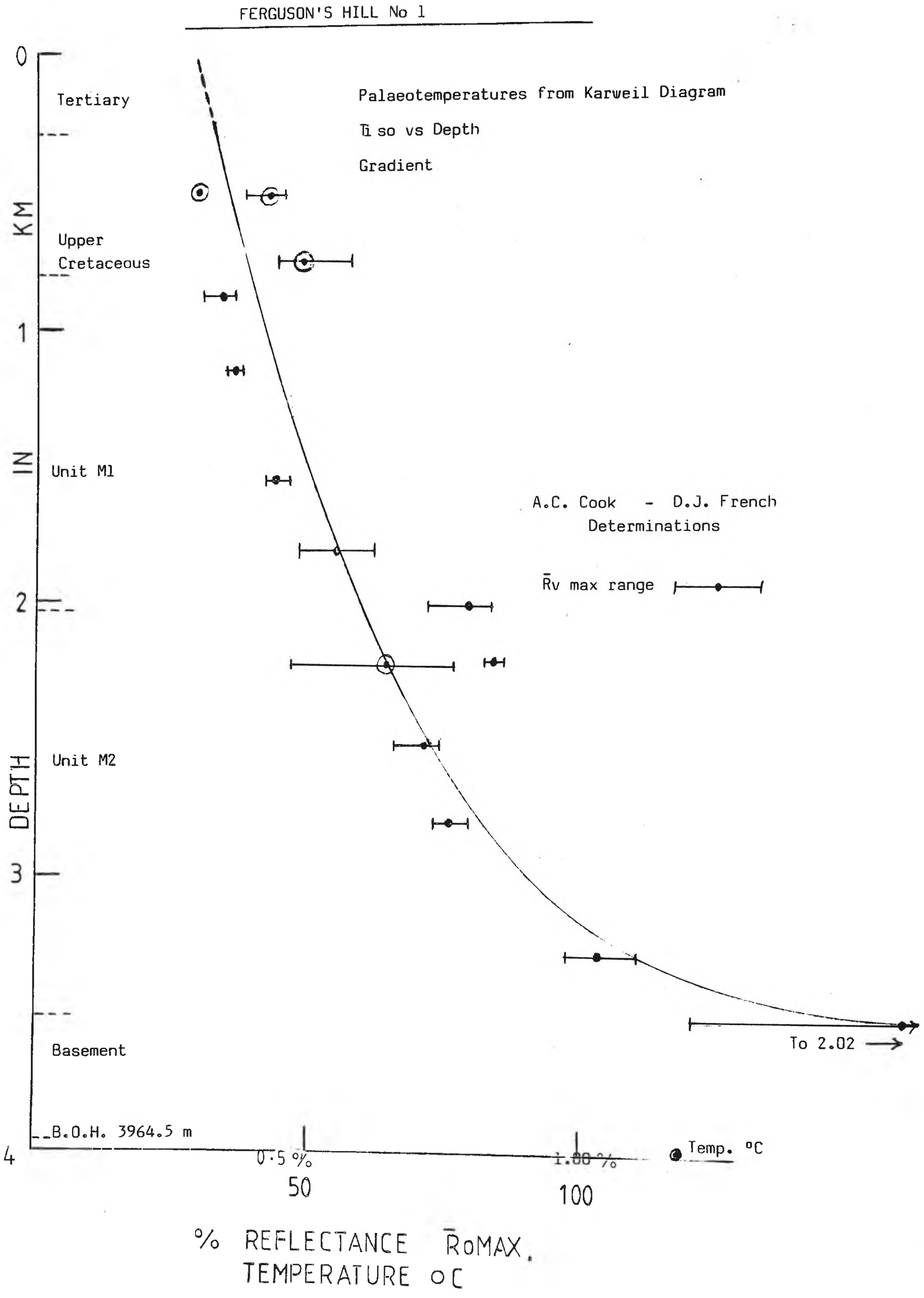
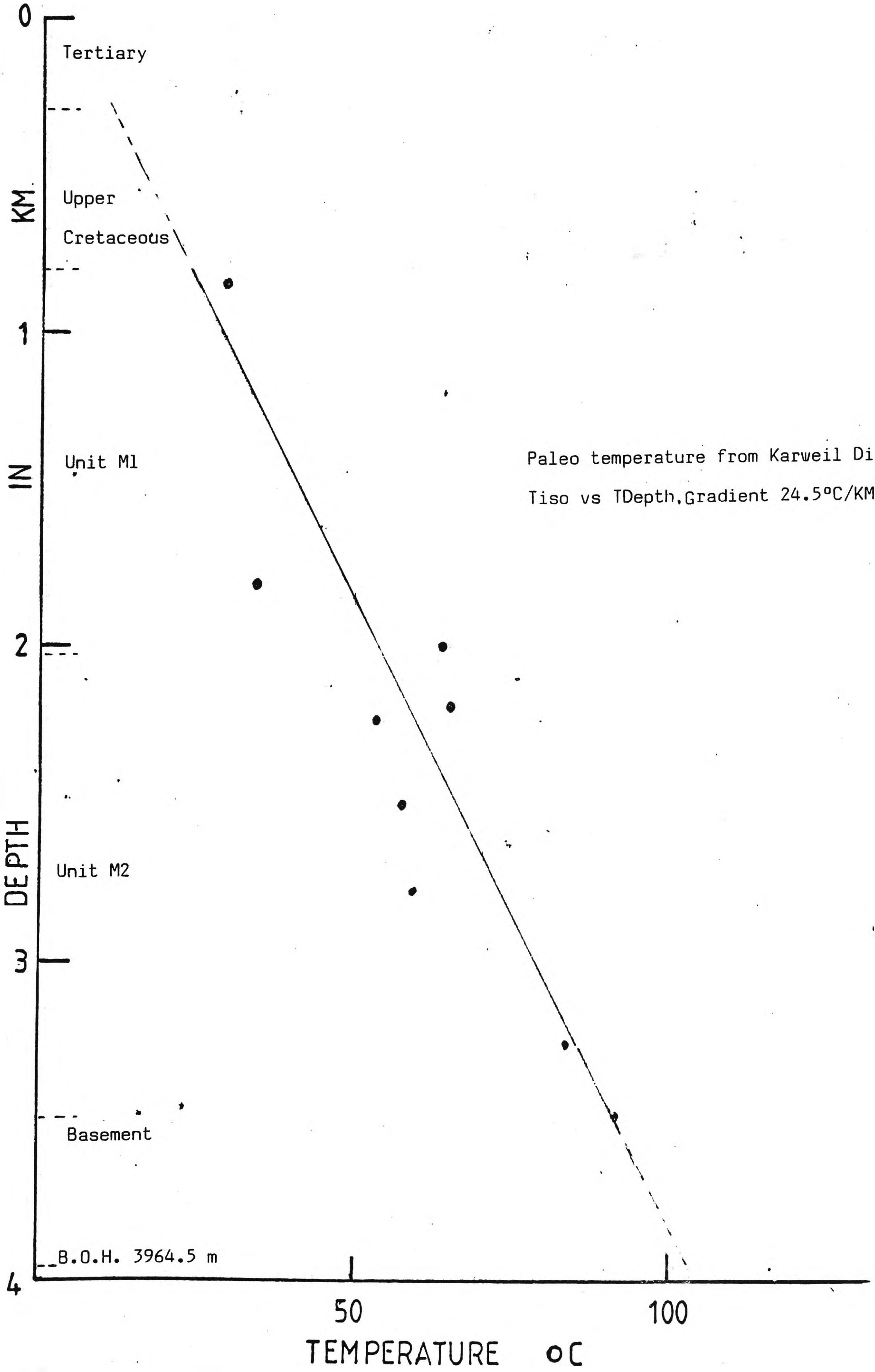

FERGUSON'S HILL No 1
Palaeotemperatures from Karweil Diagram
Ti so vs Depth
Gradient
A.C. Cook - D.J. French
Determinations
R̄v max range
0
1
2
3
4
Tertiary
Upper
Cretaceous
Unit M1
Unit M2
Basement
B.O.H. 3964.5 m
DEPTH IN KM
To 2.02
0·5 %
~~1.00~~ %
50
100
Temp. °C
% REFLECTANCE R̄oMAX.
TEMPERATURE oC

FIG. 20

FERGUSON'S HILL NO 1



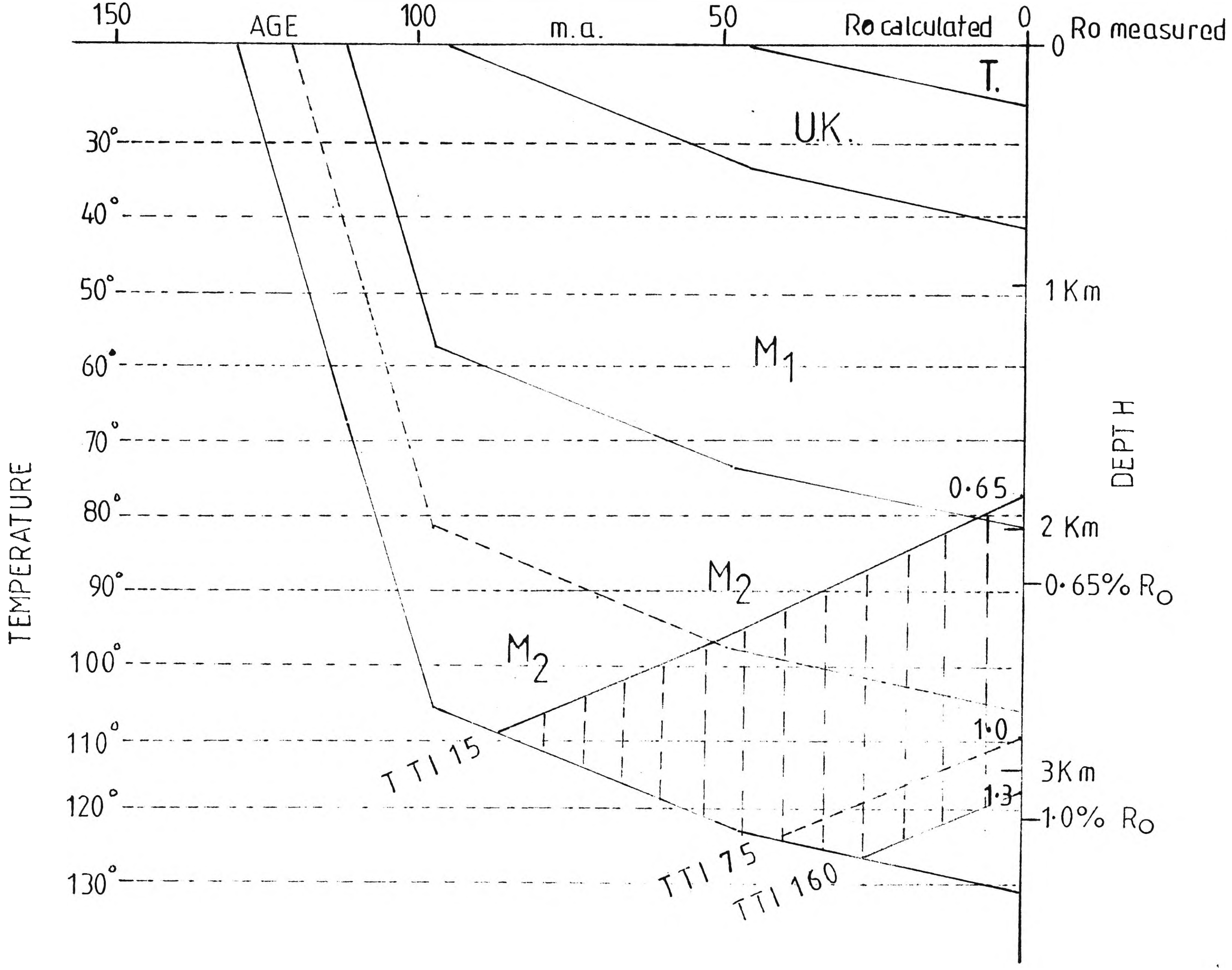
Paleo temperature from Karweil Diagram
Tiso vs TDepth,Gradient 24.5°C/KM

A.C,COOK, D.J.FRENCH DETERMINATIONS

been calculated and plotted [Fig. 21]. The onset of oil generation is at T.T.I. = 15, the peak T.T.I.= 75 and the end of oil generation is at T.T.I.= 160. This has been calculated for the base of M2 and a midpoint within M2 as well as the base of M1.The oil generation zone has then been indicated by crosshatching, and compared with the 0.65 and 1% reflectance level both calculated and measured, the discrepancy is accounted for by amounts of compaction in the well and allowed for in the diagram.

For the base of Unit M2 oil generation commenced at 87 M.a. at about 2.85 km depth, and ceased at 27.5 M.a. at 3.3. km depth. Younger stratigraphic units have not reached the oil generation zone in this well except for the base of M2 at about 2 km, which has just reached the oil generation zone.

FERGUSON HILL LOPATIN DIAGRAM FIG 21



8.2 THE OTWAY RANGES

OLANGOLAH NO. 1

A. Fission Track (Duddy et al. (1982)

Duddy et al believe that there is clear evidence for a rapid uplift of the Otway Range block, followed by intense erosion, and they date this event at 93 M.a. After considering a number of options they decided that at least 1050 m of uplift and erosion had taken place. The geothermal gradient prior to 93 M.a. was 55°C/km, dropping rapidly to 31°C/km after the uplift event. This time corresponds approximately to the initial separation of Australia and Antarctica (at about 95-110 M.a.) Duddy et al (1982) - p2. The submature sediment age was determined as being 123 M.a. (fig.22).

B. Vitrinite Reflectance

(1) The well is located within the Otway Ranges High, close to the Elliot Shear zone and the Devil's Elbow Monocline, and only Lower Cretaceous sediments are present.

(2) The present geothermal gradient is 31°C/km, while the palaeo-gradient at 32.5°C/km from the graph, figure 24, is very similar - the graph intercepts the surface at 95°C which is 81° above the mean surface temperature of 15° - suggesting that a large amount of material is missing. [Fig. 23, Fig. 24].

(3) With a gradient of 32.5°C/km, the 81° difference deduced from the intercept suggests that 2.49 km of the succession has been removed by erosion.

(4) The age range of 123-130 M.a. is based on fission track data.

a) the minimum age of 123 M.a. was obtained for the submature sediment.

b) a study of fission track data from the Otway Ranges, (See Annexure 3.2), suggests the bulk of the volcanogenic sediments were deposited in the post-Neogene period of the Lower Cretaceous.

(5) Decrease of the coalification period to 93-130 M.a. from 0-130 M.a. and recalculation of the Olangolah Palaeo-temperatures gives a gradient of 57°C/km and a much higher intercept at surface - viz. 130° which at

a gradient of 57°C gives $\frac{130}{57}$ = 2.28 km of erosion which reduces the amount of succession that has been removed by erosion by only 9.2%. See Table 6A and figure 25.

(6) Discussion with Bruce Thompson (Vic. D.M.E.) suggests that the Otway Ranges form an overthrust block, the latest age of overthrusting is Post-Lower Cretaceous and this would suggest that some of the increase in rank may be due to the thrusting - i.e. a temporary high gradient, close into the thrust, this would favour a lengthy coalification period, not uniform, that is not restricted to the Lower Cretaceous.

TABLE 6A

Recalculation of Olangolah Palaeo-temperatures using the following criteria from the fission track data

(1) The Age at 0m=120 M.a.
The Age at the end of coalification is 93 M.a.
The maximum Age of the sediments is 130 M.a.

This gives a coalification period of 130-93 = 37 M.a.

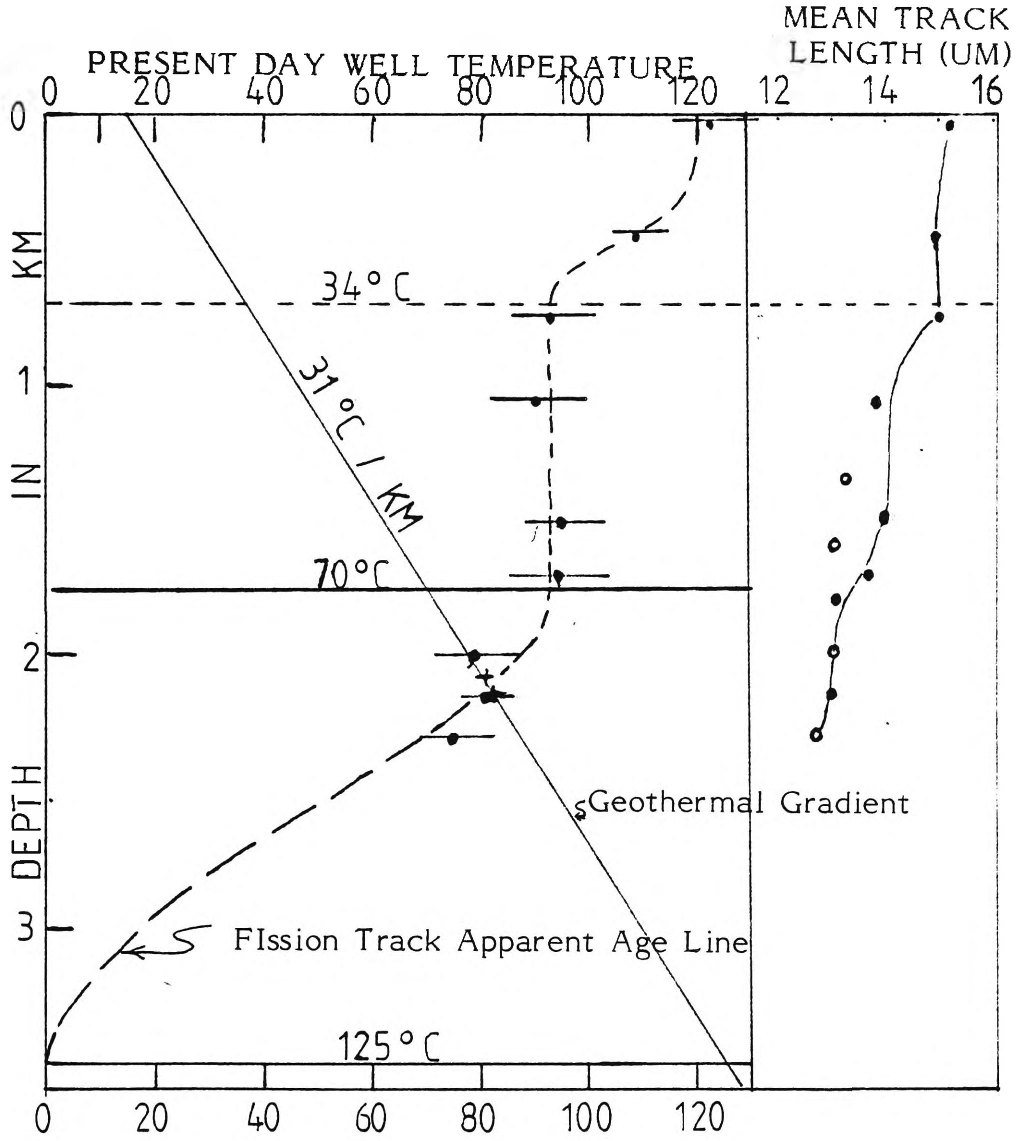
Recalculation of samples:

Coalification	Mean Vit. Reflectance	Tiso	Tgrad
14 m.a.	3.26	208	333
26.2 m.a.	3.60	215	344
28.4 m.a.	3.78	214	342
30.5 m.a.	3.90	214	342
32.4 m.a.	3.76	205	328
32.7 m.a.	4.50	222	355
34.9 m.a.	4.56	222	355
37.0 m.a.	5.69	245	392

OLANGOLAH No 1

Fig. 22 Apatite fission track age and track length variation with depth.
34°C line is the extrapolated depth of submature sediments.
70-125°C line indicates the sediments withinthe mature temperature range.
Note: The zero apatite age has been extrapolated to a depth of 3.5 km.

OLANGOLAH No 1 Fig. 22



- ○ Poor track length control
- ● Good track length control
- + Well temperature

TABLE NO. 6

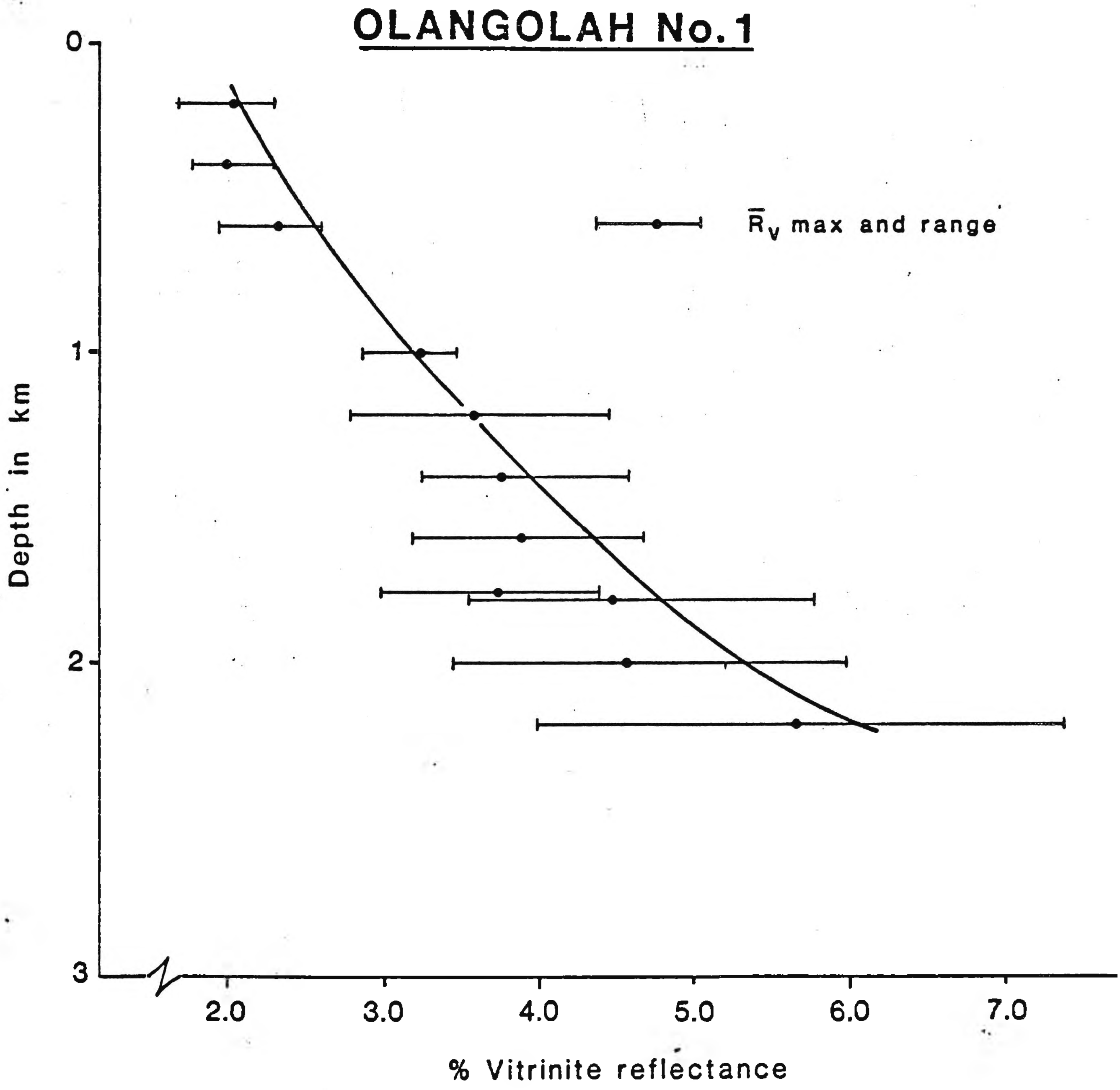
OLANGOLAH No 1

LAB. NO.	DEPTH(M)	AGE	MEAN	STD.DEV.	RANGE	NO. OF READINGS	COMMENTS	TISO	TGRAD
15902	1000	126	3.26		(2.90-3.50)	10		135°C	216°C
15903	1200	126.5	3.60		(2.80-4.44)	20		140	224
15904	1400	127	3.78		(3.25-4.60)	20		145	232
15905	1600	128	3.90		(3.20-4.70)	20		146	234
15754	1765	128.5	3.76		(3.00-4.40)	20		140	224
15906	1800	128.5	4.50		(3.57-5.80)	20		153	245
15907	2000	129	4.56		(3.47-6.00)	20		155	248
15908	2200	130	5.69		(4.00-7.40)			176	282

BOTTOM OF HOLE 2300m Temperatures 81°C AT 2089 m, 82°C AT 2154 m

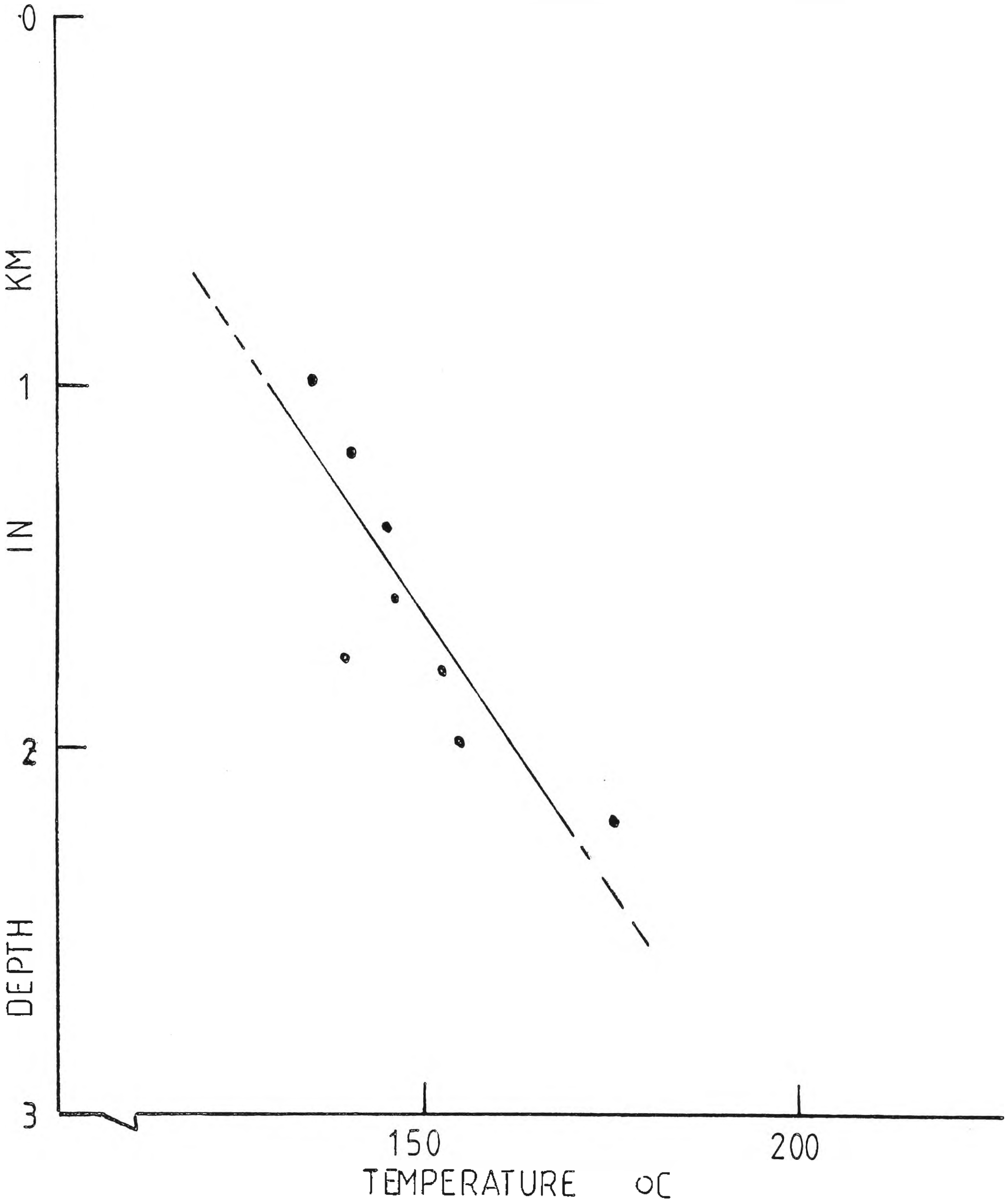
DETERMINATIONS BY A.C.COOK.

FIG. 23



Source: Cook 1982 (b)

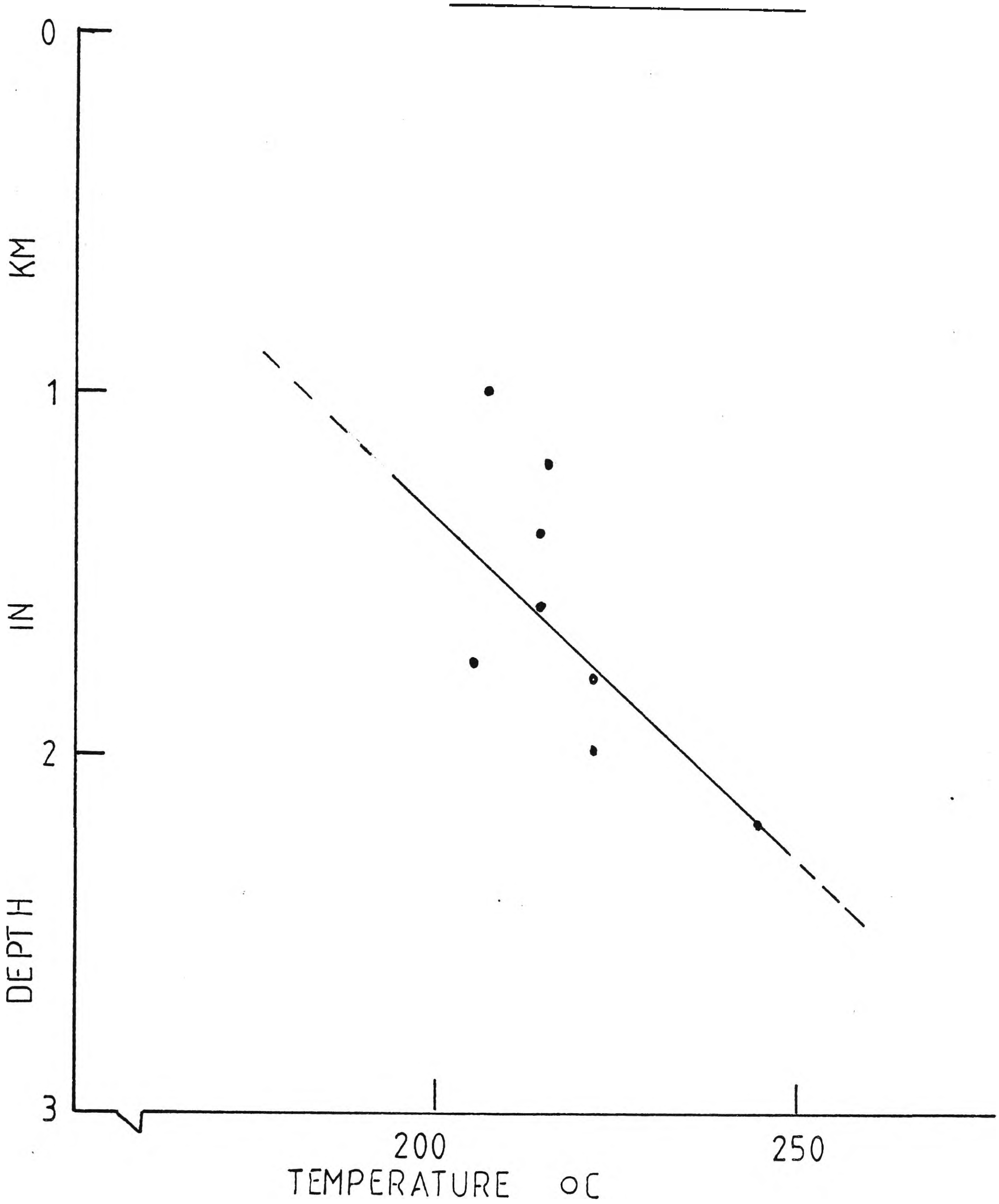
FIG. 24.



Paleo temperature from Karweil Diagram

Tiso vs TDepth Gradient 32.5°C/KM
Surface intersection at 95°C

FIG 25



Paleo temperature from Karweil Diagram

Tiso vs TDepth Gradient 57 °C/KM
Surface intersection at 130°C

RECALCULATED PALAEOTEMPERATURE

KRUMBRUK NO. 13

(1) Well located in the Otway Ranges High, on the coast at Apollo Bay.

(2) Present day geothermal gradients are as follows:

Surface to 825 m = 28°C/km
925 - 1475 m = 38.8°C/km
Average = 29.4°C/km

The palaeogradient of 30°C from the graph suggests no great change in the gradient, compared with that of the present day. The surface intercept of 40° suggests that the equivalent of 30°C (40 °C less the surface temperature of 15°C) is missing. [Fig. 26, Fig. 27]

(3) The uplift appears to be of the order of 0.75km, assuming the gradient was 30°C at the time of uplift. This is somewhat less than at Olangolah No. 1.

(4) The Age range was estimated as follows:-

a) From R17686 - the lowest peak was 115 M.a.
[Surface outcrop age - Gleadow & Duddy Annex. 12.3].
b) From palynology -
Range 987 m - 1281 m = 113-119 M.a.
Range 1281 m - 1373 m = 119-125 M.a.
c) Correlation of γ logs between Krumbruk No. 13 and Ferguson Hill No. 1. There is an approximate equivalence at 420 m on Krumbruk 13 and at 2210m on Ferguson Hill, and this is shown up by a similar change in background of the γ logs.

The estimate is thus for a range in age of from 113 M.a. to 120.5 M.a. for the strata intersected by the Krumbruk No. 13 well.

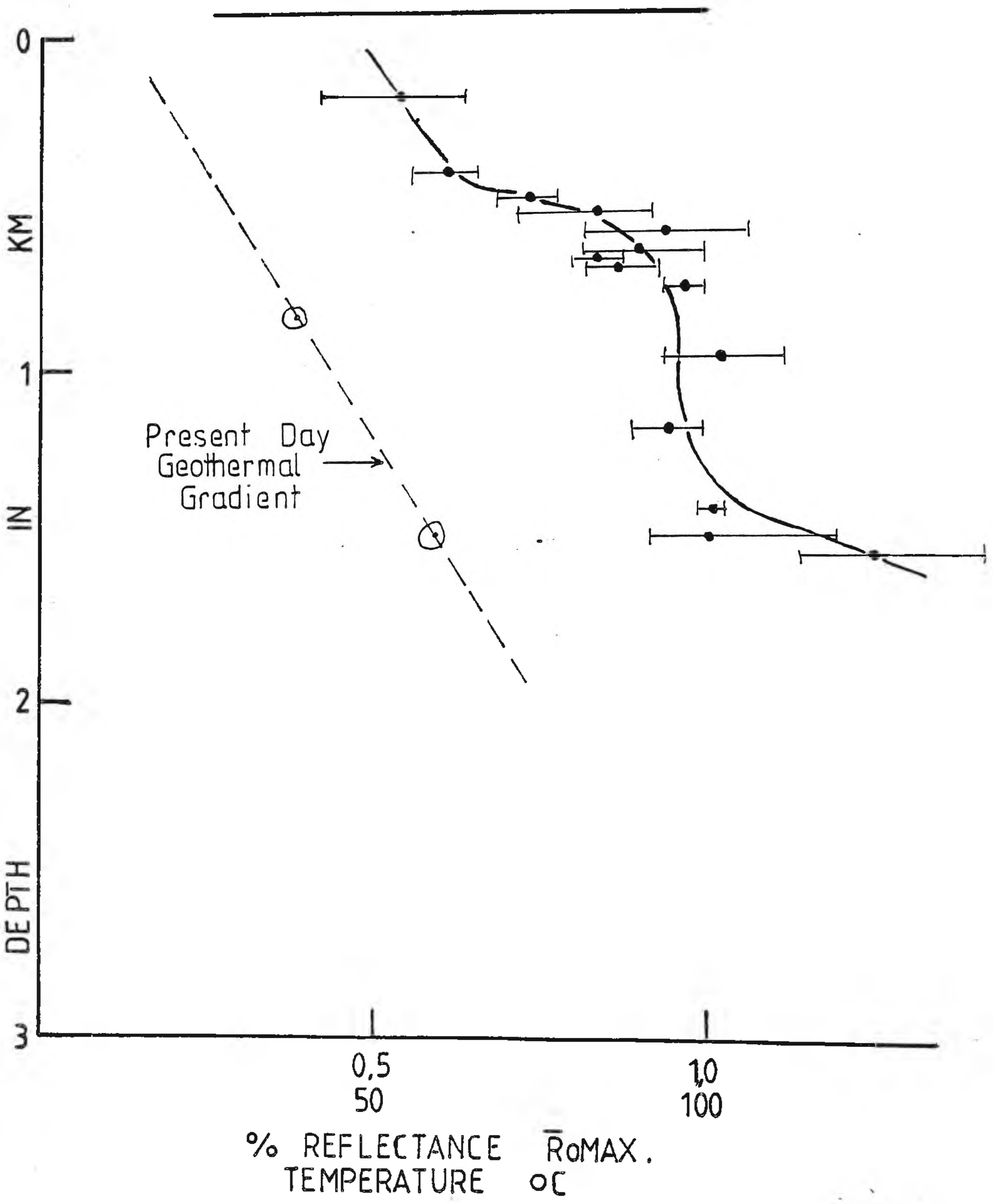
TABLE NO. 7 KRUMBRUK 13

LAB. NO.	DEPTH (M)	AGE	MEAN	STD. DEV.	RANGE	READINGS	COMMENTS	TISO	TGRAD
17944	137c	113.5	0.54	0.06	(.42 - .64)	18		45°	72°
17945	192c	114	Dud	-	- - -	-	No Vitrinite seen		
17946	342 - 345cgs	114.5	"	-	- - -	-	" " "		
17947	378 - 381"	115	0.61	0.03	(.560 - .66)	15		49°	78°
17948	-	No block	-	-	- - -	-			
17949	-	" "	-	-	- -	-			
17550	463c	115	0.74	0.004	(.693 - .780)	7		60°	96°
17951	498 - 502cgs	115.5	0.84	0.08	(.72 - .926)	13	Possible type variation	69°	110°
17952	549 - 552"	115.5	0.94	0.07	(.82 - 1.077)	19		76°	122°
17953	615 - 618"	116	0.89	0.05	(.82 - 1.00)	14		74°	118°
17954	639 - 642"	116	0.84	0.02	(.80 - .88)	7		69°	110°
17955	660c	116	0.87	0.04	(.82 - .94)	13		74°	118°
17956	723 - 726cgs	116.5	0.97	0.02	(.940 - 1.000)	12		79°	126°
17957	801 - 804				- readings .6 - .7				
17958	936 - 939cgs	117.5	1.02	0.07	(.904 - 1.2)	12		80°	128°
17959	1158 - 1161"	118.5	0.94	0.03	(.89 - 1.00)	11		77°	123°
17960	1395 - 1398"	119.5	1.02	0.02	(.987 - 1.033)	8		80°	128°
17961	1461 - 1464"	120.	1.01	0.09	(.92 - 1.2)	17		79°	126°
17962	1527 - 1530"	120.5	1.15	0.09	(1.036 - 1.32)	11		85°	136°

Bottom of hole 1549.81m Temp 59-60° at 1475m 38°C at 825m

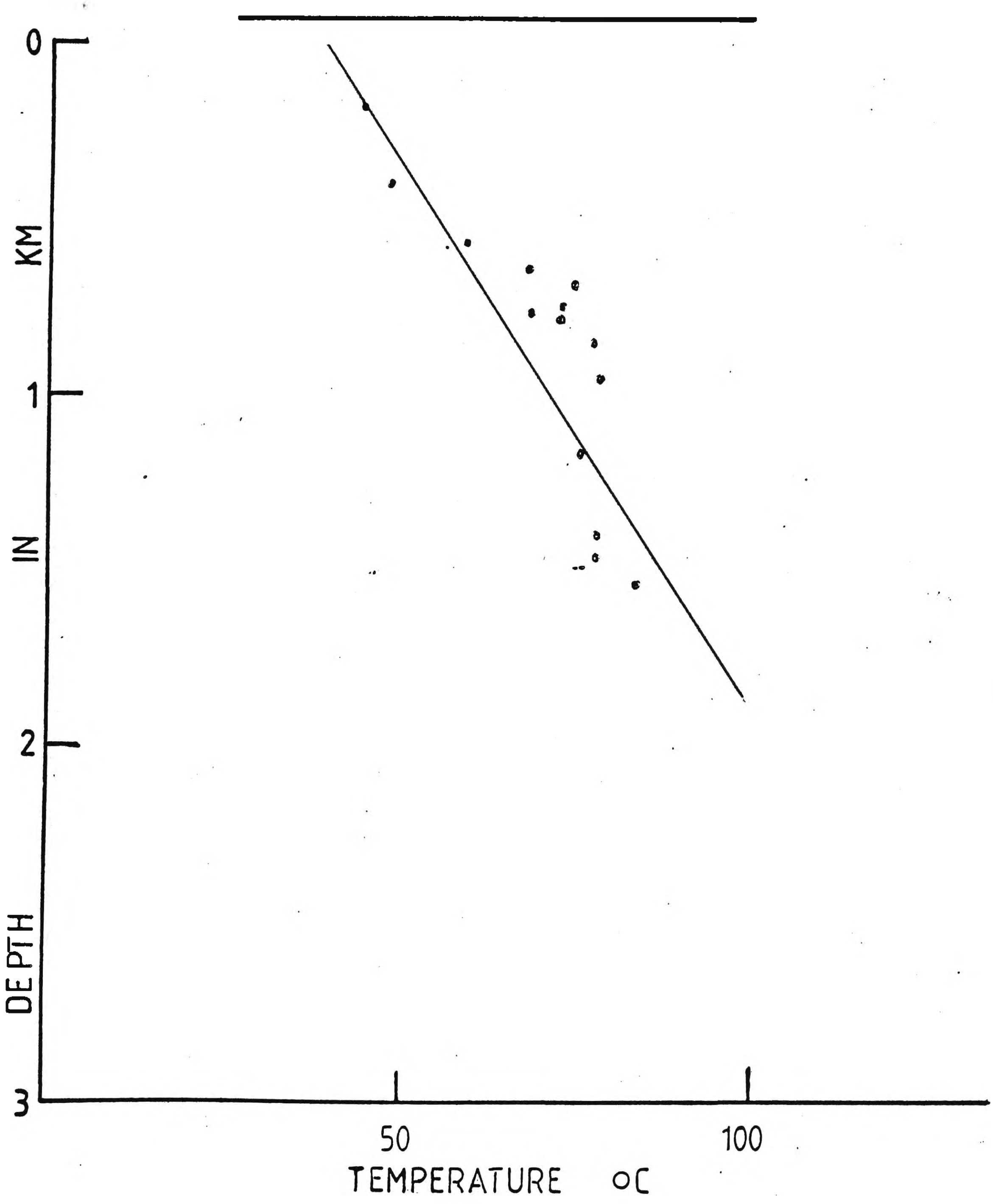
FIG. 26

KRUMBRUK NO. 13



Determinations by D. J. French

FIG. 27



Paleo temperature from Karweil Diagram

Tiso vs TDepth Gradient

THE OFFSHORE WELL

VOLTUTA NO.1

Vitrinite Reflectance

(1) Cook 1979 (a) states that the younger and more recently buried sections offshore, had a similar relative timing of their coalification history as compared with the older, thinner onshore sequences. This is difficult to reconcile with the fission track data which suggests coalification largely precedes the 93 M.a. uplift.

(2) The Isothermal model temperature approaches the present day well temperatures, in this well.

(3) The organic matter in this well reaches the mature level within the hydrocarbon generation window, being all post 93.M.a. in age.

(4) The geothermal gradient is around 25° (uncorrected) at the present time whereas the palaeo-geothermal gradient is 22°C/km from graph figure 29. This is lower than onshore, where the gradient is nearer 30°/km, except for Casterton No. 1 and Ferguson's Hill No. 1.

B. Lopatin Diagram

The plot of the Lopatin Diagram for Voluta No. 1 shows that even though it is a deep hole, the oil generation commenced at 36 M.a. for the base of the Belfast Mudstone, and has just reached the maximum rate of oil generation at the present time.This has been caused by the younger age and the lower geothermal gradient of the sediments located within the rift left by the drift of Antarctica away from Australia at about 93 (Olangolah age) - 97.5 M.a. (Commencement of the Late Cretaceous)

TABLE 8

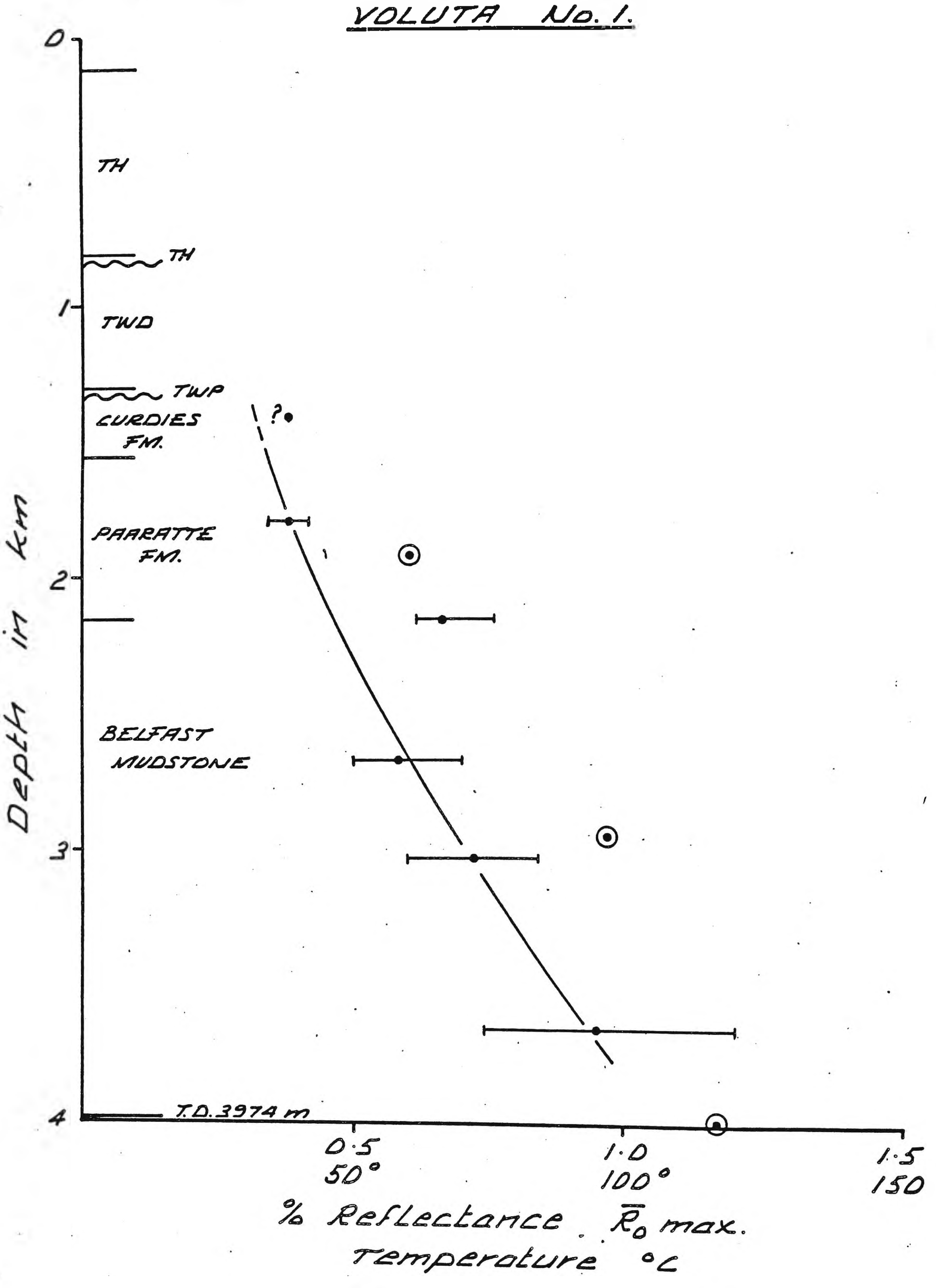
VOLUTA NO. 1

LAB NO.	DEPTH (M)	AGE	MEAN	STD DEV.
9767	1414	66ma	?0.38	
9768	1792	78.5ma	0.38	0.34
9769	2165	88.5ma	0.66	0.62
9770	2674	89.2ma	0.58	0.50
9771	3037	90.ma	0.72	0.60
9772	3653	91.ma	0.95	0.74

Geothermal Gradient is 25°C/Km

RANGE	NUMBER OF READINGS	COMMENTS/ SOURCE	TISO	TGRAD
-	1	A.C. Cook	-	-
- 0.42	3	"	-	-
- 0.76	4	"	68°	101°
- 0.70	5	"	53°	85°
- 0.84	2	"	74°	118°
- 1.20	17	"	84°	134°

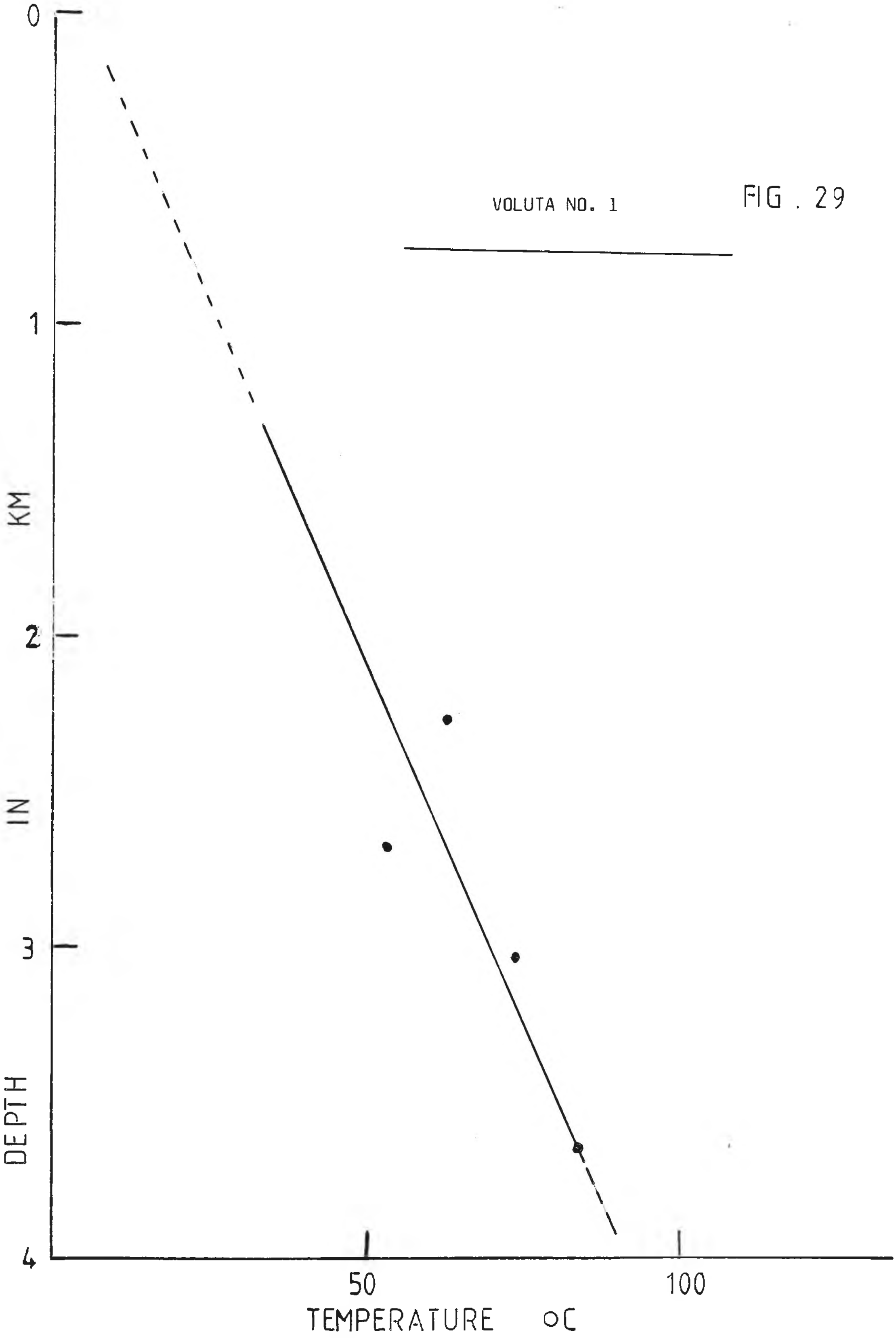
FIG. 28



├─●─┤ Rv max and range
⊙ Well temperature

Source: Cook 1979 (a)

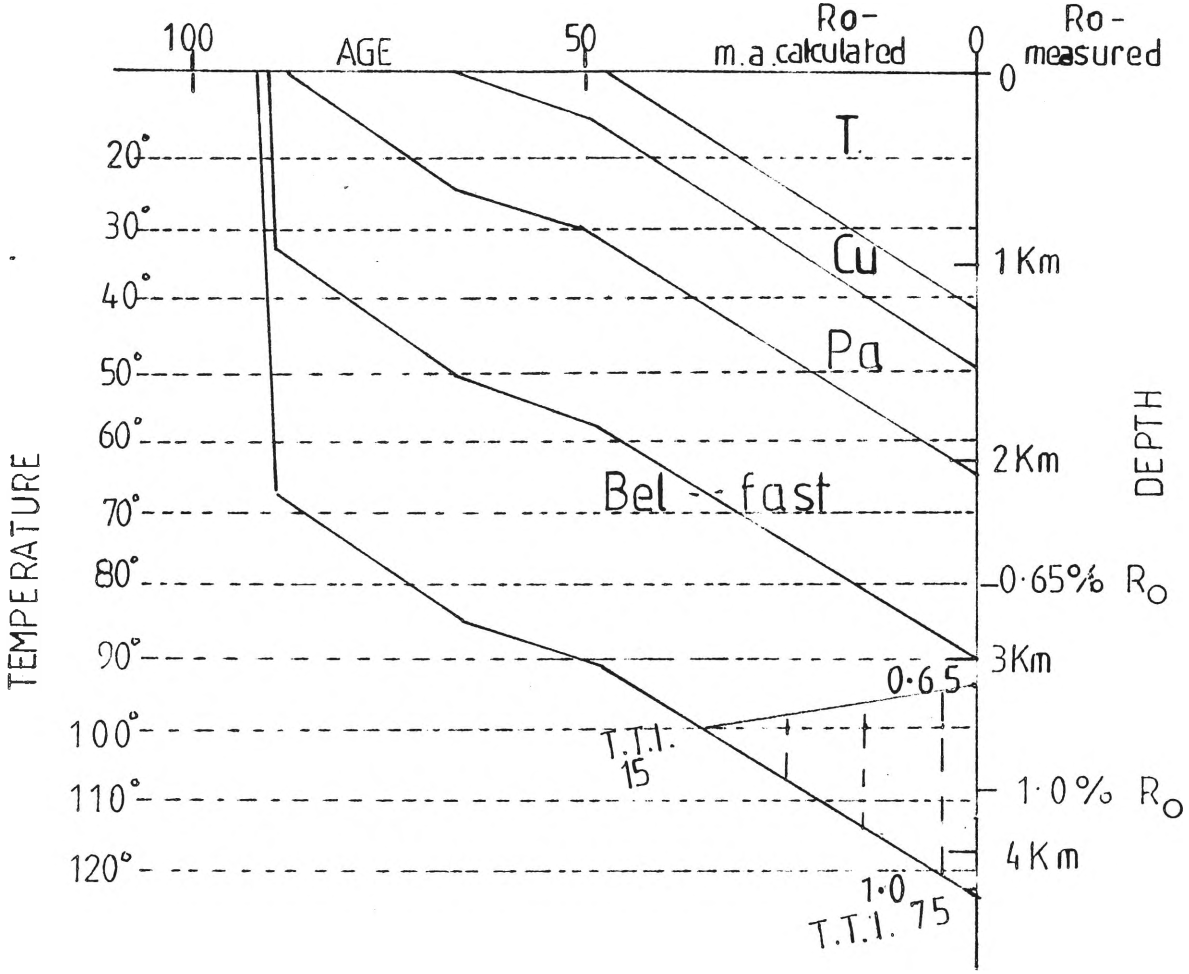
FIG . 29



Paleo temperature from Karwiel Diagram

Tiso vs TDepth
Gradient 22°C/KM

VOLUTA No 1 LOPATIN DIAGRAM FIG. 30



8.4 DISCUSSION - COMPARISON OF METHODS

8.4 (a) General Considerations

1. The major objective in any study of oil source rocks is in obtaining the correct physico-chemical conditions under which oil source material will actually produce oil, this means the correct combination of temperature, pressure and coal rank conditions must be attained for oil to generate, and then be able to migrate to a suitable trap.

2. The most direct method for obtaining the "oil generation window" is a study of rank, a study of the metamorphic grade and chemical evolution which the coal or source rock material has attained.

3. Vitrinite reflectance is a relatively direct method of determining rank. Reflectance changes are caused by changes in molecular structure caused by aromatisation and progressive ordering of aromatic lamellae within the coaly material due to the effects of increasing temperature and pressure conditions over time. This method however is reliable and shows continuous changes in rank that can be accurately measured. It is also one of the few techniques (spore colours also have the property) which permit the rejection of data from cavings or other contaminants.

4. A study of mineral changes, such as a study of zeolites, and how they change with increasing temperature and pressure, is more qualitative, and the changes are not sufficiently frequent or regular as to give a discriminating measure of chemical change.

5. The Lopatin method, for example, is a derivative method that attempts to extend the inference available from the vitrinite reflectance data, by showing the actual depth/temperature/time conditions under which oil has been generated.

6. The Karweil/Bostick Nomogram gives the palaeotemperature from which the oil generation window can be inferred, this too is a derivative method and is based on vitrinite reflectance, geothermal gradient and age,as in the Lopatin method, but makes slightly different basic assumptions from the Lopatin method.

7. The fission track method is a measure of palaeotemperature and age using defects induced by nuclear fission and is an indirect method of determining the oil generation window.

8. The present study has concentrated on vitrinite reflectance, complemented by the Karweil/Bostick Nomogram and a comparison of these results with those obtained by fission track methods, with two examples of the Lopatin method being used to compare onshore and offshore maturation.

8.1 The time taken for a fission track study on half a dozen samples is several weeks, as the samples need to be crushed, the apatite extracted, the sample irradiated at the Lucas Heights Reactor and the tracks measured and counted by microscopic methods. Vitrinite reflectance studies can be completed within 24 hours of receipt of the samples, as mounting, grinding and microscopic study of each specimen is quick and easy.

8.2 Fission track needs large quantities of material for mineral separation, of the order of 1 kilogram for each determination. The sample prepared for fission track study, should be from a sandstone, as the heavy minerals sought are generally restricted to sandstones and do not occur in shales. Vitrinite reflectance needs a minimum of 10 cubic centimetres of cuttings or a 1 cm slice of drill core, and either sandstone or shale will do, as long as there is carbonaceous matter present.

DECAY CURVE FOR A RADIO-ACTIVE SUBSTANCE

FIG. 31

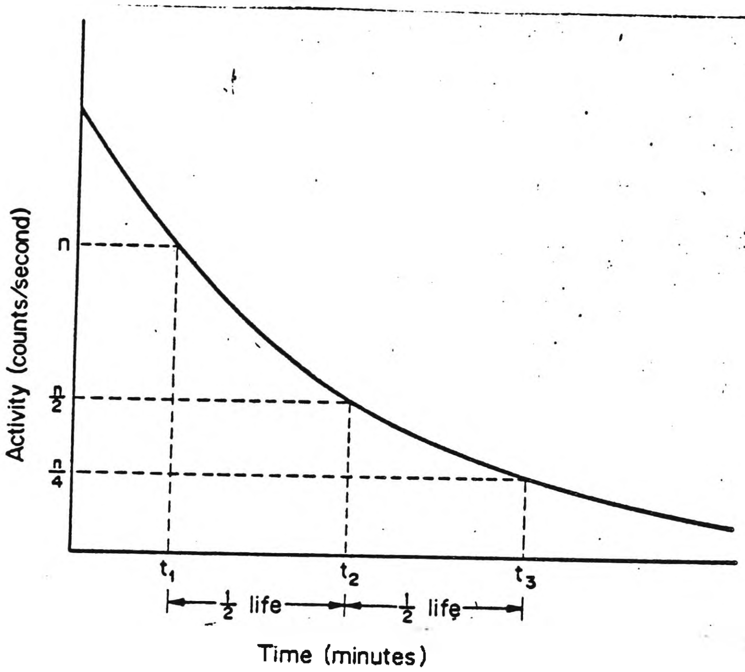


Fig. 31.. Decay curve for a radioactive substance

Fig. 31. shows a typical decay curve for a radioisotope obtained by plotting the readings of a ratemeter which is used to measure the activity over a period of about three half-lives. From such a graph the half-life may be found as follows.

If the count-rate is n at some time t_1 and has fallen to $\frac{n}{2}$ at time t_2, then the half-life is $(t_2 - t_1)$.

Similarly, if the count-rate has fallen to $\frac{n}{4}$ at time t_3 the half-life is $(t_3 - t_2)$.

[Ref. A.F. Abbott. 1977]

8.3 The fission track method shows annealing effects from 65-125°C and this gradational change with increasing temperature gives an accurate guide to the maximum temperature reached by any sample. Vitrinite reflectance shows a gradational change from 0°C to the level of anthracite (4% reflectance and higher) formation - well beyond the oil window - as vitrinite reflectance increase is an irrerversible process.

8.4 Fission track study of the age of apatite using nuclear methods, and the effect on that age dating technique by temperature changes can be utilized. The tracks formed by nuclear decay particles are annealed by heat in the 65-125°C temperature range. The age of any apatite sample unaffected by temperature can thus be determined. Also other minerals such as zircon, if present, can be dated by nuclear methods at the same time.

8.5 The decay curve for radio-active substances shows that decay is time dependant (see fig.31) but temperature can partially or wholly nullify the effects of nuclear breakdown (fission tracks) seen in an apatite crystal, for example, thus in effect resetting the nuclear clock. If the resetting is total or partial, the temperature change and time of change can be inferred for this event. Vitrinite reflectance can give the maximum rank and by inference, palaeotemperature reached at each level, from the lowest rank to the highest rank, but the calculation of the timing of thermal events is less precise as compared with fission track dating.

8.6 Vitrinite reflectance organic petrology can give direct evidence of local coking, adjacent to a fault of dyke, as bireflectance, in the vitrinite reflectance, occurs with the onset of the plastic phase of coke formation. With fission track dating this could be inferred from an annealed specimen in the midst ~~of~~ a suite of partially annealed specimens.

8.4 (b) Detailed Considerations

(1) Tullich No. 1. This well, located close to Casterton No.1 is too shallow to be suitable for fission track study. There is a very low geothermal gradient, and though Pretty Hill Sandstone was intersected the rocks throughout Unit P are expected to be immature.

(2) Casterton No. 1. This well shows that a gradthermal palacogradient prevailed, and that the temperature is now at its maximum, and that there has been no tectonic uplift.

Age dating of the igneous rocks just above the basement contact give an overall age control for this well. Fission track could not be expected to add much to the available information, other than the age of the submature strata.

(3) Eumeralla No. 1. This well demonstrates that temperatures have decreased from an earlier peak. This is confirmed by both methods. The cause of change could be related to uplift on the Warrnambool Ridge.

(4) Flaxman's No. 1. Both fission track and vitrinite reflectance agree that there has been no significant uplift, as the temperature gradient is essentially in equilibrium with maturation and fission track ages. Again vitrinite reflectance and fission track differ on the depth to the oil mature sediments.

(5) Ferguson's Hill No. 1. The fission track data suggest that the temperature has decreased slightly from an earlier peak. The geothermal gradient now is above the regional gradient so no reduction in geothermal gradient is envisaged, when compared with other wells, so the decrease may perhaps be due to slight uplift, possibly caused by the overthrusting believed to have occurred in the adjoining Otway Range Block.

The vitrinite reflectance does not concur, but suggests a thermal event was confined to the basal portion of the succession - where the reflectance is significantly higher.(This occurs at a depth of 3500m).

The Lopatin diagram suggests that the well has been drilled to the oil deadline, at least as far as Unit M2 is concerned. The oil generation commenced in Upper Cretaceous times and some of that oil could have migrated and been lost when the Tertiary block faulting or overthrusting occurred.

(6) Olangolah No.1. There is evidence of uplift from the fission track data, at approximately 93 M.a. All the coalification in the Otway Group apparently occurred prior to this date and the amount of uplift can only be inferred indirectly. (Duddy and Gleadow suggest uplift of 1 km). The vitrinite reflectance data suggests uplift of the order of 2.49 km. The coalification period is believed by Cook 1982 (b) to be rapid and early under a significant cover of younger sediments. Recalculation using an age shorter than the total coalification period, implies a very high geothermal gradient which is not suggested by the vitrinite reflectance samples, but is suggested by the fission track data.

(7) Krumbruk No.13. This well is in the same upfaulted block as Olangolah No.1 well, but the uplift has been somewhat less. The uplift, from palaeogeothermal data would appear to be of the order of 0.80 km. The whole succession is within the oil window, and uplift has therefore not improved the oil-forming potential.

(8) Voluta No. 1. This single offshore well, in which all the intersected sediments are post-lower Cretaceous, suggests that these sediments adjusted to the prevailing geothermal gradient, and there was no change in gradient in the post Lower Cretaceous period, i.e. the coalification was continuous and not pre-95 M.a. in age.

A comparative table to compare all the results obtained by the various methods has been drawn up as follows:-

Table No.8

a Onset of oil generation 70°C or 0.60% Rv max - depth from surface.

	Tgrad	Fission Track	Lopatin	Vitrinite Reflectance
1. Tullich 1	-	-	-	-
2 Casterton 1	1.9 km	-	-	-
3 Eumeralla 1	2.1 km	1.3 km	-	2.15 km
4 Flaxman's 1	2.1 km	1.7 km	-	2.7 km
5 Ferguson's Hill	1.5 km	1.6 km	1.5 km	2.0 km
6 Olangolah 1	-	0.7 km	-	-
7 Krumbruk 13	0.1 km	-	-	0.3 km
8 Voluta 1	1.7 km	-	2.15 km	2.6 km

(b) Oil deadline 125°C - 1.3% Rv max depth from surface.

	Tgrad	Fission Track	Lopatin	Vitrinite Reflectance
1 Tullich 1	-	-	-	-
2 Casterton 1	-	-	-	-
3 Eumeralla 1	-	3.2 km	-	-
4 Flaxman's 1	3.2 km	3.5 km	-	-
5 Ferguson's Hill 1	2.8 km	3.3. km	3.6 km	3.4 km
6 Olangolah 1	-	3.5 km	-	above present surface
7 Krumbruk 1	1.0 km	-	-	1.6 km
8 Voluta 1	3.2 km	-	4.6 km	-

The various methods compare broadly at the 70°C level with 0.6% Vitrinite reflectance readings giving the maximum depths in each case. The shallow depth to the level of oil generation in Krumbruk 13 suggests that any oil generated is likely to have escaped.

At the 125°C level with 1.35% vitrinite reflectance, the deadline for Krumbruk 13 occurs at very shallow depth and the depth of the oil deadline suggested by the Lopatin diagram for Voluta 1 at 4.6 km is noteworthy, other results are broadly similar.

Most noteworthy in the above table is the fission track results, they differ at the onset of oil generation from all the other values, being shallower in Eumeralla and deeper in Olangolah, also the Lopatin method is uniquely deep to the oil deadline in Voluta 1.

The fission track method does not show up Olangolah for what it is - a block lifted up so that all the rock exposed is overmature, this suggests that fission track is a method that should be relied on for onset and deadline values only in areas of slight or no tectonic disturbance, at this stage of our knowledge.

9. CONCLUSIONS

(1) The fission track method is a new, indirect, but time consuming method of obtaining the oil generation window in any basin sequence.

(2) Both fission track and vitrinite reflectance methods are quantitative and reproducible, and can therefore be used for the interpretation and modelling of the thermal histories of sedimentary basins, in the search for the oil generation window, or gas generaton zones, as part of an overall hydrocarbon resource evaluation.

(3) Fission track dating can provide a fixed age for the sub-mature sediments and a quantitative interpretation for a range of thermal histories, within the oil generation window. Vitrinite reflectance gives a cumulative thermal history that makes no allowance for relative changes in the geothermal history through time other than to give the highest rank reached.

(4) A comparison of the varying methods of studying the thermal history of a sedimentary basin show that the T grad, fission track, Lopatin method and vitrinite relectance methods all give broadly the same depths to the top and bottom of the oil generation window except in the case of the strongly uplifted Olangolah 1 well, where the fission track method appears to be in disagreement with all the other techniques (i.e. vitrinite reflectance and T grad indicate that Olangolah in toto

is beyond the oil deadline).

(5) Vitrinite reflectance unlike fission track data is directly related to the zone of hydrocarbon generation and is a relatively direct guide to the chemical changes associated with oil generation.

(6) Calculations can be made for vitrinite reflectance to give timing of oil generation, using assumed palaeo-temperatures. Jumps in the reflectance profile also indicate the presence of unconformities or structural breaks.

(7) A maturity/age profile can be drawn up using vitrinite reflectance data that can assist in locating the probable depth position of the oil window in the stratigraphic succession.

(8) The relative accuracy of the methods in assessing what has actually occurred is not clear without recourse to further geological data, unrelated to either method.

(9) Overthrusting that may have accompanied the block faulting at the time of uplift of the Otway Ranges in the Tertiary appears to have had no effect on rank distribution in Olangolah No.1 succession. The overthrust movement appears to have proceeded at too slow a rate to generate heat, in the post-Lower Cretaceous period; even though duplication occurs in the Olangolah sequence.

(10) Fission track and vitrinite reflectance are both quantitative methods that are suitable for locating the oil generation window, but vitrinite reflectance would appear at this stage to be the faster method for gaining data for modelling of thermal histories.

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12. ANNEXURES

12.1 Method of block preparation for reflectance determination, and equipment used for that determination.

Place cut coal sample or chips in an ice-cube tray, (The coal samples having been cut at right angles to the bedding), and pour in the Epoxy Resin - 100 mls with 2% of the catalyst.

Place in an oven and adjust vacuum to 600 mm Hg. - then slowly release. The reaction is exothemic and the ice-tray with specimens must be left in water for 24 hours to cool and set.

Polishing the blocks

(1) Coarse wheel-grind for 2 minutes moving the block around.

(2) Diamond wheel 3 minutes, the block is held at right angles to what it was when on coarse wheel, and all the first scratches must be removed.

(3) 400 paper, the coarsest, fifteen times in one direction, turn 180° then fifteen times again.

(4) 600 paper, twenty times in one direction, turn 180°, twenty times again.

(5) 1200 paper, twenty-five times in one direction, turn 180° twenty-five times again.

Give a fine polish holding the block lightly, five or six sweeps across the paper.

(6) Chrome oxide, let lap rotate, anticlockwise movement against lap, forty rounds, wash well.

[Note that at the S.E.C. the chrome oxide step is by-passed and for soft brown coal blocks γ Alumina is used instead of Magnesium oxide (7)].

(7) Magnesium oxide, polish as for (6).

The instruments used.

Preliminary measurements made at the S.E.C. Coal Research Laboratory, Richmond, Victoria.

The instrument used; a Leitz M.P.V. Compact Orthoplan No. 964874 with 50 x 0.85 objective with both reflectance and fluoresence capabilities.

The Standards:- .529 and 1.236

Confirmatory measurements at Wollongong University, where the instrumentation was as follows:-

The vitrinite reflectance measurements were made using a Leitz MPV 1 photometer; a fluorite lens (n.a. 0.85); plane polarized light; refractive index of the immersion oil 1.581 @ 23°C, wavelength 546nm; and standards spinel 0.42%, Yag 0.92% and GGG 1.76%. The conditions for the fluorescence observations were BG3 excitation filter, TK400 dichroic mirror and a K490 barrier filter. Both the fluorescence mode and the reflected light mode photographs were taken with the dichroic mirror as the illuminator to ensure accurate registration of fields in the two modes. A K460 filter (pale green cast) was used for the reflected light to avoid the complex colour cast given by the dichroic mirror.

12.2 Laboratory Results - Open File and newly generated results.

1. Cuttings and Cores Sampled
2. Tullich No. 1
3. Casterton No. 1
4. Eumeralla No. 1
5. Flaxman's No. 1
6. Ferguson's Hill No. 1
7. Olangolah No. 1
8. Krumbruk No. 13
9. Voluta No. 1
10. A geologic time scale.

12.21 CUTTINGS/CORES SAMPLED

CASTERTON 1

	Imperial Measure	Metric (m)
17924	2760-70'	843
17925	2910-20'	888
17926	3260-70'	995
17927	3597-Core 4	1096
17928	3740-50'	1141
17929	4506-Core 8	1373
17930	3408-Core 8	1374
17931	6500-10'	1983
17932	6596'6-Core 14	2011
17933	7253'6"	2211

Jurassic Casterton Beds to 8022

Bottom of hole is @ 2494m Temperature 179°F

FERGUSON'S HILL

	Imperial Measure	Metric (m)
17934 Core 7	2741'6"	836
17935 Core 11	3751'	1143
17936 Core 12	4112'	1253
17937 Core 14	5078'	1548
	Change noted in Zeolite type by Duddy (Verbal communication)	
17938 Core 16	5934'	1809
17939 Core 18	6557'	1999
17940 Core 20	7236'	2206
17941 Core 23	8260'	2518
17942 Core 25	9197'	2803
17943 Core 29	10660'	3249

Basement is @ 3509m Bottom of hole is @ 3964.5m
Temperature 246°F

TULLICH No. 1

	Imperial Measure	Metric (m)
17963	420-430'	129.5
17964	610-620'	186.
17965	2310-30'	705
17966	2991-Core 7A	912
17967	3290-3300	1004
17968	3479-Core 8A	1060
17969	3690-3700'	1126
17970	3760-3770'	1147
17971	4502-Core 12A	1372
17972	4542-Core 13A	1384

Bottom of Hole 1635m Temperature 134°F

KRUMBRUK 13

	Imperial Measure	Metric (m)
17944	137	
17945	192	
17946	342-345	
17947	378-381	
17950	463	
17951	498-501	
17952	549-552	
17953	615-618	
17954	639-642	
17955	660	
17956	723-726	
17957	801-804	
17958	936-939	
17959	1158-1161	
17960	1395-1398	
17961	1461-1464	
17962	1527-1530	

Bottom of hole 1549.81 Temperature 59-60° @ 1475m
48°c @ 825m

12.2.2. TULLICH NO 1

Sample No.	Depth (m)	Rvmax.	N	Remarks
17963	129.5	0.26	5	Possible volcanic rock with abundant pyrite, Fe staining. Vitrinite is present as a large grain + D.O.M., along with common fusinite and semi-fusinite. A trace of resinite (dark orange) only was seen under flourescence.
17964	186	0.26	10	Coarse quartz sandstone carrying abundant textinite, along with semi-fusinite and possible siderite. Exinite did not appear to be present.
17965	705	0.26	12	Medium to coarse sandstone with "brain" semi-fusinite along with semi-fusinite, inertodetrinite as D.O.M. Some large grains vitrinite with (dark orange) sporinite and cutinite locally present and pyrite.
17966	912	0.32	3	Sandstone with large area of layered semi-fusinite and inertodetrinite, scarce vitrinite and exinite not seen under fluorescence.

17967	1004	0.38	5	Sandstone, siltstone with a large area of vescular fusinite. Rare vitrinite with sporinite and cutinite present, fluorescing in green.
17968	1060	0.39	6	Banded sandstone, siltstone with textinite, cavings, semi-fusinite and D.O.M.
17969	1126	0.36	8	Patches of thinly banded vitrinite in arkose, with fusinite, inertodetrinite and D.O.M. Exinite not present.
17970	1147	0.36	7	Vitrinite, sporinite and cutinite rare, fluorescing in green. D.O.M. mostly inertinite in arkose.
17971	1372	0.42	14	Abundant vitrinite and semi-fusinite in banded medium-fine grain sandstone with textured vitrinite and inertodetrinite. Green/yellow fluorescing sporinite and cutinite are present in the banding with rare resinite.
17972	1384	0.45	16	Semi-fusinite-inertodetrinite and vitrinite banding, with abundant pyrite and iron staining. Exinite not seen under fluorescence.

TULLICH No1

PLATE 1

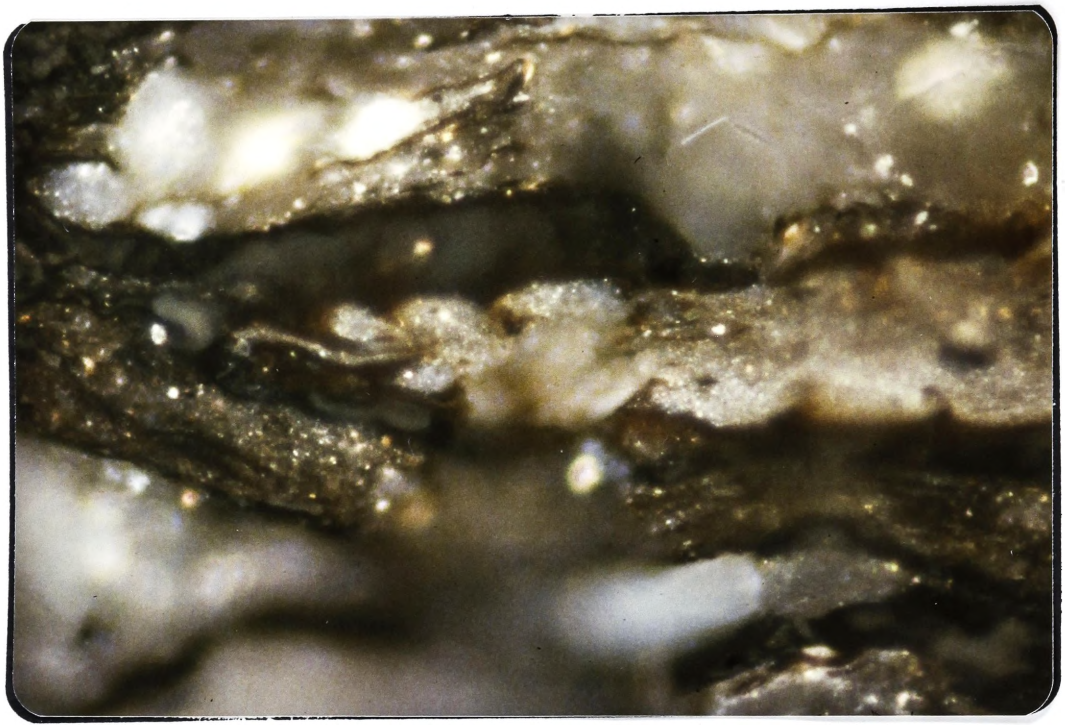
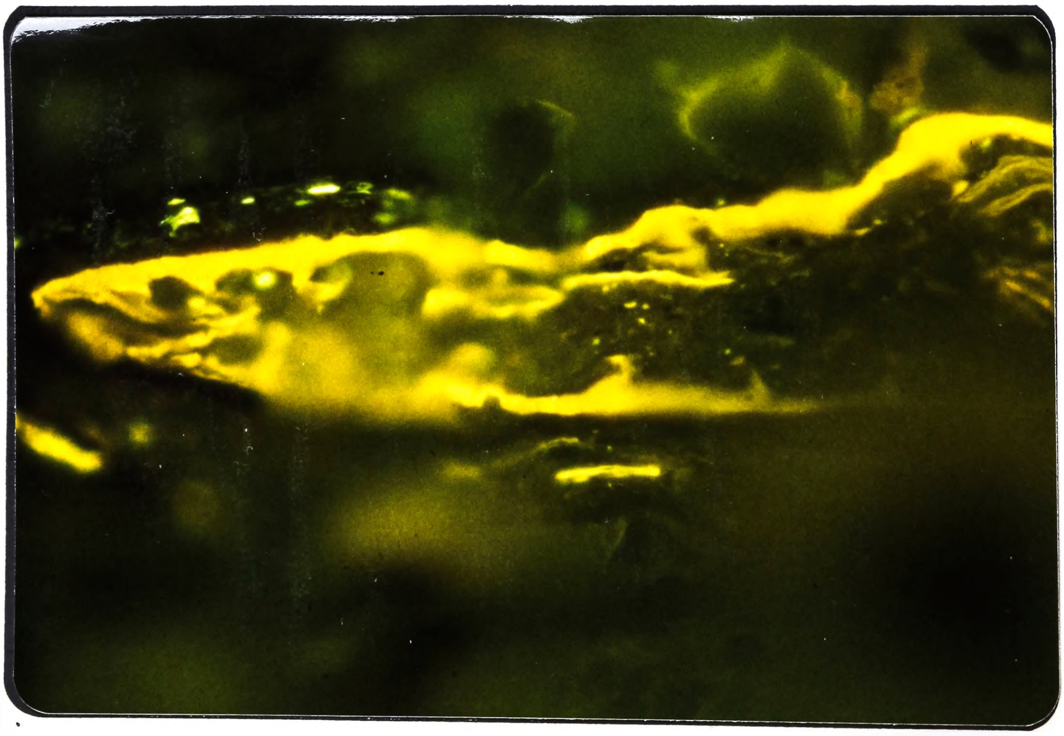


PLATE 2



12.2

TULLICH NO. 1

Plate 1

Cutininite and Vitrinite	R. 0.42%
Reflected light x 50	Block No. 17971

50X = 0.22 mm. field width

Plate 2

Cutininite in parallel section, same view as above in fluorescent light.

CASTERTON NO. 1

Sample No.	Depth (m)	RvMax	N	Remarks
17924	843	0.37	16	This is a claystone with specks of banded vitrinite present along with sclerotinite and inertodetrinite. Sporinite and cutinite fluorescing in yellow are present.
17925	888	0.46	11	Claystone containing sparce banded vitrinite, with alteration along cracks, abundant inertodetrinite and semi-fusinite, orange fluorescing sporinite and possible resinite.
17926	995	0.46	5	This is a sandstone/siltstone with textured vitrinite (telinite), rare inertodetrinite and sparse orange fluorescing sporinite.
17927	1096	0.46	4	A medium to coarse-grained sandstone with wisps of vitrinite, some inertodetrinite and orange fluorescing cutinite.
17928	1141	0.47	10	A claystone with large coal and pyrite specks. Dark orange fluorescing sporinite and minor cutinite and resinite. Banded vitrinite fusinite/semi-fusinite and inertodetrinite.
17929	1373	0.54	10	Claystone with vitrinite and greenish fluorescing sporinite.

17930	1373	0.56	6	A claystone with banded vitrinite-inertinite and scarce yellow fluorescing sporinite.
17931	1983	0.63	6	Medium to coarse sandstone with vitrinite, inertinite and some yellow fluorescing sporinite.
17932	2011	0.56	6	Bands of semi-fusinite along with abundant cracked vitrinite and scarce sporinite and cutinite, fluorescing in green, in coarse sandstone.
19733	2211	0.66	6	Medium to coarse sandstone with banded inertinite grading to vitrinite. Semi-fusinite after vitrinite and abundant yellow fluorescing sporinite and cutinite.

Eumeralla-1

UW No.	Depth m	$\bar{R}o$ max %	Range R max %	N	Exinite fluorescence (Remarks)
	471	0.36			
	541	0.42			
	952	0.46			
	1160	0.41			
	1340	0.48			
	1742	0.49			
	1785	0.48			
	2047	0.61			
	2204	0.61			
	2440	0.67			
	2610	0.74			
	2738	0.80			
	2757	0.79			

Source: Cook 1979 (a)

EUMERALLA No 1

PLATE 3

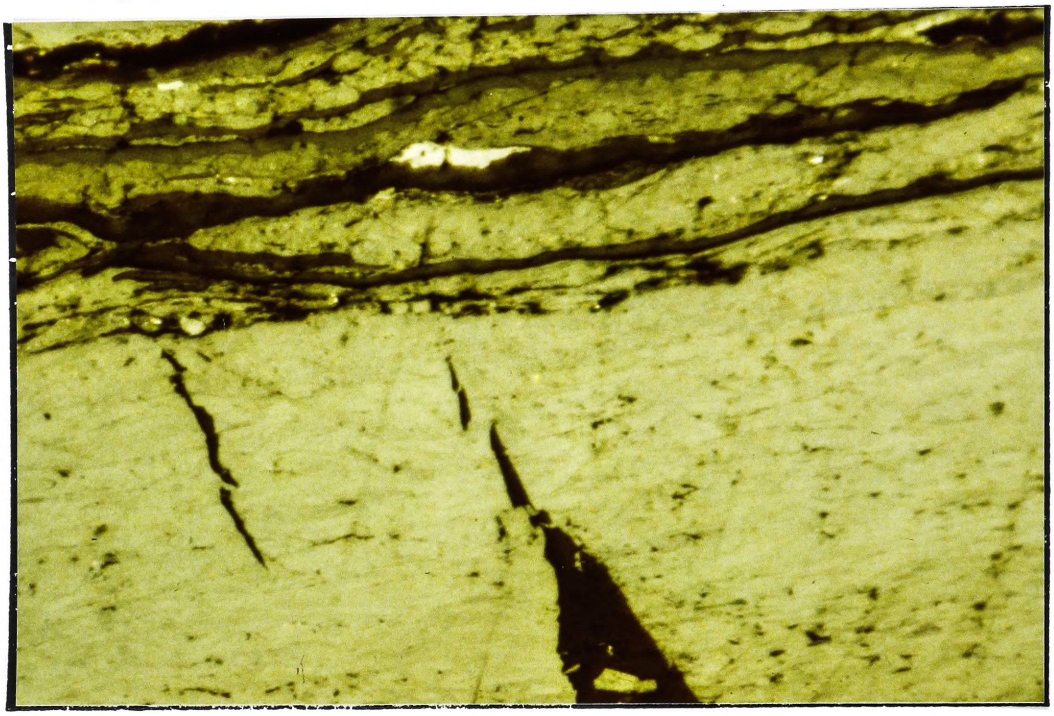
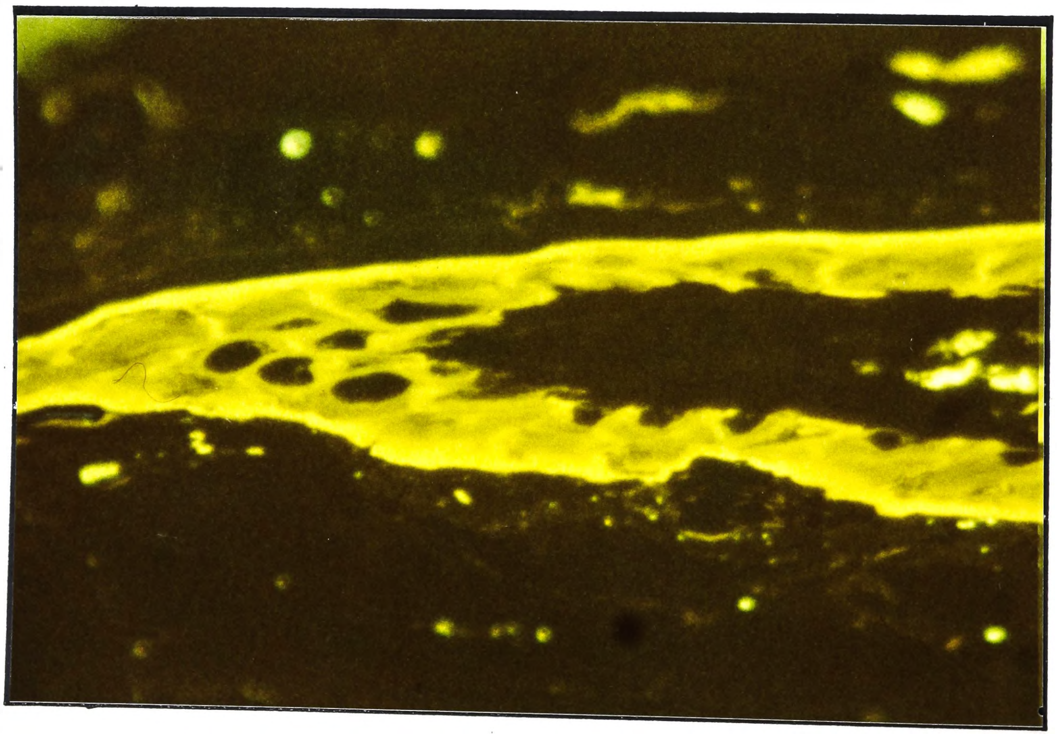


PLATE 4



12.2.4 EUMERALLA NO. 1

Plate 3

Shrinkage cracks in vitrinite with exinite x 32, R= 054%. Reflected light.

32X = 0.34 mm. field width

Plate 4

Cutinite in vitrinite, fluorescent light x 32.

32X = 0.34 mm. field width

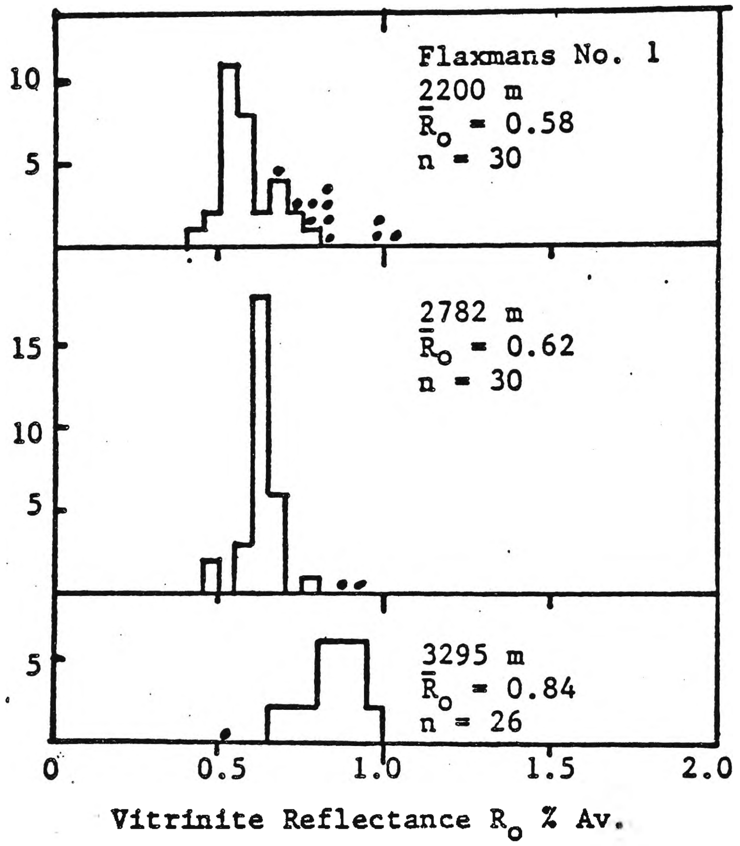


Fig. 8 **Reflectance histograms for Flaxmans No. 1,**

NOTE

Definite vitrinite particles - solid lines

Doubtful vitrinite particles - dots.

Source: Saxby, et. al 1977

9800	1519	0.50	0.39-0.60	4	Sparse exinite, sporinite, cutinite, resinite, bright yellow to orange. (Dirty ss. with common I but V is rare.)
9801	1945	0.42	0.32-0.51	2	Very rare dull orange liptodetrinite. (Sandy to silty mudstone, pyritic. D.o.m. common, chiefly of small grain size and mainly I.)
9802	2397	0.65	0.54-0.80	7	Sporinite and liptodetrinite yellow to orange, abundant in carb. siltst., but rare in claystone and ss. (D.o.m. ranges from common to rare, chiefly I and E with rare vitrinite.)
9803	2709	0.70	0.68-0.71	2	Trace of liptodetrinite, orange. (Claystone, d.o.m. very rare.)
9804	3513	1.17	1.00-1.25	10	No fluorescing exinite. (Lithic ss. with rare d.o.m. interbedded with siltst. with common d.o.m., predominantly I, but some V. Patchy mineral fluorescence.)

Source: Cook (1976) (b)

12.25 (cont'd). **FLAXMANS No. 1**

K.K. No.	Depth (m)	$\bar{R}_v$max	Range	N	Exinite Fluorescence (Remarks)
					WANGERRIP GROUP SHERBROOK GROUP TIMBOON/CURDIES 1071m
15352	1258 Core	0.45	0.39-0.53	3	Rare ?dinoflagellates yellow to orange, and cutinite and sporinite, orange to dull orange. (Mudstone, d.o.m common, I>E>V. Inertinite common, vitrinite rare.)
					BELFAST MUDSTONE 1698m
15353	1815 Core	?0.52	0.45-0.61	?3	Rare dinoflagellates and sporinite yellow to orange. (Mudstone, d.o.m. sparse I>E>?V. Inertinite sparse, vitrinite identification uncertain and material categorised to vitrinite, is rare. Pyrite abundant.)
					FLAXMAN FORMATION 1984m
15354	2095 Core	0.51	0.40-0.62	7	Rare dinoflagellates and sporinite, yellow to orange. (Siltstone and sandstone with sparse d.o.m., I>V>E. Vitrinite and inertinite locally common as large phytoclasts, but inertinite sparse and vitrinite rare overall.)
					WAARRE FORMATION 2096m
15355	2105 Core	0.43	0.26-0.55	9	Rare cutinite and sporinite, orange. (Sandstone with rare large phytoclasts of inertinite and vitrinite. D.o.m. rare, I>V. Some of the vitrinite is derived from wood with very dark "resinous" cell-fillings. Rare pyrite and some detrital grains of iron oxide minerals present.)
					OTWAY GROUP 2165m
15356	2199 Core	0.51	0.40-0.59	20	Exinite sparse to common, sporinite and cutinite, orange, fluorinite, rare, green. (Siltstone, d.o.m. abundant, I>E>V. I common to abundant, vitrinite rare to sparse. Pyrite rare. Most phyterals small, some cutinite in large shreds. A grain of reworked clarite is present, R_v 0.67%.)
15357	3513 Core	0.92	0.79-1.02	14	No fluorescing exinite. (Siltstone, d.o.m. common, I>V, no E. Massive I is present in association with vitrinite and the vitrinite population is unusually well-defined as compared with most other samples from the deeper part of the Otway Group. Much of the vitrinite measured appears to be part of a root.)
					T.D. 3514+m

Source: Paltech 1982

12.25(cont'd) Flaxmans No. 1

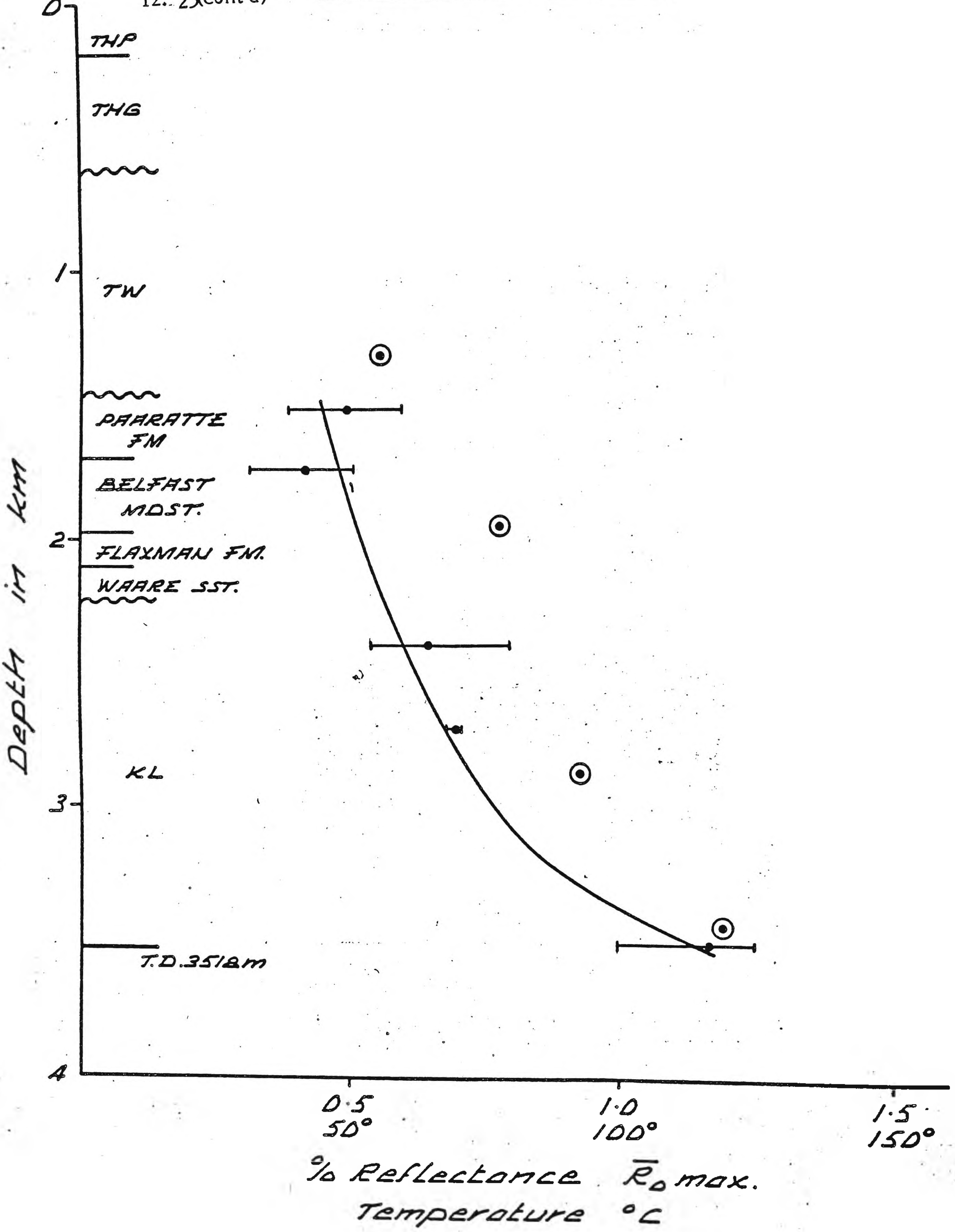
The dispersed organic matter is dominantly inertinite, but exinite is abundant in the sample from 2397m. Organic matter is rare in the sample from 2709m and the vitrinite reflectance for the sample from 3513m is sufficiently high for any exinite in this sample to have lost the property of autofluorescence.

The vitrinite populations in the samples were poorly defined and the data quality is not as good as for some other wells. The reflectances agree with the exinite fluorescence colours and are thought to be an adequate indication of the maturity of the section. The top of the zone of initial oil maturity appears to be relatively shallow at between 1500m and 2000m. The zone of prolific oil generation lies from 2400m to about 3000m and one of the samples within this zone contains abundant exinite. The lowest sample is close to the oil deadline, and within the zone dominated by wet gas. The reflectance gradient is relatively low down to below 2709m but increases rapidly towards T.D., with the main inflexion probably being close to 3200m.

Source: Cook 1979 (b)

12.. 25(c0nt'd)

FLAXMANS No. 1.



Source: Cook (1979 (b)

FLAXMAN'S No1

PLATE 5

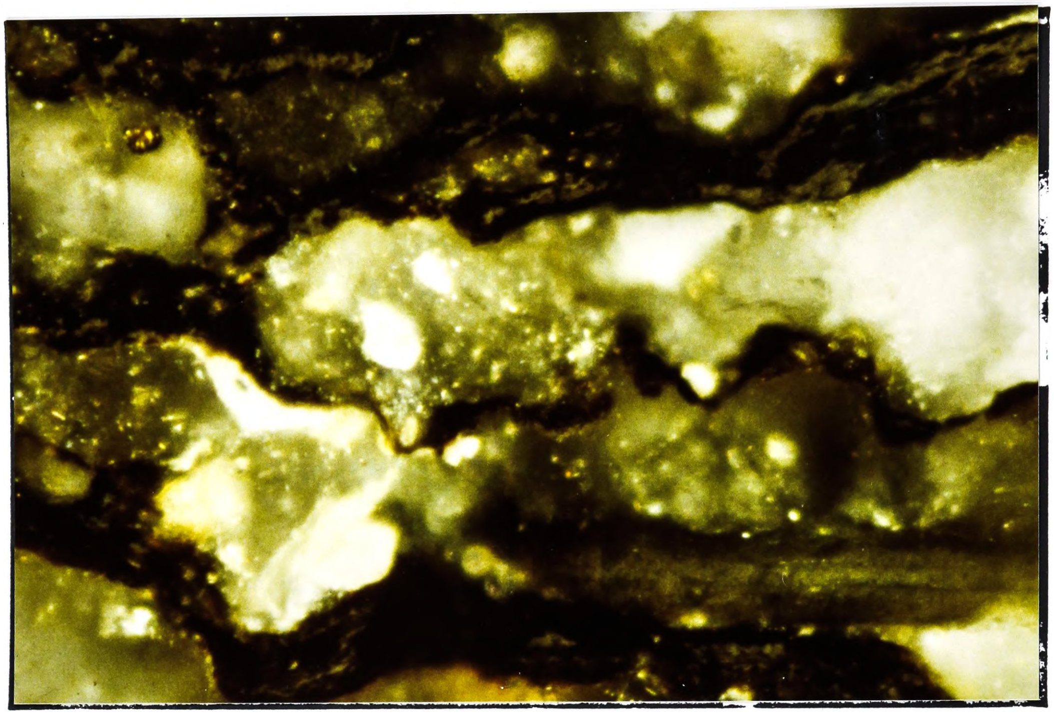


PLATE 6

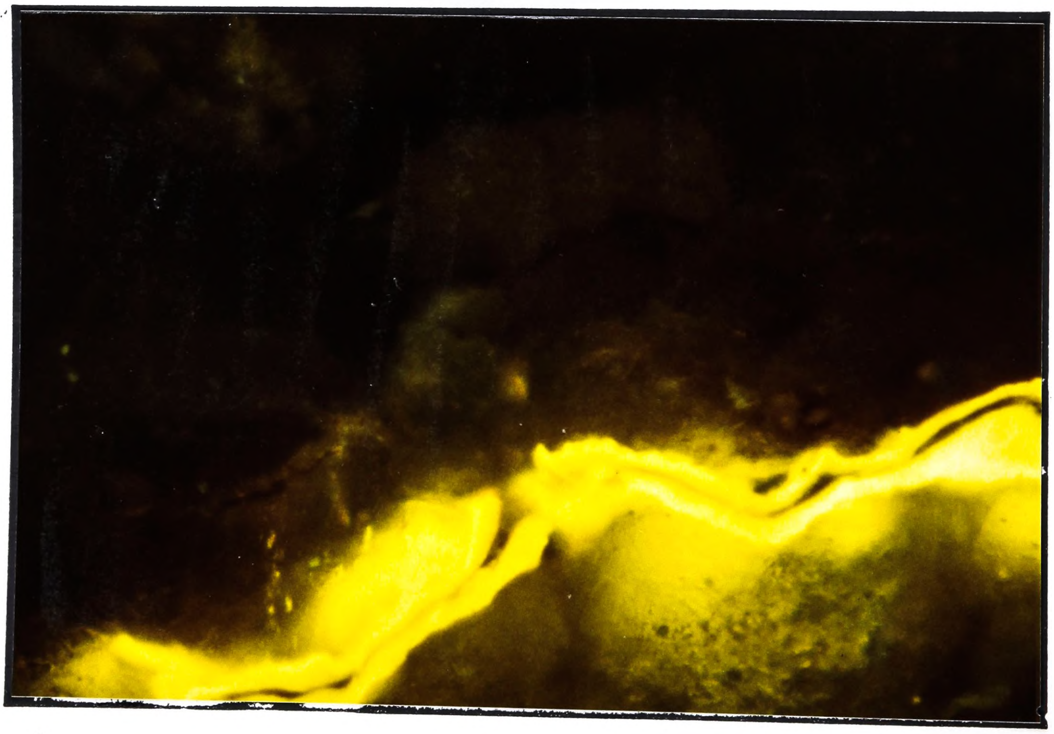


Plate 4

Vitrinite in sandstone with resinite and sporinite.
R = 073. Reflected light x 32.

32X = 0.34 mm. field width

Plate 6

Yellow cutinite x 32 in fluorescent light. Vitrinite Reflectance = 0.73%

32X = 0.34 mm. field width

FERGUSON'S HILL

Sample No.	Depth (m)	$R_v$max	N	Remarks
17934	836	0.33	6	Specks and whisps of coal in sandstone with Vitrinite and inertodetrinite common. Exinite is rare to absent.
17935	1143	0.37	11	Siltstone/claystone with large areas of vitrinite and inertodetrinite/semi-fusinite, rare green fluorescing cutinite. The vitrinite displays shrinkage cracks.
17936	1253	-	-	Exclusively cellular fusinite, semi-fusinite and inertodetrinite.
17937	1548	0.44	7	Sandstone with abundant coal, composed of vitrinite grading to inertodetrinite, with abundant sporinite and some cutinite, fluorescing in yellow.
17938	1809	0.54	12	Large areas of vitrinite showing alteration to inertodetrinite in a sandstone groundmass The vitrinite is massive and exinite is absent.
17939	1999	0.8	11	Vitrinite and fusinite/semi-fusinite as wisps and bands in sandstone. Sporinite is present, fluorescing in green.
17940	2206	0.84	10	Sparse vitrinite in claystone.

17941	2518	0.72	4	Medium-fine sandstone with banded vitrinite and semi-fusinite/ inertodetrinite, with minor sporinite, fluorescing in yellow.
17942	2803	0.75	12	Sandstone/siltstone with pyrite and D.O.M. Vitrinite semi-fusinite and inertodetrinite only.
17943	3249	1.02	6	Sandstone containing minor vitrinite with pyrite, iron staining and inertodetrinite.

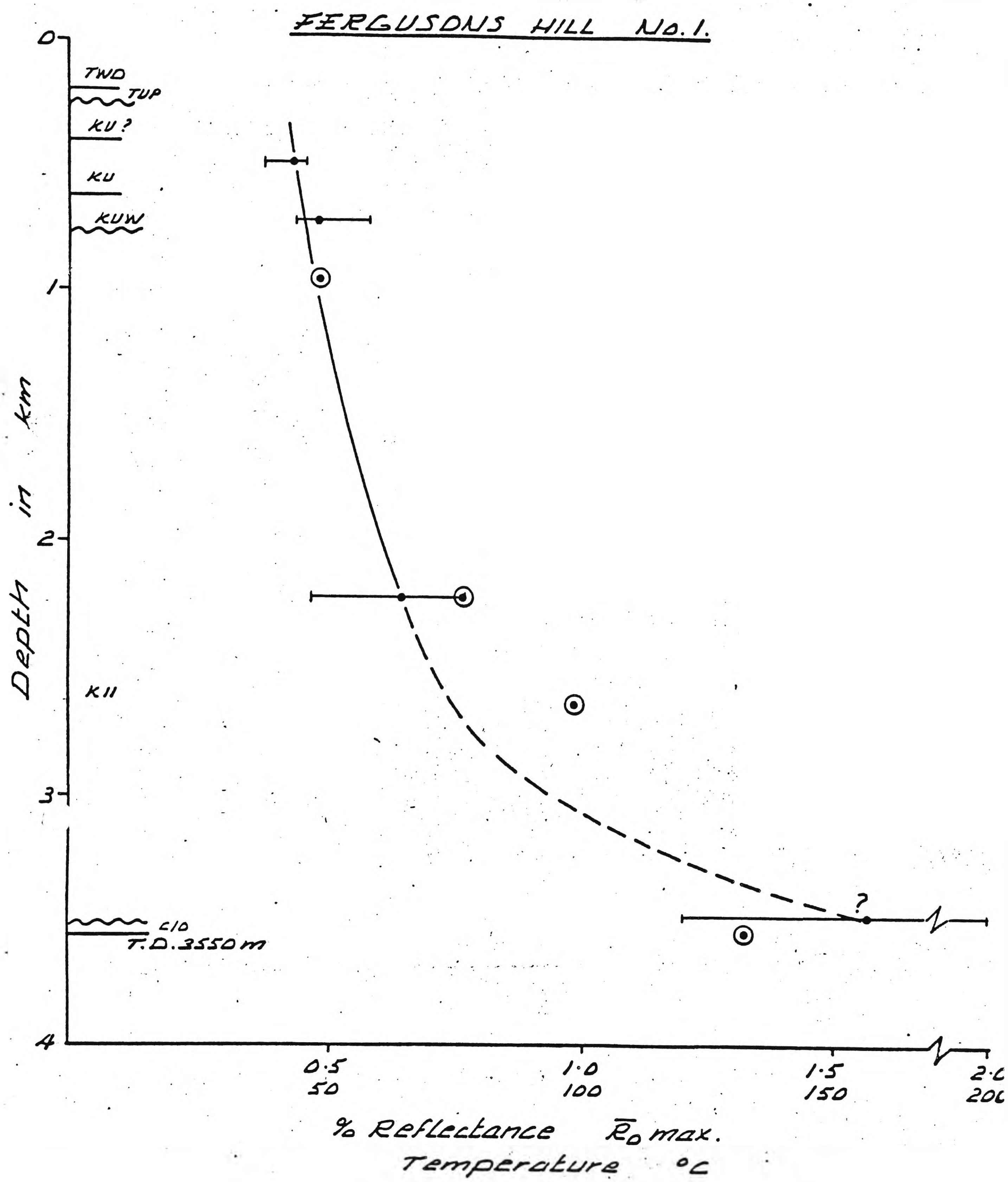
12.26 (cont'd) Fergusons Hill No.1

12.26

U.Woll. No.	Depth (m)	$\bar{R}$%	Range	N	Exinite fluorescence (remarks)
9836	471	0.30		1	Rare sporinite and cutinite, yellow to orange. (Silty ss., d.o.m. common chiefly I, takes a poor polish.)
9837	478	0.43	0.38-0.46	6	As for 9836.
9838	743	0.49	0.44-0.58	19	Sparse cutinite, sporinite and liptodetrinite, orange yellow to yellow. (Siltstone and shaly coal, abundant vitrinite, I rare. Framboidal pyrite abundant.)
9839	947	-	-	-	Rare yellow to orange sporinite. (Siltstone with sparse inertinite and no vitrinite.)
9840	2237	0.65	0.47-0.77	15	Exinite common, sporinite and cutinite yellow to dull orange, dinoflagellates and liptodetrinite greenish yellow to dull orange. (Siltstone with finely comminuted inertinite, common and vitrinite, rare. Pyrite present.)
9841	3484	1.57	1.20-2.02	14	No exinite fluorescence. (Coarse siltstone, common d.o.m. Vitrinite population poorly defined. Some ?coke mosaic present on one edge of sample pyrite present.)

Source: Cook 1979 (b)

12.26 (cont'd)



Source : Cook 1979 (b)

Fergusons Hill No. 1

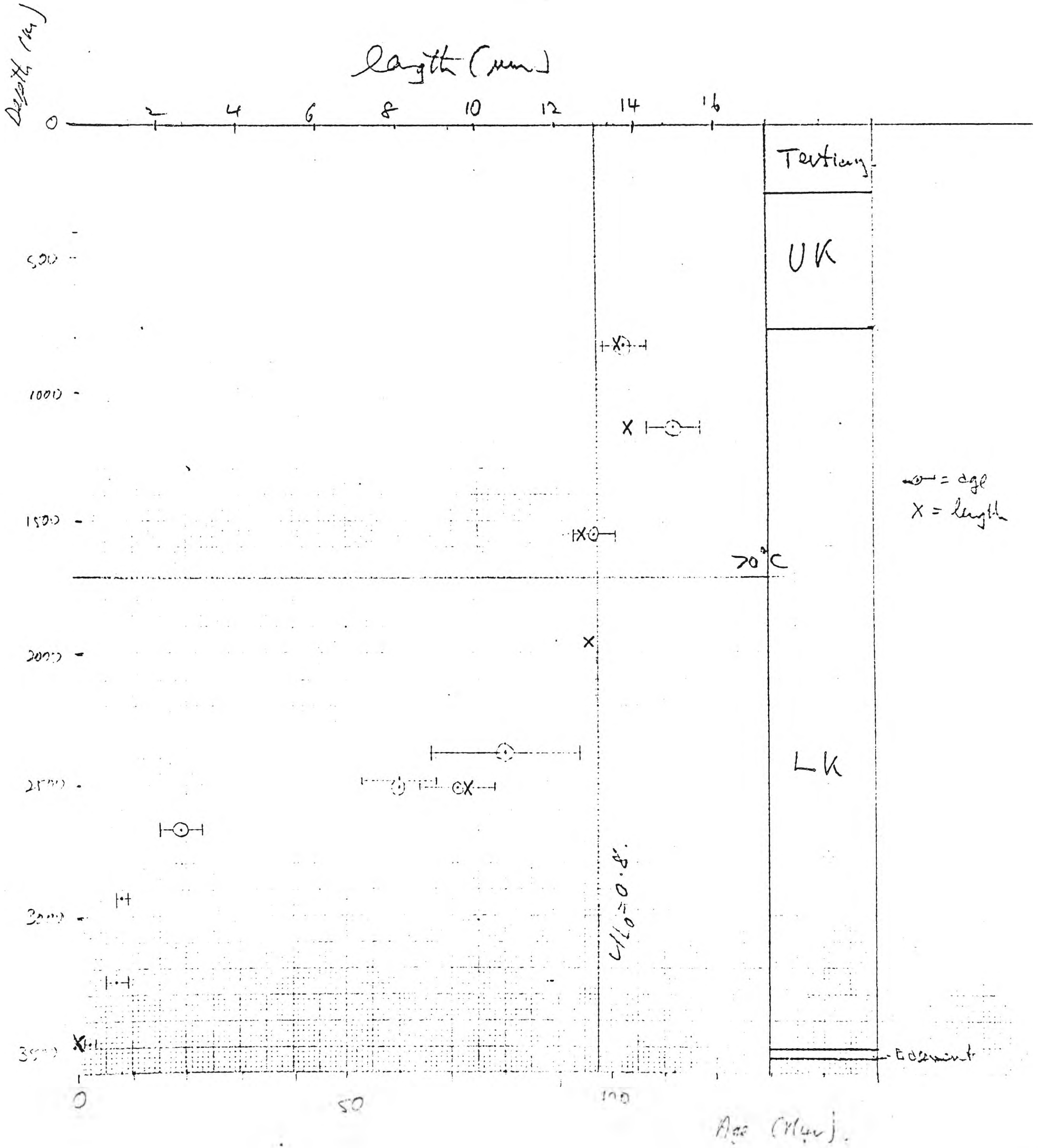
The samples are silty sandstones and siltstones, with common to abundant d.o.m., chiefly inertinite, with a significant amount of vitrinite present in the sample from 743m. Fluorescing exinite is common in the sample from 2237m, sparse in that from 743m, absent from the deepest sample, and rare in the other samples. With the exception of the sample from 743m, most of the humic material shows evidence of reworking. The absence of fluorescing exinite from the sample from 3484m is believed to be due to rank rather than type effects. Most samples contain pyrite.

The upper part of the section is characterized by low maturity and a low vitrinite reflectance gradient. The 0.5% vitrinite level is reached at about 1000m, and the reflectance gradient at the 0.6% reflectance level is low at about 0.1%/km. Below 2300m, a sharp inflexion must occur in the vitrinite reflectance profile, on the evidence provided by the data from the deepest sample. The vitrinite population in this sample (3484m), is poorly defined, and the large range of values, suggests that the mean may be accurate only to ±0.15%. The absence of fluorescing exinite does, however, confirm that the sample is of high maturity. The presence of ?coke structures in this sample implies that localized contact metamorphism has been a factor near T.D.

Source: Cook 1979 (b)

12.26

Fergusons Hill.



Source A.Gleadow - Personal Communication.

12.26 cont.

FERGUSON'S HILL

Depth(m)	Age	
835	103 + 4 Myr	
1141	112 + 5 Myr	
1551	97 + 4 Myr	[233 + 39 Myr
2384	80 + 14	[271 + 23
2516	71 + 7	
2516	60 + 7	
2672	19 + 4	
2935	8 + 1	
3250	7 + 2	
3482	2 + 1	

Source: Gleadow, 1984
(Personal Communication)

FERGUSON'S HILL No 1

PLATE 7

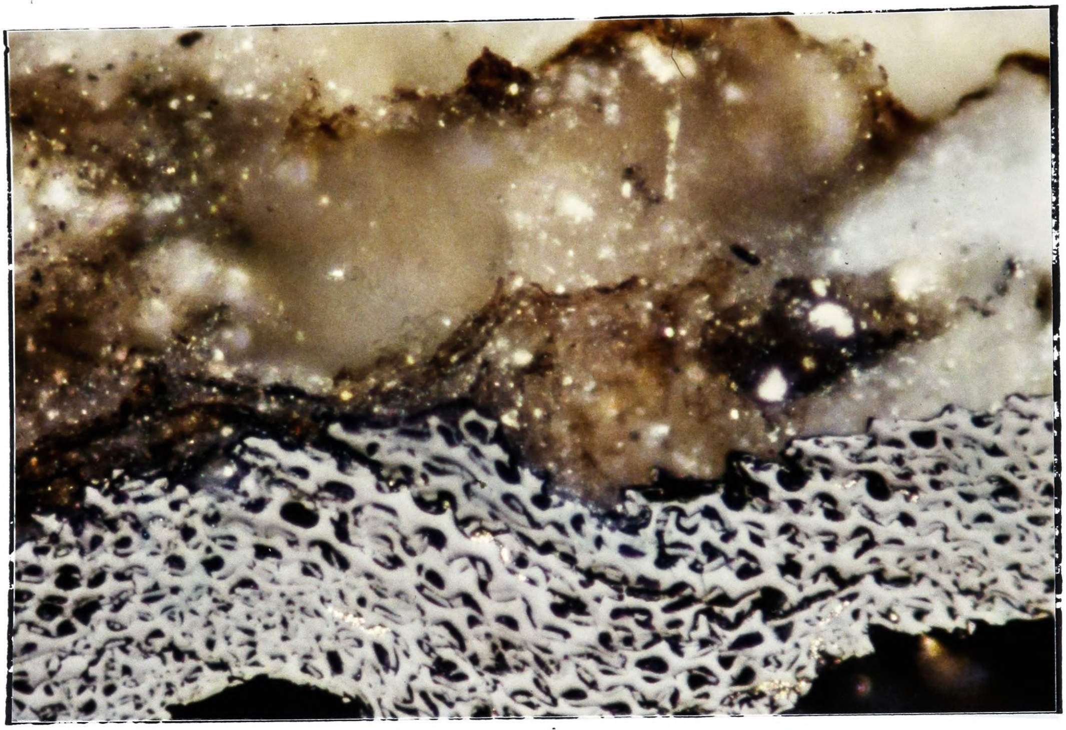
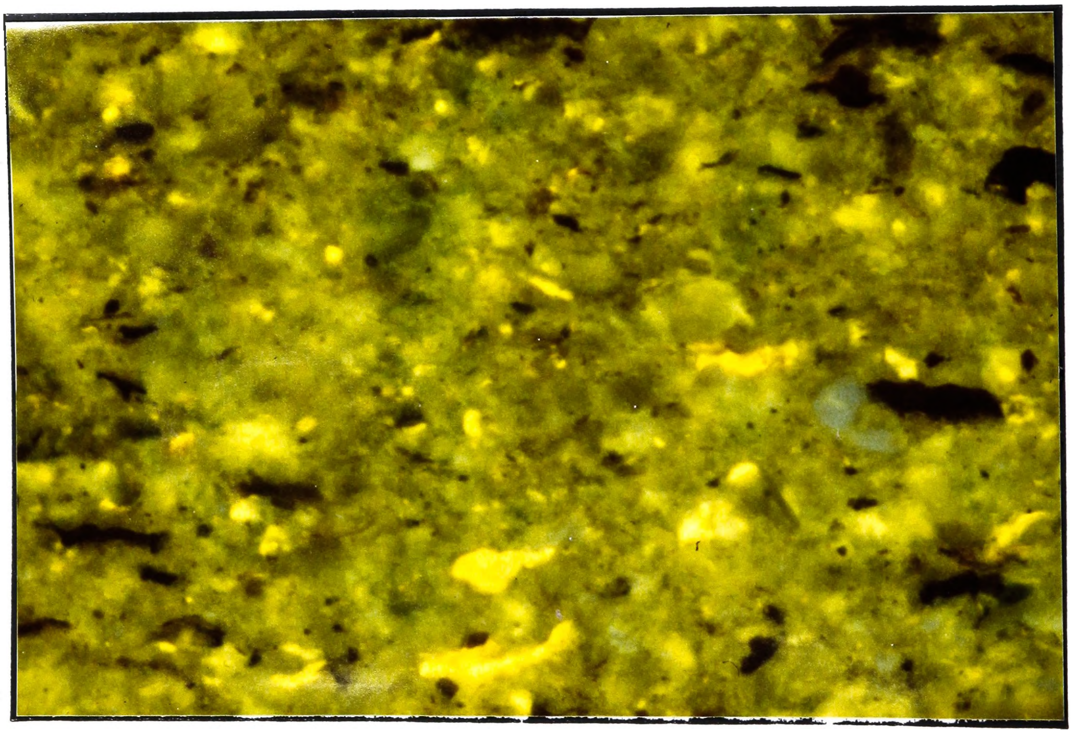


PLATE 8



FERGUSON'S HILL NO. 1

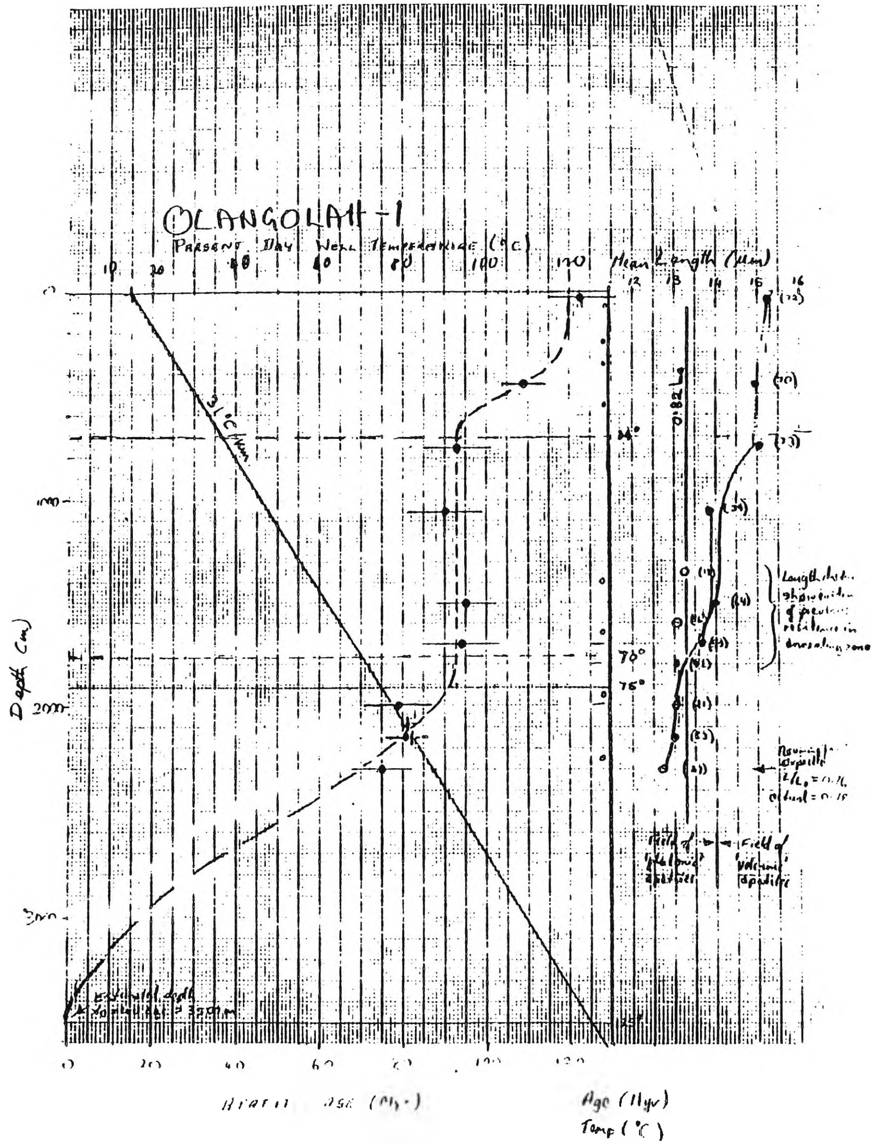
Plate 7

Fusinite in Sandstone x 32 32X = 0.34 mm. field width
Reflected light.

Plate 8

Spores and inertinite x 32 32X = 0.34 mm. field width

Fluorescent light. Vitrinite Reflectance 0.65%



Source: Gleadow 1984 (Personal Communication)

ESTIMATION OF EROSION, PALAEOTHERMAL GRADIENT AND MAXIMUM BOTTOMHOLE TEMPERATURE.

There are several methods of approach to calculation of both the amount of section removed by erosion and the past geothermal gradients and maximum paleotemperatures. The primary interpretation depends upon the temperature reached by the sample now at 750 m depth (R23086) and having an apatite age of 93 Myr. Time-temperature relationships given in Gleadow et al. (1983) indicate that this temperature must have been between about 110 and 125°C. The lower estimate holding if this sample was not completely annealed at 93 Myr. In addition the sample now at 30 m depth could not have been subjected to temperatures above about 70°C as this apatite age has not been lowered.

The first approach to be taken here is to assume that the entire track annealing zone occurred between the samples now at 30 and 750 m prior to the uplift at 93 Myr. Using 10 Myr for the time for which maximum burial was maintained, this implies a temperature range of 70 to 125°c over 720 m, and thus a geothermal gradient of 76°C/km. It also leads to an estimate of 700 m of erosion and a maximum bottomhole temperature of 243°C. These initial estimates are incompatible with both the zircon ages from 2300 m and palaeontological evidence suggesting about 1200 m of Early Cretaceous section missing (see below).

If we assume that the sample at 750 m was in fact somewhat above the base of the track annealing zone at about 110°C, then using the same reasoning as above gives a gradient of about 56°C/km, 950 m of erosion and a maximum BHT of 196°C.

A second approach is to calculate the amount of erosion from the vertical section of the apatite age profile at 93 Myr. The mimimum uplift is indicated by the distance between the top of the present day Track Annealing Zone and the sample at 750 m, giving 1050 m. Using this value, and a maximum temperature reached by R23086 (750 m) of 125°C as before, results in an estimated gradient of 61°C/km and a maximum BHT of 219°C at 3.35 km. Similarly, using 110°C for the maximum palaeotemperature of R23086 gives 53° C/km and 177°C at 3.35km.

The final approach used here is to make an independent estimate of the amount of section removed by erosion. The limited palaeontological data available indicated that the well commenced in sediments belonging to Megafloral Zone C of Douglas (1969) with the C. paradoxa zone and the C. striatus subzone completely missing. These zones total about 1430 m in the nearby Ross Creek-1 and 1250 m in Ferguson's Hill-1 wells. Assuming that the amount removed from the ranges was 1250 m and the maximum temperatures reached by R23086 as used above gives gradients ranging from 48 to 55 °C/km and maximum BHT's of 184 to 210°C.

These results are summarized in Table 4 and it is clear that while there is some variation in the estimates there is strong evidence that before the major uplift event at 93 Myr the geothermal gradient was considerably higher than it is at present. Estimates based on the present gradient require unrealistic degrees of erosion and a thickness of Otway Formation in excess of 5Km.

The evidence favours schemes with greater than about 1 km of erosion as this fits more convincingly with the palaeontological evidence and the thickness of the rapid uplift zone in the apatite age profile. Also, I consider that the zircon ages from R23095 at 2300 m are not compatible with temperatures much in excess of 200°C. From this I conclude that the Early Cretaceous thermal gradient lay between about 48 and 61 °C/km with of between 950 and 1250 m of Otway Formation immediately following the 93 Myr uplift. The minimum Otway Formation thickness is thus 3.25 to 3.55 km.

Since 93 Myr the rocks have been subjected to declining temperatures and there is no evidence that the high gradient was maintained for any significant length of time after the uplift.

Table : Estimated erosion, palaeothermal gradients and maximum bottom-hole temperatures for Olangolah-1.

Basis of calculation	Section Eroded (m)	Thermal Gradient (°C/km)	Max. BHT (°C)	Max. Burial (m)
Present thermal gradient and 125°C of R23086	2800	31	173	5100
Samples now between 30 and 750 m represent the entire TAZ (70-125°C)	700	76	243	3000
Samples now between 30 and 750 m represent temps. between 70-110°C	950	55.6	196	3250
Erosion of 1050 m est. from the vertical age profile α 125°C of R23086	1050	61	219	3350
Erosion of 1050 m est. from the vertical age profile α 110°C of R23086	1050	53	177	3350
Palaeontological est. of 1250 m of erosion and 125°C of R23086	1250	55	210	3550
Palaeontological est. of 1250 m of erosion and 110°C of R23086	1250	47.5	184	3550

TAZ = Track Annealing Zone

Source: Duddy et al 1982

12.27 (cont'd)

OLANGOLAH No. 1

K.K. No.	Depth	$\bar{R}_o$max	Range	N	Exinite Fluorescence (Remarks)
15902	1000 Ctgs	3.26	2.90-3.50	10	No fluorescing exinite. (Claystone with abundant carbonate, d.o.m. rare, V>I, E not distinguished. Vitrinite and inertinite are both rare. Pyrite rare, some iron oxide minerals present.)
15903	1200 Ctgs	3.60	2.80-4.44	20	No fluorescing exinite. (Claystone with d.o.m. sparse, V>I. Vitrinite sparse, inertinite rare. The bireflectance of the vitrinite ranges up to 2.11%.)
15904	1400 Ctgs	3.78	3.25-4.60	20	No fluorescing exinite. (Similar to 15903, d.o.m. sparse V>I. Vitrinite sparse, small phytoclasts.)
15905	1600 Ctgs	3.90	3.20-4.70	20	No fluorescing exinite. (Silstone and claystone, d.o.m. sparse, V>I. Vitrinite and inertinite sparse.)
15754	1765 Junk basket	3.76	3.00-4.40	20	No fluorescing exinite. (Silty mudstone with abundant d.o.m., macerals difficult to distinguish due to very high rank, probably V>I>E. The vitrinite has a high bireflectance, R$_{min}$ approx 1.9%, and the highest reflectance values were probably measured on cutinite. The level of maturity indicated is higher than that usually associated with adequate permeability for gas production.)
15906	1800 Ctgs	4.50	3.57-5.80	20	No fluorescing exinite. (Siltstone, sandstone and claystone, d.o.m. common, V>I, vitrinite common, inertinite sparse. Pyrite sparse to common.)
15907	2000 Ctgs	4.56	3.47-6.00	20	No fluorescing exinite. (Claystone and siltstone with abundant carbonate, d.o.m. rare to sparse, V>I.)
15908	2200 Ctgs	5.69	4.00-7.40	20	No fluorescing exinite. (Siltstone, claystone and sandstone, d.o.m. common V=I, vitrinite and inertinite both sparse. Bireflectance of vitrinite high, up to 4.18%.)

Source: Cook 1982 (b)

OLANGOLAH No1

PLATE 9

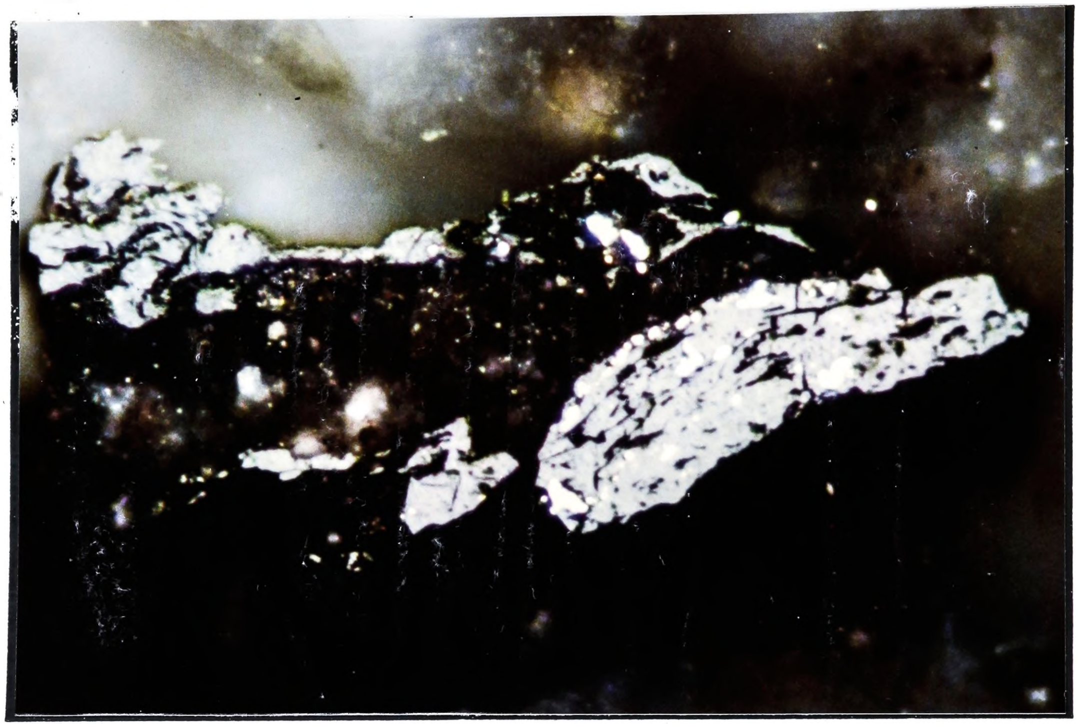


PLATE 10

Plate 9

Vitrinite with pyrite. R = 3.26 x 32 in Reflected Light

32X = 0.34 mm. field width

Plate 10

Shrinkage cracks in Vitrinite, under partial crossed nicols x 50 in Reflected Light.

50X = 0.22 mm. field width

KRUMBRUK NO. 13

Sample No.	Depth (m)	Rv Max	N.	Remarks
17944	137	0.54	18	Iron-stained sandstone with telinite, sparcer semi-fusinite and inertodetrinite
17945	192	-	-	D.O.M. consisting of inertodetrinite no vitrinite.
17946	342-345	-	-	D.O.M. in siltstone with inertodetrinite only. No vitrinite, also some cutinite.
17949	378-381	0.61	15	Sandstone/siltstone with isolated coal specks (D.O.M.) both vitrinite and inertinite with minor sporinite and cutinite (yellow)
17950	463	0.74	7	Sandstone with minor dark orange fluorescing sporinite and cutinite.
17951	498-501	0.84	13	Sandstone with large area of semi-fusinite. Iron-staining and pyrite and vitrinite less abundant, and rare sporinite and cutinite.
17952	549-552	0.94	19	A medium to coarse sandstone with vitrinite, streaked by inertodetrinite.
17953	615-618	0.89	14	A fine to medium sandstone/siltstone, with trace pale cutinite in the vitrinite, small areas pyrite and inertinite.
17954	639-642	0.84	7	A fine to medium sandstone with vitrinite and minor semi-fusinite and pyrite and yellow fluorescing cutinite.

17955	660	0.87	13	Thin band in sandstone semi-fusinite grading to vitrinite, with yellow fluorescing sporinite and cutinite.
17956	723-726	0.97	12	Medium to coarse sandstone with vitrinite and inertinite common (some floaters) and dark orange sporinite.
17957	801-894	-	-	All cavings with low reflectances around 6 and 7 in medium coarse sandstone. Sporinite, orange fluorescing, is present.
17958	936-939	1.02	12	Sandstone with banded vitrinite and streaks of exinite. Stringers of inertodetriite with pyrite. Greenish-fluorescing cutinite and sporinite.
17859	1158-1161	0.94	11	Fine-grained sandstone/siltstone with vitrinite showing shrinkage cracks, and rare inertinite and no exinite.
17960	1395-1398	1.024	7	Fine-grained sandstone/siltstone with rare vitrinite and inertinite as D.O.M. and minor cutinite and sporinite.
17961	1461-1464	1.01	17	Fine-grained sandstone carrying banded vitrinite inertodetrinite and exinite with pyrite.
17962	1527-1530	1.15	11	Banded fragments in sandstone /siltstone some floaters. Vitrinite shows shrinkage cracks, also rare inertodetrinite sporinite and cutinite.

PLATE 11

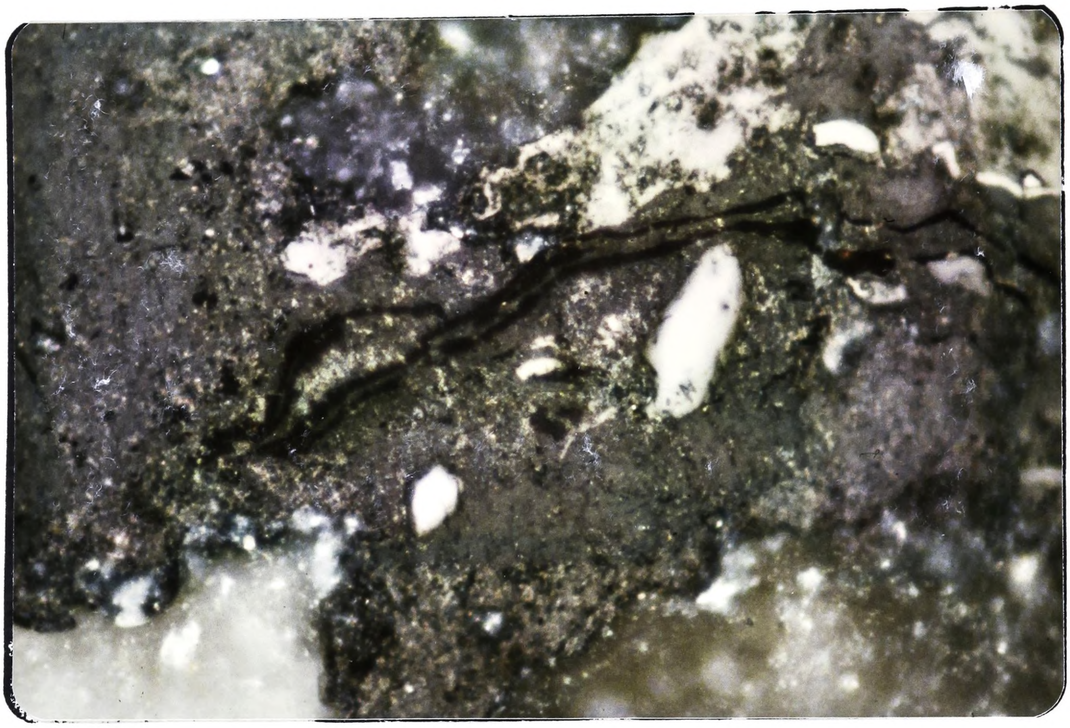


PLATE 12

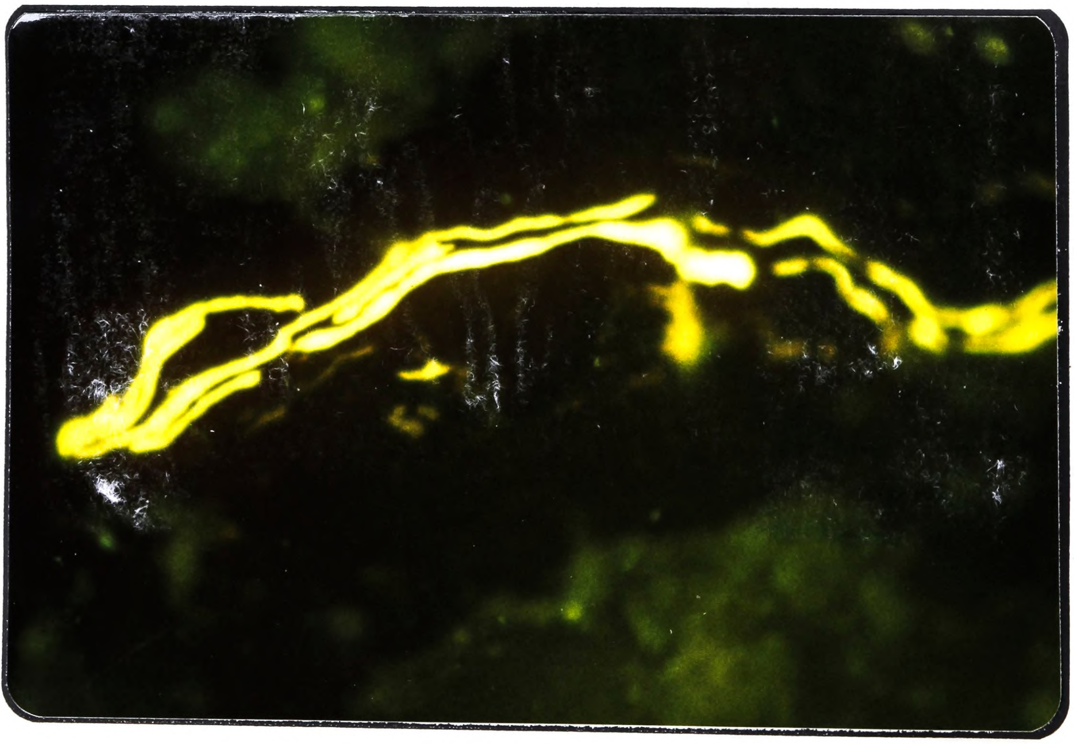


Plate 11

Exinite, reworked vitrinite and exinite. R = 0.87% Reflected Light x 50, Block No. 17955

50X = 0.22 mm. field width

Plate 12

Exinite, same view as above in fluorescent light.

12.29

Voluta No. 1

9767	1414	?0.38	-	1	Rare sporinite yellow to orange. (Siltstones with abundant inertinite, vitrinite rare or absent.)
9768	1792	0.38	0.34-0.42	3	Sporinite sparse, bright yellow to orange. (Siltstones with abundant inertinite but other macerals rare.)
9769	2165	0.66	0.62-0.76	4	Sporinite and resinite, rare, yellow to orange. (Clay rich carb. silts., I abundant, mineral fluorescence rare.)
9770	2674	0.58	0.50-0.70	5	Sporinite and liptodetrinite, rare, yellow to orange. (Silty ss. with abundant I.)
9771	3037	0.72	0.60-0.84	2	Similar to 9770, but shelly fossils present.
9772	3653	0.95	0.74-1.20	17	Rare orange liptodetrinite. (Siltstone with prominent patchy bright orange mineral fl., small vitrinite phytoclasts, elongate to equidimensional.)

Source: Cook 1979 (a)

VOLUTA No 1

PLATE 13

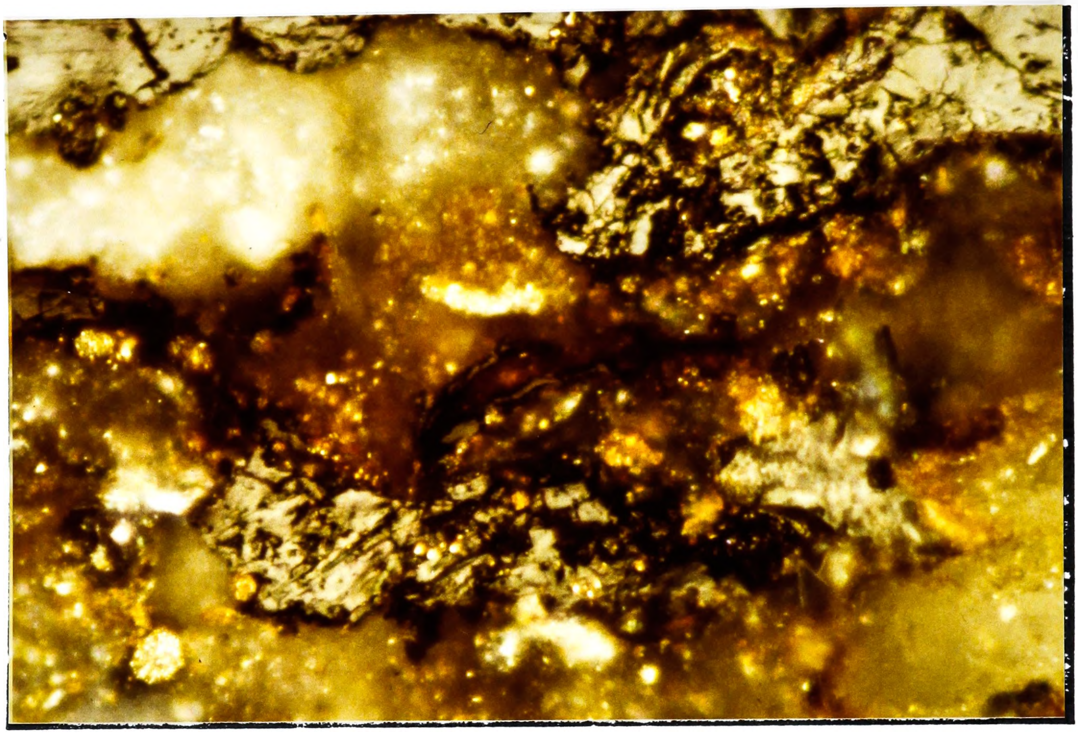


PLATE 14

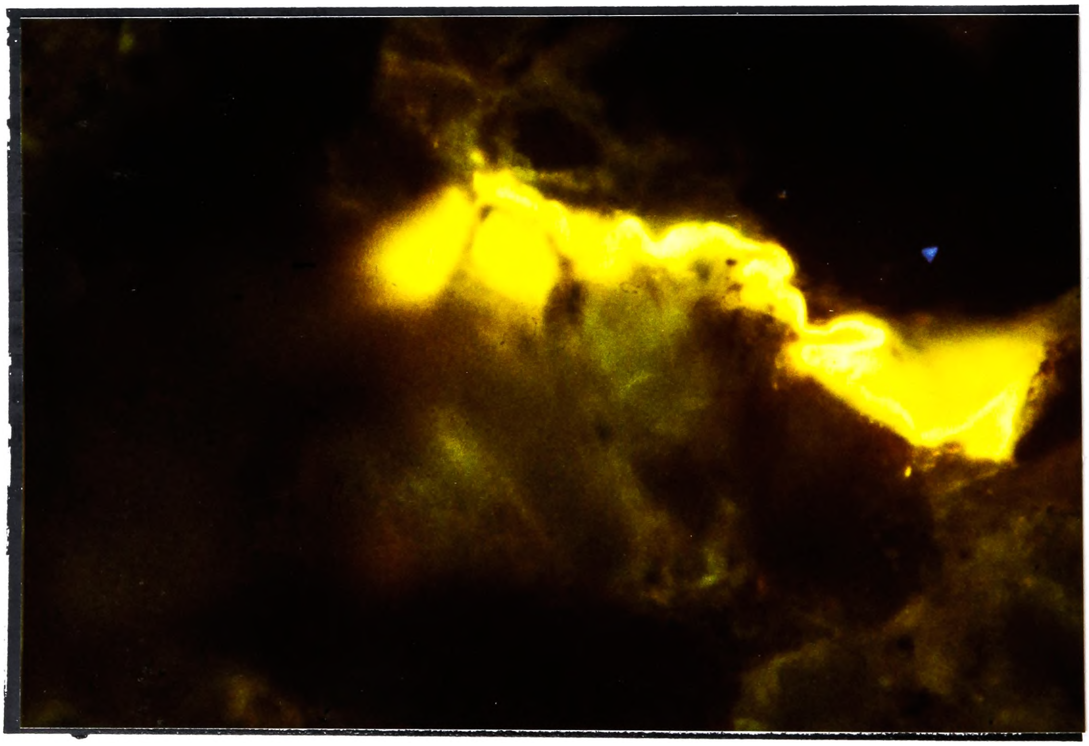


Plate 13

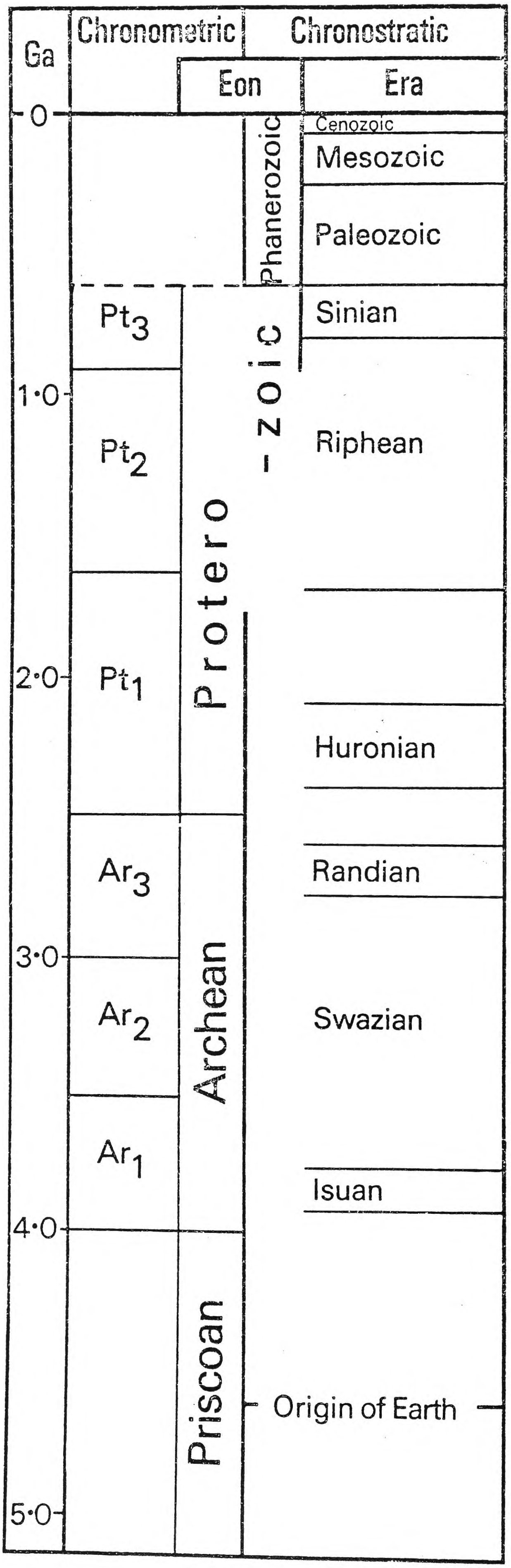
Vitrinite in Sandstone. Reflected Light x 32

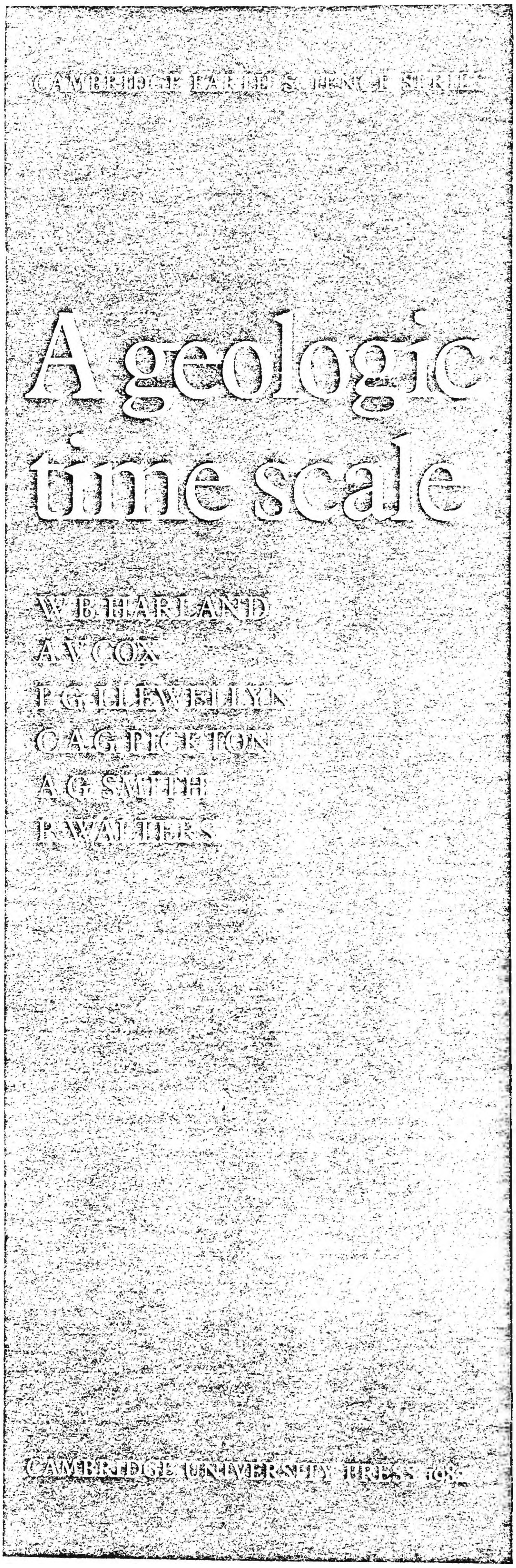
32X = 0.34 mm. field width

Plate 14

Cutinite x 32 under fluorescent light.

32X = 0.34 mm. field width




CAMBRIDGE EARTH SCIENCE SERIES

A geologic time scale

W.B. HARLAND
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C.A.G. PICKTON
A.G. SMITH
R. WALTERS

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Era	Sub-era Period Sub-period			Epoch		Age	Ma age	Age abbrev.	Ma inter -vals	
Cenozoic Cz	Quaternary or Pleistogene			Holocene			0·01	Hol	·01	2
				Pleistocene			2·0	Ple	1·99	
	Tertiary TT	Neogene Ng		Pliocene	2	Piacenzian		Pia	3·1	22·6
					1	Zanclian	5·1	Zan		
				Miocene	3	Messinian		Mes	6·2	
						Tortonian		Tor		
					2	Serravallian		Srv	3·1	
						Langhian-Late	14·4	Lan2		
					1	Langhian-Early		Lan1	10·2	
						Burdigalian		Bur		
						Aquitanian	24·6	Aqt		
		Paleogene Pg		Oligocene	2	Chattian	32·8	Cht	8·2	40·4
					1	Rupelian	38·0	Rup	5·2	
				Eocene	3	Priabonian	42·0	Prb	4	
					2	Bartonian		Brt	8·5	
						Lutetian	50·5	Lut		
					1	Ypresian	54·9	Ypr	4·4	
				Paleocene	2	Thanetian	60·2	Tha	5·3	
					1	Danian	65	Dan	4·8	
Mesozoic Mz		Cretaceous K		K$_2$	Seno-nian	Maastrichtian	73	Maa	8	79
						Campanian	83	Cmp	10	
						Santonian	87·5	San	4·5	
						Coniacian	88·5	Con	1	
						Turonian	91	Tur	2·5	
						Cenomanian	97·5	Cen	6·5	
				K$_1$		Albian	113	Alb	15·5	
						Aptian	119	Apt	6	
						Barremian	125	Brm	6	
					Neoc-omian	Hauterivian	131	Hau	6	
						Valanginian	138	Vlg	7	
						Berriasian	144	Ber	6	
		Jurassic J		Malm J$_3$		Tithonian	150	Tth	6	69
						Kimmeridgian	156	Kim	6	
						Oxfordian	163	Oxf	7	
				Dogger J$_2$		Callovian	169	Clv	6	
						Bathonian	175	Bth	6	
						Bajocian	181	Baj	6	
						Aalenian	188	Aal	7	
				Lias J$_1$		Toarcian	194	Toa	6	
						Pliensbachian	200	Plb	6	
						Sinemurian	206	Sin	6	
						Hettangian	213	Het	7	
		Triassic Tr		Tr$_3$		Rhaetian	219	Rht	6	35
						Norian	225	Nor	6	
						Carnian	231	Crn	6	
				Tr$_2$		Ladinian	238	Lad	7	
						Anisian	243	Ans	5	
				Scythian Tr$_1$		Spathian		Spa	1¼	
						Smithian		Smi	1¼	
						Dienerian		Die	1¼	
						Griesbachian	248	Gri	1¼	
Paleozoic		Permian P		P$_2$		Tatarian	253	Tat	5	38
						Kazanian		Kaz	2·5	
						Ufimian	258	Ufi	2·5	
				P$_1$		Kungurian	263	Kun	5	
						Artinskian	268	Art	5	
						Sakmarian		Sak	9	
						Asselian	286	Ass	9	
		Carboniferous	Pennsylvanian C$_2$	Gzelian		Noginskian		Nog		34
						Klazminskian		Kla		
				Kasimov-ian		Dorogomilovsk.		Dor		
						Chamovnichesk.		Chv		
						Krevyakinskian		Kre		
				Moscov-ian		Myachkovskian	296	Mya		
						Podolskian		Pod		
						Kashirskian		Ksk		
						Vereiskian		Vrk		
				Bashkir-ian		Melekesskian		Mel		
						Cheremshansk.	315	Che		
						Yeadonian		Yea		
						Marsdenian		Mrd		
						Kinderscoutian	320	Kin		
			C$_1$	Serpukhov-ian		Alportian		Alp		40
						Chokierian		Cho		

Era	Sub-era Period Sub-per.			Epoch		Age	Ma age	Age abbrev.	Ma inter -vals	
Paleozoic Pz		Carboniferous C	C$_2$	Bashkir-ian		Marsdenian		Mrd		34
						Kinderscoutian	320	Kin		
			Mississippian C$_1$	Serpukhov-ian		Alportian		Alp	13	40
						Chokierian		Cho		
						Arnsbergian		Arn		
						Pendleian	333	Pnd		
				Visean		Brigantian		Bri	19	
						Asbian		Asb		
						Holkerian		Hlk		
						Arundian		Aru		
						Chadian	352	Chd		
				Tournaisian		Ivorian		Ivo	8	
						Hastarian	360	Has		
		Devonian D		D$_3$		Famennian	367	Fam	7	48
						Frasnian	374	Frs	7	
				D$_2$		Givetian	380	Giv	6	
						Eifelian	387	Eif	7	
				D$_1$		Emsian	394	Ems	7	
						Siegenian	401	Sig	7	
						Gedinnian	408	Ged	7	
		Silurian S		Pridoli			414	Prd	6	30
				Ludlow		Ludfordian		Ldf	7	
						Gorstian	421	Gor		
				Wenlock		Gleedon		Gle	7	
						Whitwell		Whi		
						Sheinwoodian	428	She		
				Llandovery		Telychian		Tel	10	
						Fronian		Fro		
						Idwian		Idw		
						Rhuddanian	438	Rhu		
		Ordovician	O$_3$	Ashgill		Hirnantian		Hir	10	67
						Rawtheyan		Raw		
						Cautleyan		Cau		
						Pusgillian	448	Pus		
				Caradoc		Onnian		Onn	10	
						Actonian		Act		
						Marshbrookian		Mrb		
						Longvillian		Lon		
						Soudleyan		Sou		
						Harnagian		Har		
						Costonian	458	Cos		
			O$_2$	Llandeilo		Late		Llo3	10	
						Middle		Llo2		
						Early	468	Llo1		
				Llanvirn		Late		Lln2	10	
						Early	478	Lln1		
			O$_1$	Arenig			488	Arg	10	
				Tremadoc			505	Tre	17	
		Cambrian €		Merioneth		Dolgellian		Dol	9	85
						Maentwrogian	523	Mnt	9	
				St David's		Menevian		Men	9	
						Solvan	540	Sol	8	
				Caerfai		Lenian		Len	15	
						Atdabanian		Atb	15	
						Tommotian	590	Tom	20	
Sinian Z		Vend-ian V		Ediacaran		Poundian		Pou	40	80
						Wonokian	630	Won		
				Varangian		Mortensnes	650	Mor	20	
						Smalfjord	670	Sma	20	
	Sturtian U						800			
							1050			
Riphean R						Yurmatin Y	1350			
						Burzyan B	1650			
							2100			
Huronian H							2400			
							2630			
Randian Ran							2800			
Swazian Sw							3750			
Isuan I							3900			
Hadean Hde										

Harland ,Cox, Llewellyn,
Pickton, Smith, Walters 1982
A geologic time scale
Cambridge University Press

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12.3 Fission Track Results from Melbourne University Earth Science Department.

1. Eumeralla No. 1 - Fission Track Results.
   - see text, detailed study of wells.

2. Flaxman's Hill No. 1 - Fission Track Results
   - see text, detailed study of wells.

3. Ferguson's Hill No. 1 - Fission Track Results
   - see detailed study of wells and Appendix 12.26

4. Olangolah No. 1 - Fission Track Results
   - see detailed study of wells and Appendix 12.27

5. Fission track ages - surface outcrops

FISSION TRACK AGES - SURFACE OUTCROPS
IN THE OTWAY RANGES

Tables 1-3 show that most of the fission track ages obtained for sphenes, apatites and, to a lesser extent, zircons, fall within the early Cretaceous (96 - 143 m.y.). Fig. 2 shows the distribution of all the single grain ages as well as that of only the more precise results, those with errors <12 m.y. (about 10%). No sphene or apatite ages are older than Jurassic and none of the more precise ages lies outside the early Cretaceous. This is also true for just over half of the zircon ages, the remainder being much older, 218 - 495 m.y. Sphene and apatite ages have a very similar distribution, but the apatite ages are more scattered.

The close coincidence of ages for sphene and apatite (Table 1), which have effective geological track retention temperatures of about 250° and 100°C respectively, argues strongly that these ages have remained unchanged during sedimentation, diagenesis and any subsequent event. This is further supported by the close agreement of the younger zircon ages and the preservation of Paleozoic ages in many of the zircons. The early Cretaceous ages are therefore interpreted to represent the time of volcanic activity which produced the abundant volcanogenic detritus in the Otway Gp.

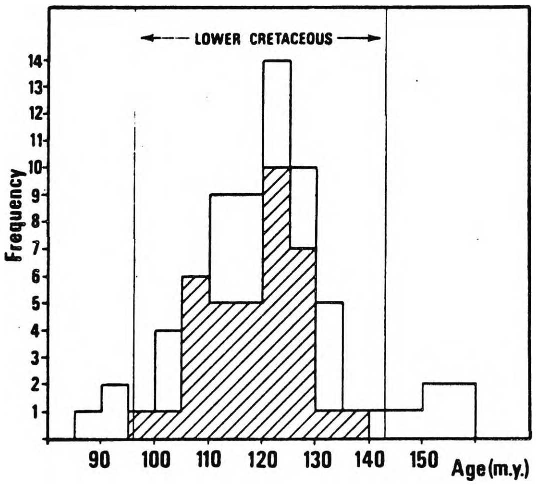

Fig.2. Distribution of fission track ages. Larger histogram shows results (Tables 2, 3) for all grains of sphene, zircon and apatite; hatched area shows only results where calculated error was ≤ 12 m.y.

The simplest possible explanation of the results is that they represent a single and very short major volcanic episode. It would be dated closely by the combined results for sphene and apatite (Table 1) and the major peak in Fig.2, which define an age of about 120 m.y. According to this explanation the dispersion of single grain ages shown in Fig. 2 would be due entirely to experimental uncertainty. However, the more precise single grain age suggest a more complex situation with a bimodal distribution of ages representing pulses of volcanism at about 106 and 123 m.y. within a longer episode, perhaps 20 m.y. These pulses may correlate with peaks in the abundance of apatite and sphene in a number of wells in the western Otway Basin (Fig.3).

Apatites from the trachyandesite lava at Cape Portland give an early Cretaceous age of 98 ± 4 m.y. (Table 1), in close agreement with K-Ar and Rb-Sr ages (Sutherland & Corbett 1974), and younger than nearly all the grains dated from the Otway Gp sandstones.

The older zircon grains (Table 3) appear to belong to two separate groups. One has ages ranging from 190 - 257 m.y. with a mean and standard deviation of 210 ± 29 m.y. and is found in both the zircon samples. These ages could represent either early Jurassic volcanism or cooling ages from basement rocks The second group is found only in sample R17686 and has Paleozoic ages ranging from 319-495 m.y. with a mean of 387 ± 65 m.y. This sample occurred near the margin of the basin and has a relatively high content of non-volcanic detritus presumably derived from the adjacent basement high culminating in King Island. Zircon fission track dating often gives very similar results to K-Ar dating of biotites, and McDougall and Leggo (1965) reported biotite ages for granitic rocks from King Island ranging from 352 - 467 m.y. with a mean of 398 ± 38 m.y. These are consistent with the King Island High's being the source of the old zircons.

In accordance with stratigraphic position (Fig.3), there is a progressive decrease in the youngest age observed in each of the three samples. Only in the stratigraphically youngest sample, R17685, is there a definite bimodal distribution of the mineral ages. The proposed younger pulse of volcanism at about 106 m.y. must

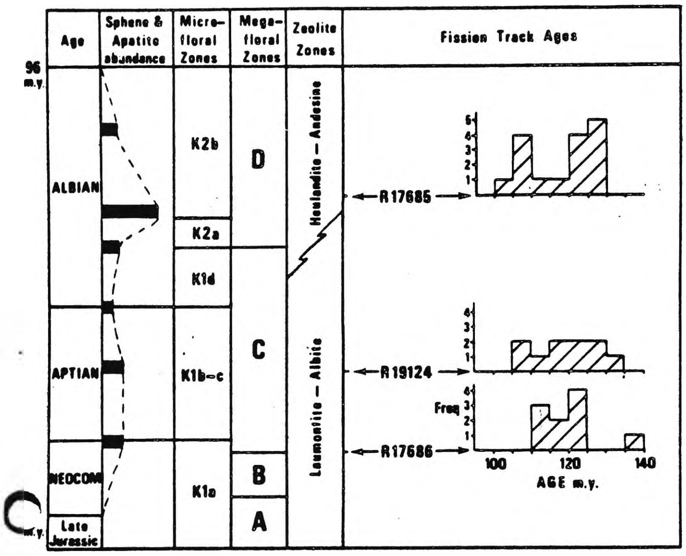

Fig. 3 Distribution of fission track ages compared with stratigraphic subdivision. Thickness of zones is approx. proportional to stratigraphic thickness. Grain ages used had error of ≤ 12 m.y. Sphene and apatite data are from Kalangadoo No. 1 well (see Rochow 1971).

therefore be represented between samples R17685 and R19124. Abundant fresh volcanic material in R17685 suggests that this sample is close to the horizon representing the time of the younger pulse which would therefore be middle Albian in age.

The relative thickness of microfloral (Evans 1971) and megafloral (Douglas 1969) zones shown in Fig. 3 indicates that most of the Otway Gp lies above R17686 (late Neocomian). Less than 500 m of sediment are known below this in megafloral zones A and B. It is possible that this thickening of the sedimentary sequence from late Neocomian time may coincide with the onset of major early Cretaceous volcanism. Fig. 2 and Table 2 show a very rapid increase in the number of fission track ages at about 126 m.y. suggesting a correlation of this age with the late Neocomian.

SOURCE OF THE VOLCANICS

The volume of volcanic detritus in the Otway Gp is probably >50 000 km^3 (Duddy, in prep.). The early Cretaceous was thus one of the most significant volcanic episodes in the history of SE Australia, and it is remarkable that no volcanic source rocks are known. Two source areas seem possible, either a volcanic arc to the east or along the developing rift system between Australia and Antarctica.

Derivation from a volcanic arc to the east would explain the abrupt cessation of supply of volcanic detritus at the end of the early Cretaceous. Opening of the Tasman Sea at that time would have isolated such an arc source from Australia and prevented any more volcanic material from reaching the Otway Basin. However, an easterly arc source would require very long transportation of the sediment--by way of the Gippsland Basin and over the Mornington Peninsula tectonic high. It is difficult to reconcile such a route of more than 1000 km with the lack of contamination, very large volume and freshness of the volcanic material preserved in the sediments. Further the slightly alkaline composition of the volcanogenic detritus is more consistent with a continental rather than a volcanic arc source.

The most likely source of the detritus in the Otway Gp is therefore thought to be volcanism along the continental rift system which was developing in early Cretaceous time. This period of volcanism, previously signalled by scattered igneous activity in the Jurassic, was a major feature of the early breakup history of Australia and Antarctica.

Source: Gleadow et al 1981