

Geochemistry of selected crude oils from Sabah and Sarawak

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Abstract: A total of 35 crude oils from 15 fields from offshore Sabah and Sarawak have been analysed and characterised using liquid and gas chromatography, and gas chromatography-mass spectrometry.

The normal alkane distribution shows that the oils are of three different types, namely,

- i) normal, non-waxy crude oils;
- ii) waxy oils (high proportion of C_{20} , n-alkanes);
- iii) biodegraded oils (less abundance of n-alkanes relative to isoprenoids).

Biological marker distributions (i.e. steranes and triterpanes) show that the oils were derived from terrigenous source rocks containing mixtures of different types of landplant derived organic matter, including resins. Features of these distributions include the presence of relatively high concentrations of 18α (H)-oleanane, a number of resin-derived compounds, a predominance of C_{29} steranes compared to the relatively low concentrations of C_{28} and C_{27} steranes, and the absence of C_{30} steranes in all the samples.

Source rock matter for these oils were probably deposited under peat swamp environments, as indicated by the high pristane/phytane (>3.0) and pristane/ nC_{17} (>1.0) ratios. Biological marker distributions indicate that the oils were generated from source rocks having maturities of 0.5% to at least 0.8% VRe (Vitrinite Reflectance Equivalent).

INTRODUCTION

Oils generated from source rocks containing land plant material are generally light, highly paraffinic and with a high wax content (Hedberg, 1968). They characteristically have high pristane/phytane (>3.0) and pristane/ nC_{17} (>1.0) ratios due to deposition of the source rocks under relatively low reducing conditions and at relatively low pH, e.g. in peat swamp environments (Sofer *et al.*, 1989). Studies carried out elsewhere suggest that it is possible to distinguish oils derived from terrigenous source material on the basis of their biomarker distributions. The depositional environment and maturity level of the source rocks which have generated the crude oils may also be estimated. In certain cases, it is also possible to distinguish oils from different geological periods. The presence of 18α (H)-oleanane, for example, appears to be indicative of Tertiary oils containing a significant proportion of terrigenous source material (Philp and Gilbert, 1986).

This study describes the application of the geochemical biological markers approach to the elucidation of the origin and maturity of crude oils from offshore Sabah and Sarawak. A total of 35 crude oil samples from 15 fields, drilled offshore Sabah and Sarawak (Fig. 1A & 1B) were analysed using liquid and gas chromatography, and gas chromatography-mass spectrometry to study their biomarker distributions.

EXPERIMENTAL PROCEDURES

Analysis of physical properties such as density, pour point, and sulfur content was not done because of the small amounts of samples available. The API gravity values used in this paper are quoted from old reports prepared by Production Sharing Contractors. The following analytical techniques were utilised for characterisation of the crude oils.

Liquid column chromatography

About 50 mg of each of the crude oils was adsorbed onto some alumina and charged to a prepacked alumina/silica gel column. Elution was then carried out successively with petroleum spirit (40-60°C), dichloromethane, and methanol, giving fractions of saturated hydrocarbons, aromatic hydrocarbons and NSO (nitrogen, sulphur and oxygen) compounds, respectively.

Gas Chromatography

The saturated hydrocarbon fractions were analysed using a HP 5890A Chromatograph equipped with a flame ionisation detector (FID) and a 50 m x 0.31 mm fused silica capillary column coated with crosslinked methyl silicone (OV-1). The analytical conditions were as follows:

Injection Port Temperature	:	200°C
Detector Port Temperature	:	250°C
Initial Time	:	2 min
Initial Oven Temperature	:	80°C
Programme Rate	:	2°C/min
Final Oven Temperature	:	280°C
Final Time	:	20 min
Carrier gas (Helium)		
Flow rate	:	3 ml/min
Split ratio	:	10 : 1

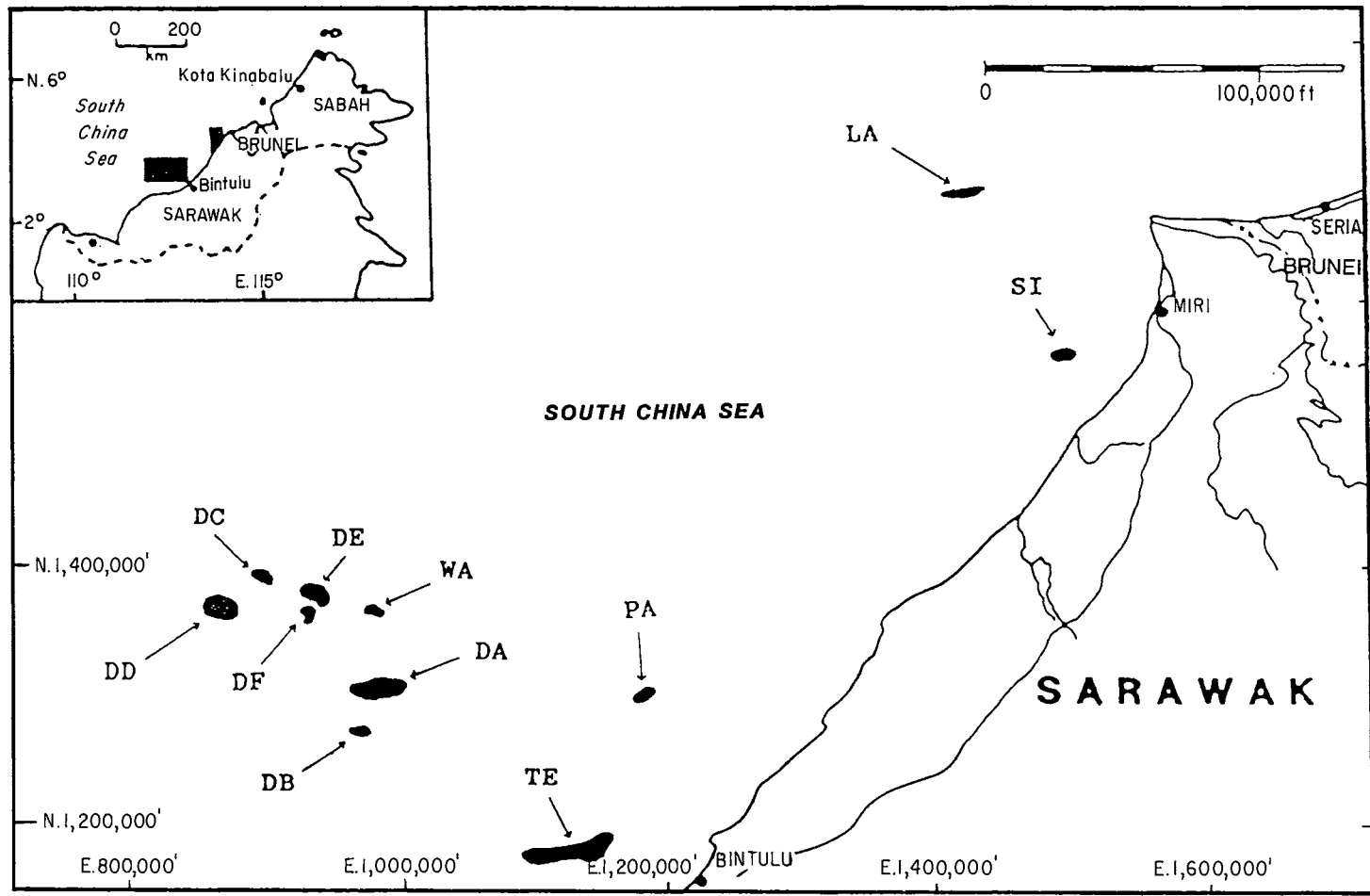


Figure 1A: Locations of oil fields, offshore Sarawak, utilized in this study

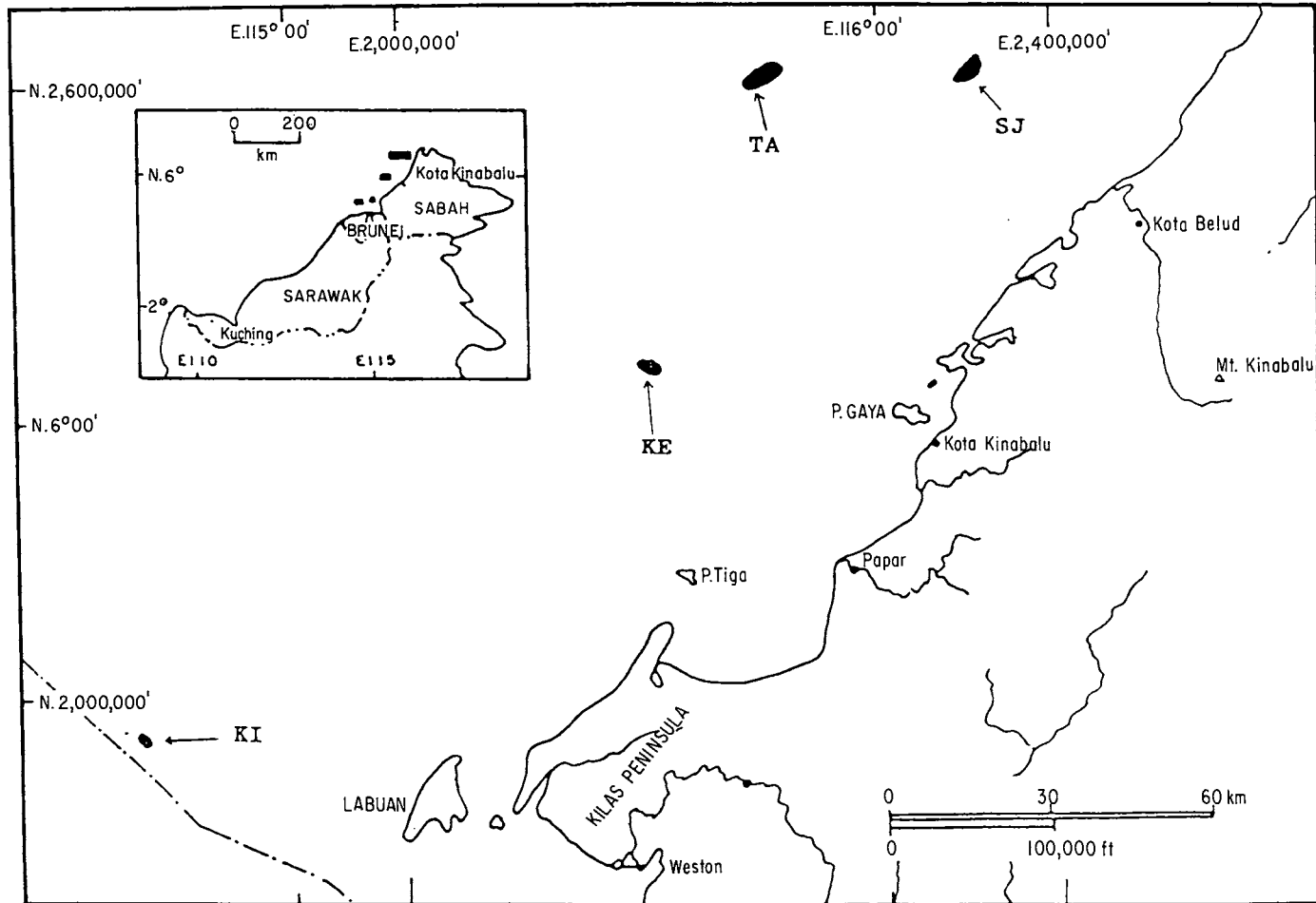


Figure 1B: Locations of oil fields, offshore Sabah, utilized in this study

Gas chromatography – mass spectrometry (GC-MS)

GC-MS analysis of the saturated hydrocarbon fractions was made using a KRATOS MS25RFA mass spectrometer coupled to a Carlo Erba gas chromatograph fitted with a 25m x 0.31 mm i.d., CP-Sil 5-CB fused silica capillary column (OV-1). Helium was used as a carrier gas with a flow rate of 2 ml/min. Each sample was injected in the split mode (25:1) at 50°C and programmed to 160°C at 5°C/min and then to 280°C at 3°C/min with a final hold at 280°C for 15 min. The mass spectrometer was operated with a filament current of 100 uA, electron ionization energy of 70 eV and ion source temperature of 240°C. Data were acquired and processed using a DS90 Data System.

Apart from the fullscan mode, the samples were also analysed using the Selected Metastable Ion Monitoring (SMIM) technique by monitoring metastable transitions; $M^+ \rightarrow 217^+$ for steranes and $M^+ \rightarrow 191^+$ for triterpanes, where M^+ is the molecular ion.

RESULTS AND DISCUSSION

API gravity

API gravity is normally used as a first checkpoint on crude oils. The values can be used to classify crude oils into biodegraded/water washed oils, normal oils, and condensates, and also gives a crude measure of thermal maturity (see Fig. 2). Oils with low API gravities (10° to 25°) are classified as immature, while oils with high API gravities (35° to 60°) are classified as mature. Additional factors affecting API gravity include biodegradation and water washing (both decrease the API gravity) and deasphalting and distance of migration (both increase the API gravity).

The API gravity values for the oils analysed in this study are given in Table 1. The API gravities for normal, non-waxy oils range from 30° to 38°, and for waxy oils, the API gravities range from 34° to 46°. Biodegraded oils are usually associated with low API gravities, generally below 25°.

N-alkane distributions

The distribution of the n-alkanes is dependent upon the type of organic matter, the depositional environment, and the thermal maturity of the source rocks. Migration distance, biodegradation, and water washing may also affect the distribution of the n-alkanes. Based on the normal alkane distributions, the crude oils are classified into three different types as discussed below:

i) *Normal, non-waxy oils*

Twenty out of the 35 samples are classified as normal, non-waxy crude oils. These oils include three KE - 1 samples, one TE - 1 sample, five DA samples, two LA samples, two DB samples, three TA samples, two KI - 1 samples, one SJ - 1 sample and one WA - 1 sample.

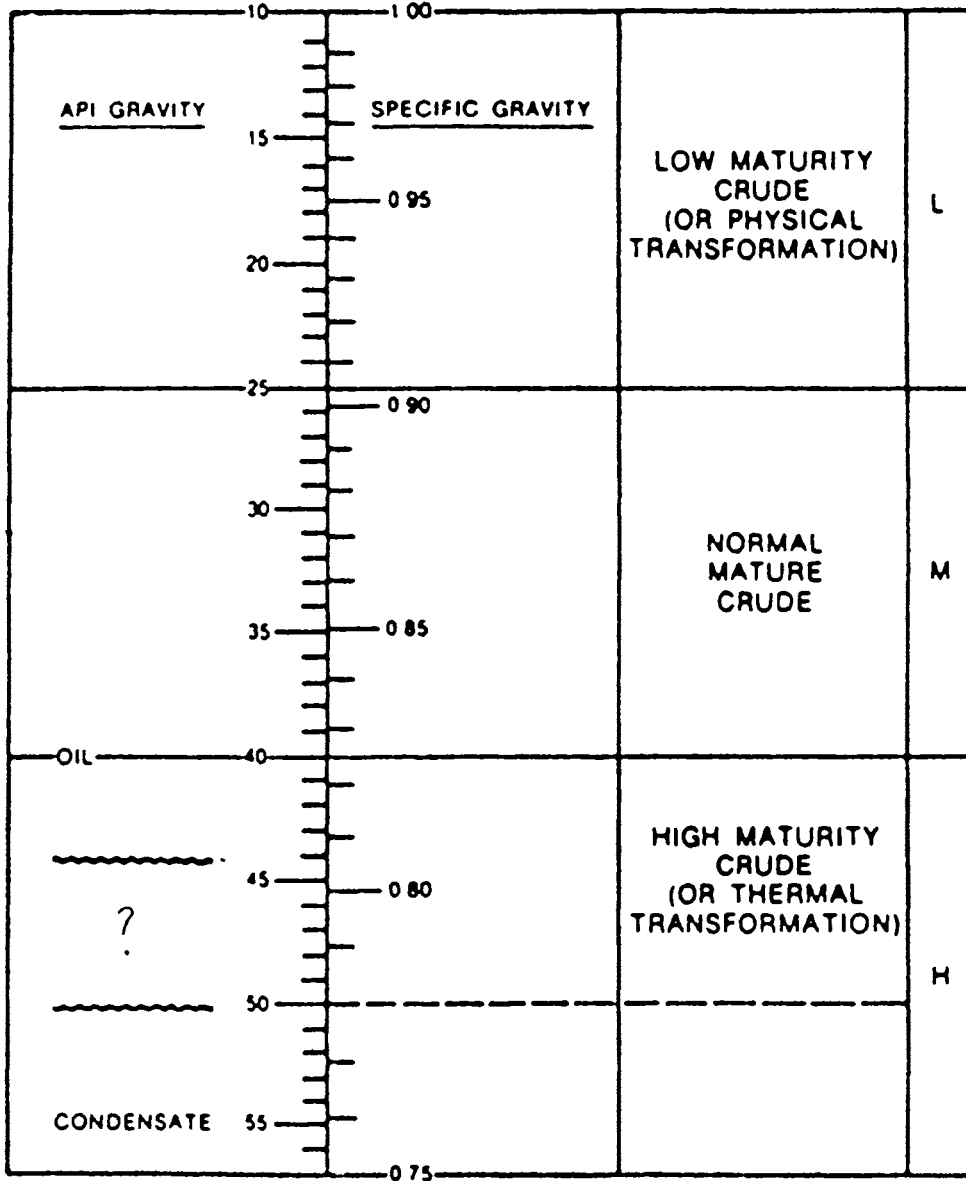


Figure 2: Classification of crude oils based on API and specific gravities (From Sofer *et al.*, 1989).

Table 1: Percentage composition, characteristic ratios and API gravity of oils examined in the study.

NAME OF SAMPLE	% COMPOSITION			PR	PR	PHY	CPI	API	REMARK
	% SAT	% ARO	% NSO	PHY	nC ₁₇	nC ₁₈			
KE - 1 (A)	65.5	18.4	16.1	3.9	1.2	0.3	1.05	37°	NORMAL
KE - 1 (B)	80.2	6.0	13.8	3.4	1.8	0.4	1.10	37°	NORMAL
KE - 1 (C)	80.9	7.5	11.6	4.0	1.4	0.4	0.88	37°	NORMAL
TE - 1 (A)	88.1	9.6	2.3	7.9	1.5	0.2	1.08	35°	NORMAL
DA - 1 (A)	90.7	7.8	1.5	6.9	1.4	0.2	1.14	N.A.	NORMAL
DA - 1 (B)	72.4	1.1	26.5	9.0	1.5	0.2	1.06	N.A.	NORMAL
DA - 1 (C)	80.1	3.9	16.0	8.7	1.5	0.2	1.12	N.A.	NORMAL
DA - 2	73.7	2.5	23.9	7.0	1.6	0.2	1.18	38°	NORMAL
DA - 3	82.0	1.6	16.4	7.5	1.8	0.2	1.12	35°	NORMAL
LA - 1	75.8	2.8	21.4	4.9	1.4	0.3	1.10	N.A.	NORMAL
LA - 2	52.1	5.3	42.6	4.8	1.4	0.3	1.10	N.A.	NORMAL
DB - 1 (A)	64.9	10.5	24.6	7.3	1.6	0.2	1.15	40°	NORMAL
DB - 1 (B)	67.9	2.4	29.7	7.4	1.6	0.2	1.09	38°	NORMAL
WA - 1	85.1	4.2	10.7	3.8	1.5	0.4	1.11	37°	NORMAL
SJ - 1	82.6	5.1	12.3	4.6	1.5	0.3	1.10	37°	NORMAL
KI - 1 (A)	61.2	12.7	26.1	4.7	1.6	0.3	1.04	39°	NORMAL
KI - 1 (B)	55.9	13.9	30.2	4.1	2.3	0.66	1.00	29°	NORMAL
TA - 1	83.4	2.1	14.5	3.7	1.6	0.3	1.09	37°	NORMAL
TA - 2	89.1	1.8	9.1	4.0	1.8	0.4	1.06	35°	NORMAL
TA - 3	77.4	4.7	17.9	4.0	1.3	0.3	1.08	38°	NORMAL
DC - 1 (A)	64.0	3.9	32.1	7.3	1.3	0.2	1.11	35°	WAXY
DC - 1 (B)	87.6	3.0	9.4	6.0	1.4	0.2	1.11	38°	WAXY
DD - 1	54.9	10.0	35.1	6.6	1.4	0.2	1.11	38°	WAXY
DD - 2	82.0	1.6	16.4	6.9	1.4	0.2	1.09	41°	WAXY
DD - 3	76.3	2.6	21.1	6.6	1.8	0.3	1.11	40°	WAXY
DE - 1 (A)	64.9	10.5	24.6	7.3	1.6	0.2	1.15	34°	WAXY
DE - 1 (B)	77.3	12.9	9.8	6.9	1.4	0.2	1.09	35°	MAXY
DF - 1 (A)	79.9	3.5	17.4	5.4	0.9	0.2	1.05	44°	WAXY
DF - 1 (B)	81.1	6.2	12.7	4.5	1.2	0.2	1.09	40°	WAXY
SI - 1 (A)	87.8	3.8	8.4	2.6	14.0	3.2	1.13	N.A.	BIODEGRADED
SI - 1 (B)	70.5	8.8	20.7	4.6	6.7	0.8	1.10	N.A.	BIODEGRADED
SI - 1 (C)	88.6	1.8	9.6	3.1	32.0	6.1	1.01	N.A.	BIODEGRADED
TE - 1(B)	70.4	9.4	20.2	5.6	4.8	0.7	1.07	35°	BIODEGRADED
TE - 2	70.8	11.1	18.1	5.7	5.4	0.8	1.09	25°	BIODEGRADED
PA - 1	77.0	10.7	12.3	4.4	5.5	0.8	1.06	N.A.	BIODEGRADED

These oils exhibit high percentages of the saturated hydrocarbon compounds (>60%). The gas chromatograms obtained show similar n-alkane distributions ranging from C_{11} to C_{34} , and maximum peaks appear in the region which is less than nC_{20} peak (see Fig 3). These samples are termed as normal, non-waxy oils as the nC_{20+} alkanes are less abundant.

ii) Waxy oils (high proportion of C_{20+} n-alkanes)

The type of organic matter originally deposited has a very strong influence on the n-alkane distribution or the waxiness of the oils. The wax content of oils has been attributed to the protective outer covering (cuticles) of stems, leaves and fruits of certain land plants (Hedberg, 1968 and Brown, 1989).

Nine samples are classified as waxy oils. They are two DC - 1 samples, three DD samples, two DE - 1 samples and two DF - 1 samples. This type of oil is associated with a substantial proportion (>54%) of saturated hydrocarbons. The gas chromatograms obtained for these samples exhibit broad n-alkane distributions (C_{11} to C_{35}) with peaks maximising in the nC_{20+} region (see Fig. 4). The oils are classified as waxy due to the presence of abundant nC_{20+} alkanes which are land-plant derived.

iii) Biodegraded oils (less abundant of n-alkane relative to isoprenoids)

Biodegradation of oil can occur when the following three conditions in the reservoir exist (Connan, 1984):

- a) the temperature drops below 80°C
- b) the oil is in contact with oxygenated water (mostly fresh or sea-water but sometimes with sulfate-rich water)
- c) the reservoir is inoculated with biodegrading bacteria.

Biodegradation is always associated with water washing because the process can proceed only if the water is replaced continuously, carrying more oxygenated water. Biodegradation removes n-alkanes, leaving a residual oil enriched in aromatic and naphthenic hydrocarbons (Tissot & Welte, 1975).

Six samples are classified as biodegraded samples. These include three SI - 1 samples, two TE samples and one PA - 1 sample. The oils are slightly biodegraded because only the light ends of the n-alkanes have been removed or reduced in content (see Fig 5). More prominent naphthenic humps coupled with the increased values of pristane/ nC_{17} and phytane/ nC_{18} ratios of the oils are also noticed.

DEPOSITIONAL ENVIRONMENT

The ratios of pristane/phytane (pris/phy) and pristane/ nC_{17} (pris/ nC_{17}) reflect the nature of organic matter and the degree of oxidation in the depositional

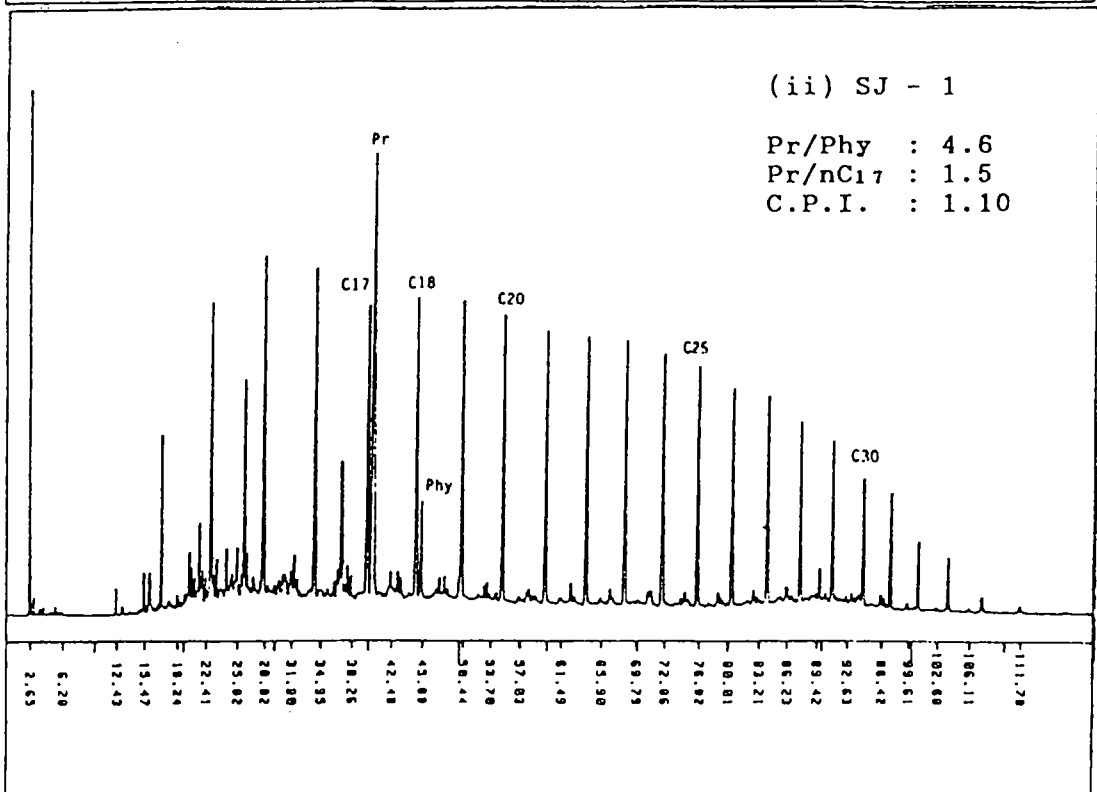
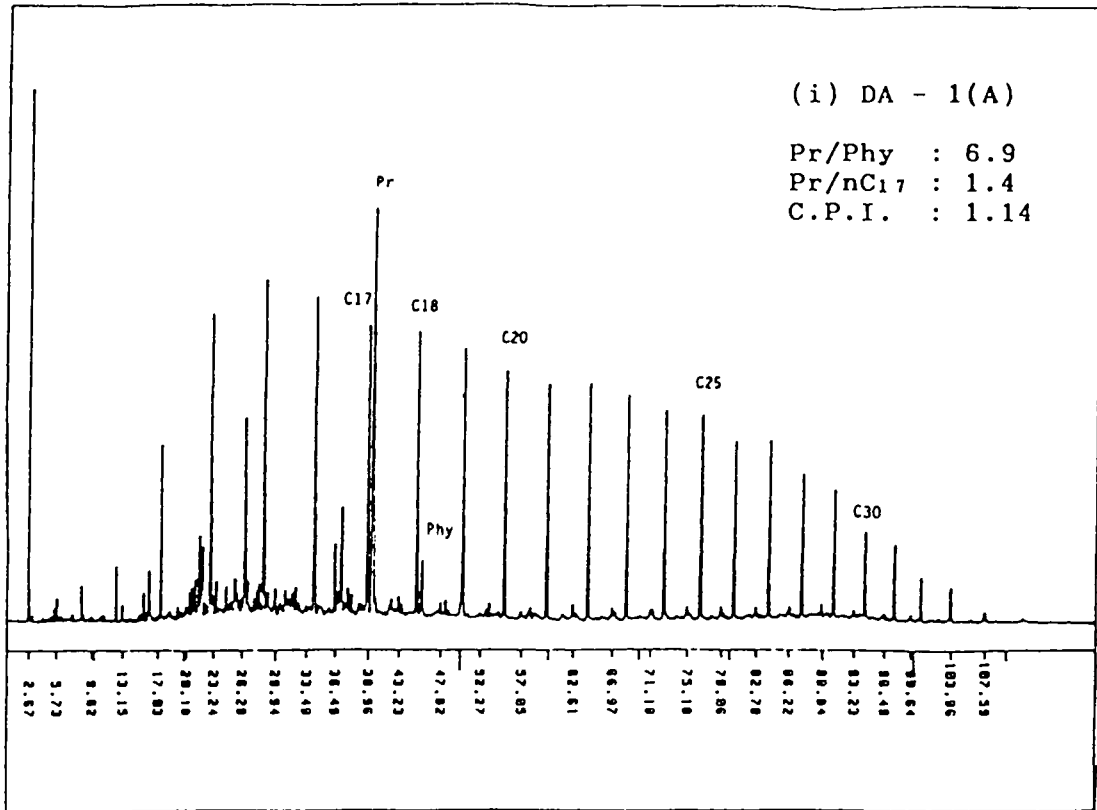


Figure 3: Examples of gas chromatogram of saturated fraction of normal crude oil (i) DA - 1(A) and (ii) SJ -1.

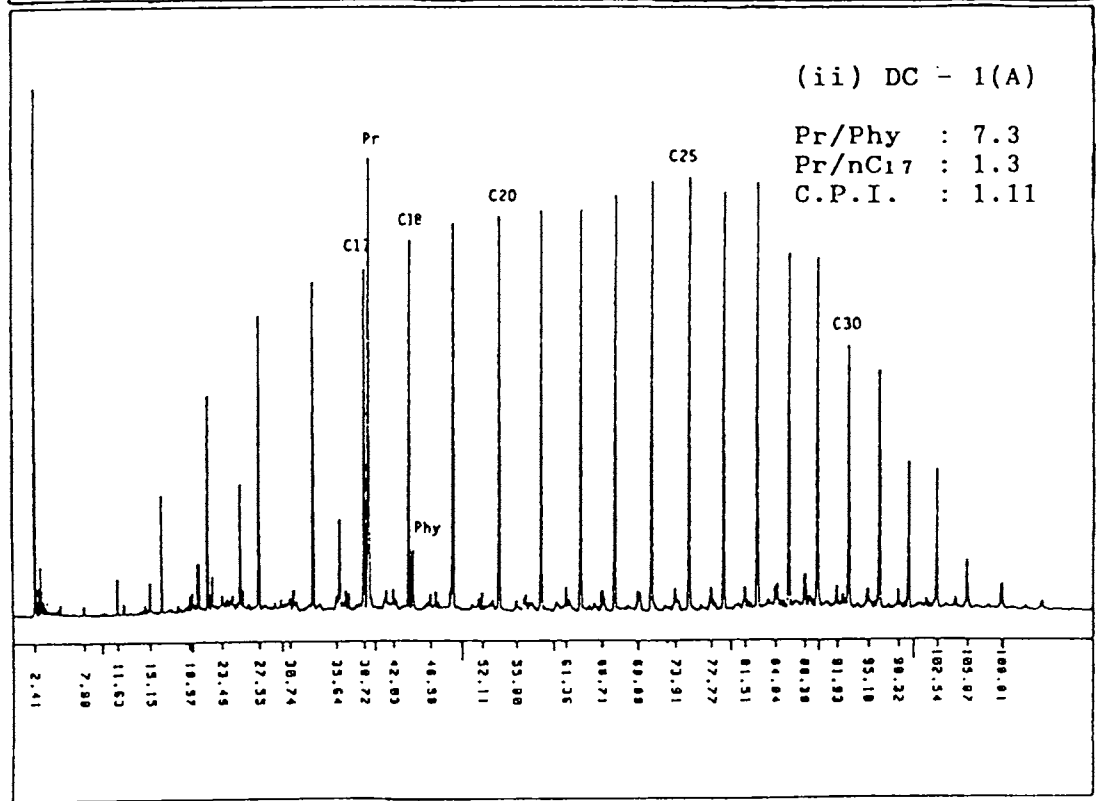
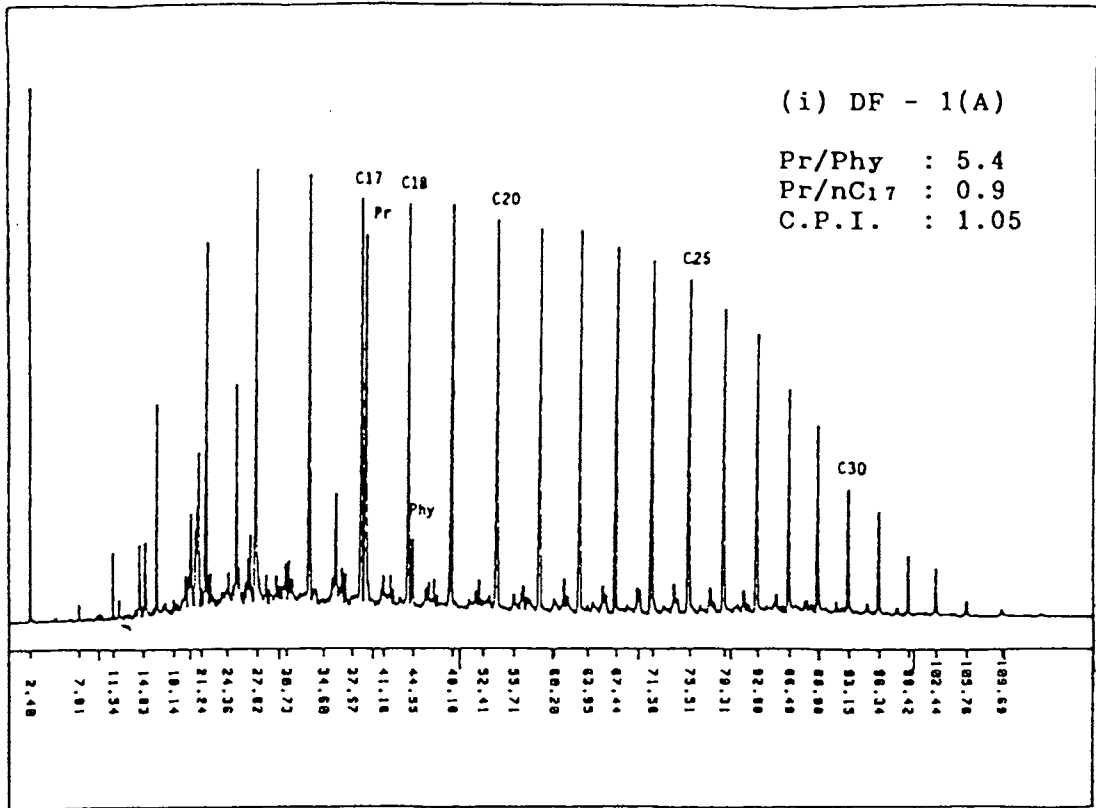


Figure 4: Examples of gas chromatogram of saturated fraction of highly waxy crude Oil (i) DF - 1 (A) and (ii) DC - 1 (A)

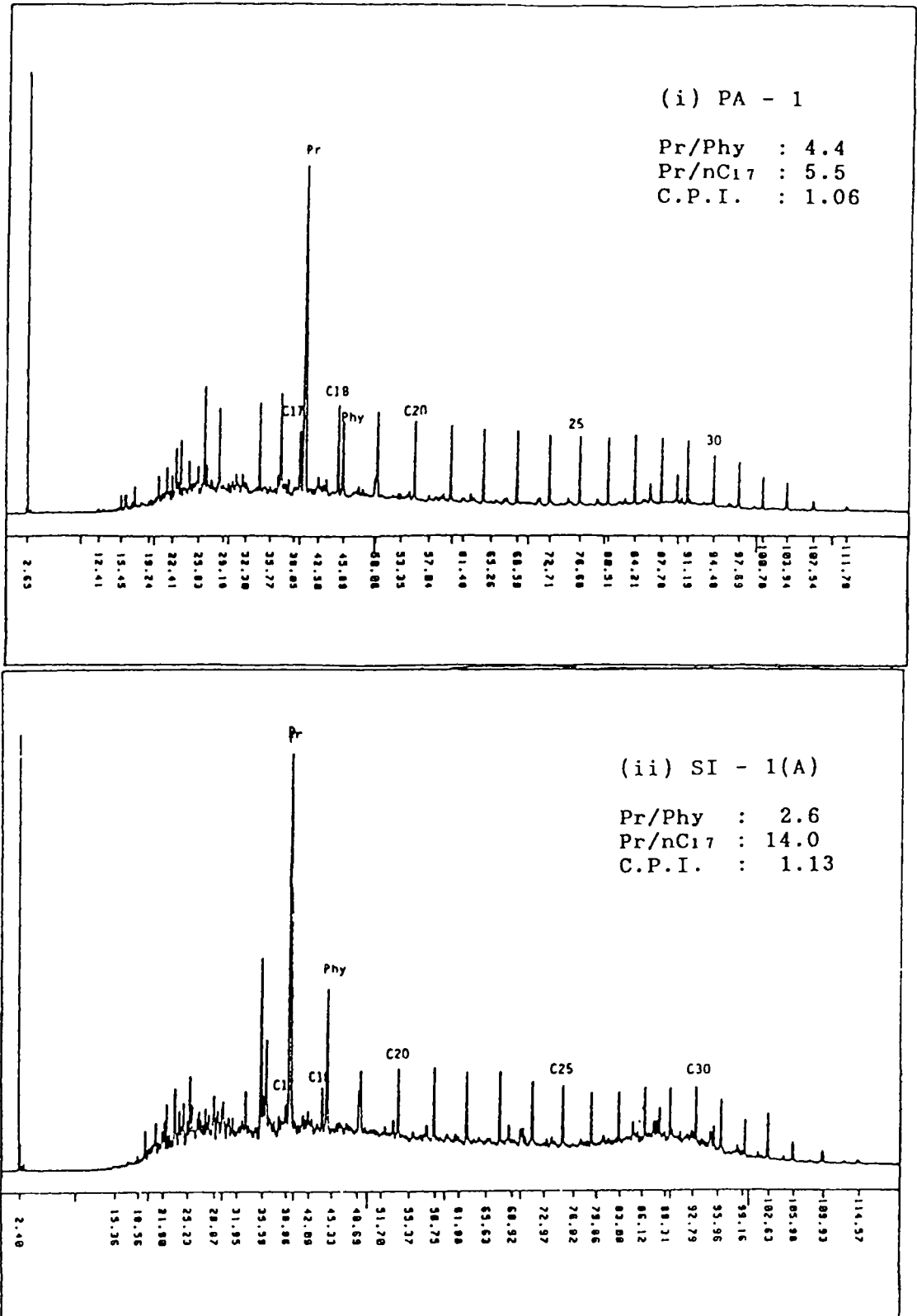


Figure 5: Examples of gas chromatogram of saturated fraction of Biodegraded Crude Oil
(i) PA - 1 and (ii) SJ - 1 (A)

environment during early chlorophyll diagenesis, which is the primary source of pristane and phytane (Brooks and Smith, 1969; Powell and Mc Kirdy, 1975). Marine or open-water sedimentation with high bacterial activity yields only relatively small amounts of pristane and phytane and as a result gives low pris/phy (<2.0) and pris/nC₁₇ (<1.0) ratios, whereas under peat swamp environment, with low aerobic bacterial activity, most of the phytol are converted to pristane with small amounts of phytane. Thus, oils from source rocks deposited under peat swamp conditions will have high pris/phy (>3.0) and pris/nC₁₇ (>1.0) ratios (Didyle *et al.*, 1978; Lijmbach, 1975).

The pris/phy and pris/nC₁₇ ratios are given in Table 1. For the normal, non-waxy oils, the ratios of pris/phy and pris/nC₁₇ range from 3.7 to 9.0 and from 1.2 to 4.7, respectively. For the waxy oils, these ratios range from 4.5 to 7.3 and from 0.9 to 1.8, respectively. The pris/phy ratios for biodegraded oils range from 2.6 to 5.7 and this range does not differ much from both normal and waxy oils. However, the pris/AC₁₇ ratios for biodegraded oils are higher compared to values of normal and waxy oils.

The results of our analysis with high pris/phy (>3.0) and pris/nC₁₇ (>1.0) ratios indicate that the oils were derived from organic matter that was deposited under peat swamp environments.

The Carbon Preference Index or CPI (nC₂₅ - nC₃₁) of the oils ranges from 1.0 to 1.2, indicating that the oils are all mature (Hunt, 1989).

GAS CHROMATOGRAPHY - MASS SPECTROMETRY (GC-MS)

Examples of triterpane and sterane distributions are given in Figures 6 and 7. Figures 9 and 12 are examples of triterpane and sterane mass fragmentograms obtained by the Selected Metastable Ion Monitoring (SMIM) technique. The identification of the various peaks are given in Tables 3 and 4.

Tripterpanes (m/z 191)

All oils show similar triterpane distributions (see Fig. 6). The hopane-type pentacyclic triterpanes or simply hopenes range from C₂₇ up to C₃₃₊ with the extended hopenes showing predominance of the 22S over the 22R epimers. The β(H), α(H)-hopenes or moretanens are present at relatively lower concentrations than the α(H), β(H)-hopenes. In addition to the ubiquitous hopenes, m/z 191 also shows the presence of 18α(H)-oleanane (O), C₃₀ resin-derived compounds (Rn) and unidentified triterpanes (X).

18α(H)-oleanane is found in all of the crude oils. Its mass spectrum is given in figure 8(i). The ratio of 18α(H)-oleanane to C₃₀ 17α(H), 21β(H)-hopane which is the oleanane due to variations in the composition of the land-plant organic matter in the source rocks. The presence of 18α(H)-oleanane is indicative of a terrigenous source. It has been inferred (Philp and Gilbert, 1986) that this

Table 3: Peak identifications for mass fragmentogram at m/z 191 and selected metastable ion monitoring (SMIM)

Rn	Resin-derived Compounds
X	Unidentified Triterpanes
A	18 α (H), 21 β (H) – trisnorneohopane (Ts) (C ₂₇)
B	17 α (H), 21 β (H) – trisnorhopane (Tm) (C ₂₇)
B	17 α (H), 21 β (H) – norhopane (C ₂₉)
D	17 β (H), 21 α (H) – normoretane (C ₂₉)
O	18 α (H) – oleanane
E	17 α (H), 21 β (H) – hopane (C ₃₀)
F	17 β (H), 21 α (H) – homohopane (C ₃₀)
G	22S-17 α (H), 21 β (H) – homohopane (C ₃₁)
H	22R-17 α (H), 21 β (H) – homohopane (C ₃₁)
I	22S-17 α (H), 21 β (H) – bishomohopane (C ₃₂)
J	22R-17 α (H), 21 β (H) – bishomohopane (C ₃₂)
K	22S-17 α (H), 21 β (H) – trishomohopane (C ₃₃)
L	22R-17 α (H), 21 β (H) – trishomohopane (C ₃₃)

Table 4: Peak identifications for SMIM of steranes

C ₂₇ STERANES & DIASTERANES (372 ⁺ → 217 ⁺)
1. 13 β (H), 17 α (H) – diacholestane (20S)
2. 13 β (H), 17 α (H) – diacholestane (20R)
3. 14 α (H), 17 α (H) – cholestane (20S)
4. 14 β (H), 17 β (H) – cholestane (20R)
5. 14 β (H), 17 β (H) – cholestane (20S)
6. 14 α (H), 17 α (H) – cholestane (20R)
C ₂₈ STERANES & DIASTERANES (386 ⁺ → 217 ⁺)
1. 24-methyl-13 β (H), 17 α (H) – diacholestane (20S)
2. 24-methyl-13 β (H), 17 α (H) – diacholestane (20R)
3. 24-methyl-14 α (H), 17 α (H) – cholestane (20S)
4. 24-methyl-14 β (H), 17 β (H) – cholestane (20R)
5. 24-methyl-14 β (H), 17 β (H) – cholestane (20S)
6. 24-methyl-14 α (H), 17 α (H) – cholestane (20R)
C ₂₉ STERANES & DIASTERANES (400 ⁺ → 217 ⁺)
1. 24-ethyl-13 β (H), 17 α (H) – diacholestane (20S)
2. 24-ethyl-13 β (H), 17 α (H) – diacholestane (20R)
3. 24-ethyl-14 α (H), 17 α (H) – cholestane (20S)
4. 24-ethyl-14 β (H), 17 β (H) – cholestane (20R)
5. 24-ethyl-14 β (H), 17 β (H) – cholestane (20S)
6. 24-ethyl-14 α (H), 17 α (H) – cholestane (20R)

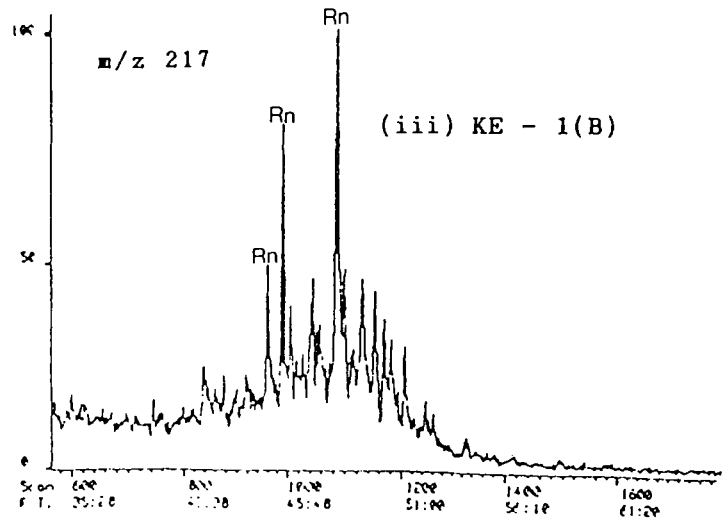
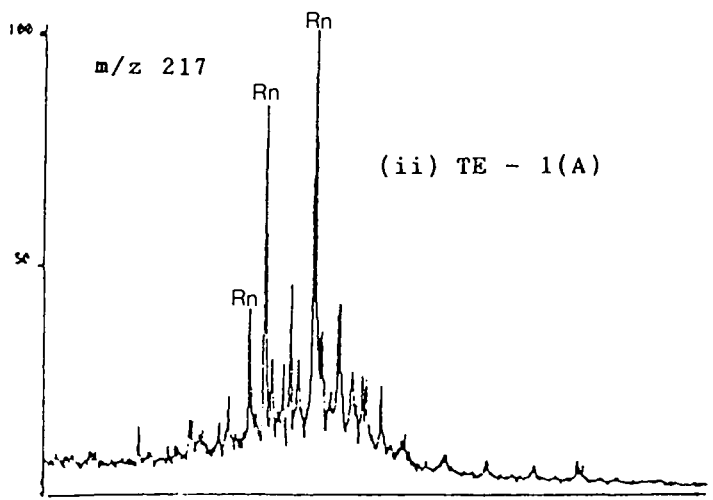
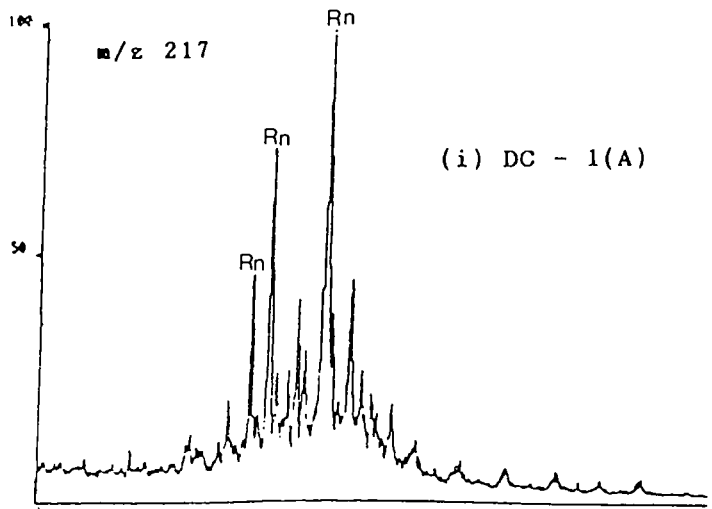


Figure 6: Example of triterpane (m/z 217) distributions
 (i) DC - 1(A), (ii) TE - 1, (iii) KE - 1(B).

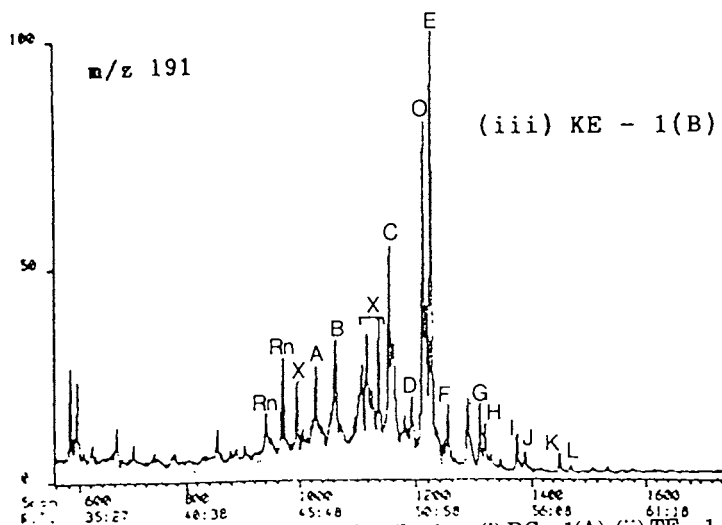
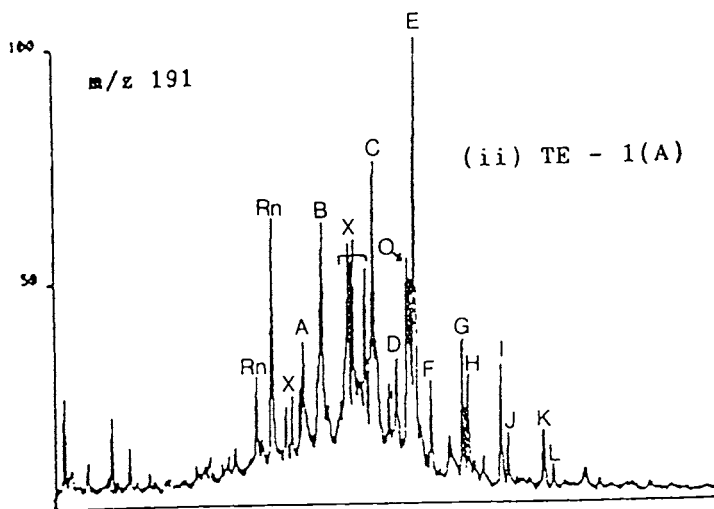
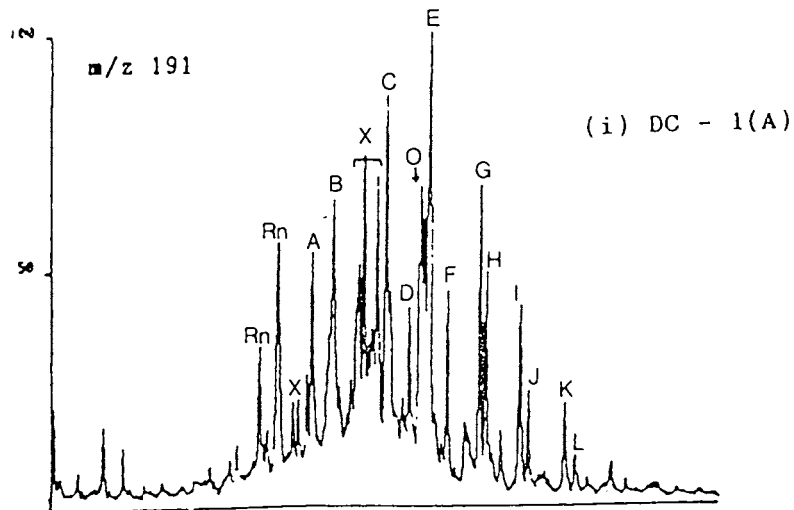


Figure 7: Example of sterane (m/z 217) distributions (i) DC - 1(A), (ii) TE - 1, (iii) KE - 1(B).

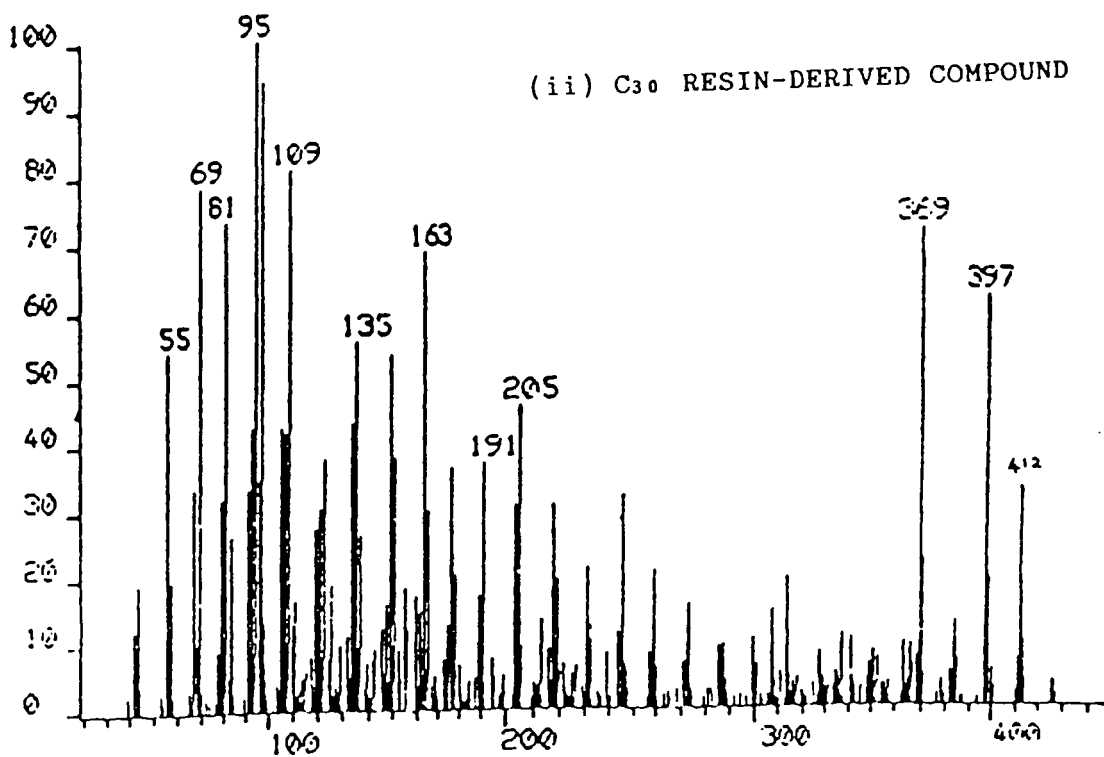
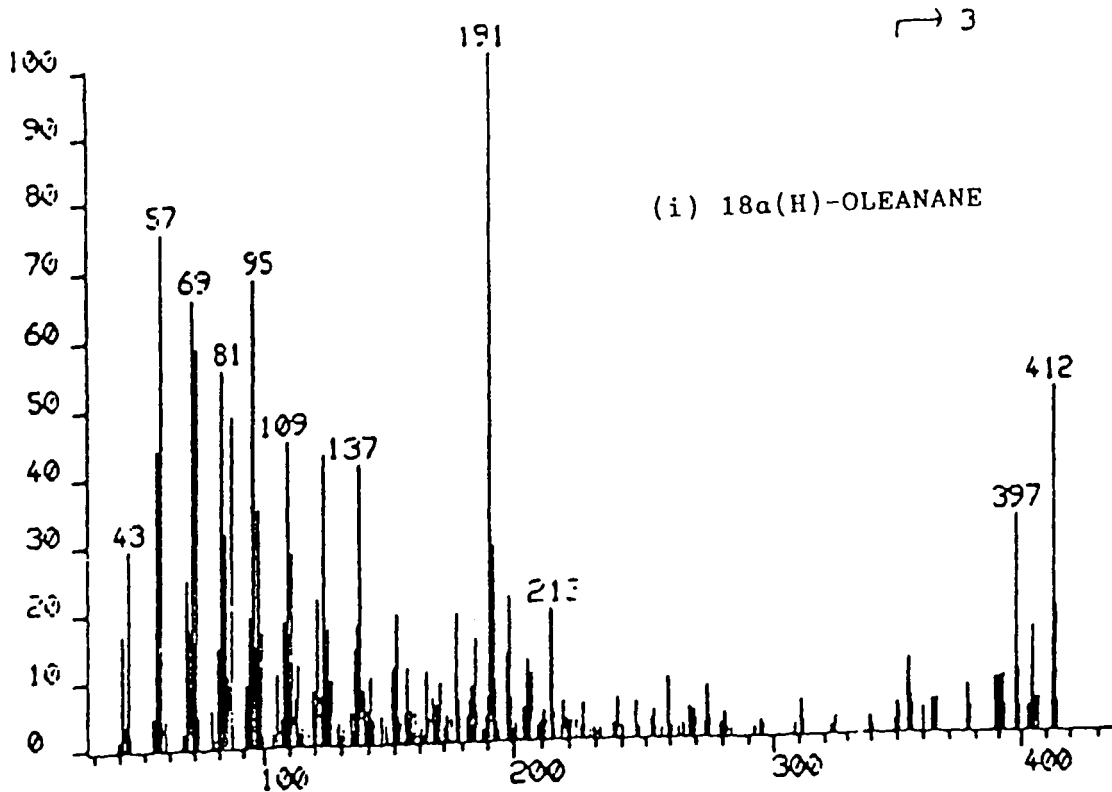


Figure 8: Mass spectra of (i) 18 α (H)-oleanane and (ii) C₃₀ resin-derived compound

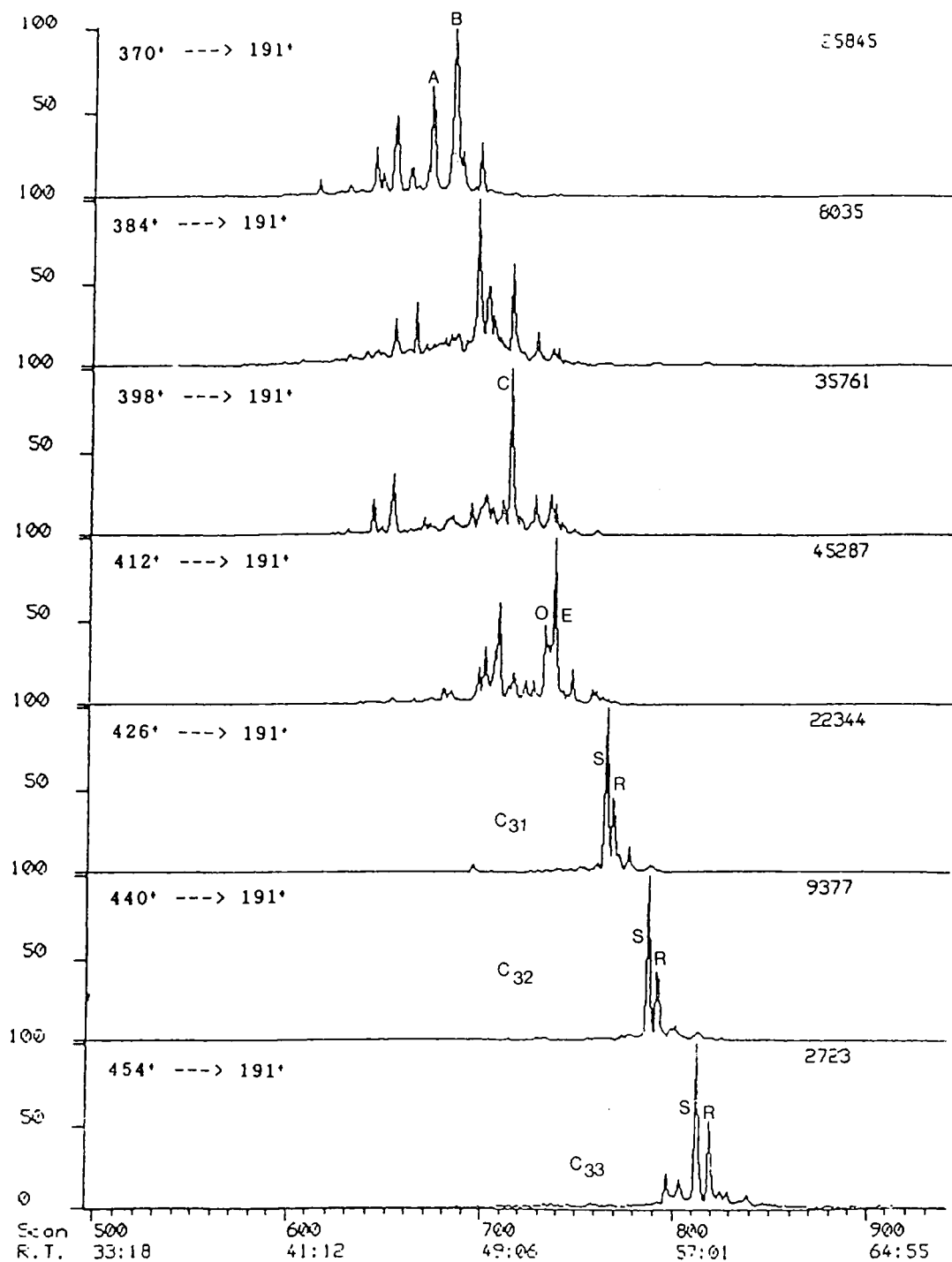


Figure 9: Mass fragmentogram of triterpanes obtained by Selected Metastable Ion Monitoring (SMIM), ($M^+ \rightarrow 191^+$) for DC - 1(A).

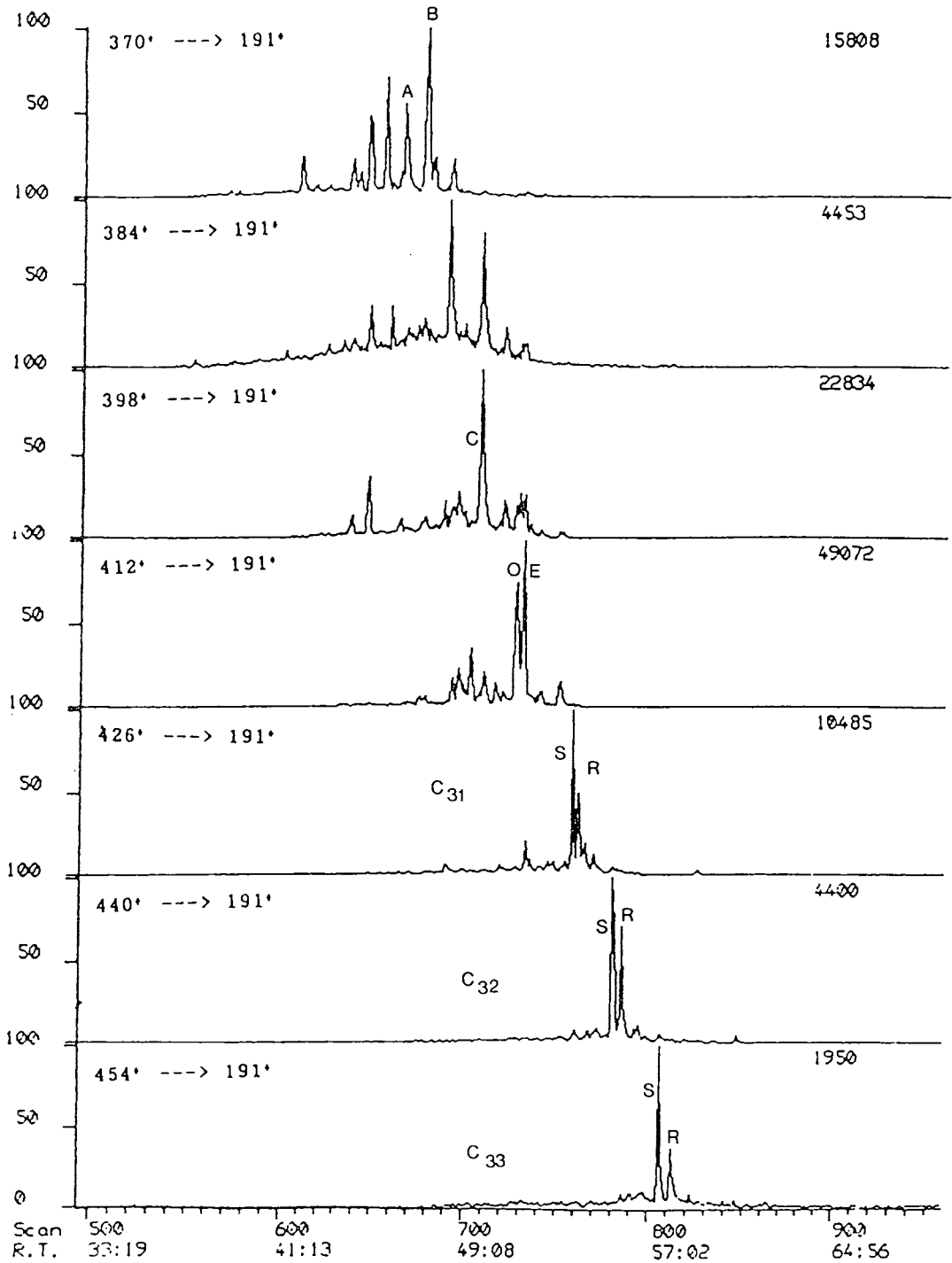


Figure 10: Mass fragmentogram of triterpanes obtained by Selected Metastable Ion Monitoring (SMIM), ($M^+ \rightarrow 191^+$) for KE - 1(B).

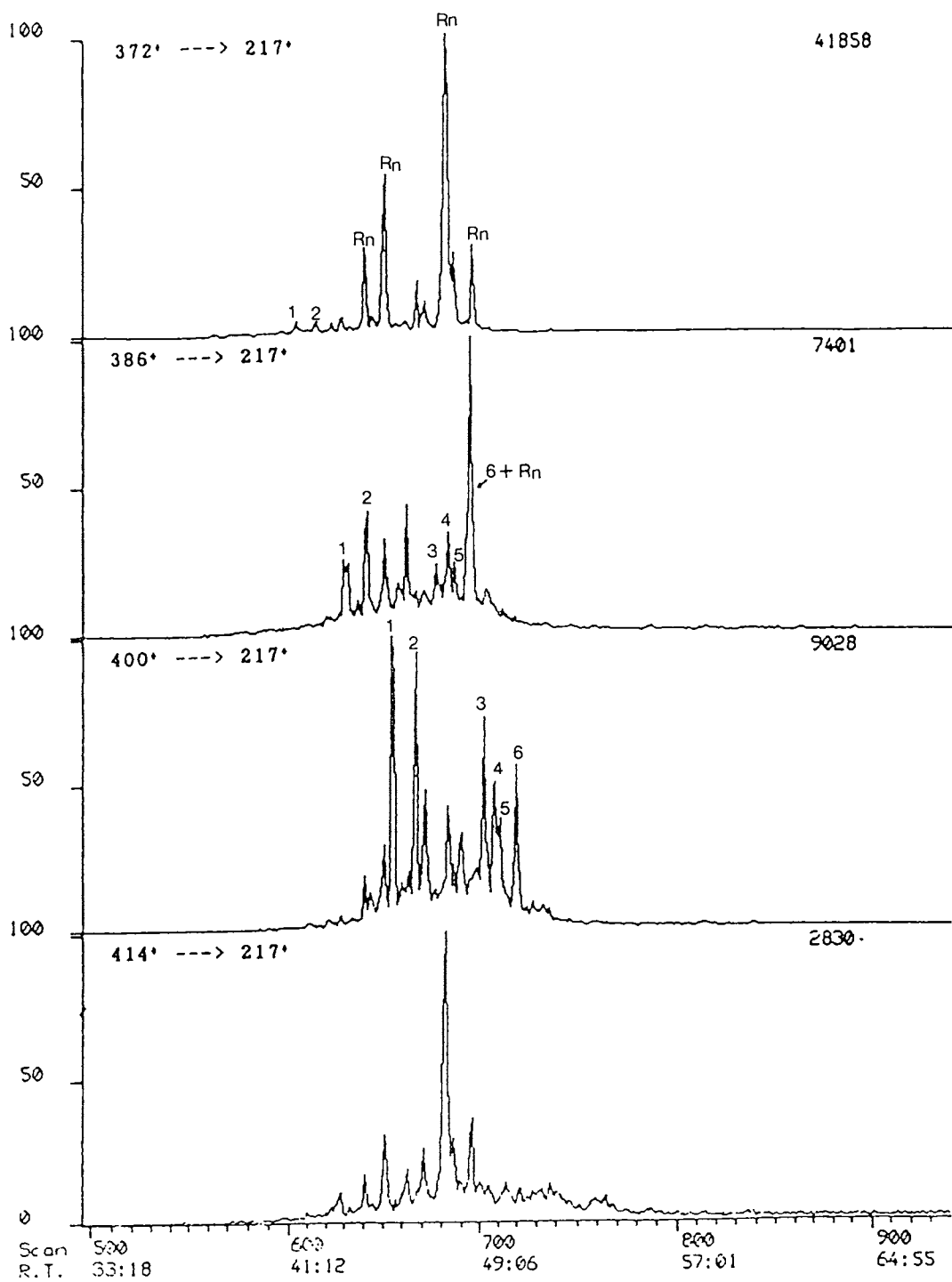


Figure 11: Mass fragmentogram of triterpanes obtained by Selected Metastable Ion Monitoring (SMIM), ($M^+ \rightarrow 217^+$) for DC - 1(A).

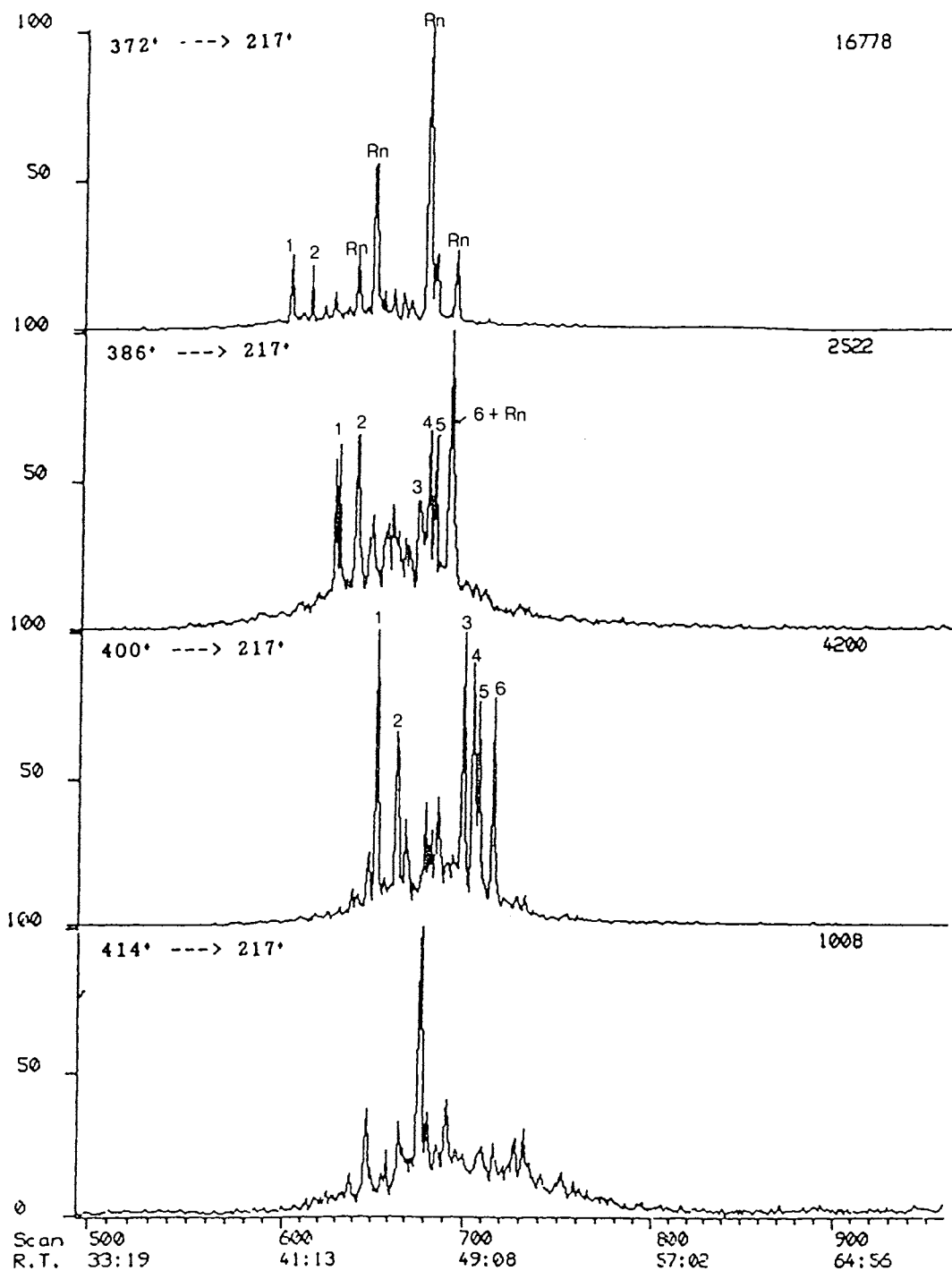


Figure 12: Mass fragmentogram of triterpanes obtained by Selected Metastable Ion Monitoring (SMIM), ($M^+ \rightarrow 217^+$) for KE - 1(B).

compound, which has been found in Tertiary oils and rock extracts, is a marker for the presence of angiosperm debris in the source rocks. This compound is also found in oils from Indonesia (Robinson, 1987), New Zealand (Czochanska *et al.*, 1988), and Nigeria (Ekweozor *et al.*, 1979), which also contain a predominance of higher plant source material.

The presence of C_{30} resin-derived compounds (Rn) is confirmed by their mass spectra with characteristic peaks at m/z 163, 313, 369, 397 and 412 [see Fig. 8(ii)]. Various researchers have identified these Rn peaks, three of which were labelled W,T and R by Grantham *et al.* (1983) and Grantham (1986). Compound T has been found to be trans-trans-trans-bicadinane (Cox *et al.*, 1986), while van Aarssen *et al.*, (1990b) has determined W to be cis-cis-trans-bicadinane.

The presence of $18\alpha(H)$ -oleanane and resin-derived compounds in all of the oils suggest that the oils were derived from source rocks of terrigenous origin containing mixtures of different types of land-plant organic matter including resins.

Steranes (m/z 217)

The mass fragmentogram (m/z 217) shows similar sterane distributions for all of the oils. The steranes are present at relatively lower concentrations than the resins (Rn) and are difficult to identify (See Fig. 7). However, when the sample is monitored using the SMIM technique, the regular steranes and diasteranes are clearly shown and positively identified (see Figs. 11 and 12).

The distributions of the C_{27} , C_{28} , and C_{29} steranes shows that the C_{29} steranes are present in greater concentrations than the C_{27} - and C_{28} -steranes. It has been commonly suggested that C_{29} steranes are derived from C_{29} steranes at the expense of the C_{28} and C_{27} steranes is clearly indicative of a significant input of terrigenous organic material (Philp and Zhaoan, 1986).

Oils which contain high concentrations of components derived from terrigenous organic material customarily contain relatively high proportions of triterpanes relative to steranes (Czochanska *et al.*, 1988). For the 35 crude oils analysed, the hopane to sterane ratios tend to be relatively high, ranging from 1.75 to 8.41, with the majority (29) higher than 3. This indicates variation in the nature of the original organic matter from which the oils were derived, which is to be expected as the area covered is extensive.

A land-plant origin for all of the oils is further indicated by the absence of C_{30} -steranes, which are typical of marine-derived oils (Moldowan *et al.*, 1985).

MATURITY

Two maturity parameters based on hopane and sterane isomer ratios were used to assess the maturity level of the oils (Seifert and Moldowan 1980, 1981). These are the epimerisation of 22R to 22S of the extended hopanes and

isomerisation of the 20R to 20S C_{29} - $\alpha\alpha$ steranes. The results are given in Table 2.

Table 2: Biomarker correlation and maturity parameters

SAMPLE NAME	H O P A N E							REGULAR STERANE	
	$C_{30} \frac{\alpha\beta}{\alpha\beta+\beta\alpha}$	$C_{31} \frac{22S}{22S+22R}$	$C_{31} \frac{22S}{22S+22R}$	$C_{30} \frac{\beta\alpha}{\alpha\beta}$	Tm Ts	Oleanane Index	Hopane Sterane	$C_{29} \frac{20S}{20S+20R}$	$C_{29} \frac{\alpha\beta\beta}{\alpha\beta\beta+\alpha\alpha\alpha}$
KE-1 (A)	0.86	0.59	0.69	0.16	1.59	1.08	3.91	0.55	0.39
KE-1 (B)	0.88	0.59	0.64	0.14	1.89	0.75	6.83	0.56	0.48
KE-1 (C)	0.87	0.59	0.67	0.15	1.30	0.70	8.05	0.59	0.47
SI-1 (A)	0.86	0.61	0.57	0.16	0.95	0.73	7.00	0.51	0.44
SI-1 (B)	0.83	0.63	0.67	0.20	0.96	0.95	5.14	0.47	0.40
SI-1 (C)	0.84	0.61	0.58	0.19	0.81	0.82	8.41	0.46	0.47
TE-1 (A)	0.82	0.57	0.69	0.22	1.59	0.46	5.90	0.47	0.56
TE-1 (B)	0.73	0.60	0.65	0.35	2.38	0.69	5.21	0.47	0.48
TE-2	0.68	0.55	0.66	0.46	0.98	0.71	6.36	0.45	0.46
DA-1 (A)	0.77	0.52	0.65	0.29	0.75	0.35	2.51	0.37	0.42
DA-1 (B)	0.68	N.D.	0.68	0.48	0.79	0.52	3.26	0.34	0.38
DA-1 (C)	0.75	N.D.	0.60	0.34	1.08	0.45	2.24	0.48	0.52
DA-2	0.75	0.51	0.63	0.34	1.25	0.54	3.46	0.35	N.D.
DA-3	0.75	0.48	0.66	0.34	1.39	0.58	3.11	0.24	N.D.
LA-1	0.89	0.59	0.65	0.12	1.96	0.93	4.34	0.48	0.43
LA-2	0.88	0.60	0.59	0.14	1.85	0.81	3.30	0.56	N.D.
DC-1 (A)	0.71	0.59	0.65	0.42	1.59	0.63	4.22	0.55	0.39
DC-1 (B)	0.73	0.57	0.67	0.37	1.11	0.56	4.97	0.51	N.D.
DD-1	0.84	0.58	0.68	0.20	0.90	0.44	3.60	0.51	0.42
DD-2	0.75	0.59	0.66	0.33	0.90	0.63	5.35	0.53	0.44
DD-3	0.73	0.57	0.69	0.38	0.53	0.59	5.31	0.39	0.45
DB-1 (A)	0.82	0.58	0.62	0.22	4.35	0.46	4.28	0.48	0.49
DB-1 (B)	0.84	0.59	0.70	0.19	3.03	0.54	5.36	0.52	0.51
DE-1 (A)	0.73	0.60	0.70	0.36	1.89	0.73	4.22	0.60	0.41
DE-1 (B)	0.85	0.55	0.72	0.17	2.13	0.47	3.13	0.50	0.49
DF-1 (A)	0.89	0.55	0.70	0.13	3.23	0.39	2.59	0.71	0.55
DF-1 (B)	0.89	0.57	0.70	0.12	3.03	0.39	2.21	0.60	0.59
WA-1	0.77	0.55	0.62	0.30	1.19	0.66	5.00	0.36	N.D.
SJ-1	0.76	0.60	0.69	0.32	1.53	1.07	2.76	0.43	0.39
PA-1	0.84	0.58	0.68	0.20	N.D.	0.62	1.75	0.53	0.49
KI-1 (A)	0.82	0.62	N.D.	0.22	0.98	1.01	4.43	0.39	0.49
KI-1 (B)	0.80	0.66	N.D.	0.24	0.79	0.97	4.37	0.42	0.49
TA-1	0.87	0.59	0.52	0.15	1.48	0.81	4.87	0.23	N.D.
TA-2	0.88	0.60	0.57	0.14	1.36	0.78	4.32	0.26	N.D.
TA-3	0.85	0.58	0.58	0.18	1.17	0.77	4.58	0.24	N.D.

Table 2: cont'd

NOTE:

N.A. – Not Available

N.D. – Not Determined

$$\frac{\text{Hopane}}{\text{Sterane}} : \frac{C_{30} \text{ } 17\alpha(\text{H}), 21\beta(\text{H})\text{-hopane}}{C_{29} \text{ } 5\alpha(\text{H})\text{-steranes (20S + 20R)}} = \frac{\text{E}}{3 + 6}$$

$$\text{Oleanane Index} : \frac{18\alpha(\text{H})\text{-oleanane}}{C_{30} \text{ } 10\alpha(\text{H}), 21\beta(\text{H})\text{-hopane}} = \frac{\text{O}}{\text{E}}$$

$$\frac{\text{Tm}}{\text{Ts}} : \frac{17\alpha(\text{H}), 21\beta(\text{H})\text{-trisnorhopane}}{18\alpha(\text{H}), 21\beta(\text{H})\text{-hopane}} = \frac{\text{A}}{\text{B}}$$

$$C_{30} \frac{\beta\alpha}{\alpha\beta} : \frac{17\beta(\text{H}), 21\alpha(\text{H})\text{-moretane}}{17\alpha(\text{H}), 21\beta(\text{H})\text{-hopane}} = \frac{\text{F}}{\text{E}}$$

$$C_{30} \alpha\beta/(\alpha\beta + \beta\alpha) = \text{E}/(\text{E} + \text{F}) \longrightarrow \text{Equil. Value: 0.75}$$

$$C_{31} \text{ } 22\text{S}/(22\text{S} + 22\text{R}) = \text{G}/(\text{G} + \text{H}) \longrightarrow \text{Equil. Value: 0.60}$$

$$C_{32} \text{ } 22\text{S}/(22\text{S} + 22\text{R}) = \text{I}/(\text{I} + \text{J}) \longrightarrow \text{Equil. Value: 0.60}$$

$$C_{29} \text{ } 20\text{S}/(20\text{S} + 20\text{R}) = 3/(3 + 6) \longrightarrow \text{Equil. Value: 0.50}$$

$$C_{30} \frac{\alpha\beta\beta}{\alpha\beta\beta + \alpha\alpha\alpha} = \frac{(4 + 5)}{(4 + 5) + (3 + 6)} \longrightarrow \text{Equil. Value: 0.75}$$

$$\text{CPI} = \frac{1/2 [(C_{25} + C_{27} + C_{29} + C_{31}) + (C_{25} + C_{27} + C_{29} + C_{31})]}{[(C_{24} + C_{26} + C_{28} + C_{30}) + (C_{26} + C_{28} + C_{30} + C_{32})]}$$

The epimerisation ratio of 22R to 22S of C_{31} - or C_{32} -hopane, i.e. 22S/(22S + 22R), have an equilibrium value of 0.60 and is complete before the onset of intense hydrocarbon generation (Mackenzie, 1984). The ratio covers a maturity range of ca. 0.4 to 0.6% vitrinite reflectance equivalent (VRe). The 22S/(22S + 22R) ratio calculated for all of the oils are close to 0.60 or higher, indicating that the epimerisation has attained equilibrium. Hence, the maturities of the source rocks for these oils may be inferred to be 0.6% VRe or higher (Mackenzie, 1984; Mackenzie and Mckenzie, 1983).

The isomerisation of the C_{29} 5 α (H), 14 α (H), 17 α (H)-steranes, as shown by the epimer ratio of 20S/(20S + 20R), cover a maturity range from ca. 0.4 to 0.8% VRe. This isomerisation reaches the equilibrium value of ca. 0.5 at the peak of hydrocarbon generation. The ratios of the oils studied show that the majority of the oils have reached maturity except for oils from the TA and DA fields, and

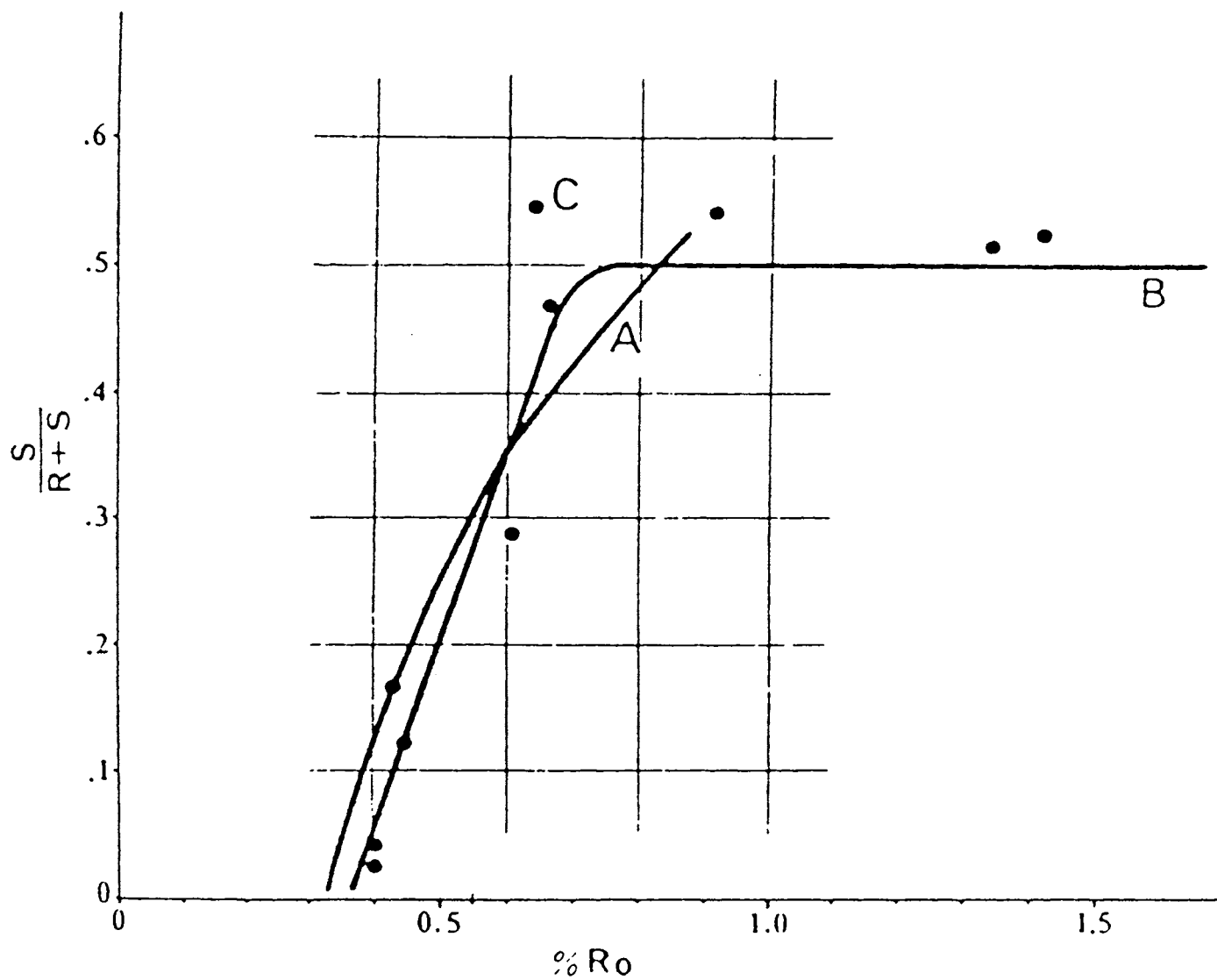


Figure 13: Correlation between 20S/(20S + 20R) ratio for C_{29} regular steranes & vitrinite reflectance ($\%R_o$) (From Waples, & Machihara, 1990)

from wells KI - 1, DD - 3 WA - 1 and SJ - 1. Comparison of results with published data (see Fig. 13) indicates that the oils were generated from source rocks with maturities that range from 0.5% to 0.8% VRe or higher.

Based on the $C_{29} 20S/(20S + 20R)$ ratio, it appears that samples from DF, KE, LA - 2, DE - 1 (A) and DC - C (A) wells are most mature, while samples from TA and DA fields and KI - 1 and WA - 1 are least mature.

Other maturity parameters such as aromatisation of steranes which cover high VRe need to be applied in order to determine the high end of the maturity of source rocks. However, this data is not currently available.

CONCLUSIONS

1. The oils may be classified into three groups based on their n-alkane distributions: normal non-waxy; waxy; and slightly biodegraded.
2. High pris/phy (>3.0) and pris/nC₁₇ (>1.0) ratios indicate that the oils were derived from organic matter that was deposited under peat swamp environments.
3. Mass fragmentograms of steranes and triterpanes show that the oils were generated from terrigenous source rocks containing mixtures of different types of land-plant organic matter including resins.
4. The triterpane and sterane distributions show little variation, suggesting that all the oils were derived from the same general type of organic matter, namely land-plants. The large ranges of oleanane index and hopane to sterane ratios probably reflect differences in the vegetation in different parts of the extensive study area.
5. Triterpane and sterane maturity parameters show that the oils were generated from source rocks with maturities ranging from 0.5% to at least 0.8% VRe.

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