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OIL GEOCHEMISTRY AND ASSESSMENT OF HYDROCARBON-SOURCE POTENTIAL OF CAMBRIAN AND DEVONIAN ROCKS, OFFICER BASIN, SOUTH AUSTRALIA

REPORT NO. 9 of the OFFICER BASIN
STUDY GROUP

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ABSTRACT

Oil shows over a significant interval of the Cambrian Observatory Hill Beds in SADME stratigraphic well Byilkaoora-1 demonstrated for the first time that oil has been generated in the Officer Basin. The shows vary in character from "light" oils with a pale stain and strongly petroliferous odour bleeding from fracture porosity, through to heavy viscous bitumen in vugs. They occur in a non-marine alkaline playa-lake sequence of bituminous carbonate and argillite with calcite pseudomorphs of sodium carbonate-bicarbonate evaporite minerals.

Geochemical analysis of the oils suggests that they are immature and belong to two primary genetic families. Some oils have been severely biodegraded. The less altered oils are rich in the C_{15}-C_{25} and C_{30} acyclic isoprenoid alkanes and are quite unlike Cambrian oils from Santos Wilkatana-1 (Arrowie Basin, S.A.), Exoil Alice-1 (Amadeus Basin, N.T.) and Morrow County field, Ohio, U.S.A. Potential source beds in the Byilkaoora evaporitic sequence contain 0.5-1.0% total organic carbon and yield up to 1900 ppm solvent-extractable organic matter. Oil-source rock correlations based on gas chromatographic "finger-prints" and specific ion detection mass spectrometry of the alkane fraction indicate that the oils originated within those facies which were drilled, making them the first reported examples of *non-marine* Cambrian petroleum. The main precursor organisms were benthonic algae (probably blue-greens) and various bacteria. Squalane and the C_{21}-C_{25} sesterterpanes in the oils and their source rocks are attributable to archaebacteria.

Geochemical and petrographic studies of the organic matter in Cambrian sediments from five other wells in the basin reveal regional variations in hydrocarbon source potential that relate to differences in precursor microbiota, depositional environment and regional maturation. At Wilkinson-1 and Wallira West-1 (both SADME wells), located on the southeast margin of the basin adjacent to the Karari Fault, micritic carbonates deposited in a marine sabkha environment are rated as marginally mature to mature, good to prolific sources of oil. Cambrian siltstones and shales from SADME Murnaroo-1 and Exoil Emu-1, farther north, and Conoco Birksgate-1, adjacent to the Musgrave Block, have low organic carbon values (<0.3%) and hydrocarbon yields, and at best are only marginally mature.

Petrographic examination of dispersed organic matter in Officer Basin carbonates, using both ordinary and fluorescent reflected-light microscopy, shows that source and reservoir facies are intimately related. Varieties of organic matter recognised include lamellar alginite (alginite B), and fine aggregates (or "balls") of bitumen, with a reflectance in the range 0.2-1.4%. The former type probably is derived via diagenesis from algal mats. The latter is referable to various asphaltic reservoir bitumens.

A 2926 m thick sequence of Devonian marine clastics was penetrated by Conoco's Munyarai-1 wildcat. Organic carbon contents (0.2-0.5%) and hydrocarbon yields (<15 mg/g organic carbon) are low. Graptolite and bitumen reflectances, fluorescence colours of phytoplankton, and estimates of equivalent vitrinite reflectance based on published coalification models suggest that the sequence becomes initially mature at about 2300 m. The kerogen is apparently gas-prone.

INTRODUCTION

In mid-1979 the South Australian Department of Mines and Energy (SADME) well, Byilkaoora-1, was drilled on the northeastern margin of the Officer Basin (Figure 1) with the main objective of coring a complete stratigraphic section of the Early Cambrian Observatory Hill Beds. Carbonates of the formation previously had been shown by McKirdy (*in* Gatehouse, 1979) to have excellent source potential for oil in SADME stratigraphic well, Wilkinson-1, drilled in 1978 about 300 km SSW of Byilkaoora (Figure 1). Moreover, during sampling of Wilkinson core for source rock analysis, slabbing of micritic carbonate revealed a set of oil-stained *en echelon* fractures. Confirmation of the oil-generating potential of the Observatory Hill Beds came with the discovery in Byilkaoora-1 of oil shows between the depths of 203 m and 330 m. Core recovered from this interval displays abundant evidence of hydrocarbons, viz. petroliferous odour, pale yellow fluorescence on minor joints and fractures, oil bleeding from fractures (Plate 1.1) and vugs (Plates 1.2 and 1.3), and heavy black reservoir bitumen infilling larger vugs (Plate 1.4). The hydrocarbon shows occur in a sequence of bituminous carbonate and calcareous mudstone, with Magadi-type cherts and calcite pseudomorphs after the evaporite minerals, trona, shortite and ?gaylussite (Pitt *et al.*, 1980). These sediments were deposited in a non-marine, alkaline playa-lake, and seem to be an excellent Cambrian analogue of the Wilkins Peak Member of the Eocene Green River Formation, Wyoming (White & Youngs, 1980), which comprises dolomitic mudstone and marl, thick bedded evaporites (principally trona, halite and shortite) and some rich oil-shales (Shanks *et al.*, 1976).

We report here results of the comparative geochemical analysis of seven oils from Byilkaoora-1 (Table 1) and three Cambrian oils from elsewhere (Table 2); and organic geochemical and petrographic analyses of fine-grained sediments from Byilkaoora-1, Wilkinson-1 and five other wells drilled in the South Australian portion of the Officer Basin (Figures 1 & 2). The purpose of this investigation was fourfold:

1. to establish the type (or types) of oil present;
2. to determine whether or not the oils had originated from source beds within the Observatory Hill Beds;
3. to ascertain the regional variation in type, maturation state and hydrocarbon-generating potential of dispersed organic matter in Cambrian carbonates, argillites and siltstones across the eastern Officer Basin; and finally

4. to reassess the source-rock potential and thermal history of a thick-sequence of Devonian marine clastics penetrated by Conoco's wildcat, Munyarai-1.

This report updates and supersedes our previous preliminary reports (Kantsler, 1979; McKirdy *in* Gatehouse, 1979; McKirdy *in* Benbow and Pitt, 1979). Prior to the present investigation, Munyarai-1 was the only well in the Officer Basin on which any source rock or maturation studies had been attempted (Vlierboom, 1973; Shell Development (Australia) Pty Ltd, 1975; Cassou, 1977). In terms of petroleum exploration, the Officer Basin remains one of the least explored prospective onshore sedimentary basins in Australia.

Substantial departures from routine methods of source-rock evaluation were necessitated by the age and lithofacies of the sediments encountered in this study. Cambrian sediments, by virtue of their Early Palaeozoic age, antedate the appearance in the geological record of abundant continental floras and therefore lack humic coals and/or woody-herbaceous organic matter from which degree of thermal alteration can be determined by measurement of, for example, vitrinite reflectance or spore colour (McKirdy & Kantsler, 1978). The Devonian succession at Munyarai also lacks recognisable vitrinite and contains only a very sparse and poorly preserved microflora, presumably because of its distal marine facies. The majority of the Cambrian rock samples analysed were carbonates. Little published information exists on petroleum source-rock studies of carbonates. Nevertheless, it is probable that the process of hydrocarbon generation in carbonates differs significantly from that in argillaceous clastic rocks

(Momper *et al.*, 1975; McKirdy, 1977; McKirdy & Kantsler, 1978). This is evidenced by, for example, the low average total organic carbon (TOC) content of ancient carbonates (0.24%: Gehman, 1962); and the anomalous "humic" or H-poor composition of kerogen in some thermally-mature marine carbonate sequences which display obvious signs of having generated hydrocarbons (e.g. petroliferous odour, residual bitumen in vugs). Thus, caution is necessary in applying standard source-rock evaluation techniques to carbonates and evaporites (cf. Malek-Aslani, 1979).

GEOLOGICAL SETTING

The Officer Basin is an east-west trending elongate intracratonic depression containing sediments of Late Proterozoic (Adelaidean) to Devonian age, in western South Australia (Figure 1). A portion of the basin extends into Western Australia. The basin is flanked by Precambrian crystalline basement rocks of the Musgrave Block to the north, the Gawler Block to the southeast and the Yilgarn Block to the west. The eastern and southern margins of the basin are poorly defined, being overlain by sediments of the Permian Arckaringa Basin and Tertiary Eucla Basin, respectively. The basin fill is thickest in the north where depths to magnetic basement exceed 5 km, and thins irregularly southward. The subsurface lithology and stratigraphy of the Officer Basin is summarised in Figure 2. For a recent review of the geology of the Officer Basin and its history of petroleum exploration, the reader is referred to Pitt *et al.* (1980).

WELLS STUDIED

Conventional cores from two Conoco wildcat wells, Munyarai-1 and Birksgate-1; and five stratigraphic wells, Exoil Emu-1 and SADME Wallira West-1, Murnaroo-1, Wilkinson-1 and Byilkaoora-1, were sampled for source rock analysis. The locations of the wells are shown in Figure 1. The depths and gross lithologies from which samples were taken are indicated on Figure 2.

ANALYTICAL METHODS

OILS

Of the seven oils from Byilkaoora-1 that were analysed only one was recoverable in sufficient quantity for measurement of API gravity. This sample (3131, Table 1), a black viscous "heavy" oil, was scraped from the vug in which it occurred (Plate 1.4) and transferred to a glass vial. Each of the remaining oils was isolated by a 5 minute ultrasonic washing of the core in benzene/methanol (60:40), followed by rotary evaporation of the solvent. The oil then was fractionated in the same manner as a source rock extract (see below). The Morrow County oil (Table 2) was topped to 210°C by distillation before analysis. It should be noted that lubricants and mud additives used during the drilling of Byilkaoora were screened for hydrocarbons, and deemed acceptable, prior to spudding of the well.

SOURCE ROCKS

All rock samples analysed were portions of slabbed or broken core. To ensure removal of any surficial hydrocarbons, each core sample was washed by brief sonication in solvent prior to crushing in a Siebtechnik mill. This routine precaution appears to have been effective in eliminating possible contamination from such sources as diesel spotted to the drilling mud and core barrel lubricant. Cores from Byilkaoora-1 selected for source-rock analysis were free of visible oil staining and lacked obvious vuggy or fracture porosity.

Total organic carbon (TOC) was determined by digestion in dilute HCl to remove carbonate minerals, followed by combustion in a Leco induction furnace and measurement of organic carbon as CO_2. Powdered core (100-150 g) was extracted for 24 hours with benzene/methanol (60:40) in a Soxhlet apparatus. In the case of the Birksgate samples, the solvent was azeotropic chloroform/methanol (87:13). Evaporation of the solvent yielded the extractable organic matter (EOM, nominally C_{15+}) as a brown gum. After precipitation of asphaltenes from the EOM (IP method 143/57), the asphaltene-free extract was fractionated into saturated hydrocarbons (alkanes), aromatic hydrocarbons and polar (i.e. O, N & S-bearing) compounds by liquid chromatography on Merck Grade 1 neutral alumina (alumina : sample ratio = 300 : 1), eluting successively with petroleum ether, benzene and methanol. Where necessary, elemental sulphur was removed from the petroleum ether eluate by treatment with colloidal copper. This chromatographic procedure later was modified following the discovery of C_{26+} n-alkanes in the aromatic hydrocarbon fraction of some extracts. Thus, the asphaltene-free Birksgate extracts, and Alice, Wilkatana and Morrow oils, were chromatographed on a column comprising 80 parts silica gel (Grace Bros. Grade 12, 28-200 mesh, activated at 250°C for 24 hours) over 20 parts alumina (adsorbent : sample ratio = 100 : 1), using petroleum ether and methanol as the eluting solvents. For the Byilkaoora asphaltene-free extracts (and oils), however, this amended procedure commonly gave a coloured petroleum ether eluate. The coloured "saturates" were rechromatographed on a short silica gel/alumina column, eluting with petroleum ether to recover a colourless saturates fraction free of aromatic compounds. Final washing of the column with 15% benzene in petroleum ether gave a coloured eluate which was combined with the original aromatics fraction. In the case of the Byilkaoora deasphaltened oils, a preliminary fractionation into hydrocarbons and non-hydrocarbons was achieved by chromatography on a silica gel/alumina column (eluting respectively with benzene and methanol) before proceeding to a final separation of the saturates and aromatics as above.

The saturated hydrocarbons were analysed by gas chromatography (GC) using an OV-101 SCOT column (50 m x 0.5 mm i.d.). The column liquid phase employed for the Wilkinson samples was SP-2100. Normal alkanes were identified by coinjection of standards. Identification of the C_{13}-C_{25} regular and C_{30} irregular acyclic isoprenoid alkanes was achieved by comparison of retention indices with published values (e.g. Shlyakhov *et al.*,1975) and, in the case of pristane (C_{19}), phytane (C_{20}), and squalane (C_{30}), coinjection of standards. Mass spectral confirmation of the identity of the isoprenoids was obtained for two samples from Byilkaoora-1 (oil 2280; rock extract 2284: Tables 1 & 4). Computerised capillary gas chromatographic-mass spectrometric (C-GCMS) analysis of the alkanes in two oils and one rock extract from Byilkaoora-1 was conducted by Masspec Analytical Limited, Stroud, U.K., using a Finnigan 3200 GCMS fitted with a 10 m x 0.3 mm OV-1 WCOT column and interfaced to an INCOS 6100 data system.

On the basis of TOC content and EOM data, certain samples were selected for further examination, involving isolation of the insoluble organic matter (kerogen) and subsequent determination of its elemental and stable carbon isotopic composition; and petrographic analysis of the dispersed organic matter *in situ* by ordinary and fluorescence-mode reflected-light microscopy. Kerogen was isolated using the procedure of Powell *et al.* (1975), and analysed for carbon, hydrogen, nitrogen, sulphur and ash by the Australian Microanalytical Service, Melbourne. Complete removal of pyrite from the kerogen concentrates rarely was achieved, resulting in anomalously high sulphur and low ash values. Accordingly, pyritic iron was determined by atomic absorption spectrophotometry, and appropriate corrections made for pyritic sulphur and the conversion of pyrite to haematite during ashing. Stable carbon isotope ratios of the kerogens (and of selected oils) were determined by the Chemistry Department, Western Australian Institute of Technology. Values are quoted as $S^{13}C$ ^{o}/oo relative to the PDB standard (estimated precision, ± 0.05 ^{o}/oo). For organic petrography, representative chips of core were mounted in cold setting ASTIC resin with the polished surface being a face perpendicular to the plane of the bedding. Following standard grinding procedures, final polish was achieved with chromium sesquioxide followed by magnesium oxide (both polishing grade) in a water slurry. The reflectance measurements were carried out using a Leitz MPV 1 microphotometer (due to its ease of operation when searching for maximum reflectance from fine particulate organic matter) calibrated against glass standards of 0.53%, 1.01% and 1.82% R_o. Measurements were made in oil immersion (n = 1.518) at a wavelength of 546 nm at a temperature of 23°C ± 1°C. Observations with fluorescent light utilised a 3 mm BG3 excitation filter (UV light) with a K490 suppression filter.

OIL GEOCHEMISTRY

Analyses of seven oil shows from Byilkaoora-1 are listed in Table 1. For comparison, the analyses of three oils recovered from Cambrian carbonate rocks in other sedimentary basins are given in Table 2.

On the basis of their stratigraphic position, asphaltene and saturates contents, and the type of porosity in which they occur, the Byilkaoora oils can be grouped into two genetic families (Table 3). Family A oils have moderately high asphaltene values (6.9-16.3%), and are found in the lower part of the oil-bearing interval (290-330 m). Oils belonging to Family B have negligible asphaltene contents (0.2-0.5%) and come from the middle of the petroliferous zone (240-290 m). The oils of both these families occur in vugs within grey-green carbonates (Plates 1.2-1.4). The uppermost oil analysed (depth 219.52 m), although low in asphaltenes (0.5%) like the oils of Family B, is associated with vertical fractures in brown calcareous siltstone (Plate 1.1) and appears to have resulted from secondary migration of one of the primary oil types. It is assigned to a third, stratigraphically separate group, Family A'. The concentration of aromatic hydrocarbons in all the Byilkaoora oils is uniformly low (3.5-7.7%).

FAMILY A OILS

Saturated hydrocarbons comprise only 23.5-37.5% (i.e. < 50%) of Family A oils which therefore may be classified as "aromatic" (Tissot & Welte, 1978). The alkanes are predominantly naphthenic in composition (as illustrated by oil from 317.10 m, Figure 3). The naphthenes have a bimodal distribution, with a dominant mode peaking at about n-C_{27}, and a lesser mode centred on the n-C_{18} position, broadly corresponding to the triterpanes and steranes (C_{30}) and diterpanes (C_{20}), respectively. The dominance of the higher molecular weight naphthene "hump" is more pronounced in the oil from 317.10 m (Figure 3) than in the other two oils of this family (Table 1). All Family A oils are rich in acyclic isoprenoid alkanes. It is evident from Figure 3 that individual isoprenoids typically are present in higher concentration than the adjacent n-alkanes. Thus, for example, pristane >> n-C_{17}, phytane >> n-C_{18}, C_{25} isoprenoid > n-C_{22}, and squalane >> n-C_{26} (Table 1). In terms of physical appearance, these oils are black, viscous, heavy crudes (Plate 1.4), a reflection of their high ONS + asphaltene content (54.8-72.5%). Oil from 293.17 m has an API gravity of 14.4°. Its sulphur content (0.3%) and H/C atomic ratio (1.50) are typical of aromatic-naphthenic crude oils (Bell & Hunt, 1963; Tissot & Welte, 1979).

The extent to which the tar-like aromatic-naphthenic oils of Family A represent immature original oils (in the sense of Milner *et al.*, 1977), or are products of the partial biodegradation of paraffinic-naphthenic oils, as implied by Tissot & Welte (1978, p. 377), is difficult to assess. A high proportion of acyclic isoprenoid alkanes in crude oils commonly is regarded as a sign of biodegradation in the reservoir, whereas the presence of a distinct naphthene hump in the sterane/triterpane region of the chromatogram, is evidence of relative immaturity (see e.g. Snowdon & Powell, 1979). That both these features are seen also in the alkanes of Byilkaoora source-rock extracts (Figure 7) makes it unnecessary to invoke substantial post-accumulation biodegradation to explain the composition of the Family A oils. Nevertheless, the possibility of some biodegradation cannot be ruled out, particularly as their source beds contain Type I kerogen (see below) from which the expected products of catagenesis are paraffinic or paraffinic-naphthenic oils (Tissot & Welte, 1978).

FAMILY B OILS

The oils of Family B display a marked variation in the concentration and composition of their saturated hydrocarbons which is attributable to differing degrees of biodegradation. The least altered oils (samples 2279 and 2280, Table 1) contain 53-59% saturates which are mostly branched and cyclic alkanes (Figure 3, oil from 278.77 m). Thus, according to the classification of Tissot & Welte (1978), those two oils belong to the relatively rare naphthenic class. The C_{15}-C_{25} and C_{30} acyclic isoprenoid alkanes again are strikingly abundant, possibly indicating some biodegradation, although the n-alkanes are slightly less depleted than in Family A oils (Table 1).

The effect of severe biodegradation on Family B oils is illustrated by sample 2278 (277.00 m): its content of ONS compounds becomes markedly enhanced at the expense of the saturated hydrocarbons (Table 1) from which the normal alkanes, and then the acyclic isoprenoids, are preferentially and completely removed (Figure 3). As a result the oil is changed from a relatively light naphthenic crude with a pale stain (Plate 1.2) to a heavier, darker, aromatic-naphthenic oil (Plate 1.3).

The cogenetic relationship between oils 2278 and 2280 (Table 1) is confirmed by the similarity of their m/e = 191 (triterpane) and m/e = 217 (sterane) mass fragmentograms (Figures 4 & 5). Minor differences in the m/e 217 plot of oil 2278 (e.g. single peaks in place of doublets) probably are due to the preferential biodegradation of rearranged steranes (diasteranes) (A.K. Aldridge, written communication, 1979; cf. Seifert & Moldowan, 1979).

FAMILY A' OILS

Oil 3129 (depth 219.52 m), although similar in gross composition to biodegraded oil 2278 of Family B (Table 1), has a significantly different alkane distribution which justifies its inclusion in a separate group. Its alkane chromatogram (Figure 3) is characterized by the presence of C_{15}-C_{35} n-alkanes (maximum, n-C_{17}; C_{15}-C_{25} and C_{30} acyclic isoprenoids; and a bimodal naphthene distribution in which the lower-molecular weight "hump" is dominant). The concentration of pristane exceeds that of phytane (cf. pr < ph in Family A & B oils). Moreover, the oil has the highest ratio of normal to acyclic isoprenoid alkanes of all the Byilkaoora oils (as indicated by the pr/n-C_{17}, ph/n-C_{18}, C_{25} isoprenoid/n-C_{22} and squalane/n-C_{26} values listed in Table 1). This sample (one of several similar shows over the depth interval 218-220.25 m) is interpreted to be an aromatic-naphthenic oil, originally of similar composition to the Family A oils, which has migrated some distance from its source. In the process of migration it has undergone a natural chromatographic fractionation resulting in depletion of asphaltenes, high molecular weight naphthenes, and possibly also acyclic isoprenoids (relative to n-alkanes). This would explain its occurrence in fractures (partly healed with calcite) in redbeds, and its relatively pale stain (Plate 1.1). By contrast, the oils of Family A and B appear not to have migrated very far at all. Rather, they occupy the available porosity (mainly vugs) *within* their respective source-bed sequences of grey-green carbonates and mudstones. For these oils, therefore, source and reservoir facies are closely interbedded and juxtaposed.

COMPARISON WITH OTHER CAMBRIAN OILS

As a group, the Byilkaoora oils are characterised by their distinctive C_{15+} alkane distributions which are dominated by the C_{15}-C_{25} and C_{30} acyclic isoprenoids (except where severely biodegraded). Comparison with three oils recovered from porous Cambrian carbonates in other sedimentary basins (Table 2, Figure 6) highlights the unusual character of the Officer Basin oils and, by implication, their precursor organic matter and its depositional environment. In the Alice, Morrow and Wilkatana crudes, isoprenoids are subordinate to n-alkanes, pristane >> phytane, and the higher (C_{21+}) isoprenoids were not detected. With the exception of the Wilkatana sample, the oils represented in Figure 6 have n-alkane profiles in which there is a marked predominance of odd over even-carbon-numbered homologues in the range C_{12}-C_{20}. This is a feature of many Early Palaeozoic crude oils (McKirdy & Kantsler, 1978). The n-alkane profile of the waxy Wilkatana crude oil suggests that it may be a residual reservoir bitumen from which light ends have been removed by water washing or lost by evaporation. The carbon isotopic composition of the Cambrian oils listed in Table 2 falls well within the range for pre-Devonian crude oils (viz. $\delta^{13}C_{PDB}$ = -35 to -24 $^{o}/oo$).

OIL-SOURCE ROCK CORRELATION

Any identification of the source(s) of the Byilkaoora oils must account for the following aspects of their composition and occurrence, as elaborated in the previous section:

1. the abundance and extended carbon number range of the acyclic isoprenoid hydrocarbons;
2. the existence of three geochemically distinct families of oils; and
3. the apparent threefold stratigraphic zonation of oil families within the Observatory Hill Beds at Byilkaoora-1.

Inspection of the chromatograms of the saturated hydrocarbons in the EOM of dark grey dolomite and calcareous mudstone from the Observatory Hill Beds between 202 m and 322 m depth in Byilkaoora-1 (Figure 7) reveals the same relative abundance and carbon number distribution of the isoprenoid alkanes that is characteristic of six of the oils analysed. The close similarity of the alkane fractions of oil from 278.77 m depth (Family B) and EOM from stained core sample 2284 (289.77 m) is evidenced further by their m/e = 191 (triterpane) and m/e = 217 (sterane) mass fragmentograms (Figures 4 & 5).

The Byilkaoora cores selected for source-rock analysis (Table 4), primarily because of their grey colour, all come from the Observatory Hill Beds and can be assigned to three stratigraphically distinct units (after Benbow & Pitt, 1979) on the basis of the yield and composition of their saturated hydrocarbons, as follows:

1. Unit 3 (lower), 284.5-322 m (abundant calcite pseudomorphs of trona and shortite);
2. Unit 3 (upper), 259-284.5 m (only minor pseudomorphs of unidentified evaporite minerals); and
3. Unit 4, 200-259 m.

Unit 3 (lower) source rocks, excluding those which display geochemical and petrographic evidence of staining, yield an average 30 mg of saturates per gram of organic carbon (Table 4). The chromatograms of these hydrocarbons are characterised by a bimodal naphthenic distribution in which the higher molecular weight "hump" is dominant (see e.g. Figure 7 : 285.00 m & 316.50 m). Pristane to phytane ratios are low (range = 0.89-1.08, mean = 0.97). Unit 3 (upper) source rocks (not including the stained sample) give a significantly higher mean yield of saturated hydrocarbons (45 mg/g TOC, Table 4) in which the low and high molecular-weight naphthenes are present in roughly equal proportions. Phytane again exceeds pristane in concentration (mean pr/ph ratio = 0.94). The mean saturated hydrocarbon content of unstained Unit 4 core samples is very low (10 mg/g TOC). The lower molecular-weight naphthene hump is predominant, and pristane > phytane. In some cases (viz. samples 59 & 65, Table 4) the C_{21+} acyclic isoprenoids apparently are absent (see e.g. Figure 7, 200.30 m), and hence these particular Unit 4 samples can be excluded from consideration as potential sources of the Byilkaoora oils so far analysed.

The foregoing geochemically-based bipartite division of source rock intervals parallels, and indeed largely explains, that of the oils. The aromatic-naphthenic oils of Family A appear to have been sourced by the evaporite-rich carbonates and mudstones which comprise the lower part of Unit 3. Additional support for this correlation comes from the similar carbon isotopic compositions of oil 3131 from 293.17 m depth ($\delta^{13}C$ = -28.75 ^{o}/oo, Table 2) and of kerogen in this part of the sequence (mean $\delta^{13}C$ = -29.06 ^{o}/oo, Table 5). The naphthenic oils of Family B are correlated with source beds in the upper part of Unit 3. Both have a higher saturates content than Family A oils and their source rocks located lower in Unit 3, possibly because of a difference in the lacustrine microbiota which altered in response to changes in the water chemistry and/or the height of the water table.

Notwithstanding the similarity of their respective saturated hydrocarbon fractions, the poor quality of the potential source rocks in Unit 4 (see next section) casts doubt on their ability to generate the aromatic-naphthenic oils of Family C. As suggested previously, these oils may have originated in the lower evaporite facies of Unit 3, and subsequently migrated to their present stratigraphic level following the development of fracture porosity.

SOURCE ROCK ANALYSIS

A source rock may be defined as a kerogen-bearing sedimentary rock in which petroleum hydrocarbons have been generated and then subsequently expelled. In practice this means that the migrated oil and/or gas, having accumulated in the pore space of a reservoir rock (or carrier bed), has been sampled, analysed and reliably correlated with the dispersed organic matter (DOM and/or kerogen) and its source rock. Thus, in the Officer Basin, source rocks *sensu stricto* occur only within Unit 3 of the Observatory Hill Beds at or near the Byilkaoora-1 well locality. Elsewhere, the fine-grained rocks under consideration are either *potential source rocks* or *immature potential source rocks* (cf. Powell, 1978). The former contain suitable dispersed organic matter (oil-prone, or gas-prone) of appropriate thermal maturity. The latter possess all the attributes of a source rock except adequate maturity.

ASSESSMENT OF MATURATION STATE AND HYDROCARBON POTENTIAL

The range of chemical and optical techniques employed here to determine the abundance, type and maturity of the dispersed organic matter in fine-grained Early-Middle Palaeozoic sediments of the eastern Officer basin is summarised in Table 6.

Abundance

TOC content is a widely-used parameter in petroleum source-rock evaluation. Purely on empirical grounds, various cut-off values are assigned to designate different grades of source-rock quality. For example, in a study of Tertiary marine carbonates from the South Florida Basin, Pontigo *et al.* (1979) used the following scale: <0.25%, poor; 0.26-0.50%, fair; 0.51-1.00%, good; >1.00%, excellent. Shales and siltstones containing less than 0.5% TOC commonly are regarded as being unable to generate producible quantities of oil or gas. However, Powell (1978, p. 15) has pointed out that "it is not possible to determine a lower limit on the organic carbon required for a rock to act as a source for hydrocarbons". Like Powell, we regard the TOC value as a secondary parameter in evaluating hydrocarbon generating potential, and place more emphasis on the yield of extracable hydrocarbons per unit weight of TOC.

Type

The type of dispersed organic matter was ascertained by a combination of chemical and petrographic (optical) methods. Its oil-prone versus gas-prone character at optimum maturity was measured against the hydrocarbon yield scale of Powell (1978). Yields of hydrocarbons (saturates plus aromatics) in excess of 80 mg per gram TOC signify excellent source potential for oil, whereas values in the ranges 50-80 mg per gram TOC and 30-50 mg per gram TOC indicate good and marginal oil potential, respectively. Rocks yielding less than 30 mg hydrocarbons per gram TOC are considered gas-prone. It should be noted that short-distance primary migration of hydrocarbons, such as might be expected to occur within porous carbonate sequences, may cause either depletion, or enhancement (through staining), of the indigenous hydrocarbon content. The type of kerogen was determined by plotting H/C and O/C atomic ratios on a modified van Krevelen diagram (Figure 10).

Several petrographic varieties of dispersed organic matter were recognised using white and fluorescence mode incident-light microscopy. These include:

1. alginite B (cf. Hutton *et al.*, 1980)
2. oil stain
3. bitumen
    1) reservoir bitumen (cf. Rogers *et al.*, 1974; Jacob, 1975)

    2) thucolite (cf. Jedwab, 1966; Schidlowski, 1969)
    3) bitumen balls
4. phytoplankton (acritarchs, ?*Tasmanites*)
5. liptodetrinite
6. algal mucilage.
7. fragments of graptolites (and ?chitinozoa) (cf. Kurylowicz *et al.*, 1976)
8. graphite.

Conventional petrographic nomenclature was inapplicable to the bulk of the dispersed organic matter because of its non-higher plant origin and the evaporitic affinity (i.e. marine sabkha and non-marine alkaline playa) of much of the Observatory Hill Beds.

Maturation State

In the absence of a suitable established scale, assessment of degree of thermal alteration was attempted using several complementary maturation-dependent parameters. Potential source rocks were designated immature, marginally mature or mature according to the proportion of hydrocarbons in their EOM (see Figures 8,9,14,15 & 19; cf. Powell, 1978). Some adjustment of Powell's suggested boundaries between the three maturation zones was necessary because of the markedly different organic matter and rock types encountered in the present study. Even so, a considerable spread was noted in the data from relatively narrow depth (and hence maturation) intervals. As with anomalous variations in hydrocarbon yield, this probably also is the result of short-distance migration. Another useful indicator of rank was the H/C atomic ratio of the kerogen, particularly where a complete elemental analysis permitted recognition of its type (see Figure 10).

Optical measurement of rank was based on fluorescence colours of alginite B and discrete phytoplankton, and the reflectance of various bitumens (cf. Sikander & Pittion, 1978) and possible graptolite fragments (cf. Kurylowicz *et al.*, 1976). The colour in transmitted light of microfossils (sphaeromorph acritarchs) and amorphous organic matter isolated from fresh core material by careful acid maceration provided supplementary information on the degree of thermal alteration of the Observatory Hill Beds at Byilkaoora-1, Wilkinson-1 and Murnaroo-1.

Flakes of detrital graphite (reflectance 4.2-11.4% R_o max) are common throughout the Devonian clastic sequence at Munyarai-1. Similar graphite in trace amounts was observed very rarely in the Observatory Hill Beds (viz. at Wilkinson-1, 656.32 m; Wallira West-1, 330.50 m; Byilkaoora-1, 240.90 m & 252.75 m). It is assumed to be reworked material derived from igneous and metamorphic basement rocks of the Musgrave and Gawler Blocks, and therefore is of no use in elucidating the thermal history of the sedimentary rocks in which it now occurs.

OBSERVATORY HILL BEDS

Geochemical data on TOC content, yield and composition of the EOM, and the elemental and isotopic composition of kerogen in the Observatory Hill Beds are presented in Tables 4 and 5.

Byilkaoora-1, Wilkinson-1 & Wallira West-1.

The Observatory Hill Beds penetrated at these three well localities (Figure 1) comprises predominantly fine-grained limestones and dolomites (Figure 2). Acid-insoluble residues are highest at Byilkaoora, reflecting the higher clay content of the carbonates which grade locally into argillaceous dolomite, and calcareous and dolomitic argillite and siltstone. Deposition in a marginal marine sabkha environment is envisaged for the carbonates at Wilkinson-1 and Wallira West-1, whereas the equivalent sequence at Byilkaoora-1 was deposited in a non-marine alkaline lake (Pitt *et al.*, 1980).

The TOC contents of the carbonates analysed fall in range 0.03-0.70%. Above average values (> 0.25%) are relatively common between 330 m and 345 m in Wallira West-1, 314 m and 514 m in Wilkinson-1, and in Unit 3 at Byilkaoora-1. The organic-rich intervals generally coincide with the darker carbonate colours logged by Lydyard (1979) and Benbow & Pitt (1979). Somewhat higher TOC values (0.32-0.96%) were obtained for calcareous and dolomitic argillites from Byilkaoora-1 (samples 59, 67, 70-72, 83 & 84, Table 4).

Figures 8 and 9 are plots of extract data which employ the diagrammatic technique of Powell (1978) to indicate maturation state and hydrocarbon-generating potential. They show that at Byilkaoora-1 and Wilkinson-1 the Observatory Hill Beds are marginally mature to mature. Although all but one of the samples were stained, it is reasonable to infer that the formation has attained a similar level of maturity at Wallira West-1. Some Byilkaoora samples also are stained. The geochemical identification of staining was confirmed by petrographic examination (see e.g. Table 8). In all cases the staining appears to be a result of short-distance primary migration *within* the carbonate sequence sampled, reflecting the close juxtaposition of source and reservoir facies. The majority of the Byilkaoora and Wilkinson samples analysed contain in excess of 30 mg hydrocarbons per gram TOC, indicating marginal to good source potential for oil. At Byilkaoora-1 these samples occur only in Unit 3; Unit 4 has poor source characteristics. Three micritic carbonates from Wilkinson-1 (viz. samples 23-25, Table 4 and Figure 9) yield more than 80 mg hydrocarbons per gram TOC and contain 0.6-0.7% TOC; these samples are rated as excellent potential source rocks for oil. Their EOM has a low asphaltene content (9-12%), in contrast to the EOM in good potential oil sources (samples 19, 26 & 30) which is much richer in asphaltenes (16-46%). This suggests that initial oil genesis in carbonate rocks may involve the disproportionation of asphaltenes into hydrocarbons and O, N & S bearing compounds. Notwithstanding their stained condition, the four organicrich (0.440.54% TOC) micrites from Wallira West-1 (samples 37-39, Table 4 and Figure 9) are regarded as mature, oil-prone potential source rocks.

Kerogen (or insoluble organic matter) in the oil-prone sediments of the Observatory Hill Beds is of either the Type I or Type II variety (Figure 10). Type I kerogen (atomic H/C = 1.19-1.37) appears to be characteristic of the non-marine carbonates and calcareous argillites at Byilkaoora, reinforcing the analogy between this Cambrian lacustrine sequence and that of the Eocene Green River Formation (see Tissot *et al.*, 1978). It has a high original H/C ratio, reflecting its strongly aliphatic character and high potential for the generation of oil and gas. Such kerogen is derived mainly from algal lipids or other organic matter reworked by heterotrophic bacteria and thereby enriched in microbial lipids. Unlike the Type I kerogen of the Green River Formation in the Uinta

Basin, Utah, which gives rise to highly paraffinic oils, Type I kerogen of the Observatory Hill Beds at Byilkaoora seemingly has generated naphthenic and aromatic-naphthenic oils. As already discussed, this may be due to a combination of the relative immaturity of the oils in question and their partial biodegradation. However, it is doubtful whether any of the oils from the Uinta Basin analysed by Tissot *et al.* (1978) were generated in units of the Green River Formation characterised by the kerogenous dolomitic marlstone-bedded evaporite association. The main oil-source beds identified by Tissot and coworkers are located below the so-called Middle Marker in that part of the Green River Formation comprising the Douglas Creek Member, Black Shale Facies and Flagstaff Member. These units lack oil shales and extensive bedded evaporites (Shanks *et al.*, 1976). It seems likely, therefore, that the Byilkaoora oils more closely resemble, in composition, mode of occurrence and genetic affinity, certain of the Uinta Basin asphaltic bitumens (notably, wurtzilite and gilsonite) found in joints, veins, fissures, crystal cavities and other pore space within and adjacent to lacustrine oil shales (Hunt *et al.*, 1954). Wurtzilite has a naphthenic composition (atomic H/C ≃ 1.60) and is rich in both sulphur and nitrogen-bearing compounds, whereas gilsonite (atomic H/C ≃ 1.45) is somewhat more aromatic in composition. The latter, because of its high solubility in organic solvents and probable generation from nacholite ($NaHCO_3$)-bearing oil shales of the Parachute Creek Member, appears to be the closest Eocene analogue of the Byilkaoora oils. Oils from fields with reservoirs in the Parachute Creek Member (Duchesne County and Roosevelt) or the underlying Douglas Creek Member

(Redwash) are exceedingly rich in the C_{13}-C_{20} acyclic isoprenoids (Reed & Henderson, 1972). Inspection of the gas chromatograms of their C_{12+} alkanes reveals that the C_{21}-C_{25} acyclic sesterterpanes probably also are present.

Type II kerogen is the dominant variety of insoluble organic matter in the *marine* sabkha carbonates of the Observatory Hill Beds at Wilkinson-1 and Wallira West-1. It has a lower H/C atomic ratio (0.86-1.06) than the Type I kerogen of the Byilkaoora sequence, and a correspondingly lower (but still considerable) oil potential. Moreover, the *marine* Type II kerogen is somewhat richer in sulphur (mean content, 4.3%) and, to a lesser degree, nitrogen (mean content, 1.67%) than is the *non-marine* Type I kerogen (mean S content, 3.3%; mean N content, 1.32%). As pointed out by Tissot & Welte (1978), Type II kerogen contains more aromatic and naphthenic rings, has a medium to high sulphur content, and usually is derived from the remains of marine organisms (phytoplankton, zooplankton, and bacteria) deposited in a reducing environment.

In terms of their petrography and carbon isotopic composition, there is little to distinguish the two major varieties of kerogen found in the carbonate-evaporite lithofacies of the Observatory Hill Beds. Petrographically, both are best described as lamellar alginite (i.e. alginite B, described in more detail below). Their carbon isotopic composition (^{13}C = -28.47 to -31.81^{o}/oo, Table 5) also is consistent with a lipid-rich algal-source. Kerogen isotopic values at the heavy end of the range (-28 to -30 ^{o}/oo) tend to be associated with evaporitic sediments, namely, carbonates and argillites containing pseudomorphs of trona and shortite from the lower part of Unit 3 at Byilkaoora, and gypsiferous micrites from the depth interval 270-440 m in Wilkinson-1. On the other hand, the isotopically lighter kerogens ($\delta^{13}C$ = -30 to -32 $^{o}/oo$) were isolated from sediments which petrographic examination showed to contain a significant amount of insoluble reservoir bitumen, thucolite or bitumen balls. Such "mobilised" organic matter characteristically is enriched in ^{12}C (Eichmann & Schidlowski, 1975).

The foregoing geochemical assessment of the maturity and oil-prone character of the organic-rich Cambrian micrites and argillites at Wilkinson-1 and Byilkaoora-1 is entirely consistent with the appearance in transmitted light of the dispersed organic matter isolated by maceration of rock chips in cold HCl and HF. The abundant organic matter is pale yellow to amber yellow in colour and mostly amorphous. Small microfossils (acritarchs) also occur but are rare (Muir, 1979; W.V. Preiss, pers. comm., 1979). According to Muir, the organic matter from Wilkinson-1 "forms sheet-like masses, up to several hundred microns across, which retains the impression of the fine-grained carbonate crystals which were present before maceration. Some of the organic matter has the fine, granular texture of cyanophyte mucilage, and some of it is smooth. Most of the amorphous organic matter is very similar in appearance to (that) from proven oil source rocks, such as the Kimmeridge Oil Shale of Dorset in England".

Further information on the origin and diagenetic alteration of the organic matter preserved in the carbonate-evaporite lithofacies of the Observatory Hill Beds is provided by gas chromatograms of their C_{15+} alkanes

(Figures 7, 11-13). The prominence of n-heptadecane (n-C_{17}) in most n-alkane distributions from the *marine* carbonates at Wilkinson-1 and Wallira West-1 is indicative of a primary algal source for the organic matter (Powell & McKirdy, 1973a), whereas uniformly low pr/ph values (0.42-1.58, Table 4) show that anoxic conditions prevailed during its deposition and early diagenesis (Powell & McKirdy, 1973b). The n-alkanes of some Wilkinson samples display a marked predominance of odd-carbon-numbered homologues over the range C_{15}-C_{30} (Figure 11). Probably this is a sign of relative thermal immaturity, although an odd-carbon-number preference in the C_{23+} n-alkanes is very unusual for sediments of Cambrian age. Such a feature generally is associated with organic matter derived from vascular plants and therefore is unexpected in pre-Devonian sedimentary rocks. Some alkane distributions, including those from Wilkinson-1 samples rated as excellent potential oil sources, have a prominent naphthene hump with a maximum near the n-C_{27} position (Figures 12 & 13). In such cases the n-alkane profile either is bimodal (maxima at n-C_{17} and n-C_{27}), or has a single maximum at n-C_{22} or n-C_{24}. These features may reflect a higher degree of anoxic reworking (i.e. sapropelization) of the primary algal debris by anaerobic bacteria, including sulphate reducers (Dembicki *et al.*, 1976; McKirdy, 1977).

Apart from the lack of a prominent n-C_{17} component, and any appreciable odd or even-carbon-number preference in their n-alkanes, the C_{15+} alkane distributions of the *non-marine* Byilkaoora (Unit 3) extracts are distinguished by an unusually high concentration of the acyclic C_{15}-C_{25} regular isoprenoids and the C_{30} irregular isoprenoid, squalane (Figure 7). The same extended isoprenoid homology apparently is present in the alkanes of some of the *marine* sabkha carbonates at Wilkinson-1 and Wallira West-1 (Table 4), but in much lower concentration relative to the n-alkanes (Figures 11-13). The C_{15}-C_{20} regular isoprenoids occur ubiquitously in ancient sediments (including coals) and crude oils. Their most likely origin is *via* the diagenesis and catagenesis of phytol, the diterpenoid (C_{20}) alcohol which forms an ester-linked side-chain in the photosynthetic pigment, chlorophyll *a*. The C_{21}-C_{25} regular isoprenoids have been reported less widely. Spyckerelle *et al.* (1972) documented their occurrence in a Cretaceous shale and concluded (p. 5703) that they "may be formed by diagenetic maturation and fragmentation either of polyprenols, or of naturally occurring acyclic sesterterpenoids". Squalane, also present in the shale, was ruled out as a possible precursor because of its irregular "tail-to-tail" structure. Sesterterpenoid (C_{25}) alcohols are known from fungi, leaves, and insect wax (Tissot & Welte, 1978), but none of these sources is plausible for the acyclic sesterterpanes preserved in Cambrian evaporitic sediments. Although unable to propose a specific biological precursor for the regular C_{25} isoprenoid alkane, Waples *et al.* (1974) suggested that it may be useful as a geochemical indicator of lagoonal, hypersaline conditions on the basis of its occurrence in significant concentrations in Tertiary sediments known to have been deposited in such an environment. More recently, Tornabene *et al.*, (1978) and Holzer *et al.* (1979) reported the identification of squalene and other high molecular-weight isoprenoid compounds in the lipids of a newly recognised group of primitive halophilic, thermoacidophilic and methanogenic bacteria, the so-called archaebacteria (Woese *et al.*, 1978). We conclude that similar halophilic and methanogenic bacteria were an integral part of the microbial ecosystem inhabiting the hypersaline, highly reducing environments in which the non-marine (Byilkaoora) and marine (Wilkinson, Wallira West) evaporitic sediments of the Observatory Hill Beds were deposited. Their organic input to the sediments was particularly high at Byilkaoora.

Murnaroo-1, Emu-1 & Birksgate-1

Basinward of the Karari Fault, at the Murnaroo-1 and Emu-1 well localities, and to the immediate south of the Musgrave Block at Birksgate-1 (Figure 1), the proportion of carbonate rocks in the Observatory Hill Beds decreases at the expense of shale and siltstone (Figure 2). The palaeoenvironmental significance of this changed lithofacies association is not clear. Nonetheless, the episodic influx of clastic sediments to the (?)marine environment is associated with generally lower TOC values (0.03-0.33%, Table 4), an indication that stable anoxic conditions conducive to the preservation of sedimentary organic matter were less prevalent. The highest values in the range were obtained from calcareous and dolomitic siltstones. Within the carbonate intervals, unlike those at Byilkaoora-1, there is little evidence of periodic intense evaporation, lowering of the water table, and consequent widespread sealing of underlying organic-rich sediments by crusts of carbonate and Magadi-type chert, although there are limited occurrences of the latter at Murnaroo-1 and Emu-1 (Figure 2).

Hydrocarbon yields also are low (mostly <30 mg/g TOC) and, in general, hydrocarbons comprise <30% of the EOM, indicating that the sediments at best are only marginally mature (Figures 14 & 15). Even if more deeply buried elsewhere, or exposed to a higher geothermal gradient, it is doubtful whether this particular lithological development of the Observatory Hill Beds would be capable of generating appreciable amounts of liquid hydrocarbons. Marginal oil-source potential is displayed by the several samples from Murnaroo-1 which contain >30 mg hydrocarbons per gram TOC (Figure 14), but its significance is diminished by the very low TOC contents (<0.2%) of the sediments in question.

The C_{15+} alkane distribution patterns of non-reservoir rocks in the Murnaroo, Emu and Birksgate well sections of the Observatory Hill Beds (Figures 16-18), reflect the microbial affinity of their dispersed organic matter. In most cases the n-alkane profile has a maximum in the C_{17}-C_{19} region, and the majority of the alkanes contain less than 23 carbon atoms, consistent with a predominantly algal origin (Powell & McKirdy, 1973a). A significant imput from heterotrophic bacteria may be inferred for those samples with a relatively high proportion of C_{23+} alkanes (Figure 18) and/or the C_{18}-C_{20} acyclic isoprenoid alkanes (Figures 16 & 18) (McKirdy, 1977; Reed, 1977). At Murnaroo, the progressive increase in pr/n-C_{17} and ph/n-C_{18} ratios shown by core samples 23-25 (Table 4, Figure 16) correlates well with an increase in their carbonate content as determined by acid digestion (sample 23, 22%; sample 24, 35%; sample 25, 58%). The extended isoprenoid homology in sample 43 from Emu-1 (Figure 17) is reminiscent of the hydrocarbon "finger-print" of halophilic and/or methanogenic bacteria noted in Unit 3 at Byilkaoora-1

(Figure 7), and in certain carbonates from Wilkinson-1 (Figures 11 & 12) and Wallira West-1 (Figure 13), and signifies deposition under anoxic, probably hypersaline conditions. The relative immaturity of the Birksgate samples (Figure 18) is confirmed by the slight predominance of odd over even-carbon-numbered C_{23+} n-alkanes and the presence of a prominent "naphthene hump" in the sterane/triterpane region of each chromatogram.

Reliable analytical data are not yet available on the elemental composition, and hence the type(s), of kerogen preserved in the Observatory Hill Beds at these three well localities. Without such information it is difficult to ascertain whether or not the poor oil potential of the sediments is attributable entirely to their lack of thermal maturity.

UN-NAMED DEVONIAN FORMATION

Conoco wildcat well, Munyarai-1 (Figure 1), penetrated a thick sequence of Devonian marine shale, sandstone and minor carbonate (Figure 2). TOC values are uniformly low (0.19-0.33%) throughout the sequence (Table 7). Only in the bottom sample analysed (TOC = 0.47%) does the organic carbon content approach the average for shales. Extract data plotted in Figure 19 show that the upper 2300 m of section is immature. This is consistent with the odd carbon-number predominance displayed by the waxy C_{23+} n-alkanes in core sample 44 from 632.20 m depth (Figure 20). Optimum maturity for oil generation is attained below 2500 m, but hydrocarbon yields are low (<15 mg/g TOC) indicating no oil-source potential. The presence of detrital graphite ("dead" carbon) throughout the sequence (Kantsler, 1979) will tend to depress the measured hydrocarbon yield (expressed as milligrams by hydrocarbons per gram of TOC). The ratio of pristane to phytane increases only slightly with depth, from 0.82-0.96 in the immature part of the well section above 2300 m, to 1.00-1.58 in the zone of maturity (Table 7). The wet-gas prone character of the sediments accords with the humic nature of the palynological preparations examined by Harris (1978) and Vlierboom (1973), but is somewhat at odds with the appearance of the dispersed organic matter in polished section (see below). Partial analysis of the insoluble organic matter isolated from core sample 51 (2610.61 m depth: percent C, dry ash-free, = 82.53%; atomic H/C = 0.82), given its apparent initial maturity, is suggestive of a kerogen which plots between the maturation pathways for Type II and Type III organic matter on a van Krevelen diagram.

ORGANIC PETROLOGY, OBSERVATORY HILL BEDS

Several types of organic matter are present in the Observatory Hill Beds. A review based on the examination of core material from Byilkaoora-1, Wilkinson-1, Wallira West-1, Murnaroo-1 and Emu-1, is presented below. Detailed observations on individual samples from Byilkaoora-1 are summarised in Table 8.

Alginite B (Plates 2.1 & 2.2)

This is a term introduced by Hutton *et al.* (1980) to encompass the fine lamellar organic matter which constitutes the bulk of the organic content of Tertiary oil shales (e.g. Rundle, Queensland; Green River, Wyoming). This algal material corresponds to the "algal filaments" described by McKirdy & Kantsler (1978) in the Kyalla Member of the 1600 m.y. McMinn Formation, McArthur Basin, and the "translucent red-brown stylolitic films" reported previously from Cambrian carbonates of the Officer Basin (Kantsler, 1979). That this organic matter is algal in origin seems virtually unequivocal as there is no other group or organisms so wide ranging in time.

In hand specimen, layers rich in alginite-B are most conspicuous in the well laminated carbonates of Byilkaoora and Wilkinson. Typically the layers are thin (1-5 mm thick), have a dark grey or brown colour, and are associated with very fine-grained argillaceous or micritic mineral matter (<10 μm across) and pyrite. The paler layers of the carbonates are coarser grained (up to 20-30 μm), barren of organic matter and contain relatively little pyrite.

In polished section under incident white light, alginite-B is translucent and has a pale brown or red-brown colour. Fluorescence colours range from moderate orange or light brown to dull orange and dull brown. The intensity and colour of the fluorescence is partly (although not entirely) dependent on the thickness of the individual films or strands, with thicker strands usually being associated with an intense fluorescence. In general, prolonged irradiation causes a positive colour shift but instances of negative colour shift also have been observed. The fluorescence intensity of the alginite invariably is enhanced around grains of thucolite. Unlike the McMinn alginite, which locally occurs in sufficient density to lose its translucence and become more reflecting, the alginite in Cambrian sediments of the Officer Basin always is translucent.

Some thick strands of alginite range from 0.2 mm to 20 mm in length, while thin individual films generally are less than 20 μm in length. The strands may be as much as 5 μm thick, but only where several individual films occur together without intervening mineral matter. Individual films are rarely more than 2 μm, thick. In some samples, particulate algal material less than 5 μm in length is referable to liptodetrinite. The alginite content of the samples examined generally falls in the range 0.5-5% by volume, but any estimate must be regarded as approximate because of the fineness of the individual films.

A feature of the alginite is the manner in which it is finely interwoven with carbonate and argillaceous mineral matter. The alginite films tend to follow grain boundaries in the plane of the bedding (or sub-parallel with it), and commonly can be seen to form a web of organic matter such as might be expected from an algal mat. Gross lamination of the rock suggests a succession of seasonal or other episodic events and also indicates the absence of infaunal benthos. In the more coarsely grained carbonates this "lamellar" alginite becomes very cryptically interbedded with mineral matter so that discrete layers of algal mat are difficult to discern. Organic intergranular matrix material in these sediments is very fine grained and recognised by a diffuse yellow fluorescence suggesting its adsorption onto clays. Locally this particular form of organic matter may be described as amorphous although it too almost certainly is of algal origin. Both forms of 'alginite-B' are the 'amorphous sapropel' of palynologists and organic geochemists.

The algal organic matter is typically associated with pyrite. Micropyrite is the most prevalent form, particularly in the Byilkaoora samples, but framboids are common. Granular and semi-crystalline aggregates of pyrite are more typical of organically barren zones.

Oil Stain (Plates 2.3-2.5)

Many carbonates and calcareous mudstones contain an oil stain which fluoresces a very bright green to bright orange. Typically, this oil stain is found in the coarsely crystalline carbonate which infills vugs and forms veins. The same live oil also is associated with fractures of varying width. Commonly the stain can be seen to originate in the alginite-B described above. When viewed under white incident light the stain appears colourless and featureless in the coarser grained carbonates, whereas in the associated fractures it may have a dull brown colour.

In many Byilkaocra samples the orange-fluorescing and bright green or yellow-fluorescing oil stains appear to be quite separate. The bright green variety occurs mostly in fractures, but also in intercrystalline spaces in vugs, whereas the orange variety usually is found in vugs. Locally, however, they may be intermixed. The bright orange stain may represent the heavy aromatic-napthenic oil (Family A, or biodegraded Family B), with the bright green variety being related to the lighter naphthenic oil of Family B. Alternatively, the orange stain may be "old" oil, generated at an early stage and subsequently biodegraded; whereas the green stain may be considered "new" or migrated oil, derived from the same source material but at a later stage.

Bitumen

Three classes of bitumen were recognised:-

Reservoir Bitumen (Plate 2.6)

Bitumens of this type occupy large cavities in coarsely crystalline vugs, calcite pseudomorphs after evaporite minerals, and veins. Their reflectance (generally 0.5-0.8%, but also up to 1.4%), insolubility in immersion oil, lack of

fluorescence and nonporous appearance suggest that they are referable to the asphaltite *grahamite* or the asphaltic pyrobitumens *albertite* and, in the case of the higher reflectance varieties, *epi-impsonite* (Jacob, 1975). These bitumens range in size from <10 µm at Wilkinson to 200 µm at Byilkaoora. They are present in only minor amounts and commonly comprise <1% of the total organic matter by volume. Large "cauliflower-shaped" aggregates of bitumen present in various Byilkaoora samples (notably at 285.00 m, 289.77 m, 306.15 m and 312.30 m depth) are enigmatic in that their rounded margins bear little relation to the fabric of the rock in which they occur. Kantsler (1979) has suggested that individual "balls" of bitumen (see below) may owe their formation to the precipitation of an asphaltene fraction at surface temperature and pressure, but the lack of relief in polished section and the need to displace rigid mineral matter seem to preclude this as an explanation for the genesis of the "cauliflower" aggregates.
Thucolite (cf. Jedwab, 1966; Schidlowski, 1969).

Small granules of "bitumen" commonly occur mantling small crystals or fragments of metamict zircon. This bitumen appears to be composed of polymerised hydrocarbons and alginite. Individual thucolites range from 5 µm to 100 µm in diameter. Lamellar alginite can be seen merging with the thucolite, but this may be fortuitous. The fluorescence of such alginite generally is enhanced in the vicinity of the thucolite grain. Thucolites are characterised by high reflectance, non-fluorescing cores, and by lower reflectance, slightly fluorescing halos, suggesting that they are not strictly comparable to the reservoir-type bitumens described above. Despite their ubiquity, thucolites form a very small proportion of the total organic matter.

"Bitumen Balls" (Plates 2.7 & 2.8)

Spherical aggregates of bitumen occur that are analogous to thucolite but show no evidence of having a central uraniferous core. Their reflectance ranges from 0.5% to 1.1%. Some of these bitumens have a honey-brown fluorescence, whereas others are non-fluorescing. There is little enhancement of alginite fluorescence around these apparently non-radiogenic bitumen balls. Like the thucolites, they are present in most samples, but only in very minor quantities.

Phytoplankton

Very small bodies of bright yellow or bright orange fluorescence probably represent the cysts of microplanktonic organisms (acritarchs). They are extremely small (5-10 μm across in longitudinal section) and appear to be very thin walled (<1 μm). Although present in many samples they cannot be considered common. They reach local eminence in the Byilkaoora sample from 306.15 m depth. In incident white light they are translucent and have a very pale amber colour. Acritarchs have been isolated by maceration techniques from micritic carbonates and calcareous siltstones of the Observatory Hill Beds in Wilkinson-1, Murnaroo-1 and Byilkaoora-1 (Muir, 1979; W.V. Preiss, pers. comm.).

Liptodetrinite

This term embraces all finely particulate organic matter of indeterminate origin which is visible in small amounts in nearly all of the samples examined. It encompasses fragments of lamellar alginite, acritarchs and small "spots" (2-3 μm across) of probable oil stain. In no sample is it a significant component of the total organic matter.

Algal Mucilage

This material occurs in short (0.03 - 0.07 mm) laths of chitinous carbonate, 5-10 μm thick, which are translucent and cream to dark brown in colour. The carbonate laths, previously described as 'fragmented chitinophosphatic shell material' (Kantsler, 1979), appear to represent brecciated laminae of cryptalgal carbonate perfused with humic organic matter derived from the mucilage of benthonic blue-green algae (cf. Shearman & Skipwith, 1965; McKirdy, 1976). Partial replacement of the carbonate by pyrite is common, although in one notable case (Byilkaoora-1, 240.90 m) the sulphide is sphalerite.

DISCUSSION

Alginite-B is the most likely source material for the oil shows in the Byilkaoora-1 well. Although overall concentrations are not high, it can form up to 20% by volume of some organic-rich layers (the dark laminae observed in hand specimen), and up to 10% of some rock samples (e.g. Byilkaoora-1, 316.50 m). Its translucence and bright fluorescence, together with the fluorescence colours observed for the acritarchs, suggest an upper maturation limit equivalent to a vitrinite reflectance of 0.8% R_o. The petrographic features observed are characteristic of "liptinitic" organic matter (kerogen Types I and II) in the range 0.5-0.8% R_o, which corresponds to its initial phase of oil generation.

THERMAL AND MATURATION HISTORY

MUNYARAI-1

Organic Matter Type

Table 9 shows the results of maturation studies using optical methods undertaken on core material from Munyarai-1.

Reflectance measurements were made on a variety of bitumens and possible graptolite fragments (cf. Kurylowicz *et al.*, 1976). The identification of the graptolites is, at best, tentative because of the very small size of the fragments. Another possible source of this material is chitinozoa. Intact chitinozoans were identified in macerates of sandstone and silty shale from three cores by Harris (1968). No positive identification yet has been made in polished section of land plant-derived organic matter, which is surprising in view of the recovery of tracheidal wood fragments by Harris (1968) and higher plant palynomorphs by Vlierboom (1973) using maceration techniques.

Low reflectance bitumens occur in small pore spaces, among carbonate crystals in healed fractures, or along stylolitic partings. These bitumens are insoluble in immersion oil, non-porous, homogeneous and, in some rare instances, display a low-intensity fluorescence. They appear to be referable to the asphaltic pyrobitumen, *albertite*, which forms *in situ* by localised diagenetic processes (Rogers *et al.*, 1974). Higher reflectance bitumens (1.6-2.2% R_o), generally found as rounded to sub-rounded balls (cf. Plates 2.7 and 2.8), also are present in some samples (Table 8). Their high reflectance indicates that they may be similar to the asphaltic pyrobitumen, *impsonite* (a more mature version of *albertite*). The reflectance of these bitumens is unreliable for the determination of thermal maturity since bitumens are readily and continuously generated during the migration of hydrocarbons from source rocks. However, Sikander & Pittion (1978) have described significant downhole increases in bitumen reflectance in Early Palaeozoic rocks from Gaspe Peninsula, Quebec.

Examination of the samples in fluorescence mode reveals:-

1. the presence of some large phytoplankton *(? Tasmanites)* with strong gold fluorescence, and lamellar alginite with very pale yellow to pale brown fluorescence, in the uppermost sample at 634.1 m ;
2. rare, bright orange (?)acritarchs in samples from 1693.09 m, 2289.71 m and 2441.08 m;
3. abundant bright orange liptodetrinite (?fragments of phytoplankton) in samples at 2611.61 m and 2753.43 m; and
4. some strong orange fluorescence, of undefined affinity, at 2897.30 m.

None of the samples examined contains sufficient organic matter to be called a source rock. Although, liptodetrinite is abundant in some samples, it is generally so fine that it does not comprise a significant volume of the rock.

Maturation History

The present-day temperature gradient at Munyarai-1 is low - about 19.6°C/km based on an uncorrected bottom-hole temperature (BHT) of 76.6°C at 2896.3 m. Application of the 10% rule of Dowdle & Cobb (1975) gives a corrected BHT of 86°C and a temperature gradient is 22.8°C/km. Estimates of coalification at the 2286.6 m (7500 ft.) and 2896.3 m (9500 ft.) level, assuming no pronounced post-Devonian uplift or erosion (i.e. a coalification time of 350 m.y.), are given in Table 10. Section loss at Munyarai-1 is thought to be of the order of 200-300 m (G.M. Pitt & B.C. Youngs, pers.

comm.)

Vitrinite reflectances estimated from the combined effects of temperature and time, according to the Karweil nomogram (as modified by Bostick, 1973) are close to the observed reflectance from (?)graptolite fragments and high reflectance bitumens (Table 8). However, both the estimated and measured reflectance do not appear to agree with the fluorescence characteristics noted in these samples and tend to confirm the opinion that graptolite-derived reflectances (Kurylowicz *et al.*, 1976) are a little high when compared to the equivalent vitrinite reflectance.

The fluorescence colours assocated with (?)phytoplankton-derived organic matter indicate vitrinite reflectances in the range 0.6%-1.0% R_o by analogy with some Late Palaeozoic sequences from Western Australia. These values correspond with those obtained from the low reflectance bitumen and are slightly lower than those derived from the (?)graptolites.

The estimates of vitrinite reflectance based on the model of Hood *et al.* (1975) indicate that the lower part of the Devonian section is at least marginally mature and possibly near the zone of peak hydrocarbon generation. The approach of Lopatin (1976) yields results within the limits provided by the Karweil and Hood *et al.* estimates. The estimated vitrinite reflectances obtained by all three methods imply that formation temperatures never have been much higher than their present values (Table 9).

Assessing both the measured and calculated data, realistic limits to maturation (expressed in terms of equivalent vitrinite reflectance) for the lower part of the Devonian sequence are 0.6-1.2% R_o. This straddles the initially mature (oil) zone of hydrocarbon generation and enters the mature (wet gas) zone. Thus a long, slow period of continuous hydrocarbon generation at relatively low temperatures similar to those found at present is envisaged for the Devonian sequence at Munyarai-1. Such a maturation history would favour the formation of small, rather than large, hydrocarbon accumulations.

BYILKAOORA-1

The Byilkaoora-1 section is thought to have been buried to a depth of at least 2500 m (G.M. Pitt & B.C. Youngs, pers. comm., 1979) but is now within 350 m of the surface. Up to 2000 m of this missing section is presumed to have been of Ordovician age whereas the remainder is likely to have comprised Devonian sediments. Assuming a full 2500 m of cover and that the temperature gradient has remained at about 20°/km, a palaeotemperature high of about 80°C can be envisaged for the Observatory Hill Beds. However, taking into account post-Ordovician erosion, the maximum temperature over any prolonged period of time was probably of the order of 50°C to 60°C.

Burial, during and immediately after Ordovician deposition, at a temperature of 70°C to 80°C for a minimum period of 50 m.y. would, according to any of the three models listed in Table 9, be sufficient to bring the Observatory Hill Beds at Byilkaoora to the earliest stages of oil generation. Post-Ordovician burial at temperatures of 50°C to 60°C would add to the initial coalification and could possibly bring the rocks to a maturation stage equivalent to 0.8% to 1.0% vitrinite reflectance. Declining temperatures (<50°C) during the subsequent phase of burial would do little to enhance maturation despite the great length of time available.

Bitumen reflectance in the range 0.55% to 1.30% R_o, together with the fluorescence colours of lamellar alginite, suggest equivalent vitrinite reflectances of about 0.8% ± 0.2% R_o - the same range as indicated by model data. These data suggest that the Cambrian sequence intersected by Byilkaoora-1 is oil-mature.

WILKINSON-1

The Cambrian section in Wilkinson-1 is enigmatic in that although it appears to have attained thermal maturity, the poorly consolidated nature of the sediments in the upper part of the section implies that it has almost certainly never been deeply buried.

However, the proximity of the Karari Fault (Figure 1), and the possibility of vertical migration of hot subterranean water along the fault, suggest that it may not be necessary to invoke deep burial to explain this anomaly. High temperature regimes have been observed around many deep-seated faults and result from either compaction or temperature-induced lateral density gradients (Buntebarth & Schopper, 1976). Prolonged exposure to temperatures of about 50°C would probably be sufficient to bring the Cambrian rocks at Wilkinson to initial maturity.

WALLIRA WEST-1, MURNAROO-1 & EMU-1

Limited fluorescence and reflectance data from these wells, when reviewed in relation to the data above, indicate that their Cambrian sections also are mature.

However, extract data from Emu-1 and Murnaroo-1 suggest a lower degree of maturity. The Cambrian carbonates at Wallira West-1 may be slightly more mature than those at Wilkinson-1, having undergone a two-phase thermal history. In addition to their exposure to an enhanced heat flow near the Karari Fault, the Observatory Hill Beds at this locality probably have been buried under an additional 200 m of Early Permian cover and >100 m of Cretaceous sediments, subsequently removed during separate erosional episodes along the western margins of the Arckaringa and Eromanga Basins, respectively (Figure 1). This may account for the two optically-distinct generations of oil stain associated with the lamellar alginite in samples 36 and 39 (Table 4).

SUMMARY AND CONCLUSIONS

1. Oil shows found within the Early Cambrian Observatory Hill Beds at Byilkaoora-1 in the northeastern Officer Basin are of two primary genetic types: aromatic-naphthenic and naphthenic. The former are heavy ($\sim 15^{o}$API), low sulphur ($\sim 0.3\%$ S), tar-like crudes, whereas the latter are less viscous and of apparently higher API gravity. Both types are immature, possibly partially biodegraded oils, rich in the regular C_{15}-C_{25} acyclic isoprenoid alkanes and the irregular C_{30} isoprenoid, squalane. In some shows the original composition of the oil has been substantially modified by migration (depletion of asphaltenes), or by severe biodegradation (complete removal of normal and branched alkanes).

2. The oils occupy vugs and partly healed fractures in an alkaline playa-lake sequence of bituminous carbonate with Magadi-type chert, and argillite which contains calcite pseudomorphs of evaporite minerals, including trona, shortite and ?gaylussite. Source and reservoir facies are intimately related.
3. The source beds for the oils are organic-rich (0.5-1.0% TOC) dolomites and calcareous argillites within the lacustrine evaporitic facies that were drilled. A two-fold stratigraphic zonation of geochemically distinct source beds accounts for the existence of two primary families of oil. The aromatic-naphthenic group of oils is correlated with sediments in which trona and shortite were most abundant. Sodium carbonate-bicarbonate evaporites were less common in the source beds of the naphthenic oils.
4. The Byilkaoora oils are the first reported examples of *non-marine* Cambrian oils. Their composition, mode of occurrence and genetic affinity are similar to certain oils and asphaltic bitumens associated with oil shales and bedded evaporites in the Parachute Creek Member of the lacustrine Eocene Green River Formation, Uinta Basin, Utah.
5. Marginally mature to mature, good to excellent potential hydrocarbon-source beds occur within the Observatory Hill Beds at the Wilkinson-1 and Wallira West-1 well localities, adjacent

to the Karari Fault along the southeast margin of the Officer Basin. Here organic-rich (up to 0.8% TOC), oil-prone micrites were deposited in a *marine* sabkha environment. By contrast, the shale-siltstone lithofacies of the Observatory Hill Beds penetrated by the Murnaroo-1, Emu-1 and Birksgate-1 wells is characterised by low organic carbon contents and hydrocarbon yields, and at best only marginal maturity.

6. Kerogen in the oil-prone sediments of the Observatory Hill Beds is either Type I or Type II. Petrographically, the major component of both liptinitic kerogens is lamellar alginite (the alginite- of Hutton *et al.*, 1980). Likely precursor materials include the lipids of benthonic algae (probably blue-greens) and heterotrophicteria.
7. The acyclic C_{15}-C_{25} isoprenoid alkanes and the irregular C_{30} isoprenoid, squalane, present in high relative concentrations in the Byilkaoora oils and their source rocks, may be biological markers of heterotrophic halophilic and/or methanogenic bacteria.
8. Extract data from the thick succession of Devonian marine shale, siltstone, sandstone and minor carbonate penetrated by Munyarai-1, the deepest well so far drilled in the eastern Officer Basin, indicate that although optimum maturity for oil generation is attained below

2500 m, the sediments mostly are gas-prone.

9. In the absence of recognizable higher plant residues (e.g. vitrinite) in the dispersed organic matter, optical measurement of rank was based on fluorescence colours of alginite-B and rare phytoplankton, and on the reflectance of ?graptolite fragments in the case of the Devonian sediments. With the possible exception of the Observatory Hill Beds at Murnaroo-1 and Emu-1, the optical estimates of rank agree reasonably well with the levels of maturity determined from extract data. Contrary to the experience of Sikander & Pittion (1978), bitumen reflectance proved to be an unreliable indicator of thermal alteration, mainly because of the diversity of bitumen types and modes of origin represented.

10. The reconstructed burial histories of the Cambrian Observatory Hill Beds at Byilkaoora-1, and of the Devonian sequence at Munyarai-1, are adequate to account for their present level of maturation. The Cambrian carbonate section in Wilkinson-1, however, probably never has been deeply buried and enhanced heat flow along the Karari Fault is invoked to explain its position within the upper oil window.

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DMMcK,AJK:AF

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LIST OF CAPTIONS TO PLATES

Plate 1: Oil shows in Observatory Hill Beds, Byilkaoora-1. Core diameter 47 mm.

1. Oil (Family A') bleeding from fracture partly healed with calcite and adjacent calcite-lined, pyrite-containing vug, in red-brown siltstone (219.52 m).
2. Oil (? Family B) bleeding from small vug in cryptalgal laminated dolomite (297.15 m).
3. Oil (? Family B, biodegraded) bleeding from vug in dolomite (295.50 m).
4. Oil (Family A) filling large vug in dolomite (293.17 m).

Plate 2: Photomicrographs of polished sections (perpendicular to bedding) of carbonates from Observatory Hill Beds, taken using incident illumination (oil immersion). Fluorescence-mode photography employed a 490 nm barrier filter. Field width 0.34 mm unless otherwise stated.

1. Anastomosing lameller alginite and mineral grains. Byilkaoora-1, 316.50 m. Fluorescence mode, field width 0.23 mm.
2. Fine, weakly fluorescing, lamellar alginite (dull brown to yellow) in matrix of marl. The very thin discontinuous band of fluorescence appears to be an oil stain in the earliest stage of primary migration. The small, thin yellow bodies in the lower field of view may be acritarchs. Byilkaoora-1, 306.15 m. Fluorescence mode.
3. Oil stain in vuggy carbonate showing strong orange fluorescence and possibly representing the heavy, aromatic-napthenic oil type. Surrounding coarse carbonate grains are associated with a very strong gold fluorescence from lighter (? naphthenic) oil trapped below the polished surface. Byilkaoora-1, 262.95 m. Fluorescence mode.

4. As for Plate 2.3. The bright 'flecks' in the heavy oil may be sulphides precipitated by sulphate-reducing bacteria. White light.

5. Exsudatinite-like material filling fracture. Migration 'pathways', similar to that figured in Plate 2.2, commonly merge with, or cut across, such fractures suggesting a bulk-flow mechanism for primary migration in the Byilkaoora carbonates.
Byilkaoora-1, 306.15 m. Fluorescence mode.

6. Reservoir bitumen, probably the asphalite grahamite ($R_o$max = 0.54%) filling porosity in carbonate vug. Such bitumens may be formed by the degradation of oil like that illustrated in Plate 2.3, possibly by inspissation and water-washing.
Byilkaoora-1, 285.00 m. White light.

7. Bitumen 'ball', with halo of gold fluorescing organic matter, in micritic dolomite. In many Early Palaeozoic rocks, strands of lamellar alginite merge into such 'balls'. Bitumen 'balls' with a core of zircon or some other uraniferous mineral are referable to thucolite. Decreasing reflectance, and increasing fluorescence, from centre to margin indicate that the cores of these balls

may be older and more coalified than their outer rims. This implies a continuous process of hydrocarbon polymeritization and accretion. Wilkinson-1, 512.07 m. Fluorescence mode.

8. As for Plate 2.7. $R_o$max = 0.7% at centre; 0.5% at rim. Rare, fine, dark brown strands surrounding the 'ball' are lamellar alginite. White light.

PLATE 1.1

PLATE 1.2

PLATE 1.3

PLATE 1.4

PLATE 2.1

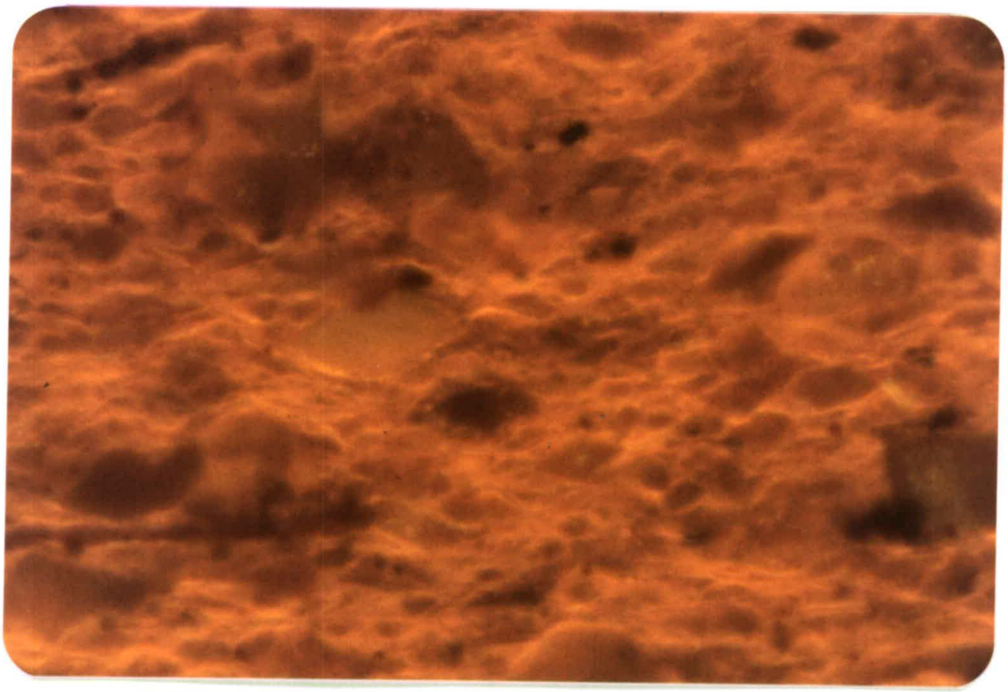

PLATE 2.2

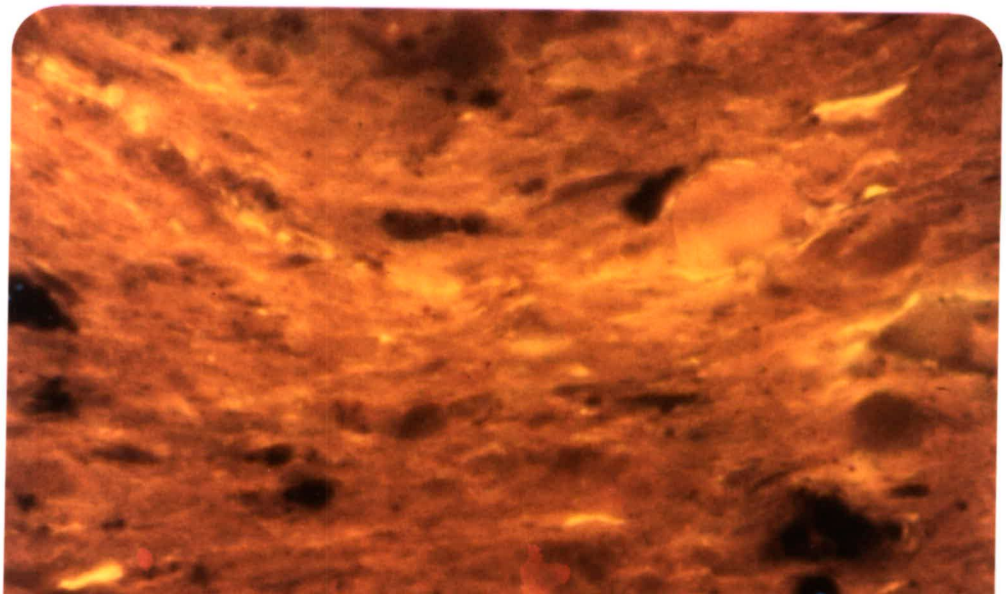

PLATE 2.3

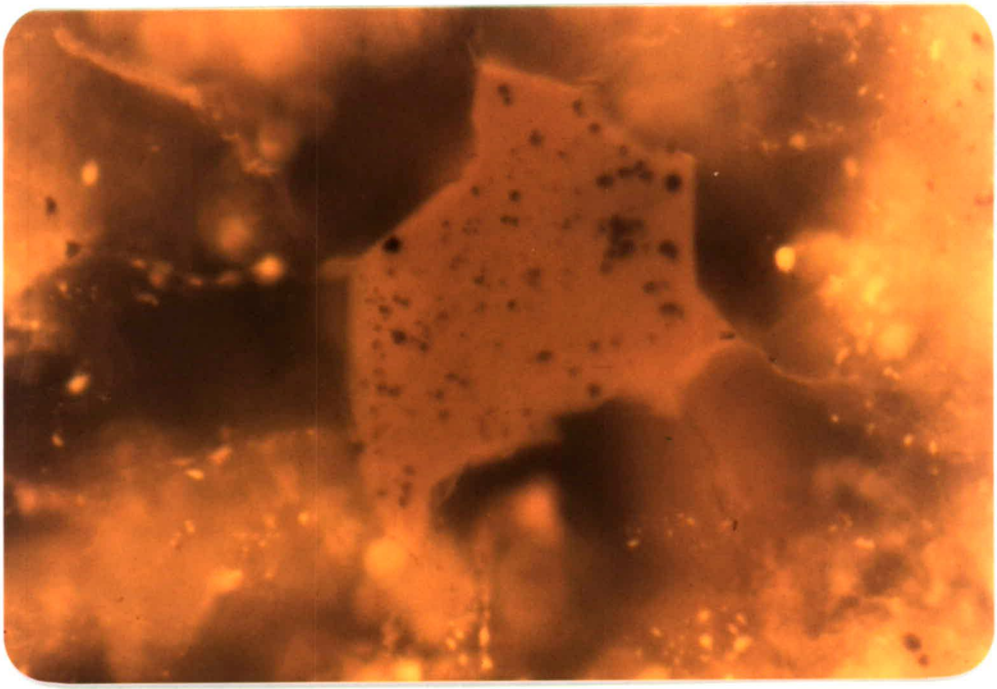

PLATE 2.4

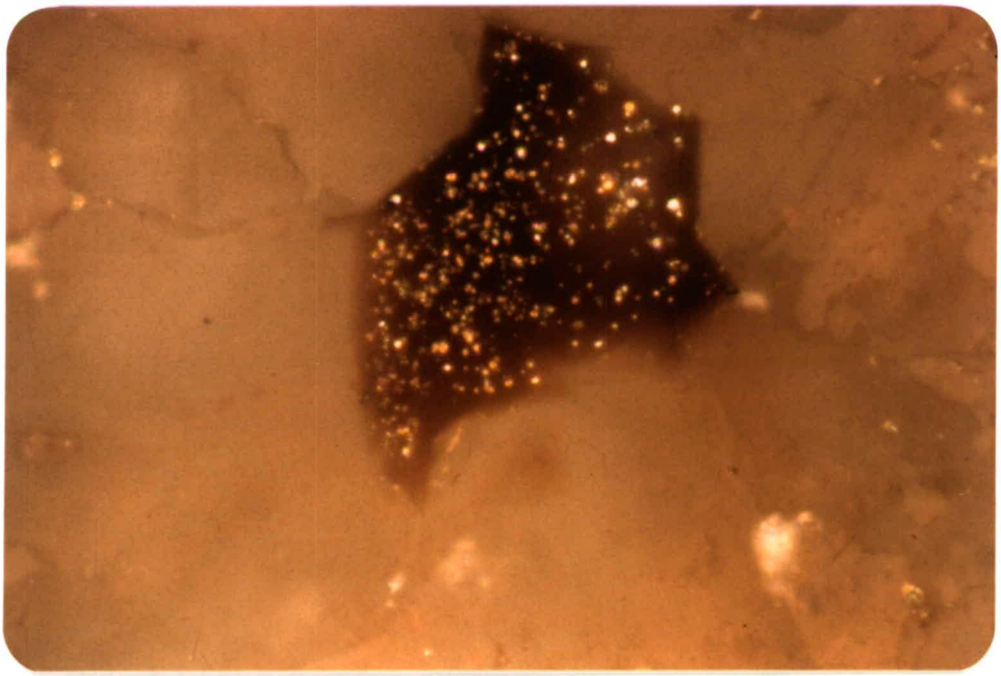

PLATE 2.5

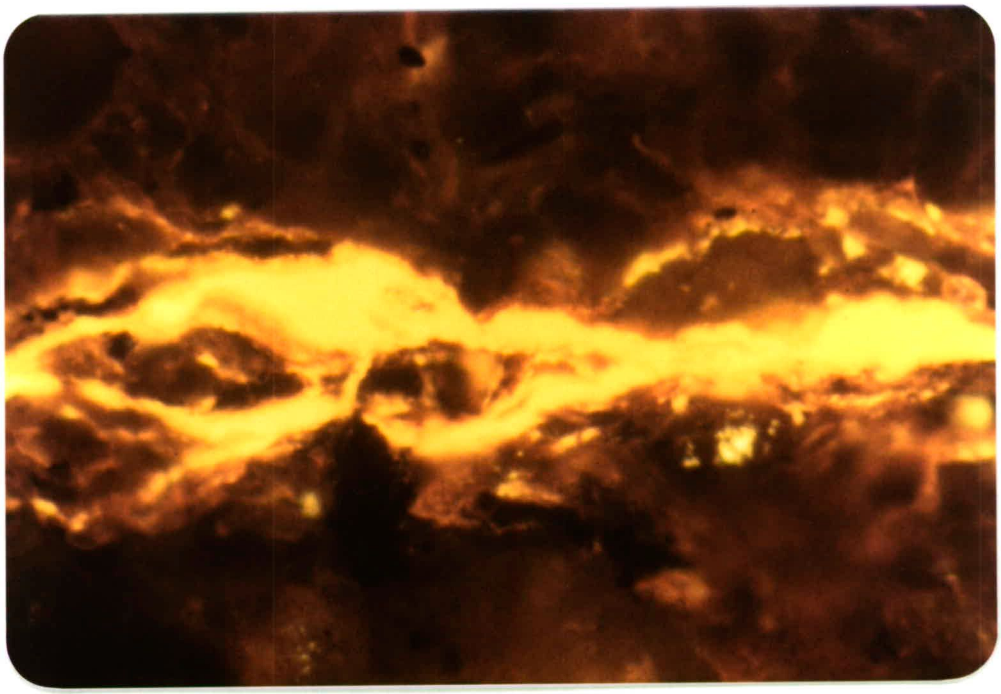

PLATE 2.6

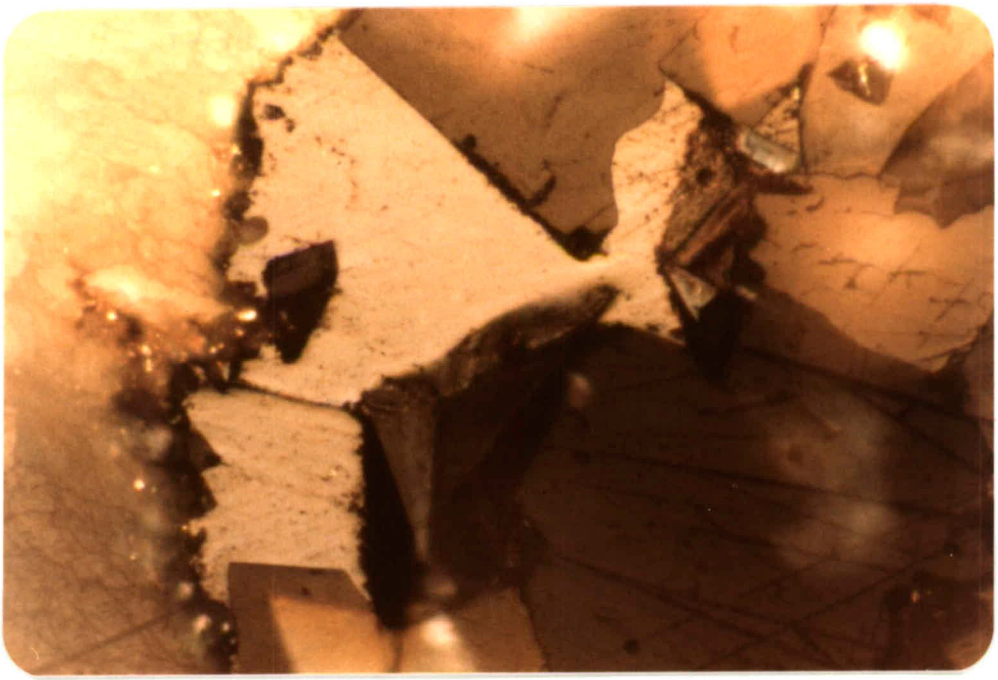

PLATE 2.7

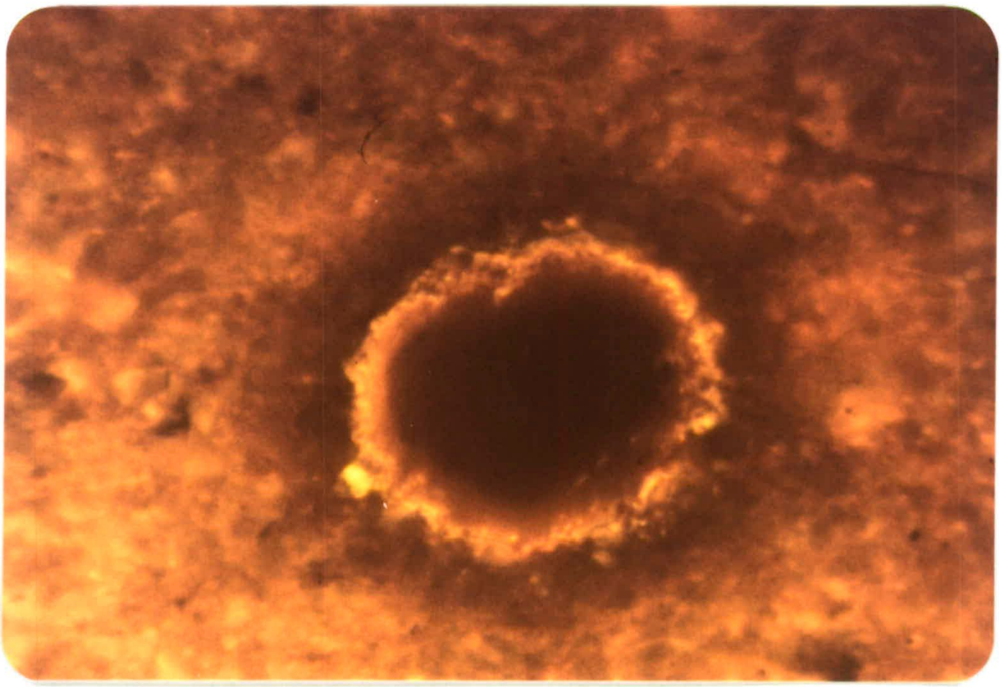

PLATE 2.8

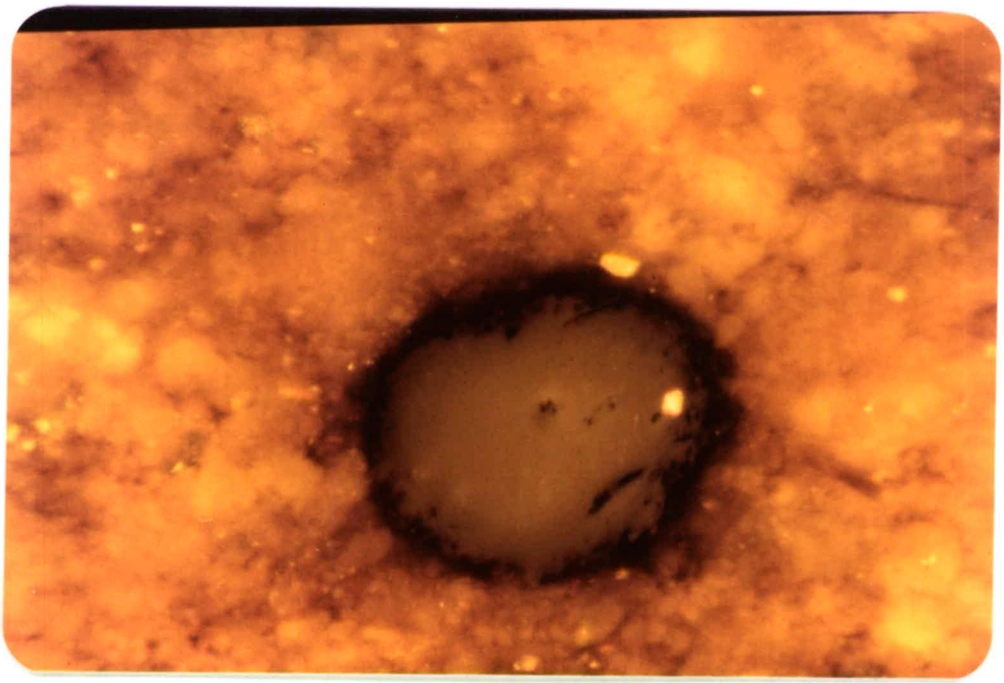

TABLE 1: OIL GEOCHEMISTRY, BYILKAOORA-1

Sample no. (A..../79)	Depth (m)	Composition* (wt.%)				Alkane parameters**				
		Sat.	Arom.	ONS	Asph.	Pr/n-C_{17}	Ph/n-C_{18}	Pr/Ph	i-C_{25}/n-C_{22}	Sq/n-C_{26}
3129	219.52	24.0	4.4	1.1	0.5	1.21	1.38	1.10	0.57	0.43
2278	277.00	24.9	7.7	67.1	0.2	(featureless naphthene hump)				
2279	278.55	58.7	3.8	37.0	0.5	2.22	2.92	0.89	0.95	0.88
2280	278.77	53.4	3.5	42.6	0.5	2.28	2.98	0.94	0.98	0.96
3130	292.94	23.5	4.0	60.1	12.4	3.06	4.05	0.82	1.96	3.00
3131***	293.17	23.7	6.4	53.6	16.3	2.72	3.35	0.92	1.56	2.23
2281	317.10	37.5	7.7	47.9	6.9	3.10	3.92	0.82	2.36	1.31

* Approximates to C_{15+} fraction. Oils 2281 & 3131 scraped from core; all others isolated by 3 min. ultrasonic washing of core in benzene-methanol (3:2), followed by rotary evaporation of solvent.

Sat. = saturates, Arom. = aromatics, ONS = O, N & S - bearing compounds, Asph. = asphaltenes.

** Measured from chromatogram of C_{15+} alkanes. Pr = pristane, Ph = phytane, i-C_{25} = acyclic C_{25} regular isoprenoid, Sq = squalane.

*** $\delta^{13}C_{PDB}$ = -28.75‰ (whole oil).

TABLE 2: COMPARATIVE GEOCHEMISTRY OF SELECTED CAMBRIAN OILS

Well/Field & Basin	Formation	Type	API gravity (S content)	Composition >210°C fraction					Alkane parameters		
				Sat.	Arom.	ONS %	Asph.	$\delta^{13}C_{PDB}$ ‰	Pr/n-C_{17}	Ph/n-C_{18}	Pr/Ph
Morrow County Ohio, U.S.A.	Knox Dol.	paraffinic-naphthenic	40.1	70.3	13.2	15.6	0.9	-29.46	0.39	0.33	1.67
Alice-1 (Amadeus)*	Giles Creek Dol.	aromatic-naphthenic	43.0 (0.2)	43.8	10.0	45.1	1.1	-28.80	0.20	0.17	2.57
Wilkatana-1 (Arrowie)	Wilkawillina Lst.	paraffinic (high wax)	33.8 (0.6)	54.7	1.1	38.3	5.9	-27.43	0.91	0.49	2.05
Byilkaoora-1 (Officer)	Observatory Hill Beds	aromatic-naphthenic (Family A)	14.4 (0.3)	23.7	6.4	53.6	16.3	-28.75	2.72	3.35	0.92
		naphthenic (Family B)	n.d.	53.4	3.5	42.6	0.5	n.d.	2.28	2.98	0.94
		aromatic-naphthenic (Family A')	n.d.	24.4	4.4	71.1	0.5	-30.16	1.21	1.38	1.10

*After McKirdy (1977)

TABLE 3: A CLASSIFICATION OF OILS FROM BYILKAOORA-1

Parameter	Family A	Family B	Family A'
Depth range (m)	330-292	297-240	221-218
Host porosity	Vugs in grey-green carbonates (e.g. Plate 1.4)	Vugs in grey-green carbonates (e.g. Plate 1.2)	Partly healed vertical fractures in red-brown siltstone (e.g. Plate 1.1)
Stain	Dark	Pale*	Pale
Asphaltene content (wt %)	6.9 - 16.3	0.2 - 0.5	0.5
Saturates content (wt %)	<50	>50*	<50
Naphthene distribution[1]	Bimodal L<H	Bimodal L≪H	Bimodal L>H
Pr/Ph	<1	<1	>1
Type[2]	Aromatic-naphthenic	Naphthenic*	Aromatic-naphthenic

1. L = low molecular-weight mode, in diterpane (C_{20}) region
   H = high molecular-weight mode, in sterane-triterpane (C_{30}) region.

2. According to crude oil classification scheme of Tissot & Welte (1978).

* Except where severely biodegraded (e.g. sample 2278, Table 1).

TABLE 4: EXTRACTABLE ORGANIC MATTER YIELD & COMPOSITION, OBSERVATORY HILL BEDS

Sample no.	Depth (m)	TOC (wt %)	EOM yield (ppm)	H'c yield* (mg/g TOC)	EOM composition (% EOM)				Alkane parameters**			
					Sat.	Arom.	ONS	Asph.	Pr/n-C_{17}	Ph/n-C_{18}	Pr/Ph	i-$C_{21-25,30}$
Byilkaoora-1												
5643/RS59	200.30	0.66	195	6	12.0	6.5	48.9	14.1	0.47	0.35	1.20	-
60	207.45	0.04	60									
61	211.60	0.18	566	147	35.3	11.5	48.1	5.1	1.21	1.66	1.21	++
62	213.50	0.03	40									
63	225.90	0.21	92	8	14.3	3.4	45.3	37.0	1.19	0.79	1.12	++
64	240.90	0.03	15									
65	252.75	0.09	152	28	11.7	5.0	38.3	45.0	0.27	0.24	1.00	-
66	262.95	0.56	1329	79	22.0	11.5	61.5	5.0	0.75	0.98	1.35	+
A2282/ 79	278.66	0.50	1128	47	17.8	3.1	70.9	8.2	0.83	1.30	0.97	++
A2283/ 79	278.86	0.45	508	42	33.4	3.5	54.2	8.9	1.20	1.64	0.92	++
5643/RS67	279.50	0.32	745	69	24.4	5.4	48.6	21.6	1.02	1.51	0.92	++
68	285.00	0.70	1877	57	16.3	4.8	73.7	5.2	1.40	1.84	0.89	++
A2284/ 79	289.77	0.96	1806	83	41.4	3.0	47.7	7.9	1.57	1.94	0.98	++
5643/RS69	293.40	0.10	61									
70	296.25	0.38	1304	129	31.6	5.9	57.0	5.5	1.14	1.96	0.96	++
71	306.15	0.64	1043	49	23.5	6.8	60.3	9.4	1.27	1.69	1.02	++
72	312.30	0.33	267	21	17.6	8.8	53.8	20.8	1.15	1.54	0.90	++
73	313.30	0.42	270	12	13.2	6.1	39.5	41.2	0.83	0.93	1.08	+
74	316.50	0.48	753	56	29.7	6.2	51.4	12.7	2.20	3.25	0.93	++
Wilkinson-1												
A6114/ 78	273.43	0.04	70									
15	288.52	0.15	345	53	8.1	14.2	11.8	65.9	0.54	0.45	1.31	+
16	310.44	0.15	128									
17	314.47	0.37	127	2	2.5	1.9	41.6	54.0				
18	315.05	0.18	152	14	11.7	5.1	29.9	53.3	0.21	0.26	0.89	-
19	333.07	0.29	605	71	24.7	9.8	32.4	33.1	0.31	0.34	0.98	+
20	333.63	0.08	93									
21	344.54	0.56	299	16	22.8	8.1	45.9	23.2	0.44	0.65	0.85	+
22	390.08	0.43	799	43	16.8	6.7	39.9	36.6	0.44	0.78	1.36	+
23	461.42	0.68	1638	88	28.9	8.7	50.2	12.2	0.34	0.64	0.48	+
24	461.87	0.60	1939	110	20.4	13.6	54.6	11.4	0.26	0.42	0.80	+
25	462.17	0.63	1576	93	24.3	13.0	53.9	8.8	0.97	1.45	0.42	+
26	463.57	0.18	459	65	18.3	7.5	28.6	45.6	0.28	0.25	1.14	-
27	464.71	0.10	281									
28	481.62	0.23	341	45	21.1	9.2	55.7	14.0	0.12	0.15	1.10	-
29	482.02	0.06	118									
30	512.07	0.34	660	78	31.4	8.6	44.3	15.7				
31	513.45	0.22	290	23	9.7	8.1	53.7	28.5	0.10	0.13	1.00	-
32	527.60	0.12	38									
33	538.41	0.16	106	13	10.5	8.8	47.4	33.3	0.18	0.20	0.99	-
34	553.37	0.28	406	40	19.4	8.9	29.2	42.5	0.18	0.18	1.58	-
35	656.32	0.05	13									
Wallira West-1												
A6136/ 78	330.50	0.54	1321	139	41.7	14.8	36.8	6.7	0.09	0.16	1.25	-
37	330.97	0.44	1187	157	44.0	13.9	37.8	4.3	0.10	0.18	1.08	-
38	343.63	0.49	1250	139	40.0	13.9	40.8	5.3	0.69	1.35	0.73	+
39	344.30	0.45	1337	161	42.3	11.9	43.8	2.0	0.56	0.98	0.93	+
40	357.15	0.06	60	23	13.3	10.0	51.7	25.0	0.27	0.22	0.81	-
Murnaroo-1												
5339/RS20	62.20	0.04	55	42	25.8	4.5	50.0	19.7	0.32	0.32	0.85	-
21	67.45	0.15	141	31	30.5	2.4	46.3	10.8	0.34	0.37	0.97	-
22	95.30	0.16	197	86	60.5	9.5	28.2	1.8	0.33	0.32	1.06	-
23	161.60	0.14	97	14	19.5	0.8	43.1	36.6	0.31	0.32	0.88	-
24	182.45	0.28	149	10	14.9	3.4	--81.7--		0.74	0.62	1.21	-
25	186.40	0.18	469	30	8.5	4.1	--87.4--		1.27	1.04	1.57	-
26	216.30	0.04	14									
27	229.45	0.07	58	10	8.9	3.6	--87.5--		0.41	0.33	1.23	-
Emu-1												
A6141/ 78	64.97	0.06	59	17	13.6	4.1	46.8	35.6				
42	153.44	0.06	69	18	12.7	2.8	50.7	33.8				
43	247.22	0.22	111	15	20.9	9.1	28.2	41.8	0.62	0.52	1.60	+
Birksgate-1												
4842/RS29	818.39	0.07	76	13	10.5	1.8	54.4	33.3	0.56	0.57	1.59	-
30	819.61	0.03	28									
31	966.22	0.33	266	15	15.3	3.0	54.2	27.5	0.95	0.53	2.21	-
32	967.13	0.21	132	20	24.6	6.9	47.0	21.5	1.00	0.51	1.65	-
33	969.26	0.07	17									
34	972.01	0.12	46	7	15.4	1.9	57.7	25.0	0.41	0.31	0.57	-
35	1099.26	0.25	199	16	13.2	6.9	42.9	37.0	2.44	0.54	3.75	-

* Saturated plus aromatic hydrocarbons (approx C_{15+}).

** i-$C_{21-25,30}$ = acyclic sesterterpanes & squalane; ++ prominent, + present, - not detected.

TABLE 5: KEROGEN ELEMENTAL & ISOTOPIC COMPOSITION,

OBSERVATORY HILL BEDS

Sample no.	Depth	C	H	N	S	O	Ash	H/C	O/C	Type	$\delta^{13}C_{PDB}$
	(m)			(wt% d.a.f.)*			(wt%)	(atomic)			(‰)
Byilkaoora-1											
5643/RS59	200.30	77.75	6.08	2.35	7.8	6.0	28.8	0.93	0.058	II	-30.07
66	262.95	77.83	8.17	1.20	8.8	4.0	24.3	1.25	0.039	I	-31.30
68	285.00	85.29	9.07	1.42	1.7	2.5	7.6	1.27	0.022	I	n.d.
A2284/ 79	289.77	86.80	8.70	1.28	1.4	1.8	7.7	1.19	0.015	I	-29.00
5643/RS70	296.25	86.95	9.98	1.38	1.0	0.8	7.0	1.37	0.007	I	n.d.
71	306.15	82.51	8.65	1.30	3.7	3.8	13.4	1.25	0.035	I	-28.47
74	316.50	------------not determined-------------						1.24	n.d.	n.d.	-29.07
Wilkinson-1											
A6117/78	314.47	73.56	5.61	2.88	3.7	14.2	16.0	0.91	0.144	III	-29.81
19	333.07	77.56	6.57	1.71	7.5	6.7	12.5	1.01	0.065	II	-29.58
21	344.54	79.57	7.10	1.44	3.9	8.0	9.5	1.06	0.075	II	-29.10
22	390.08	78.71	6.31	2.26	2.8	9.9	10.8	0.96	0.094	II	-28.60
23	461.42	79.29	7.08	1.79	4.8	7.0	4.0	1.06	0.066	II	-31.06
25	462.17	78.67	6.36	1.97	4.1	8.9	2.7	0.96	0.085	II	-30.70
28	481.62	83.26	7.03	1.77	4.1	3.8	26.6	1.01	0.034	I(?)	-31.81
30	512.07	79.52	6.55	2.17	2.6	9.2	6.7	0.98	0.087	II	-30.62
34	553.37	80.58	5.84	2.22	3.2	8.2	14.3	0.86	0.076	II	-30.23
Wallira West-1											
A6136/78	330.50	80.68	6.68	1.30	6.1	5.2	8.1	0.99	0.048	II	-31.95
39	344.30	75.45	6.28	1.70	7.7	8.9	8.4	0.95	0.089	II	-30.92

* d.a.f. = dry ash free ; oxygen determined by difference.

TABLE 6: METHODS USED FOR SOURCE-ROCK EVALUATION

Technique/Parameter	Abundance of DOM	Type of DOM	Maturation state
TOC (wt%)	++	-	-
Incident-light microscopy of *in situ* DOM			
- white light	+	++	+
- fluorescence-mode	+	++	++
Transmitted-light microscopy of DOM concentrate	+	+	+
Kerogen analysis			
- elemental (H/C, O/C)	-	++	++
- isotopic (δ^{13}C)	-	+	-
C_{15+} hydrocarbon yield (mg/g TOC, % EOM)	-	++	++
C_{15+} alkane analysis (n-alkanes, acyclic isoprenoids, naphthenes)	-	++	+

++ very useful, + useful, - not applicable

TABLE 7: EXTRACTABLE ORGANIC MATTER YIELD & COMPOSITION, MUNYARAI-1

Sample no. (A../78)	Depth (m)	TOC (wt%)	EOM yield (ppm)	H'c yield* (mg/g TOC)	EOM composition (% EOM)				Alkane parameters		
					Sat.	Arom.	ONS	Asph	Pr/n-C_{17}	Ph/n-C_{18}	Pr/Ph
6144	632.20	0.19	144	8	8.3	2.8	51.0	37.9	0.39	0.30	0.96
6145	633.70	0.19	177	11	11.4	0.6	48.0	40.0	0.41	0.29	0.82
6136	1693.09	0.20	141	12	14.9	1.4	44.7	39.0	0.47	0.35	0.91
6147	2134.16	0.20	35	5	5.6	6.5	53.7	34.2	0.60	0.37	0.82
6148	2289.71	0.30	197	15	9.9	13.7	44.3	32.1	0.33	0.21	1.41
6149	2441.03	0.22	71	10	23.8	6.9	58.4	10.9	0.52	0.34	1.58
6150	2533.31	0.22	103	9	11.3	8.5	69.3		0.41	0.28	0.99
6151	2610.61	0.33	119	13	26.0	11.0	80.2		0.19	0.15	1.07
6152	2753.43	0.24	81	15	28.4	14.8	30.7	26.1	0.45	0.27	1.38
6153	2897.30	0.47	49	2	13.3	3.3	60.0	23.3	0.48	0.32	1.51

* Saturated plus aromatic hydrocarbons (C_{15+})

TABLE 8: DETAILED ORGANIC PETROLOGY, OBSERVATORY HILL BEDS, BYILKAOORA-1

Sample No.	Depth (m)	TOM (vol. %)	Pyrite	Organic matter type									Dominant type	Source rock rating
				Alginite B	Oil stain		Bitumen			Phyto-plankton	Lipto-detrinite	Algal mucilage		
					green	orange	reservoir	thucolite	balls					
5643/RS59	200.30	3	H	C	R	R	R	S	VR	R	S	S	Alginite B	M-F
60	207.45	0.2	L	VR	VR	R	NO	VR	NO	NO	S	S	Alginite B	P
61*	211.60	1**	L-M	S	C	S	NO	S	S	R	S	NO	Alginite/ Oils stain	M
62	213.50	trace	L	VR	NO	NO	NO	NO	NO	NO	NO	A	-	VP
63	225.90	1-2	L	C	S	R	R	S	S	S	S	S	Alginite B	M-F
64*	240.90	trace	M	R	NO	NO	NO	NO	NO	NO	NO	A	Alginite B	VP
65*	252.75	trace	L	S	NO	NO	NO	NO	NO	NO	NO	C	Alginite B	P
66	262.95	?	L	S	VC	VC	NO	C	S	NO	R	C	Oil stain	P
67	279.50	2-3	M	A	S	S	NO	S	R	C	S	C	Alginite B	F
68	285.00	1-2**	L/H	VC	VC	S	S***	S	S	S	S	S	Alginite B	F
A2284/79	289.77	trace	M	R	A	R	S***	R	R	R	R	R	Oil stain	P
5643/RS69	293.40	1	L	S	S	R	S	S	S	VR	R	C	Oil stain	P-M
70	296.25	5+	M	A	VC	S	NO	R	R	VR	NO	NO	Alginite/Oil Stain	G-E
71	306.15	3+	L-M	A	A	C	R***	S	C	C	R	S	Alginite/Oil Stain	F-G
72	312.30	3-5	M	A	VC	R	C***	NO	NO	VR	R	C	Alginite/Oil Stain	G
73	313.30	3+	L	A	VC	C	R	R	R	NO	R	S	Alginite/Oil Stain	F-G
74	316.50	10+	L	A	C	C	NO	NO	VR	VR	NO	NO	Alginite B	E

TOM = total organic matter   Pyrite vol. % : H = high (>15%), M = moderate 5-15%), L = low (<5%)

Abundance: NO = not observed, VR = very rare, R = rare, S = some, C = common, VC = very common, A = abundant

Source rock rating: VP = very poor, P = poor, M = marginal, F = fair, G = good, E = excellent

* Contains rare detrital graphite

** Percentage and type of organic matter is very variable within all samples, but is particularly so in this sample

*** Includes "cauliflower-shaped" bitumen aggregates

TABLE 9: REFLECTANCE & FLUORESCENCE DATA, MUNYARAI-1

Sample no. (A.../78)	Depth (m)	Graptolite reflectance (% R_o max)	Bitumen Low refl. (% R_o max)	Bitumen High refl. (% R_o max)	Fluorescence colour & intensity *
6145	633.70	-	-	-	Some BO <u>?Tasmanites</u> Y, O, B <u>acritarchs</u>
6146	1693.09	-	-	1.6-2.2	V. rare BO acritarchs
6147	2134.16	-	-	-	" " "
6148	2289.71	1.2	0.58-0.92	-	Some BO acritarchs
6149	2441.03	-	0.64	-	Minor DO acritarchs
6150	2533.31	-	0.68-0.90	-	Some BO acritarchs
6151	2610.61	-	-	-	Abundant BO liptodetrinite
6152	2753.43	1.1-1.3	0.75	-	" " " "
6153	2897.30	1.3-1.8	-	1.7-1.8	Some MO liptodetrinite

* Y = yellow O = orange B = brown BO = bright orange MO = moderate-intensity orange DO = dull orange

TABLE 10: ESTIMATES OF VITRINITE REFLECTANCE, MUNYARAI-1

Depth	Uncorrected temperature	Corrected temperature	Measured R_o%		Estimated vitrinite reflectance (R_o%)					
					Karweil/Bostick		Hood et al.		Lopatin	
(m)	T_u °C	T_c °C	Graptolite	Bitumen*	T_u	T_c	T_u	T_c	T_u	T_c
2286.6	65	72	1.2	0.6-0.9	1.20	1.35	0.55	0.59	n.d.	≈0.8
2896.3	77	85	1.3+	≈0.8	1.60	1.90	0.62	0.67	≈0.8	≈1.5

* "low-reflectance" type n.d. = not determined

LIST OF CAPTIONS TO FIGURES

Figure 1:

Locality map of western South Australia, showing outcrop limits of the Officer Basin and well locations.

Figure 2:

Well correlations and source-rock sample points, Officer Basin. Well locations shown in Figure 1.

Figure 3:

Gas chromatograms of alkanes from selected oils, Observatory Hill Beds, Byilkaoora-1: 2281 (317.10 m), Family A; 2280 (278.77 m), Family B; 2278 (277.00 m), Family B (severely biodegraded); 3129 (219.52 m), Family A'. Key Numbers refer to carbon-number of normal alkanes; a - m are the acyclic C_{13}-C_{25} regular isoprenoids (note: g = pristane, h = phytane); * is squalane.

Figure 4:

Triterpane (m/e 191) mass fragmentograms of Family B oils 2278 (277.00 m) and 2280 (278.77 m), and of the EOM from stained rock sample 2284 (289.77 m), Byilkaoora-1.

Figure 5:

Sterane (m/e 217) mass fragmentograms of Family B oils 2278 (277.00 m) and 2280 (278.77 m), and of the EOM from stained rock sample 2284 (289.77 m), Byilkaoora-1.

Figure 6:

Normal alkane profiles (heavy line) and acyclic isoprenoid distributions (vertical bar plot) of four oils from Cambrian carbonate reservoir rocks.

Figure 7:

Gas chromatograms of alkanes from selected fine grained rocks, Observatory Hill Beds, Byilkaoora-1. See Figure 3 for key.

Figure 8:

Maturation state and hydrocarbon potential, Observatory Hill Beds, Byilkaoora-1.

Key Numbers refer to sample numbers listed in Table 3; underlined numbers indicate stained samples.

Oil-source potential scale (mg/g TOC) : <30, none (gas only); 30 - 50, marginal; 50 - 80, good; >80, excellent.

Figure 9:

Maturation state and hydrocarbon potential, Observatory Hill Beds, Wilkinson-1 and Willira West-1. See Figure 8 for key.

Figure 10:

Van Krevelen diagram showing the elemental composition of kerogens isolated from the Observatory Hill Beds. Solid lines are the maturation pathways for the principal kerogen types defined by Tissot & Welte (1978). Dashed lines indicate the approximate limits of the oil window.

Figure 11:

Gas chromatograms of alkanes from selected fine grained rocks, Observatory Hill Beds, Wilkinson-1. See Figure 3 for key.

Figure 12:

Gas chromatograms of alkanes from excellent potential oil-source rocks, Observatory Hill Beds, Wilkinson-1. See Figure 3 for key.

Figure 13:

Gas chromatograms of alkanes from selected fine grained rocks, Observatory Hill Beds, Wallira West-1. See Figure 3 for key.

Figure 14:

Maturation state and hydrocarbon potential, Observatory Hill Beds, Murnaroo-1. See Figure 8 for key.

Figure 15:

Maturation state and hydrocarbon potential, Observatory Hill Beds, Birksgate-1 and Emu-1. See Figure 8 for key.

Figure 16:

Gas chromatograms of alkanes from selected fine grained rocks, Observatory Hill Beds, Murnaroo-1. See Figure 3 for key.

Figure 17:

Gas crhomatograms of alkanes from a silty shale. Observatory Hill Beds, Emu-1. See Figure 3 for key.

Figure 18:

Gas chromatograms of alkanes from selected fine grained rocks, Observatory Hill Beds, Birksgate-1. See Figure 3 for key.

Figure 19:

Maturation state and hydrocarbon potential, un-named Devonian formation, Munyarai-1. See Figure 8 for key.

Figure 20:

Gas chromatogram of alkanes from a Devonian siltstone, Munyarai-1. See Figure 3 for key.

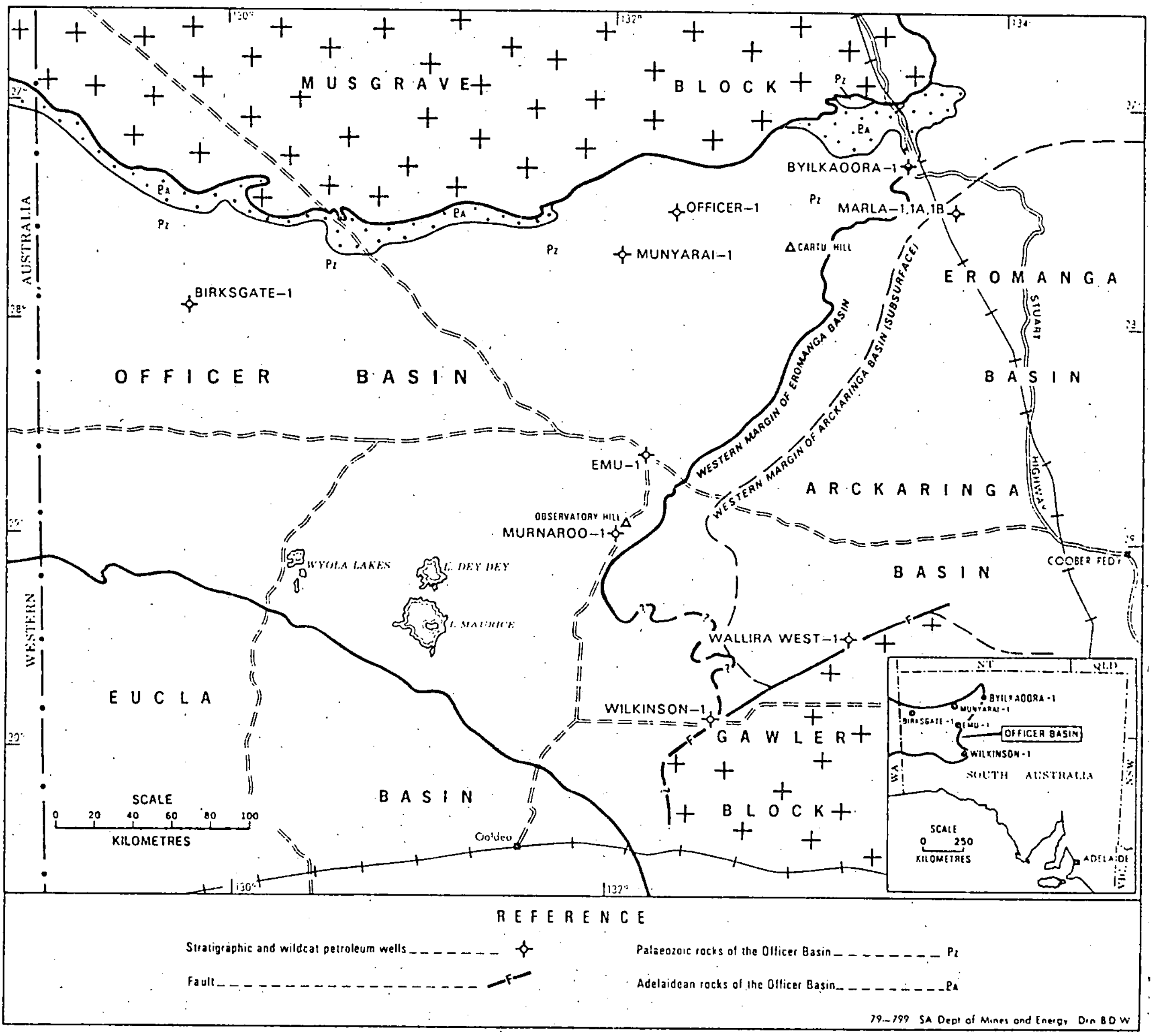

Fig. 1

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN

LOCALITY PLAN

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DRAWN N.R.S.	SCALE
DATE 13-1-81	PLAN NUMBER S 15261
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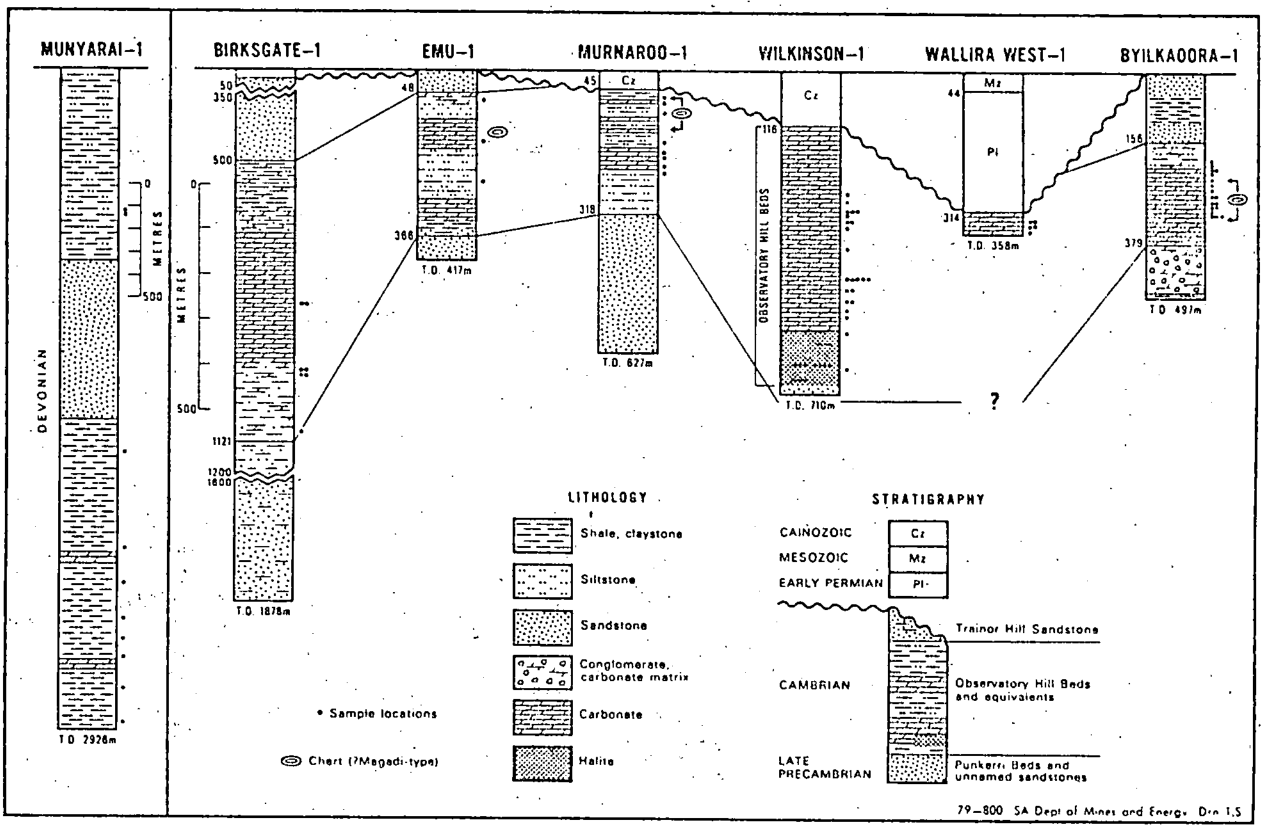

79—800 SA Dept of Mines and Energy Drn I.S

Fig. 2

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
WELL CORRELATIONS AND
SOURCE ROCK SAMPLE POINTS

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DRAWN N.R.S.	SCALE
DATE 13-1-81	PLAN NUMBER S 15262
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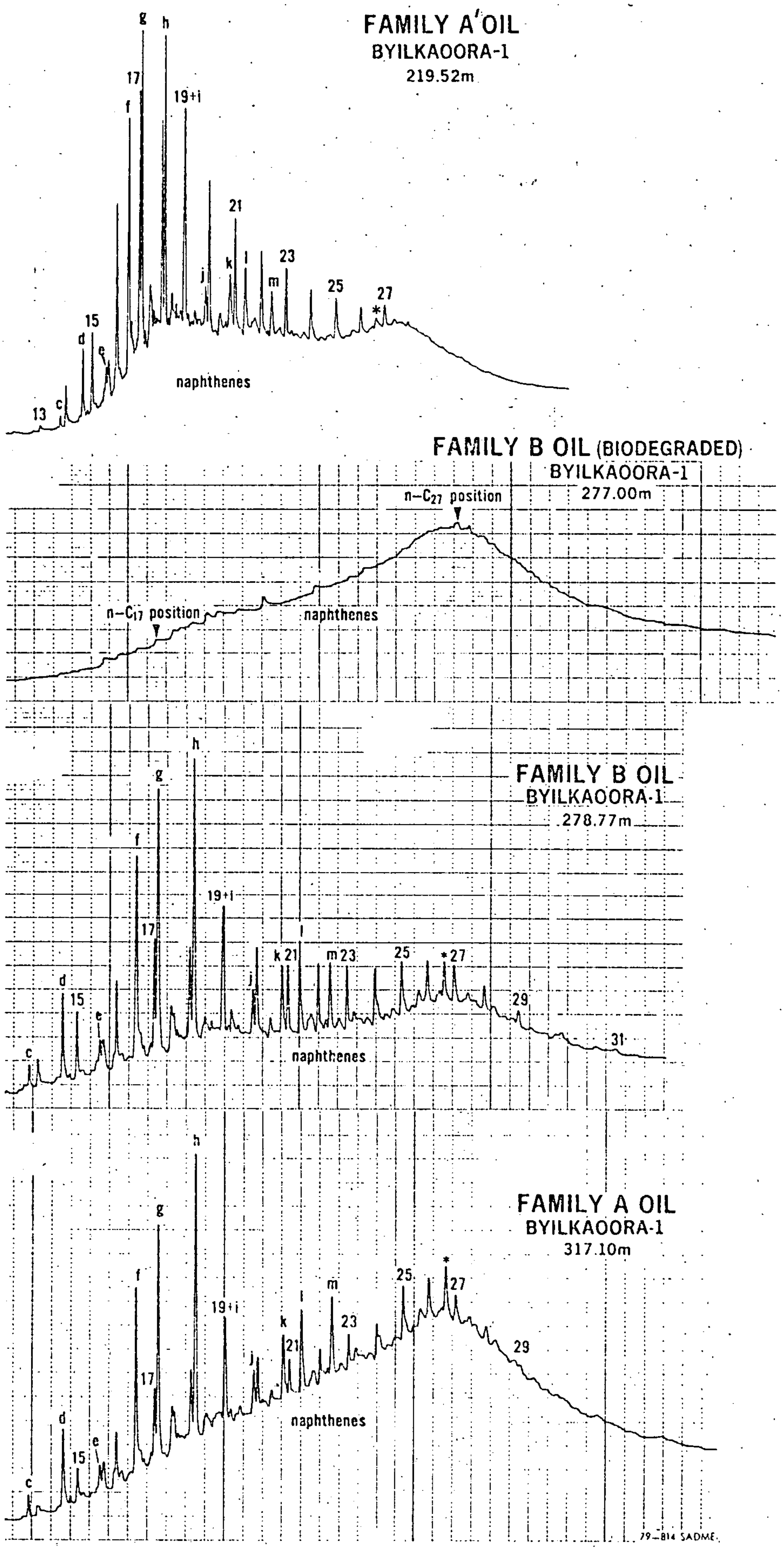

Fig. 3

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
ALKANES FROM SELECTED OILS
BYILKAOORA -1

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DATE 13-1-81
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2283

TRITERPANES m/e 191

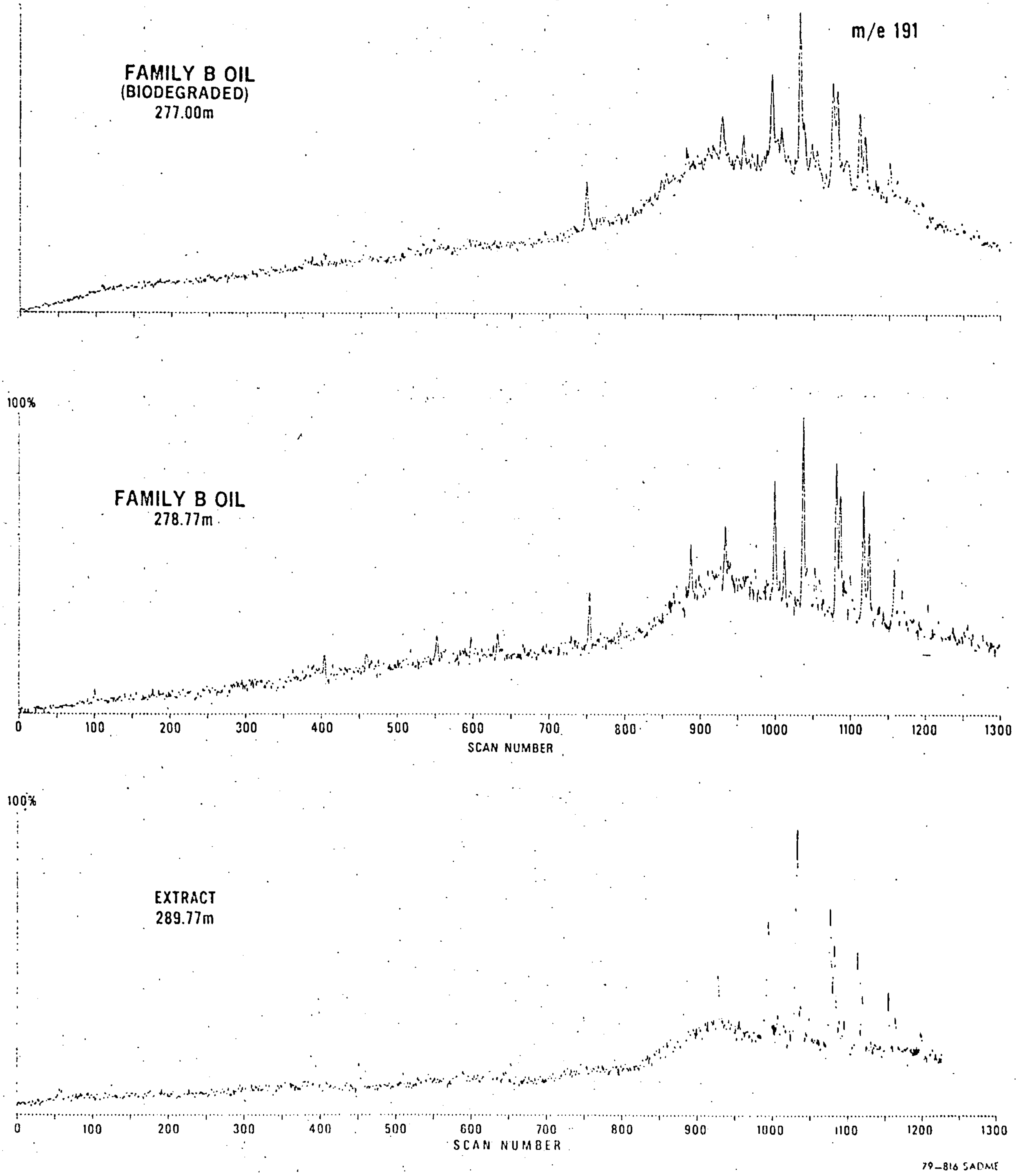

Fig. 4

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
TRITERPANE MASS FRAGMENTOGRAMS
BYILKAOORA -1

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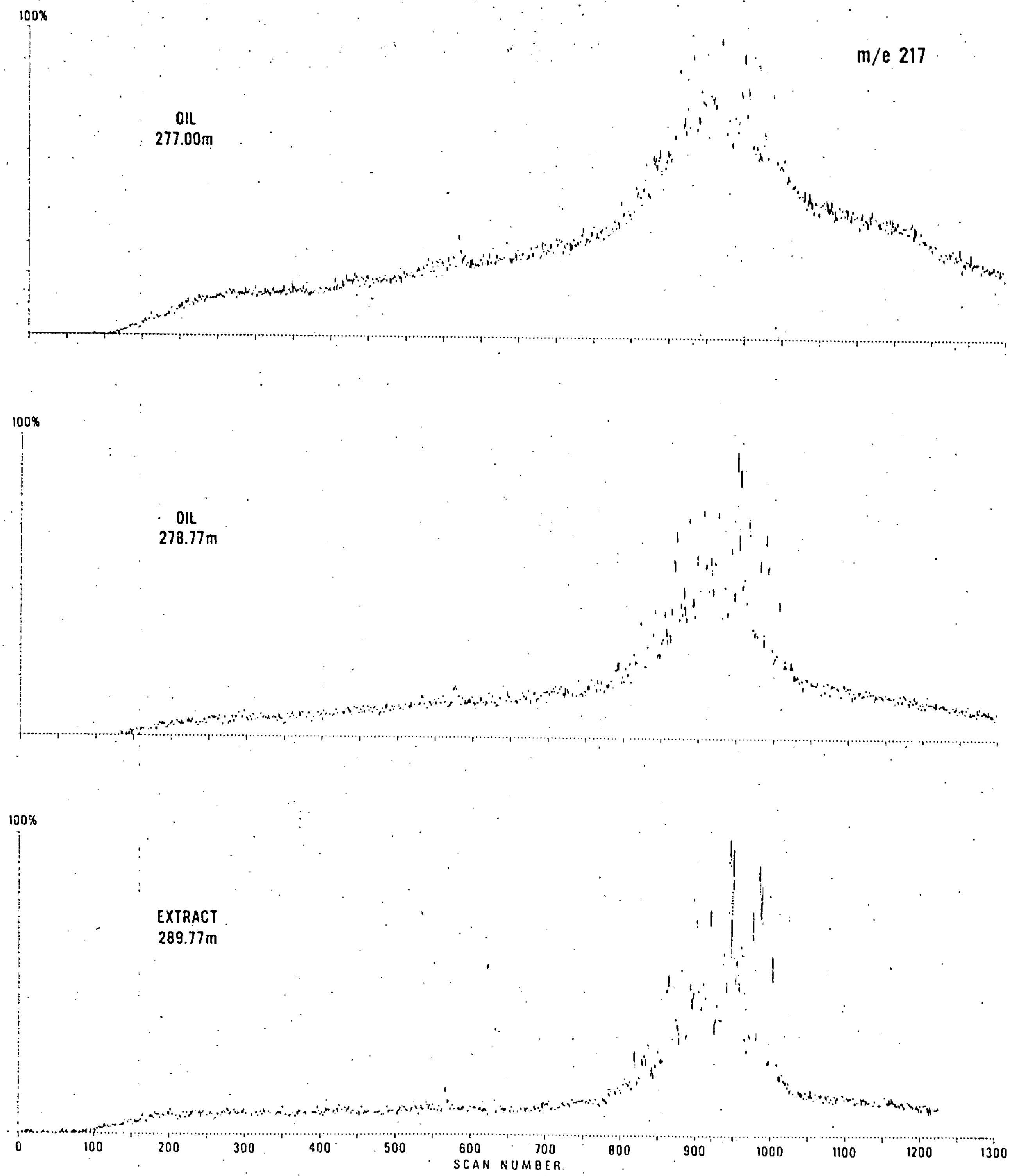

79–815 SADME

Fig. 5

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
STERANE MASS FRAGMENTOGRAMS
BYILKAOORA -1

COMPILED D.M.M.
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DATE 13-1-81
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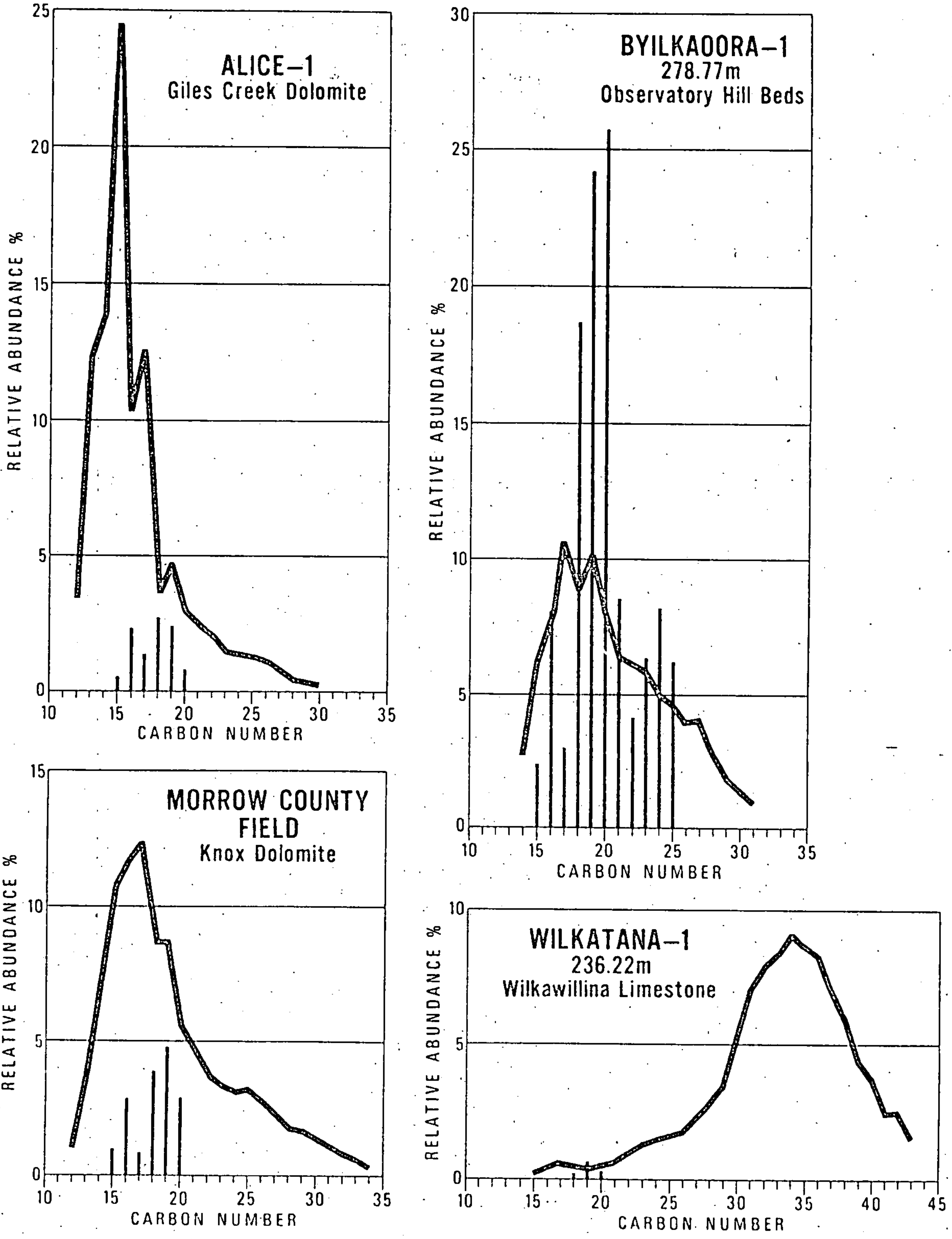
CDO DATE
SCALE
PLAN NUMBER S15265



79–817 SA Dept of Mines and Energy Drn T.S.

Fig. 6

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN

NORMAL AND ISOPRENOID ALKANE DISTRIBUTIONS

CAMBRIAN OILS

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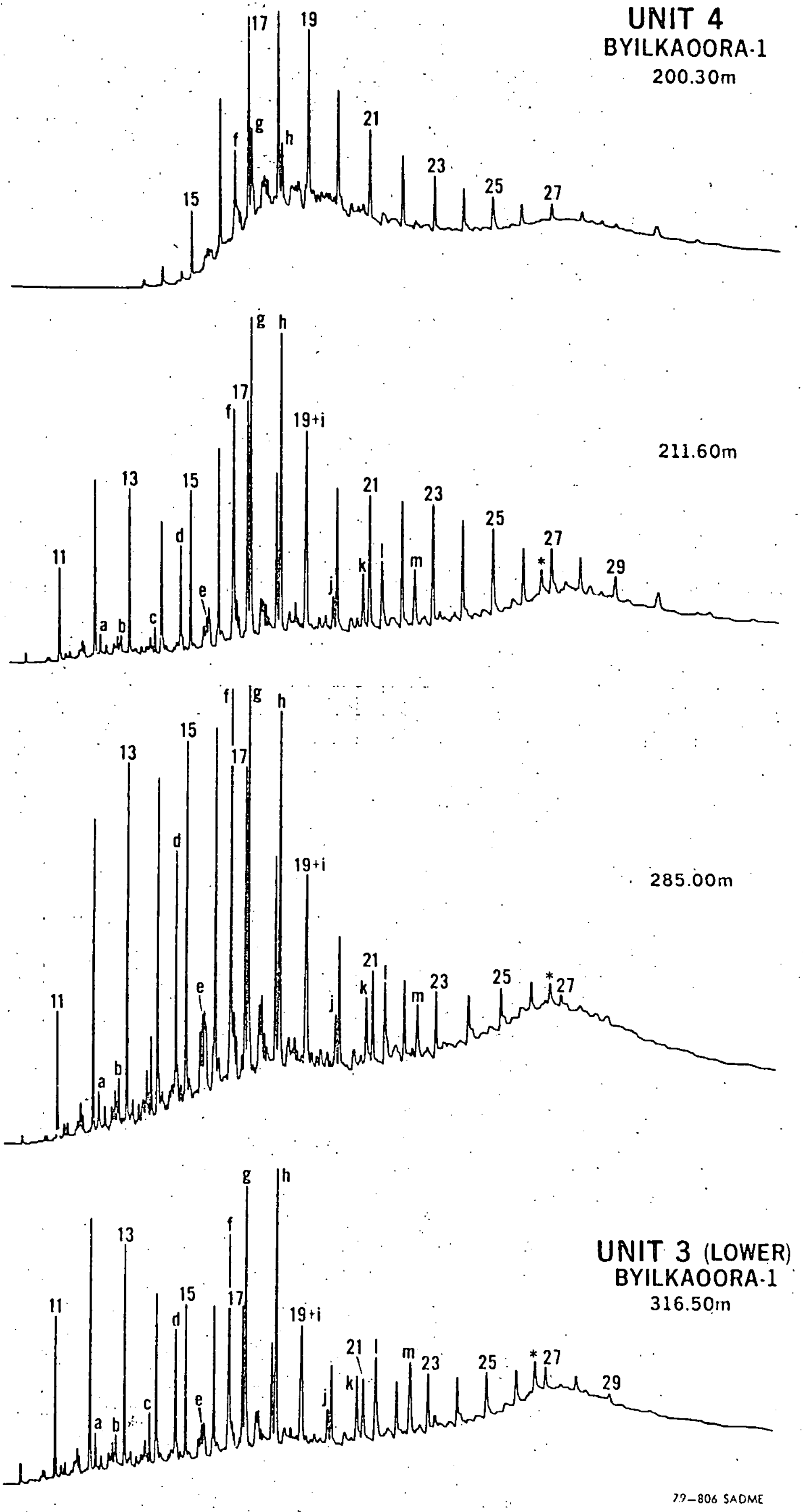

Fig. 7

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
ALKANES FROM ROCK EXTRACTS
OBSERVATORY HILL BEDS
BYILKAOORA -1

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BYILKAOORA–1

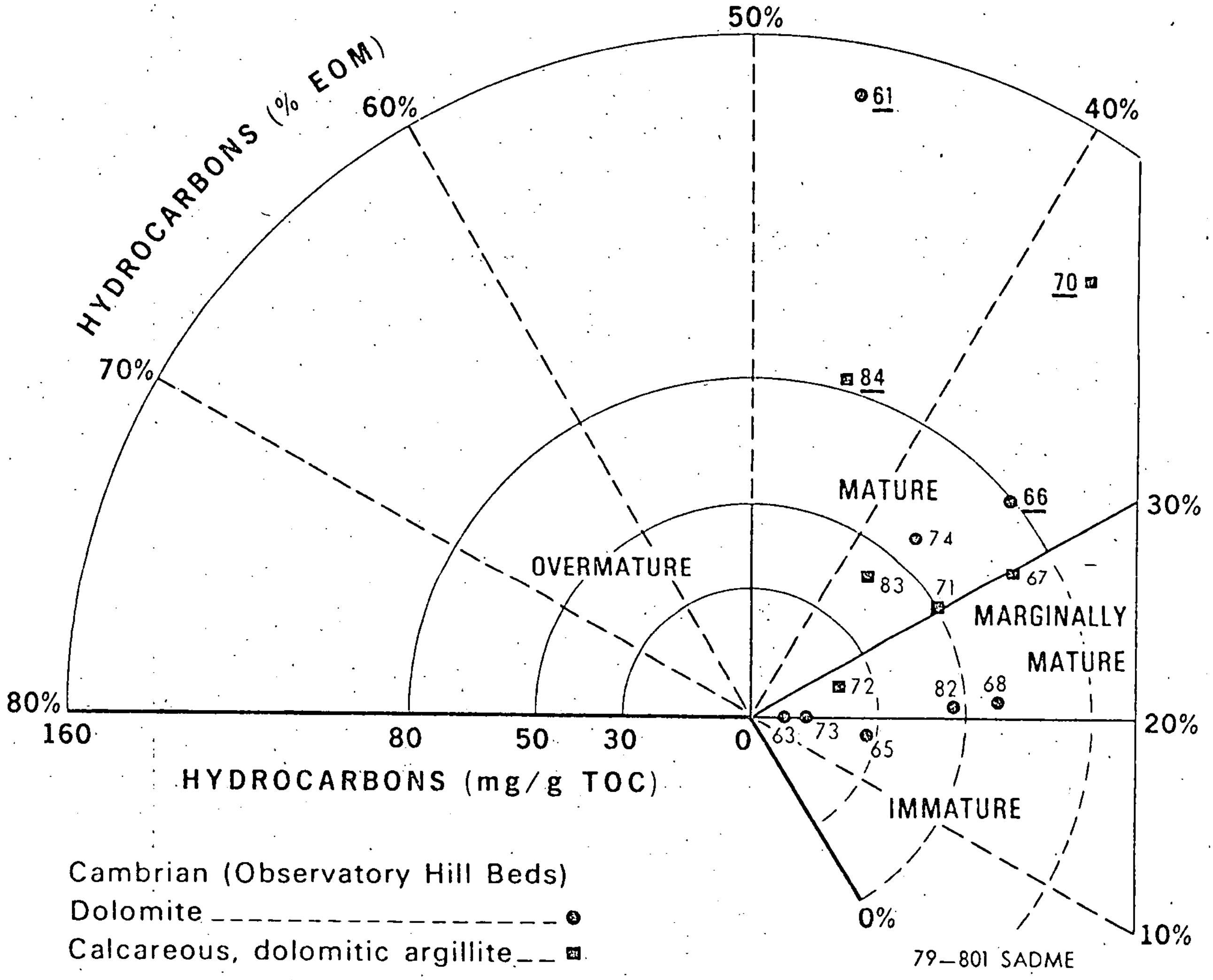

Fig. 8

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
MATURATION STATE AND HYDROCARBON POTENTIAL
OBSERVATORY HILL BEDS
BYILKAOORA -1

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WILKINSON—1 AND WALLIRA WEST—1

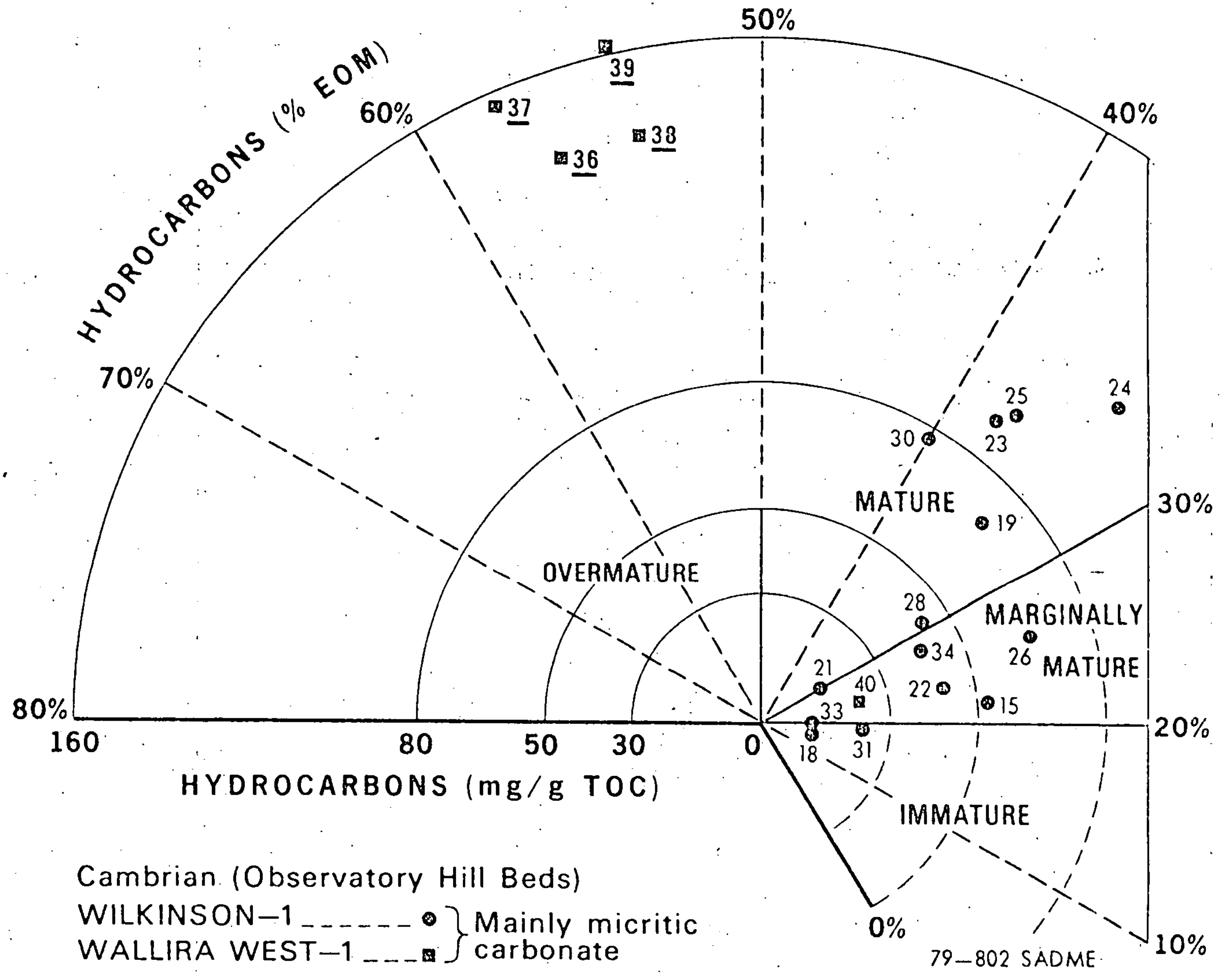

Fig. 9

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES — OFFICER BASIN
MATURATION STATE AND HYDROCARBON POTENTIAL
OBSERVATORY HILL BEDS
WILKINSON -1 & WALLIRA WEST -1

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C.D.O. DATE
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PLAN NUMBER S15269

KEROGEN – OBSERVATORY HILL BEDS

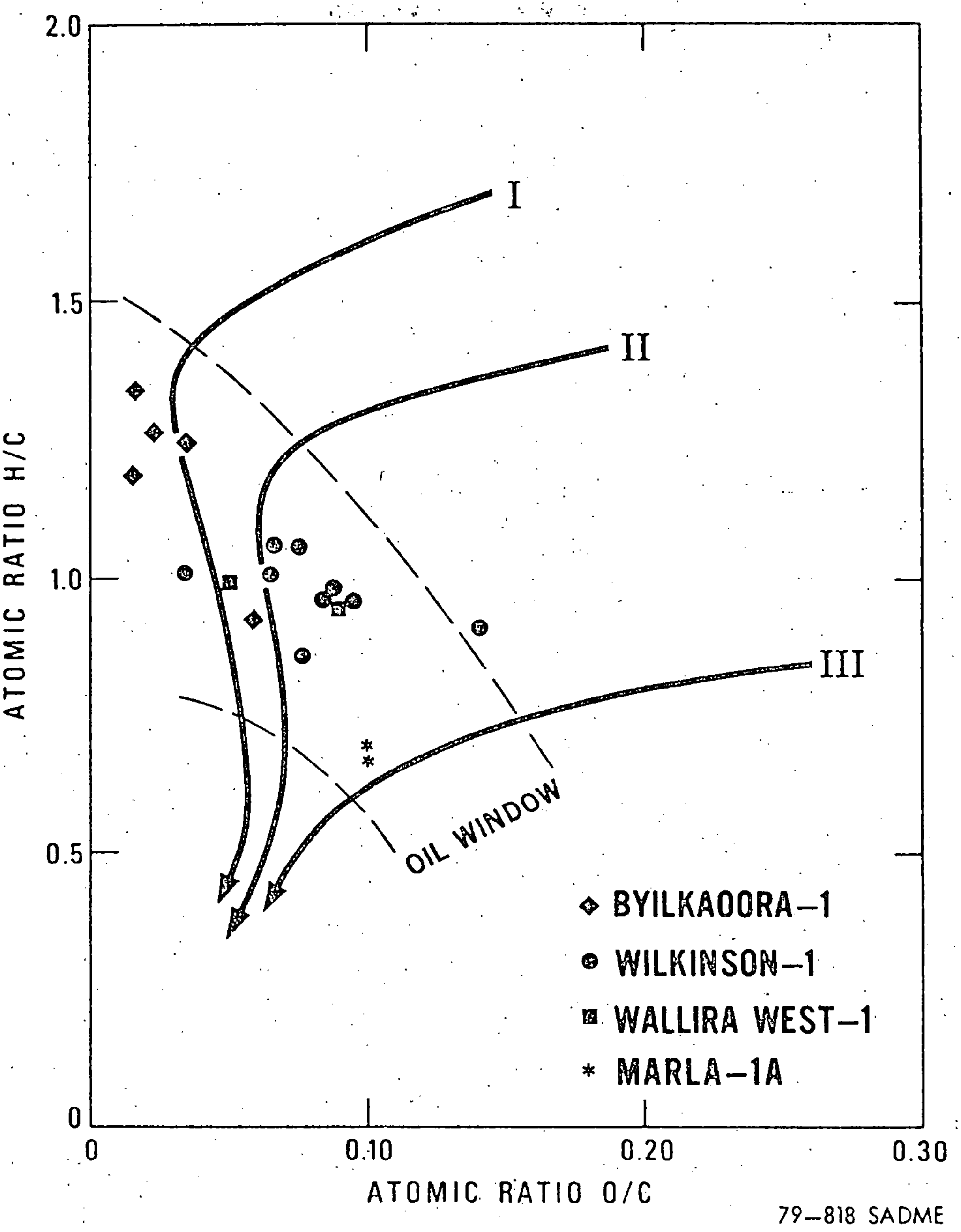

Fig. 10

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED D.M.M.
SOURCE ROCK STUDIES – OFFICER BASIN KEROGEN COMPOSITION AND MATURITY OBSERVATORY HILL BEDS	DRAWN N.R.S. DATE 13-1-81 CHECKED
C D O DATE	SCALE
PLAN NUMBER	S 15270

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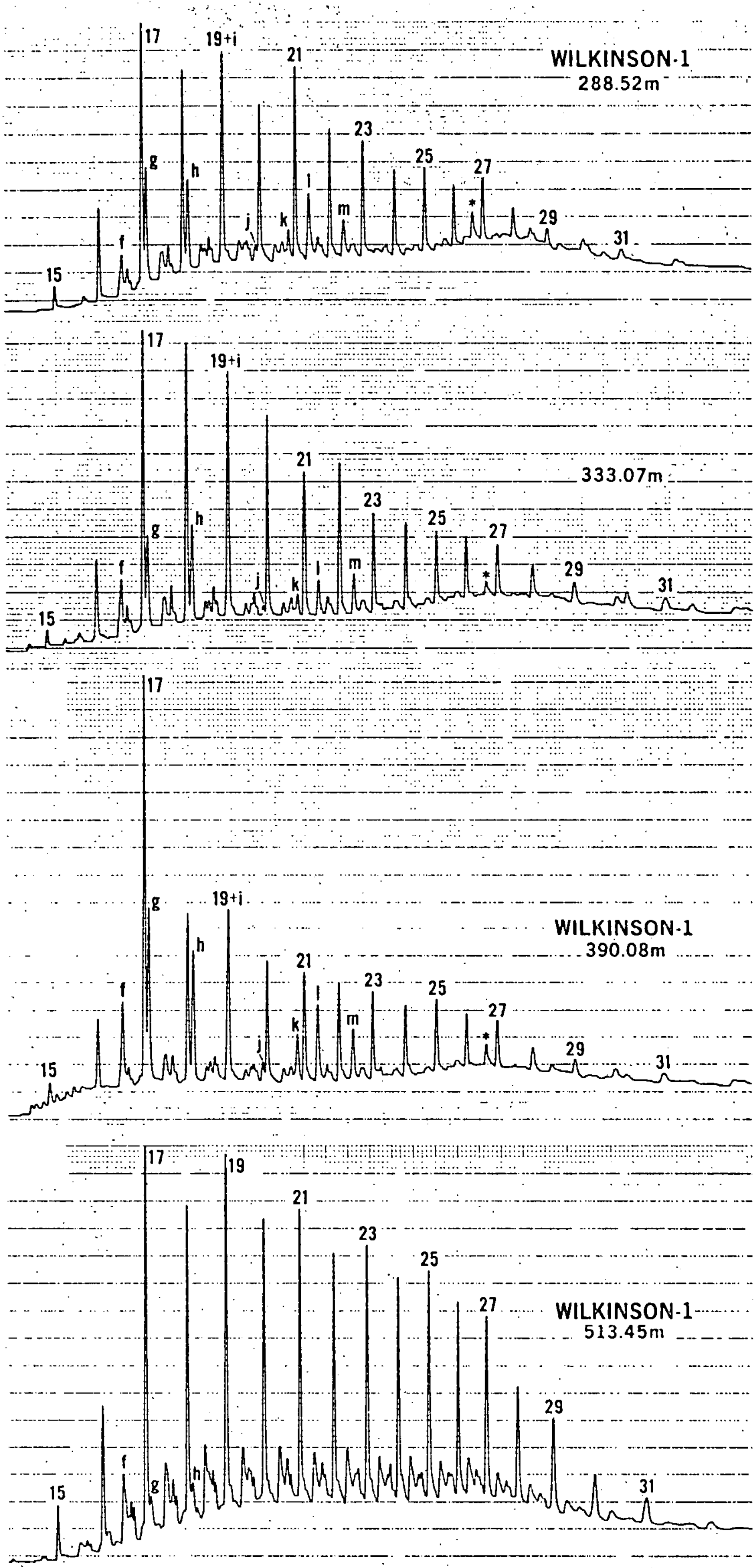

79—807 SADME

Fig. 11

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES — OFFICER BASIN
ALKANES FROM ROCK EXTRACTS
OBSERVATORY HILL BEDS
WILKINSON -1

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DATE 13-1-81	PLAN NUMBER S 15271	
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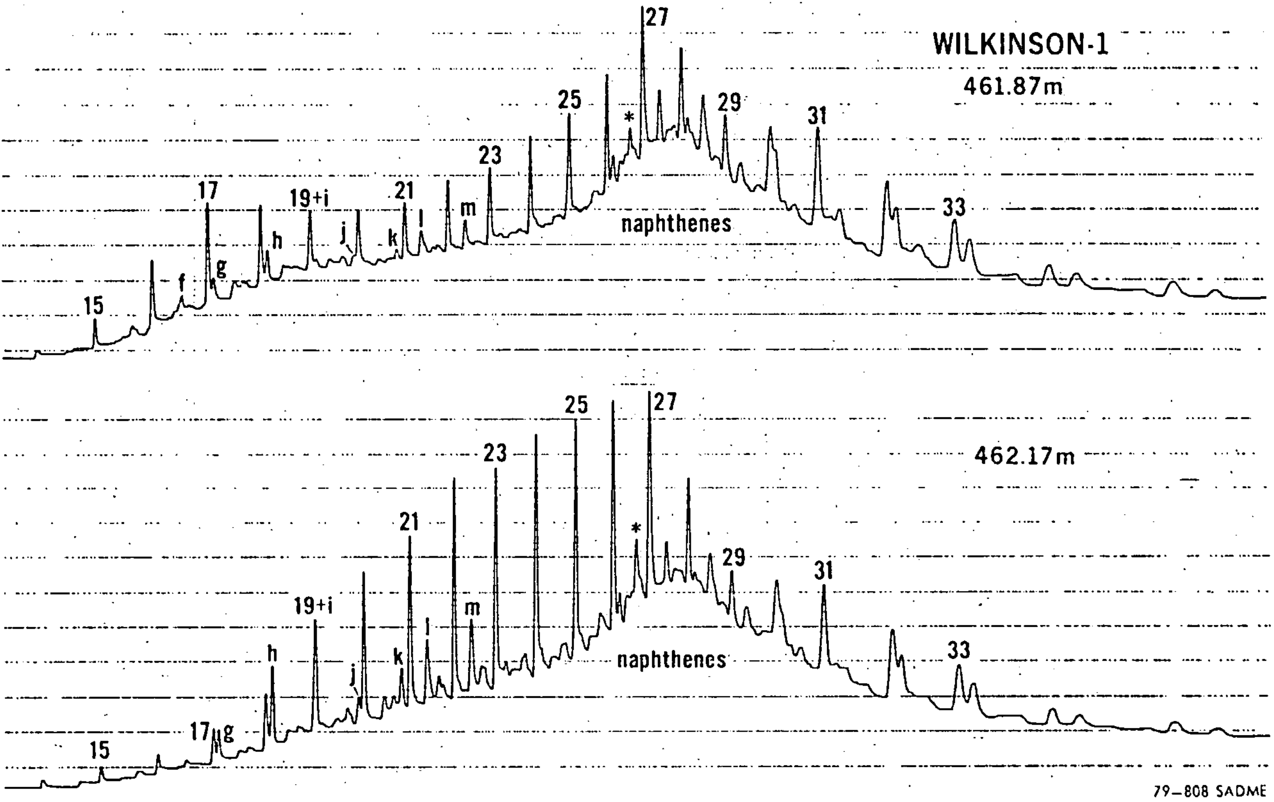

79–808 SADME

Fig. 12

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
ALKANES FROM POTENTIAL OIL-SOURCE ROCKS
OBSERVATORY HILL BEDS
WILKINSON -1

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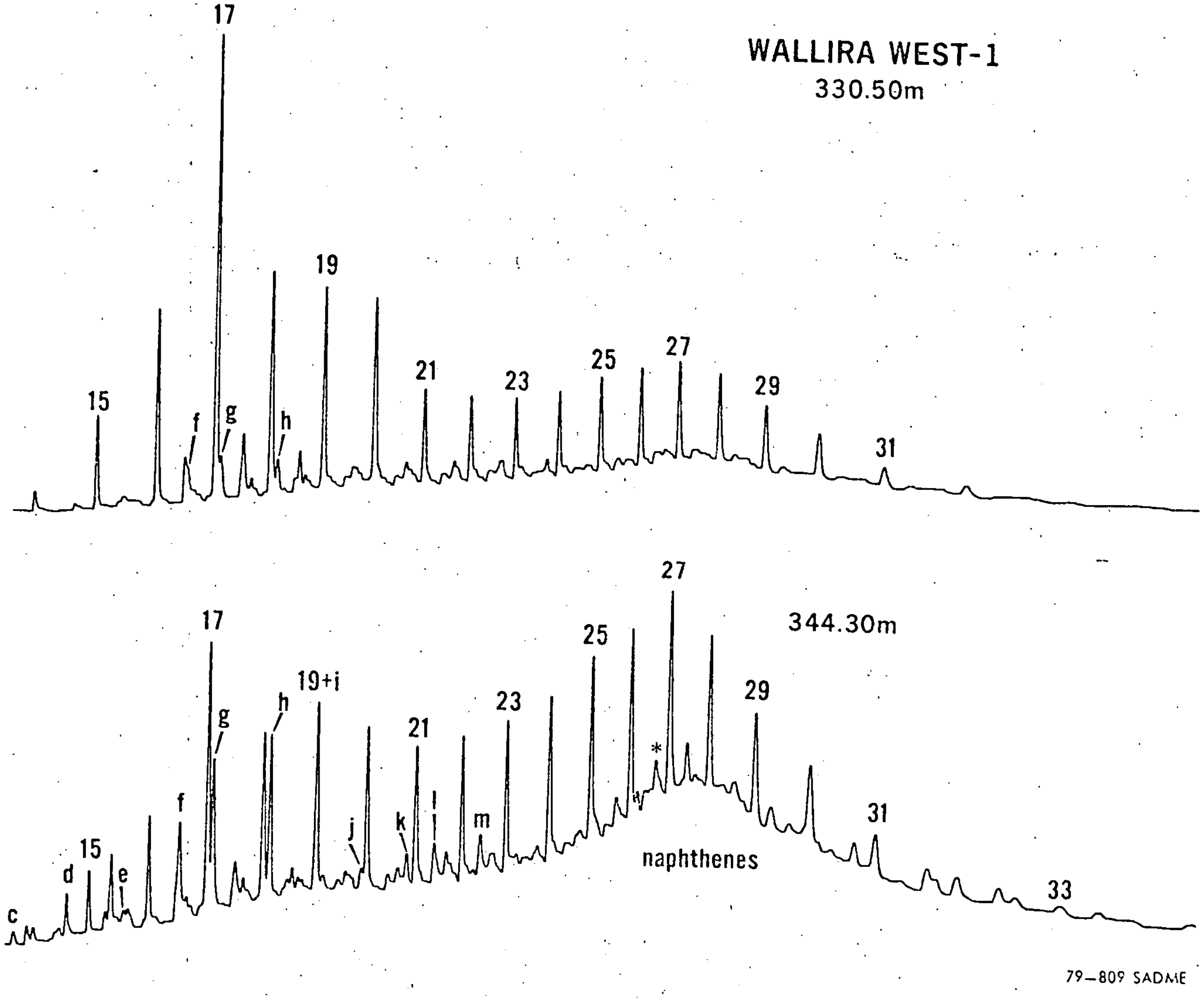

Fig. 13

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
ALKANES FROM ROCK EXTRACTS
OBSERVATORY HILL BEDS
WALLIRA WEST -1

COMPILED D.M.M.	C.D.O. DATE
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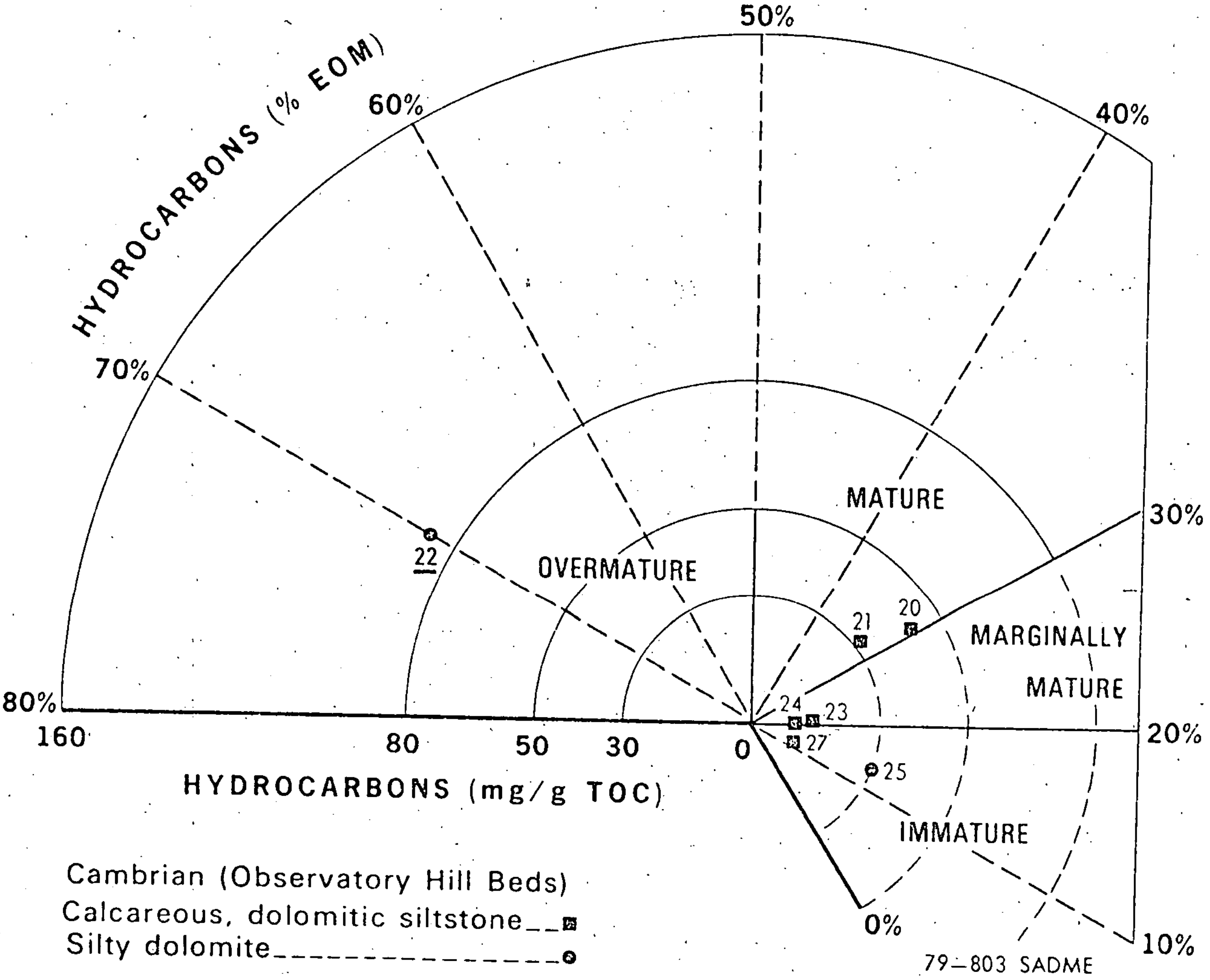
MURNAROO–1



Cambrian (Observatory Hill Beds)
Calcareous, dolomitic siltstone ▣
Silty dolomite ⊙

Fig. 14

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
MATURATION STATE AND HYDROCARBON POTENTIAL
OBSERVATORY HILL BEDS
MURNAROO -1

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DATE 13-1-81	PLAN NUMBER S 15274	
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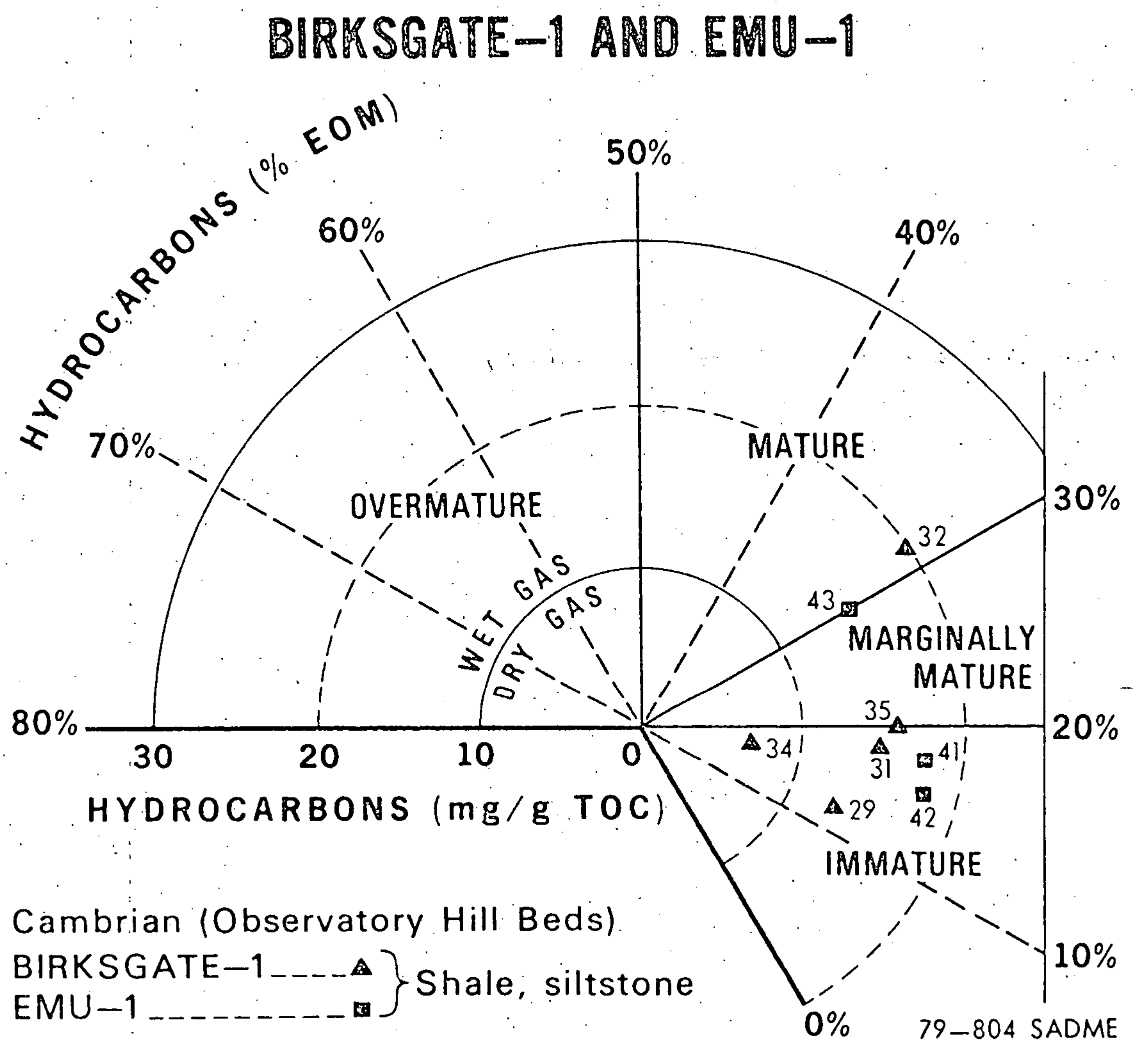

Fig. 15

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
MATURATION STATE AND HYDROCARBON POTENTIAL
OBSERVATORY HILL BEDS
BIRKSGATE -1 & EMU -1

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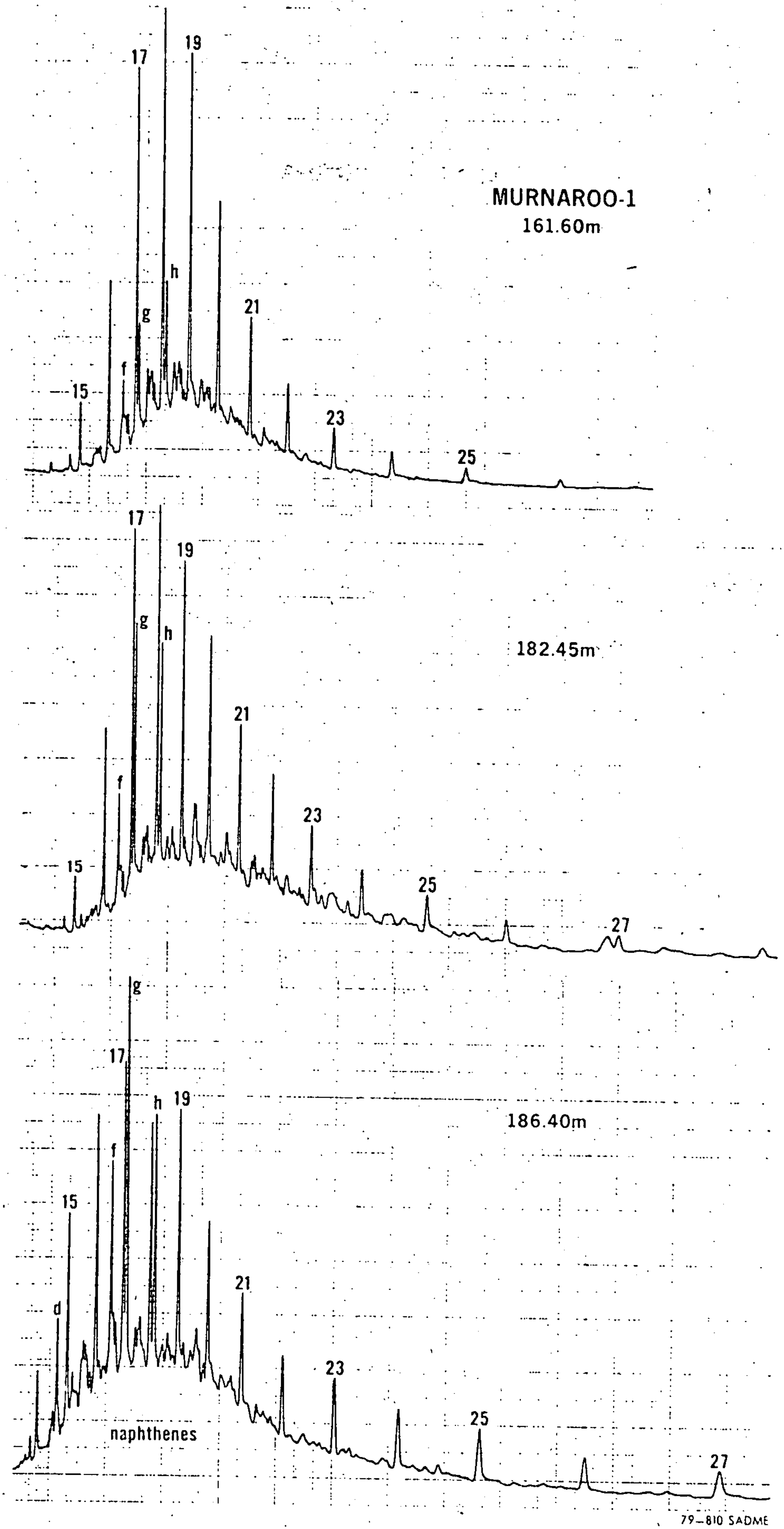

Fig. 16

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES — OFFICER BASIN
ALKANES FROM ROCK EXTRACTS
OBSERVATORY HILL BEDS
MURNAROO -1

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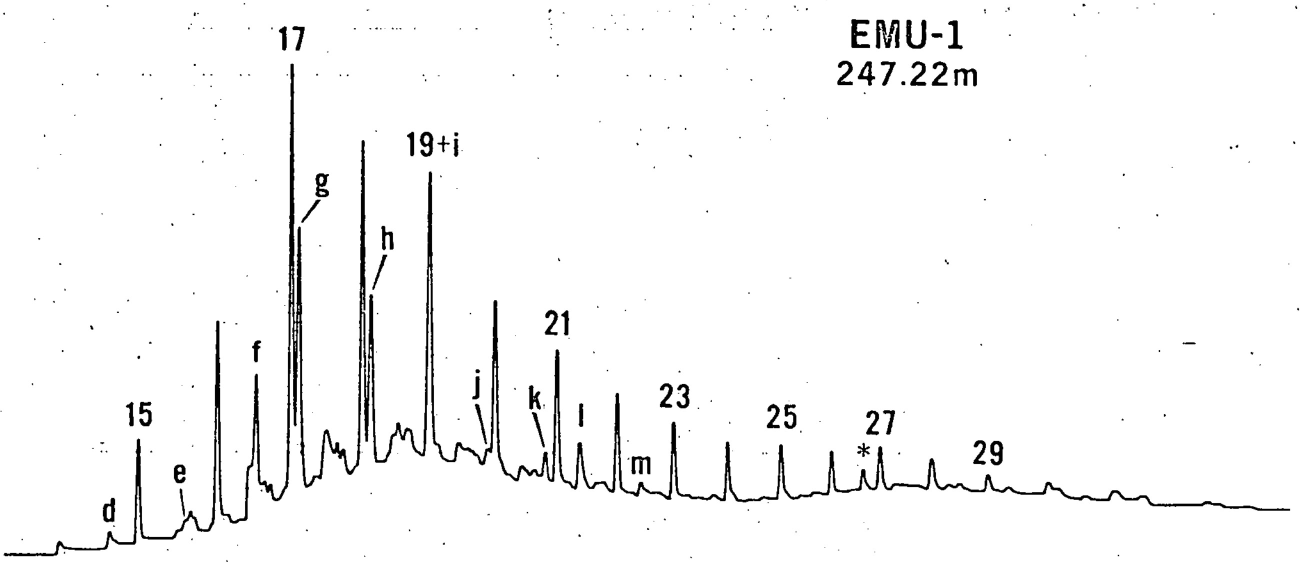

EMU-1
247.22m

79—811 SADME

Fig. 17

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES — OFFICER BASIN
ALKANES FROM SILTY SHALE
OBSERVATORY HILL BEDS
EMU -1

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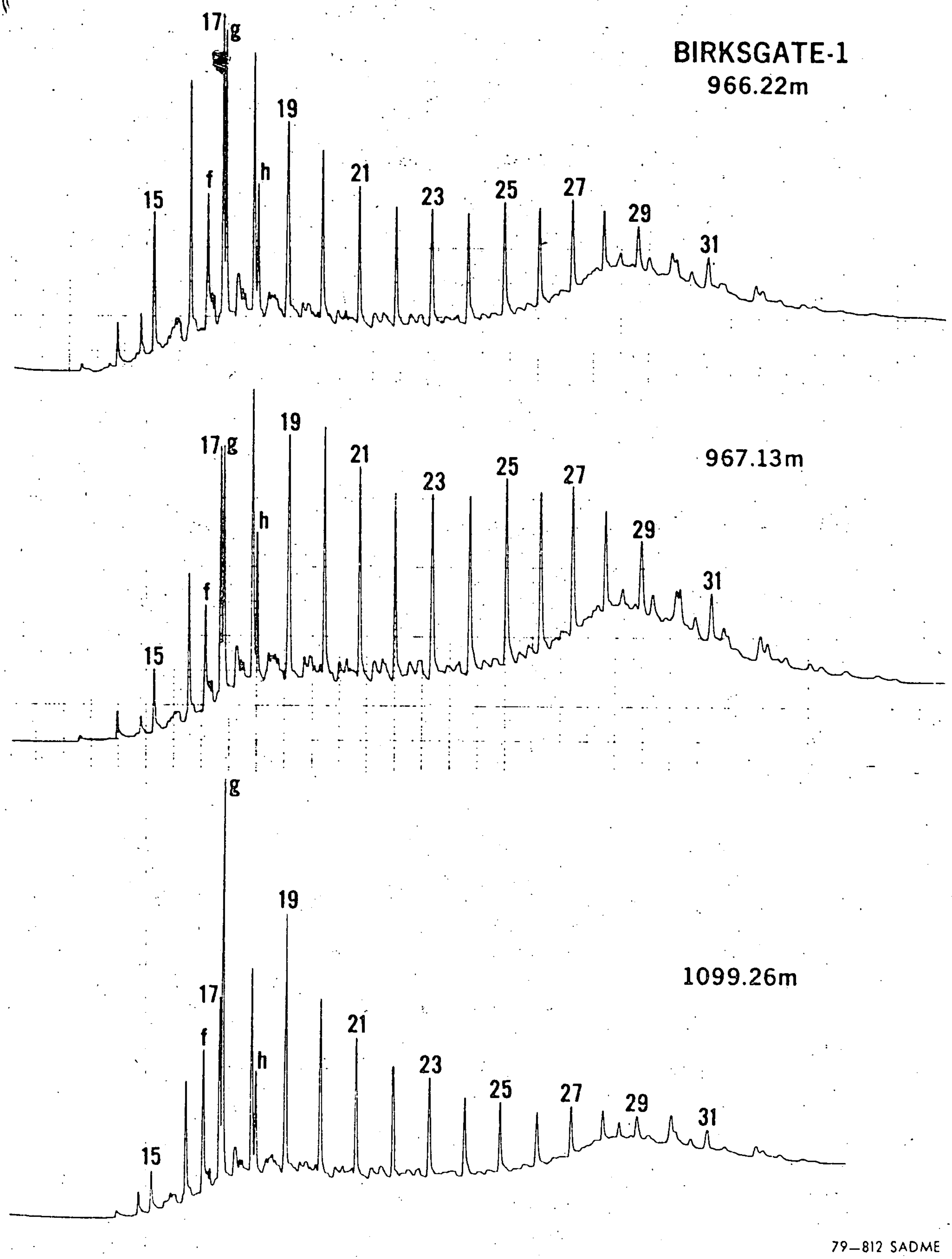

Fig. 18

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES — OFFICER BASIN
ALKANES FROM ROCK EXTRACTS
OBSERVATORY HILL BEDS
BIRKSGATE -1

COMPILED D.M.M.	C D O DATE
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DATE 13-1-81	PLAN NUMBER S 15278
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MUNYARAI–1

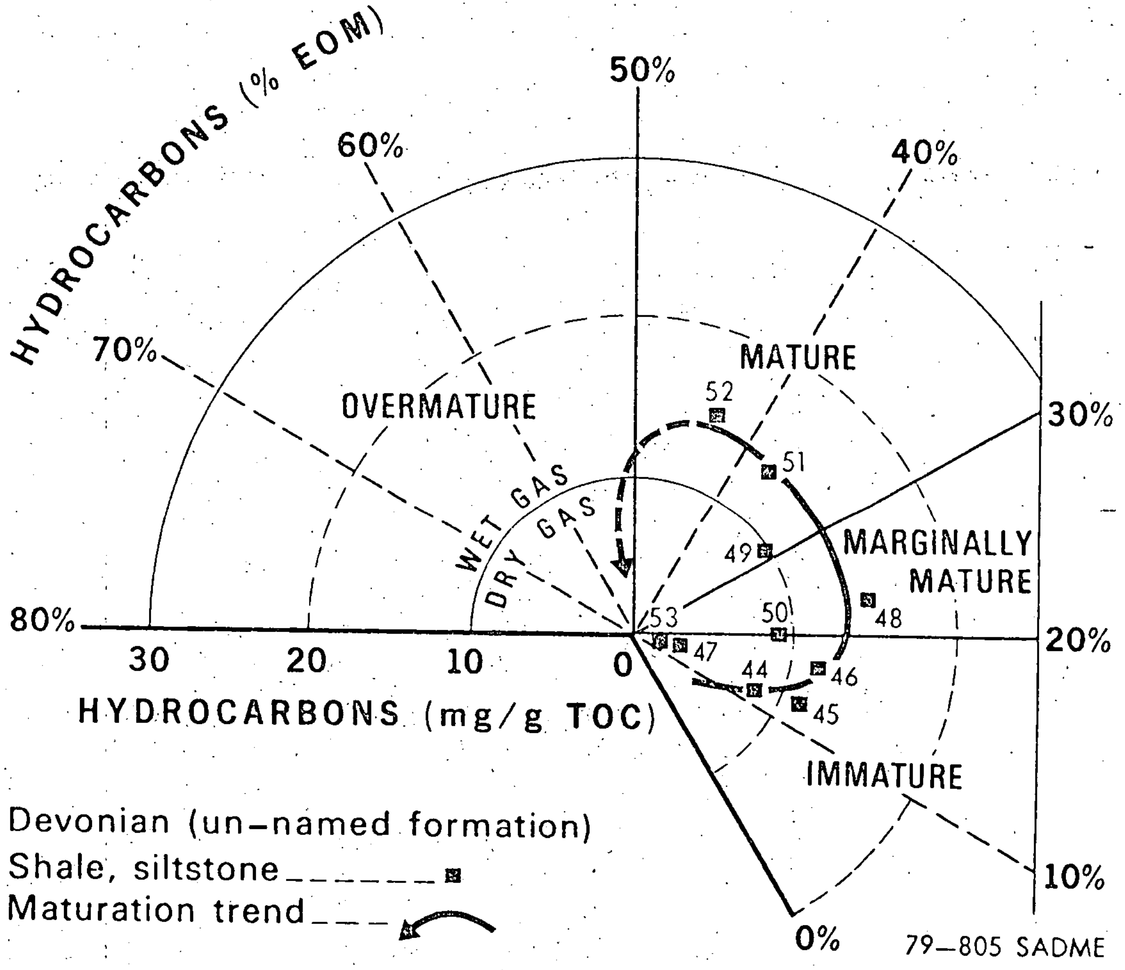

Fig. 19

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES – OFFICER BASIN
MATURATION STATE AND HYDROCARBON POTENTIAL
UNNAMED DEVONIAN FORMATION
MUNYARAI -1

COMPILED D.M.M.
DRAWN N.R.S.
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CDO DATE
SCALE
PLAN NUMBER S 15279

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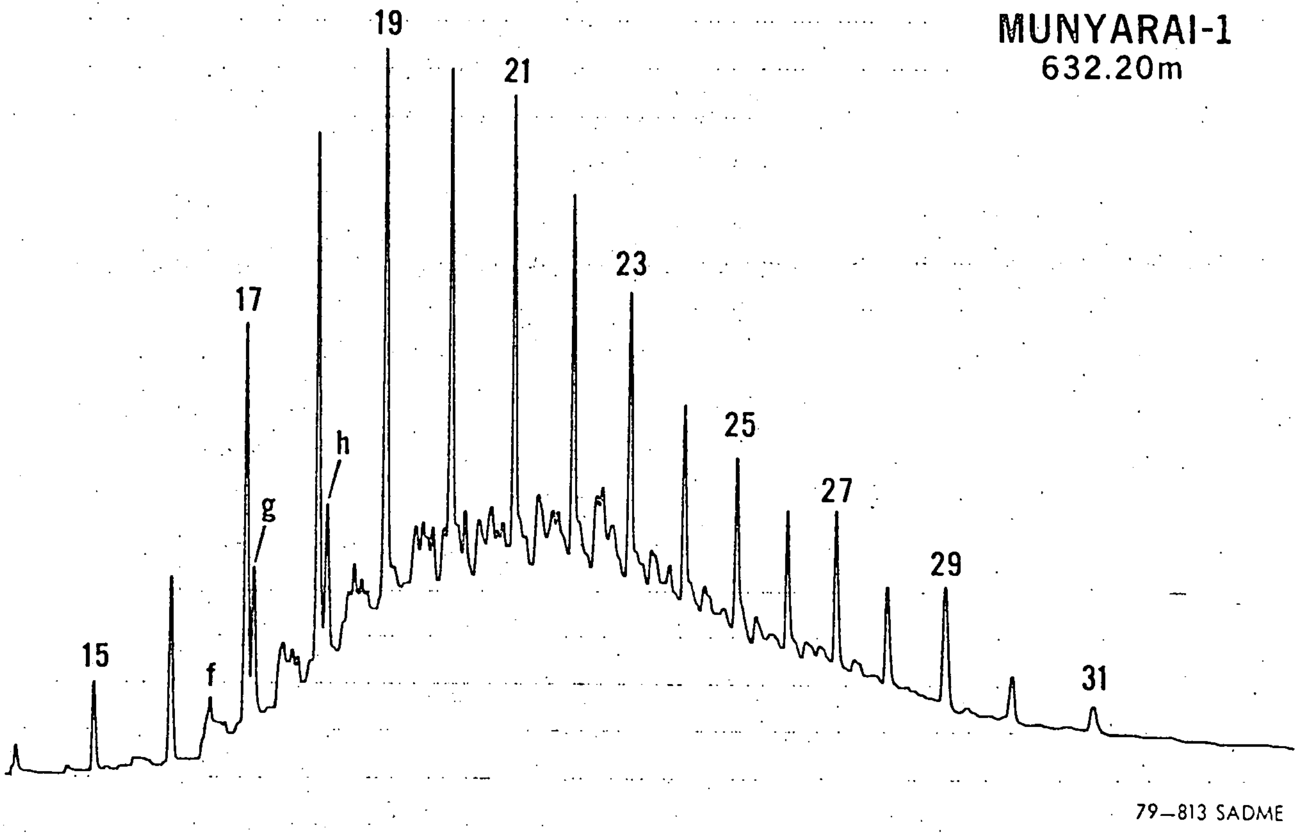

Fig. 20

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

SOURCE ROCK STUDIES — OFFICER BASIN

ALKANES FROM DEVONIAN SILTSTONE

MUNYARAI -1

COMPILED D.M.M.	C D O	DATE
DRAWN N.R.S.	SCALE	
DATE 13-1-81	PLAN NUMBER S 15280	
CHECKED		

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