7. PETROLEUM-GENERATING POTENTIAL OF SEDIMENTS FROM LEG 40, DEEP SEA DRILLING PROJECT

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INTRODUCTION AND SUMMARY

Leg 40 of the Deep Sea Drilling Project (DSDP), along the southwestern margin of Africa, recovered numerous cores of sediment containing greater than 1% organic carbon. We have studied several samples from these cores in order to evaluate their petroleum-generating potential. In addition, data on the levels of organic metamorphism of these sediments were used to determine whether any of the sediments have been heated sufficiently to generate petroleum.

The results of this study indicate that many Leg 40 sediments contain sufficient amounts of effective organic carbon (C_{eff}) to be considered potential petroleum source rocks. Probably none of the samples, however, have been buried deeply enough to reach the zone of significant petroleum generation (see Foresman, this volume).

Comparison of effective organic carbon with the total organic carbon indicates that a large fraction of the organic matter in many samples is not thermally convertible to hydrocarbons. Visual observations further indicate that some sediments contain significant amounts of reworked organic matter.

ANALYTICAL METHODS

Organic richness and temperature history are major parameters for identifying petroleum source rocks. The organic richness is an indicator of the petroleum-generating potential of a rock, and therefore organic-rich rocks may be referred to as "potential source rocks." The thermal history determines whether the potential source rock has reached the stage at which petroleum has been generated and expelled, and thus whether it has become an actual source rock.

Probably the most commonly used measure of organic richness is total organic carbon ($\%C_{org}$) which is the acid-insoluble carbon in the sample. In addition, it is important to have a measure of a sample's *effective* organic carbon content (C_{eff}), i.e., that portion of the organic matter which can be converted to petroleum during burial at greater depths and temperatures. As measures of the effective carbon content, we have used two laboratory pyrolysis methods. The first pyrolysis method—pyrolysis fluorescence (PF)—is used primarily as a rapid screening tool which measures the amount of fluorescing bitumen (in arbitrary PF units) formed by pyrolysis. PF values in rocks can range from zero to several thousand units. The second pyrolysis method—pyrolysis-FID (P-FID)—measures the amount of volatile hydrocarbon-like compounds generated in the laboratory temperature range of 300-650°C, and it approximates the amount of hydrocarbons generated at lower temperatures in the subsurface. The effective carbon content of a sample is calculated as 85% of the pyrolysis hydrocarbon content.

To determine whether the sediments had been subjected to temperatures sufficient for the thermal conversion of kerogen to petroleum, we measured the reflectance (in oil) of vitrinite, a coal maceral which is disseminated in many sediments. Vitrinite reflectance provides a measure of the level of organic metamorphism (LOM) (Hood et al., 1975) and is applicable over a wide range of coal rank and conditions during which oil and gas are formed (Figure 1).

A more complete description of the analytical techniques has been given by Hood et al. (1976).

RESULTS AND DISCUSSION

Level of Organic Metamorphism

The results of the vitrinite reflectance measurements are summarized in Table 1. In converting vitrinite reflectance (R_O) to LOM, all R_O values less than ~0.4% were assigned the LOM value <7 because of the difficulty in resolving the LOM 0-7 range by means of vitrinite reflectance. In addition, the effect of lithology on vitrinite reflectance (Bostick and Foster, 1973) raises some questions about the relationship of reflectance to LOM in deep-sea sediments with R_O less than 0.8%-1.0%.

Several of the samples from Leg 40 exhibit a broad distribution of vitrinite reflectance values. The reflectance values for vitrinite in a humic coal commonly fall into a narrow range. The occurrence of broader reflectance distributions in several Leg 40 samples (see comparison in Figure 2) implies that some vitrinite has either been partially oxidized or recycled from older sedimentary units with a prior thermal history. Consequently, the mean value of Ro for core samples with reworked, or secondary, vitrinite will be greater than that for the primary vitrinite. For this reason Table 1 includes two values of R_O and LOM for each sample which appears to contain secondary vitrinite. The "X" value is the mean of all R_O observations for the sample, and it represents a maximum estimate of LOM. The "A" value is an estimate of the mean R_O of primary vitrinite, obtained by omitting sample observations which appear to be attributable to

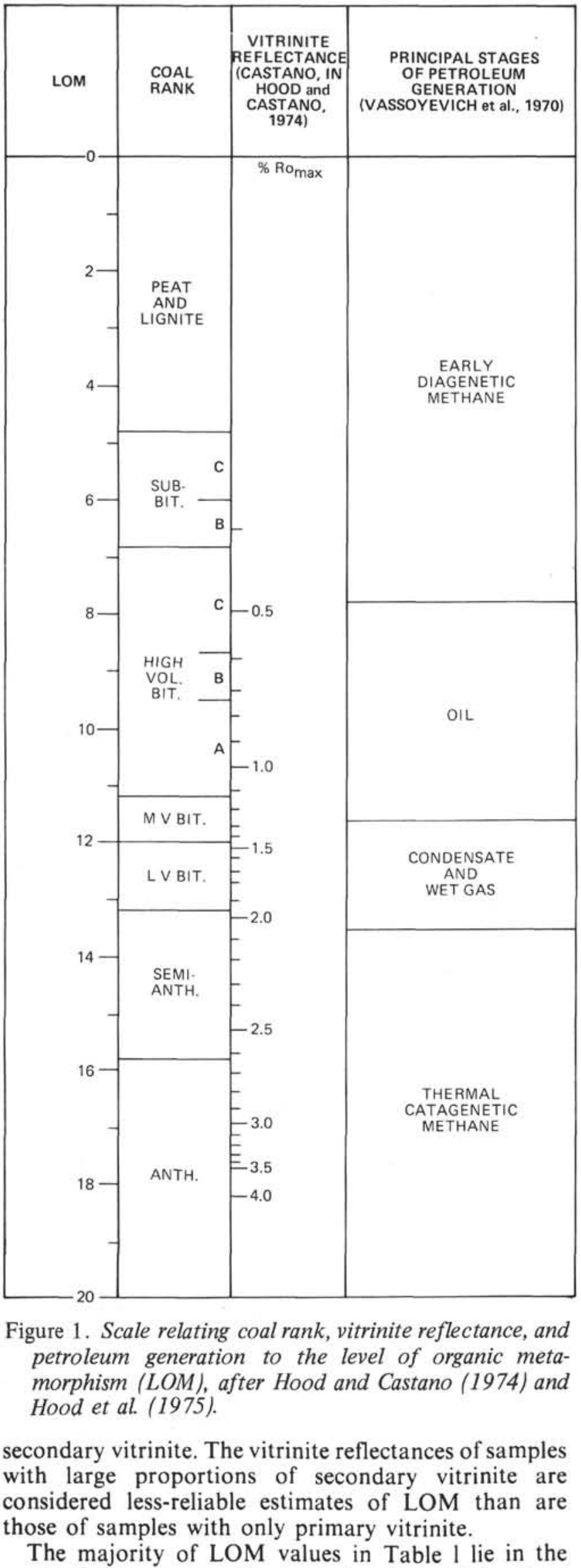

Figure 1. *Scale relating coal rank, vitrinite reflectance, and petroleum generation to the level of organic metamorphism (LOM), after Hood and Castano (1974) and Hood et al. (1975).*

secondary vitrinite. The vitrinite reflectances of samples with large proportions of secondary vitrinite are considered less-reliable estimates of LOM than are those of samples with only primary vitrinite.

The majority of LOM values in Table 1 lie in the range of ≤7 corresponding to coal ranks no higher than subbituminous B. Such samples probably have not been buried sufficiently to reach the LOM (~8) at which significant oil generation begins (Figure 1; Hood et al., 1975; Vassoyevich et al., 1970). Although several samples from Site 361 exhibit LOM values greater than 8, these samples contain large amounts of secondary vitrinite. The interpreted, or "A," values of LOM for Site 361 are in good agreement with the low LOM values from comparable depths in Site 364, implying that the Site 361 sediments have indeed not yet reached the oil-generation stage.

Organic Richness

Numerous values of organic carbon content have been suggested as minimum requirements for potential petroleum source rocks. Ronov (1958) concluded that the critical C_{org} value for source rocks of economic petroleum accumulations lies somewhere between the average values for clays of petroliferous (1.4%) and nonpetroliferous (0.4%) areas of the Russian Platform—and probably closer to the former. This suggests a minimum value of about 1.0% C_{org}. Schrayer and Zarrella (1963) reported a value of about 1.5% C_{org} as a minimum requirement for oil source rocks based on studies of the Mowry Shales of Wyoming. The organic carbon contents of the Leg 40 sediments (Table 2) range from 0.1% to 13.8%. The above criteria indicate that several of these samples are good potential source rocks.

The results of the pyrolysis-FID and pyrolysis fluorescence measurements (Table 2) place an additional constraint on determining which samples should be considered potential source rocks. As a general rule, we do not consider samples with less than 0.3% hydrocarbons (by P-FID) or less than 10 PF units to be potential source rock for economic oil accumulations. Similarly, samples with less than 0.8% hydrocarbons or less than 30 PF units are considered to be marginal source rocks at best. While generally there is good agreement between organic carbon and pyrolysis-FID in the evaluation of source rock potential, there are some exceptions. For example, Samples 361-36-3, 140-150 cm and 365-1-5, 130-133 cm contain about 2% C_{org}, but less than 0.3% hydrocarbons, implying that a large fraction of the organic material in these samples is not thermally convertible to petroleum. Consequently, some samples with moderate amounts of organic carbon may not contain sufficient amounts of reactive organic matter to be considered potential petroleum source rocks.

A comparison of effective carbon with organic carbon provides information about the composition and nature of the organic matter. Tissot et al. (1974) have demonstrated that differences in the elemental composition (especially hydrogen and oxygen contents) of the kerogen strongly influence the amounts of petroleum produced during heating. The graph of effective carbon versus organic carbon (Figure 3) suggests that consistent compositional differences exist between sediments from different sites. In particular, the sediments at Site 362 contain greater amounts of effective carbon per unit of organic carbon than do the

TABLE 1
Vitrinite Reflectance and Level of Organic Metamorphism

Sample (Interval in cm)	Depth Below Sea Floor (m)	Age	-[a]	Vitrinite Reflectance (in Oil)			
				No. of Observations	Range of $\%R_o$	Mean $\%R_o$ [b]	LOM[c]
Site 361							
23-3, 143-150	768	Cretaceous?	A	23	0.29-0.52	0.44 ±0.03	7
			X	66	0.29-0.91	0.61 ±0.04	9
25-3, 140-150	863	Cretaceous		0	Barren		
27-3, 140-150	958	Albian-Aptian	A	12	0.29-0.53	0.44 ±0.05	7
			X	54	0.29-1.00	0.66 ±0.05	9
29-5, 140-150	1037	Aptian?	A	33	0.27-0.60	0.47 ±0.04	7.5
			X	55	0.27-0.87	0.57 ±0.04	8.5
31-2, 144-150	1051	L. Aptian?	A	48	0.21-0.58	0.40 ±0.03	<7
			X	50	0.21-0.68	0.41 ±0.04	7
34-4, 134-136	1082	L. Aptian	A	26	0.33-0.55	0.47 ±0.03	7.5
			X	60	0.33-1.04	0.62 ±0.05	9
36-3, 140-150	1099	L. Cretaceous	A	17	0.16-0.52	0.42 ±0.04	7
			X	54	0.26-0.93	0.64 ±0.05	9
38-2, 130-133	1117	L. Aptian?	A	26	0.24-0.52	0.40 ±0.04	<7
			X	54	0.24-0.95	0.53 ±0.05	8
40-3, 130-138	1147	–	A	37	0.31-0.60	0.46 ±0.04	7.5
			X	62	0.25-1.02	0.57 ±0.05	8.5
42-0, 11-13	1181	–	A	27	0.30-0.57	0.46 ±0.04	7.5
			X	59	0.25-0.95	0.59 ±0.05	8.5
44-3, 137-144	1223	–	A	41	0.32-0.64	0.47 ±0.04	7.5
			X	60	0.26-0.89	0.55 ±0.05	8.5
Site 362							
3-4, 130-140	61	Pleistocene		13	0.20-0.35	0.26 ±0.03	<7
5-4, 130-135	80	Pleistocene		17	0.15-0.36	0.24 ±0.03	<7
7-5, 145-150	91	Pleistocene		21	0.17-0.34	0.23 ±0.02	<7
9-5, 144-150	120	Pleistocene		19	0.18-0.40	0.27 ±0.04	<7
11-5, 130-135	138	L. Pliocene	A	17	0.19-0.45	0.31 ±0.05	<7
			X	18	0.19-0.53	0.32 ±0.05	<7
13-4, 130-140	156	L. Pliocene		6	0.23-0.47	0.33 ±0.11	N.D.[d]
15-5, 130-150	186	U. Miocene	A	5	0.23-0.47	0.36 ±0.13	N.D.
			X	6	0.23-0.62	0.41 ±0.15	N.D.
19-5, 130-136	262	U. Miocene	A	19	0.23-0.51	0.40 ±0.04	<7
			X	26	0.23-0.70	0.46 ±0.05	
25-5, 142-150	376	U. Miocene	A	10	0.22-0.53	0.35 ±0.08	<7
			X	14	0.22-0.85	0.45 ±0.11	N.D.
Site 363							
30-5, 130-136	523	U. Albian	A	7	0.40-0.45	0.42 ±0.02	7
			X	30	0.40-0.99	0.65 ±0.07	9
34-2, 142-150	595	Albian-Aptian		9	0.66-1.18	0.98 ±0.13	N.D.
Site 364							
20-3, 130-136	582	Coniacian	A	7	0.27-0.45	0.33 ±0.06	<7
			X	33	0.27-1.01	0.66 ±0.08	9
22-2, 120-123	618	Turonian		9	0.68-1.25	0.89 ±0.15	N.D.
39-5, 145-150	975	Albian-Aptian	A	20	0.23-0.36	0.28 ±0.02	<7
			X	24	0.23-0.70	0.34 ±0.06	<7
41-3, 144-150	1010	Albian-Aptian	A	18	0.23-0.48	0.32 ±0.04	<7
			X	19	0.23-0.69	0.34 ±0.06	<7
43-1, 130-133	1035	–		3	0.20-0.26	0.24 ±0.08	<7
Site 365							
1-5, 130-133	233	Miocene w/ reworked Cret.		24	0.22-0.53	0.32 ±0.04	<7
3-1, 130-135	397	Miocene w/ reworked Cret.		17	0.19-0.53	0.35 ±0.06	<7

[a] "X" represents the entire range of vitrinite observations; "A" represents the interpreted range of primary vitrinite observations. Where "A" and "X" are not noted, they are the same.

[b] $\%R_o \pm 95\%$ confidence limit.

[c] All R_o *values less than 0.4% are assigned LOM<7* because of the difficulty of resolving the LOM 0-7 range by means of vitrinite reflectance. R_o values <0.4% are converted to LOM on the basis of Castaño's R_o-LOM relationship (Hood and Castaño, 1974).

[d] N.D. - Not determined, because variance of data was too great.

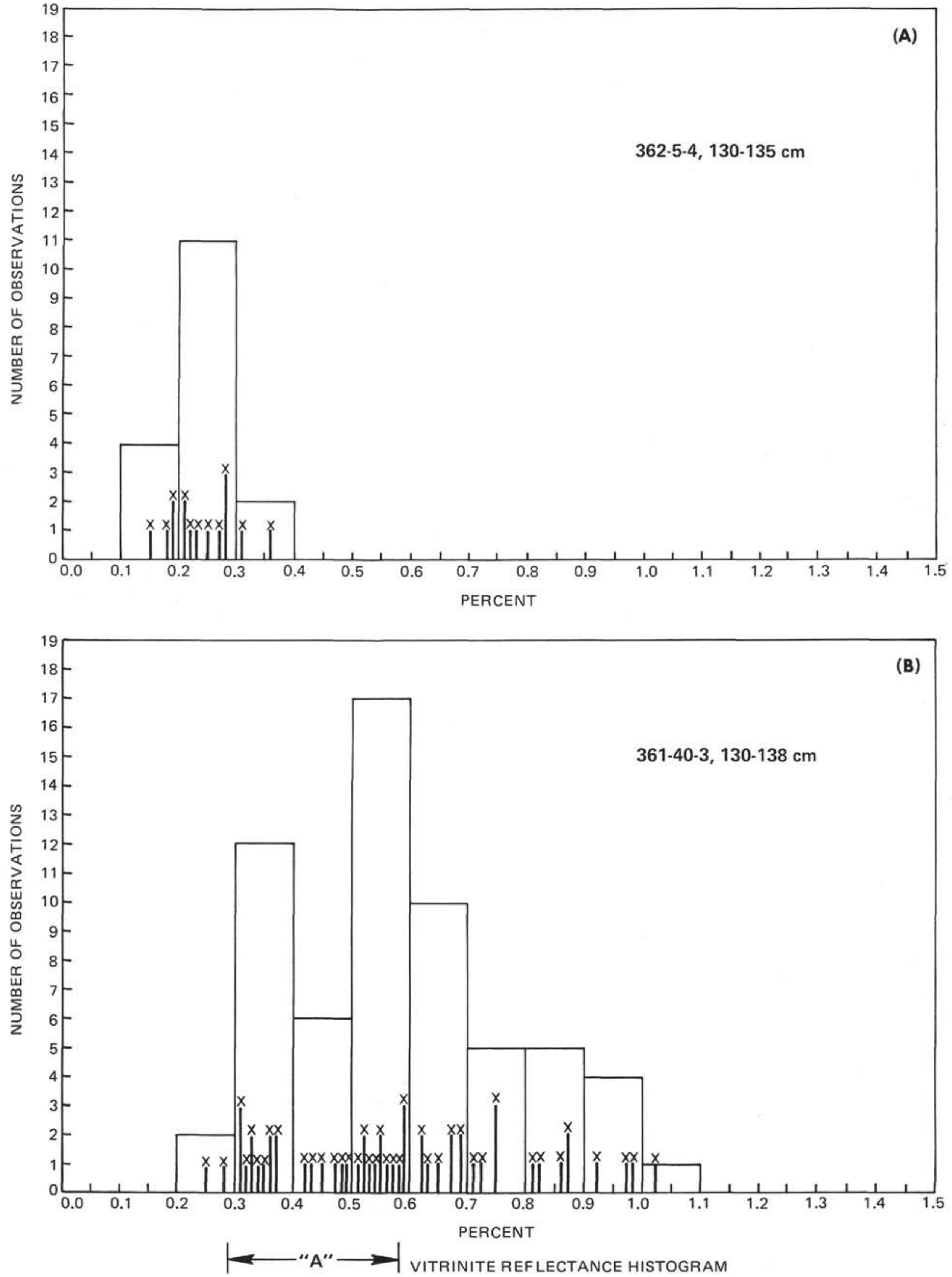

Figure 2. *Histograms of vitrinite reflectance for samples with (A) primary vitrinite (362-5-4, 130-132 cm); (B) primary and secondary vitrinite (361-40-3, 130-138 cm). "A" denotes the range of interpreted primary reflectance values.*

TABLE 2
Organic Richness

Sample (Interval in cm)	% C_{org}	PF	% HC from P-FID (300-650°C)	% C_{eff} (% HC × 0.85)
Site 361				
23-3, 143-150	0.86	0	0.02	0.01
25-3, 140-150	0.25	5	0.00	0.00
27-3, 140-150	0.67	4	0.09	0.08
29-5, 140-150	4.23	83	0.85	0.73
31-2, 144-150	2.68	350	0.47	0.40
34-4, 134-136	1.76	28	0.37	0.31
36-3, 140-150	1.88	4	0.21	0.18
38-2, 130-133	3.54	19	0.39	0.33
40-3, 130-138	0.95	2	0.22	0.19
42-0, 11-13	3.88	240	0.92	0.78
44-3, 137-144	2.80	32	0.29	0.25
Site 362				
3-4, 130-135	3.57	210	1.58	1.35
5-4, 130-135	3.75	240	1.89	1.61
7-5, 145-150	2.33	120	1.44	1.22
9-5, 144-150	3.35	180	1.09	0.93
11-5, 130-135	2.44	150	0.70	0.60
13-4, 130-140	2.46	120	0.80	0.68
15-5, 130-150	2.35	98	0.57	0.48
19-5, 130-136	1.06	10	0.20	0.17
25-5, 142-150	0.70	2	0.14	0.12
Site 363				
30-5, 130-136	0.14	2	0.00	0.00
34-2, 142-150	0.19	2	0.00	0.00
Site 364				
20-3, 130-136	0.10	1	0.02	0.02
22-2, 120-123	0.10	3	0.00	0.00
39-5, 145-150	1.58	120	0.31	0.26
41-3, 144-150	6.12	240	1.70	1.44
43-1, 130-133	13.8	1500	11.0	9.35
Site 365				
1-5, 130-133	2.48	9	0.28	0.24
3-1, 130-135	8.56	300	4.305	3.66

TABLE 3
Relative Abundance of Types of Organic Matter
by Visual Kerogen Analysis

Sample (Interval in cm)	Amorphous	Exinitic	Primary Humic	Reworked Humic and Inert
Site 361				
23-3, 143-150	6	2	2	5
25-3, 140-150	1	1	1	1
27-3, 140-150	6	2	2	5
29-5, 140-150	5	2	3	5
31-2, 144-150	6	2	4	5
34-4, 134-136	6	2	4	5
36-3, 140-150	6	2	2	5
38-2, 130-133	6	2	4	4
40-3, 130-138	5	2	3	5
42-0, 11-13	6	2	4	5
44-3, 137-144	6	2	4	4
Site 362				
3-4, 130-140	7	2	2	2
5-4, 130-135	7	2	2	2
7-5, 145-150	7	2	2	2
9-5, 144-150	7	2	2	1
11-5, 130-135	7	2	2	2
13-4, 130-140	7	2	2	2
15-5, 130-150	7	2	2	2
19-5, 130-136	7	1	1	3
25-5, 142-150	7	1	1	1
Site 363				
30-5, 130-136	1	1	6	6
34-2, 142-150	1	1	6	6
Site 364				
20-3, 130-136	1	1	4	7
22-2, 120-123	1	1	1	7
39-5, 145-150	7	2	2	1
41-3, 144-150	7	2	2	1
43-1, 130-133	7	1	5	1
Site 365				
1-5, 130-133	1	2	6	5
3-1, 130-135	7	1	2	2

Note: Numerical abundance scale and percentages (by area): 1=0-1%; 2=2-5%; 3=6-10%; 4=11-25%; 5=26-50%; 6=51-75%; 7=76-100%.

sediments at Site 361, implying that the organic matter at Site 361 contains a greater percentage of either oxygenated carbon compounds or recycled, thermally less reactive organic matter.

During the measurement of vitrinite reflectance, we made visual estimates of the types of organic matter in the sediments (Table 3). From these qualitative visual estimates, it is apparent that the samples from Site 362 contain relatively large amounts of amorphous (generally hydrogen-rich) organic matter, whereas the samples from Site 361 contain significant amounts of humic material as well as some amorphous organic matter. The greater proportions of humic matter in the kerogens of Site 361 sediments help to explain their lower values of effective carbon per unit of organic carbon.

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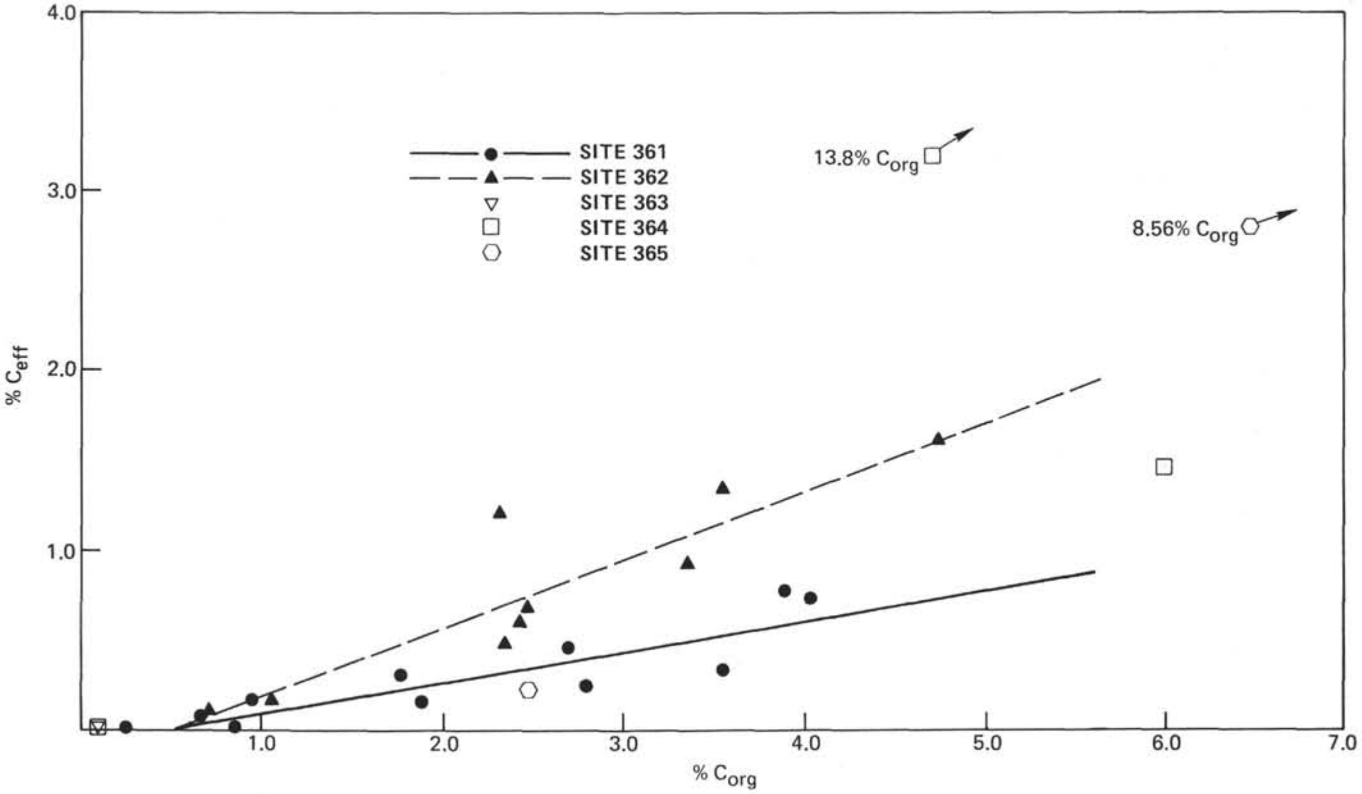

Figure 3. *Graph of effective organic carbon (C_{eff}) versus total organic carbon (C_{org}).*