THERMAL MATURITY AND BIOMARKER GEOCHEMISTRY OF THE EARLY CAMBRIAN KULPARA FORMATION, STANSBURY BASIN

Report for Canyon (Australia) Pty Limited

by

DAVID M. McKIRDY, BERND H. MICHAELSEN and XINKE YU

Organic Geochemistry in Basin Analysis Group

Department of Geology and Geophysics

University of Adelaide

January 1996

INTRODUCTION

As part of its technical evaluation of PEL 53, Canyon (Australia) Pty Limited has been attempting to model the burial and maturation history of the Early Cambrian sequence in the Stansbury Basin. An essential prerequisite of any such thermal modelling exercise is reliable maturity data. Measurement of the present-day maturation levels of the target formations in strategically located drillholes and outcrops around the basin margin makes possible determination of the timing of oil and gas generation in relation to trap formation.

Previous studies of the Stansbury Basin by McKirdy (1987), McKirdy and Cox (1986) and McKirdy *et al.* (1986a,b, 1987, 1991) exploited the capability of triaromatic hydrocarbon distributions (Radke and Welte, 1983; Radke *et al.*, 1984; Radke, 1987) to provide thermal maturity data on pre-Devonian sediments devoid of vitrinite phytoclasts (Summons *et al.*, 1994).

The primary aim of the present investigation was to augment the existing aromatic maturity database for the Stansbury Basin (Table 1) by undertaking measurements of methylphenanthrene index (MPI), methylphenanthrene ratio (MPR), methylphenanthrene distribution factor (MPDF) and calculated vitrinite reflectance (VR_{calc}) on the triaromatic hydrocarbons extracted from another six mudstone samples (Table 2). The samples were selected to provide data on the Early Cambrian Kulpara Formation in Aquitaine SYC-101 and Port Clinton-1 (submitted by G. Weste, consultant) and the Permian sequence exposed at Waterloo Bay (collected and submitted by Dr D.I. Gravestock, MESA). These six samples were screened by total organic carbon analysis and the results forwarded to G. Weste on 21 August 1995.

Subsequently, the client expressed interest in documenting the alkane biomarker distribution of the Kulpara Formation for comparison with that of the asphaltic bitumen (asphaltite) which strands along the coastline of southern Australia (McKirdy *et al.*, 1994). Given their lower thermal maturity (Table 3), the three core samples from Port Clinton-1 were selected for biomarker analysis.

EXPERIMENTAL

The rock samples (five pieces of conventional core and one outcrop specimen) were scraped and brushed clean to remove surficial contamination before crushing in a Siebtechnik mill. Powdered rock (50–110 g) was extracted in Soxhlet apparatus for 72 hours using an azeotropic solvent mixture (CH_2Cl_2:CH_3OH; 93:7). The extract was fractionated by open column liquid chromatography on activated silica into saturated hydrocarbons, aromatic hydrocarbons and nonhydrocarbons (NSO compounds and asphaltenes).

GC-MS analyses of the aromatic hydrocarbons were undertaken using a Varian 3400 gas chromatograph interfaced with a Finnigan TSQ 70 mass spectrometer. The gas chromatograph was fitted with a 30 m x 0.25 mm i.d. fused silica column (DB-5, 0.25 µm film thickness; J&W Scientific). Helium was used as the carrier gas at an inlet pressure of approximately 10 psi. The temperature program of the oven was as follows: 50°C for 2 min, 50°C to 120°C at 8°C min^{-1}, 120°C to 300°C at 4°C min^{-1} and then held at 300°C for 35 min. Mass spectrometer operating parameters included an ionization voltage of 70 eV, a filament current of 200 µA and a photomultiplier voltage of 1100 V. Aromatic fractions in CH_2Cl_2 were injected on-column. The injector was held at 50°C for 10 seconds then ramped to 300°C at 180°C min^{-1}, and held at 300°C for 5 minutes. The mass spectrometer was programmed (MID mode) to monitor *m/z* 128 (naphthalene), *m/z* 141+142 (methylnaphthalenes), *m/z* 156 (dimethylnaphthalenes), *m/z* 170 (trimethylnaphthalenes), *m/z* 178 (phenanthrene), *m/z* 192 (methylphenanthrenes), *m/z* 206 (dimethylphenanthrenes), *m/z* 219 (retene), m/z 231+245 (triaromatic steranes) and *m/z* 253 (monoaromatic steranes).

GC-MS analysis of the saturates fractions (Port Clinton-1) was performed in the multiple reaction (metastable peak) monitoring (MRM) mode as described in McKirdy *et al.* (1994), with the following modifications: the sample was introduced to the column via a split/splitless injector operated in the splitless mode; and the GC oven temperature program was 60°C for 2 min, 60°C to 150°C at 15°C min^{-1}, 150°C to 310°C at 4°C min^{-1} and then isothermal at 310°C for 20 min. This portion of the analytical work was carried out at AGSO, Canberra under the supervision of Dr D. Edwards.

RESULTS

Analytical data are summarised and presented herein as follows:

	Table	Figure
Existing triaromatic maturity data, western Stansbury Basin	1	–
TOC and extract yield and composition	2	–
Triaromatic maturity data	3	1–5
Alkane biomarker data	4	6–7

Although the alkylnaphthalene distributions of the sediment extacts were recorded, only the nominated maturity parameters based on the relative abundances of phenanthrene and the isomeric methylphenanthrenes are considered in this report.

DISCUSSION

Total Organic Carbon Content

All six rock samples analysed in this study are organically lean. Neither the Permian mudstone (0.22% TOC) nor the Cambrian carbonates of the Kulpara Formation (0.06–0.16% TOC) are rich enough in dispersed organic matter to be effective source rocks of commercially producible hydrocarbons.

Duplicate samples of core from 96.01 metres depth in Port Clinton-1 have markedly divergent TOC values (0.63%, Table 1; 0.08%, Table 2). The former assay appears to be in error. The available TOC data on Cambrian carbonates from the western Stansbury Basin may now be summarised as follows:

Formation	*Range*	*Mean*	*n*
Ramsay Limestone	0.12–0.57%	0.25%	5
Parara Limestone	0.07–0.91%	0.29%	9
Kulpara Formation	0.06–0.18%	0.10%	7

Extract Yield and Composition

The concentration of extractable organic matter (EOM: Table 2) in these mudstones is for the most part poor (<500 ppm). The highest yield was obtained from the Kulpara Formation at 378.5 metres depth in Aquitaine SYC-101 (663 ppm). A similar fair yield (505 ppm) was reported by McKirdy *et al.* (1986a) for an adjacent sample of the same core (see Table 1). This interval of the Kulpara Formation appears to be stained by non-indigenous (i.e. migrated) hydrocarbons. Accordingly, its total hydrocarbon content (saturates + aromatics = 231–277 ppm) is appreciably greater than that of the other Kulpara samples analysed (8–30 ppm: Tables 1 and 2). Discounting the stained sample, the yield of EOM per unit weight of TOC is higher at Aquitaine SYC-101 (282 mg/g TOC) than at Port Clinton-1 (134–225 mg/g TOC).

Saturated hydrocarbons account for 5–10%, and aromatic hydrocarbons 1–6%, of the EOM in these Cambrian mudstones. With the exception of one sample (Port Clinton-1, 96.62 m), the ratio of saturated to aromatic hydrocarbons is reasonably uniform (sat/arom = 2–4: Table 2).

The low absolute amount of aromatic hydrocarbons (0.6 mg) recovered from the Permian mudstone, its weathered condition and the very real possibility of contamination of its indigenous hydrocarbons by recent plant and soil lipids, are factors that collectively render this outcrop sample unsuitable for GC-MS analysis.

Thermal Maturity

For both targetted well localities, the new maturity measurements on the Kulpara Formation (Table 3) are broadly consistent with existing data (Table 1). Particularly significant is the near coincidence of the respective MPI and MPDF values determined on the duplicate samples from 96.01 metres depth in Port Clinton-1.

Before considering further the regional trend in maturity that emerges from the consolidated data sets, it is necessary to note and comment on the discrepancy evident in Table 3 between the MPI-derived maturities [VR_{calc} (a) and (b)] and those based on MPR and MPDF [VR_{calc} (c) and (d)]. Without exception, the former are lower than the latter. This discrepancy (and its modality) appears to be characteristic of the Kulpara Formation at Port Clinton-1 and Aquitaine SYC-101 (although not at Stansbury West-1), and also of the Mt McDonnell Formation at Investigator-2 (Table 1). Such a phenomenon has been previously noted by the senior author in Cambrian sediments from the Warburton Basin (McKirdy *et al.*, 1987). It may tentatively be attributed to a mineral matrix effect which influences the relative rates of the phenanthrene methylation and demethylation reactions (Radke, 1987) in pre-Devonian, calcareous sediments. It is our experience that lithofacies-related variation in triaromatic maturity parameters is more pronounced in those which incorporate phenanthrene (e.g. MPI) than in those based only on the relative abundances of the isomeric methylphenanthrenes (e.g. MPR, MPDF). Accordingly, the latter two parameters and their corresponding calculated vitrinite reflectance values are the *preferred maturity indicators* for the present suite of samples.

The Kulpara and Mt McDonnell Formations are stratigraphically correlative (see e.g. McKirdy, 1995, fig. 2). These two units display the following north-south trend in thermal maturity:

Well Locality	*Depth (m)*	*Mean VR_{calc} (%)*
Port Clinton-1	96–102	1.16
Aquitaine SYC-101	368–379	1.46
Stansbury West-1	1166	1.23
Investigator-2	139–344	0.98

Biomarker Geochemistry

The sterane and triterpane distributions in extracts of the Kulpara Formation at Port Clinton-1 (Figs 6 and 7), for the most part, are consistent with the Early Cambrian age, carbonate lithofacies and marine shelf depositional environment of the host rock. Selected source-dependent biomarker parameters of the Kulpara extracts are presented in Table 4.

Features indicative of a major *marine algal contribution* to the organic matter preserved within the Kulpara Formation are:

- a cholestane-dominant C_{27}–C_{29} sterane signature (parameter a, Table 4);
- the presence of 24-*n*-propylcholestane (the C_{30} sterane marine marker) in low abundance relative to 24-ethylcholestane (parameter b, Table 4);
- the presence of dinosterane (4α,23,24-trimethylcholestane) as a significant component of the A-ring-methylated sterane assmblage (parameter c, Table 4); and
- a low hopane/sterane ratio (C_{30} hop / C_{29} ster <1: parameter e, Table 4).

Dinosterane, a marine dinoflagellate marker, is common in mid-Triassic and younger marine sediments (Summons *et al.*, 1992). However, we have recently found this compound in the Early Cambrian Ouldburra Formation of the Officer Basin (Michaelsen *et al.*, 1995); and triaromatic dinosteroids occur in rocks as old as Neoproterozoic (Moldowan *et al.*, 1995). There is a notable dominance of 3β-methyl steranes (bacterial alteration products) over 4α-methyl steranes (primary algal products) (Fig. 6). This feature is characteristic of Palaeozoic and Precambrian oils (Summons and Capon, 1988) and hence sits comfortably with the Cambrian age of the Kulpara Formation.

In common with many other limestones, the Kulpara Formation exhibits the following features that are attributable to its *carbonate lithofacies* (cf. Peters and Moldowan, 1993):

- a low abundance of diasteranes (C_{29} dia / C_{29} ster <1: parameter d, Table 4);
- a high concentration of 30-norhopane relative to hopane (C_{29} / C_{30} hop >1: parameter f, Table 4); and
- the presence of other members of the 30-norhopane series, viz. 29,30-bisnorhopane, 28,30-bisnorhopane (parameters g and h, Table 4) and 30-norhomohopane.

If these biomarker hydrocarbons are indeed indigenous to the Kulpara Formation at Port Clinton-1, one would expect their *maturity-dependent isomer ratios* to be consistent with the previously assigned maturation level based on triaromatic hydrocarbons (VR_{calc} = 1.16%), i.e. within the lower oil generation window. This appears to be so, as is demonstrated by the following data:

Depth (m)	*Steranes*		*Triterpanes*	
	C_{29} 20S / 20S+20R	C_{29} αββ / αββ+ααα	Ts / Tm	C_{31} 22S / 22S+22R
96.01	0.57	0.42	1.15	0.58
96.62	0.61	0.52	0.86	0.57
101.80	0.57	0.48	0.93	0.59

There is one aberrant feature of the Kulpara triterpane distributions illustrated in Figure 7, namely the presence of minor amounts of 18α-oleanane in all three Kulpara extracts. This compound is a reliable

marker for higher plants (angiosperms: Peters and Moldowan, 1993), and as such should not be present in Cambrian rocks! Its unexpected appearance in these organically lean carbonates suggests some form of contamination, either of the original core samples (e.g. from an oil-based lubricant or mud additive) or introduced during the analytical workup procedure.

Oil-Source Correlation?

Comparison of the Kulpara Formation extracts with two representative coastal asphaltites from southern Australia, using the source-specific biomarker parameters listed in Table 4, reveals some striking similarities. In particular, their sterane signatures, reflecting the respective eukaryotic algal inputs, are almost identical. The major differences occur in the bacterial markers (triterpanes: parameters f–j, Table 4). Of these differences, the most notable is the lack of detectable 2α and 3β-methylhopanes in the asphaltites, which in turn indicates the unusual absence of methanotrophic bacteria in their source rock depositional environment (McKirdy *et al.*, 1994).

The shallow intertidal carbonates of the Kulpara Formation (mean TOC = 0.1%) are far too lean, and the hydrogen content of their Type III/IV kerogen far too low, for them to have been an effective source of oil, let alone a sour crude like the typical coastal asphaltite (3–6% S). The latter requires an anoxic marine source rock (e.g. bituminous marl, limestone, evaporite or phosphorite) containing sulphur-rich Type II kerogen. The most likely hosts for such organic facies within the Stansbury Basin are the Parara Limestone and the Heatherdale Shale. The marine algae contributing organic matter to these sediments would have been similar to those which populated the Early Cambrian ocean during Kulpara time. Thus it is conceivable that the hitherto orphan asphaltites (and their characteristic biomarker signature) may have originated from an intra-Stansbury source rock.

Finally, it is noteworthy that the C_{27}–C_{29} sterane distribution of the Kulpara Formation at Port Clinton-1 differs from those of the Wilkatana-1 reservoir bitumen (Arrowie Basin) and various Cambrian oils and source rocks in the Officer Basin (McKirdy, 1994, fig. 8).

CONCLUSIONS

1. Marine limestones of the Early Cambrian Kulpara Formation, where sampled along the western margin of the Stansbury Basin, are organically very lean (mean TOC = 0.1%; EOM typically <200 ppm). Such rocks are poor potential sources for petroleum hydrocarbons. Higher EOM yields (505–663 ppm) at about 378 metres depth in Aquitaine SYC-101 signify staining by migrated hydrocarbons.

2. The thermal maturity of the Kulpara Formation at Port Clinton-1 is within the oil generation and preservation window (mean VR_{calc} = 1.16%; present depth 96–102 m), whereas the same unit in Aquitaine SYC-101 is overmature (mean VR_{calc} = 1.46%; present depth 368–379 m).

3. The sterane biomarker signature of asphaltic coastal bitumen from southern Australia is sufficiently similar to that of the Kulpara Formation to indicate possible sourcing of the asphaltite from Early Cambrian anoxic marine sediments within the Stansbury Basin.

4. In view of their very low EOM contents, organically lean rocks like the Kulpara limestones are particularly susceptible to having their indigenous biomarker distributions distorted or, in extreme cases, overprinted by background contamination.

5. The identification of oleanane in the Kulpara extracts confirms that they are contaminated. Whether or not the integrity of their sterane signature has been compromised by the same contamination can only be determined by the analysis of richer Cambrian sediments of equivalent (or lower) maturity from elsewhere in the Stansbury Basin.

REFERENCES

BOREHAM, C.J., CRICK, I.J. and POWELL, T.G., 1988. An alternative calibration of the Methylphenanthrene Index against vitrinite reflectance: Application to maturity measurements in oils and sediments. *Organic Geochemistry,* 12, 289–294.

KVALHEIM, O.M., CHRISTY, A.A., TELNAES, N. and BJORSETH, A., 1987. Maturity determination of organic matter in coals using methylphenanthrene distribution. *Geochimica et Cosmochimica Acta,* 51, 1883–1888.

McKIRDY, D. M., 1987. Source rock and petroleum geochemistry of Cambrian basins in South Australia. *In*: GRAVESTOCK, D. I., HIBBURT, J. E., McKIRDY, D. M. and KUANG, K. S. (compilers), *The Setting for Cambrian Oil and Gas in South Australia.* APEA Conference, Surfers Paradise, Poster Display and Extended Abstract.

McKIRDY, D.M., 1994. Biomarker geochemistry of the Early Cambrian oil show in Wilkatana-1: implications for oil generation in the Arrowie and Stansbury Basins. *PESA Journal,* 22, 3–17.

McKIRDY, D. M. and COX, R. E., 1986. Source rock maturity study, Arrowie Basin, South Australia *AMDEL Report F6376/86 (Part 2-final) for Delhi Petroleum Pty Limited.* (Stansbury West-1)

McKIRDY, D. M., COX, R. E. and O'LEARY, T., 1986a. Thermal maturity of Early Palaeozoic potential hydrocarbon source rocks, South Australia. *AMDEL Report F6521/86 (Part 1) for South Australian Department of Mines and Energy.* (Stansbury Town-1, Port Clinton-1, Aquitaine SYC-101) [SADME Open File Envelope 5530]

McKIRDY, D. M., COX, R. E. and O'LEARY, T., 1986b. Thermal maturity of Early Palaeozoic potential hydrocarbon source rocks, South Australia. *AMDEL Report F6521/86 (Part 2) for South Australian Department of Mines and Energy.* (Minlaton-1, Stansbury West-1) [SADME Open File Envelope 5530: 143-158]

McKIRDY, D. M., COX, R. E., FOSTER, C. B., GORTER, J. D. and MORRIS, D. G., 1987. Biomarker geochemistry of some Early Palaeozoic crude oils: influence of precursor microbiota and source rock environment. *8th International Symposium on Environmental Biogeochemistry, Nancy, France, Abstracts,* p. 53.

McKIRDY, D. M., COX, R. E., O'LEARY, T. and WATSON, B.L., 1987. Aromatic maturity of Jurassic, Permian and Cambrian sediments in Gidgealpa-1, Eromanga/Cooper/Warburton Basin, S.A. *AMDEL Report F6636/87 (Part 2) for South Australian Department of Mines and Energy.*

McKIRDY, D. M., GRAVESTOCK, D. I. and GATEHOUSE, C. G., 1991. Cambrian petroleum and source rock geochemistry of South Australia. *Australian Society of Exploration Geophysicists and Geological Society of Australia Conference, Sydney, Abstracts*, 30, 63–64.

McKIRDY, D.M., SUMMONS, R.E., PADLEY, D., SERAFINI, K.M., BOREHAM, C.J. and STRUCKMEYER, H.I.M., 1994. Molecular fossils in coastal bitumens from southern Australia: signatures of precursor biota and source rock environments. *Organic Geochemistry*, 21, 265–286.

MICHAELSEN, B.H., KAMALI, M.R. and McKIRDY, D.M.,1995. Unexpected molecular fossils from Early Cambrian marine carbonates of the Officer Basin, South Australia. *In*: GRIMALT, J.O. and DORRONSORO, C. (eds), *Organic Geochemistry: Developments and Applications to Energy, Climate, Environment and Human History.* A.I.G.O.A., Donostia-San Sebastián, pp. 218–221.

MOLDOWAN, J.M., DAHL, J., FAGO, F.J., SHETTY, R., WATT, D.S., JACOBSON, S.R., HUIZINGA, B.J., McCAFFREY, M.A. and SUMMONS, R.E., 1995. Correlation of biomarkers with geologic age. *In*: GRIMALT, J.O. and DORRONSORO, C. (eds), *Organic Geochemistry: Developments and Applications to Energy, Climate, Environment and Human History.* A.I.G.O.A., Donostia-San Sebastián, pp. 418–420.

PADLEY, D., 1995. *Petroleum Geochemistry of the Otway Basin and the Significance of Coastal Bitumen Strandings on Adjacent Southern Australian Beaches.* PhD Thesis, University of Adelaide.

PETERS, K.E. and MOLDOWAN, J.M., 1993. *The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments.* Prentice Hall, Englewood Cliffs, 363 p.

RADKE, M., 1987. Organic geochemistry of aromatic hydrocarbons. *In*: BROOKS, J. and WELTE, D. (eds), *Advances in Petroleum Geochemistry*. Academic Press, London, pp. 141–207.

RADKE, M. and WELTE, D.H., 1983. The methylphenanthrene index (MPI): a maturity parameter based on aromatic hydrocarbons. *In*: BJOROY, M. *et al.* (eds), *Advances in Organic Geochemistry 1981*. Wiley, Chichester, pp. 504–512.

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.

SUMMONS, R.E. and CAPON, R.J., 1988. Fossil steranes with unprecedented methylation in ring A. *Geochimica et Cosmochimica Acta*, 52, 2733–2736.

SUMMONS, R.E., THOMAS, J., MAXWELL, J.R. and BOREHAM, C.J., 1992. Secular and environmental constraints on the occurrence of dinosterane in sediments. *Geochimica et Cosmochimica Acta*, 56, 2437–2444.

SUMMONS, R.E., TAYLOR, D. and BOREHAM, C.J., 1994. Geochemical tools for evaluating petroleum generation in Middle Proterozoic sediments of the McArthur Basin, Northern Territory, Australia. *APEA Journal*, 34(1), 692–706.

WATSON, B.L., 1987. Maturity of five limestone samples, Stansbury Basin, S.A. *AMDEL Report F6918/87 for South Australian Department of Mines and Energy.*

TABLE 1 : Existing aromatic maturity database on core samples from the western Stansbury Basin †

Depth m	Formation	TOC %	EOM ppm	MPI	MPR	MPDF	VR_{calc} % (a)	VR_{calc} % (b)	VR_{calc} % (c)	VR_{calc} % (d)	Reference
Investigator-2											
138.9	Mt McDonnell Fm	0.11	279	0.48	1.18	0.494	0.70	0.56	1.01**	0.94	McKirdy (1994)
244.3	Mt McDonnell Fm	0.12	187	1.04	1.49	0.510	1.01	0.95	1.11**	0.98	McKirdy (1994)
343.5	Mt McDonnell Fm	0.08	120	0.59	1.12	0.458	0.76	0.63	0.99**	0.86	McKirdy (1994)
Stansbury Town-1											
987.40	Ramsay Lst	0.12	113	1.46	1.84	0.544	1.28	1.24	1.20	1.05	McKirdy *et al.* (1986a)
Stansbury West-1											
616.92	Stansbury Lst	0.10	179	1.47	1.72	0.559	1.28	1.25	1.17	1.09	McKirdy *et al.* (1986b)
762.61	Ramsay Lst	0.15	245	1.25	1.38	0.505	1.15	1.10	1.08	0.97	McKirdy *et al.* (1986b)
763.52	Ramsay Lst	0.20	150	[1.82]	1.82	0.565	nd	1.49	1.20	1.10	McKirdy and Cox (1986)
957.22	Parara Lst	0.25	164	[3.46]	[6.97]	[0.828]	nd	nd	nd	nd	McKirdy and Cox (1986)
958.60	Parara Lst	0.30	87	1.29	3.88	[0.750]	1.17	1.12	1.52	nd	McKirdy *et al.* (1986b)
1166.47	Kulpara Fm	0.07	53	1.53	1.99	0.615	1.32	1.29	1.24	1.21	McKirdy *et al.* (1986b)
Minlaton-1											
210.01	Ramsay Lst	0.57	285	1.37	1.12	0.510	1.22	1.18	0.99	0.98	McKirdy *et al.* (1986b)
353.35	Minlaton Fm	0.13	98	0.82	1.69	0.551	0.89	0.80	1.16	1.07	Watson (1987)
392.60	Parara Lst	0.11	64	1.34	2.26	0.614	1.20	1.15	1.29	1.21	Watson (1987)
491.80	Parara Lst	0.19	88	1.79	3.28	[0.720]	1.47	1.47	1.45	nd	Watson (1987)
511.76	Parara Lst	0.91	148	[2.21]	2.51	[0.689]	nd	1.77	1.34	nd	McKirdy *et al.* (1986b)
Aquitaine SYC-101											
164.30	Parara Lst	0.07	423*	1.04	0.95	0.442	1.02	0.95	0.92	0.83	McKirdy *et al.* (1986a)
221(?)	Parara Lst	0.30	149	1.71	2.04	0.634	1.43	1.42	1.25	1.25	McKirdy *et al.* (1986a)
378.00	Kulpara Fm	0.18	505*	[1.91]	3.55	0.638	nd	1.56	1.48	1.26	McKirdy *et al.* (1986a)
Port Clinton-1											
96.01	Kulpara Fm	0.63	29	0.82	2.10	0.616	0.89	0.79	1.26	1.22	McKirdy *et al.* (1986a)

[ ] Anomalously high value; outside range of values encompassed by published calibration
nd = not determined
* Stained by migrated hydrocarbons
** Incorrectly reported in McKirdy (1994)
† See next page for key

KEY TO AROMATIC MATURITY PARAMETERS

Methylphenanthrene index (MPI), methylphenanthrene ratio (MPR), methylphenanthrene distribution factor (MPDF) and VR_{calc} are defined by Radke and Welte (1983), Radke *et al.* (1984), Radke (1987), Kvalheim *et al.* (1987) and Boreham *et al.* (1988) as follows:

$$MPI = \frac{1.5\,[\,2\text{-MP} + 3\text{-MP}\,]}{P + 1\text{-MP} + 9\text{-MP}}$$

$$MPR = \frac{2\text{-MP}}{1\text{-MP}}$$

$$MPDF = \frac{2\text{-MP} + 3\text{-MP}}{2\text{-MP} + 3\text{-MP} + 1\text{-MP} + 9\text{-MP}}$$

VR_{calc} (a) = 0.60 MPI + 0.40 (for VR in the range 0.65–1.35%; r = 0.96)

= – 0.60 MPI + 2.30 (for VR >1.35%)

VR_{calc} (b) = 0.70 MPI + 0.22 (for VR in the range 0.5–1.7%; r = 0.84)

VR_{calc} (c) = 0.99 $\log_{10}$ MPR + 0.94 (for VR in the range 0.4–1.7%; r = 0.84)

VR_{calc} (d) = – 0.166 + 2.242 MPDF (for VR in the range 0.5–1.3%)

where

P	=	phenanthrene*
1-MP	=	1-methylphenanthrene
2-MP	=	2-methylphenanthrene
3-MP	=	3-methylphenanthrene
9-MP	=	9-methylphenanthrene

* *Note* : a response factor of 0.69 was applied to the area of this peak in Figures 1–5 when calculating MPI

TABLE 2 : Total organic carbon and extract data on selected samples from the western Stansbury Basin

Locality & Depth	Formation	TOC	Weight extracted	EOM Yield		EOM Composition			
m		%	g	ppm	mg/gTOC	Sat %	Arom %	NSO %	S/A
Waterloo Bay									
outcrop	Undifferentiated Permian	0.22	107.25	131	59	2.1	4.3	93.6	0.50
Aquitaine SYC-101									
368.0	Kulpara Fm	0.06	53.77	169	282	12.1	5.5	82.4	2.20
378.5	Kulpara Fm	0.16	79.67	663*	414	28.8	6.1	65.1	4.75
Port Clinton-1									
96.01	Kulpara Fm	0.08	96.70	108	134	7.7	1.9	90.4	4.00
96.62	Kulpara Fm	0.08	79.37	180	225	10.5	0.7	88.8	15.00
101.80	Kulpara Fm	0.10	91.34	178	178	4.9	2.5	92.6	2.00

S/A = saturated hydrocarbons/aromatic hydrocarbons

* Stained by migrated hydrocarbons

TABLE 3 : Aromatic maturity data on selected core samples from the western Stansbury Basin †

Depth m	Formation	TOC %	EOM ppm	MPI	MPR	MPDF	VR_{calc} % (a)	VR_{calc} % (b)	VR_{calc} % (c)	VR_{calc} % (d)
Aquitaine SYC-101										
368.0	Kulpara Fm	0.06	169	1.22	3.05	0.686	1.13	1.07	1.42	1.37
378.5	Kulpara Fm	0.16	663*	1.07	4.77	0.788	1.04	0.97	1.61	1.60
Port Clinton-1										
96.01	Kulpara Fm	0.08	108	0.82	1.42	0.569	0.89	0.79	1.09	1.11
96.62	Kulpara Fm	0.08	180	0.73	1.83	0.600	0.84	0.73	1.20	1.18
101.80	Kulpara Fm	0.10	178	0.46	1.53	0.547	0.67	0.54	1.12	1.06

† Key as for Table 1 * Stained by migrated hydrocarbons

Table 4 : Source-dependent biomarker parameters of Kulpara Formation, western Stansbury Basin, and two coastal asphaltites

Locality & Depth (m)	Steranes 27 : 28 : 29	Steranes 30/29	Dino-sterane	Dia/Ster 29	Hop/Ster 30/29	Hopanes 29/30	29BNH/Hop	28BNH/Hop	Ts/Hop	MeHop/Hop
Parameter *	*a*	*b*	c	*d*	*e*	*f*	*g*	*h*	*i*	*j*
Port Clinton-1										
96.01	45 : 24 : 31	0.11	√	0.59	0.82	1.14	0.16	0.13	0.67	0.12
96.62	54 : 21 : 25	0.10	√	0.69	0.74	1.49	0.25	0.09	0.90	0.13
101.80	46 : 24 : 30	0.11	√	0.56	0.78	1.25	0.18	0.13	0.75	0.11
Asphaltites										
CB-32 **	46 : 25 : 29	0.08	√	0.52	1.36	0.79	0.02	0.06	0.32	0
CB-177 **	40 : 27 : 33	0.11	nd	0.69	0.60	0.78	0.04	0.05	0.36	0

* Parameters defined in key on following page

** Data on asphaltites are from McKirdy *et al.* (1994) and Padley (1995)

√ = present nd = none detected

Analyst : D. Edwards, AGSO

KEY TO BIOMARKER PARAMETERS

Parameter	*Explanation*
a	C_{27} : C_{28} : C_{29} 5α(H),14α(H),17α(H) 20R steranes
b	C_{30} 24-*n*-propylcholestane (ααα 20R) / C_{29} 24-ethylcholestane (ααα 20R)
c	4α,23,24-trimethylcholestane (four isomers)
d	C_{29} 13β(H),17α(H) diasteranes (20R + 20S) / C_{29} 5α(H) steranes (20R + 20S)
e	C_{30} 17α(H),21β(H) hopane / C_{29} 5α(H) steranes (20R + 20S)
f	C_{29} 17α(H),21β(H) hopane / C_{30} 17α(H),21β(H) hopane
g	29,30-bisnorhopane / C_{30} 17α(H),21β(H) hopane
h	28,30-bisnorhopane / C_{30} 17α(H),21β(H) hopane
i	C_{27} 18α(H)-22,29,30-trisnorneohopane (Ts) / C_{30} 17α(H),21β(H) hopane
j	C_{31} 2α-methylhopane + 3β-methylhopane / C_{30} 17α(H),21β(H) hopane

Figures 1–5

GC-MS of Triaromatic Hydrocarbons
in Kulpara Formation

Fig. 1	Aquitaine SYC-101	368.0 m
Fig. 2	Aquitaine SYC-101	378.5 m
Fig. 3	Port Clinton-1	96.01 m
Fig. 4	Port Clinton-1	96.62 m
Fig. 5	Port Clinton-1	101.80 m

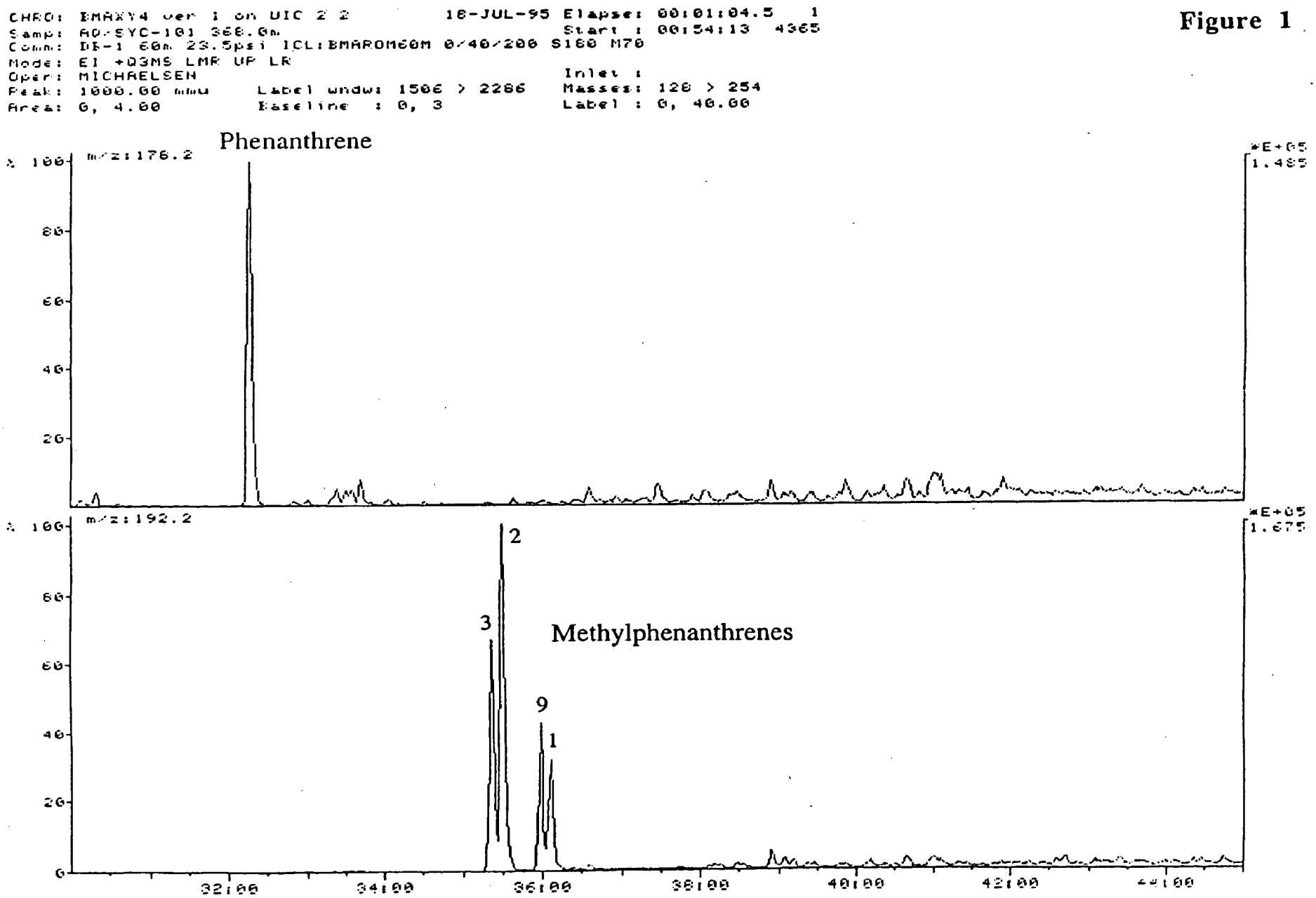
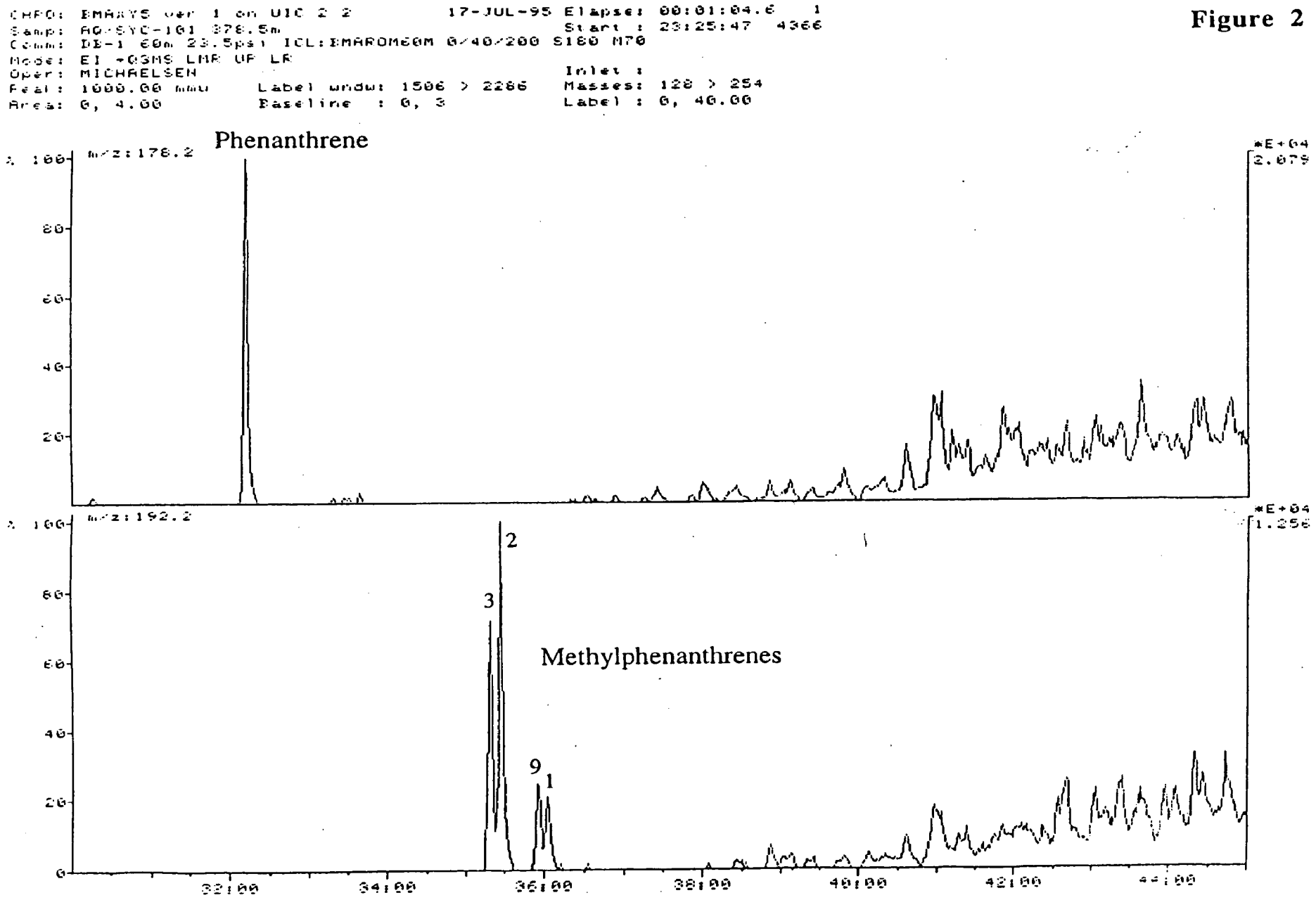

CHRO: BMAXY4 ver 1 on UIC 2 2 18-JUL-95 Elapse: 00:01:04.5 1
Samp: AO-SYC-101 368.0m Start : 00:54:13 4365
Comm: DB-1 60m 23.5psi ICL:BMAROM60M 0/40/200 S160 M70
Mode: EI +Q3MS LMR UP LR
Oper: MICHRELSEN Inlet :
Peak: 1000.00 mmu Label wndw: 1506 > 2286 Masses: 128 > 254
Area: 0, 4.00 Baseline : 0, 3 Label : 0, 40.00
Phenanthrene
m/z:176.2
m/z:192.2
2
3
9
1
Methylphenanthrenes
32:00
34:00
36:00
38:00
40:00
42:00

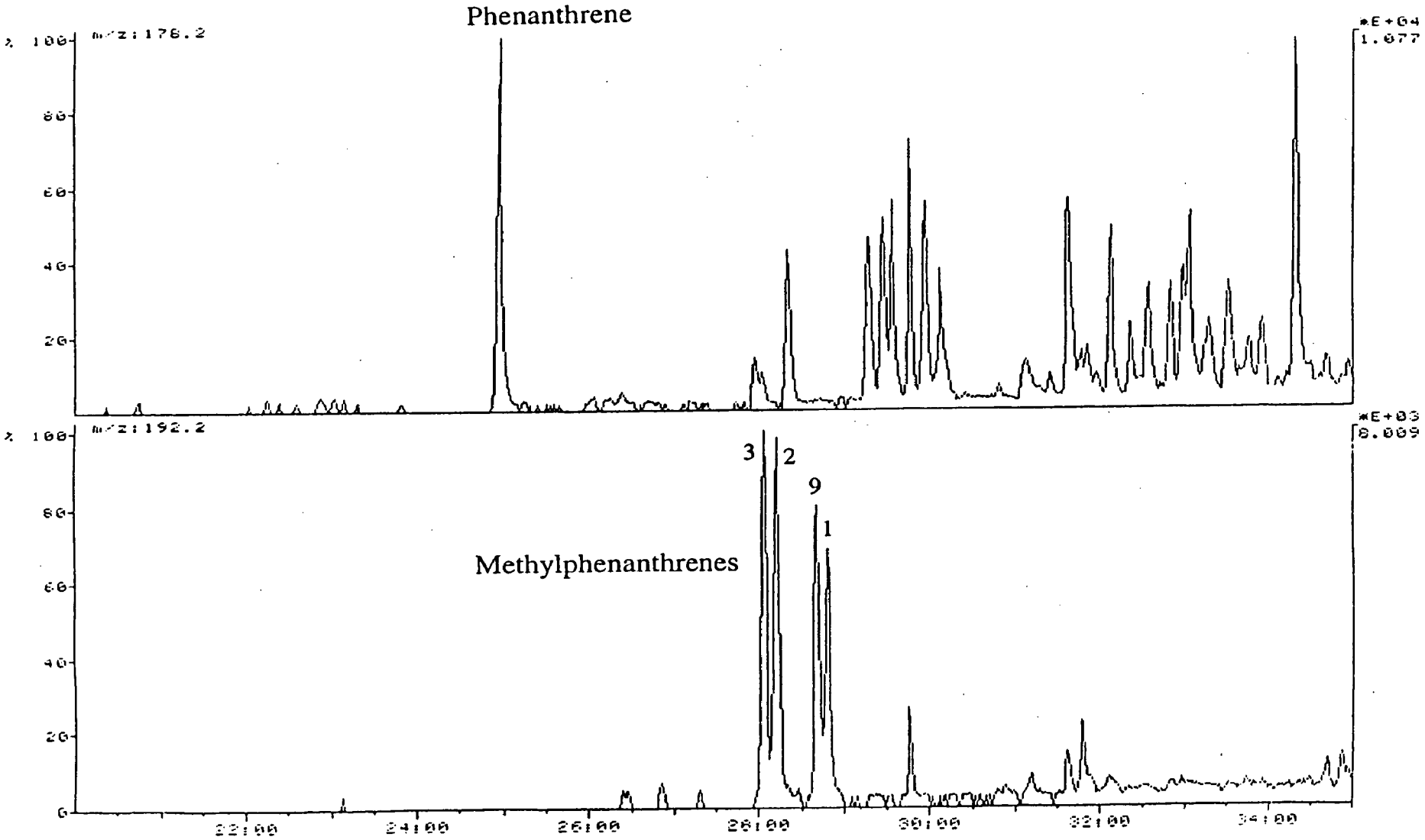
Figure 1

Figure 2


CHFO: EMARYS ver 1 on UIC 2 2
17-JUL-95 Elapse: 00:01:04.6 1
Samp: AG-SYC-101 378.5m
Start : 23:25:47 4366
Comm: DB-1 60m 23.5psi ICL:EMAROM60M 0/40/200 S180 M70
Mode: EI +QSMS LMR UF LR
Oper: MICHAELSEN
Inlet :
Peal: 1000.00 mmu Label wndw: 1506 > 2286 Masses: 128 > 254
Area: 0, 4.00 Baseline : 0, 3 Label : 0, 40.00
Phenanthrene
m/z:178.2
*E+04
2.079
m/z:192.2
*E+04
1.256
Methylphenanthrenes
1
2
3
9
32:00
34:00
36:00
38:00
40:00
42:00
44:00

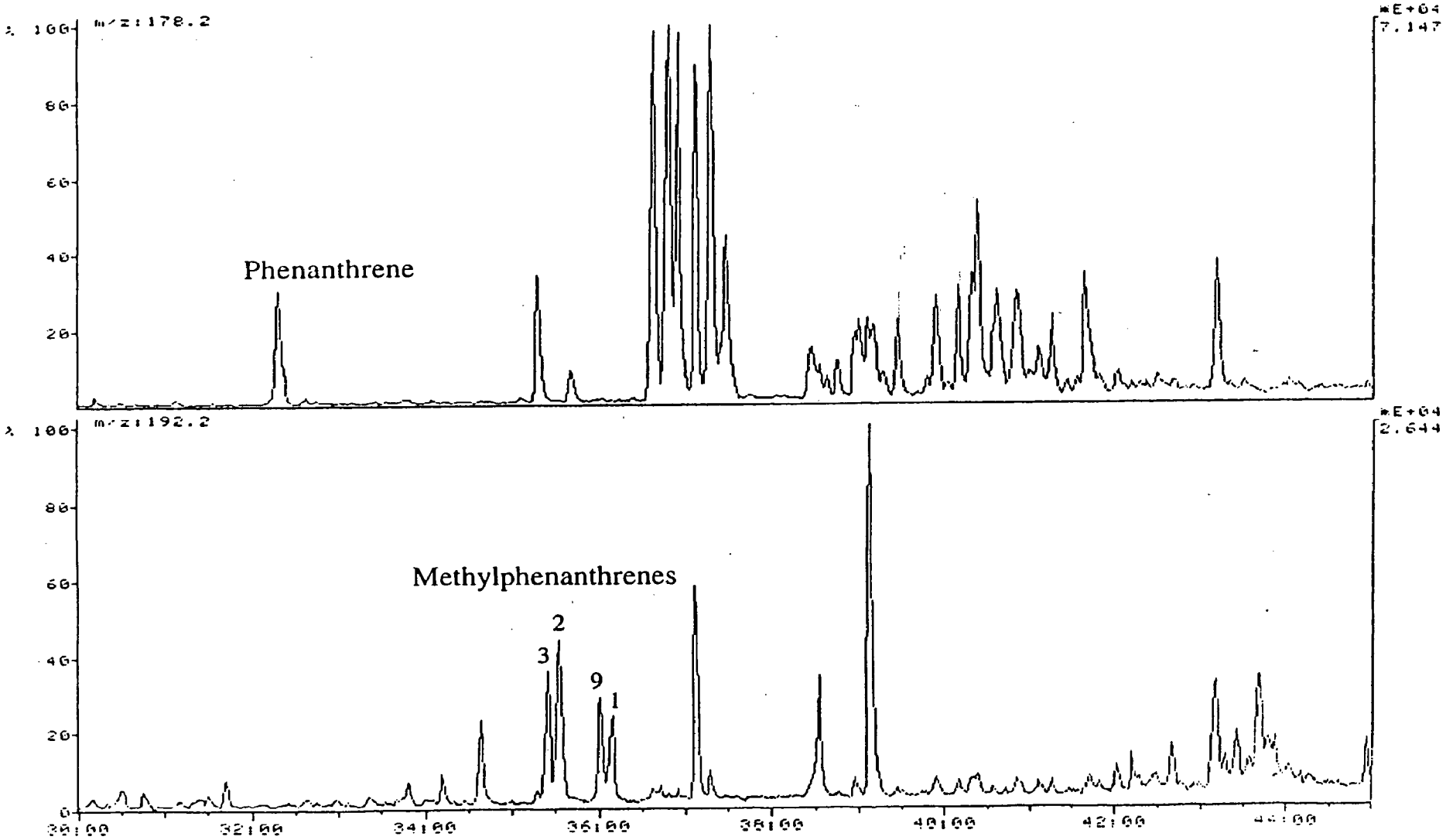
CHRO: BMAXY1 ver 2 on UIC 2 2 17-JUL-95 Elapse: 00:01:07.4 1
Samp: PORT CLINTON-1 315' (AROM) Start : 13:00:48 4212
Comm: DB-1 60m 23.5psi ICL:BMAROM60M 0/40/200 S180 M70
Mode: EI +Q3MS LMR UP LR
Oper: MICHAELSEN Inlet :
Peak: 1000.00 mmu Label wndw: 983 > 1762 Masses: 126 > 254
Area: 0, 4.00 Baseline : 0, 3 Label : 0, 40.00

Figure 3



CHRG: BMAXY2 ver 1 on UIC 2 2 17-JUL-95 Elapse: 00:01:04.8 1
Samp: PORT CLINTON-1 317' (AROM) Start : 14:23:59 4365
Comm: DB-1 60m 23.5psi ICL:BMAROM60N 0/40/200 S180 M70
Mode: EI +03MS LMR UP LR
Oper: MICHAELSEN Inlet :
Peak: 1000.00 mmu Label wndw: 1505 > 2285 Masses: 128 > 254
Area: 0, 4.00 Baseline : 0, 3 Label : 0, 40.00

Figure 4



CHRO: BMAXY3 ver 1 on UIC 2 2 17-JUL-95 Elapse: 00:01:04.4 1
Samp: PORT CLINTON-1 3347' (AROM) Start : 15:54:00 4365
Comm: DB-1 60m 23.5psi ICL:BMAROM60M 0/40/200 S180 M70
Mode: EI +03MS LMR UP LR
Oper: MICHAELSEN Inlet :
Peak: 1000.00 mmu Label wndw: 1506 > 2286 Masses: 128 > 254
Area: 0, 4.00 Baseline : 0, 3 Label : 0, 40.00

Figure 5

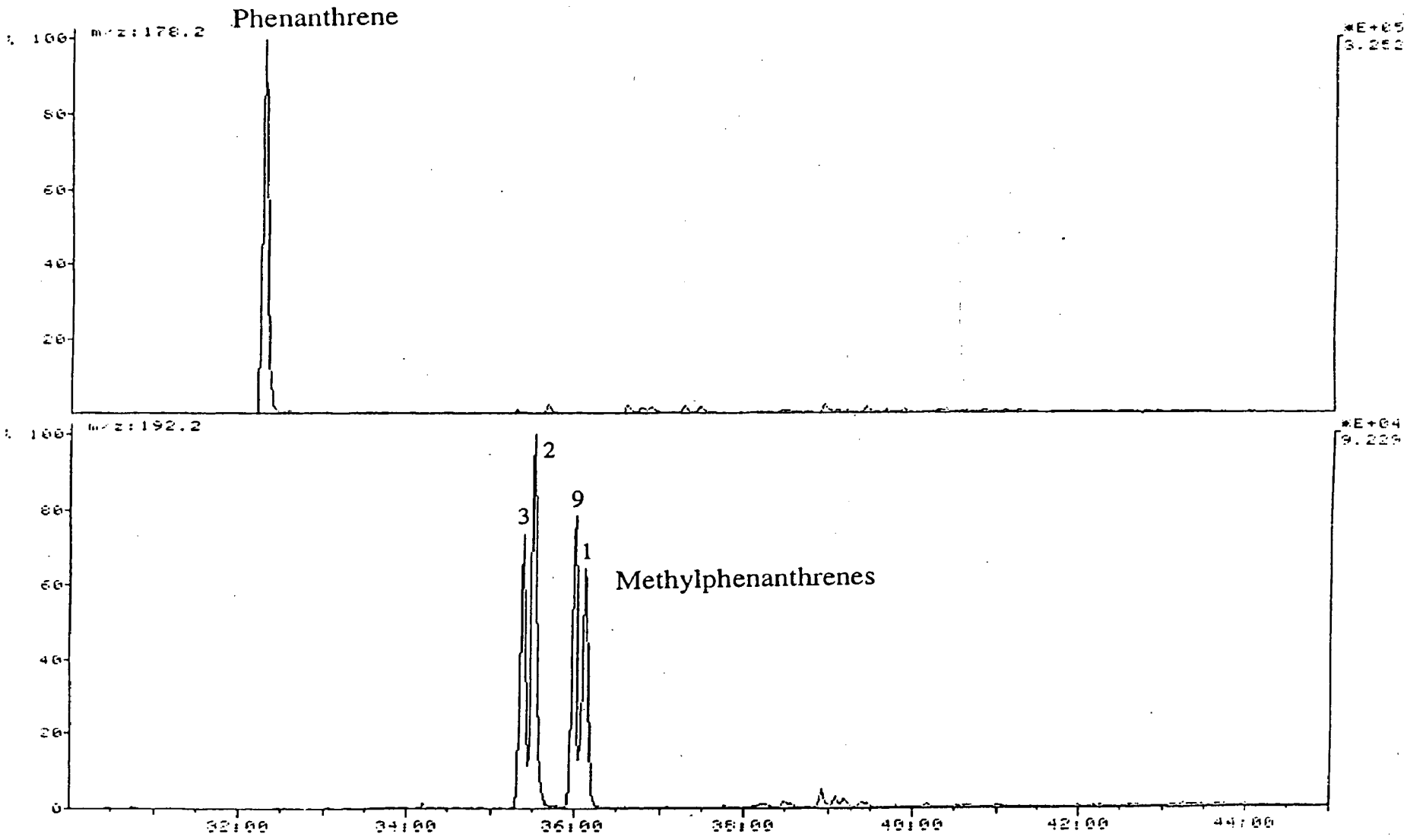


Figure 6

GC-MS of Steranes
in Kulpara Formation at Port Clinton-1

Fig. 6 a,b	96.01 m
Fig. 6 c,d	96.62 m
Fig. 6 e,f	101.80 m

Figure 6a

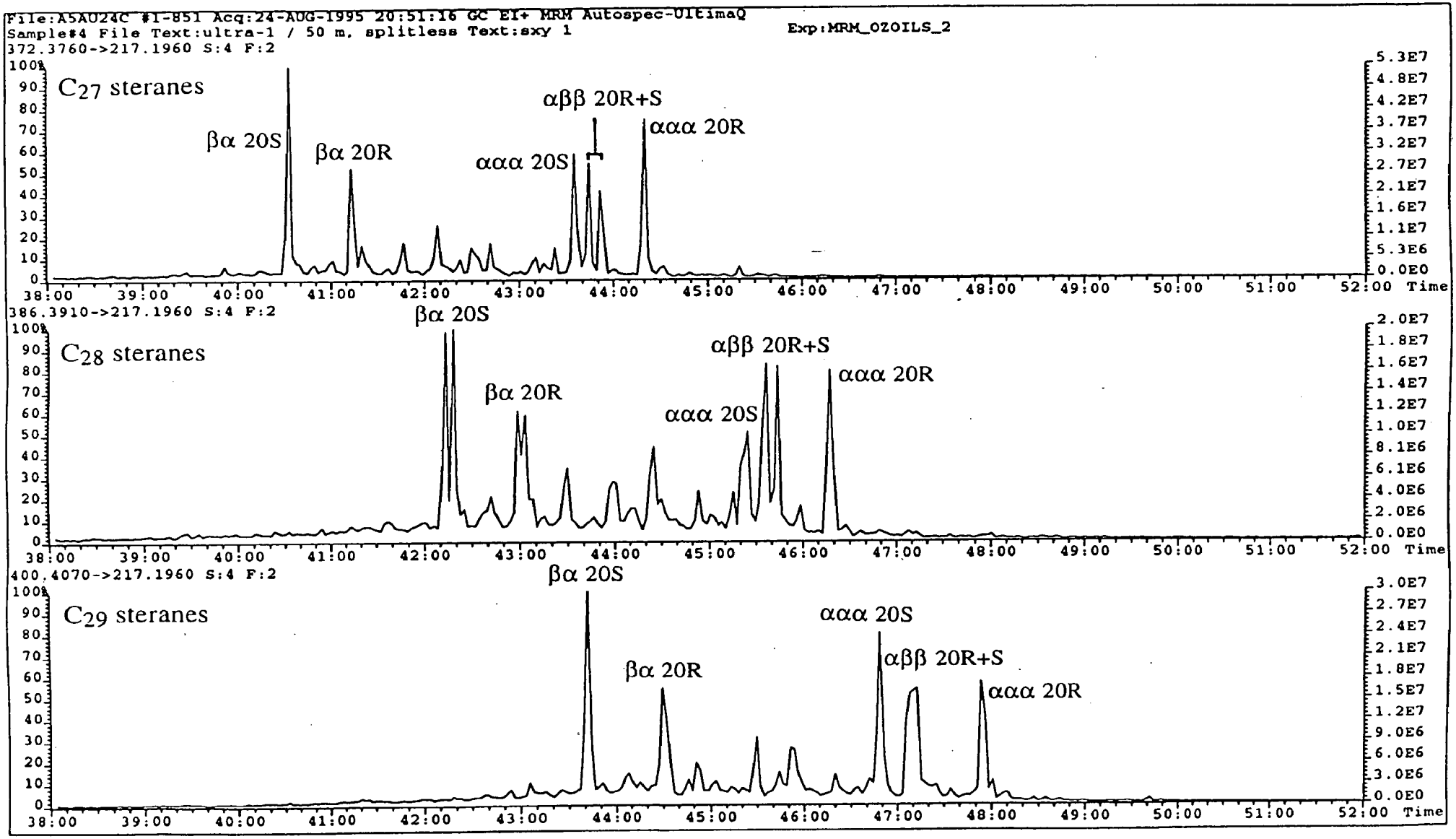

File:A5AU24C #1-851 Acq:24-AUG-1995 20:51:16 GC EI+ MRM Autospec-UltimaQ
Sample#4 File Text:ultra-1 / 50 m, splitless Text:sxy 1
Exp:MRM_OZOILS_2
372.3760->217.1960 S:4 F:2
C27 steranes
βα 20S
βα 20R
ααα 20S
αββ 20R+S
ααα 20R
386.3910->217.1960 S:4 F:2
C28 steranes
βα 20S
βα 20R
ααα 20S
αββ 20R+S
ααα 20R
400.4070->217.1960 S:4 F:2
C29 steranes
βα 20S
βα 20R
ααα 20S
αββ 20R+S
ααα 20R
Time

Figure 6b

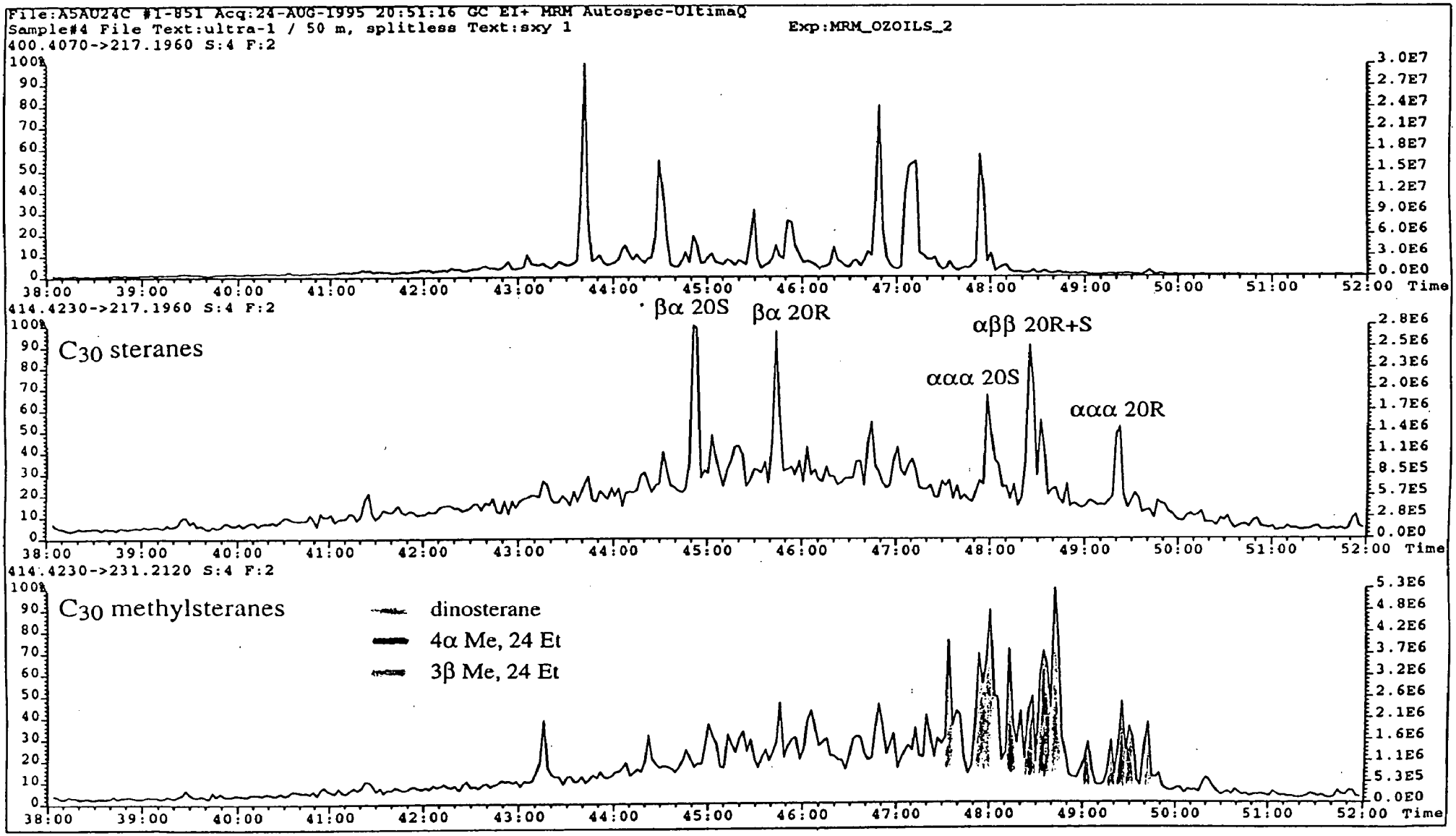

File:A5AU24C #1-851 Acq:24-AUG-1995 20:51:16 GC EI+ MRM Autospec-UltimaQ
Sample#4 File Text:ultra-1 / 50 m, splitless Text:sxy 1
Exp:MRM_OZOILS_2
400.4070->217.1960 S:4 F:2
414.4230->217.1960 S:4 F:2
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
C30 steranes
414.4230->231.2120 S:4 F:2
C30 methylsteranes
dinosterane
4α Me, 24 Et
3β Me, 24 Et
Time

Figure 6c

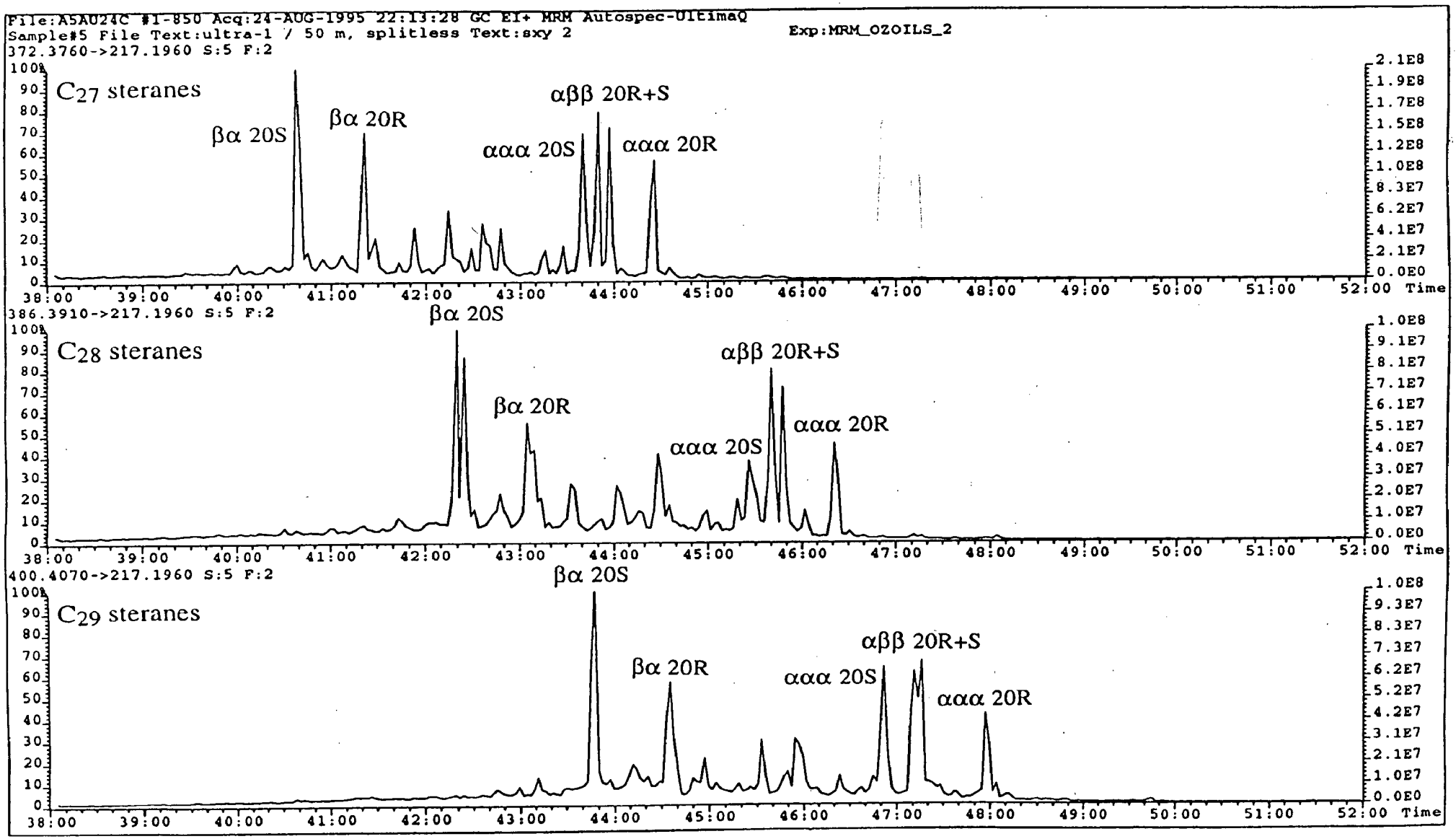

File:A5AU24C #1-850 Acq:24-AUG-1995 22:13:28 GC EI+ MRM Autospec-UltimaQ
Sample#5 File Text:ultra-1 / 50 m, splitless Text:sxy 2
Exp:MRM_OZOILS_2
372.3760->217.1960 S:5 F:2
C27 steranes
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
386.3910->217.1960 S:5 F:2
C28 steranes
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
400.4070->217.1960 S:5 F:2
C29 steranes
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
Time

Figure 6d

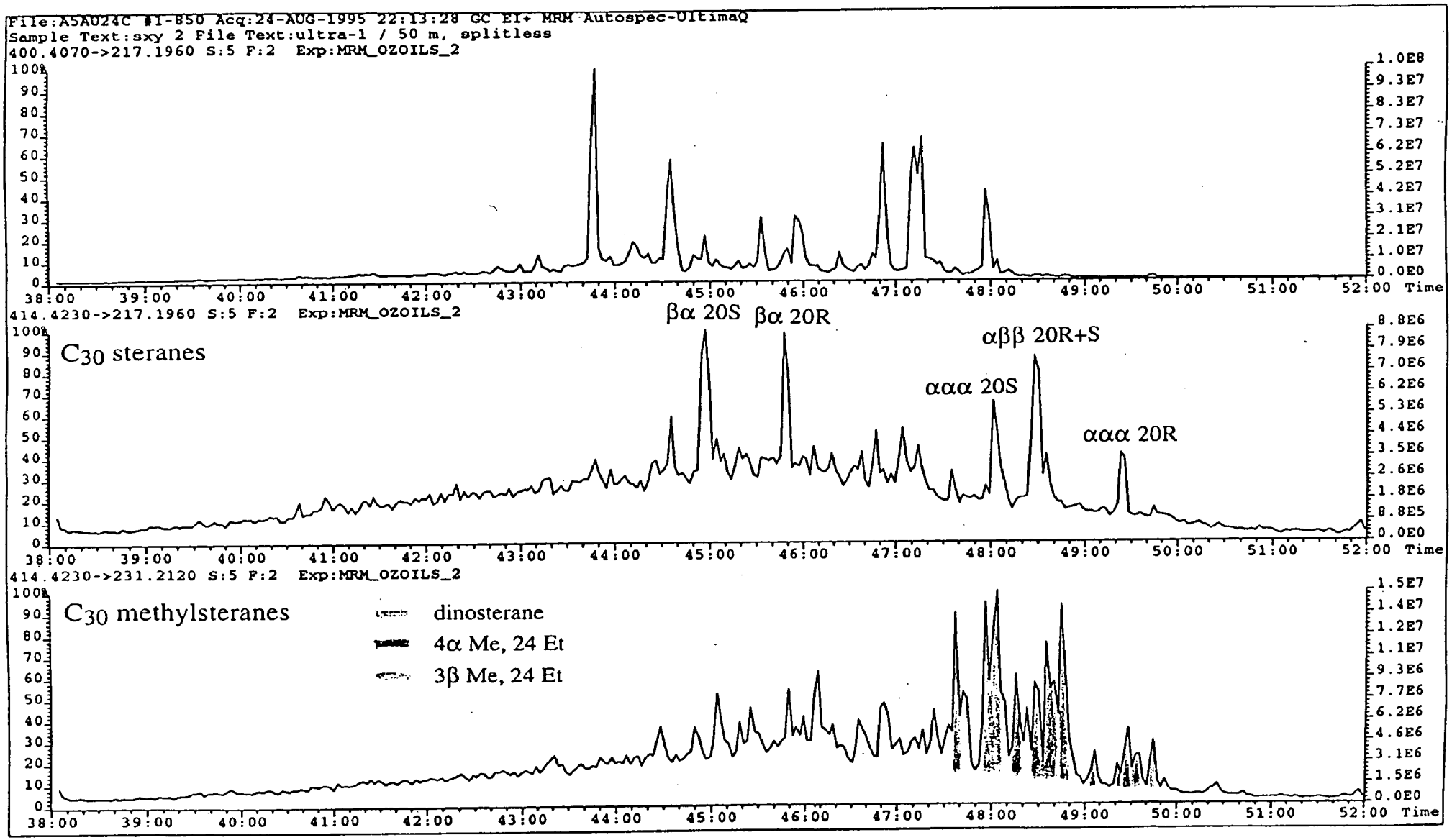

File:A5AU24C #1-850 Acq:24-AUG-1995 22:13:28 GC EI+ MRM Autospec-UltimaQ
Sample Text:sxy 2 File Text:ultra-1 / 50 m, splitless
400.4070->217.1960 S:5 F:2 Exp:MRM_OZOILS_2
414.4230->217.1960 S:5 F:2 Exp:MRM_OZOILS_2
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
C30 steranes
414.4230->231.2120 S:5 F:2 Exp:MRM_OZOILS_2
C30 methylsteranes
dinosterane
4α Me, 24 Et
3β Me, 24 Et
Time

Figure 6e -

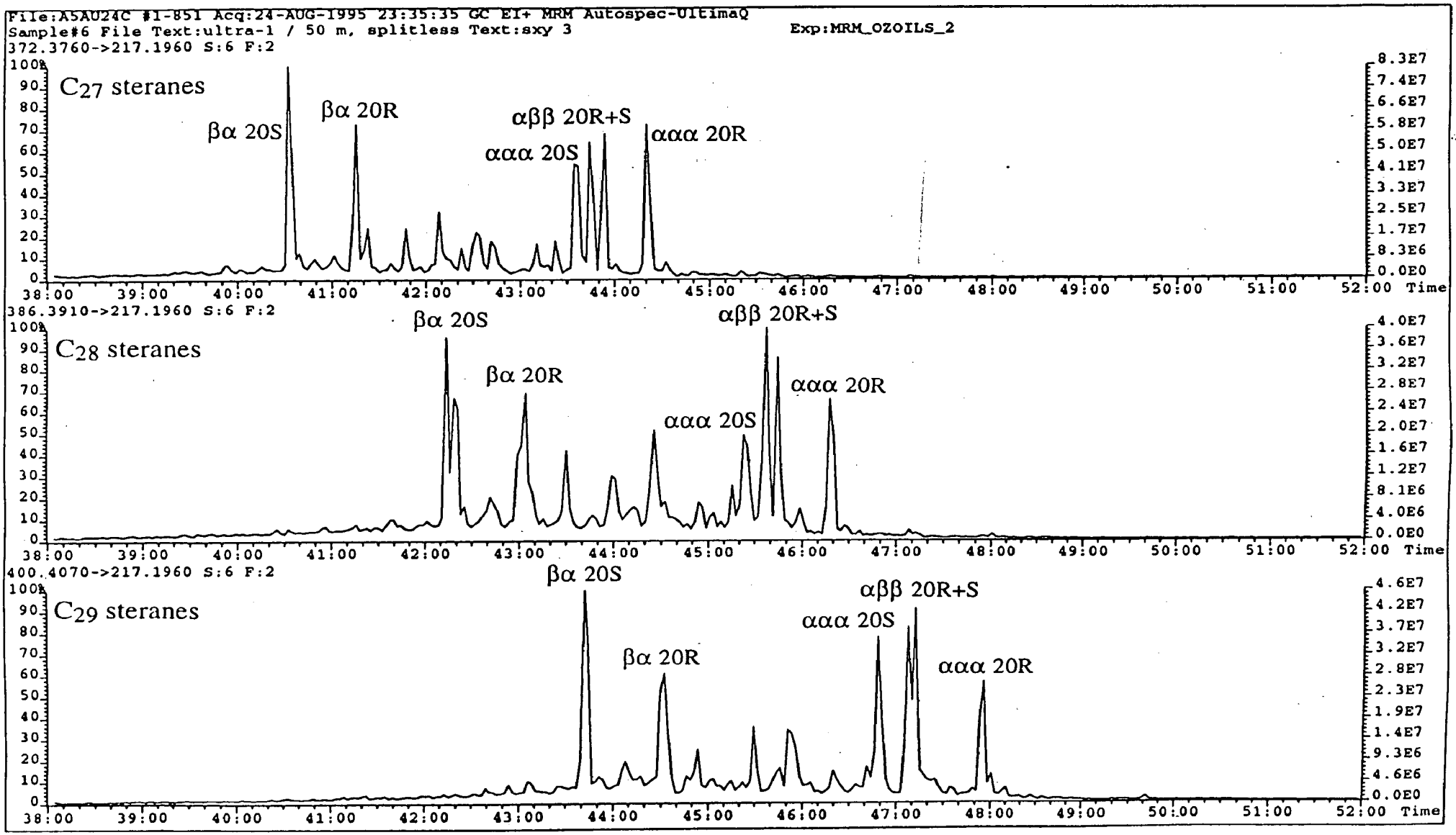

File:A5AU24C #1-851 Acq:24-AUG-1995 23:35:35 GC EI+ MRM Autospec-UltimaQ
Sample#6 File Text:ultra-1 / 50 m, splitless Text:sxy 3
Exp:MRM_OZOILS_2
372.3760->217.1960 S:6 F:2
C27 steranes
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
386.3910->217.1960 S:6 F:2
C28 steranes
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
400.4070->217.1960 S:6 F:2
C29 steranes
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
Time

Figure 6f

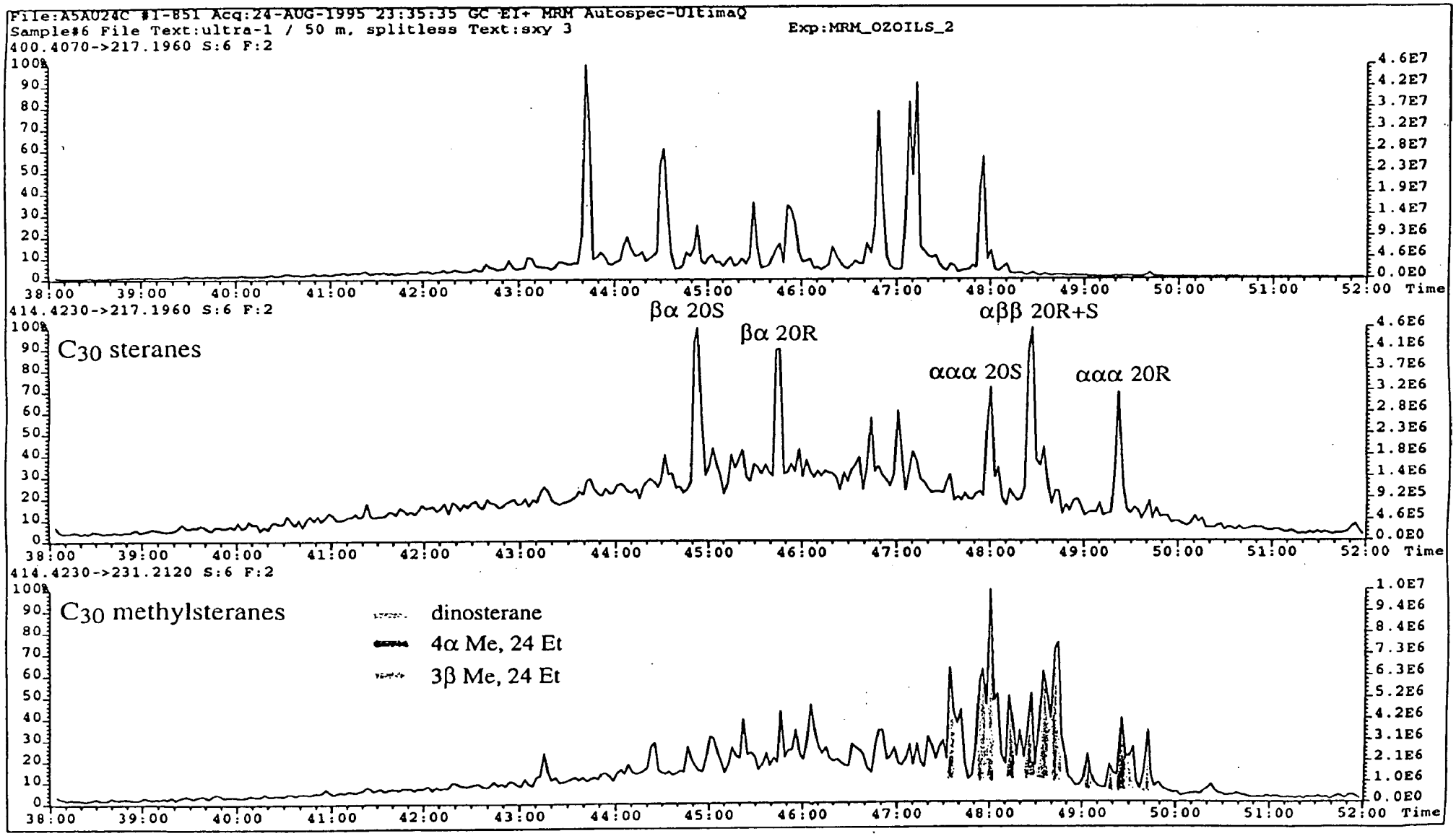

File:A5A024C #1-851 Acq:24-AUG-1995 23:35:35 GC-EI+ MRM Autospec-UltimaQ
Sample#6 File Text:ultra-1 / 50 m, splitless Text:sxy 3
Exp:MRM_OZOILS_2
400.4070->217.1960 S:6 F:2
414.4230->217.1960 S:6 F:2
βα 20S
βα 20R
αββ 20R+S
ααα 20S
ααα 20R
C30 steranes
414.4230->231.2120 S:6 F:2
C30 methylsteranes
dinosterane
4α Me, 24 Et
3β Me, 24 Et
Time

Figure 7

GC-MS of Triterpanes
in Kulpara Formation at Port Clinton-1

Fig. 7 a,b	96.01 m
Fig. 7 c,d	96.62 m
Fig. 7 e,f	101.80 m

Figure 7a

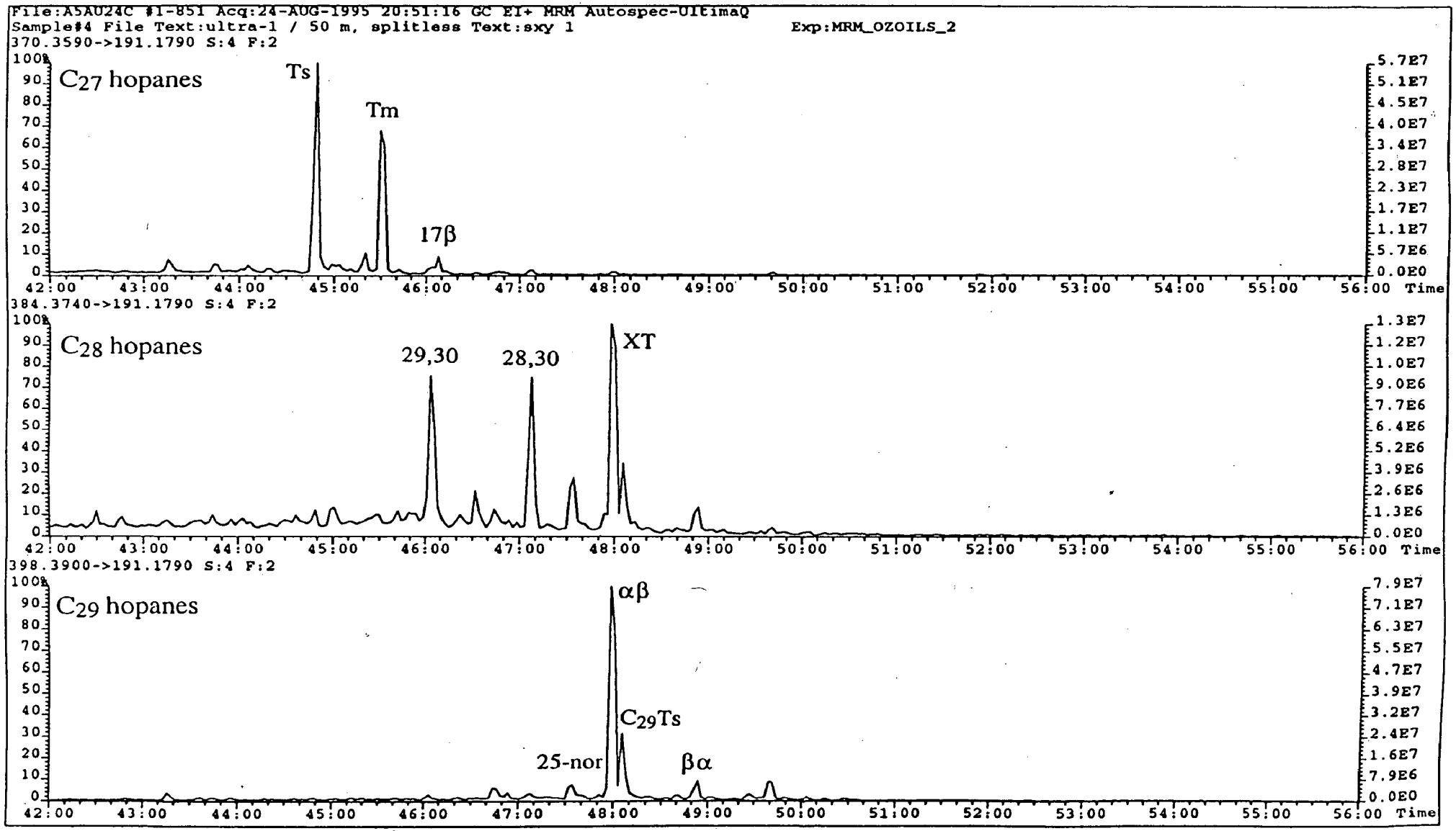

File:A5AU24C #1-851 Acq:24-AUG-1995 20:51:16 GC EI+ MRM Autospec-UltimaQ
Sample#4 File Text:ultra-1 / 50 m, splitless Text:sxy 1
Exp:MRM_OZOILS_2
370.3590->191.1790 S:4 F:2
C27 hopanes
Ts
Tm
17β
384.3740->191.1790 S:4 F:2
C28 hopanes
29,30
28,30
XT
398.3900->191.1790 S:4 F:2
C29 hopanes
αβ
C29Ts
25-nor
βα
Time

Figure 7b

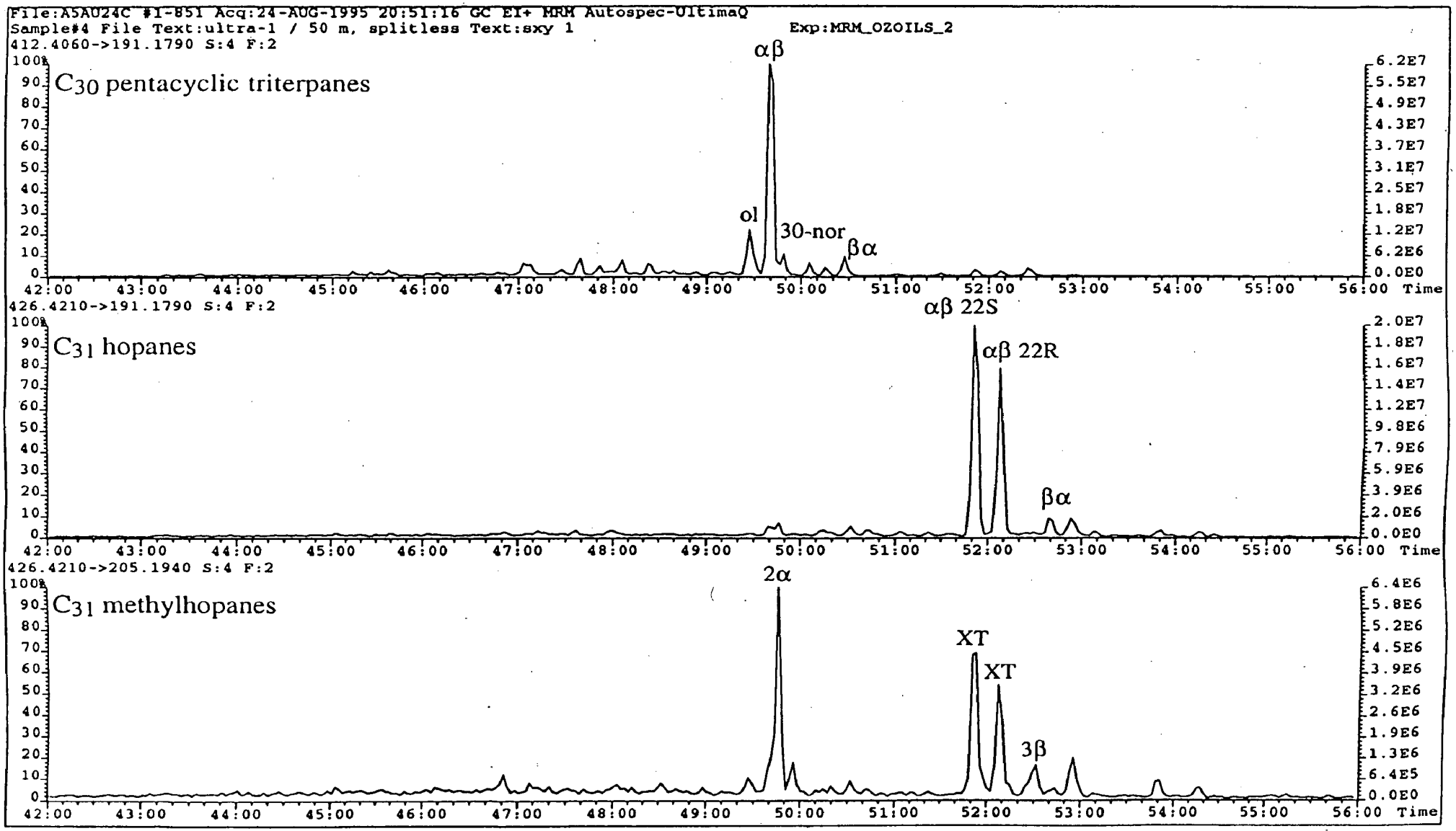

File:A5AU24C #1-851 Acq:24-AUG-1995 20:51:16 GC EI+ MRM Autospec-UltimaQ
Sample#4 File Text:ultra-1 / 50 m, splitless Text:sxy 1
Exp:MRM_OZOILS_2
412.4060->191.1790 S:4 F:2
C30 pentacyclic triterpanes
αβ
ol
30-nor
βα
426.4210->191.1790 S:4 F:2
C31 hopanes
αβ 22S
αβ 22R
βα
426.4210->205.1940 S:4 F:2
C31 methylhopanes
2α
XT
XT
3β
Time

Figure 7c

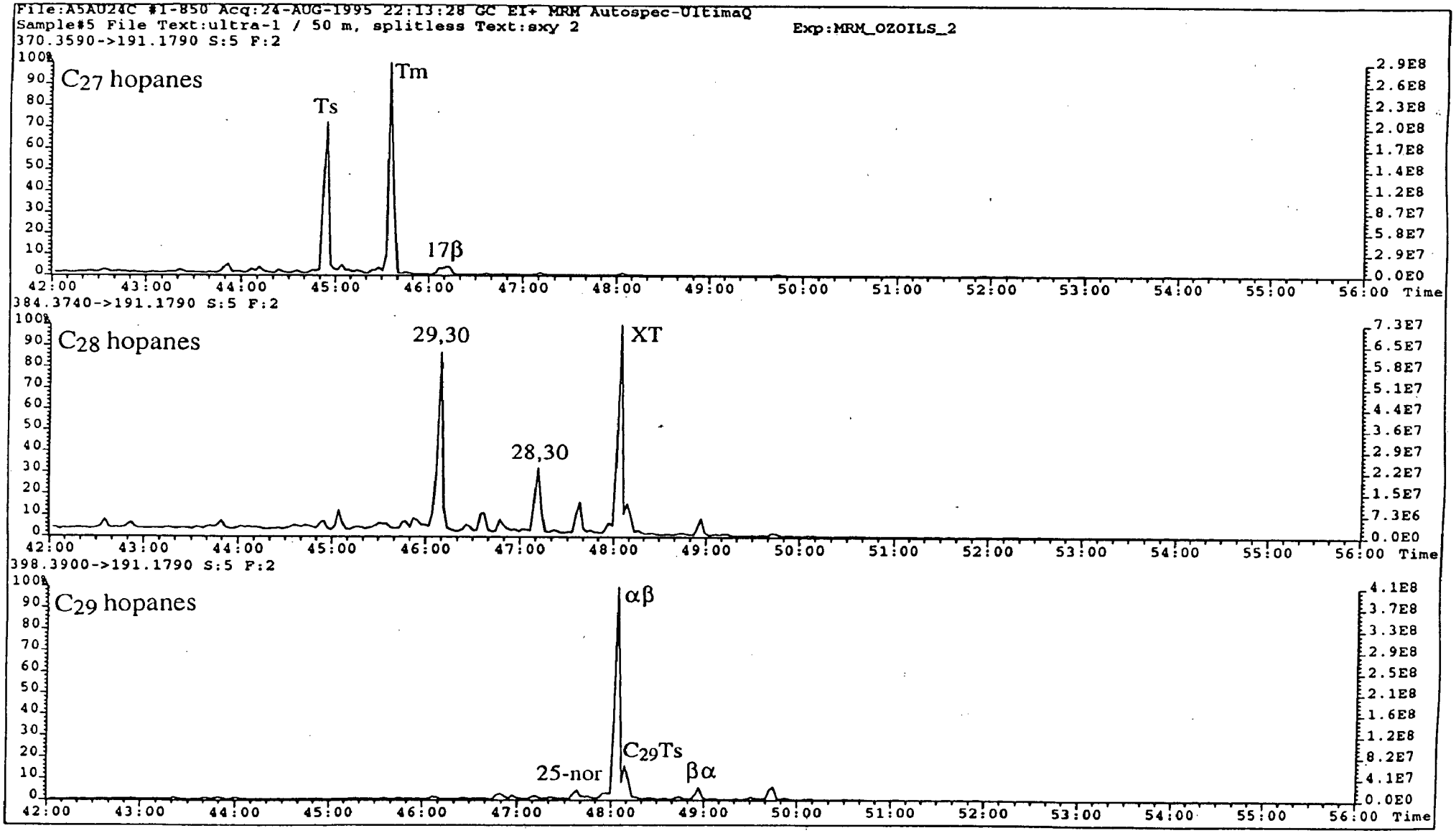

File:A5AU24C #1-850 Acq:24-AUG-1995 22:13:28 GC EI+ MRM Autospec-UltimaQ
Sample#5 File Text:ultra-1 / 50 m, splitless Text:sxy 2
Exp:MRM_OZOILS_2
370.3590->191.1790 S:5 F:2
C27 hopanes
Ts
Tm
17β
384.3740->191.1790 S:5 F:2
C28 hopanes
29,30
28,30
XT
398.3900->191.1790 S:5 F:2
C29 hopanes
αβ
C29Ts
25-nor
βα
Time

Figure 7d

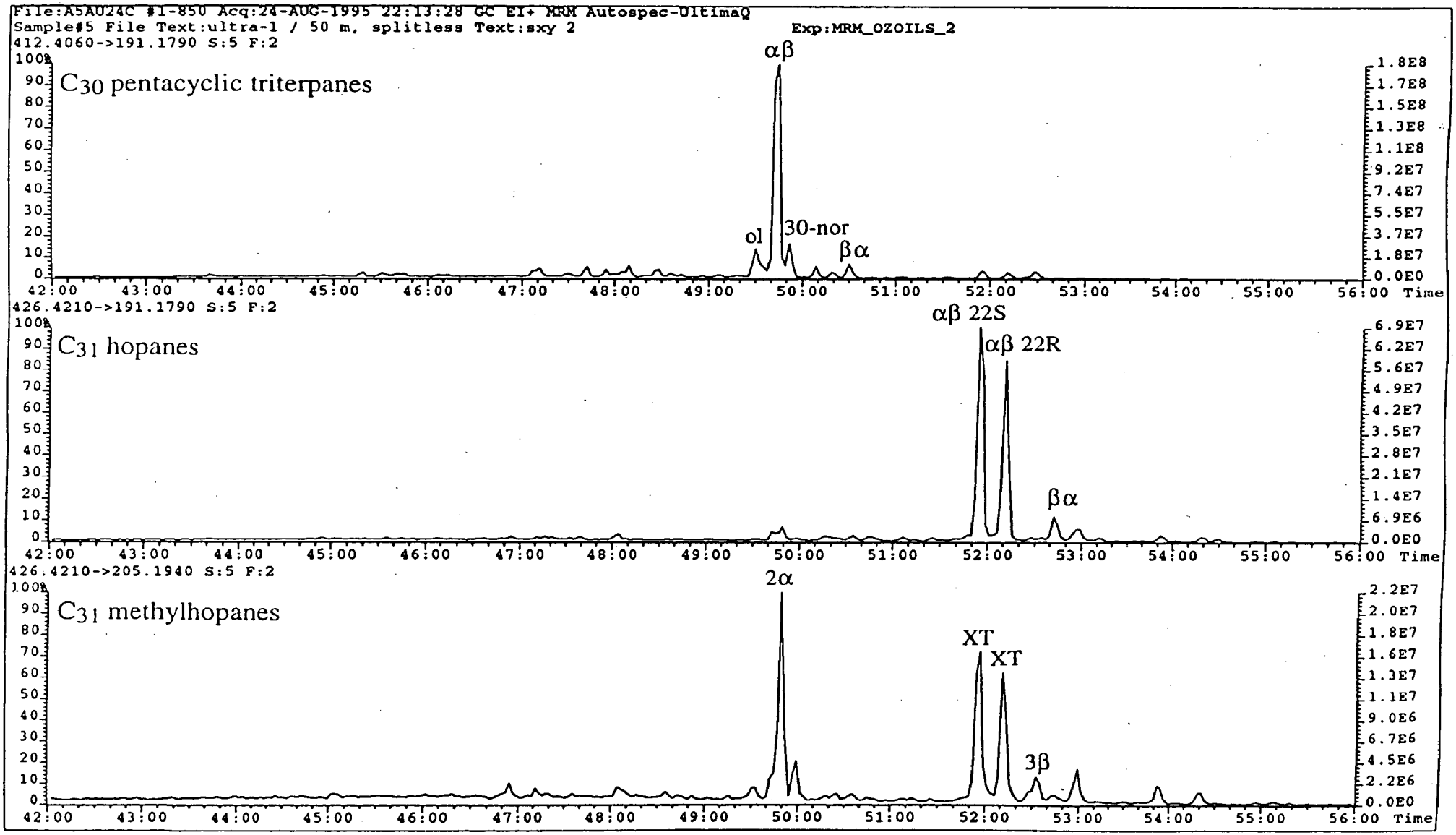
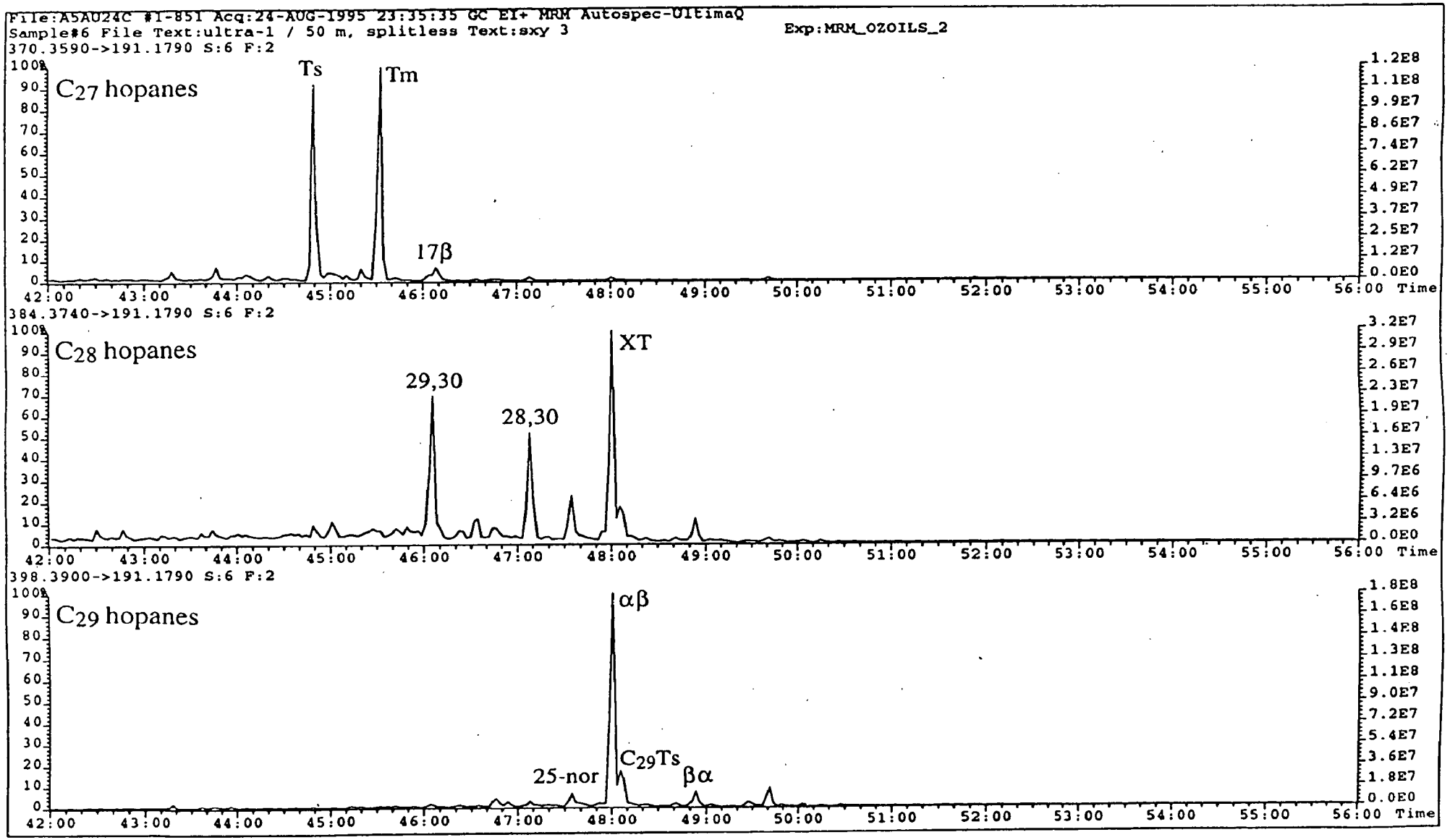
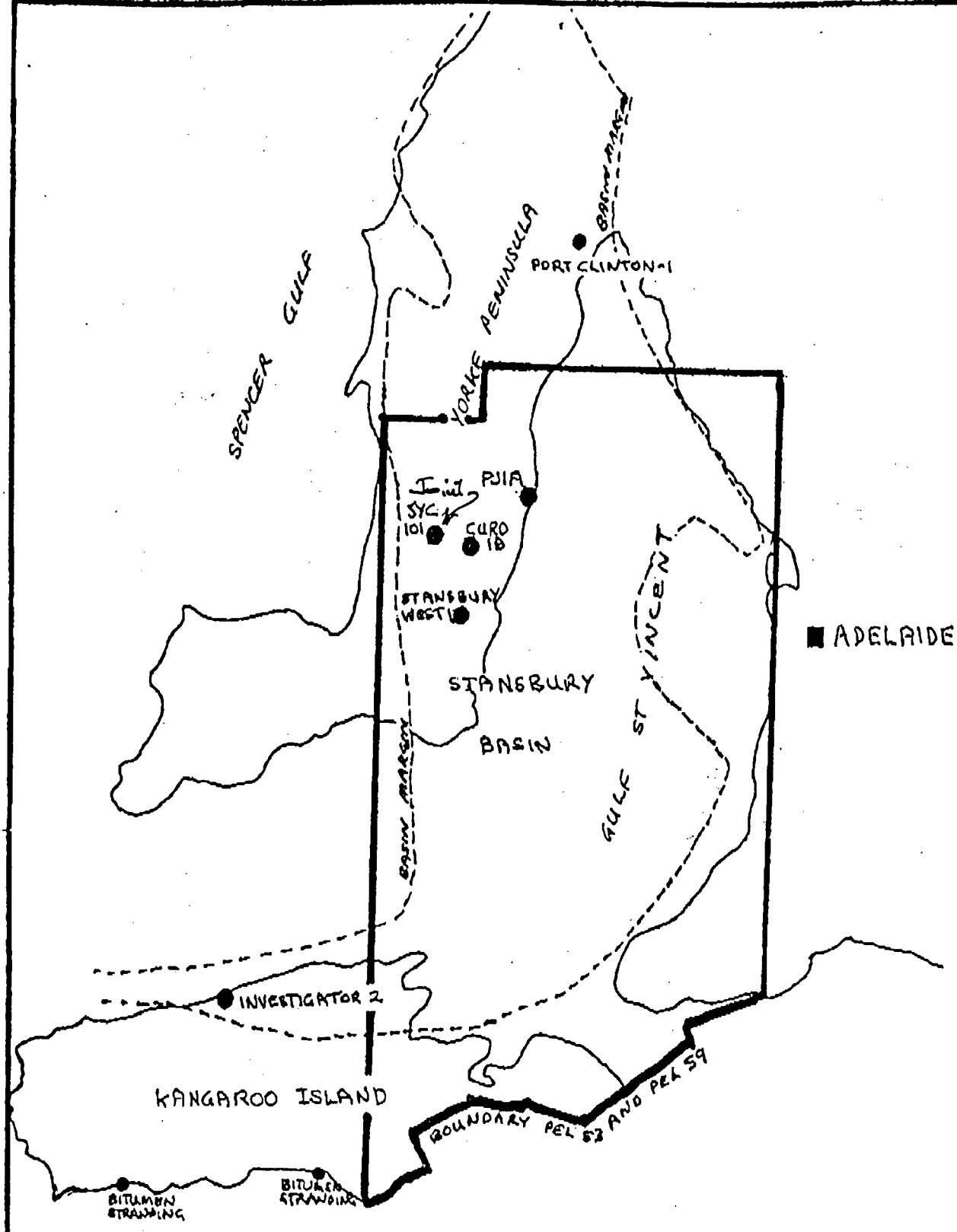

File:A5AU24C #1-850 Acq:24-AUG-1995 22:13:28 GC EI+ MRM Autospec-UltimaQ
Sample#5 File Text:ultra-1 / 50 m, splitless Text:sxy 2
Exp:MRM_OZOILS_2
412.4060->191.1790 S:5 F:2
C30 pentacyclic triterpanes
αβ
ol
30-nor
βα
426.4210->191.1790 S:5 F:2
C31 hopanes
αβ 22S
αβ 22R
βα
426.4210->205.1940 S:5 F:2
C31 methylhopanes
2α
XT
XT
3β
Time

Figure 7e


File:A5AU24C #1-851 Acq:24-AUG-1995 23:35:35 GC EI+ MRM Autospec-UltimaQ
Sample#6 File Text:ultra-1 / 50 m, splitless Text:sxy 3
Exp:MRM_OZOILS_2
370.3590->191.1790 S:6 F:2
C27 hopanes
Ts
Tm
17β
384.3740->191.1790 S:6 F:2
C28 hopanes
29,30
28,30
XT
398.3900->191.1790 S:6 F:2
C29 hopanes
αβ
25-nor
C29Ts
βα
Time

STANSBURY BASIN PEL 53 AND PEL 59
BIOMARKER SAMPLE LOCATIONS



WELL	FORMATION	ANALYST
PJ 1A (Port Julia)	Moonan Fm.	Zumberge
	Stansbury Lst.	Zumberge
CURD 1B (Curdimurka)	Ramsay Lst.	Zumberge
	Parara Lst.	Zumberge
SYC 101 (Aquitane)	Kulpara Fm.	Zumberge
	Kulpara Fm.	McKirdy
Port Clinton-1	Kulpara Fm.	McKirdy