CAMBRIAN SOURCE ROCK GEOCHEMISTRY, STANSBURY BASIN

1. PRELIMINARY EVALUATION OF MOUNT McDONNELL FORMATION IN COASTAL EXPOSURES ON NORTHERN KANGAROO ISLAND

Report for Canyon (Australia) Pty Limited

by

DAVID M. McKIRDY and DIANNE PADLEY

Organic Geochemistry Laboratory
Department of Geology and Geophysics
University of Adelaide

February 1993

INTRODUCTION

The Mount McDonnell Formation is the basal unit of the Early Cambrian Kangaroo Island Group, a sequence of predominantly shelf clastics and carbonates. These mildly deformed strata crop out along the northern coast of Kangaroo Island (Fig. 1) where they display broad open folding and, supposedly, lower greenschist facies metamorphism (Van der Stelt *et al.*, 1992). The adjacent east-west trending Cygnet-Snelling Fault Zone marks both the southern onshore boundary of the Stansbury Basin and the southeastern margin of the Gawler Craton (Belperio and Flint, 1992).

The exposed cover rocks north of the Cygnet and Snelling Faults (Fig. 1) are a valuable window on the petroleum prospectivity of the platform sediments of the southern Stansbury Basin. The Mount McDonnell Formation, by virtue of its low stratigraphic position and high proportion of fine-grained siliciclastics, is a possible source rock; and even if itself not rich enough to have generated commercial quantities of hydrocarbons, will be capable of providing useful information on the *thermal maturity of kerogen and the preservation potential of petroleum elsewhere in the Kangaroo Island Group.* The latter consideration should not be overlooked, in view of possible long-distance migration of hydrocarbons from the Kanmantoo Trough northwards across the hinge zone into reservoir facies of the contiguous platform sequence. Deep-water shales of the Heatherdale Shale on Fleurieu Peninsula contain up to 1.6% TOC and, although now overmature, may have been a prolific source of oil and gas earlier in their burial history (McKirdy *et al.*, 1991)

A previous geochemical study of the Mount McDonnell Formation, based on two samples of shale from outcrop near Cape Cassini, revealed poor source richness (total organic carbon, TOC = 0.22-0.29%; extractable organic matter, EOM = 35-38 ppm) (AMDEL Core Services, 1991). Significantly, Rock–Eval data on one of the samples suggested the presence of oil and gas-prone Type II-III kerogen (hydrogen index, HI = 309) of relatively low thermal maturity (Tmax = 435°C). However, attempted determination of aromatic maturity indicators (e.g. methylphenanthrene index, MPI) was unsuccessful because of the low abundance of di- and triaromatic hydrocarbons in the shale extracts.

The present study is based on a suite of grey to brown mudstones collected from four coastal exposures in the vicinity of Hummocky Point by J. Hibburt (SADME) and A. M. Pearce (Department of Geology and Geophysics, University of Adelaide). The location of the sample sites is shown in Figure 1. The seventeen samples selected for organic geochemical analysis are listed in Table 1 according to height above stratigraphic datum (viz. the base of the section measured by Moore, 1983). They span a 540 metre-thick interval of the Mount McDonnell Formation. Many of these mudstone samples are from intervals displaying linsen bedding (small, starved ripples of very fine sand and coarse silt) which indicate deposition in a shallow marine environment with a strong tidal influence.

The objectives of this study were twofold:

1. To determine the source richness and thermal maturity of the mudstones; and

2. To compare the maturation level of the Mount McDonnell Formation at Hummocky Point with those of Early Cambrian sediments from the northwestern Stansbury Basin on Yorke Peninsula (McKirdy *et al.*, 1991).

WEATHERING

Since all the samples examined in this preliminary investigation are from outcrop, the impact of weathering on their dispersed organic matter must be considered. Previous studies of the effects of subaerial weathering on organic matter in shales (Leythaeuser, 1973; Clayton and Swetland, 1978) demonstrate that caution is necessary when interpreting organic geochemical data obtained from surface samples.

Weathering of shales has been shown to

1) lower TOC values (by as much as 60%);
2) decrease EOM yields (by up to 50%);
3) decrease the ratio of hydrocarbons (saturated and aromatic) to nonhydrocarbons (resins and asphaltenes);
4) increase the ratio of saturated to aromatic hydrocarbons;
5) enrich aromatic hydrocarbons slightly in the ^{13}C isotope; and

6) lower the concentration of *n*-alkanes relative to branched/cyclic alkanes

Each of these effects also can be produced by thermal maturation. Thus, as noted by Clayton and Swetland (1978, p. 307), "in cases of extreme weathering of shale it may be difficult to separate the effects of weathering from those of thermal maturation."

The severity of the weathering of shale-hosted organic matter is dependent on climate. Although there are no published comparative organic geochemical studies of shales exposed to contrasting climatic regimes, the weathering of their organic content is likely to be more intense under humid, tropical or temperate conditions than in arid areas. Other factors which influence the the susceptibility to weathering of organic matter in argillaceous rocks are its rank or thermal maturity, the induration (mudstone) or fissility (shale) of the host rock, and the presence of fractures. Kerogen is somewhat less susceptible to alteration by weathering than is the associated extractable organic matter.

ANALYTICAL METHODS

Details of the analytical procedures are given in Appendix 1.

RESULTS

Analytical data are summarised and presented herein as follows:

	Table	Figure
TOC, C_{15+} extract data	1	-
GC of saturated hydrocarbons	2	2
GC-MS of aromatic hydrocarbons	3	3
Calculated vitrinite reflectance	3	4

DISCUSSION

Source Richness

The mudstones examined in this study are very lean in both total organic carbon (TOC = 0.06-0.18%) and extractable organic matter (EOM = 14-64 ppm; 13-80 mg/g TOC). Allowing for the detrimental effects of weathering on these two parameters, the richest of the mudstones (where fresh) are estimated to contain no more than 0.45% TOC and 80-100 ppm EOM. Hence, the *source richness* of the mudstone lithofacies of the Mount McDonnell Formation must be regarded as poor.

In most cases, hydrocarbons comprise less than 15 percent of the EOM, a feature jointly attributable to the aforementioned effects of weathering and a relatively advanced level of organic maturation (see below). Hydrocarbons have been generated from kerogen and the non-hydrocarbon fraction of the associated EOM, and preferentially expelled from the mudstone, during catagenesis.

The ratio of saturated to aromatic hydrocarbons is reasonably consistent throughout the lower half of the exposed formation at sample sites 1 and 2 (S/A = 0.26-1.7). This parameter becomes more erratic towards the top of the outcrop (sample sites 3 and 4) where S/A values in the range 2–4 probably indicate more severe weathering.

These mudstones are never likely to have been particularly organic-rich and this is consistent with their interpreted shallow, tidally-influenced environment of deposition. However, it may be significant that the TOC values recorded in the lower 330 metres of outcrop are up to three times greater than those measured in the upper part of the exposed section. This increase in organic richness (partly due to less intense weathering) may also reflect a deeper shelf environment, as indicated by the presence of turdidite beds and slope-associated clastics in the section penetrated by the stratigraphic drillhole SADME Investigator-2 (D. I. Gravestock, pers. comm.).

Type of organic matter

In the absence of reliable kerogen typing (based on H/C and O/C atomic ratios, Rock-Eval pyrolysis, pyrolysis-GC or maceral analysis), the saturated hydrocarbon distributions of the mudstones (Fig. 2) provide the only available clues to the origin of their dispersed organic matter. On the other hand, the saturates fraction of the EOM is particularly susceptible to contamination (e.g. by soil organics introduced during weathering).

Molecular signatures of a primary algal/bacterial input to these mudstones include:

1) *n*-alkane distribution with a maximum at C_{16-18};
2) pristane/*n*-heptadecane ratios in the range 0.3-0.65;
2) phytane/*n*-octadecane ratios in the range 0.2-0.55; and
3) high concentrations of singly branched (iso, anteiso) alkanes.

These features are highlighted in Figure 2A. Pristane/phytane ratios are uniformly low (pr/ph = 0.9-1.5) and indicate that this microbial organic matter was exposed to suboxic conditions during deposition and early diagenesis.

Five samples have saturates distributions that display an unusual predominance of C_{16}-C_{24} even carbon-numbered *n*-alkanes (Table 2; Fig. 2D, G, H, K and L). The same feature is evident in the two Mount McDonnell samples analysed by AMDEL Core Services (1991). Although uncommon, such even-predominance has been reported over the C_{12}-C_{18} range in Holocene lacustrine carbonate muds from the Coorong (Hayball, 1990); and over the C_{18}-C_{32} range in ancient evaporitic carbonates deposited under reducing conditions (Waples, 1985; Peters and Moldowan, 1993). In all these sediments, bacteria (including cyanobacteria) were important sources of the organic matter.

Recent plant-derived waxes (and other hydrocarbons?) appear to have left their mark on all of the saturates fractions analysed by gas chromatography (Fig. 2), as indicated by the presence of C_{25}-C_{35} *n*-alkanes with a marked predominance of odd-carbon-numbered homologues (CPI at *n*-C_{31} ≥4). These contaminants give rise to otherwise inexplicable bimodal *n*-alkane profiles with maxima at C_{16-18} and C_{31} (or, in the case of the sample from 480 m, at C_{25}). Some idea of the relative contributions of indigenous (algal and bacterial) and adventitious (land plant) hydrocarbons is provided by the C_{17}/C_{31} *n*-alkane ratio (Table 2); the higher the ratio, the less the contamination. Clearly, the least contaminated/weathered sample is that from 40 metres above datum, near the base of the exposed sequence.

Thermal maturity

The aromatic hydrocarbons isolated from four mudstones (including the least weathered sample) were selected for analysis by GC-MS. This allowed determination of several isomer ratios (Table 3), based on their respective distributions of methyl-, dimethyl- and trimethylnaphthalenes (Fig. 3), that are known to respond systematically to increasing thermal maturity (Radke, 1987). Radke *et al.* (1984) measured two of these isomer ratios (MNR and DNR-1) in a suite of humic coals and calibrated their observed increase with rank against vitrinite reflectance.

Using this approach we have been able to define the "chemical rank" or "aromatic maturity" of the organic matter preserved in the Mount McDonnell Formation, and to express it in terms of equivalent or calculated vitrinite reflectance (VR_{calc}). The maturity data summarised in Table 3 are remarkably consistent, given the low concentrations of aromatic hydrocarbons in these mudstones and the preferential loss of aromatics from the EOM during weathering. For each sample there is good agreement between the two values of VR_{calc}; and the greatest maturity is displayed by the stratigraphically lowest (most deeply buried) mudstone (40 metres, VR_{calc} = 1.24%). That this particular sample also happens to be the least weathered adds to the reliability of its measured aromatic maturity. On the other hand, the high saturates/aromatics ratio of the sample from 365 metres (S/A = 4.2) suggests that it may have lost a significant proportion of its catagenetically-derived aromatic hydrocarbons during weathering. Hence, the calculated vitrinite reflectance of the latter sample (VR_{calc} = 1.03%) should be regarded as suspect.

Thermal maturities in the range VR_{calc} = 1.10-1.24% place the Mount McDonnell Formation at Hummocky Point within *the late mature, gas-condensate stage of petroleum generation.* Such aromatic maturities are broadly consistent with the pristane/*n*-heptadecane and phytane/*n*-octadecane values measured from the saturated hydrocarbons (Table 2). The two isoprenoid/*n*-alkane ratios are both source- and maturity-dependent. It is also interesting to note that these mudstones appear to have a maturation level which coincides with the mode of the maturity distribution exhibited by other Early Cambrian sediments (mainly carbonates) from the Stansbury Basin on Yorke Peninsula (Fig. 3). In particular, comparable maturities have been documented (albeit at higher stratigraphic levels, viz. Parara and Ramsay Limestones) in the Stansbury Town-1, Stansbury West-1 and Minlaton-1 exploration wells (McKirdy *et al.*, 1991).

Kerogen isolated from the Emu Bay Shale (upper Kangaroo Island Group) near White Point, some 30 km east of the present study area, has an atomic H/C ratio of 0.48 (McKirdy and Powell, 1974). If this kerogen is of Type II-III composition (a reasonable assumption given the low organic carbon content of the shale: TOC = 0.37%), then its measured H/C value is consistent with a maturation level approaching VR = 2.0%, the deadline of wet gas formation (Tissot and Welte, 1984). Although providing only a single data point, this kerogen further constrains the maturity of the Early Cambrian sequence along the southern margin of the Stansbury Basin. Moreover, when considered in relation to the aromatic maturity data obtained from the Mount McDonnell Formation, it suggests a trend of decreasing maturation towards the west.

CONCLUSIONS

1. Mudstones from coastal exposures of the Early Cambrian Mount McDonnell Formation near Hummocky Point, northern Kangaroo Island, are organically lean (TOC <0.2%) and contain low concentrations of extractable organic matter (EOM <70 ppm).

2. Hydrocarbons (saturates and aromatics) generally comprise less than fifteen percent of the EOM due to the combined effects of weathering and advanced thermal alteration (late catagenesis).

3. GC analysis of the saturated hydrocarbons shows them to consist of indigenous microbial alkanes and appreciable (but variable) amounts of adventitious, waxy alkanes. The latter are clearly contaminants derived from higher plants and/or soil organic matter.

4. GC-MS analysis of the two-ring aromatic hydrocarbons (methyl-, dimethyl- and trimethylnaphthalenes) reveals maturity levels equivalent to the wet gas-condensate stage of petroleum generation ($VR_{calc} = 1.10\text{-}1.24\%$).

5. The hydrocarbon source potential of the mudstone lithofacies of the Mount McDonnell Formation, at the stratigraphic levels sampled in outcrop, is poor. The interpreted shallow tidal to deeper marine shelf environment of deposition was not conducive to the accumulation and enhanced preservation of oil-prone organic matter.

CAUTION AND RECOMMENDATION

Any interpretation of the organic geochemical data presented in this report should not lose sight of the following facts:

1) all the rocks so far analysed are surface samples from coastal outcrops;
2) the mudstones examined are organically very lean;
3) the effects of weathering on such low concentrations of extractable organic matter are potentially great, involving both contamination by recent plant- and soil-derived hydrocarbons, and selective removal of indigenous aromatic hydrocarbons; and
4) previous geological investigations of northern Kangaroo Island found (assumed?) that its Cambrian sediments had undergone regional metamorphism to lower greenschist facies (see e.g. Van der Stelt *et al.*, 1992).

The latter observation seems to be at odds with the maturity picture which has emerged from the present study. It is therefore recommended that the aromatic maturity measurements made on outcrop material be validated by analysing in the same manner core samples of the Mount McDonnell Formation from the nearby SADME drillhole, Investigator-2. A suite of ten samples (quarter core) has already been assembled for this purpose (Table 4).

REFERENCES CITED

AMDEL Core Services (1991) Geochemical evaluation of source potential and thermal maturity, Stansbury Basin. *Report for South Australian Department of Mines and Energy* (unpublished).

Belperio, A. P. and Flint, R.B. (1992) The southeastern margin of the Gawler Craton. *South Australian Department of Mines and Energy Report Book,* 92/6.

Clayton, J. L. and Swetland, P. J. (1978) Subaerial weathering of sedimentary organic matter. *Geochimica et Cosmochimica Acta* **42,** 305-312.

Hayball, A. J. (1990) Organic geochemistry of Holocene lacustrine carbonates in the Coorong region, South Australia. *B.Sc. Honours Thesis, Flinders University of South Australia.*

Leythaeuser, D. (1973) Effects of weathering on organic matter in shales. *Geochimica et Cosmochimica Acta* **37,** 113-120.

McKirdy, D. M. and Powell, T. G. (1974) Metamorphic alteration of carbon isotopic composition in ancient organic matter: new evidence from Australia and South Africa. *Geology* **2,** 591-595.

McKirdy, D. M., Gravestock, D. I. and Gatehouse, C. G. (1991) Cambrian petroleum and source rock geochemistry of South Australia. In: Australian Society of Exploration Geophysicists/Geological Society of Australia Conference, Sydney. *Geological Society of Australia Abstracts* **30,** 63-64.

Moore, P. S. (1983) *Geological Fieldguide to the Northeast Coast of Kangaroo Island.* Australasian Sedimentologists Group, Adelaide.

Pearce, A. M. (1992) Carbon and oxygen isotopic compositions of some Late Proterozoic and Early Cambrian carbonates in the southern Adelaide Geosyncline. *B.Sc. Honours Thesis, University of Adelaide.*

Peters, K. E. and Moldowan, J. M. (1993) *The Biomarker Guide.* Prentice-Hall, Englewood Cliffs, New Jersey.

Radke, M. (1987) Organic geochemistry of aromatic hydrocarbons. In: *Advances in Petroleum Geochemistry, Vol. 2.* (J. Brooks and D. Welte, eds.), Academic Press, London, pp. 141-207.

Radke, M., Leythaeuser, D. and Teichmuller, M. (1984) Relationship between rank and composition of aromatic hydrocarbons for coals of different origins. *Organic Geochemistry* **6**, 423-430.

Tissot, B. P. and Welte, D. H. (1978) *Petroleum Formation and Occurrence*, Springer-Verlag, Berlin, 2nd edition.

Van der Stelt, B. J., Belperio, A. P. and Flint, R. B. (1992) Geophysical appraisal of northern Kangaroo Island. *South Australian Department of Mines and Energy Report Book*, 92/2.

Waples, D. W. (1985) *Geochemistry in Petroleum Exploration*, D. Reidel Publishing Company, Dordrecht.

APPENDIX 1: ANALYTICAL METHODS

1. Sample preparation

Pieces of rock with freshly broken surfaces were removed from larger (several kg) samples of mudstone collected from outcrop specifically for organic geochemical analysis (this report) and isotopic studies (Pearce, 1992). Obviously weathered surfaces were avoided, or removed with a water-lubricated diamond saw. The rock was crushed to 1 cm-sized chips which were then pulverised in a Siebtechnik mill for 20-30 secs. Approximately 600 g of powdered rock was prepared from each of the 17 samples chosen for analysis.

2. Total organic carbon (TOC)

Total organic carbon was determined by digestion of a known weight (~200 mg) of rock powder in 50% HCl to remove carbonates, followed by combustion in oxygen in the induction furnace of a Leco IR-12 Carbon Determinator and measurement of the resultant CO_2 by infra-red detection.

3. Extractable organic matter (EOM)

Powdered rock (215-540 g) was extracted with azeotropic dichloromethane/methanol (93:7) in a Soxhlet apparatus for 72 hours. Removal of the solvent under vacuum in a Büchi rotary evaporator gave the EOM (nominally C_{15+}). In many cases, salt (NaCl) was a significant component of the crude extract and this had to be removed by careful washing with distilled water.

4. Liquid chromatography

Because of the low extract yields, asphaltenes were not precipitated from the EOM prior to liquid chromatography. The EOM was separated into hydrocarbons (saturates and aromatics) and NSO-compounds (resins and asphaltenes) by liquid chromatography on activated silica gel (70-230 mesh Kieselgel 40; sample:adsorbent ratio = 1:100). The saturates were eluted with petroleum ether, the aromatics with petroleum ether/dichloromethane (40:60) and an NSO fraction with methanol/dichloromethane (65:35). Each fraction was then transfered to a pre-weighed vial and stored under refrigeration.

5. Gas chromatography (GC)

The total saturated hydrocarbon fraction (viz. *n*-alkanes, branched and cyclic alkanes) was examined by gas chromatography using the following instrumental parameters:

Instrument	Varian 3400 gas chromatograph
Injector	Split/splitless; operated in the split mode at 20:1
Column	30 m x 0.25 mm fused silica, DB-1
Carrier gas	Hydrogen with a linear flow rate of 30 cm/sec
Temperature program	40°C for 2 min, 40-300°C at 4°C/min and then held isothermal at 300°C for 20 min
FID temperature	305°C

6. Gas chromatography-mass spectrometry (GC-MS)

GC-MS analysis of the total aromatic hydrocarbon fraction was undertaken in the selected ion monitoring (SIM) mode. The instrument and its operating parameters were as follows:

System	Varian 3400 gas chromatograph coupled with a Finnegan TSQ 70 triple quadrupole-multiple scanning mass spectrometer and Finnegan MAT data system
Column	30 m x 0.25 mm fused silica, DB-5; interfaced directly to source of mass spectrometer
Injector	Varian on-column
Carrier gas	Helium
Temperature program	5°C for 2 min, 50-180°C at 8°C/min, 180-300°C at 4°C/min, and then held isothermal at 300°C for 20 min
Mass spectrometer settings	EI mode, 70 eV; 10 ions monitored; 0.2 sec dwell time for each ion

The following ions were monitored and recombined in a single RIC trace:

m/z	Compound type
128	naphthalene
141+142	methylnaphthalenes
156	dimethylnaphthalenes
170	trimethylnaphthalenes
178	phenanthrene
192	methylphenanthrenes
206	dimethylphenanthrenes
231	triaromatic steroids
253	C-ring monoaromatic steroids

7. Analysts

AMDEL Core Services, Frewville

- TOC analysis

Organic Geochemistry Laboratory, Department of Geology and Geophysics, University of Adelaide

- sample preparation, Soxhlet extraction, liquid chromatography (Xu Gu)
- GC, GC-MS (Dianne Padley)

Table 1. Total organic carbon and extract data on Mount McDonnell Formation, northern Kangaroo Island

Height above datum	Weight sample	TOC	EOM Yield		EOM Composition			
m	g	%	ppm	mg/g TOC	Sat %	Arom %	NSO %	S/A
Sample Site 4								
580	535.41	0.08	64	80	0.7	1.2	98.1	0.58
575	542.22	0.06	15	24	5.8	2.6	91.6	2.23
Sample Site 3								
480	529.60	0.08	14	17	10.0	3.0	87.0	3.33
380	523.45	0.09	36	24	1.4	1.9	96.7	0.74
365	511.71	0.10	19	19	6.3	1.5	92.2	4.20
340	531.00	0.05	17	34	3.6	4.2	92.2	0.86
330	505.20	0.15	19	13	9.1	2.2	88.7	4.14
Sample Site 2								
240	503.61	0.09	34	37	4.4	3.1	92.5	1.42
220	243.38	0.10	37	37	4.9	3.1	92.0	1.58
210	551.93	0.14	26	19	1.6	3.0	95.4	0.53
205	501.58	0.14	49	35	4.1	2.4	93.5	1.71
190	489.12	0.12	23	19	3.5	2.4	94.1	1.46
130	463.92	0.18	34	19	3.8	3.0	93.2	1.27
120	216.48	0.12	54	45	3.9	3.5	92.6	1.11
100	234.20	0.09	23	25	7.9	6.4	85.7	1.23
90	225.00	0.11	37	33	4.5	17.5	78.0	0.26
Sample Site 1								
40	469.19	0.12	38	22	2.8	3.1	94.1	0.90

S/A = saturated hydrocarbons/aromatic hydrocarbons

Table 2. Alkane parameters in mudstones from Mount McDonnell Formation, northern Kangaroo Island

Height above datum	Pr/Ph	Pr/*n*-C_{17}	Ph/*n*-C_{18}	*n*-Alkane Profile			
m				Maxima	C_{17}/C_{31}	CPI at C_{17}	EOP
Sample Site 3							
480	0.93	0.39	0.28	25,18	0.80	nd	+
365	0.98	0.39	0.35	18,31	5.52	1.05	+
Sample Site 2							
240	1.22	0.45	0.39	31,16	5.36	0.50	-
220	1.34	0.47	0.41	16,31	6.80	1.31	-
210	1.06	0.36	0.21	18,31	6.52	0.70	+
205	1.21	0.39	0.27	16,31	4.89	1.22	+
190	nd	nd	nd	31,16	7.05	0.03	-
130	1.46	0.41	0.45	31,16	4.08	0.29	-
120	0.94	0.39	0.21	31,18	5.70	0.46	+
100	1.36	0.66	0.53	17,31	4.87	1.03	-
90	1.33	0.32	0.30	17,31	3.80	0.57	-
Sample Site 1							
40	1.33	0.36	0.38	17,31	4.82	1.92	-

Carbon preference index (CPI) at $C_{31} = 2 \times n\text{-}C_{31} / [n\text{-}C_{30} + n\text{-}C_{32}]$

EOP = even/odd predominance in C_{16}-C_{24} *n*-alkanes

nd = not determined   + = present   - = absent

Table 3. Thermal maturity based on diaromatic hydrocarbons in four mudstones from Mount McDonnell Formation, northern Kangaroo Island

Height above datum m	MNR	DNR-1	TNR-1	VR_{calc} % (a)	VR_{calc} % (b)
Sample Site 3					
365	1.44	2.95	0.66	1.07	1.03
Sample Site 2					
240	1.92	6.73	0.65	1.15	1.20
220	1.30	4.46	0.68	1.04	1.10
Sample Site 1					
40	2.18	7.66	0.53	1.19	1.24

Methylnaphthalene ratio (MNR), dimethylnaphthalene ratio (DNR-1), trimethylnaphthalene ratio (TNR-1) and VR_{calc} are defined by Radke *et al.* (1984) and Radke (1987) as follows:

$$\text{MNR} = \frac{\text{2-MN}}{\text{1-MN}}$$

$$\text{DNR-1} = \frac{\text{2,6-DMN} + \text{2,7-DMN}}{\text{1,5-DMN}}$$

$$\text{TNR-1} = \frac{\text{2,3,6-TMN}}{\text{1,3,5-TMN} + \text{1,4,6-TMN}}$$

VR_{calc} (a) = 0.17 MNR + 0.82 (for VR in the range 0.7-1.5%; r = 0.75)

VR_{calc} (b) = 0.0.46 DNR + 0.89 (for VR in the range 0.7-1.5%; r = 0.83)

where
1-MN = 1-methylnaphthalene
2-MN = 2-methylnaphthalene
1,5-DMN = 1,5-dimethylnaphthalene
2,6-DMN = 2,6-dimethylnaphthalene
2,7-DMN = 2,7-dimethylnaphthalene
1,3,5-TMN = 1,3,5-trimethylnaphthalene
1,4,6-TMN = 1,4,6-trimethylnaphthalene
2,3,6-TMN = 2,3,6-trimethylnaphthalene

Table 4. Core samples of Cambrian mudstone from SADME Investigator-2 selected for organic geochemical analysis *

Depth in metres
138.9
244.3
343.5
429.0
505.3
566.5
693.4
766.0
880.1
956.9

* Samples are lengths of quarter core

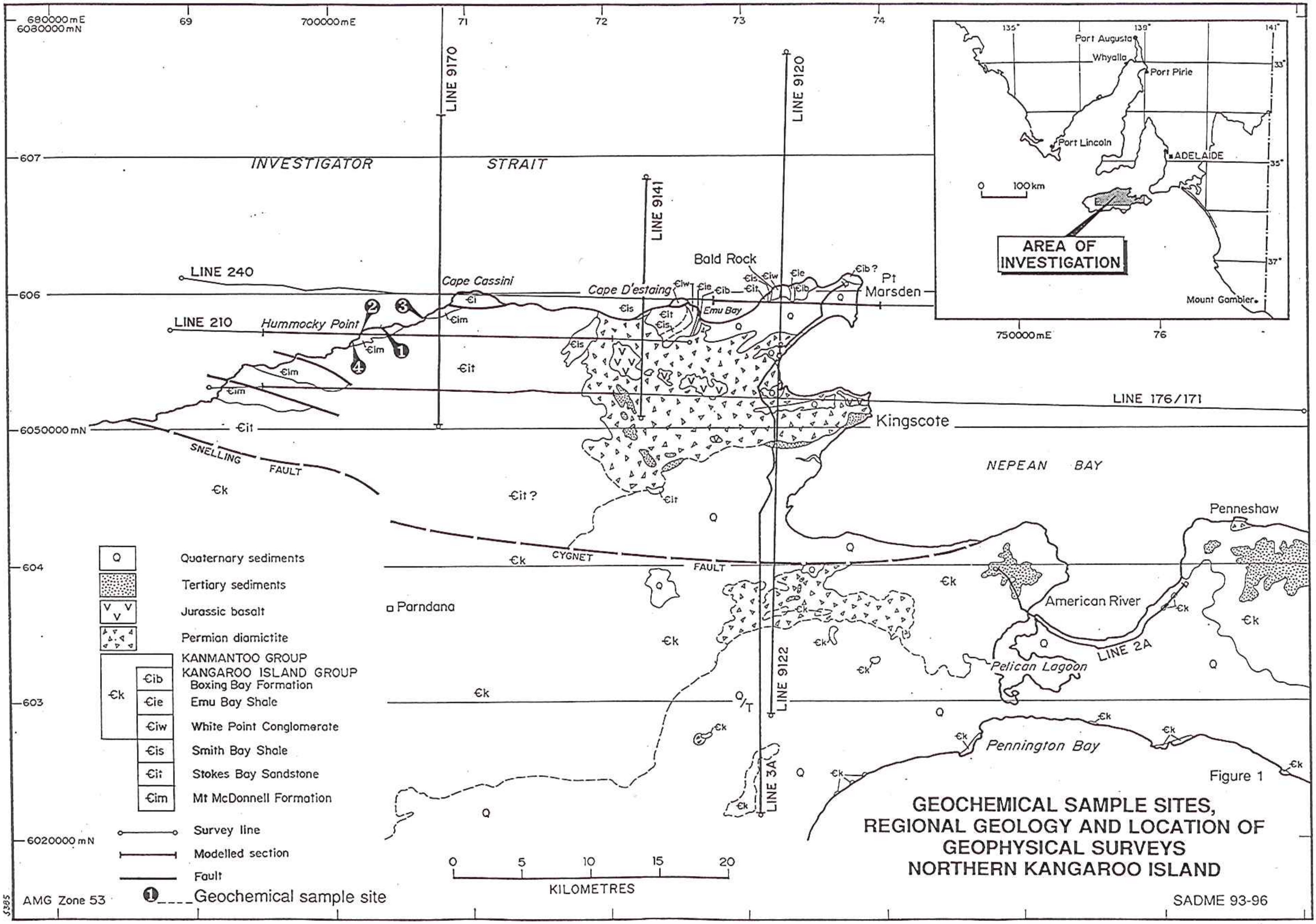


Figure 1

GEOCHEMICAL SAMPLE SITES, REGIONAL GEOLOGY AND LOCATION OF GEOPHYSICAL SURVEYS NORTHERN KANGAROO ISLAND

SADME 93-96

FIGURE 2

Gas chromatograms of saturated hydrocarbons in outcrop samples of Cambrian mudstone, Mount McDonnell Formation

Figure	*Sample Site*	*Height above datum (m)*
2A	1	40
2B	2	90
2C	2	100
2D	2	120
2E	2	130
2F	2	190
2G	2	205
2H	2	210
2I	2	220
2J	2	240
2K	3	365
2L	3	480

FIGURE 2A

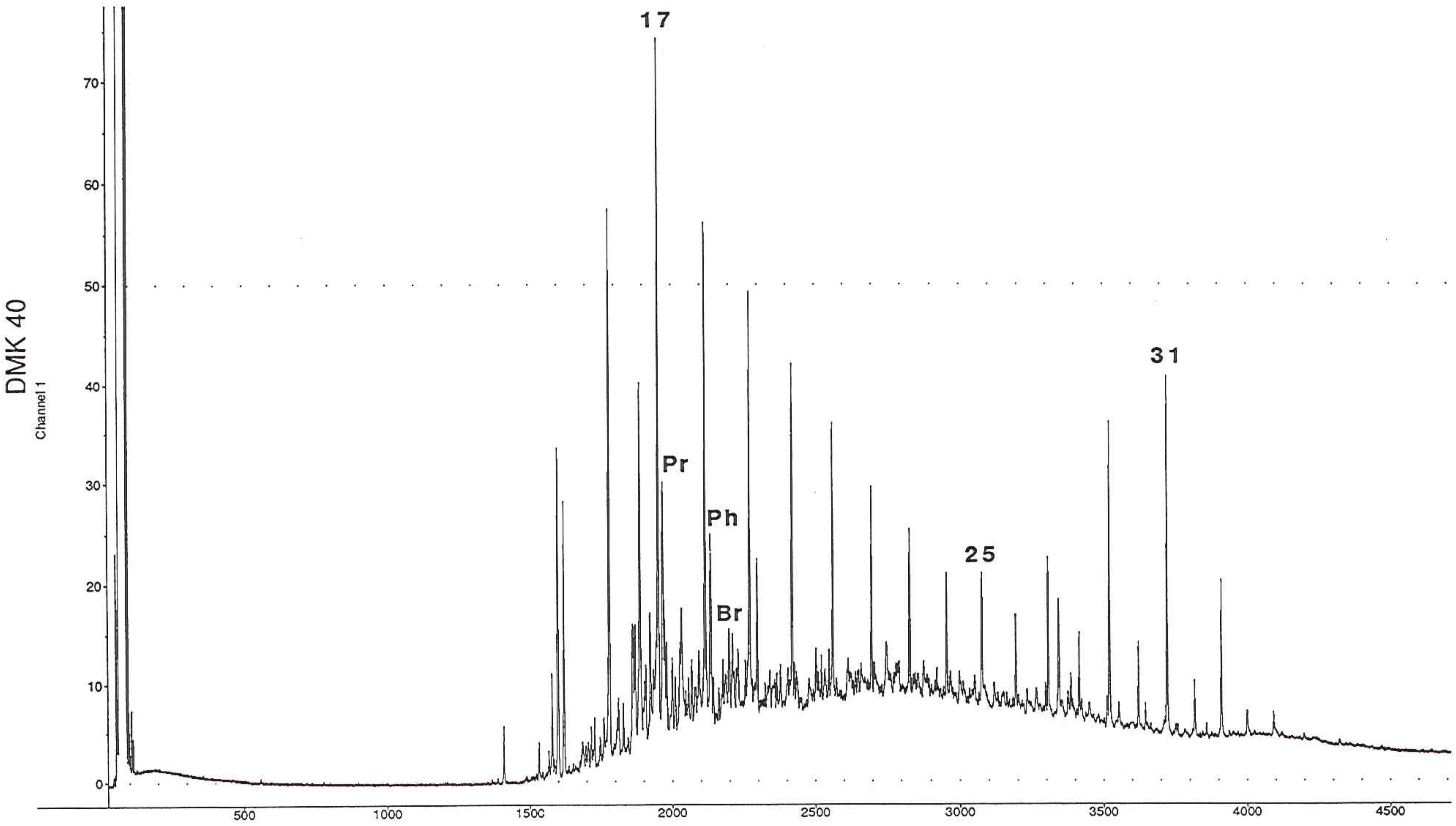

DMK 40
Channel 1
70
60
50
40
30
20
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
17
Pr
Ph
Br
25
31

FIGURE 2B

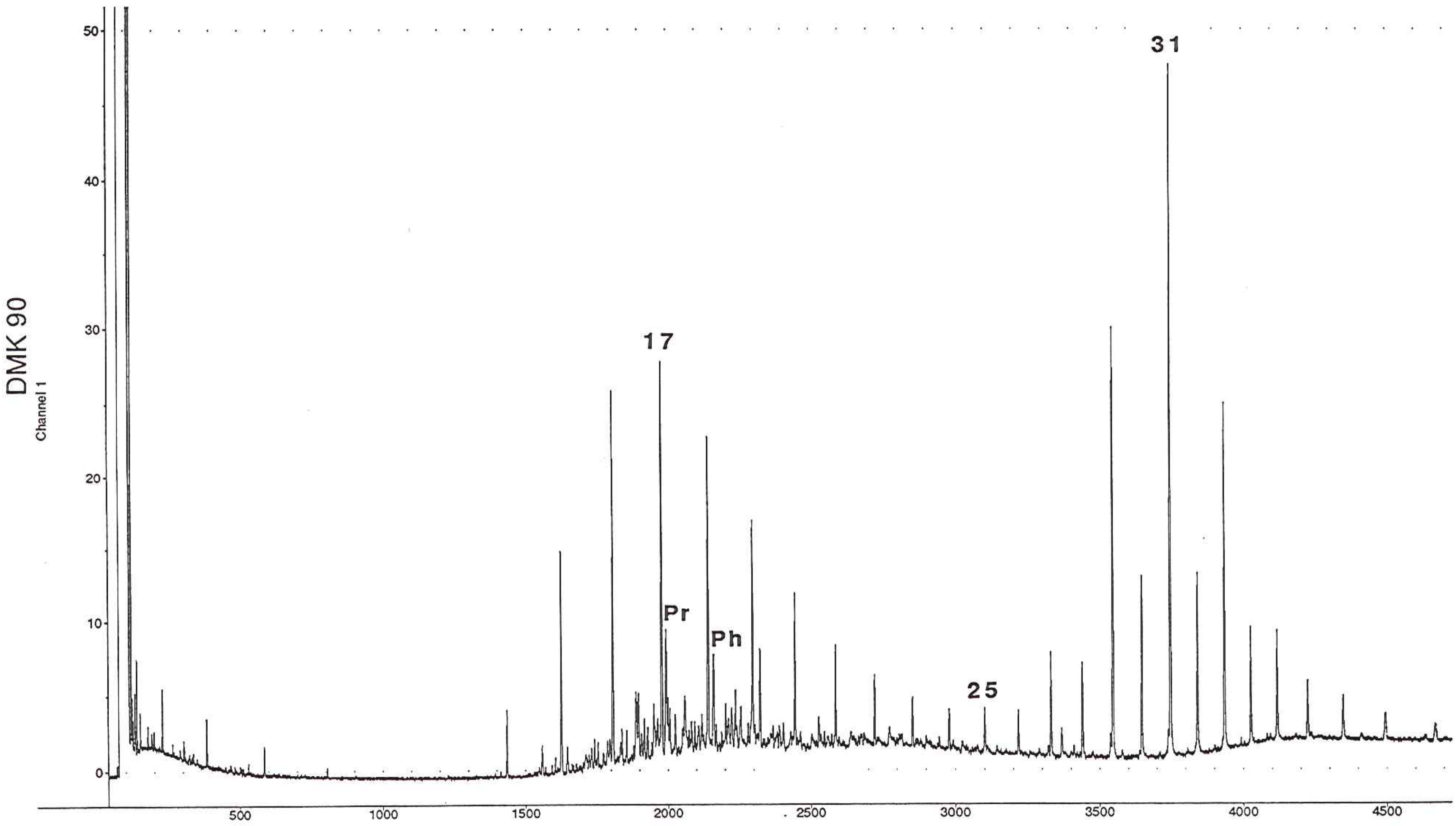

DMK 90
Channel 1
0
10
20
30
40
50
17
Pr
Ph
25
31
500
1000
1500
2000
2500
3000
3500
4000
4500

FIGURE 2C

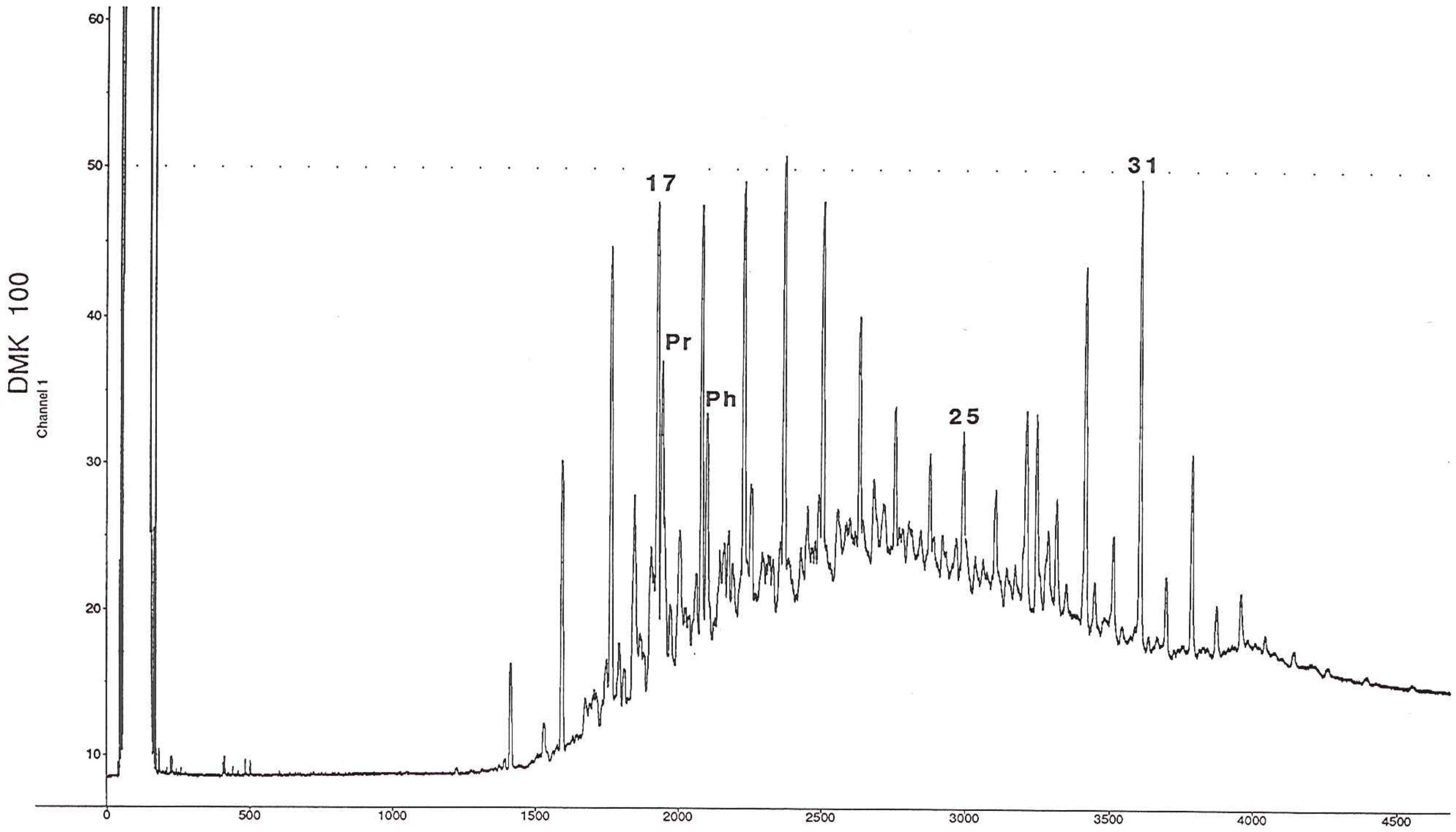

DMK 100
Channel 1
60
50
40
30
20
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
17
Pr
Ph
25
31

FIGURE 2D

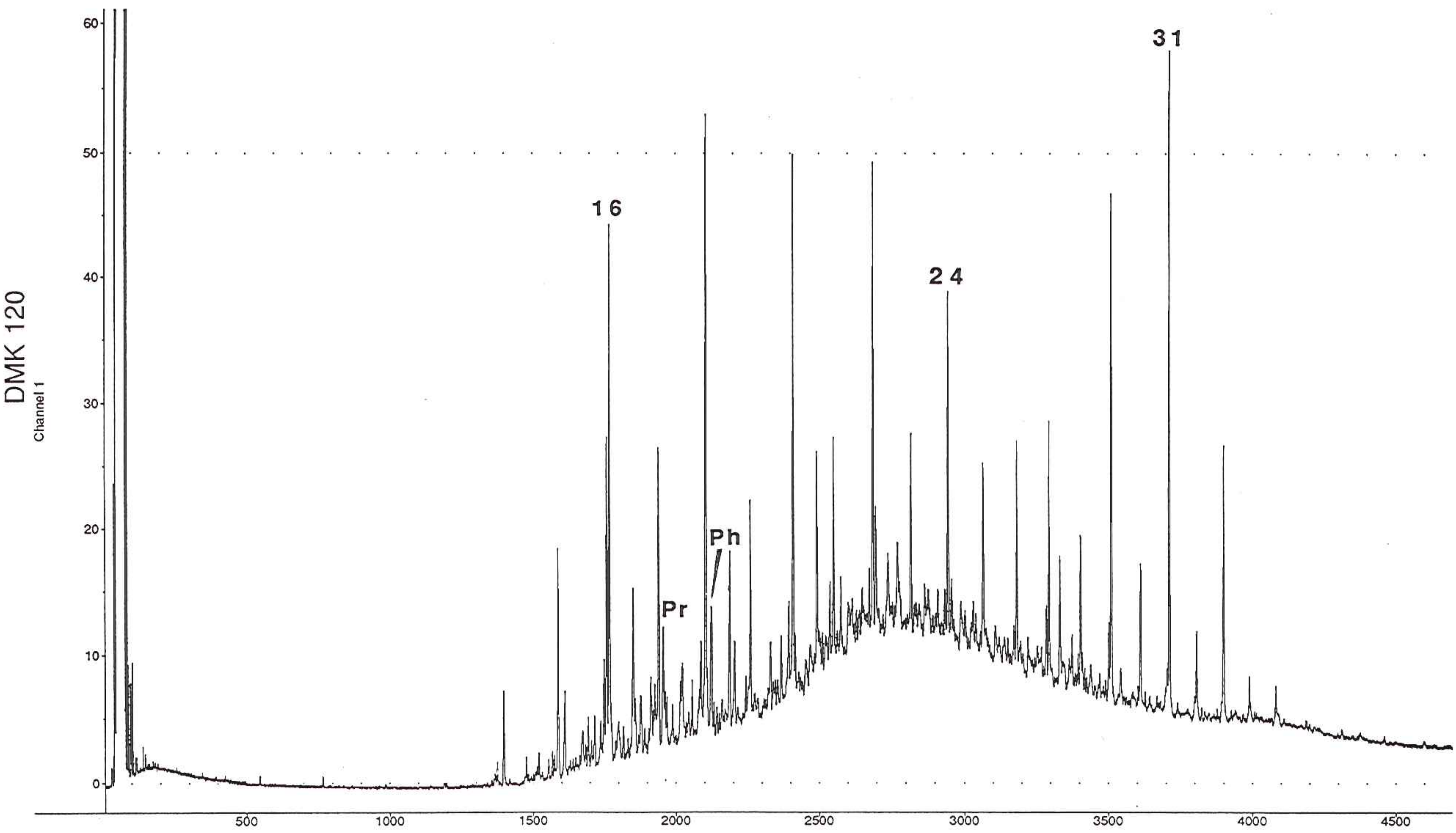

DMK 120
Channel 1
0
10
20
30
40
50
60
500
1000
1500
2000
2500
3000
3500
4000
4500
16
Pr
Ph
24
31

FIGURE 2E

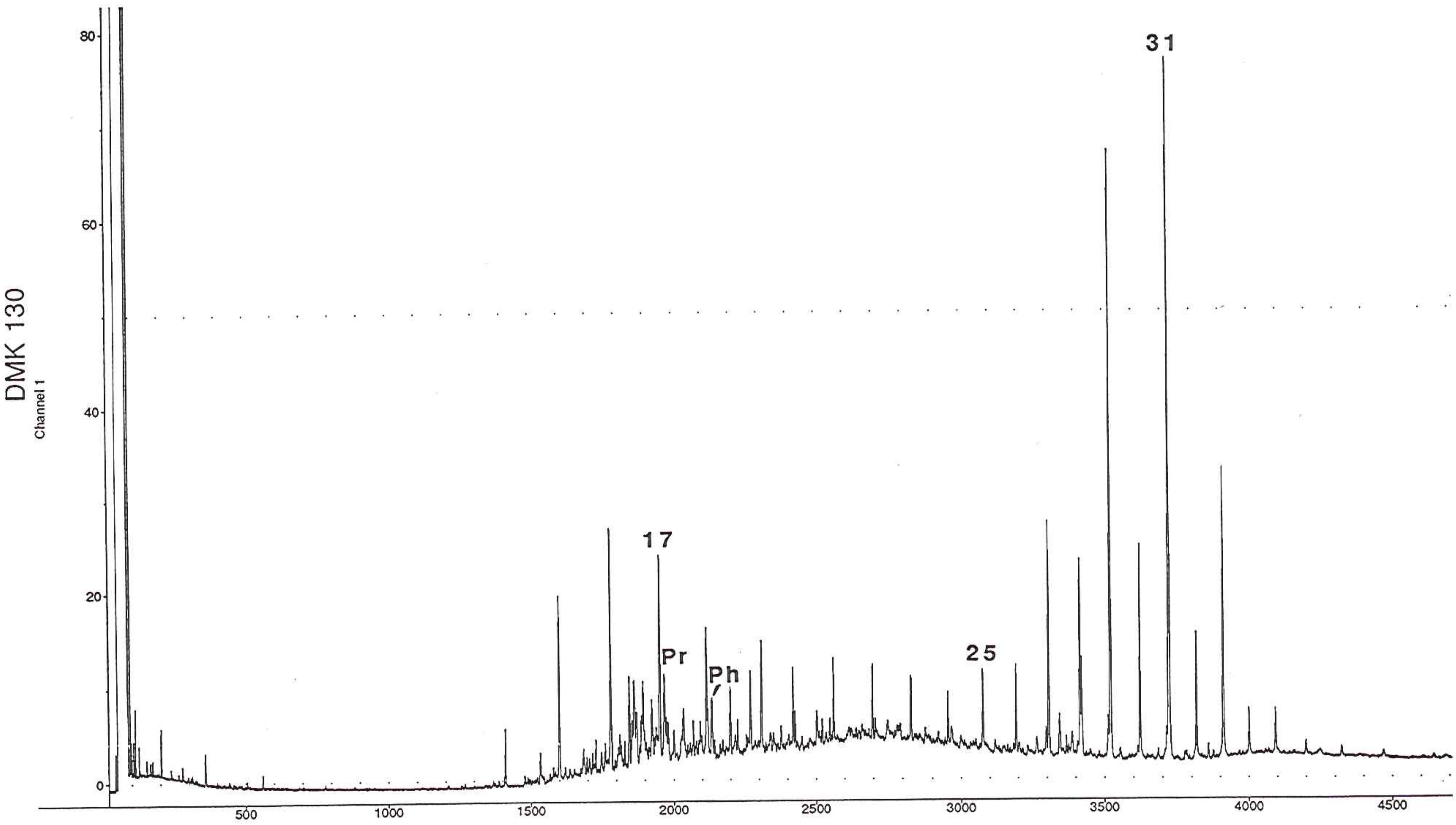

DMK 130
Channel 1
80
60
40
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
17
Pr
Ph
25
31

FIGURE 2F

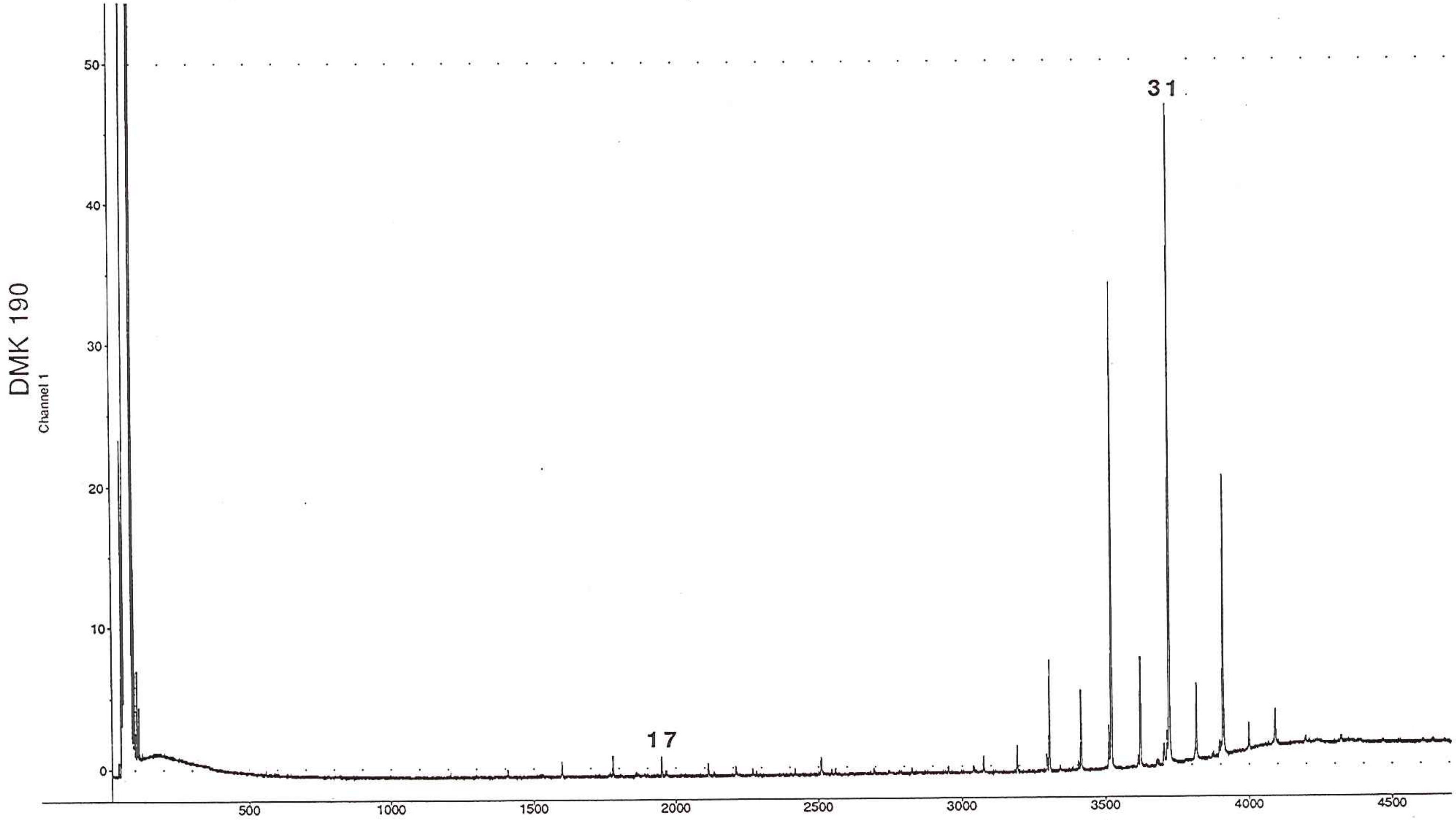

DMK 190
Channel 1
50
40
30
20
10
0
31
17
500
1000
1500
2000
2500
3000
3500
4000
4500

FIGURE 2G

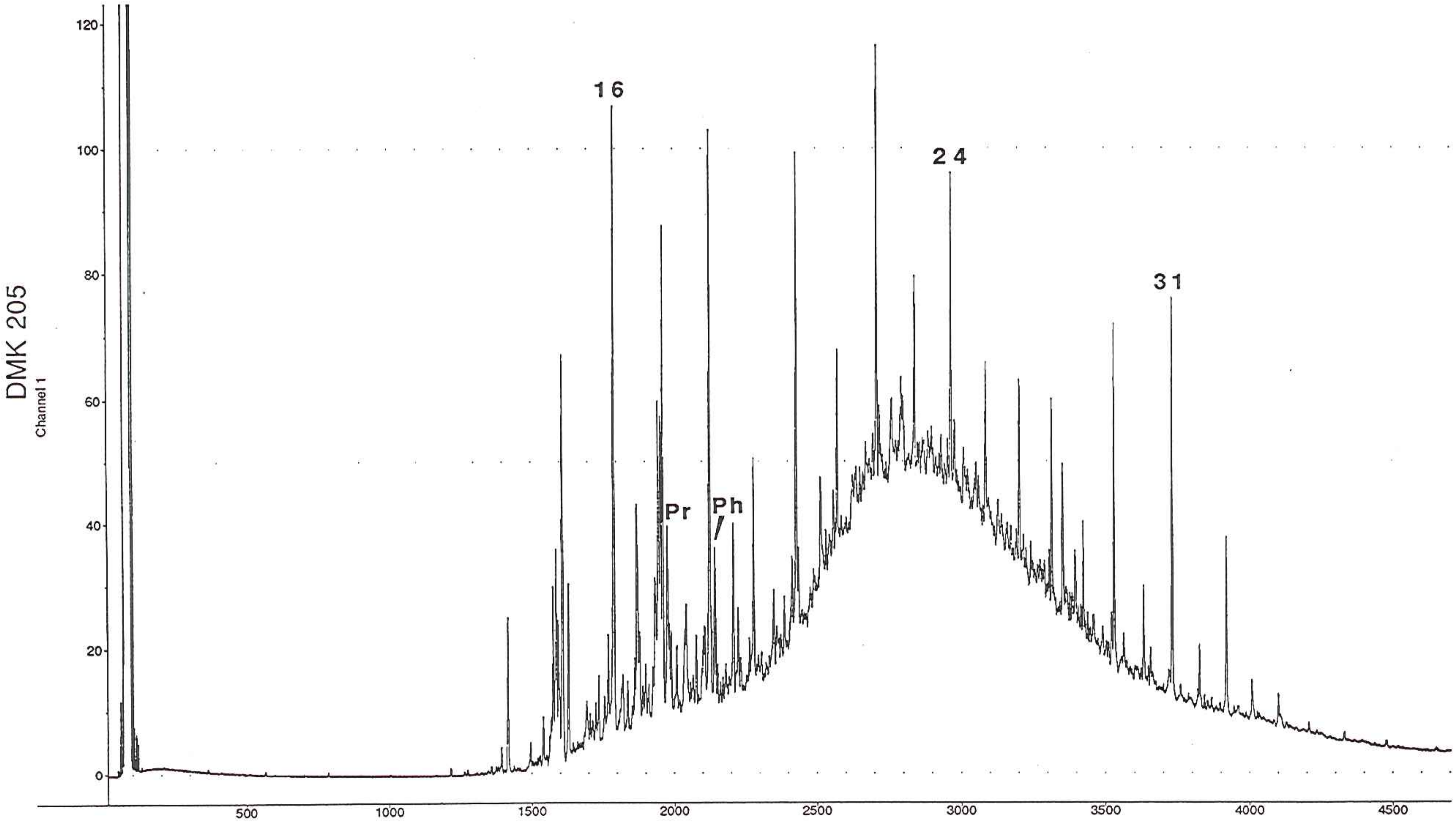

DMK 205
Channel 1
120
100
80
60
40
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
1 6
Pr
Ph
2 4
3 1

FIGURE 2H

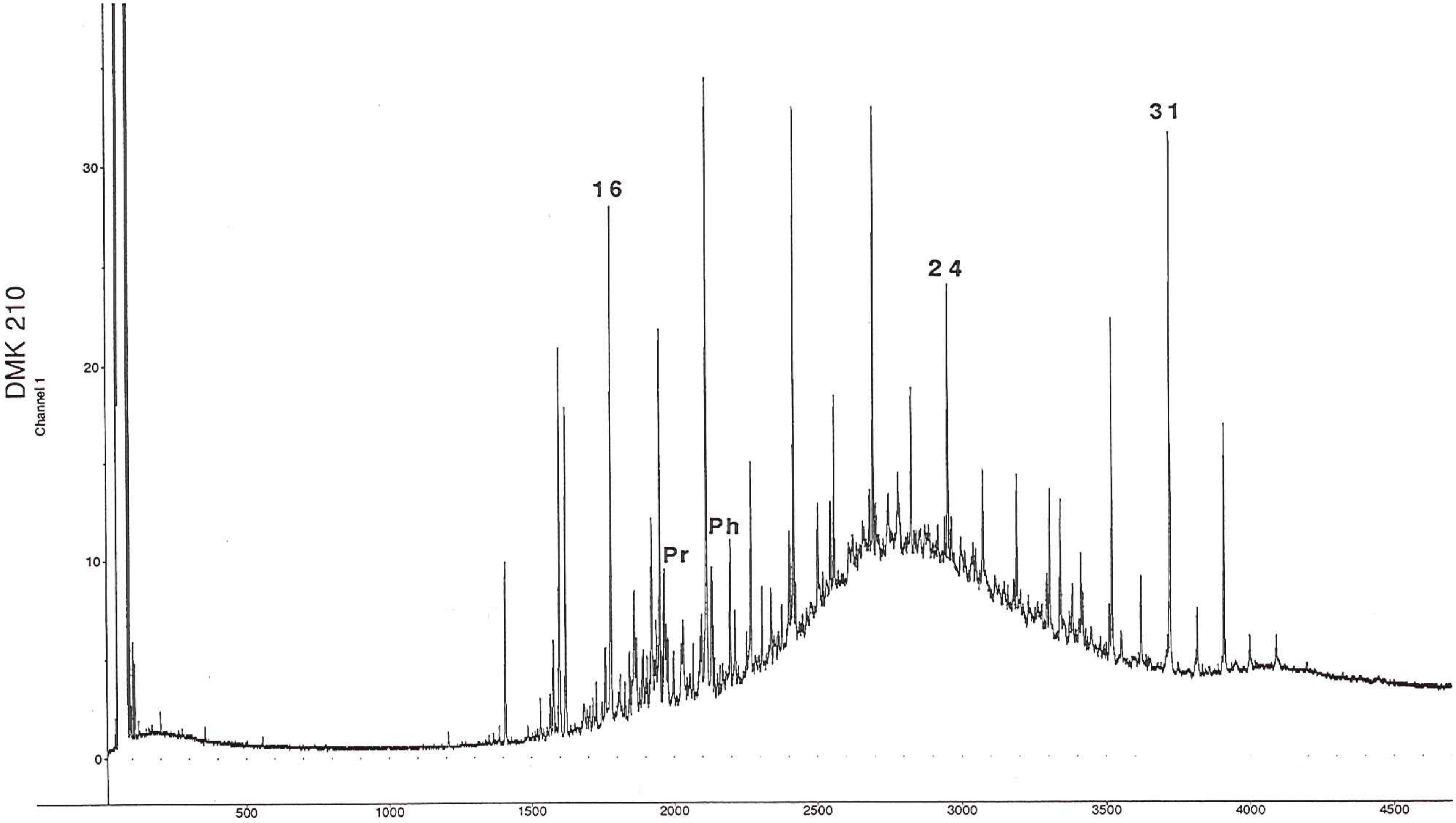

DMK 210
Channel 1
30
20
10
0
16
Pr
Ph
24
31
500
1000
1500
2000
2500
3000
3500
4000
4500

FIGURE 2I

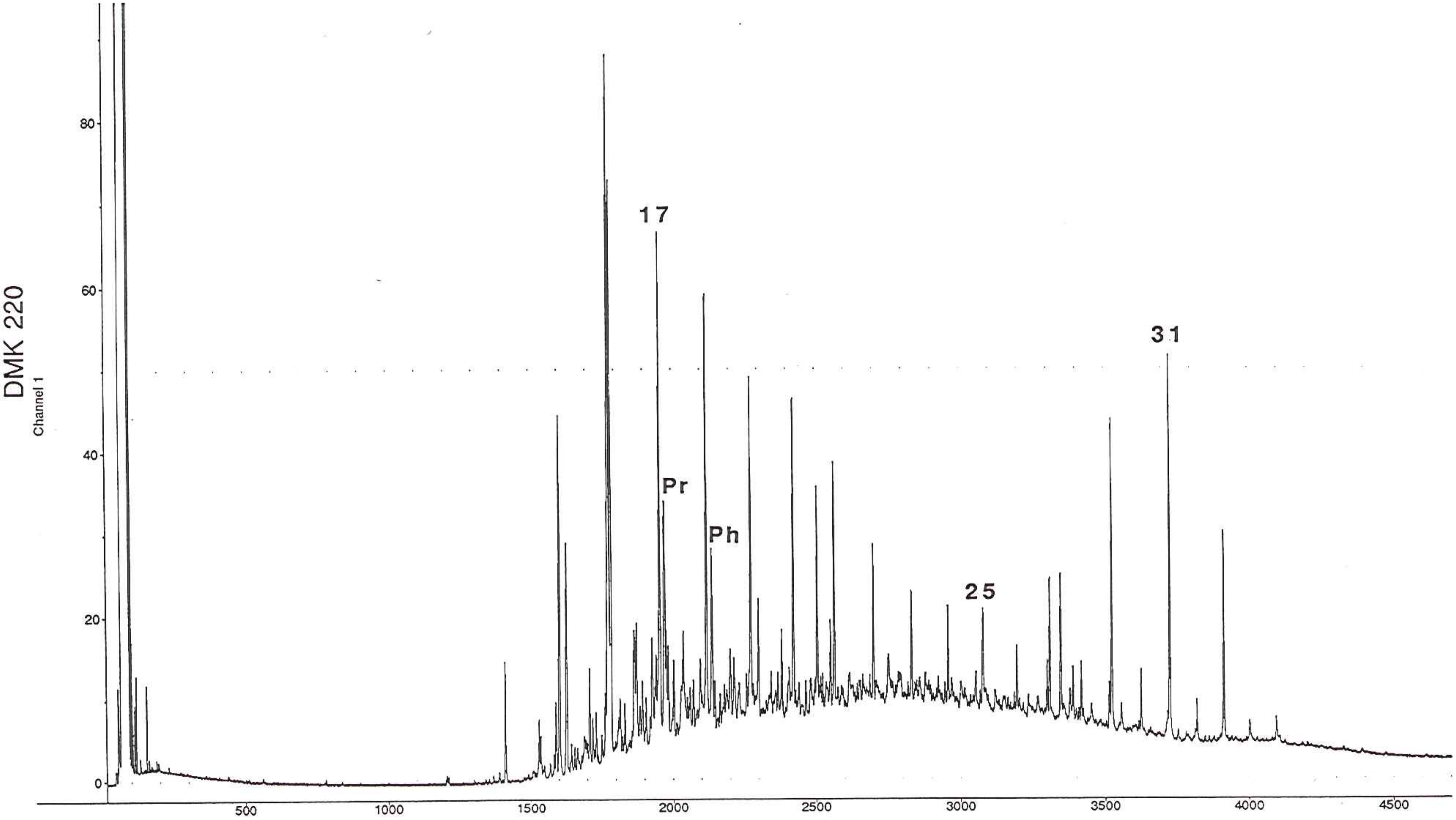

DMK 220
Channel 1
0
20
40
60
80
500
1000
1500
2000
2500
3000
3500
4000
4500
17
Pr
Ph
25
31

FIGURE 2J

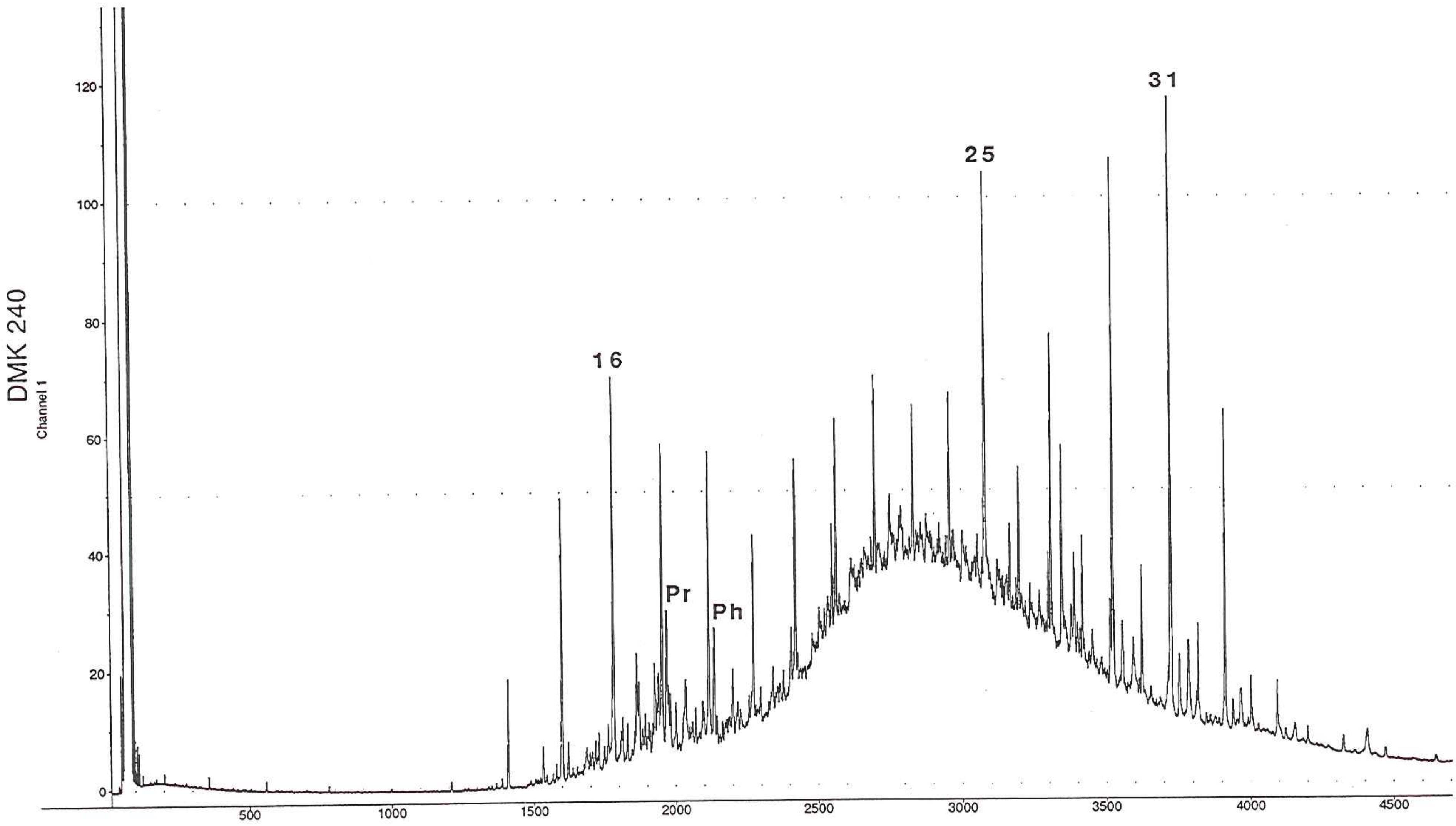

DMK 240
Channel 1
120
100
80
60
40
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
16
Pr
Ph
25
31

FIGURE 2K

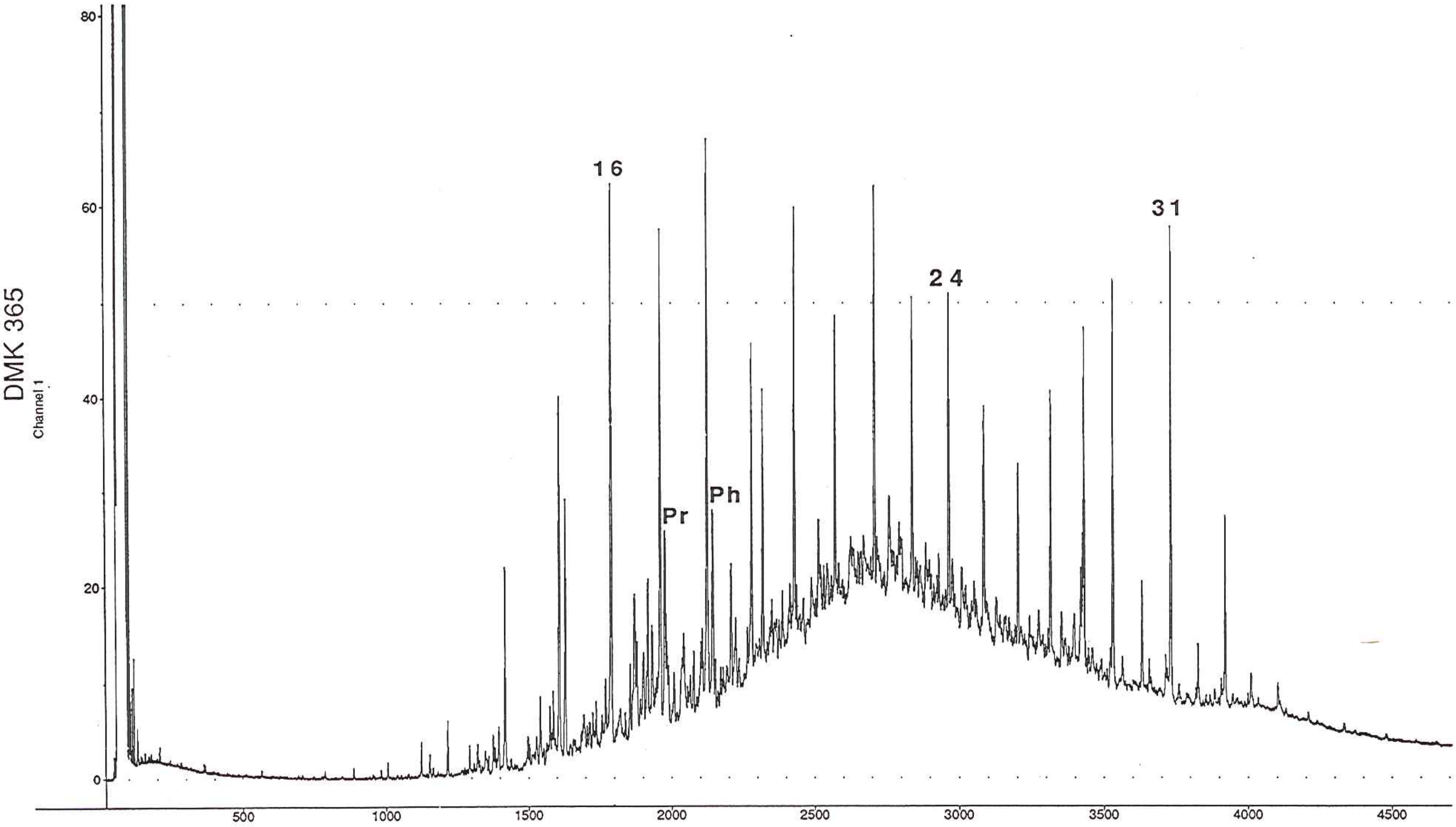

DMK 365
Channel 1
80
60
40
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
16
Pr
Ph
24
31

FIGURE 2L

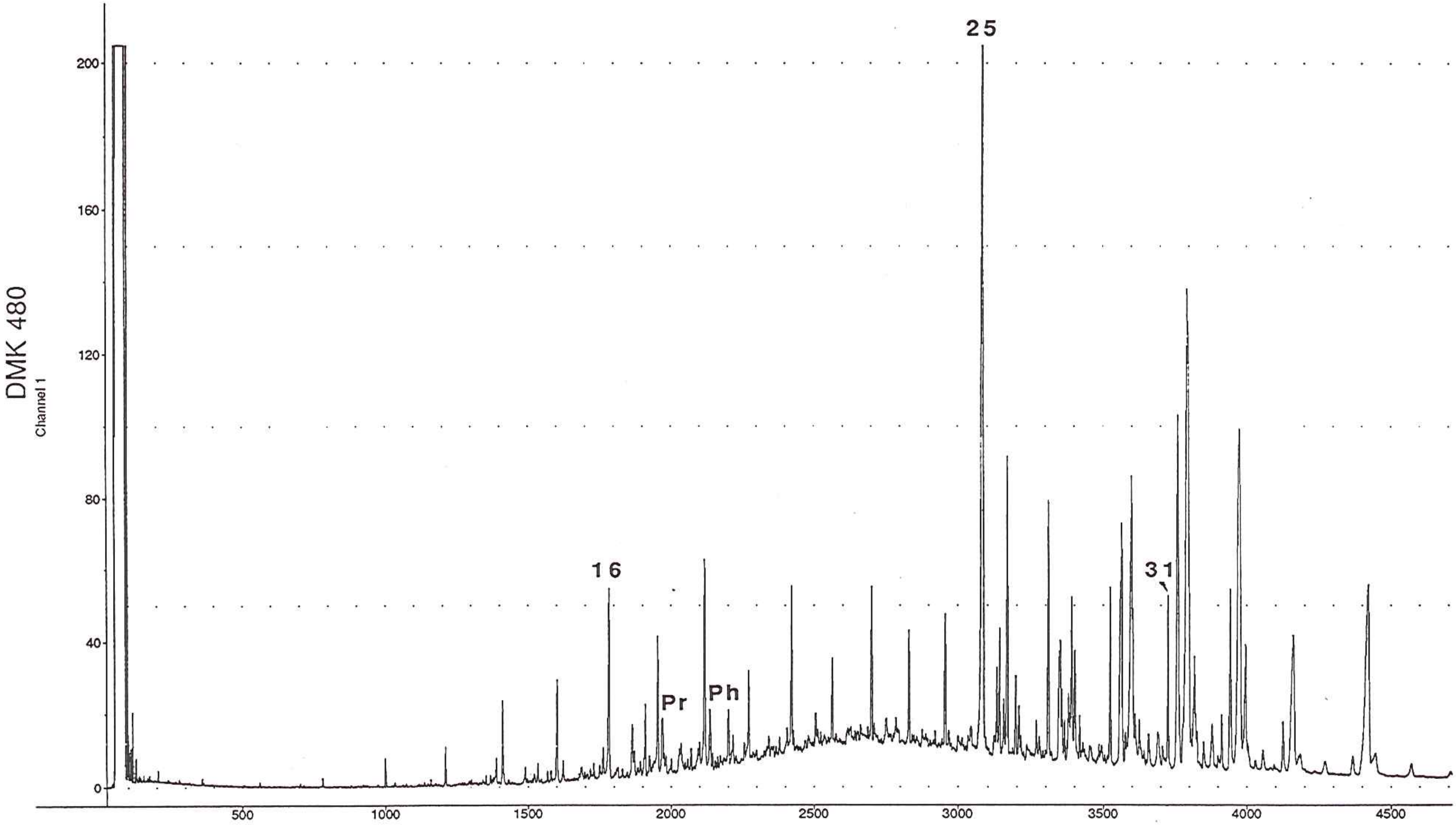

DMK 480
Channel 1
200
160
120
80
40
0
500
1000
1500
2000
2500
3000
3500
4000
4500
16
Pr
Ph
25
31

FIGURE 3

Reconstructed ion chromatograms of diaromatic hydrocarbons in outcrop samples of Cambrian mudstone, Mount McDonnell Formation

Figure	*Sample Site*	*Height above datum (m)*
3A	1	40
3B	2	220
3C	2	240
3D	3	365

Key to peak identification :

1.	2-Methylnaphthalene
2.	1-Methylnaphthalene
3.	2,6- and 2,7-Dimethylnaphthalene
4.	1,5-Dimethylnaphthalene
5.	1,3,5- and 1,4,6-Trimethylnaphthalene
6.	2,3,6-Trimethylnaphthalene

FIGURE 3A

```
CHRO: MAR40 ver 1 on UIC 3 1          25-JUL-92 Elapse: 00:03:06.8   1
Samp: KANGAROO ISLAND CAMBRIAN 40               Start : 09:39:23  3125
Comm: DB5 SIM 50-50 2M 50-180/8 180-300/4 300-300 20M 0NCOL INJ
Mode: EI +Q3MS LMR UP LR
Oper: D. PADLEY                                 Inlet :
Peak: 1000.00 mmu     Label wndw: 550 > 1508    Masses: 128 > 253
Area: 0, 4.00         Baseline  : 0, 3          Label : 0, 40.00
```

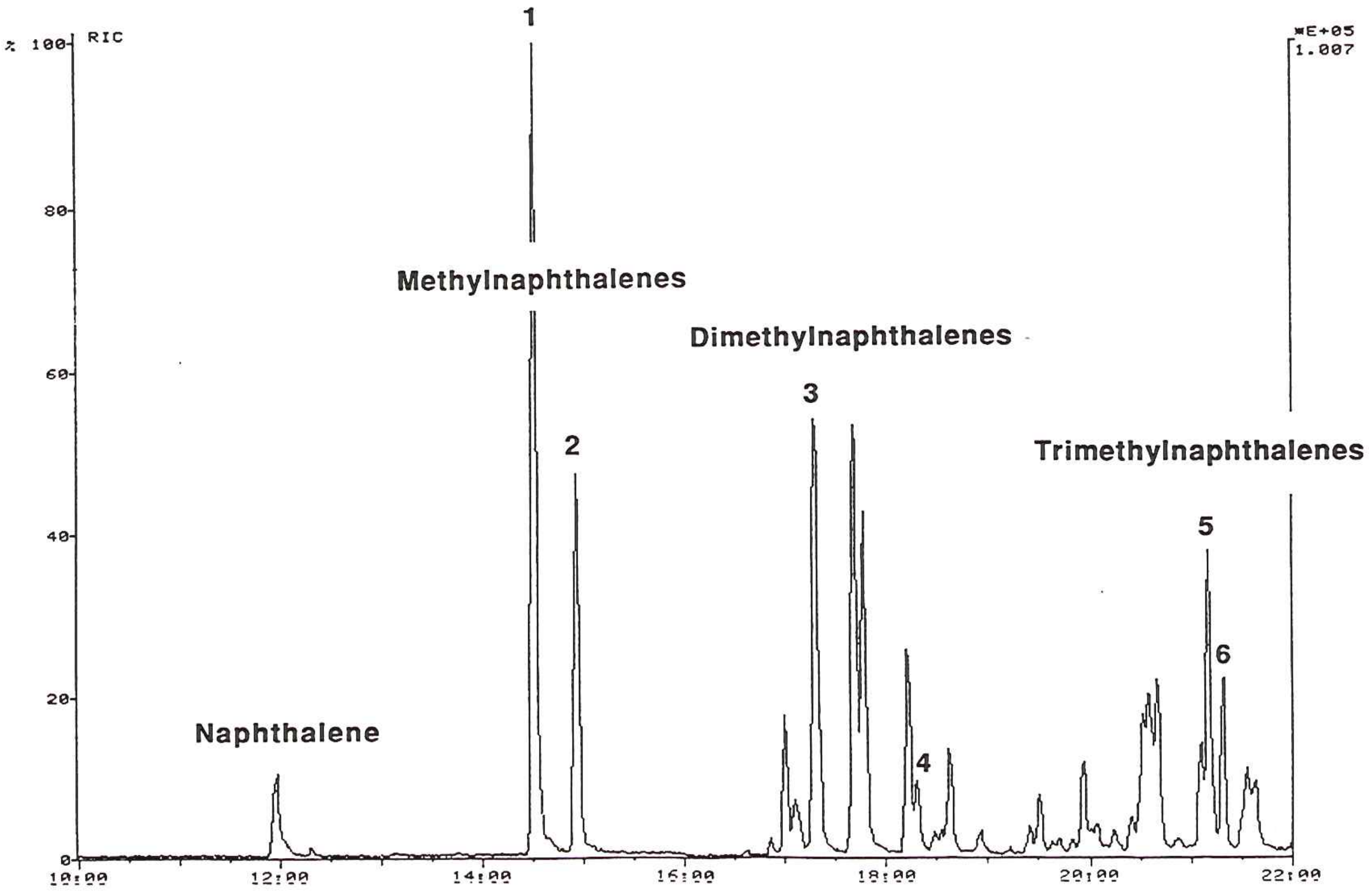
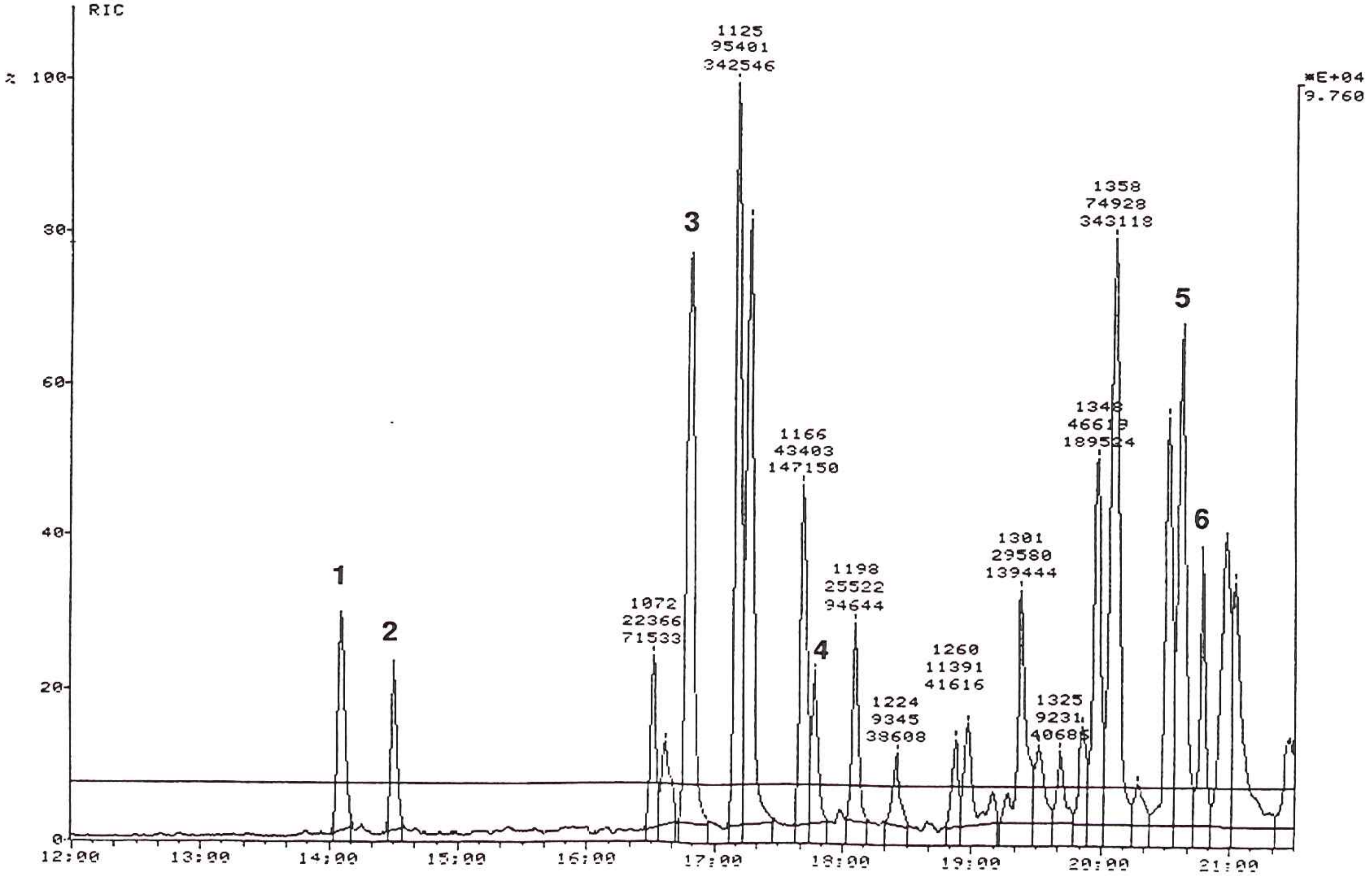


FIGURE 3B

```
CHRO: DMK220 ver 1 on UIC 3 1         5-NOV-92 Elapse: 00:03:04.9   1
Samp: D. MCK KANGAROO ISLAND                   Start : 14:48:28  2610
Comm: DB5 SIM 50-50 2M 50-120/8 120-300/4 300-300 20M ONCOL INJ
Mode: EI +Q3MS LMR UP LR
Oper: D.PADLEY                                 Inlet :
Peak: 1000.00 mmu    Label wndw: 712 > 1470    Masses: 128 > 253
Area: -10, 1.00      Baseline  : 0, 3          Label : -1, 50.00
Disp: Height Area
```



```
CHRO: MAR240 ver 1 on UIC 3 1          25-JUL-92 Elapse: 00:03:07.3   1
Samp: KANGAROO ISLAND CAMBRIAN 240               Start : 10:54:00  3125
Comm: DB5 SIM 50-50 2M 50-180/8 180-300/4 300-300 20M 0NCOL INJ
Mode: EI +Q3MS LMR UP LR
Oper: D. PADLEY                                  Inlet :
Peak: 1000.00 mmu      Label undw: 550 > 1507    Masses: 128 > 253
Area: 0, 4.00          Baseline  : 0, 3          Label : 0, 40.00
```

FIGURE 3C

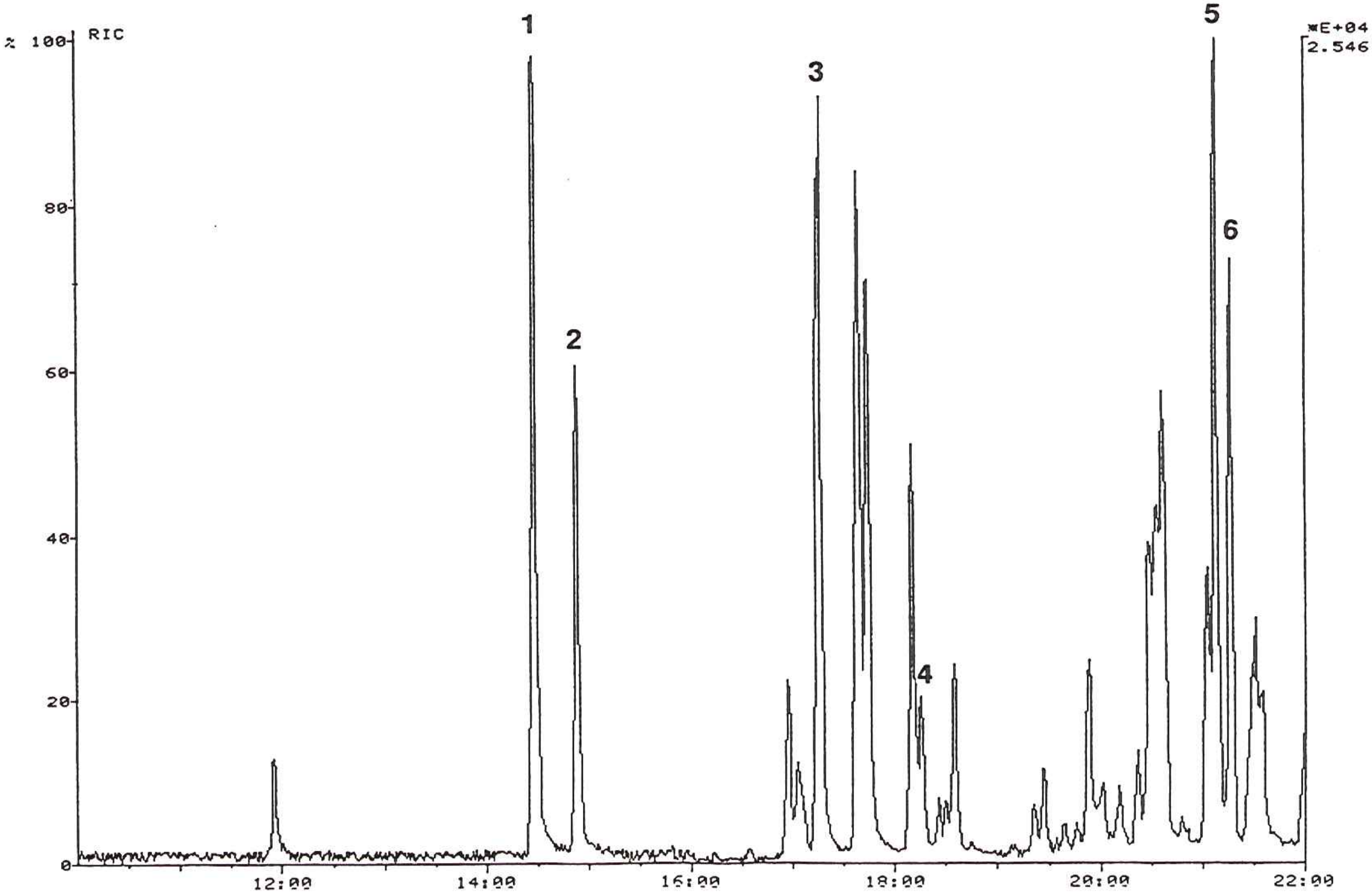


FIGURE 3D

```
CHRO: DMK365 ver 1 on UIC 3 1          5-NOV-92 Elapse: 00:03:05**   1
Samp: FOR D. MCKIRDY 365 KANGAROO ISLAND        Start : 16:03:48  2609
Comm: DB5 SIM 50-50 2M 50-120/8 120-300/4 300-300 20M ONCOL INJ
Mode: EI +Q3MS LMR UP LR
Oper: D.PADLEY                                  Inlet :
Peak: 1000.00 mmu     Label wndw: 791 > 1442    Masses: 128 > 253
Area: 0, 4.00         Baseline  : 0, 3          Label : 0, 40.00
```

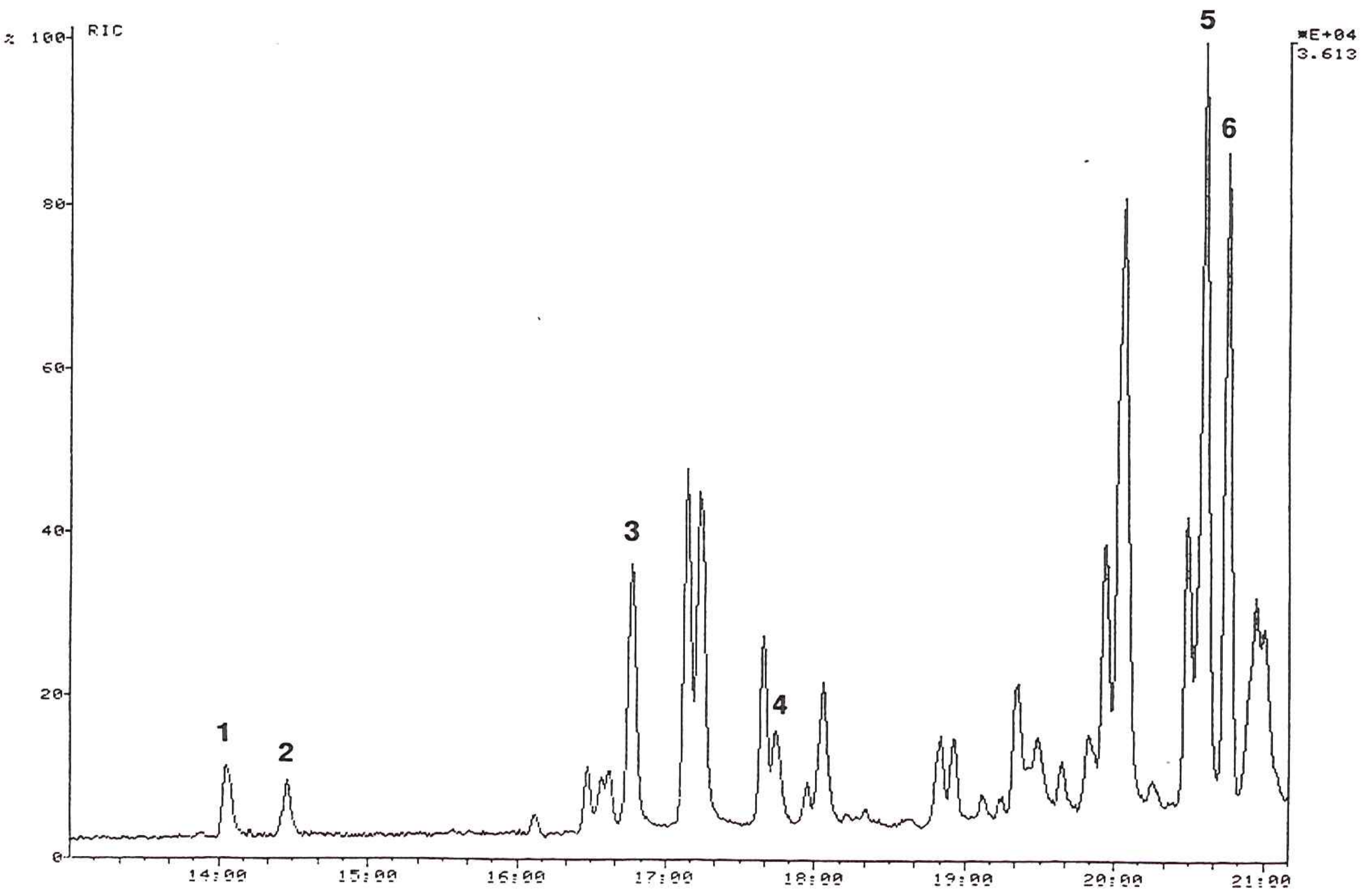


FIGURE 4

Histogram of calculated vitrinite reflectance data on Early Cambrian sediments from the Stansbury Basin. Based on methylphenanthrene index (MPI) measured from triaromatic hydrocarbons in core samples (after McKirdy *et al.*, 1991)