THE OIL SANDS DEPOSITS OF ALBERTA: THEIR ORIGIN AND GEOCHEMICAL HISTORY

G. Deroo

Institute Français du Pétrole, 1 et 4 Avenue de Bois-Preau, Rueil Malmaison, France

T.G. Powell

Institute of Sedimentary and Petroleum Geology,
3303-33rd Street N.W., Calgary, Alberta, T2L 2A7

INTRODUCTION

The heavy oil deposits and heavy conventional oils of eastern Alberta (Fig. 1) occur in various reservoirs within the Mannville Group of Lower Cretaceous age. The Mannville Group is separated from underlying rocks by a profound angular unconformity which allows strata of different ages to underlie the Mannville Group in different parts of the Alberta syncline. At Peace River the underlying rocks are of Mississippian, Permian and Jurassic age whilst at Athabasca, Cold Lake and Lloydminster the underlying rocks are various formations of Devonian age. Montgomery *et al.* (1) have summarized the various theories that pertain to the origin of heavy oil deposits of eastern Alberta. Briefly these theories are:

1. The heavy oils are conventional oils which have become altered by biodegradation and associated phenomena. They could have either a Devonian or a Lower Cretaceous source.
2. The heavy oils are young immature unaltered oils.
3. The heavy oils are derived from organic matter which was deposited *in situ* with the host sands.

In this report, evidence will be presented to show the chemical similarity of the heavy oils of the Lloydminster area and the heavy oil deposits, to conventional oils occurring in the central part of the Alberta syncline. Secondly the effects of alteration, particularly biodegradation, will be demonstrated for both the conventional oils and the heavy oil deposits. Finally the geochemical processes which lead to the formation of heavy oils and oil sands will be examined by detailed comparison of the composition of normal and secondarily altered oils at various levels of thermal maturation. The techniques and samples employed in this study have been summarized by Deroo *et al.* (2, 3). Saturated hydrocarbons obtained from rock extracts and oils were examined by capillary gas chromatography and mass spectrometry. The distribution of monoaromatics, diaromatics, polyaromatics and thiophenic compounds were determined by capillary gas chromatography using both flame ionisation and flame photometric detectors and by mass spectrometry at a low ionisation potential (10eV).

HEAVY OILS OF THE LLOYDMINSTER REGION

In the central part of the basin, oils (Group 2) reservoired in the Mannville Group (Lower Cretaceous) Jurassic and Mississippian are readily distinguished from the oils occurring in the Devonian (Group 3) and the Colorado Group (Lower to Upper Cretaceous) (Group 1) on the basis of their gross composition (Fig. 2). The oils occurring in the Mannville, Jurassic and Mississippian are richer is sulphur, aromatic hydrocarbons, resins and asphaltenes than either Groups 1 or 3 (Fig. 2) The high sulphur contents are reflected in the large amounts of benzothiophenes and dibenzothiophenes in the oils (Fig. 2) and the dibenzothiophenes have a characteristically wide distribution by carbon number (range C_{21} to C_{30}) (2, 3). Detailed analysis of rock extracts has shown that the Group 2 oils have their source in the fine-grained sediments of the Mannville Group. This correlation is based on the

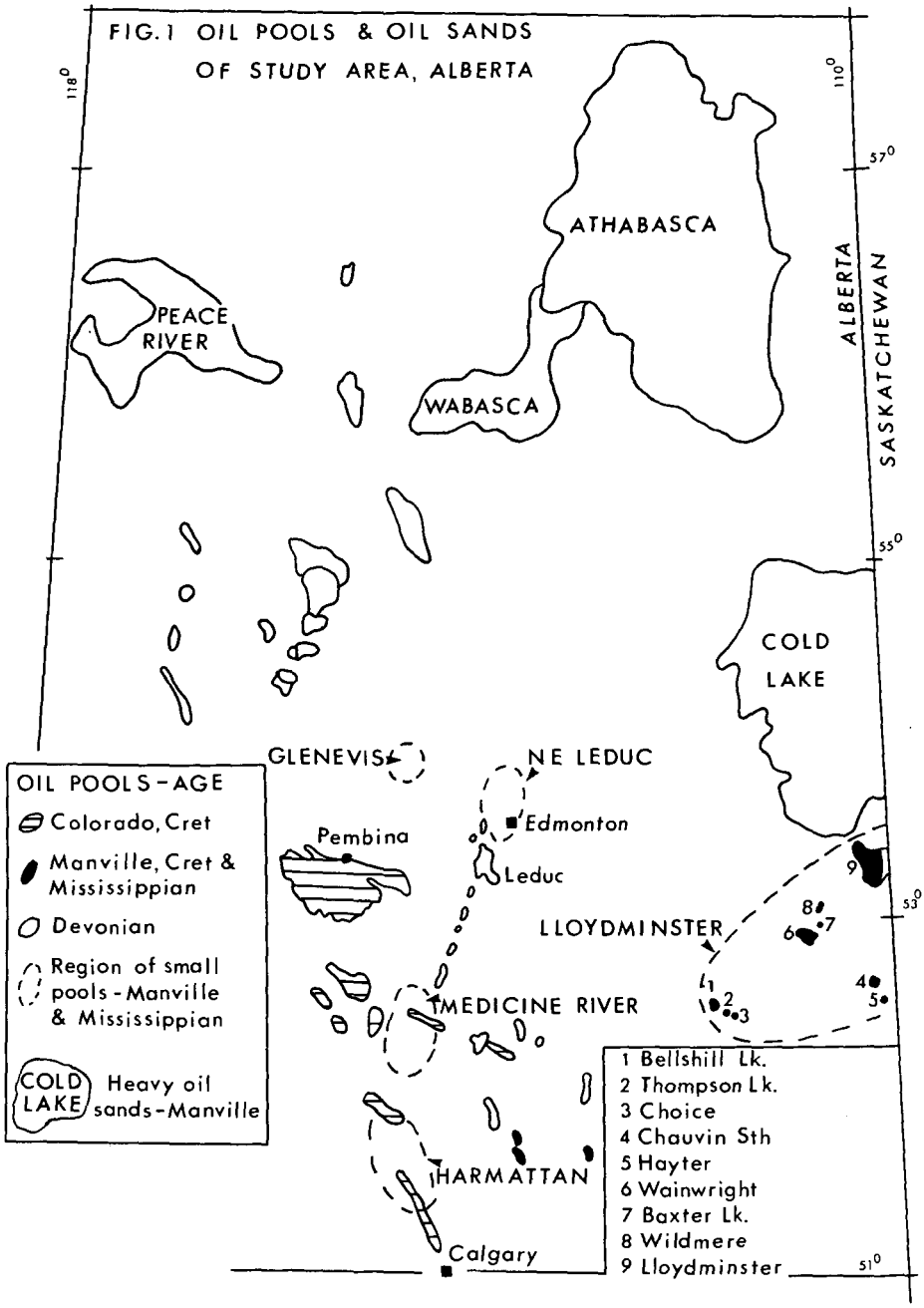
FIG. 1 OIL POOLS & OIL SANDS
OF STUDY AREA, ALBERTA
118°
110°
57°
55°
53°
51°
ATHABASCA
PEACE RIVER
WABASCA
ALBERTA
SASKATCHEWAN
COLD LAKE
GLENEVIS
NE LEDUC
Edmonton
Pembina
Leduc
LLOYDMINSTER
MEDICINE RIVER
HARMATTAN
Calgary
OIL POOLS - AGE
Colorado, Cret
Manville, Cret & Mississippian
Devonian
Region of small pools - Manville & Mississippian
COLD LAKE
Heavy oil sands - Manville
1 Bellshill Lk.
2 Thompson Lk.
3 Choice
4 Chauvin Sth
5 Hayter
6 Wainwright
7 Baxter Lk.
8 Wildmere
9 Lloydminster

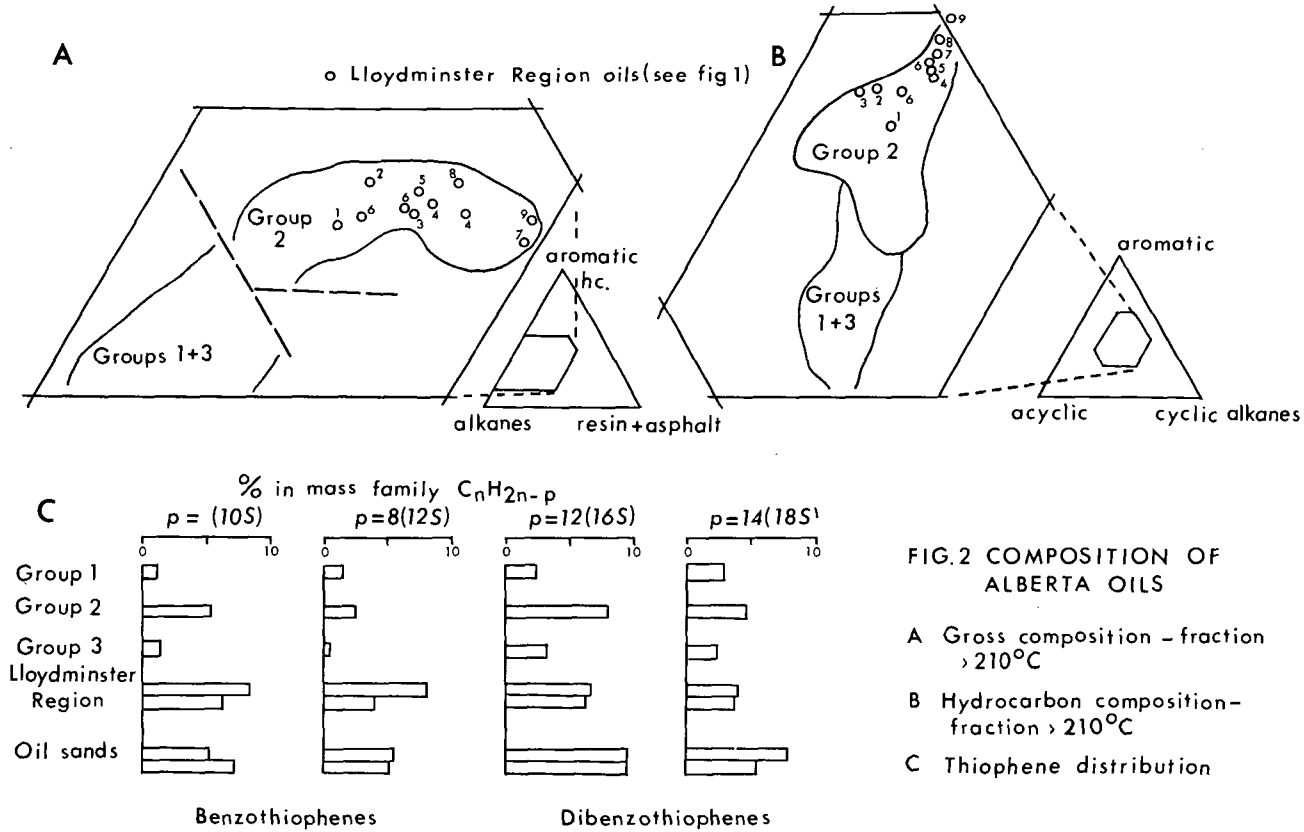

FIG. 2 COMPOSITION OF ALBERTA OILS

A Gross composition – fraction > 210°C

B Hydrocarbon composition – fraction > 210°C

C Thiophene distribution

distribution of the various mass families in the aromatic fractions and in particular the distribution of benzothiophenes and dibenzothiophenes (3).

The oils from the Lloydminster region which are reservoired within the Mannville Group, have similar sulphur contents (above 2%) and are similar in composition to the Group 2 oils (Fig. 2). They are however, slightly richer in aromatic hydrocarbons, resins and asphaltenes than the majority of the oils and form a discrete group at the limit of the field of composition of the Group 2 oils. However, within the Lloydminster region there is considerable variation in the distribution of the saturated hydrocarbons. Gas chromatographic analysis reveals that a number of samples have undergone biodegradation i.e. the n-alkanes have been partially or completely removed by bacterial activity. This can be appreciated by comparison of the ratio of pristane and phytane to the C_{17} and C_{18} normal alkanes in the different oils. The oils with ratios below 0.60 are unaltered, namely Bellshill Lake, Thompson Lake, Choice and Wainwright (Lloydminster Fm.). Those with ratios between 0.60 and 1.00 have had some n-alkanes removed, namely Wainwright (Wainwright Fm.). A ratio of 1.00 corresponds to the type a stage of biodegradation previously defined (2) for the heavy oil extracts (Fig. 3). Ratios between 1.00 and 2.00 (Baxter Lake, Chauvin South - Sparky Fm.) demonstrate the progressive renewal of n-alkanes. Finally in the Wildmere and Lloydminster samples only the isoprenoids remain and are equivalent to the type b level of biodegradation in the heavy oil extracts (Fig. 3).

Biodegradation of the saturated hydrocarbons has occurred in the Mannville oils between the Wainwright, David and Lloydminster pools but it has not affected those from Bellshill Lake, Thompson Lake and Choice lying to the southwest (Fig. 1). The alternate theory (1) that an immature unaltered oil (Lloydminster) has undergone cracking reactions to yield oils with n-alkanes (Thompson Lake, Bellshill Lake and Choice) is untenable for the following reasons.

(1) The oils lie at closely similar depths 2500 ± 500 feet which is insufficient for any marked maturation difference.
(2) Independent indicators of thermal maturation such as moisture contents and vitrinite reflectance values of coals indicate little maturation variation (4).
(3) The progressive change in n-alkane content relative to isoprenoids is explained on the basis of biodegradation but is not explained by a thermal maturation theory.

Mass spectrometric evidence from two oils (Choice and Lloydminster) indicates a close similarity to the Group 2 oils but they contain a higher proportion of monoaromatic steroids and triterpenoids than the oils from the central part of the basin.

HEAVY OIL DEPOSITS

Evidence showing the progressive biodegradation of the heavy oil extracts between Bellshill Lake and the heavy oil deposits at Athabasca has been presented previously (2). The stages in the transformation are illustrated in Figure 3 with type examples. Type a is illustrated by the Edgerton sample in which there is a decrease in the n-alkane content with an apparent increase in the proportion of isoprenoid compounds. Type b oils are those in which the n-alkanes have disappeared totally but pristane and phytas are relatively unaffected. Type c extracts contain no normals or isoprenoids. The coincidence of alteration with the occurrence of relatively fresh water in the reservoirs and the selective removal of first the n-alkanes and then the isoprenoids support the biodegradation theory.

It is evident from the distribution of the cyclo-alkanes that the heavy oil deposits resemble the Group 2 oils (2). The same conclusions have been reached

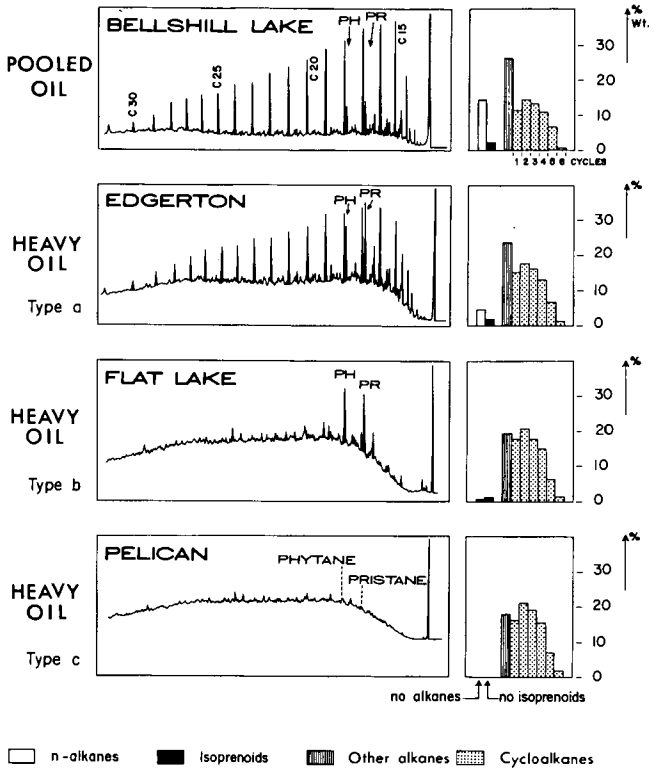

FIG 3 EFFECTS OF BIODEGRADATION ON NORMAL AND ISOPRENOID ALKANES IN OIL SANDS

when one considers the distribution of aromatic hydrocarbons and sulphur compounds as determined by capillary gas chromatography (2) and mass spectrometry (Fig. 3). The characteristic features are the importance of the thiophenes particularly the dibenzothiophenes in the range C_{21} to C_{35} in the mass families $C_nH_{2n-16}S$ and $C_nH_{2n-18}S$ and the higher concentration of these families than the phenanthrene family (C_nH_{2n-18}) is the polyaromatic fraction.

PROCESSES LEADING TO THE FORMATION OF HEAVY OIL DEPOSITS

On the basis of the foregoing discussion one would suppose that the higher sulphur, resin and asphaltene contents of oils in the Lloydminster region might be solely a consequence of concentration brought about by alteration processes. This is not exclusively the case since the unaltered oils in this region (Wainwright, Thompson Lake, Choice and Bellshill Lake) have resin and asphaltene contents which are higher than many unaltered oils in the Mannville from the central part of the basin (Fig. 2). The question is put in perspective if we examine the distribution of reserves of Group 2 oils against an independent measure of maturity such as vitrinite reflectance (Fig. 4).

It is evident that the Lloydminster oils occur at a relatively low maturation level compared with the remainder of the oils in the central part of the basin. In addition in the Lloydminster region the content of steroids and triterpenoids (C_{25} and above) in the mass families C_nH_{2n-12} and C_nH_{2n-14} is higher than in the unaltered oils to the west and is indicative of a maturation trend across the basin. In Figure 5 the maturation trend across the basin is illustrated by variations in gross composition of oils which occur in the Mannville Group. There is a progressive decrease in resin, asphaltene and aromatic hydrocarbon content towards the west. However, at each stage of maturation there is an enrichment in resins and asphaltenes in certain oils. In the Lloydminster region this is attributed at least in part to biodegradation whereas in the central part of the basin it occurs where oil from the Mannville crosses the pre-Cretaceous unconformity into underlying formations (Mississippian or Devonian).

In order to distinguish the effects of alteration relative to thermal maturation, it is necessary to examine these effects in restricted areas within which variations in maturation levels are minimal. For this purpose detailed examination of the aromatic fractions of a series of oils has been undertaken in areas where the geothermal gradient is relatively constant. The relative stages of maturation within these areas can be distinguished by consideration of the maximum depth of burial.

The effects of alteration on the aromatic fraction can be summarized as follows:

1. In the mass family C_nH_{2n-8} there is a shift in the mode to higher carbon numbers.
2. In the mass families C_nH_{2n-12} and C_nH_{2n-14} there is an overall enrichment, particularly in the range above C_{20} or C_{25} in the former family.
3. In the diaromatics of the families C_nH_{2n-12} and C_nH_{2n-14} there is
   (a) a decrease in the total percentage
   (b) a decrease in the mode or/and
   (c) a displacement of the mode to higher carbon numbers
4. In the thiophene families $C_nH_{2n-10}S$, $C_nH_{2n-12}S$ and $C_nH_{2n-18}S$ there is
   (a) an increase in their concentration
   (b) an enrichment in the higher carbon number ranges (C_{20} and above) accompanied by/or -
   (c) a decrease in the concentration of compounds in below C_{20}.

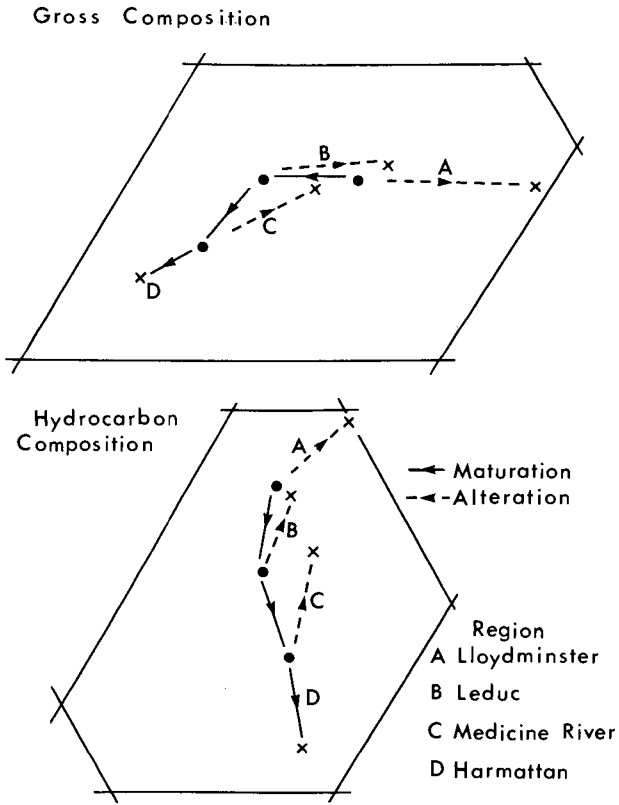

FIG. 5 EFFECTS OF MATURATION AND ALTERATION ON OIL COMPOSITION (GROUP 2) (see fig 2 for key)

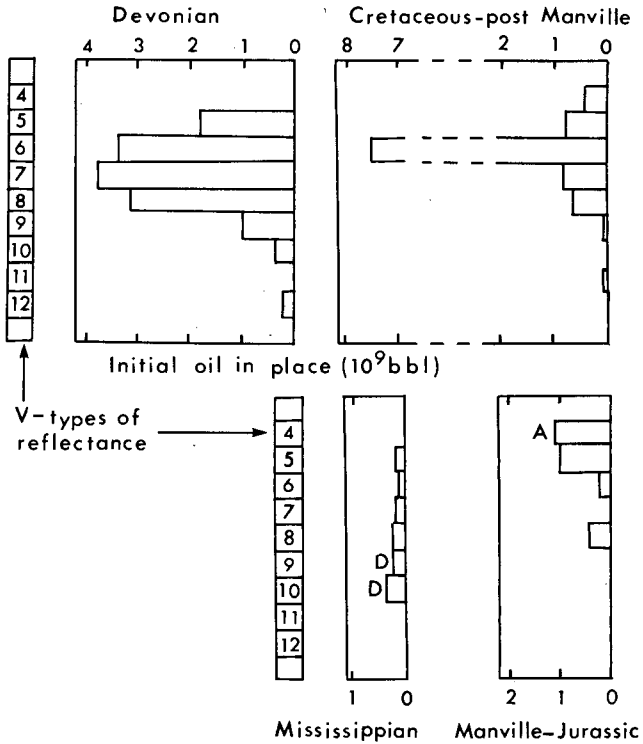

FIG. 4 RELATION BETWEEN OIL DISTRIBUTION AND MATURATION LEVEL (after Hacquebard)

In this context the term alteration is used to designate both the consequences of secondary migration and bacterial degradation, water washing and inorganic oxidation. These processes are examined in successive maturation zones.

Zone 1 Geothermal Gradient 30°C per 1000 m. This zone includes the oil pools adjacent to the Foothills and the Glenevis region. In the Medicine River region the Jurassic and Mississippian oils have a shallower depth of burial than the from the Mannville because of the structural position of the pools. They have variations 1, 3a and b, in comparison with the Mannville oil and they have a higher content of benzothiophenes (Fig. 6A). The Mississippian and Jurassic oils at Medicine River are in reservoirs of similar depths of burial and have similar gas to oil ratios (GOR) which are lower than that for the Mannville reservoir. The observed variations are considered to be due to secondary migration of the more mobile compounds. The oils in the Jurassic and Mississippian are trapped beneath the pre-Cretaceous unconformity. Leakage of light components along the unconformity would explain the observed phenomena.

The Mississippian oils from Harmattan to the southwest of the Medicine River pools are clearly more deeply buried. The high distillate content, overall composition, (Fig. 5) distribution of n-alkanes, cyclic-alkanes and aromatic compounds (Fig. 5) indicate a higher degree of maturation than the Medicine River oil. However, as well as being richer in non-aromatics (Fig. 6A) than the previous oils it also shows variations 1, 3a and b for the mass families C_nH_{2n-12}. This anomaly can be explained by secondary migration of the more mobile components to higher reservoirs. In the Harmattan East field the oils in the Mannville reservoirs have a higher GOR than that in the underlying Mississippian.

The Mississippian oil from the Glenevis region lying to the north of the oils discussed above has been the least buried of oils from this zone. It shows variations 1, 2, 3a and b in the mass families C_nH_{2n-14}, a relative increase in the concentration of dibenzothiophenes beyond C_{10} and a lower maturation state than the Medicine River oils. Thus within this zone the oils of the Glenevis region have undergone least maturation whilst that from Harmattan East has suffered the most maturation. This conclusion is consistent with the palaeotemperatures derived from coal rank studies (4). The estimated palaeotemperature of pools in the Glenevis region is 76°C whilst those at Medicine River and Harmattan East are 111°C and 127°C respectively. Oils occurring in Mississippian and Jurassic reservoirs have been affected by secondary migration; the lighter hydrocarbons have probably escaped from the reservoirs along the unconformity leaving in place the less mobile components.

Zone 2 Geothermal Gradient 40°C per 1000 m. This zone includes most of the oils in production and contains altered oils such as Lloydminster or unaltered oils as at Leduc and Pembina. It also includes heavy oil extracts which may be altered or unaltered.

The Pembina sample (Fig. 6B) which has been buried the deepest of this group, has characteristics similar to the Mannville sample from Medicine River. The latter is more deeply buried but occurs in a zone with a lower geothermal gradient. An oil from Leduc-Woodbend occurs in the Wabamun (Devonian) directly under the pre-Cretaceous unconformity. It shows varieties 1, 3a and b in the aromatic compounds and variation 4a in the thiophenic compounds (Fig. 6B). The oil occurring in the Wabamun Formation has a lower GOR than oils in the reservoirs above the unconformity in the same field. Here again, the variations can be attributed to secondary migration.

Impregnations consisting of concentrations of heavy fractures could be residues from migration, a product of alteration processes or could be an original unaltered oil. A heavy oil extract from the Wabamun at Golden Spike (adjacent to the Leduc

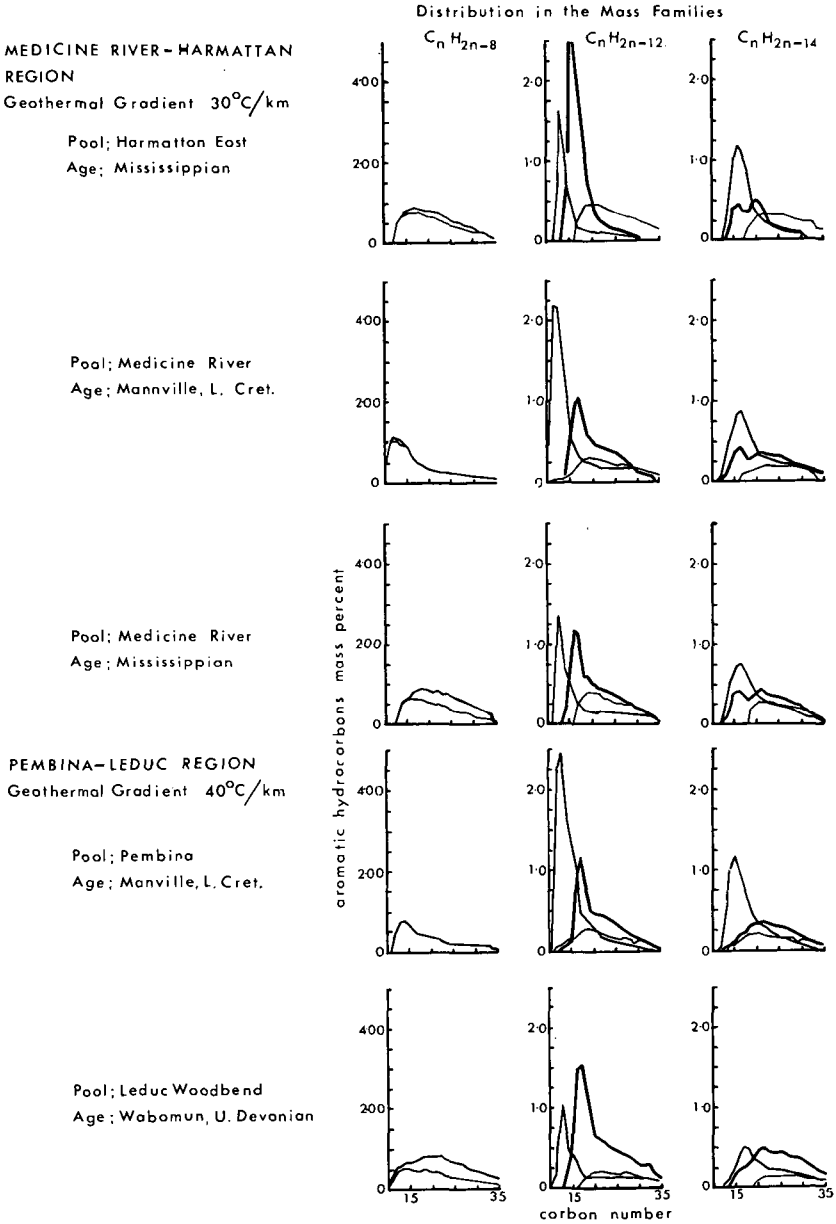

FIG 6 DISTRIBUTION OF AROMATICS IN GROUP 2 OILS AT VARIOUS MATURATION LEVELS

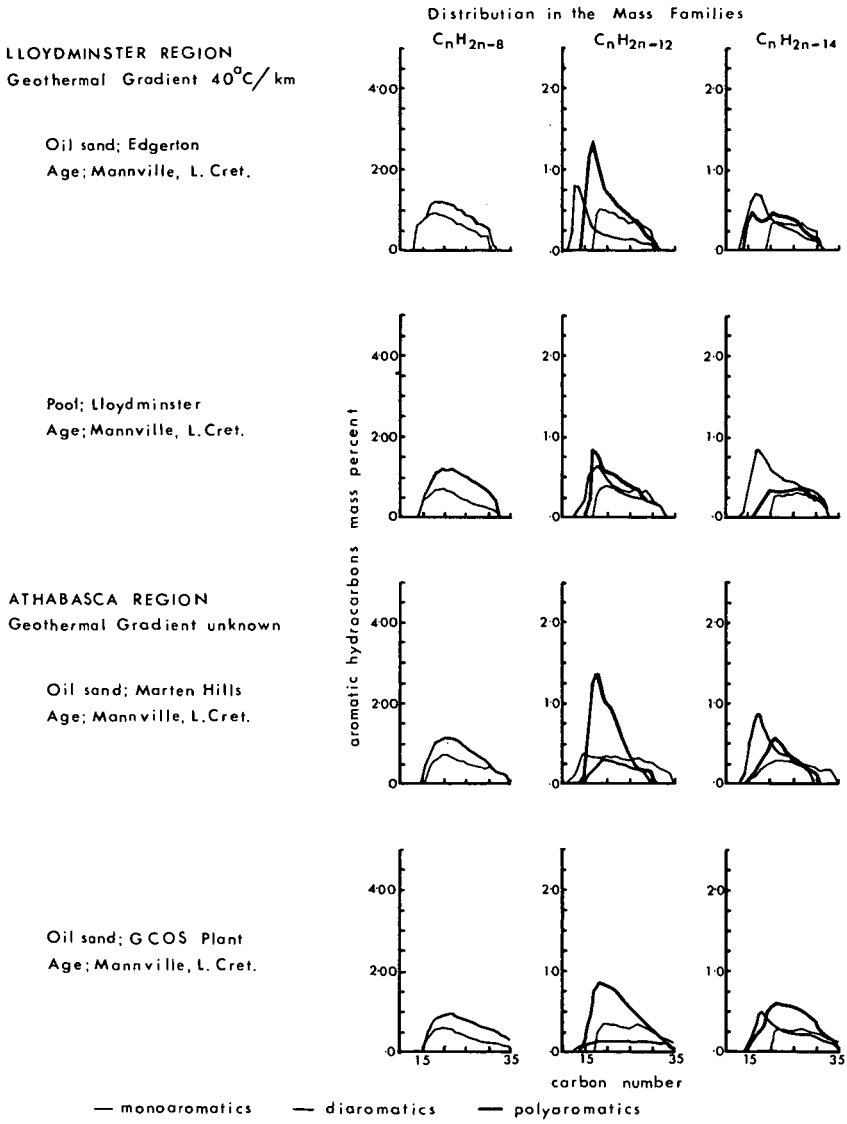

FIG 6 continued

field) is very similar to the Wabamun oil at Leduc Woodbend discussed above. It is considered to be a residue left from secondary migration. A heavy oil extract from Edgerton (Mannville) Figure 6C closely resembles the Golden Spike extract. Although less deeply buried, the Edgerton sample can only be C_nH_{2n-8} distinguished from the Golden Spike sample by its higher content of monoaromatic (mass families C_nH_{2n-12} and C_nH_{2n-14}) particularly the steroid and triterpenoid compounds above C_{25}. The difference can be attributed to the lower degree of maturation of the former. The Edgerton and Golden Spike samples tend to contain few light monoaromatic compounds ($<C_{20}$) in the mass family C_nH_{2n-8} and even less in the families C_nH_{2n-12} and C_nH_{2n-4}; this is probably the result of secondary migration.

The heavy oil from the Lloydminster pool is in its turn compared with the Edgerton sample (Fig. 6C) since the geothermal gradient and depths of burial are similar. The relative importance of the monoaromatics beyond C_{25} in the mass families C_nH_{2n-12} and C_nH_{2n-14} can be interpreted as due to a low degree of maturation, but the effect of concentration due to alteration must be considered. The effects of alteration are shown in the aromatic and thiophenic compounds by variations 1, 3c, 4b and c. These changes are greater than those attributed solely to secondary migration. A certain degree of alteration of the aromatic fraction accompanies the bacterial removal of n-alkanes in the saturate fraction (Type b). This alteration is attributed to water washing of the relatively soluble aromatic compounds, to inorganic oxidation of weakly soluble or insoluble compounds and/or possibly the biodegradation of some benzothiophenes.

Zone 3 Unknown Geothermal Gradient. This part concerns the heavy oil deposits in the most northerly part of the study area (Fig. 1). The present geothermal gradients are unknown but the burial depths are estimated to be equivalent to those of the preceding samples; this assumption is supported by the parallel significance of the heavy monoaromatics (C_{25+}) in the families C_nH_{2n-12} and C_nH_{2n-14} (Fig. 6D).

The aromatics from the Marten Hills sample (type b biodegradation) show the same alteration effects observed in the Lloydminster oil and are attributed to water washing and inorganic oxidation. The sample from the GCOS Plant has the most degraded saturated hydrocarbons (type c). The same changes occur with regard to the aromatics as were observed in the Marten Hills and Lloydminster oils but variation 3c is particularly significant. This sample represents the most advanced stage of alteration of the aromatics by water washing and inorganic oxidation.

Summary

The heavy oil deposits and the heavy conventional oils of eastern Alberta resemble the conventional oils reservoired in Lower Cretaceous (Mannville) sediments in the central part of the basin and as such differ in origin from the Devonian oils. They are, however, relatively less mature than the contemporaneous oils to the west. Although their relative immaturity can partially account for their heavy character, secondary processes such as biodegradation, water washing, secondary migration of light components and possibly some inorganic oxidation results in the concentration of heavy ends with the ultimate formation of solid bitumen.

Comparative analyses of the aromatic hydrocarbons of the Group 2 oils allows the relative significance of maturation and alteration to be assessed as follows:

1. In the main oil field area, all oils located beneath the unconformity (Jurassic, Mississippian or Devonian) are altered as a result of secondary migration of the lightest components from the reservoir to vertically or laterally higher reservoirs. The geochemically defined

maturation state of the oils in zones with comparable geothermal gradients correspond well to their respective depths of burial.

2. In the heavy oil zone, to the north of the main field area, all oils have undergone less maturation than the preceding oils. In addition to the effects of secondary migration, the aromatics from these oils have undergone degradation by water washing and inorganic oxidation which are associated with the biodegradation of the alkanes. These effects are at a maximum in the reservoirs closest to the Cretaceous unconformity even if the biodegradation of the normal alkanes has not reached the most advanced stage. In all probability, the unconformity corresponds to an aquifer and controls the distribution and alteration of hydrocarbons in its vicinity.

LITERATURE CITED

1. Montgomery, D.S., Clugston, D.M., George, A.E., Smiley, G.T. and Sawatzky, H., Can. Soc. Petroleum Geol. Mem. 3, 168 (1974).
2. Deroo, G., Tissot, B., McCrossan, R.G. and Der, F., Can. Soc. Petroleum Geol. Mem. 3, 148 (1974).
3. Deroo, G., Powell, T.G., Tissot, B. and McCrossan, R.G., Geol. Surv. Can. Bull. 262 in press.
4. Hacquebard, P.A., Geol. Surv. Can. Bull. 262 in press.