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16. GEOCHEMICAL INVESTIGATION OF SITES 1108 AND 1109, LEG 180[1]

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ABSTRACT

The organic geochemistry of Sites 1108 and 1109 of the Woodlark Basin, offshore Papua New Guinea, was studied to determine whether thermally mature hydrocarbons were present in the penetrated section and, if present, whether they are genetically related to the penetrated "coaly" interval.

Both the organic carbon and pyrolysis data indicate that there is no significant hydrocarbon source-rock potential at Site 1108. The hydrocarbons encountered during drilling appear to be indigenous and not migrated products or contaminants. In contrast, the coaly interval at Site 1109 contains zones with significant hydrocarbon-generation potential. Several independent lines of evidence indicate that the coaly sequence encountered at Site 1109 is thermally immature.

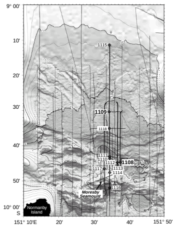
The Site 1108 methane stable–carbon isotope composition does not display a clear trend with depth as would be expected if it was solely reflecting a maturation profile. The measured isotopic composition of methane has most probably been altered by fractionation during sample handling and storage. This fractionation would result in isotopically heavier values than would be obtained on free gas.

The organic geochemical data gathered indicate that Site 1108 can be safely revisited and that the organic-rich sediments encountered at Site 1109 were not the source of the gas encountered at Site 1108.

INTRODUCTION

Leg 180 drilling took place in the western Woodlark Basin, offshore Papua New Guinea (Fig. **F1**), to examine the mechanics of lithospheric

F1. Locations of Sites 1108 and 1109, p. 10.



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[1] Katz, B.J., 2001. Geochemical investigation of Sites 1108 and 1109, Leg 180. *In* Huchon, P., Taylor, B., and Klaus, A. (Eds.), *Proc. ODP, Sci. Results,* 180, 1–19 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/180_SR/VOLUME/CHAPTERS/151.PDF>. [Cited YYYY-MM-DD]

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extension and continental breakup. This study focuses on two of the eleven sites drilled during Leg 180, Sites 1108 and 1109. Site 1108 is located in a seismically active region of incipient continental separation within the Woodlark Basin. The primary objectives of drilling at Site 1108 were to examine in situ properties such as stress, permeability, temperature, and fluid pressure and to determine the vertical motion histories of both the hanging- and footwalls. Site 1109 is situated on the Woodlark Rise. It was located to cross a major sequence boundary (~350 meters below seafloor; mbsf) and an angular unconformity (~770 mbsf). The primary objective at Site 1109 was to determine the nature and history of the synrift sedimentary sequence and the character of the sequence beneath the angular unconformity.

Site 1108 was terminated at 485 mbsf, prior to reaching its proposed total depth because of pollution prevention and safety concerns. Concerns were raised on the drillship because of changes in headspace composition, which displayed a significant decrease in the C_1/C_2 ratio (Shipboard Scientific Party, 1999a). Decreasing C_1/C_2 ratios typically indicate the presence of thermogenic hydrocarbons (Claypool and Kvenvolden, 1983). Regular changes in this ratio are expected through normal thermal maturation processes, which are controlled by the sediment's time-temperature history. And, at locations similar to Site 1108 where the geothermal gradient exceeds 65°C/km (Shipboard Scientific Party, 1999b), these regular changes in hydrocarbon composition may be stratigraphically compressed.

At Site 1109, a series of coaly intervals was encountered below 671 mbsf. These sediments are thought to have been deposited within a lagoonal setting that experienced major changes in salinity (Shipboard Scientific Party, 1999c). These coals, if subjected to the appropriate levels of thermal stress, could act as a viable hydrocarbon source.

This study was initiated to supplement the available shipboard data to help determine whether the drillship can return safely to Site 1108 and to determine whether there is a genetic relationship between the gas encountered at Site 1108 and the coaly sediments recovered at Site 1109.

ANALYTICAL METHODS

Twenty-three samples from Hole 1108B were selected from the interval between 172 and 476 mbsf. Gas was released from the samples using a microball mill. The methane stable–carbon isotopic compositions were determined using a tandem gas chromatography–isotope ratio mass spectrometer system consisting of a Varian 3400 gas chromatograph (GC) interfaced with a Finnigan-MAT 252 isotope ratio mass spectrometer. Gas samples are separated using a Poroplot Q (25 m × 0.32 mm) GC column. The column effluent is fed directly into a GC combustion interface, which is connected to the isotope ratio mass spectrometer. The interface utilizes a preoxidized Cu-Ni-Pt combustion reactor that converts the hydrocarbons to carbon dioxide and water. Water is removed by a Nafion membrane tube prior to entry into the mass spectrometer. Reference standards were intermixed with samples to monitor instrumental performance. Data are reported in standard $\delta^{13}C$ format relative to the PDB (Peedee Formation belemnite) standard. Organic carbon content (C_{org}) was determined for each sample using a LECO CS-344 analyzer after decarbonation with HCl. Whole-rock pyrolytic assays were performed on a subset of these samples using the Rock-Eval II Plus instrument as described by Espitalié et al. (1977).

In addition, nine samples from Hole 1109D were selected from the interval between 688 and 707 mbsf. LECO and Rock-Eval analyses were performed on each of these samples. The organic matter in these sediments was further characterized using pyrolysis gas chromatography as described by Colling et al. (1986). This technique utilizes a CDS 2000 pyroprobe, which flash heats the sample (~100 mg) to 700°C for 5 s, trapping the products in a liquid nitrogen cold trap. The products are then permitted to achieve thermal equilibrium with the initial GC (Hewlett-Packard 5890 GC; 30-m HP-1 column) oven temperature set at 50°C. After 18 min, the oven temperature is increased to 225°C at a rate of 8°/min and then to 310°C at a rate of 6°/min. This final temperature is held for 6 min. The coals were also extracted using a high-pressure extractor and an azeotrophic mixture of methanol, acetone, and chloroform. High-performance liquid chromatography was used to separate the bitumen into saturated and aromatic hydrocarbons, resins, and asphaltenes. The saturated hydrocarbon fraction was further characterized by gas chromatography on a Hewlett-Packard 5890 GC with a 30-m HP-1 column.

ANALYTICAL RESULTS

Organic Carbon

Organic carbon (C_{org}) contents on samples from Site 1108 ranged from 0.11 to 1.23 wt%, with a mean value of 0.58 wt%. These data are detailed in Table **T1.** Only two of the samples contained >1.0 wt% C_{org}.

In contrast, organic carbon contents of the nine samples from Site 1109 ranged from 1.46 to 32.86 wt% (Table **T2**). Although all of the samples studied from Site 1109 are organic rich and the interval from which they were obtained has been described as coal bearing (Shipboard Scientific Party, 1999c), only samples from Section 180-1109D-38R-1 approach the necessary levels of organic enrichment for classification as a coal. True coals contain a minimum of 50% organic matter by weight (~34 wt% C_{org}).

T1. Organic carbon and pyrolysis data, Hole 1108B, p. 16.

T2. Organic carbon and pyrolysis data, Hole 1109D, p. 17.

Rock-Eval Pyrolysis

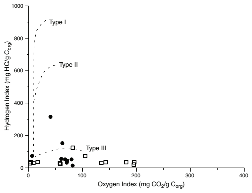
Pyrolytic assay provides information about hydrocarbon-generation potential, organic character, and the extent of thermal diagenesis (maturation).

The results of the pyrolytic assay on the Hole 1108B samples are included in Table **T1.** Total hydrocarbon yields ($S_1 + S_2$ = free distillable hydrocarbons [HC] + generatable HC) are all <1.0 mg HC/g rock. Such low hydrocarbon yields indicate no significant hydrocarbon-generation potential is present and that any heavy hydrocarbons generated would be retained within the rock and released as gas following thermal cracking. The free hydrocarbons measured by pyrolysis equate to the more “oily” fraction and do not represent the light (gaseous) hydrocarbons.

The results of the pyrolytic assay for Hole 1109D are included in Table **T2.** Total hydrocarbon yields range from 0.34 to 98.37 mg HC/g rock. Good and excellent potential and/or effective hydrocarbon source rocks yield >6 mg HC/g rock (Tissot and Welte, 1984). Using this criterion, five of the samples represent good to excellent hydrocarbon source rocks. However, caution should be exercised when evaluating these data because of the suspected low levels of thermal maturity of the sediments. In samples having very low levels of thermal maturity, both the S_1 and S_2 peaks may not represent exclusively hydrocarbons but may instead contain significant amounts of heterocompounds (i.e., molecules containing O, N, and S). The presence of these labile compounds may result in a slight overestimation of the hydrocarbon yields. The remaining samples, although organic rich, have yields that indicate a significant amount of the organic matter is inert and is not capable of generating hydrocarbons.

Although limited by organic enrichment and mineral matrix effects (Katz, 1983), Rock-Eval pyrolysis can be used to provide insight into the nature of the sedimentary organic matter. The hydrogen index (HI) (in milligrams "S_2" hydrocarbons per gram organic carbon) and oxygen index (OI) (in milligrams CO_2 per gram organic carbon) and a modified van Krevelen–type diagram, as described by Espitalié et al. (1977), are used to accomplish this interpretation. Most of the data from both of the sites plot below the type III reference curve (Fig. F2), indicating that the organic matter is largely inert or type IV (Tissot et al., 1979). Type IV or inert organic matter forms through oxidation at the sediment-water interface when sedimentation rates are low and exposure time is great, or it may represent sedimentary recycling or the introduction of charcoal. A few of the samples are slightly more hydrogen enriched. Even these samples are, however, principally gas prone.

F2. Modified van Krevelen–type diagram, Sites 1108 and 1109, p. 11.

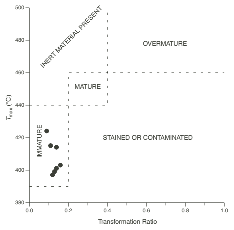


As noted above, there are problems associated with the pyrolysis assay of immature sediments. Pyrolysis does not accurately characterize organic matter in immature sediments as a result of the abundance of oxygenated functional groups in protokerogen. These functional groups are lost during the formation of kerogen. As a result of the presence of these compounds in very immature sediments, the HI values are often depressed and the OI values are elevated, making the organic matter appear more gas prone. Even when these effects are taken into consideration, the interpretation of the organic-matter character of this data set is not significantly changed.

Neither of the two pyrolysis thermal-maturity indicators, T_{max} (temperature at which maximum pyrolytic hydrocarbon-generation occurs) nor the transformation ratio (TR = $S_1/[S_1+S_2]$), are reliable for Site 1108 because of the low pyrolysis (S_2) hydrocarbon yields. An S_2 yield of at least 1.0 mg HC/g rock is considered necessary for a geochemically meaningful T_{max} to be determined, and an $S_1 + S_2$ yield of at least 1.0 mg HC/g rock is considered necessary for the TR to have significance.

The yields for samples from Site 1109 are sufficient for both pyrolysis thermal-maturation indices to be considered meaningful. These indices indicate that the sampled sequence is thermally immature (i.e., has not yet achieved levels of organic diagenesis consistent with the main stage of hydrocarbon generation and expulsion) (Fig. F3). The T_{max} values for all samples with S_2 yields >1.0 are <425°C, and the transformation ratios are <0.2 for samples with a total hydrocarbon-generation potential of at least 1.0 mg HC/g rock. The main stage of hydrocarbon generation and release is marked by T_{max} values of ~440°C and a TR value of ~0.2 (Espitalié et al., 1977).

F3. Transformation ratio vs. T_{max}, Site 1109, p. 12.



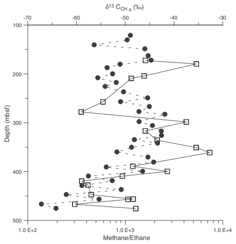
Methane Stable–Carbon Isotope Composition

The carbon isotope composition of methane and other light hydrocarbons is dependent on bacterial contribution, level of source thermal maturity, and alteration history. The methane stable–carbon isotope composition increases (i.e., becomes more positive) with increasing thermal maturity. Methane δ^{13}C values lighter than –55‰ are thought to have a bacterial origin, with more positive values assumed to have a thermogenic origin (Feux, 1977).

The methane δ^{13}C values range from –60.36‰ to –32.70‰. These data are summarized in Table T3 and Figure F4. Many of the samples are significantly heavier than would routinely be associated with a biogenic origin (–55‰) and may therefore be interpreted to indicate a thermogenic origin. There is, however, no clear trend in isotopic composition with depth as would be expected if these data reflected thermogenic hydrocarbon generation. Partial microbial oxidization can result in the isotopic enrichment of the residual gas through the preferential consumption of the isotopically lighter carbon. Such enrichment could result in the masking of the true mode of gas formation and/or thermal maturity (Coleman et al., 1981) and would result in a more mature appearing gas than would be observed in an unaltered gas.

T3. Methane stable carbon isotope composition, Hole 1108B, p. 18.

F4. Methane/ethane ratio and $\delta^{13}C_{CH4}$ plotted against depth, Site 1108, p. 13.



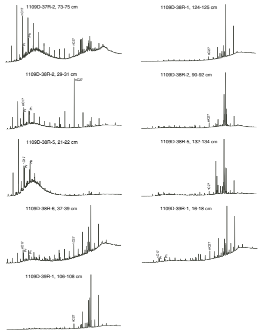
More likely, the reported values reflect fractionation of methane as a result of the degassing of the samples during handling and storage. Faber and Stahl (1983) have shown that degassing of sediment results in the enrichment of ^{13}C in the residual gas. Berner and Bertrand (1991) reported similar fractionation while examining sediments from Site 768. They reported isotopically lighter values for gases obtained from gas pockets compared to "total" gases, which included desorbed gases. Therefore, although these values do not represent in situ gas composition, they clearly do not appear to support a thermogenic origin. The isotopically lighter values observed below 400 mbsf might be a reflection of increases in the degree of lithification and the associated decrease in degassing, which in turn would result in reduced isotopic fractionation (G. Claypool, pers. comm., 2000).

Bitumen Characterization

The total bitumen (or total organic extract [TOE]) yields for the samples from Site 1109 range from 899 to 56,929 ppm (Table T4). The extractable fraction is dominated by nonhydrocarbons (resins and asphaltenes; >73%), and the saturate/aromatic hydrocarbon ratios are typically <1.0. Such characteristics are consistent with the previously suggested low level of thermal maturity of the sample suite (Le Tran et al., 1974). With increasing thermal maturity there is an increase in both the hydrocarbon (saturate + aromatic) content and the saturate/aromatic hydrocarbon ratio.

T4. Bitumen yield and bulk composition, Hole 1109D, p. 19.

F5. C_{15+} saturated hydrocarbon–fraction gas chromatograms, Site 1109, p. 14.



Results of the saturated hydrocarbon–fraction gas chromatography are presented in Figure F5. These chromatographic signatures are also consistent with low levels of thermal maturity. The chromatograms either display a bimodal character with a full suite of *n*-alkanes or a unimodal pattern dominated by steranes and terpanes (biomarkers) with the *n*-alkanes being nearly absent. The bimodal samples also typically display a more pronounced naphthenic envelope or "hump." This hump represents a complex mixture of unresolved hydrocarbon compounds. With increasing thermal maturity, the bimodality decreases and there is an increase in the relative abundance of *n*-alkanes and corresponding decrease in the relative abundance of biomarker compounds.

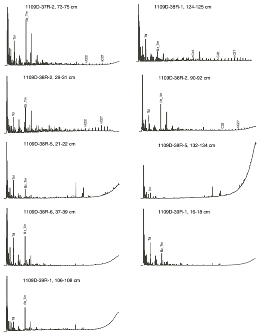
A comparison of these data with the other available geochemical data reveals no clear relationship between the chromatographic signature and level of organic enrichment, free hydrocarbon content, or kerogen type. This suggests that there is no clear relationship between molecular and bulk chemistry. These observed differences might be the result of variations in both organic input and preservation caused by the suggested changes in salinity within the lagoon (Shipboard Scientific Party, 1999c).

Pyrolysis Gas Chromatography

Pyrolysis gas chromatography provides additional information about the nature of kerogen (Larter and Douglas, 1980) as well as a qualitative assessment of principal hydrocarbon products that may be generated upon thermal maturation (Dembicki et al., 1983).

The pyrolysis gas chromatograms are presented in Figure **F6.** As with the C_{15+} saturate hydrocarbon–fraction gas chromatograms, the pyrolysis gas chromatograms can be divided into two groups. However, unlike the saturate fraction gas chromatograms, there does appear to be a relationship between the chromatographic pattern and the pyrolysis results. Samples with low Rock-Eval S_2 yields (e.g., Sample 180-1109D-38R-5, 21–22 cm) had chromatograms dominated by lower molecular weight compounds and generally lacking higher molecular weight components. In contrast, samples with S_2 yields >10 mg HC/g rock (e.g., Sample 180-1109D-38R-2, 29–31 cm), although dominated by lower molecular weight compounds, did contain a full suite of alkane-alkene doublets, extending beyond n-C_{30}. The presence of these higher molecular weight compounds suggests that the samples with the higher hydrocarbon yields contain a greater percentage of exinitic or waxy material. Differences in maceral composition could result from variations in the nature of organic input and/or selective preservation, both of which would change as depositional conditions evolve.

F6. Pyrolysis gas chromatograms, Site 1109, p. 15.



Both chromatographic signatures confirm that the gas would be the primary product generated at the appropriate levels of thermal maturity. Relatively small amounts of a waxy crude oil could be generated by those samples with higher hydrocarbon yields. Although this coaly material could generate longer-chain hydrocarbons, it is not considered likely that they would be expelled as liquids. As a result of their limited volumes, high molecular weights, and the physical structure of the coal, it is more likely that these hydrocarbons would be retained within the coal until they are cracked and released as gas at higher burial temperatures (Katz et al., 1991).

DISCUSSION

The data gathered from Hole 1108D as part of this study indicate that no liquid hydrocarbon source was penetrated and that the stratigraphic sequence has only minimal gas source potential. A review of the shipboard data reveals that even with an expanded sample population the penetrated section has only limited gas source potential (Shipboard Scientific Party, 1999b). The organic matter present is largely inert (type IV, according to the scheme of Tissot et al., 1979).

Although the penetrated section at Site 1108 exhibits insufficient hydrocarbon-generation potential for commercially significant gas, sufficient organic matter is present to explain the limited gas present within the recovered cores. Shipboard measurements report a maximum headspace methane concentration of 59,668 ppmv for the sample obtained from 370.71 mbsf. The increase in gas wetness with depth (i.e., lower methane/ethane ratios) (Fig. F4) observed by the Shipboard Scientific Party (1999b) is not associated with an increase in gas abundance. These observations are consistent with an in situ origin for the gas at Site 1108. The increases in gas wetness can be attributed to a continuum of microbial and low-temperature nonbiological processes. The increase in gas wetness with depth does appear to be more rapid than at other ocean drilling locations (Claypool and Kvenvolden, 1983). This more rapid increase in gas wetness may be a reflection of the site's elevated geothermal gradient, which approaches ~100°C/km (Shipboard Scientific Party, 1999b). The elevated geothermal gradient acts to compress the different hydrocarbon-generation zones. The measured temperatures are, however, still consistent with microbial and low-temperature (<75°C) nonbiological gas generation rather than high-temperature thermogenic gas generation (>75°C).

The examined interval at Site 1109 included a number of highly organic enriched zones. A significant portion of the organic matter is inert and has relatively limited hydrocarbon-generation potential. Although most of the samples appear to be dominated by inert material, both the extractable fraction and the pyrolysis products suggest that the organic facies vary. The pyrolysis gas chromatography data indicate that some of the samples may contain slightly higher percentages of exinitic material capable of generating higher molecular weight products. These variations in organic facies may reflect changes in both the character of the organic input as well as organic preservation potential. These variations could be reflecting the suspected changes in the salinity of the lagoon in which they were deposited (Shipboard Scientific Party, 1999c).

The apparent in situ origin of the gas and the limited gas generation potential of the section suggest that Site 1108 could be revisited and the primary objective reached safely. However, because of the elevated geothermal gradient, careful hydrocarbon monitoring would be required. The greatest gas risk is associated with a stratigraphically equivalent organic-rich interval similar to that observed at Site 1109. The high geothermal gradient and the elevated generation potentials of the coaly zone could result in elevated gas concentrations.

SUMMARY

No significant hydrocarbon source-rock potential was identified in Hole 1108B. In contrast, zones within the coaly interval encountered in Hole 1109D displayed good to excellent hydrocarbon source-rock potential. At the appropriate levels of thermal maturity, these organic-rich intervals would yield largely gas. Limited oil potential was identified in one of the samples (180-1109D-38R-2, 29–31 cm).

The coaly interval at Site 1109 is thermally immature, based on the two pyrolysis thermal maturation indexes, the relative abundance and gross composition of the bitumen, and the nature of the saturated hydrocarbon–fraction gas chromatograms.

No clear trend with depth in methane stable–carbon isotope composition was detected, suggesting that the isotope values are not simply reflecting a thermal maturation trend. It appears that the isotopically heavier values are not the result of the introduction of thermally mature gas but are an artifact of fractionation during sample handling and storage.

The in situ origin and limited hydrocarbon-generation potential of Site 1108 suggest that the location can be safely revisited, but because of the elevated geothermal gradient, careful monitoring will be required, especially if a stratigraphic equivalent to the coaly interval observed at Site 1109 is penetrated.

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Tissot, B., Deroo, G., and Herbin, J.P., 1979. Organic matter in Cretaceous sediments of the North Atlantic: contribution to sedimentology and paleogeography. *In* Talwani, M., Hay, W., and Ryan, W.B.F. (Eds.), *Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironments*. Am. Geophys. Union, 362–374.

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Figure F1. Locations for Leg 180 drill sites and multichannel seismic tracks, plotted on a shaded relief map with 200-m bathymetric contours (thicker contours labeled every kilometer). Sites 1108 and 1109 are highlighted (modified from Shipboard Scientific Party, 1999a).

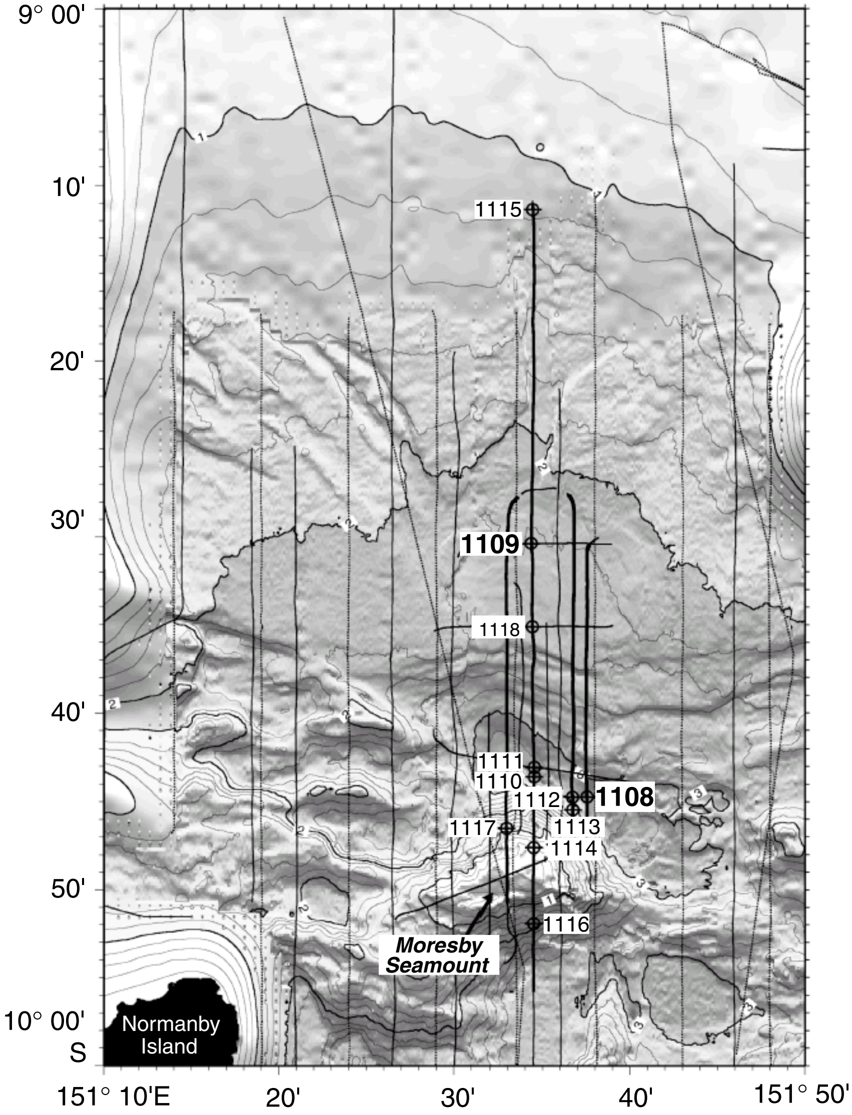

Figure F2. Modified van Krevelen–type diagram, Sites 1108 (solid circles) and 1109 (open squares).

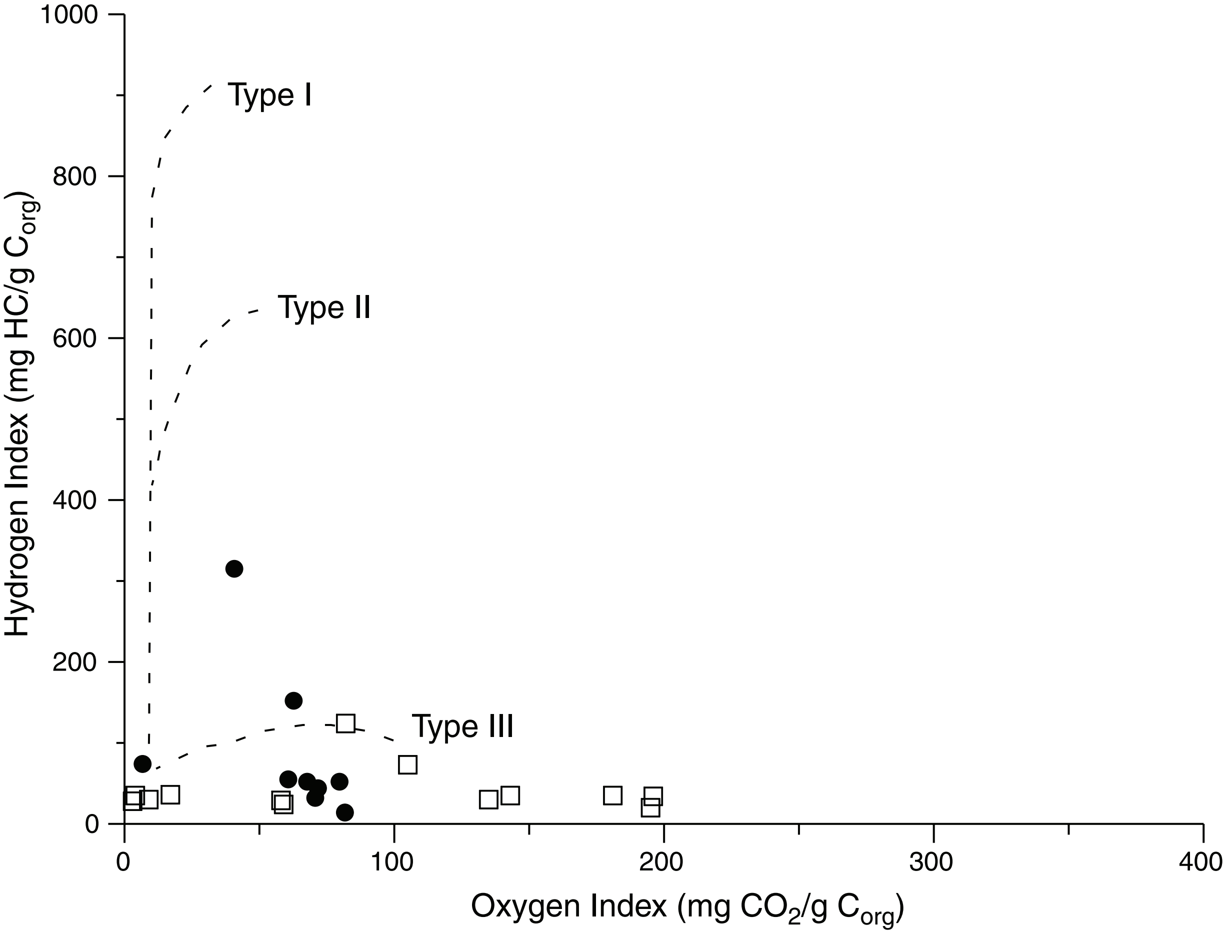

Figure F3. Relationship between T_{max} and transformation ratio for samples from Site 1109.

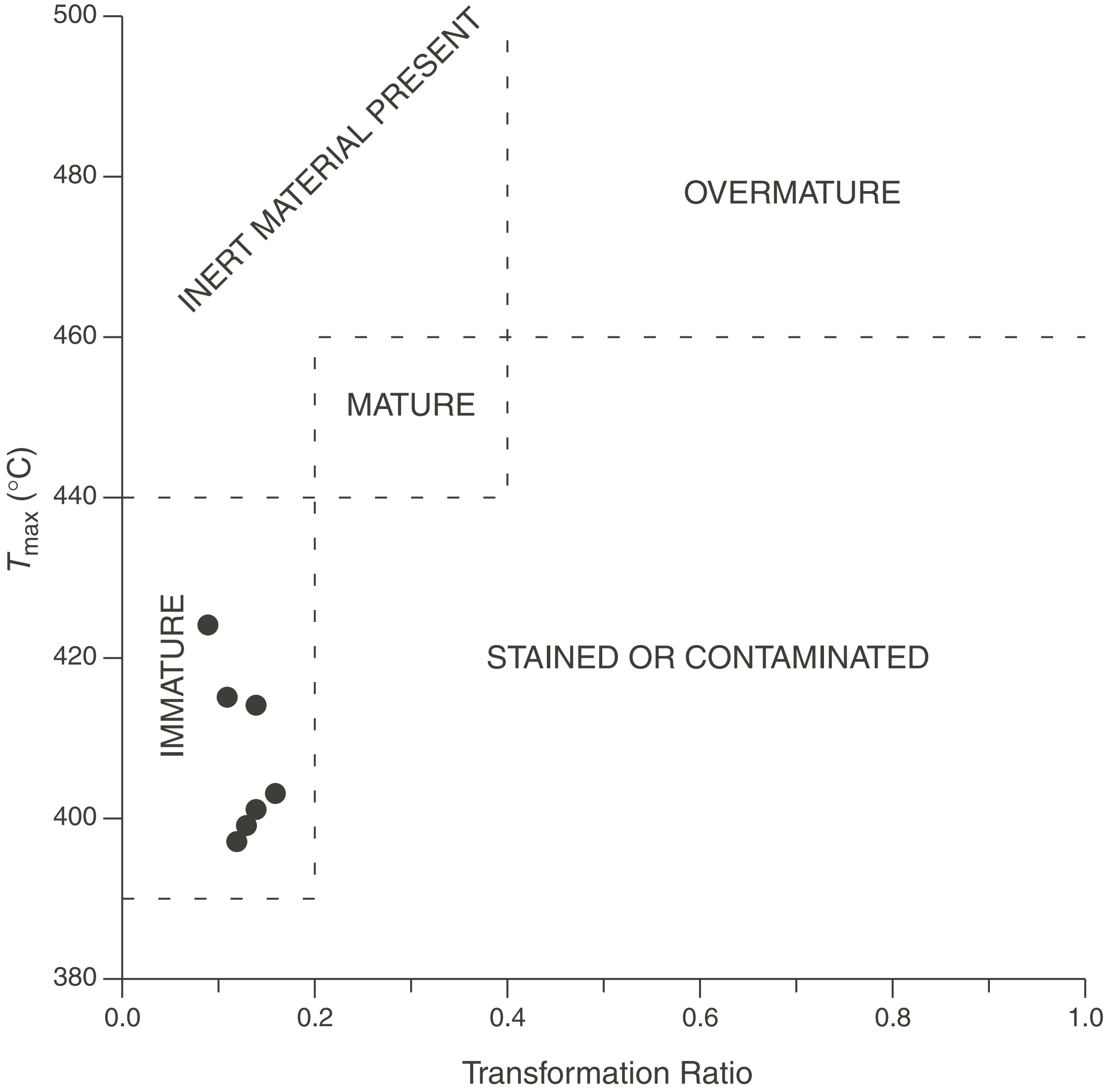

Figure F4. Methane/ethane ratio (solid circles) and methane stable–carbon isotopic composition (open squares) as a function of depth for Site 1108. Methane and ethane concentration data used to calculate the methane/ethane ratios were obtained from Shipboard Scientific Party (1999b).

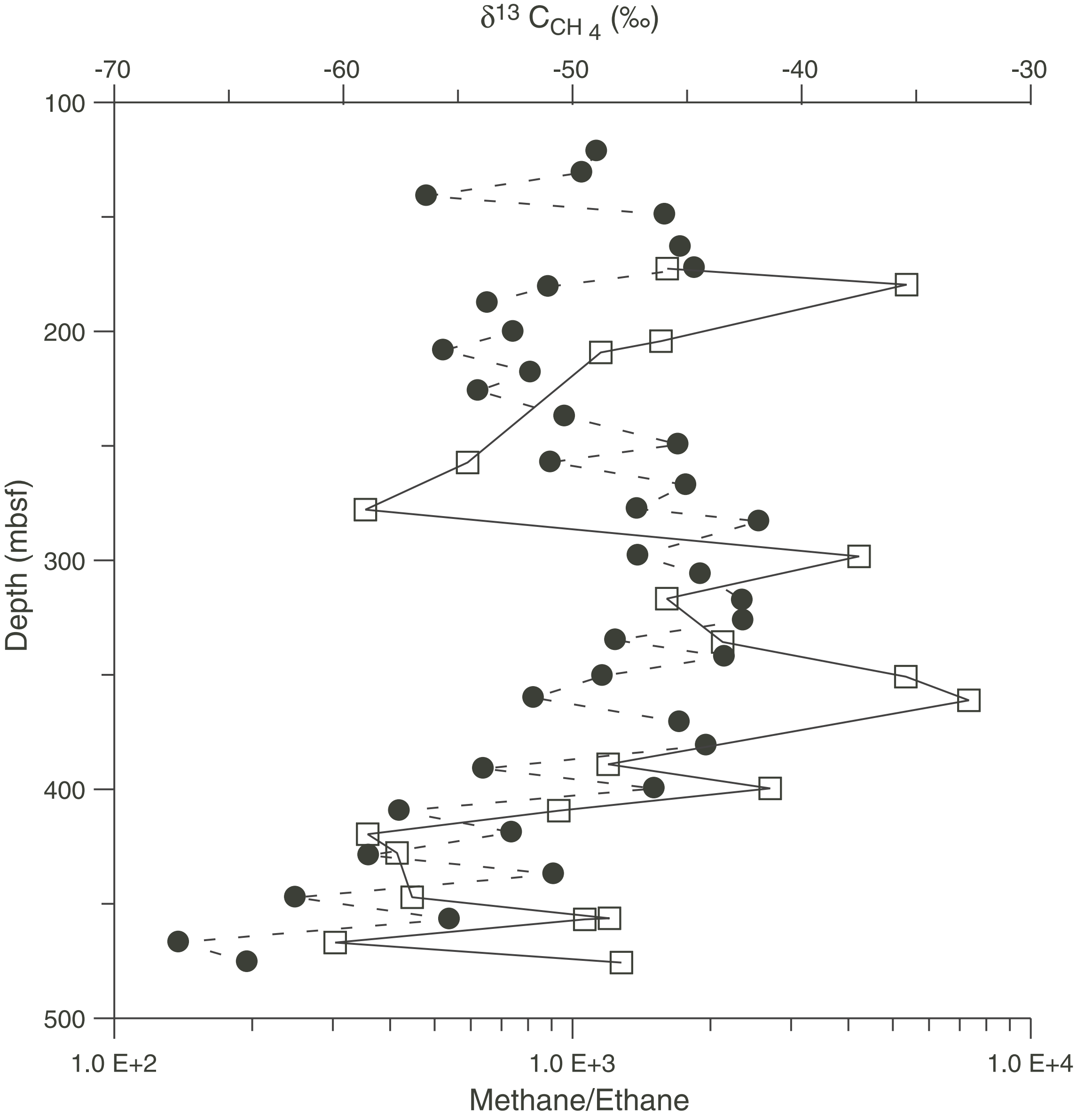

Figure F5. C_{15+} saturated hydrocarbon–fraction gas chromatograms, Site 1109. Pr = pristane, Ph = phytane.

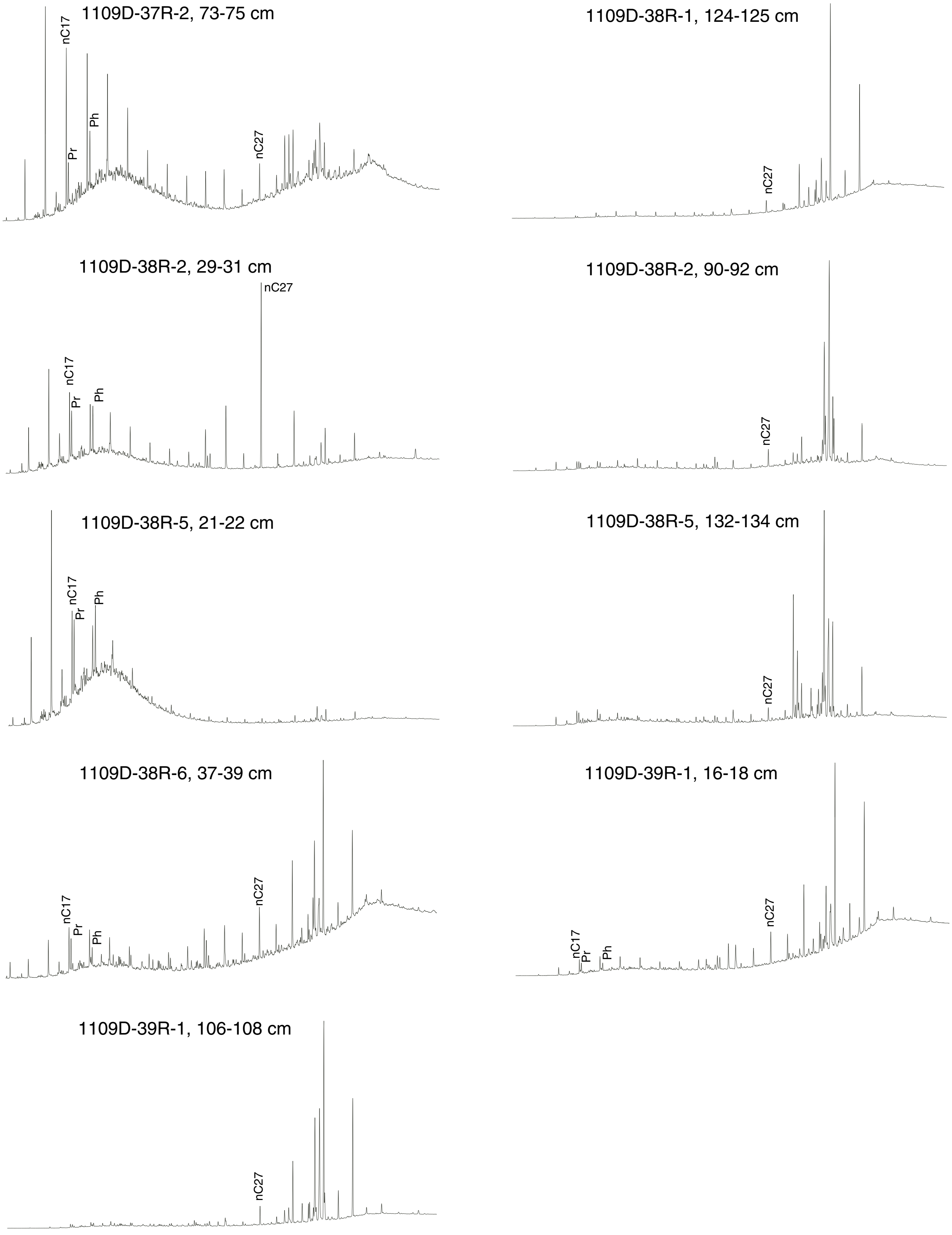

Figure F6. Pyrolysis gas chromatograms, Site 1109. Tol = toluene, Bz_Tm = 1,3,5-trimethylbenzene.

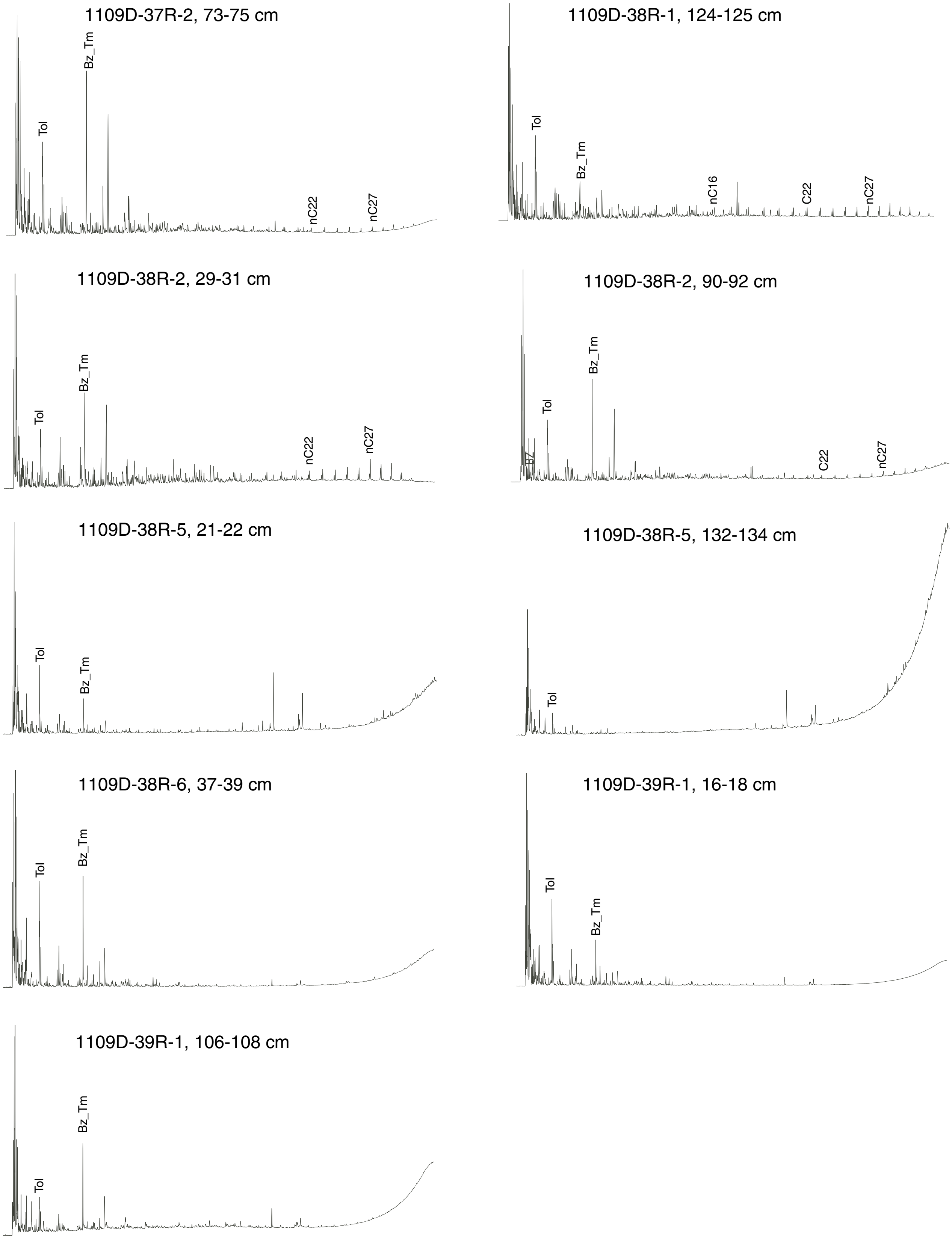

Table T1. Organic carbon and pyrolysis data, Hole 1108B.

Core, section, interval (cm)	Depth (mbsf)	C_{org} (wt%)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI (mg HC/g C_{org})	OI (mg CO_2/g C_{org})
180-1108B-						
19R-5, 30-32	172.60	0.64	0.06	0.18	28	3
20R-2, 10-12	179.60	0.64	0.06	0.19	30	9
22R-5, 124-126	204.24	0.89	0.10	0.27	30	135
23R-2, 86-88	209.16	0.44				
24R-1, 108-110	217.08	0.24				
26R-2, 134-136	238.34	0.81				
28R-3, 21-23	257.21	0.81	0.05	0.28	35	181
30R-4, 31-33	277.81	0.59	0.07	0.14	24	59
32R-5, 32-34	298.32	0.16				
34R-4, 54-56	316.74	0.12				
36R-4, 80-84	335.70	0.55	0.05	0.11	20	195
38R-1, 36-38	350.86	0.74	0.03	0.26	35	4
39R-1, 104-106	361.14	0.71	0.07	0.88	124	82
42R-1, 11-13	389.11	0.85	0.07	0.29	34	196
43R-1, 100-102	399.60	0.44				
44R-1, 117-120	409.37	0.72	0.04	0.21	29	58
45R-CC, 4-6	419.64	0.76	0.04	0.27	36	17
46R-1, 34-35	427.84	0.31				
48R-1, 48-50	447.18	0.25				
49R-1, 4-6	456.34	1.23	0.04	0.43	35	143
49R-CC, 4-6	456.84	0.11				
50R-CC, 4-6	466.94	0.13				
51R-1, 22-24	475.72	1.17	0.05	0.90	73	105

Note: HI = hydrogen index, OI = oxygen index.

Table T2. Organic carbon and pyrolysis data, Hole 1109D.

Core, section, interval (cm)	Depth (mbsf)	C_{org} (wt%)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI (mg HC/g C_{org})	OI (mg CO_2/g C_{org})	TR	T_{max} (°C)
180-1109D-								
37R-2, 73-75	688.23	17.33	1.60	12.61	73	7	0.11	415
38R-1, 124-125	696.84	32.86	5.03	49.69	151	63	0.09	424
38R-2, 29-31	697.21	27.69	11.45	86.92	314	41	0.12	397
38R-2, 90-92	697.90	22.99	1.97	12.38	54	61	0.14	401
38R-5, 21-22	701.51	1.46	0.09	0.75	51	80		
38R-5, 132-134	702.62	1.80	0.10	0.24	13	82		
38R-6, 37-39	703.17	5.66	0.34	1.78	31	71	0.16	403
39R-1, 16-18	705.46	3.31	0.24	1.42	43	72	0.14	414
39R-1, 106-108	706.36	14.07	1.08	7.11	51	68	0.13	399

Note: HI = hydrogen index, OI = oxygen index, TR = transformation ratio, T_{max} = temperature at which maximum pyrolytic hydrocarbon generation occurs.

Table T3. Methane stable carbon isotope composition, Hole 1108B.

Core, section, interval (cm)	Depth (mbsf)	$\delta^{13}C_{CH4}$ (‰)
180-1108B-		
19R-5, 30-32	172.60	–45.87
20R-2, 10-12	179.60	–35.42
22R-5, 124-126	204.24	–46.14
23R-2, 86-88	209.16	–48.77
24R-1, 108-110	217.08	*
26R-2, 134-136	238.34	*
28R-3, 21-23	257.21	–54.58
30R-4, 31-33	277.81	–59.04
32R-5, 32-34	298.32	–37.49
34R-4, 54-56	316.74	–45.89
36R-4, 80-84	335.70	–43.45
38R-1, 36-38	350.86	–35.45
39R-1, 104-106	361.14	–32.70
42R-1, 11-13	389.11	–48.45
43R-1, 100-102	399.60	–41.37
44R-1, 117-120	409.37	–50.60
45R-CC, 4-6	419.64	–58.94
46R-1, 34-35	427.84	–57.66
48R-1, 48-50	447.18	–57.00
49R-1, 4-6	456.34	–48.39
49R-CC, 4-6	456.84	–49.47
50R-CC, 4-6	466.94	–60.36
51R-1, 22-24	475.72	–47.87

Note: * = insufficient gas for isotope analysis.

Table T4. Bitumen yield and bulk composition, Hole 1109D.

Core, section, interval (cm)	Depth (mbsf)	C_{org} (wt%)	TOE (ppm)	Saturates (%)	Aromatics (%)	Resins (%)	Asphaltenes (%)
180-1109D-							
37R-2, 73-75	688.23	17.33	24,117	4.5	5.0	15.8	74.7
38R-1, 124-125	696.84	32.86	22,820	4.2	9.3	18.6	67.8
38R-2, 29-31	697.21	27.69	56,929	1.6	4.9	26.3	67.2
38R-2, 90-92	697.90	22.99	7,982	2.3	7.2	22.3	68.2
38R-5, 21-22	701.51	1.46	899	12.0	14.7	17.3	56.0
38R-5, 132-134	702.62	1.80	1,678	11.8	7.9	18.1	62.2
38R-6, 37-39	703.17	5.66	2,818	1.7	5.1	8.4	84.8
39R-1, 16-18	705.46	3.31	1,309	2.3	12.8	26.7	58.1
39R-1, 106-108	706.36	14.07	4,356	3.2	9.1	20.9	66.8

Note: TOE = total organic extract.