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USE OF CONODONT COLOUR ALTERATION INDEX TO PREDICT THERMAL MATURATION OF SOURCE ROCKS (HORN VALLEY SILTSTONE) AND TIMING OF STRUCTURAL MOVEMENTS DURING THE ALICE SPRINGS OROGENY, AMADEUS BASIN ...... A PRELIMINARY STUDY

ONSHORE

PANCON

Use of Conodont Colour Alteration Index to Predict Thermal Maturation of Source Rocks (Horn Valley Siltstone) and Timing of Structural Movements during the Alice Springs Orogeny, Amadeus Basin ...... A Preliminary Study

by

J.D. GORTER

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INTRODUCTION

Conodonts, the microscopic hard parts of an unknown group of animals, have become one of the most useful fossil groups for biostratigraphy and worldwide correlation. The group has a worldwide distribution in most marine rocks of Cambrian to Triassic age.

In the pase five years, a series of important papers by Epstein et al. (1977) and their various collaborators have introduced a new use for conodonts in the field of palaeotemperature analysis. In a major study of the colour alteration in conodonts with increasing temperature, Epstein et al. (1977) demonstrated the application of colour change in conodonts to palaeotemperature determination, grades of metamorphism, structural geology and to the regional assessment of oil and gas potential.

Use of conodonts as palaeotemperature tools has become standard practice in hydrocarbon exploration in the Palaeozoic and Triassic rocks of North America (Harris et al., 1978 etc), but has not been widely used elsewhere. This lack is particularly surprising in view of the ease and relative inexpensiveness of the method (Epstein et al., 1977; Bergström, 1980).

Successive colour changes shown by conodonts during gradual heating are conspicuous and irreversible (Bergström, 1980), and the method allows relatively accurate palaeotemperature estimates within the $80^{o}C$ to $500^{o}C$ plus range, considerably beyond the levels of most of the conventional methods of palaeotemperature analysis, especially the Thermal Alteration Index (TAI) of Staplin (1969). Conodont colour alteration does not commence until a late stage in palynomorph diagenesis, corresponding to a TAI of about 5 (Epstein et al., 1977).

Moreover, use of conodonts as palaeotemperature indicators allows the assessment of hydrocarbon source rock maturation levels in rocks that are too ancient to contain the materials used in other conventional palaeotemperature assessment methods, principally palynomorphs and vitrinite. Palynomorphs are generally rare in rocks of pre Devonian age, and the precursor material for vitrinite, wood, is absent in pre Devonian strata (ie. before the advent of land plants). Conodont colour can also provide an assessment of palaeotemperature in carbonate rocks, which are usually deposited in offshore areas removed from the most prolific sources of palynomorphs and wood, and consequently, poorly endowed with plant-derived matter.

For the foregoing reasons, conodonts should provide a palaeotemperature assessment tool for Early Palaeozoic rocks in Australia previously unassessable in terms of hydrocarbon source rock maturation levels. The method should prove particularly useful in the many Australian basins that contain marine carbonates of Early Palaeozoic age (eg. Canning, Officer and Georging Basins, etc). The Amadeus Basin is also a prime candidate for such a study. The basin contains a widespread Early Ordovician unit, the Horn Valley Siltstone (Enclosure 1 and Figure 1), which both contains carbonate rocks (Wells et al., 1970) and is the source rock for the oil and gas reservoired in the underlying Pacoota Sandstone at the Mereenie and Palm Valley Fields (Welte et al., 1975; Kurylowicz et al., 1976). Moreover, conodonts are extremely abundant and well preserved in the Horn Valley Siltstone (Cooper, 1981a; 1981b) and even very small samples generally provide ample conodont elements. The overlying Stairway Sandstone and Stokes Formation also contains carbonate lenses which produce conodonts, although the occurrences are sporadic and the quantitiy of elements recovered is low (B.J. Cooper, personal communication, 1981).

As the conodont element itself is comprised of the mineral apatite, it is emminently suitable for another newly developed technique now gaining prominence in hydrocarbon exploration: fission track dating (eg. Gleadow & Duddy, 1981). Future work will entail making large collections of Horn Valley carbonates to obtain enough conodont material be used for fission track dating.

In the course of a long ranging study of the hydrocarbon potential of the Amadeus Basin for Pancontinental Petroleum Limited many localities from the Horn Valley Siltstone, and several in the Stokes Formation have been sampled for conodonts, both for the purposes of regional correlation and determination of maturation levels of organic matter (kerogen).

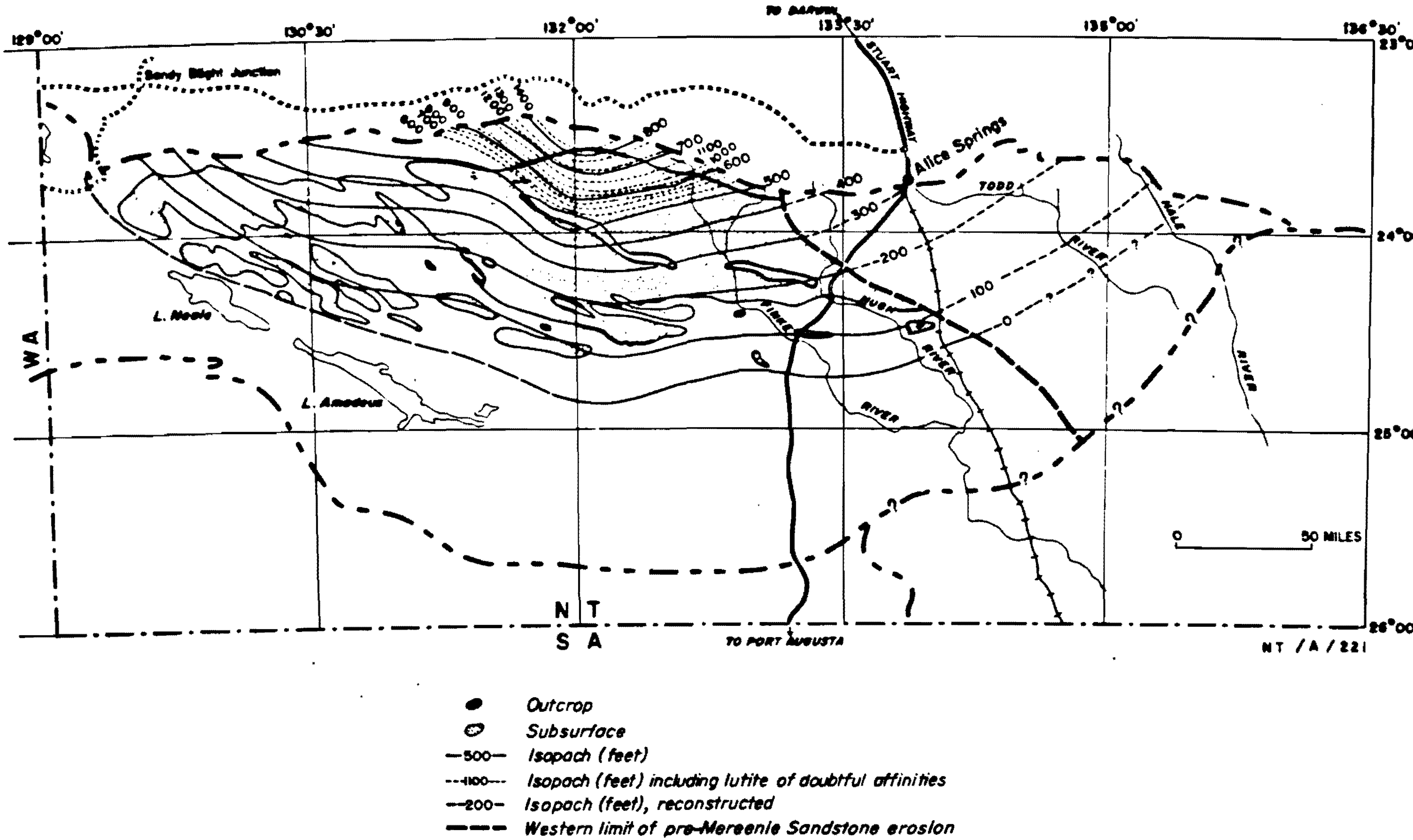

Fig. 1 . Distribution and thickness of Horn Valley Siltstone.

METHODS AND MATERIALS

Epstein et al. (1977) provided a comprehensive discussion on the use of conodont colour alteration indicies (CAI) in palaeotemperature studies, and introduced a standard colour chart with CAI values ranging from 1 to 5. They were able to demonstrate the equivalence of CAI, TAI, reflectance (R_o), percentage fixed carbon and temperature ranges in ^oC. Their chart showing these equivalencies is reproduced in Figure 2 below.

CONODONTS		PALYNOMORPHS		VITRINITE	
CAI	TEMEPERATURE °C	TRANSLUCENCY INDEX (AMOCO)	WEIGHT PERCENT CARBON IN KEROGEN	REFLECTANCE	PERCENT FIXED CARBON
1	<50–80	1–5	<82	<0.8	<60
1½	50–90	5-up. 5	81–84	0.7–0.85	60–65
2	60–140	5–6	81–87	0.85–1.3	65–73
3	110–200	up. 5–6	83–89	1.4–1.95	74–84
4	190–300	6	84–90	1.95–3.6	84–95
5	300–400	up. 6–7	+90	+3.6	+95

Figure 2 - Correlation Chart of Colour Alteration Index compared with the two other commonly used indexes of organic metamorphism (from Epstein et al., 1977).

Bergström (1980) has reiterated the findings of other workers that the colour alteration of conodonts is not solely temperature dependent, but may also be a function of the duration of heating and even the host rock type. While the effect of the heating duration is as yet difficult to assess, I have, like Bergström (1980) confined my investigation to carbonate rocks to allow comparison of the results with Epstein et al. 's equivalencies chart.

Carbonate rock and already processed samples have been collected from a variety of sources, including the Bureau of Mineral Resources Commonwealth Palaeontological Collection (CPC) - courtesy of R.S. Nicoll and P.J. Jones, from B.J. Cooper (Geology Survey of South Australia), core and cuttings from wells drilled in the Amadeus Basin previous to Pancontinental's assumption of Operatorship of the oil exploration permits in that basin (courtesy D. Benbow and N. Johns of Magellan Petroleum), cuttings from wells subsequently drilled by Pancontinental Petroleum Limited, and field collecting by Pancontinental's personnel. The location of the 100 plus collection sites is illustrated in Enclosure 1 and listed in the Appendix. All samples were processed using standard techniques for conodont preparation (Lindstrom, 1964).

As mentioned above, the prolific amount of conodont material present in the Horn Valley Siltstone allows utilization of even very small amounts of carbonate rock. For this reason, lagged cuttings from petroleum wells can be used, even from those bores drilled with air, in which the cuttings emerge on a fine dust resembling talcum powder (eg. West Mereenie-1). The recovered conodont elements from such wells are often very fragmentary, but provided several pieces are present, a CAI can usually be determined.

A preliminary study of material collected from the BMR Core and Cuttings Store in Canberra, and supplemented by material from Magellan's Core Store in Alice Springs, was conducted by Nicoll (1981). The results proved that cuttings could be used for CAI determination to augment the more conventional core and outcrop samples. This factor is particularly important in that it allows examination of conodonts from previously unaccessible depths in the basin, and afford comparison of the CAIs thus determined with outcrop data. In this way, depths of burial can be estimated for samples obtained from outcrop and may be used to compare the palaeotemperature gradients in diverse parts of the basin. This is particularly important in the search for oil and/or gas prone areas.

The Amadeus Basin already has produced two significant oil and gas fields (Pearson & Benbow, 1976), in which the Early Ordovician - Late Cambrian Pacoota Sandstone Reservoir is both sourced and sealed by the overlying Early Ordovician Horn Valley Siltstone (Welte et al., 1975; Kurylowicz et al., 1976). Consequently, samples were collected from wells in both fields in order to compare the different thermal histories of the source rocks at the Mereenie Oil and Gas Field, and at Palm Valley Field, where the hydrocarbon reserves are dry gas.

In the following discussion, any differences in the precursor kerogens (ie. gas prone or oil prone) is assumed to be negligible, although it should be remembered that the kerogen type is important in whether oil or gas is produced during thermal maturation.

The following discussions will be concerned primarily with the Pacoota/Horn Valley couplet, supplemented by conodonts recovered from the Stairway Sandstone and the Stokes Formation, although Cambrian carbonates have also been, unsuccessfully, investigated for conodont content. Nevertheless, knowledge of the Ordovician CAIs throughout the Amadeus Basin gives a minimum maturation grade for older rocks, and assessments of the stage of maturation reached by these older rocks can be made.

APPLICATION OF CONODONT CAI TO THE AMADEUS BASIN

The Amadeus Basin underwent several diastrophic episodes between the time of deposition of the Horn Valley Siltstone and Stokes Formation and the terminal orogenic event in the Late Devonian, the Alice Springs Orogeny (Wells et al., 1970). Many of these events are minor or of only local import and are unnamed (Figure 3). However, two events, the Rodingan Movement (Late Ordovician to Early Silurian, Wells et al., 1970) and the Alice Springs Orogeny are of paramount importance to the thermal history of source rock kerogens in the Amadeus Basin.

The outcrops of the Horn Valley Siltstone, Stairway Sandstone and Stokes Formation were mapped by BMR in the 1960's (Wells et al., 1970). Figures 1, 4 and 5 show the outcrop area of these three formations in the Amadeus Basin. Enclosure 1 is a time structure map (two-way time) at the top of the Pacoota Sandstone (or base Horn Valley Siltstone) throughout the basin. The map was drawn from interpretation of extensive seismic surveys conducted for the BMR, Magellan, and more recently, Pancontinental Petroleum (R.J. Schroder, B.J. Phillips and M.P. Lynn, 1982 unpublished map). This structure map is preliminary and subject to ongoing revision, but, nevertheless, serves as an important base map, when combined with the mapped outcrop, for discussion of the regional variation in CAI and hydrocarbon generation. All the available CAI data from the Horn Valley Siltstone, Stairway Sandstone and the Stokes Formation have been plotted on this composite seismic/outcrop map (Enclosure 1), to constitute a CAI

AMADEUS BASIN

GENERALIZED STATIGRAPHIC TABLE – OP 175 & OP178

AGE	GROUP	FORMATIONS – WEST	FORMATIONS – CENTRAL	FORMATIONS – EAST	OROGENIES
TERTIARY – RECENT		Surficial deposits - Lakes, rivers and dunes			
PERMIAN		Buck Formation	?	?	
LATE DEVONIAN	PERTNJARA	Undiffer-entiated: Brewer Conglom-erate; Hermannsburg S'st; Parke Siltstone		Undandita Member, Brewer Conglomerate, Ljiltera Member; Hermannsburg S'st; Amulda Member, Dare Siltstone, Harajica Sandstone, Deering Siltstone	ALICE SPRINGS; PERTNJARA
SILURO-DEVONIAN		MEREENIE		SANDSTONE	RODINGAN
? LATE ORDOVICIAN / MIDDLE ORDOVICIAN	LARAPINTA	Gosse's Bluff S'st; Carmichael S'stone	Rodingan		
MIDDLE ORDOVICIAN (?—?)	LARAPINTA	Stokes Formation; Stairway Sandstone	Erosion		
EARLY ORDOVICIAN	LARAPINTA	Horn Valley Siltstone; Pacoota Sandstone	N'dhala Member		
LATE CAMBRIAN	PERTAOORRTA	Goyder Formation			UNNAMED
MIDDLE CAMBRIAN	PERTAOORRTA	Cleland Sandstone: Petermann S'st; Deception Siltst; Illara Fm.; Tempe Fm.	Jay Ck; Hugh River Shale; Giles Ck	Shannon Fm; Giles Ck Dolomite	
EARLY CAMBRIAN	PERTAOORRTA	Mt Currie Conglomerate ?	Enita Formation/ Quandong Conglomerate ? ?	Chandler Fm; Todd Rv. Dolomite; Arumberra S'st. 3,4	PETERMANN RANGE
LATE PROTEROZOIC VENDIAN		Maurice Formation; Sir Frederick Conglom./ Ellis Sandstone ?	? Julie Fm; Winnall Beds	Arumberra S'st 1,2.; Julie Formation; Pertatataka Fm. (Cyclops Member)	
? VENDIAN – RIPHEAN		Carnegie Formation / Boord Formation	Inindia Beds	Pioneer S'st/Olympic Fm; Aralka Formation; Areyonga Formation	SOUTHS RANGE; AREYONGA
? LATE RIPHEAN		Bitter Springs Formations; Heavitree Quartzite		Loves Creek Member; Gillen Member	ARUNTA
PRECAMBRIAN		Arunta Complex			

Plan No. 3/74

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FIGURE 3

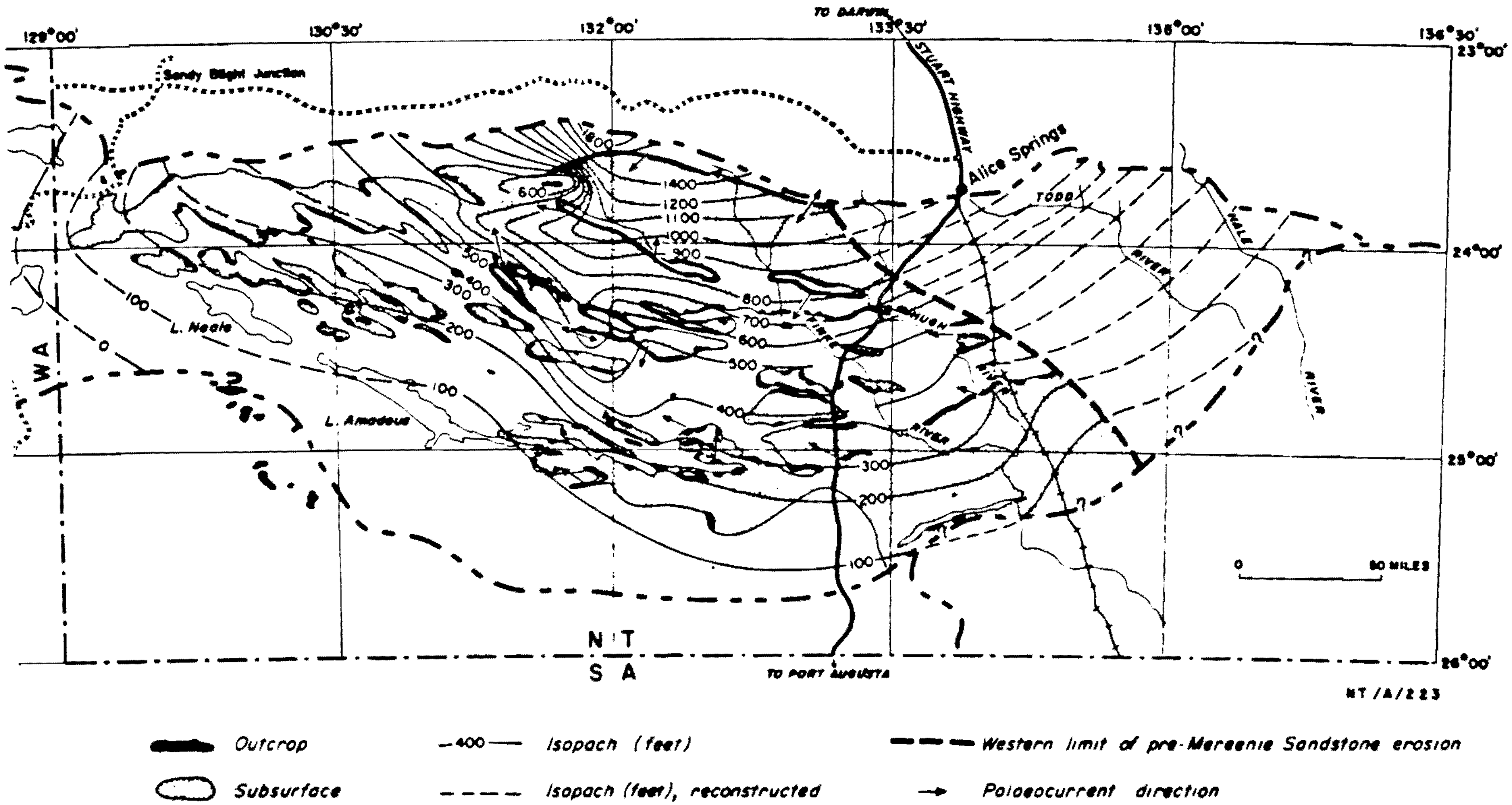

Fig. 4. Distribution and thickness of Stairway Sandstone.

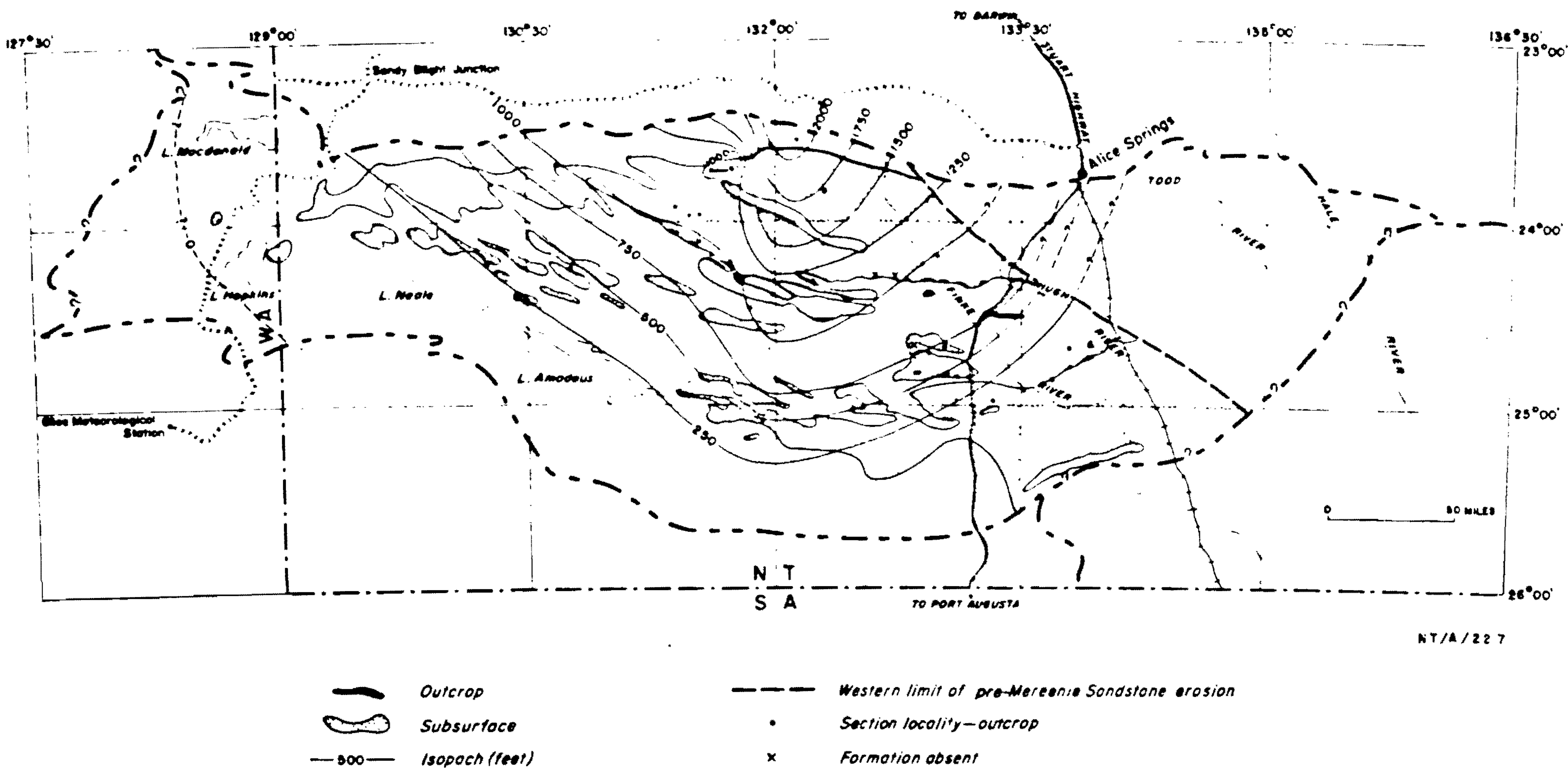

Fig. 5. Distribution and thickness of Stokes Siltstone.

isograd map, and, together with the information regarding present burial depths of the Horn Valley, give a three dimensional framework for CAI variations in the basin.

Epstein et al. (1977) concluded that in the Appalachians, variations in the CAI isograds correlate closely with the overburden thickness. Using their criteria, a CAI range of 1-1.5 suggests a maximum overburden of 2500 metres and a CAI of 3+ burial of from 4,000 to 7,500 metres. The depth/CAI relationship in the Appalachian pertain under a present day geothermal gradient of about $3.2^{o}C/100m$ (Epstein et al., 1977), whereas the present geothermal gradients in the Amadeus Basin are significantly less than this value (Figure 6). Consequently, either a higher geothermal gradient obtained in the Amadeus Basin in the past, or substantially greater depths of the burial were attained.

Fission track dating may help resolve the past geothermal gradient in the Amadeus Basin, but this question will not be further addressed herein. Suffice to say that the present day CAI isograd, irrespective of the geothermal gradient, is enough to predict areas of optimum generative or preservation temperature for oil or gas accumulations.

Several broad areas of similar CAI can be delineated on the CAI isograd map (Enclosure 1). These are:

A. The Missionary Syncline (3+), and including other areas with thick preserved Pertnjara Group.

B. Glen Edith Hills - Mereenie - Walker Creek anticlinal trend (1.5-2)

C. Cleland Hills - Johnnys Creek trend (1.5-2), and possibly including the Johnstone Hill area.

D. Gardiner Range - James Range trend (1-1.5)

E. Westward increase of CAI from Ellery Creek to Idirriki Range along the MacDonnell Tectonic Front.

F. Low CAI values south of the main anticlinal trends (1-1.5).

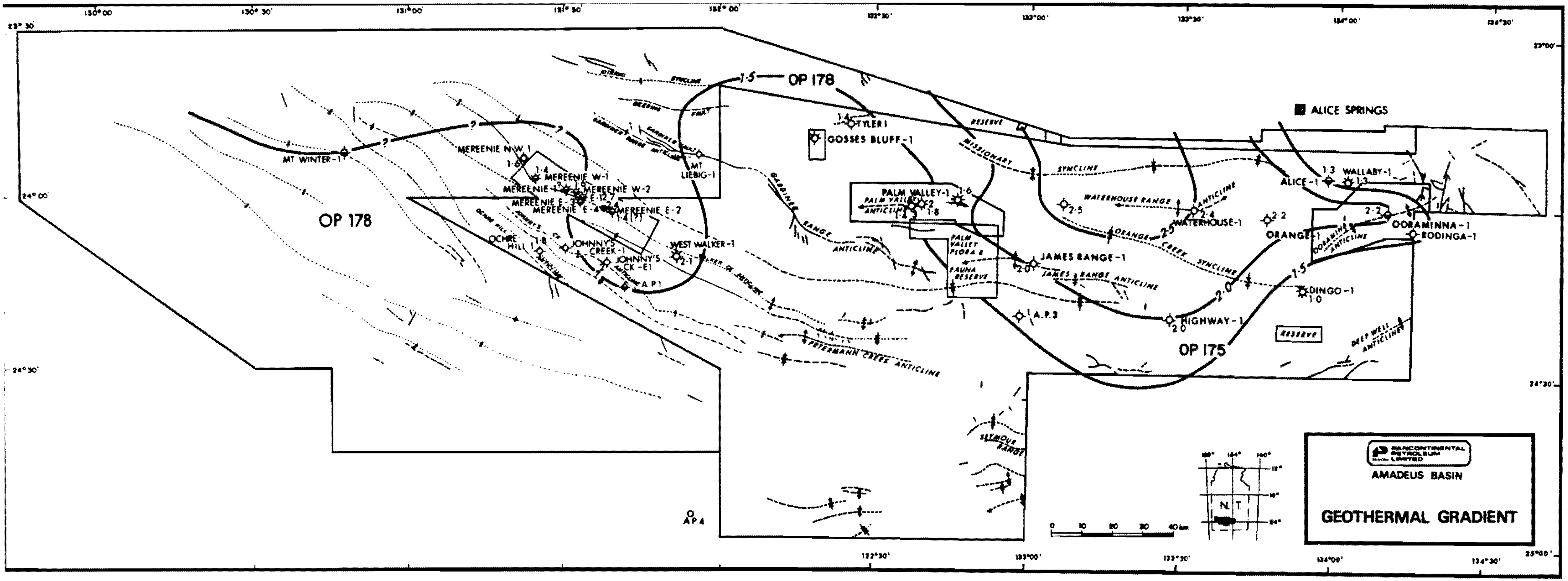
OP 178
OP 178
OP 175
ALICE SPRINGS
MT WINTER-1
MEREENIE N.W. 1
MEREENIE W-1
MEREENIE W-2
MEREENIE E-4
MEREENIE E-2
MT LIEBIG-1
WEST WALKER-1
JOHNNY'S CREEK-1
OCHRE HILL 1
A P 1
AP 4
TYLER 1
GOSSES BLUFF-1
PALM VALLEY-1
PALM VALLEY ANTICLINE
JAMES RANGE-1
JAMES RANGE ANTICLINE
A.P.3
WATERHOUSE-1
WATERHOUSE RANGE
ORANGE-1
ORANGE CREEK SYNCLINE
HIGHWAY-1
DINGO-1
ALICE-1
WALLABY-1
OORAMINNA-1
RODINGA-1
MISSIONARY SYNCLINE
GARDINER RANGE ANTICLINE
PETERMANN CREEK ANTICLINE
DEEP WELL ANTICLINE
RESERVE
AMADEUS BASIN
GEOTHERMAL GRADIENT

FIGURE 6

Two other structures are worthy of note:

G. Gosses Bluff

H. Dingo Anticline

I suggest that each of these trends of similar CAI is directly related to events during the Alice Springs Orogeny. While the Rodingan Erosion episode is also increasingly more important to the east of Palm Valley Field, its effect is minor westward of this area (Trend E). Important factors are:

I thickness of the resulting molasse sediments (Pertnjara Group) from uplift of the Arunta Block during the orogeny (Trend A); and

II differential timing of growth of discrete thrust fault bounded structural elements during the orogeny (Trend D).

Other factors that may effect the trends are the presence of diapirs, emanating from the Late Proterozoic Bitter Springs Formation evaporites, that have grown throughout the Early and Middle Palaeozoic (eg. Goyder Pass Diapir, McNaughton et al., 1968) and have thinned-section over them. It is not yet certain if this thinned-section results in lower CAI (as expected) or, because of the heat sink caused by the salt core of the structures, would lead to increased CAI.

These unknowns aside, the following broad conclusions have been drawn from the available facts.

A. The Missionary Syncline

In the area enclosing the CAI values of 3+, the Missionary Syncline, the thickness of Pertnjara Group sediments is clearly the overriding reason for the high maturation levels observed. Figure 7 shows the interpreted original thickness of the Pertnjara Group (Wells et al., 1970).

The Pertnjara Group is known to exceed 3600 m in thickness in the Missionary Syncline (Figure 8), immediately south of the MacDonnell Tectonic Front (Wells et al., 1970). CAI values are of course not available from the syncline itself, and inferences have to

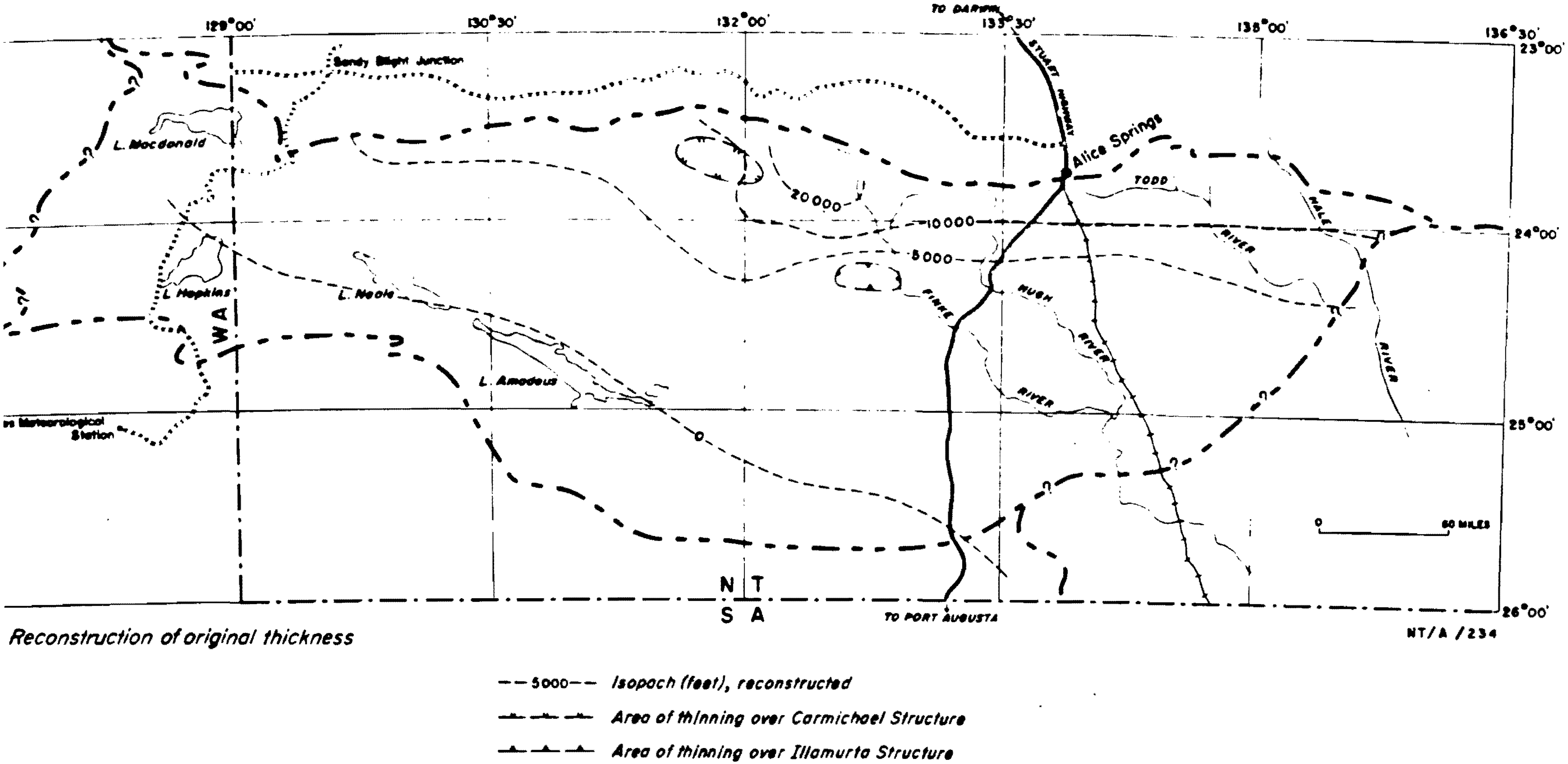

Fig. 7. Thickness of Pertnjara Group.

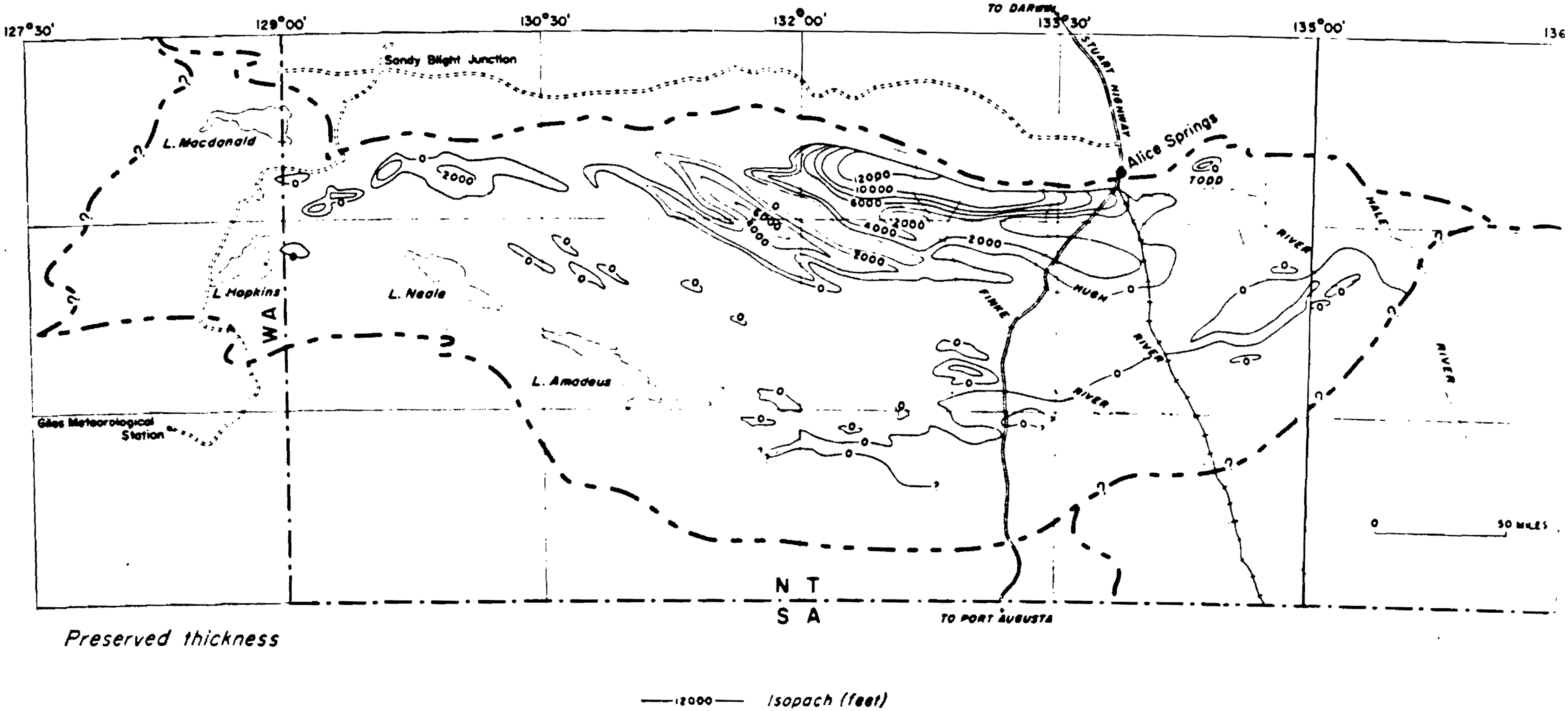

Figure 8. Preserved thickness of Pertnjara Group (from Wells et al., 1970)

be drawn from the drilled anticlines surrounding or projecting into the syncline. CAI values of 3 are recorded in the Horn Valley Siltstone from the Palm Valley Field and West Waterhouse-1 at depths of about 2000 metres, and from the Stokes Formation at Tyler-1 at 3500 metres. The value of the CAI from the Horn Valley Siltstone at Tyler-1 (not reached) can be safely assumed to be more than 3. All these high CAIs are clearly related to the thickness of the preserved overburden, which must have reached at least 4000 metres to generate CAI of 3+. As noted above, Epstein et al., (1977) suggested a maximum burial of 7500 metres for CAI of 3 in the Appalacians. A value of 3 from the Horn Valley outcrop at the west and of Idirriki Range also suggests that this area was much more deeply buried than at present (see also Waterhouse Range outcrop - discussed below).

At the Palm Valley Gas Field, where CAI values of 3 are recorded in the Horn Valley Siltstone (Nicoll, 1981), a reflectivity (R_o) of 1.4 - 1.95% is inferred (Epstein et al., 1977). At this R_o, the reservoired hydrocarbon should be dominantly dry gas (methane), and this is in fact the case (Kurylowicz et al., 1976). The present reservoir temperature is about 60^oC at about 1700 - 2000 metres burial (Kurylowicz et al., 1976). From the CAI values, a palaeotemperature of 110 - 200^oC is predicted. As at Mereenie Field (discussed below), either the present geothermal gradient is lower than that operating during earlier times (ie. Late Devonian), or erosion has removed a substantial thickness of overburden, or a combination of both factors should be invoked. The present day geothermal gradient at Palm Valley Field is less than $2^oC/100m$ (Figure 6), and on this gradient an overburden thickness of 6000 metres would be needed to obtain a 200^oC temperature in the Horn Valley Siltstone (cf 4600 metres from Kurylowicz et al., 1976, Figure 15). This is clearly in excess of the approximately 4000 metres overburden on the Horn Valley Siltstone at Tyler-1 well, located closer to the MacDonnell Tectonic Front than the Palm Valley Field, and which has a CAI of 3 in the Stokes Formation. As the molasse deposits associated with the Alice Springs Orogeny front (Pertnjara Group) thin southwards and thus should be thinner at Palm Valley Field than at Tyler-1, it is concluded that, while the Horn Valley Siltstone at Palm Valley Field was once more deeply buried, a higher heat flow than that presently operating must have occurred. This higher heat flow probably took place during Late Devonian and Early Carboniferous time, associated with the Alice Springs Orogeny.

B. Glen Edith Hills - Mereenie - Walker Creek trend

The CAI range 1.5-2 corresponds to the final stages of maturation, during which catagenesis of pooled hydrocarbons may take place. This is clearly illustrated at the Mereenie Oil and Gas Field, where conodonts from the source rock, the Horn Valley Siltstone (Kurylowicz et al., 1976) have a CAI range of 1.5-2 (Nicoll, 1981) and catagenesis of reservoired oil to gas is probably occuring. The reservoir rocks (Pacoota Sandstone), immediately below the Horn Valley Siltstone at Mereenie Field, have present day temperatures of about 30^{o}C (Kurylowicz et al., 1976). This is lower than the predicted temperature range equivalent to CAI values of 1.5-2 (Epstein et al., 1977, and see Figure 6), and is therefore not indicative of the maximum temperature reached in the Horn Valley Siltstone. From the CAI data, a maximum palaeotemperature range of 60-140^{o}C may be more reasonable (see also Kurylowicz et al., 1976).

Two possible explanations for the lower present day temperature are suggested. Kurylowicz et al. (1976) have inferred a higher heat flow during the Alice Springs Orogeny (Late Devonian) which has decreased subsequently. Alternatively, assuming a static heat flow similar to the present geothermal gradient at Mereenie Field (about 2^{o}C/100m) at about 1200 metres at present burial, it is probably that deeper burial occurred in the past (ie. about 2500 metres), probably during Late Devonian time. It is not possible at this time to choose between the two alternatives, but both higher geothermal gradient and greater depth of burial were probable in Late Devonian time during the orogeny.

C. The Cleland Hills - Johnnys Creek trend

Anomalously high CAIs were recorded at shallow depth at East Johnnys Creek-1, Mt. Winter-1 and BMR AP1 (Enclosure 1). CAIs of 1.5-2 (similar to Mereenie Field) were measured between 20m to 300 metres burial. The present day geothermal gradient of about 2^{o}C/100m again cannot account for these high values. The explanation probably lies in a similar heat flow in the past to that derived in the Mereenie Field and also to the burial of Horn Valley Siltstone to a depth of greater than 3000 metres at East Johnnys Creek-1 and Mt. Winter-1. Additional collections of conodont bearing carbonates will need to be made along the anticlinal trend to assess the regional significance of these high CAI values.

D. Gardiner Range - James Range trend

The younger carbonates of the Stokes Formation, collected from the vicinity of James Range 'B' anticline, have CAI values of 1-1.5, suggesting possible shallower burial in this locality. Similarly, anomalously low values occur in the outcropping Horn Valley Siltstone and Stokes Formation at Areyonga and elsewhere in the Gardiner Range area (Enclosure 1). These anomalously low values may be explained by postulating early uplift along the Gardiner thrust fault system, during the initial stages of the Alice Springs Orogeny. In this scenario, the Gardiner Range and James Range trend would have been elevated above synclinal areas to the north (Missionary Syncline) and to the south (Mereenie area), and was not inundated with the Pertnjara Group molasse sediments. Conversely, the Gardiner Range area may have even contributed sediment to these subsiding synclines, and lead to still more reduction of the Horn Valley burial temperatures along the trend. This idea can be checked by examining seismic sections immediately north of the Gardiner thrust fault front for northerly prograding sediment wedges above the Early Late Devonian horizons.

If the low CAI levels in the Gardiner Range are indeed attributable to early uplift during the Alice Springs Orogeny, the converse should also be true : later stage uplifted structures should contain high CAI in the Horn Valley Siltstone. Late uplift can be demonstrated for the Waterhouse Range anticline from seismic data, and indeed, conodonts from the Hugh River locality in the Waterhouse Range have a CAI of 3. This high CAI is despite the significant erosion of all post Horn Valley Siltstone sediments from the Waterhouse area during the Rodingan Movement (see Enclosure 1). Deep burial of the ancestral Waterhouse anticline below Pertnjara Group molasse sediments during the early Alice Springs Orogeny is indicated.

E. Ellery Creek to Idirriki Range

East to west CAI changes, in part attributable to erosion accompanying the Rodingan Movement, can be demonstrated along the MacDonnell Ranges. At Ellery Creek, in the east, this erosive episode has removed all the post Stairway Sandstone (Enclosure 1) sediments, and CAIs of 1-1.5 are present. Further west at Stokes Pass, where no Rodingan erosion has occurred, CAIs of 2 were measured and at the western most exposure of the Horn Valley Siltstone in the Idirriki Range, a CAI of 3 was obtained. While this westward variation in CAI is in part explainable by the amount of Rodingan erosion, it is more probably that the thickness of Pertnjara deposition is also important in the western area.

F. Low CAI values south of the main anticlinal trends (1-1.5)

An area of low CAI (1-1.5) is present from the Levi Range, south and southeast of the eastern James Ranges, and southwards of the Cleland Hills - Johnnys Creek trend. This area of low CAI values is clearly attributable to the southward thinning of Pertnjara Group sediments away from the MacDonnell tectonic front (Figures 7 and 8). Low CAI values over most of the Lake Amadeus and Bloods Range sheet areas (Enclosure 1) are similarly caused by thin Pertnjara Group deposits and by regional southwesterly thinning of the Ordovician section itself.

G. Gosses Bluff

Gosses bluff is a prominent circular feature in the Missionary Plains (Figure 9) attributed to cratering caused by cometary impact (astrobleme) about 135 million years ago (Milton et al., 1972). In this structure, strata that were previously buried beneath several thousand metres of sediment are now exposed at the surface and present an ideal area to investigate the CAI of rocks formerly buried beneath the Pertnjara Group in the Missionary syncline. Moreover, in 1965 Magellan Petroleum drilled Gosses Bluff-1 to 1382 metres total depth in the centre of the

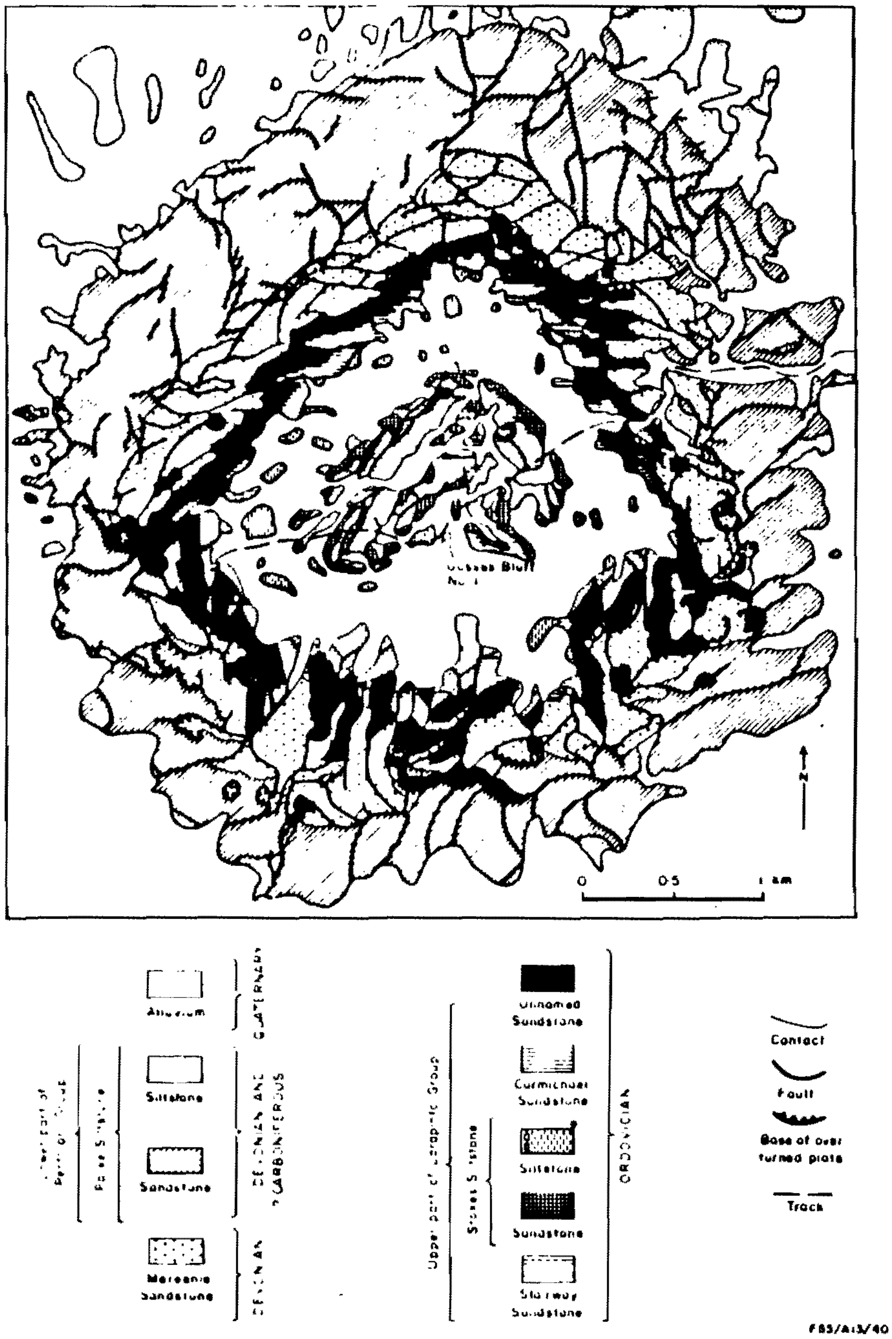

Fig. 9 . Gosses Bluff - central uplift area.

crater. The well terminated in vertically dipping Stairway Sandstone (Pemberton & Planalp, 1965) without penetrating the Horn Valley Siltstone or the target, the Pacoota Sandstone. Nevertheless, the well did encounter carbonate rocks in the Stokes Formation, which also outcrop near the wellsite. Samples from 97 to 311 metres in the well have a CAI of 3 and outcrop samples vary from 2-3. This is in general agreement with CAI values of 3 in the Stokes Formation from the nearby Tyler-1 well, presently buried to 3500 metres. Pyroclastic material was evidently produced by heat generated on impact (Milton et al., 1972), but rocks derived by rebound from great depth were not affected. This explanation is in accord with CAI data from the Siljan astrobleme in Sweden (Bergström, 1980) and other similar structures in North America (Votaw, 1980), where the CAI values reflect regional burial trends rather than heat generated by impact.

H. Dingo Anticline

According to Gorter et al. (1982), growth of the Dingo structure occurred contemporaneously with the later stages of the Alice Springs Orogeny, although the area was deeply eroded and peneplaned during the Late Ordovician Rodingan Movement. Salt flowage into the structural core, at both Bitter Springs Formation and Chandler Formation level, occurred during the Alice Springs Orogeny time : there is no evidence of structural growth or movement of either salt section preceeding the Late Devonian orogeny.

A limited conodont fauna has been recovered from cuttings samples from Dingo-1 exploration well (Nicoll, 1982). Approximately 300g of sample from the interval 1021 - 1030m was acid treated and about half of the sample dissolved leaving a shale residue.

The conodont fauna consisted of 185 discrete elements representative of taxa described from the Horn Valley Siltstone (Cooper, 1981a) and it is most probable that the sample interval studied correlates with the Horn Valley.

Conodonts from the sample have a conodont CAI of 1.5 (Nicoll, 1982). This indicates that rock from the sample interval has been subjected to a maximum temperature of between 50° to 90°C during its burial history (Figure 2).

At the maturation level attained, the Horn Valley Siltstone, the assumed source rock elsewhere in the basin, should presently be in the stage of oil generation. The virtual absence of hydrocarbons in the underlying Pacoota Sandstone, which appears to be sealed by the Horn Valley Siltstone at Dingo-1 (although perhaps not further southeast), is difficult to explain unless there is no source potential in the Horn Valley Siltstone, or other enclosing formations. Marchioni (in Gorter et al., 1982) demonstrated the non-oil source character of the Horn Valley Siltstone at Dingo-1. The underlying Goyder Formation is similarly of non-source facies.

For the above reason, ie. absence of suitable source rocks, it is suggested that the lack of hydrocarbons in the Pacoota Sandstone at Dingo-1 is due more to lack of source, rather than breaching of the seal. The non-source nature of the Horn Valley Siltstone at Dingo-1 has profound implications for further hydrocarbon search in the eastern Amadeus Basin.

CONCLUSIONS

This preliminary study of the colour alteration index (CAI) of conodonts in Early and Middle Ordovician strata in the Amadeus Basin has proven a valuable tool for assessment of organic metamorphism. It is worth reiterating in full the conclusion of Epstein et al. (1977) here:

The colour alteration index (CAI) of conodonts is a valuable tool for assessing organic metamorphism because:

1. It is a rapid and inexpensive method requiring only standard laboratory techniques and a binocular microscope.

2. A colour chart can be used for index determination or a set of standards can be assembled from field collections or cooked in the laboratory. Thus standards can be easily assembled and reproduced.

3. Conodont colour alteration begins near the upper thermal limit for many palynormorphs. The CAI of conodonts provides thermal cutoffs for oil, condensate, and dry gas production.

4. The CAI of conodonts is applicable to rocks as old as Cambrian, whereas reflectance techniques for vitrinite cannot be used for pre-Devonian rocks.

5. Conodonts are most abundant and most easily concentrated from marine carbonate rocks in which palynormorphs are generally poorly preserved and in which vitrinite is least abundant and often absent.

Specific conclusions drawn from this preliminary study are as yet only tentative, but provide important information relative to the search for hydrocarbons in the Amadeus Basin. Clearly, knowledge of the CAI at a hydrocarbon prospect can be used to predict whether oil or gas is most likely (Enclosure 1).

The conclusions of this study have profound implications for the Undandita prospect (Enclosure 1), located within the CAI of 3 isograd : early uplift of this area must be proven if liquid hydrocarbons are to be expected. Growth of similar structures by salt movement during the early stages of Pertnjara deposition is shown at the Goyder Pass diapir, and lower CAIs could be expected. However, the effects of the heat sink in the salt core on maturation are as yet indeterminate.

The high CAI values associated with the Stokes Formation at the Gosses Bluff prospect (Enclosure 1) indicate that the only hydrocarbon potential for the Pacoota Sandstone reservoirs is gas.

The CAI values from the Cleland Hills - Johnnys Creek trend suggest that the Tempe Vale prospect and Cleland Hills lead (Enclosure 1) should be presently within the late oil preservation window, similarly to the Mereenie Oil and Gas Field. Seismic data at the Tempe Vale prospect and the Cleland Hills leads indicate that the Pacoota Sandstone target is likely to be encountered at about 1500m maximum burial.

In the Glen Edith Hills area (Enclosure 1), CAI values and the present burial depth of the Horn Valley Siltstone source rock suggest that any hydrocarbons present will be gas. However, if early growth along the thrust faults is proven by seismic data, a moderate chance of some oil pooling is possible.

The Gypsum Nose area is probably oil prone on the known CAI values (see Yingurrdu lead, Enclosure 1). The Johnstone leads are similarly oil prone on CAI values. The prospectiveness of both areas is subject to the possibility that the source facies, the Horn Valley Siltstone, may be absent.

SUGGESTIONS FOR FURTHER WORK

The spread of the 100 plus localities that have provided conodonts suitable for conodont CAI determination over some 7500 square kms of the preserved Amadeus Basin, allows for only the tentative conclusion presented above. Further collections are required to supplement the already collected localities to provide infill in areas of expecially sparse data, and to answer the specific question alluded to above. Suggested areas for future collections include:

a. Collections from the Horn Valley Siltstone along the MacDonnell Ranges from Ellery Creek to Haast Bluff to determine the cumulative effects of lessening Rodingan erosion to the west.

b. Collections from the Horn Valley Siltstone over known growth structures including Goyder Pass Diapir, the Illamurta Structure (Wells et al., 1970) and salt cored anticlines (eg Parana and Levi anticlines) to determine the effects of growth and the postulated salt core heat sink on CAI.

c. Further collection from the Horn Valley Siltstone in areas of especially sparse data, particularly in the western areas, Glen Edith Hills, Cleland Hills and the Johnstone Hill areas, and from carbonate lenses within the Stokes Formation and Stairway Sandstone to the south and west of the Cleland Hills - Johnnys Creek trend.

d. Collections through the Horn Valley to Stokes Formation in areas of thickest Larapinta Group deposits to determine if trends exist in CAI through the Larapinta Group. Possibly the best site for such collections will be through Stokes Pass.

Other studies that may prove useful in determining source rock maturation trends in the Amadeus Basin are addressed below:

Fission Track Dating

Dr. R.S. Nicoll suggested that the prolific conodonts recoveries from the Horn Valley Siltstone made conodonts from that formation a prime prospect for fission track dating. Consequently, in July, 1981, collections of fossiliferous Ordovician limestones were made from three localities in the Mt. Keartland area of the James Range. Unfortunately, insufficient conodonts were recovered from the 4 kg of sample processed for fission track work. The reason for the low recovery is evidently because the collected material is from the Stokes Formation rather than the Horn Valley Siltstone (R.S. Nicoll, personal communication, 1981). Future collections will be made from undoubted Horn Valley outcrops. A suggested locality is in the western Idirriki Range near Haast Bluff. This locality should provide abundant material and be of use in determining increased heat flow generated during the Alice Springs Orogeny.

Fission track work on conodonts will allow a three pronged attack on the problems of organic maturation in that; (1) it allows precise dating of the time of deposition of the organic matter; (2) allows accurate assessment of the maximum temperature that organic matter has been subjected to (ie. CAI) and (3) allows dating of the time the palaeotemperature last fell below about 60^{o}C (Gleadow & Duddy, 1981), and thus will provide data on both the timing of the onset and cessation of maturation and migration of hydrocarbons. Also, these data points, coupled with TAI and reflectance techniques, will allow the calibration of theoretical models of organic maturation for prediction of the hydrocarbon potential elsewhere (eg. the Lopatin Method, Waples, 1980) in the basin.

Cambrian Phosphatic Microfossils

The presence of other groups of phosphatic fossils in Cambrian rocks (eg. inarticulate brachipods, bradyioriids, monoplacophorans, etc.) may result in similar colour alteration scales for these taxa. Such phosphatic fossils are known from acid insoluable residues of Cambrian strata elsewhere in Australia (eg. Jell, 1981).

Pancontinental Petroleum Limited has provided the BMR with a large amount of Cambrian age carbonate rock cuttings from drilling in the Amadeus Basin (eg. Wallaby-1 and Dingo-1) to be used in biostratigraphic studies, and any contained fossils will be assessed for their potential future use as palaeo-geothermometers. Cuttings and core from carbonate rocks in earlier wells have also been submitted by Pancontinental Petroleum (eg. East Mereenie-4, Alice-1, Orange-1, East Johnnys Creek-1 and Highway-1) with recovery of phosphatised microfossils as yet only from the Shannon Formation in Core 12 from Alice-1.

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APPENDIX

LIST OF SAMPLE LOCALITIES

Locality	Present Burial Depth	CAI	Formation	Collector	CAI Authority	Number Reading
Maloney Creek	Surface	1-1.5	Horn Valley	Cooper	Cooper	N/A
Ellery Creek	Surface	1-1.5	"	"	"	N/A
"	"	"	"	?	Nicoll	
Mereenie-1	1036-1067m	1.5-2	"	Gorter	"	21
"	1067-1097	"	"	"	"	45
"	1097-1128m	"	"	"	"	46
East Mereenie-1	1058m (Core 6)	2	"	"	"	98
"	1070-1091m	1.5-2	"	"	"	27
West Mereenie-1	518-549m	1.5	Stokes	"	"	1
"	1067-1082m	1.5-2	Horn Valley	"	"	5
"	1097-1128	?1.5-2	"	"	"	9
"	1128-1143m	?1.5-2	"	"	"	3
West Waterhouse-1	1762-1789m	3	?Horn Valley	"	"	47
East Johnnys Creek-1	61-110m	1.5-2	Horn Valley	"	"	40
"	0-366m	1.5	?	?	"	82
Orange-1	732-736m	1-1.5	Horn Valley	"	"	46
Palm Valley-1	1628-1634m	2-3	"	"	"	11
"	1673-1700m	3	"	"	"	11
"	1696-1699m	1-3	"	"	"	8
"	1969.7m(Core 14)	3	"	"	"	158
Palm Valley-3	1981-1999m	3	"	"	"	6
"	2021-2039m	3	"	"	"	10
Dingo-1	1021-1030m	1.5	"	"	"	185
Mt. Winter-1	165-256m	1.5-2	"	"	"	-
James Ranges	Surface	1	Stokes	Gorter/Svalbe	"	-
Gosses Bluff-1	97.2m	3	Stokes	Gorter	"	30
"	268-311m	3?	"	"	"	1
Gosses Bluff	Surface	-	"	Schroder	"	-
Tyler-1	3429-3520m	3	Stokes	Gorter	"	-
ML 5	Surface	3	Horn Valley		"	9
ML 12A	"	1.5	?Horn Valley		"	24
ML 44	"	1.5	Stokes		"	1
ML 46	"	1-1.5	Stokes	Wells	"	+233
ML 152	"	1-1.5	?Pacoota		"	12
ML 155	"	1.5	Stokes		"	8
ML 162	"	1-1.5	Horn Valley		"	+200
McD 1	"	1-1.5	"		"	+100
McD 14	"	3	"		"	+100
M 71	"	1	?Stokes		"	+200
A1/19	"	1	Stokes	?	"	26
A1/30	"	1-1.5	"	?	"	21
E 13	"	1-1.5	"		"	3
E 14	"	1	"		"	7
E 20	"	1	"		"	31
HY 713	"	1	?		"	84
HY 715	"	1	?		"	+200
HY 717	"	1	Stokes		"	+100
HY 722B	"	1	?Horn Valley		"	+200
MR 15	"	1-1.5	?Stairway		"	7
MR 242	"	1-1.5	Stairway		"	25
MR 24	"	1	Horn Valley		"	+500
LA 183	"	1-1.5	Stokes		"	3
LA 207	"	1-1.5	Horn Valley		"	28
LA 238 (b)	"	1	Stokes		"	5
LA 535 (F)	"	1-1.5	Stairway		"	55

Locality	Present Burial Depth	CAI	Formation	Collector	CAI Authority	Number of Reading
AP-1	9.6-9.8m	1.5-2	Stokes		"	2
"	25.6-191.8m	"	Stairway		"	61
"	219.2-269.8m	"	Horn Valley		"	104
NT 87	Surface	1	?Horn Valley		"	+100
NT 95	"	1	Stokes		"	54
NT 192	"	1-1.5	Horn Valley		"	+200
NT 130	"	1	"		"	8
NT 131	"	1	"		"	41
NT 149	"	2	base Horn Valley		"	20
NT 153	"	2	Horn Valley		"	+100
NT 157	"	2	top Horn Valley		"	31
NT 160	"	1-1.5	?		"	6
NT 184	"	1-1.5	Stokes		"	20
NT 213	"	1	Horn Valley		"	+200
NT 222	"	3	"		"	92
NT 342	"	1-1.5	?		"	13
NT 345	"	1-1.5	Horn Valley		"	+100
NT 352	"	2	Stokes		"	18
NT 353	"	2	"		"	44
NT 354	"	2	"		"	5
NT 355	"	2	"		"	3
NT 356	"	2	"		"	4
NT 357	"	1.5-2	"		"	1
NT 358	"	indet	"		"	1
NT 621	"	1-1.5	?		"	1
NT 622	"	etched	?		"	5
NT 627	"	1-1.5	?		"	20
West Walker-1	1060-1065m	1.5	Stokes	Gorter	Nicoll	-
"	1315-1330m	2-3	Horn Valley	"	Nicoll	+5
"	1390-1395m	2+	?Pacoota	"	Gorter	2
WA 1a, b	Surface	1	Horn Valley	"	Nicoll	-