



## Source rock/dispersed organic matter characterization—TSOP Research Subcommittee Results

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**Abstract**—Because sedimentary organic matter consists of a diverse mixture of organic components with different properties, a combination of chemical and petrographic results offers the most complete assessment of source rock properties. The primary purpose of this Society for Organic Petrology (TSOP) subcommittee is to contribute to the standardization of kerogen characterization methods. Specific objectives include: (1) evaluation of the applications of different organic matter (petrographic) classifications and terminology, and (2) integration of petrographic and geochemical results. These objectives were met by completing questionnaires, and petrographic, geochemical and photomicrograph round-robin exercises. Samples that were selected for this study represent different petrographic and geochemical properties, and geologic settings to help identify issues related to the utilization of different classifications and techniques. Petrographic analysis of the organic matter was completed using both a prescribed classification and the individual classification normally used by each participant. Total organic carbon (TOC), Rock-Eval pyrolysis and elemental analysis were also completed for each sample. Significant differences exist in the petrographic results from both the prescribed and individual classifications. Although there is general agreement about the oil- vs gas-prone nature of the samples, comparison of results from individual classifications is difficult due to the variety of nomenclature and methods used to describe an organic matter assemblage. Results from the photomicrograph exercise document that different terminology is being used to describe the same component. Although variation in TOC and Rock-Eval data exists, geochemical results define kerogen type and generative potential. Recommendations from this study include:

- (1) A uniform organic matter classification must be employed, which eliminates complex terminology and is capable of direct correlation with geochemical parameters.
- (2) A standardized definition and nomenclature must be used for the unstructured (amorphous) organic matter category. Subdivisions of this generalized amorphous category are needed to define its chemical and environmental properties.
- (3) Standardized techniques including multimode illumination, types of sample preparations and data reporting will help eliminate variability in the type and amount of organic components reported.

**Key words**—organic petrology, organic matter classification, maceral, amorphous, multimode illumination, petrographic and geochemical integration, kerogen, source rock

### INTRODUCTION AND BACKGROUND

Effective petrographic identification of individual constituents in sedimentary organic matter can describe source rock properties, provide insight into depositional conditions, and define thermal maturity. Petrographically, dispersed organic matter is generally divided into structured and unstructured components. Structured organic matter includes the liptinite, vitrinite, and inertinite macerals, and zooclasts (faunal remains), which are well understood. Because unstructured or amorphous organic

matter originates from a variety of precursors and processes, it varies in petrographic, physical, and chemical properties. The chemical composition of amorphous material can vary from hydrogen-rich to hydrogen-poor for a given thermal maturity (Tissot and Welte, 1984). Petrographic identification and characterization of unstructured organic matter is important because it is a major component of most hydrocarbon source rocks. However, grouping unstructured organic matter into a single generalized category prevents interpretation of its hydrocarbon generative potential and paleoenvironmental

properties. Numerous terms have been used to describe "unstructured" organic matter, which contributes to confusion in the characterization of this material. Clearly defined and well accepted terminology is essential for the effective description and characterization of unstructured organic matter.

Sedimentary organic matter consists of material insoluble in normal organic solvents (kerogen) and a soluble fraction (bitumen). Chemically, kerogen is classified into types I, II, III and IV (Tissot *et al.*, 1974; Harwood, 1977) based on elemental analysis (atomic H/C and O/C). Rock-Eval pyrolysis, which can be used to infer kerogen types, has become a standard method for the chemical evaluation of source rocks. Because a specific kerogen type often consists of a diverse mixture of chemically distinct organic components that react differently during maturation, a combination of chemical and petrographic results offer the most complete assessment of source rock properties. Therefore, it is important for organic petrographic results to complement and correlate with geochemical data and geological results. Previous studies have documented the application and importance of this integrated approach (Jones and Edison, 1978; Larter, 1985; Thompson and Dembicki, 1986).

Organic petrology applied to source rock evaluation has evolved from both coal petrology and palynology. Because of the many approaches and goals of organic petrology, a wide variety of techniques and classifications are used. Powell *et al.* (1982) indicated that the following factors often contribute to a poor correlation between optical and chemical results: unrepresentative kerogen concentrates, inadequate definition of amorphous kerogen and inadequate quantitative estimation of organic matter components. Effective utilization of organic petrology to characterize dispersed organic matter will require a uniform approach. An organic matter classification and its corresponding applications must have a strong scientific basis and provide: (1) acceptable limits of reproducibility for inter- and intra-laboratory results, (2) timely and cost efficient results, (3) data that can be applied by both organic petrologists and other earth scientists, (4) answers to industrial and academic problems, and (5) support of geochemical techniques by an integrated and comparative approach.

At the 1987 annual meeting of The Society for Organic Petrology (TSOP), a research subcommittee was formed to review problems related to the integration of organic petrographic data with geologic and geochemical data. An initial TSOP study "Influence of Kerogen Isolation Methods on Petrographic and Bulk Chemical Composition Of A Woodford Shale Sample" was completed by Senftle (1989).

#### OBJECTIVES

##### *TSOP Research Subcommittee*

The overall purpose of this subcommittee is to contribute to the standardization of kerogen

characterization methods. Primary objectives of this subcommittee include: (1) evaluation of the applications of different organic matter (petrographic) classifications and terminology, and (2) integration of petrographic and geochemical results. Secondary objectives include evaluation of: (1) techniques for petrographic analysis (light modes, types of sample preparations, etc.), (2) kerogen isolation procedures and (3) methods of sample preparation. There is an urgent need to meet these objectives to provide a standardized and usable system of organic petrographic results.

This TSOP subcommittee will complement International Committee for Coal Petrology (ICCP) objectives for the standardization of kerogen characterization methods. ICCP working groups on related subjects include isolation of organic matter and organic matter classifications.

##### *Present TSOP study*

Specific objectives for this study include:

- (1) Circulation of a questionnaire to compile and understand petrographic and geochemical methods of kerogen characterization.
- (2) Petrographic and geochemical round-robin analysis of four samples to evaluate: (1) application of various organic matter terminology and classifications, (2) different petrographic techniques to characterize dispersed organic matter, and (3) geochemical techniques for evaluating kerogen quality.
- (3) Round-robin description of photomicrographs of the four samples to directly compare nomenclature and properties used to define specific organic components.

Results of this study will contribute to identifying and standardizing methods to characterize dispersed organic matter, and integrate petrographic and geochemical results. Although different methods of kerogen isolation lead to discrepancies in petrographic and geochemical results, standardization of preparation procedures was not a primary objective of this specific study.

#### SAMPLES AND PROCEDURES

This specific study involves eight subcommittee members representing industrial, government and academic groups. Participants are a mix of European and North American organic petrologists and geochemists. All individuals or laboratory groups that were committed to completing the petrographic and geochemical analyses in the given time were invited to participate. Identification of participant results has been kept confidential to ensure objectivity and encourage participation by all laboratories.

Four thermally immature samples were selected for the round robin study. The samples contain various mixtures of oil-prone, gas-prone and inert organic

Table 1. Sample name, location, and geologic information

Sample No.	1	2	3	4*
Group	Wilcox			Mesa Verde
Formation		Monterey	Ohio Shale	Tropic Shale
Member			Cleveland	
Lithology	Shale	Shale	Shale	Coal
Age	Eocene	Miocene	Miss./Dev.	Cretaceous
Location	Hallsville, TX	Arroyo, CA	Lewis Co., KY	Kane Co., UT
Site	Sabine mine	Outcrop†	Outcrop†	Underground mine

\*Penn State Coal Sample Bank (PSOC No. 1109).

†Outcrop samples contain only minor weathering, which does not affect study objectives.

matter that represent different depositional conditions, geologic age, and wt% total organic carbon (TOC). These samples have a wide range of petrographic and geochemical properties, which help identify issues and questions related to different classifications, techniques, and sample types. Some of these samples were selected because of their difficult petrographic characteristics. Each participating laboratory was provided with representative splits consisting of 5–10 g of unprocessed rock. Sample names, locations and geologic information are listed in Table 1.

Each laboratory completed kerogen isolation and sample preparation using their normal procedures. A maceral or visual kerogen analysis was requested using both a prescribed classification and the individual classification normally used by each participant. The prescribed classification includes the following categories: amorphous, structured liptinite, vitrinite, inertinite, and other (solid bitumen, zooclasts, etc.), which is generally similar to proposed categories by the ICCP. Subdivisions of the prescribed categories were encouraged. Each participant completed a maceral analysis using their own petrographic techniques but were asked to provide: (1) descriptions of sample preparation procedures, (2) types of light modes and sample preparations used, and (3) presentation of results using their typical format (maceral percentages or description).

Participants were asked to complete wt% TOC and Rock-Eval pyrolysis to geochemically evaluate each sample. However, not all participants had access to geochemical instrumentation. Each laboratory was encouraged to conduct other geochemical analyses if possible.

In addition, sample splits were sent to various commercial laboratories for wt% TOC, Rock-Eval pyrolysis (whole rock and kerogen) and elemental analyses (atomic H/C and O/C). Kerogen isolation for these analyses was completed at a single locality to eliminate variables related to processing. Although samples were sent to commercial laboratories, contractor evaluation was not an objective of this study.

Photomicrographs illustrating specific organic components from the four samples were distributed to determine: (1) nomenclature used by each participant to describe specific organic component(s), and (2) how a specific component fits into their classification. Photomicrographs represent both whole rock

and isolated kerogen preparations (strew mounts and reflectance preparations). Input was also solicited concerning: (1) other terminology that can describe the component, (2) application of certain sample preparations, preparation techniques or light modes to effectively identify the component, and (3) hydrocarbon potential or environmental significance of an individual component.

## RESULTS AND DISCUSSION

### Questionnaire summary

A summary of questionnaire results indicates:

- (1) The primary objectives of petrographic evaluation of dispersed sedimentary organic matter are to define thermal maturity and kerogen quality/hydrocarbon generative potential. Geologic information is secondary. Geochemists and geologists are the main users of organic petrographic data.
- (2) Most laboratories use both geochemical and petrographic techniques to evaluate kerogen quality. Geochemical results are often used more extensively, and used to select samples for petrographic analyses. Most laboratories compare or integrate petrographic and geochemical results in some manner.
- (3) For petrographic analysis, most laboratories use a variety of sample preparations and light modes but with different priorities. Results are often combined, depending on the specific sample. Petrographic results are usually reported to the nearest 1–5% (of the total organic matter assemblage in the sample preparation) and incorporated into a computerized data base. Maceral groups are often subdivided for different applications. Most laboratories formally or informally subdivide “amorphous organic matter” using different petrographic properties.

### Maceral analysis

The prescribed classification was used to directly compare results of individual participants. Although significant differences exist, most laboratories distinguished amorphous-rich samples from those consisting of a mixture of amorphous and structured components. Results for the maceral analysis using

Table 2. Maceral results for TSOP samples—prescribed classification

Sample name/No.	Lab. No.	Maceral percent				
		Amorphous	Structured liptinite	Vitrinite	Inertinite	Other
Wilcox Fm Sample 1	1	35	5	60	<1	
	2	35	15	30	20	
	3	75	15	10	Trace	
	4	15	0	85	Minor	
	7	40	30	30	0	
Monterey Sample 2	1	90	<5	5	1	
	2	90	5	2	3	
	3	92	5	3	Trace	
	4	100	Minor	Minor	Trace	
	7	95	5	Trace	0	
Ohio Shale Sample 3	1	65	10	15	15	Trace solid bitumen
	2	90	0	2	8	
	3	77	10	8	5	
	4	70	20	Minor	10	
	7	80	10	10	Trace	Trace solid bitumen
Mesa Verde Sample 4	1	65	5	20	10	
	2	35	30	10	25	
	3	70.8	4.8	10.2	14.2	
	4	95	Minor	5	Minor	
	7	60	15	25	0	

Note: Not all participants provided data for prescribed classification.

the prescribed classification are listed in Table 2. Good agreement exists for the Monterey sample, which contains predominantly amorphous organic matter. Results for the other three samples, however, display differences in the relative proportions of the amorphous and structured categories. Unfortunately, not all laboratories reported results for the prescribed classification.

Differences in reported amounts of vitrinite and inertinite for individual samples are related to: (1) the exclusive use of transmitted or reflected light, (2) type of sample preparation utilized, and (3) petrographic properties used to distinguish the two macerals. Variation in structured liptinite content for individual samples is related to different definitions used by various laboratories, and the light mode and type of sample preparation used.

The absence of a standardized definition for the amorphous category contributes to discrepancies in maceral results. For the Wilcox sample, the gradational nature of the amorphous-structured vitrinite contributes to the variation in the reported amorphous content. For the Mesa Verde sample, poor distinction between alginite and amorphous components, and the bituminite-amorphous terminology contribute to variation in maceral results.

Results of individual classifications shown in Table 3 generally identify the oil-prone nature of the Monterey, Ohio Shale and Mesa Verde samples, and the gas-prone Wilcox assemblage. However, close comparison of results from individual classifications is difficult due to the wide variety of nomenclature and categories used to describe an organic matter assemblage. Comparison is also difficult because both numerical and descriptive terms are used to report maceral content. Numerous terms

were used in this exercise to describe unstructured organic matter: amorphous, sapropel, sapropelites, alginite, bituminite, SOM (structureless organic matter and sedimentary organic matter), liptinite, amorphogen, organo-mineral matrices, and herbaceous. Individual classifications are shown in Appendix 1.

Although each laboratory may be internally consistent and capable of interpreting their results, the large intra-laboratory variation makes interpretation of individual results difficult. Much of this variability is related to the method and classification used to define maceral composition. For the prescribed and individual classifications, inconsistent results are related to: (1) absence of uniform guidelines in classifying organic matter, (2) variation in terminology used to describe organic components, especially amorphous material and (3) different light modes and types of sample preparations used to petrographically evaluate the organic matter.

A uniform classification and terminology will contribute to eliminating discrepancies in identifying the type of structured organic components and evaluation of amorphous material. Numerical determination of the relative abundance of organic matter components would contribute to effective comparison of laboratory results.

Multimode illumination using different types of sample preparations improves the ability to consistently distinguish and classify individual organic components. Different sample preparations and microscopic techniques have advantages and disadvantages, which are often sample dependent. Many of these techniques are complementary to each other and should be integrated when evaluating and classifying dispersed organic matter.

Table 3. Maceral composition/visual kerogen results based on individual classifications

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w
Sample 1																							
Lab 1				35							5							60					<1
2											15	35						30					20
3		75									15							10					Z
4									15									85					Z
5													Y	Z	Z	Z			X				
6											Z							X				Z	Z
7				40													30	20			10		
Sample 2																							
Lab 1			90								<5							5					1
2												5	90					2					3
3		92									5							3					Z
4									100									Z					Z
5													X			X							
6									X		Z		X									Z	
7				94													5	1					
Sample 3																							
Lab 1			65								10							15				15	Z
2													90					2				8	
3		77									10							8				5	
4									100									Z					Z
5													Y	X	X	X				Z			Z
6											X		X									Z	
7				78													10	10				1	1
Sample 4																							
Lab 1			65								5							20					10
2												30	35					10					25
3																		10.2					14.2
4									95									5					Z
5													X	Z						Y	Z		
6													Z									Z	
7				30			30										15	15			10		

a, amorphous, unspecified; b, amorphous group 1; c, amorphous group 2; d, amorphous group 3; e, amorphous A; f, amorphous B; g, amorphous C; h, amorphous D; i, sapropel; j, bituminite; k, structured liptinite; l, exinite; m, alginite; n, resinite; o, sporinite; p, SOM; q, herbaceous; r, vitrinite/huminite; s, telocollinite; t, desmocollinite; u, woody; v, inertinite; w, bitumen/exsudate; x, abundant/frequent; y, common; z, rare/minor/present/trace.

### Photomicrographs

Results from the photomicrograph exercise indicate that different terminology is being used to describe the same component. Although differences in terminology can sometimes be understood, it often leads to discrepancies and confusion. Issues that became evident from this exercise include:

- (1) The distinction between vitrinite and inertinite is subjective when using only transmitted light. The opaque nature of these macerals can be related to composition and/or particle thickness.
- (2) It is difficult to consistently distinguish between amorphous and structured vitrinite in samples containing "degraded" vitrinite (Wilcox Fm) or "dense consolidated" amorphous material (Ohio Shale).
- (3) Multimode illumination (transmitted, reflected and fluorescence) and utilization of a variety of sample preparations are important to identify and classify organic matter.
- (4) There needs to be a better correlation and standardization of terms when different light modes and sample preparations are used.
- (5) A consistent application of nomenclature needs to be established to describe fluorescent particles that do not display distinct morphology.

- (6) Elimination or replacement of the term herbaceous should be considered, or a clear definition of the term and its correlation to other terminology needs to be established.
- (7) Organic petrologists are not always comfortable working with both isolated kerogen and whole rock sample preparations.
- (8) A better correlation needs to be developed between the identification and characterization of unstructured organic matter in isolated kerogen preparations and whole rock.
- (9) There is difficulty in identifying and classifying unstructured organic matter in reflected light preparations of isolated organic matter.

Representative photomicrographs of the round robin analysis, which illustrate specific organic components and corresponding issues, are shown in Plate 1.

### Nomenclature—unstructured organic matter

A clearly defined and well accepted term is essential for the effective application of organic petrology in characterizing unstructured organic matter. Although a large number of terms exist, many authors from both petrographic and geochemical backgrounds use the amorphous term in classifications and descriptions of sedimentary organic

matter (Combaz, 1964, 1974, 1975, 1980; Burgess, 1974; Raynaud and Robert, 1976; Batten, 1977; Fisher, 1977; Hunt, 1979; Durand and Nicaise, 1980; Alpern, 1980; Robert, 1981; Gutjahr, 1983; Tissot and Welte, 1984; Suzuki, 1984; Mukhopadhyay *et al.*, 1985; Thompson and Dembicki, 1986; Teichmuller, 1986; Senftle *et al.*, 1987). The term amorphinite was defined by van Gijzel (1982) and has been proposed by the ICCP to describe the group of material which exhibits no discrete form or shape.

Other terms used to describe amorphous organic matter sometimes erroneously imply that the material has an algal origin and is always oil-prone. Although confusion exists, alginite has been defined by the ICCP (1976) as a structured component consisting of specific recognizable algal remains (*Botryococcus*, *Tasmanites*, *Gloeocapsamorpha prisca*, etc.). Therefore, alginite is separated from amorphous material, which lacks distinctive morphology and originates from various precursors. Many other terms describing amorphous material subjectively interpret its origin and are confusing to non-experts.

Another term used to describe unstructured organic matter is bituminite. Bituminite, originally described by Teichmuller (1974) in coals, was accepted as a component of primary sedimentary organic matter by the ICCP in 1988. It exhibits no specific form but often occurs as a fine-grained groundmass, irregular laminae or pod-like masses. Teichmuller (1986) states that bituminite represents a bacterial decompositional product of algae and plankton with input of bacterial biomass. Subdivisions of bituminite have been described by Teichmuller and Ottenjann (1977) and Creaney (1980), which suggest a variety of precursors, pres-

ervational conditions and chemical properties similar to amorphous organic matter. There is an important need to standardize terminology for unstructured organic matter, including the bituminite-amorphous terms.

In mature and post-mature source rocks, bitumen (a secondary material) can be an important component that can have an amorphous appearance (Jacob, 1989; Alpern *et al.*, 1992, 1993). This material, which has a wide range of petrographic and geochemical properties, needs to be distinguished from structured and amorphous components. The classification and interpretation of this component can have important implications to source rock studies.

#### *Geochemical analyses*

Rock-Eval pyrolysis and wt% TOC were completed by six participants and three commercial laboratories. The Monterey, Ohio Shale, and Mesa Verde Coal appear to consist of a Type II kerogen; the Wilcox is a Type III kerogen. Rock-Eval Hydrogen Index and Oxygen Index (HI-OI) results for the four samples are displayed on a modified van Krevelen diagram in Fig. 1. Differences in the S2/S3 are helpful in separating oil-prone assemblages (>5) from the gas-prone Wilcox sample. Rock-Eval S2 values help define generative potential of these samples.

HI results from individual laboratories generally show good agreement for characterizing these four samples. Although variation in HI-OI values >100 mg HC/g OC and 50 mg CO<sub>2</sub>/g OC exist respectively for a single sample, results define kerogen quality and their oil- vs gas-prone nature. Wt% TOC

#### *(Plate 1 on facing page)*

Plate 1. Photomicrographs of TSOP samples. Round robin participants were asked to describe and discuss properties, classification and nomenclature used for the organic components labeled in each photomicrograph.

1A & B. *Wilcox Formation*. (A) Transmitted white light, isolated organic matter. (B) Epi-fluorescence, same field of view as (A). 1, Does particle represent structured vitrinite or amorphous material? How is the boundary between structured vitrinite and amorphous organic matter defined? 2, Describe classification or subdivision of amorphous material based on petrographic properties. 3, Name of fluorescent component that lacks specific morphology.

2A & B. *Ohio Shale*. (A) Transmitted white light, isolated organic matter. (B) Epi-illumination, white light; reflectance preparation of isolated organic matter. 2(A) and (B) represent separate fields of view. 1, Name or classification of particle. 2, Classification of amorphous material [same material as in 2(B) #4]. 3, Does particle represent an amorphous or vitrinitic component? 4, Classification of organic component (bituminite vs amorphous terminology). Compare with component #2 in transmitted light. 5, Classification or name of particle.

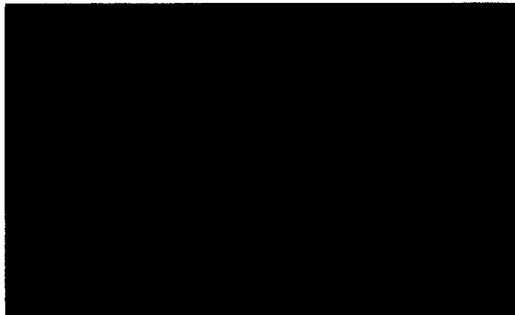
3A & B. *Monterey Formation*. (A) Transmitted white light of isolated organic matter. (B) Same field of view as (A) in epi-fluorescence. 1, Based on petrographic properties, how would this amorphous material be classified? How does this material differ from the Wilcox amorphous organic matter in 1(A) and (B) (similar level of thermal maturity). 2, Name or classification of fluorescent particle. How important are these particles in the petrographic characterization of the organic assemblage. 3, Name or classification of particle. What do the opaque particles represent?

4A & B. *Mesa Verde Coal*. (A) Epi-illumination reflected white light; whole rock preparation. (B) Epi-fluorescence; same field of view as (A). Describe the dominant type of organic constituent in the sample. 1, Name and classification of fluorescent component.

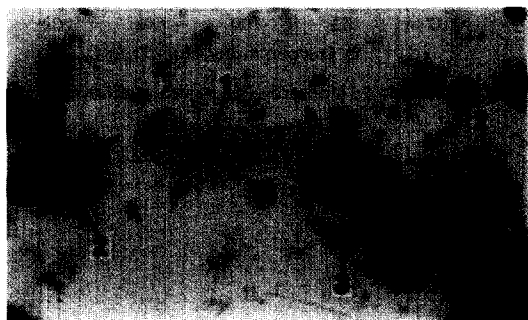
For each photomicrograph, describe how additional sample preparations and light modes would assist in the classification of the organic assemblage: 1, application of reflected white light (1 and 3), 2, use of whole rock preparations (1, 2, 3), 3, application of fluorescence (2), 4, use of transmitted light to evaluate isolated organic matter (4).



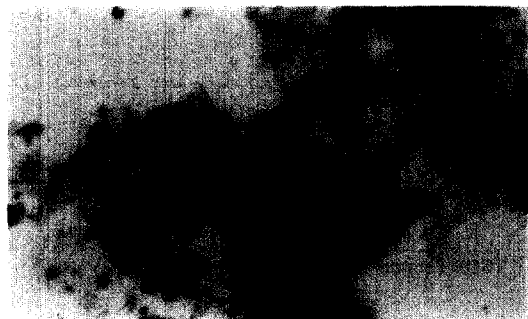
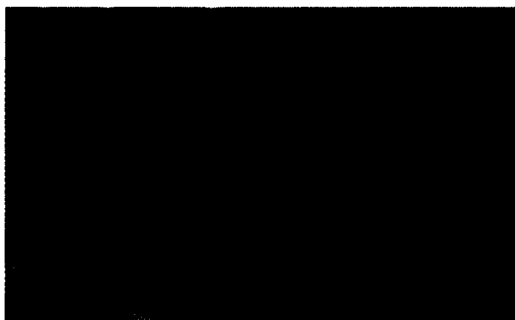
1A&B Wilcox Fm.



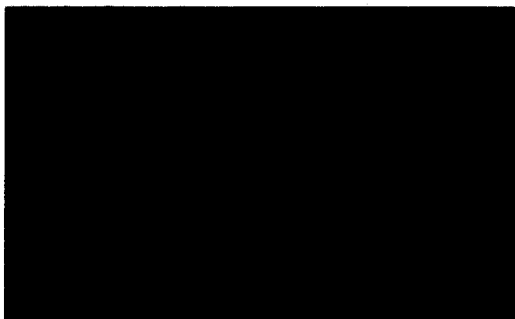
25µm



2A&B Ohio Shale



3A&B Monterey Fm.



4A&B Mesa Verde Coal



45µm

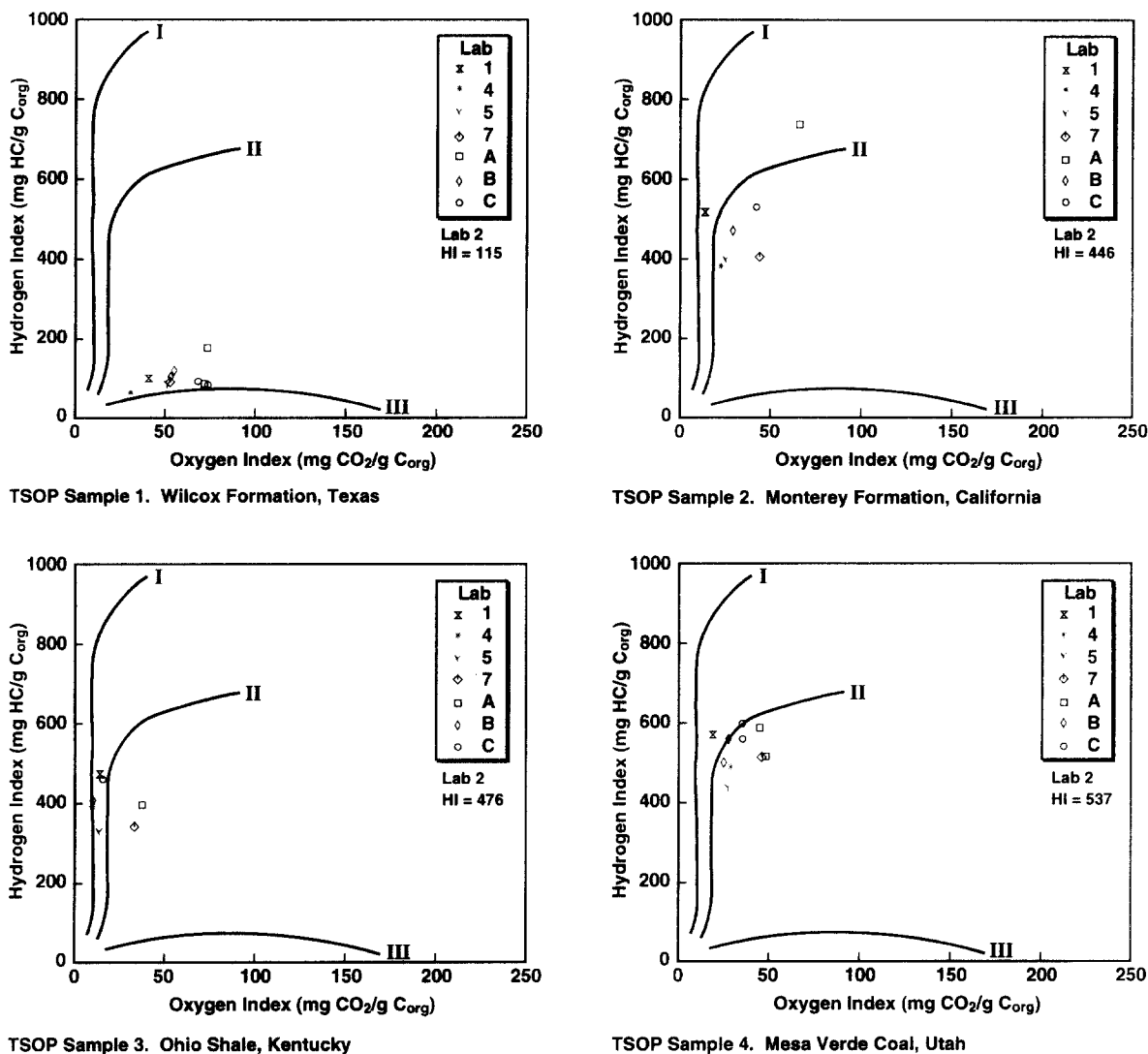


Fig. 1. Rock-Eval Hydrogen and Oxygen Index results from individual laboratories for TSOP samples (whole rock). Note Lab. No. 2 did not provide Oxygen Index values.

and Rock-Eval data from each laboratory are listed in Table 4. Consistent patterns appear in HI–OI results for individual laboratories. Differences in HI and OI are related to variation in both TOC, and S<sub>2</sub> and S<sub>3</sub> values, respectively. Sometimes, differences in TOC and S<sub>2</sub> compensate each other resulting in similar HI values. Except for the Wilcox sample, the OI is not extremely useful in sample characterization. Variation of laboratory results for individual samples are related to sample preparation, instrumentation, and analytical procedures.

Rock-Eval HI–OI values of isolated kerogen from three contractor laboratories display good agreement for each sample (Fig. 2 and Table 5). Generally, HI and OI results are similar for isolated kerogen and corresponding whole rock analyses. However, Ohio Shale and Monterey Formation HI values of isolated

kerogen are approximately 75 and 100 mg HC/g OC higher, respectively.

Atomic H/C values display good agreement for individual samples (Fig. 3 and Table 6); however, results are based on analysis from only two contractor laboratories. In contrast to the HI, the atomic H/C more accurately defines the Ohio Shale as a Type II/III kerogen, which agrees with petrographic results. Rock-Eval sometimes has limitations in defining kerogen quality for mixed organic assemblages (Scott, 1992).

Minor differences occur in the atomic O/C ratios for relatively oxygen-rich samples. Compared to Rock-Eval OI values, the atomic O/C effectively defines the nature of these kerogens and their position on maturation pathways.

Additional laboratory analysis and a statistical evaluation of the data would be beneficial for the



Table 4. Rock-Eval pyrolysis results for TSOP samples (whole rock)

Sample	Lab.	TOC (wt%)	S1 (mg HC/g Rk)	S2 (mg HC/g Rk)	S3 (mg CO <sub>2</sub> /g Rk)	PI (S1/S1 + S2)	S2/S3	HI (mg HC/g OC)	OI (mg CO <sub>2</sub> /g OC)	T <sub>max</sub> (°C)
Sample 1	1	3.45	0.25	3.28	1.53	0.07	2.14	95	44	423
	2	5.61	0.19	6.46		0.02		115		
	3	6.10								
	4	3.84	0.13	2.28	1.31	0.05	1.74	59	34	428
	5	3.70	0.24	3.01	2.01	0.07	1.50	81	54	427
	7	3.44	0.16	2.96	1.94	0.05	1.53	86	56	423
	A	4.31	0.62	7.53	3.27	0.07	2.30	175	76	423
	B	3.32	0.34	3.95	1.92	0.07	2.06	119	58	425
	C	3.44	0.41	2.81	2.66	0.12	1.06	82	77	417
	Sample 2	1	4.20	0.56	21.73	0.69	0.02	31.49	517	16
2		3.76	0.40	16.78		0.02		446		
3		3.69								
4		3.85	0.31	14.77	0.97	0.02	15.23	384	25	424
5		4.20	0.55	16.80	1.15	0.03	14.61	400	27	418
7		3.50	0.53	14.28	1.61	0.03	8.87	408	46	420
A		5.16	0.60	38.31	3.48	0.01	11.01	742	67	427
B		3.91	0.61	18.58	1.20	0.03	15.48	475	31	420
C		3.60	0.74	19.17	1.58	0.03	12.13	533	44	418
Sample 3		1	11.74	2.01	55.04	1.78	0.03	30.92	469	15
	2	13.86	2.14	65.93		0.03		476		
	3	11.90								
	4	12.50	1.42	48.38	1.33	0.02	36.38	387	11	426
	5	11.20	1.58	36.90	1.73	0.04	21.33	329	15	427
	7	11.96	2.13	40.61	4.14	0.05	9.81	340	35	421
	A	11.87	2.24	47.27	4.62	0.04	10.23	398	39	425
	B	12.12	2.38	49.47	1.46	0.04	33.88	408	12	420
	C	10.90	2.51	50.08	1.90	0.04	26.36	459	17	417
	Sample 4	1	53.01	8.01	301.40	10.50	0.03	28.68	569	20
2		57.43	6.32	308.10		0.02		537		
3										
4		53.75	2.54	266.50	12.20	0.09	21.80	496	23	433
5		54.50	10.20	236.00	15.10	0.04	15.63	433	28	437
7		57.38	3.79	293.10	27.10	0.01	10.83	511	47	428
A		64.97	6.00	333.50	31.90	0.02	10.45	513	49	435
B		48.49	5.93	242.10	12.70	0.02	19.14	499	26	435
C		49.29	7.14	292.90	17.80	0.02	16.44	594	36	436

Note: Labs A-C represent contractor labs.

geochemical study before strict conclusions are stated.

Rock-Eval  $T_{max}$  and vitrinite reflectance data to define thermal maturation of the four samples are listed in Table 4 and Appendix 2, respectively.

#### Comparison of maceral and geochemical analyses

Rock-Eval and elemental analysis effectively describe kerogen quality and the hydrocarbon generative potential of these samples. In contrast, it is difficult to use some of the petrographic results to define the generative potential of these organic matter assemblages. Although results of the prescribed classification provide useful information, the lack of definition to the generalized "amorphous" category and variation in intra-laboratory results limit effective characterization. For most individual classifications, inadequate definition of kerogen quality is related to: (1) lack of clear definition for certain petrographic terms, (2) poor correlation between petrographic terms and geochemical data, (3) variation in intralaboratory results, and (4) different methods of reporting results.

A combination of geochemical and petrographic results provides the most complete characterization of these samples. Bulk geochemical parameters

provide a quantitative evaluation of the kerogen quality and generative potential. Petrographic analysis identifies individual components that make up the kerogen, which can be used to further interpret and cross check geochemical results. In addition, the hydrocarbon characteristics of individual oil-prone

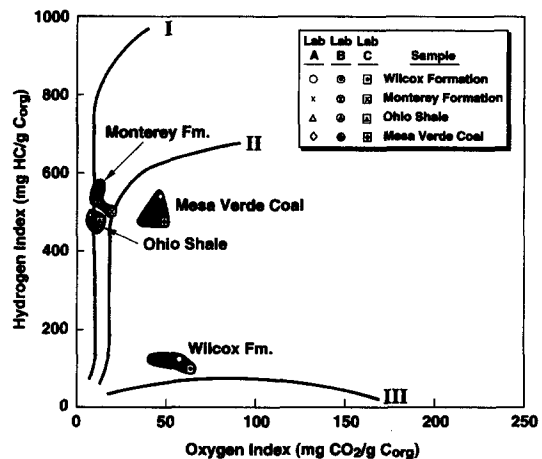


Fig. 2. Rock-Eval pyrolysis Hydrogen and Oxygen Index results—isolated kerogen from TSOP samples.

Table 5. Results of Rock-Eval pyrolysis of isolated kerogens

Sample	TOC (wt%)	S1 (mg HC/g Rk)*	S2 (mg HC/g Rk)*	S3 (mg CO <sub>2</sub> /g Rk)*	HI (mg HC/g OC)	OI (mg CO <sub>2</sub> /g OC)	T <sub>max</sub> (°C)
Sample 1							
Lab A	48.34	3.53	58.55	26.02	121	54	418
Lab B	56.56	4.26	68.26	26.69	122	47	416
Lab C	56.30	5.29	63.67	33.97	113	60	420
Sample 2							
Lab A	42.78	22.27	247.63	8.98	579	21	422
Lab B	57.33	29.54	299.42	8.62	522	15	424
Lab C	51.89	19.60	272.80	12.80	526	25	428
Sample 3							
Lab A	62.50	20.63	307.58	9.54	492	15	428
Lab B	66.84	21.30	310.11	8.92	464	13	426
Lab C	66.36	13.58	315.09	9.05	475	14	434
Sample 4							
Lab A	44.14	5.40	242.75	18.96	550	43	435
Lab B	48.85	8.69	239.66	16.00	491	33	434
Lab C	52.10	5.10	252.65	25.71	485	49	438

\*Consists of isolated kerogen and small amounts of insoluble minerals.

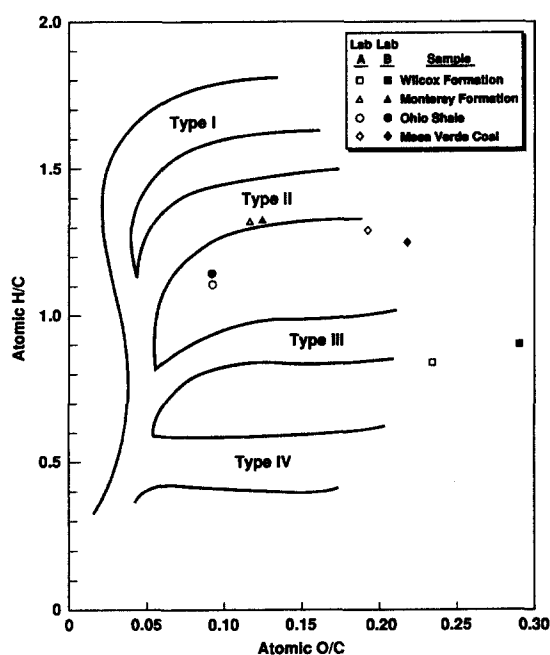


Fig. 3. Plot of elemental analysis (atomic H/C and O/C) data for isolated kerogens from TSOP samples.

constituents, organic matter occurrence, organic precursors, and depositional conditions can be described by petrographic analysis. Organic petrology can effectively identify the inertinite content and its effects on geochemical results, which is difficult based on pyrolysis techniques.

Although HI values of the Monterey, Ohio Shale and Mesa Verde samples indicate similar kerogen quality, petrographic results demonstrate the type and amount of oil- vs gas-prone, and inert components are different. The Monterey consists of predominantly oil-prone components; the Ohio Shale, a mixture of several types of oil-prone constituents, and gas-prone and inert material. The Mesa Verde sample consists of a unique mixture of oil- and gas-prone components embedded in an organic matrix. For the Wilcox sample, the HI and atomic H/C document the gas-prone nature of the organic assemblage. Petrographic analysis identifies the gas-prone vitri-nitic origin of this amorphous material.

#### *Integration of geochemical and petrographic parameters*

Correlation of a petrographic classification to geochemical results provides the integration of the two

Table 6. Results of elemental analyses.

Sample	% Carbon	% Hydrogen	% Oxygen	% Nitrogen	H/C	O/C
Sample 1						
Lab A	60.80	4.14	19.02	1.43	0.82	0.23
Lab B	61.58	4.57	24.00	1.46	0.89	0.29
Sample 2						
Lab A	55.97	6.10	7.96	2.13	1.31	0.11
Lab B	58.56	6.37	9.42	2.38	1.31	0.12
Sample 3						
Lab A	67.09	6.15	7.90	2.23	1.10	0.09
Lab B	69.51	6.62	8.54	2.22	1.14	0.09
Sample 4						
Lab A	53.31	5.73	13.62	1.22	1.29	0.19
Lab B	53.51	5.69	15.58	1.33	1.28	0.22

Note: Isolated kerogens were dried under vacuum at 60°C for 24 h prior to analysis.

techniques. Calibration between petrographic and geochemical parameters requires an understanding of the chemistry of different groups of organic components. It has long been recognized that the liptinite, vitrinite and inertinite maceral groups display distinct chemical properties (Seyler, 1943; van Krevelen, 1950; Dormans *et al.*, 1957). More recent work has shown that, within maceral groups, chemical differences occur based on the specific type of vitrinite and liptinite (Gutjahr, 1983).

Due to the variation in properties of amorphous material, a single petrographic category prevents accurate characterization of the hydrocarbon generative potential or paleoenvironmental aspects of a source rock. Various studies have demonstrated the geochemical significance of amorphous organic matter subdivisions. Van Gijzel (1982) described three types of amorphous organic matter, which have chemical definition. Sentfle (1984) described fluorescing and non-fluorescing amorphous material, which correlates to chemical properties of an organic matter assemblage. Thompson and Dembicki (1986) demonstrated that the correlation of optically distinct amorphous assemblages to geochemical properties is possible using transmitted, incident white light and fluorescence to recognize petrographic differences. Their work suggests that amorphous nomenclature should describe the optical-chemical properties rather than imply biological origins. Sentfle *et al.* (1987) suggested that multimode illumination permits the distinction of different types of amorphous organic matter. Although different nomenclature is used, Mukhopadhyay (1989) subdivided amorphous materials based on their chemical and petrographic characteristics.

An organic matter classification that can be directly correlated to geochemical data will enhance petrographic analysis and complement geochemical results. Jones and Edison (1978) grouped both structured and amorphous organic matter into four categories generally equivalent to the four defined kerogen types (Tissot *et al.*, 1974; Harwood, 1977). This approach, which eliminates complex petrographic terminology, emphasizes the identification of individual petrographic components based on their chemical properties. In addition to morphological information, this approach provides definition to bulk geochemical parameters and an important cross-check for petrographic results.

#### RECOMMENDATIONS AND FUTURE DIRECTION

There is a need to develop a uniform petrographic classification that facilitates effective organic matter characterization and provides additional value to source rock evaluation. A standardized, well defined classification is needed that routinely uses well understood nomenclature. Acceptable limits of reproducibility need to be established to provide consistent results. Organic petrographic results must complement

and provide additional information to established geochemical parameters and geological information. Unless these attributes of a uniform classification are achieved, future advancement and utilization of organic petrology will be difficult.

The following recommendations result from this study:

- (1) A uniform organic matter classification must be employed, which eliminates complex terminology and is capable of direct correlation with geochemical parameters.
- (2) A standardized definition, nomenclature, and application of amorphous organic matter is needed that can help provide useful and reproducible results.
- (3) Subdivisions of the amorphous category are needed to better characterize its chemical (hydrocarbon generative potential) and environmental properties.
- (4) Standardized techniques including utilization of multimode illumination and different sample preparations will help eliminate some of the variability in the amount and type of structured and amorphous components identified.

Future direction of this subcommittee includes: (1) additional photomicrographs of round robin and other samples, (2) standardization of microscopic techniques, (3) address "amorphous problem" and nomenclature, (4) define consistent subdivisions of amorphous organic matter, and (5) integration of microscopic and geochemical results. Future work should be carried out with the ICCP and other groups.

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**APPENDIX 1**

Amorphous				Herbaceous	Woody	Vitrinite	Inertinite	Solid Bitumen
A	B	C	D					

Amorphous*			Structured Liptinite (I)      (II)	Vitrinite (III)	Inertinite (IV)	Solid Bitumen
Group 1	Group 2	Group 3				

\*Amorphous Groups 1-3 Generally Equivalent to Type I-III Kerogen

Liquid Prone	<b>Exinite</b>	Type II Terrestrial Derived	Structured But Occasionally Amorphous	Liptinite	Herbaceous	Phyrogen	Phytoclast (Fluorescent)
	<b>Alginite</b>	Type I Lacustrine Algae  Type II Marine Algae	Amorphous Kerogen	Sapropel or Liptinite	Amorphous	Amorphogen	Protistoclast
Gas Prone	<b>Vitrinite</b>	Type III	Structured Kerogen (Rarely (?) Amorphous)	Huminite	Woody	Hylogen	Phytoclast
	<b>Other (Inertinite)</b>	Type IV	Structured Kerogen	Inertinite	Coaly	Melanogen	Inertinite

Kerogen Composition Data						
% (Visual, From Microscopy)			% (Calculated)			
Inertinite	Vitrinite	Sapropel	Inertinite	Vitrinite	Alginite Sapropel	Wxy Sapropel

—continued overleaf

Rock:  Coal

OM:

	OM	Pyrite
Quantity		
Oxidation		

Pyrite:  Framboidal  
 Crystalline  
 Massive  
 Glauconite

Maceral Composition

- SOM
- Telocollinite
- Telinite
- Desmocollinite
- Sporinite
- Cutinite
- Resinite
- Liptodetrinite
- Alginite
- Microplankton
- Sclerotinite
- Fusinite
- Semifusinite
- Macrinite
- Micrinite
- Bituminite
- Dead Carbon
- Graphite

X = Frequent      + = Common      / = Little      -- = Rare  
V = Abundant

Macerals	Reflected Light	Fluorescence
Inertinite		
Huminite/ Vitrinite Polymacerite		
Bitumenite		
Sporinite Cutinite Resinite Liptodetrinite		
Telalginite Lamaiginite		
Migrabitumen		
Exsudates		
Organo-Mineral Matrices		
Zooclasts		
Proportion: Fluo/Non-Fluo OM:		
Pollution: Oxidation or Irradiation:	Reworking:	
Conclusions:		

Descriptive Sheet of Whole Rock	
Raw Sample (as received):	
Nature:	
Mass (g):	
Color:	Black
Coaly Particles	
Migrabitumen	
Clasts (Reservoirs)	
Peri:	
Central:	
Impregnated Gloval:	
None:	
Shales	
Matrix Fluo Color	
Liptinite Fluo Color	
Q:	650/500
HC Neoproduction	
Drops:	
Films + Networks:	
Fading Reaction Under UV:	
HC Dissolution In-Resin	
Relative Fluo Intensity:	

## APPENDIX 2

Table A2. Vitrinite Reflectance Data TSOP Samples

Sample and Lab No.	% Reflectance	<i>n</i>	$\sigma$
Sample 1			
1	0.40	55	0.03
2	0.46	61	0.02
3	0.40 WR	65	0.04
	0.31 Conc	60	0.06
4	0.40	55	0.02
5	0.41	76	0.03
6	0.45	110	0.05
Sample 2			
1	0.32	26	0.04
2	0.32	26	0.02
3	0.27	10	0.05
	0.29	31	0.06
4	0.33	55	0.04
5	0.30	15	0.02
6	0.33	70	0.04
Sample 3			
1	0.39	35	0.03
2			
3	0.44 WR	40	0.06
	0.44 Conc	23	0.05
4	0.46	8	0.04
5	(0.4-0.45)		
6	0.39	21	0.05
Sample 4			
1	0.43	50	0.03
2	0.47	35	0.03
3	0.38 WR	100	0.04
4	0.42	55	0.04
5	0.41	39	0.04
6	0.36	100	0.04