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L. D. Stasiuk

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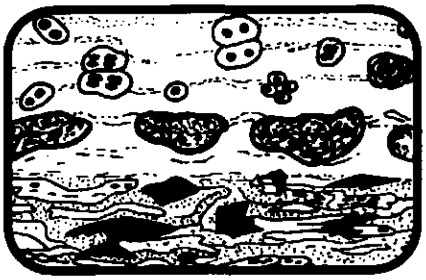
Résumé de l'article

La matière organique dans les sédi-ments et les roches sédimentaires four-nit des données et des informations surles interactions entre la géosphère et labiosphère. Dans les bassins sédimen-taires actuels ou anciens, la présencede conditions anoxiques en mêmetemps qu'une forte bio-productivité con-duit à la conservation de grands vol-umes de matière organique, lesquels setransforment par la suite en kérogène,la source des gisements de pétrole etde gaz. On utilise des méthodes de géo-chimie et de pétrologie organique pourétudier le kérogène et les donnéesqu'elles fournissent permettent de défi-nir les faciès des séquences de rochessédimentaires à grains fins. En géochi-mie organique, la pyrolyse Rock-Évalet l'analyse élémentaire permettent dedéterminer les quantités de C, H et Ïorganiques du kérogène et d'évaluer lepotentiel pétrolier ainsi que l'origine. Enpétrologie organique la microscopie enlumière réfléchie permet de caractériserla matière organique dispersée dans lesroches. Ensuite, des macéraux et facièsorganiques décrits on peut déduire lesparamètres paléo-environnementaux et paléo-écologiques des roches sédimen-taires riches en matière organique. Ontrouvera dans le présent article des de-scriptions abrégées de la pétrologieorganique de plusieurs roches mères del'Ouest canadien et qui illustrent bienl'efficacité de cette méthode dans l'éva-luation et la compréhension des rochesriches en matière organiques.

ARTICLE



Microscopic Studies of Sedimentary Organic Matter: Key to Understanding Organic-Rich Strata, with Paleozoic Examples from Western Canada Basin

L.D. Stasiuk
Geological Survey of Canada
3303 33rd Street NW
Calgary Alberta T2L 2A7

SUMMARY

Organic matter in sediments and sedimentary rocks provides data and interpretations on biosphere-geosphere interactions. In modern and ancient depositional settings, a combination of anoxia and substantial bio-productivity leads to the preservation of abundant organic matter, which in turn is transformed during subsequent burial into kerogen, the source of oil and gas deposits. Kerogen can be evaluated by organic geochemistry and organic petrological methods, whose parameters are used to define organic facies for fine-grained, sedimentary rock sequences. Organic geochemistry uses Rock-Eval pyrolysis and elemental analysis to determine amounts of organic C, H, and O in kerogen to assess petroleum potential and origin. Organic petrology uses reflected light microscopy to characterize dispersed organic matter in rocks, in terms of macerals and organic facies, which is then used to interpret the paleoenvironment and paleoecology of organic-rich sedimentary rocks. This paper outlines the organic petrology of several hydrocarbon source rocks from western Canada, illustrating the success of this method in evaluating and understanding organic-rich rocks.

RÉSUMÉ

La matière organique dans les sédiments et les roches sédimentaires fournit des données et des informations sur les interactions entre la géosphère et la biosphère. Dans les bassins sédimentaires actuels ou anciens, la présence de conditions anoxiques en même temps qu'une forte bio-productivité conduit à la conservation de grands volumes de matière organique, lesquels se transforment par la suite en kérogène, la source des gisements de pétrole et de gaz. On utilise des méthodes de géochimie et de pétrologie organique pour étudier le kérogène et les données qu'elles fournissent permettent de définir les faciès des séquences de roches sédimentaires à grains fins. En géochimie organique, la pyrolyse Rock-Éval et l'analyse élémentaire permettent de déterminer les quantités de C, H et O organiques du kérogène et d'évaluer le potentiel pétrolier ainsi que l'origine. En pétrologie organique la microscopie en lumière réfléchie permet de caractériser la matière organique dispersée dans les roches. Ensuite, des macéraux et faciès organiques décrits on peut déduire les paramètres paléo-environnementaux et paléo-écologiques des roches sédimentaires riches en matière organique. On trouvera dans le présent article des descriptions abrégées de la pétrologie organique de plusieurs roches mères de l'Ouest canadien et qui illustrent bien l'efficacité de cette méthode dans l'évaluation et la compréhension des roches riches en matière organiques.

INTRODUCTION

The study of organic matter in sediments and sedimentary rocks is an important topic which provides data and interpretations on "interactions between the geosphere and biosphere" as well as insight into processes affecting degradation, preservation and burial of organic carbon (see Tyson, 1995, p.1-6). Within some sequences of fine-grained, clastic and carbonate, sedimentary rocks, significant amounts of largely insoluble, biologically derived, dispersed organic matter (DOM), or kerogen, are preferentially preserved, thus forming actual or potential hydrocarbon source rocks for oil, gas and bitumen deposits (*e.g.*, Tissot and Welte, 1984).

In addition to their economic significance, sequences of laminated, organic-rich sediments displaying varves, couplets, or triplets are also important because they hold enormous potential as geochronometers of seasonal, annual, or longer term variations or cycles in sedimentation, primary biological production, terrestrial input, paleooxygenation, paleoproductivity, or, as recorders of anthropologic activity in the marine or lacustrine realm (Lallier-Verges *et al.*, 1993; Tribovillard *et al.*, 1994; O'Brien, 1996; Anderson, 1996; Bull and Kemp, 1996; Kemp, 1996). Perhaps most important is that laminated, marine and lacustrine sediments and rocks are one of only a few data sources which contain paleorecords at

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the temporal resolution (inter-annual, decadal) required to provide longer term assessments of climate change. Others are tree rings, ice cores, and coral records. Because of the direct forcing or control of the character of laminations induced by variations in the physical environment, the chemical environment, and in biological activity, such sediments are prime for recording and evaluating fine-scale changes and cycles over the long term (*e.g.*, Kemp, 1996).

This paper provides an introduction to the application of reflected light microscopic analysis of geological dispersed organic matter, or macerals[1], and organic microfacies (omf) from laminated, organic-rich hydrocarbon source rocks. **Microfacies analysis** in general uses "criteria appearing in thin [and polished] rock-sections under the microscope" (Brown, 1943), and by definition is "the total of all paleontological, mineral, and sedimentological criteria which can be classified in thin-sections, peels and polished sections" (Flugel, 1982). **Organic microfacies** refers specifically to the maceral classification of organic constituents relative to the distribution of inorganic fossils, mineral matter and sedimentary microtextures, as seen in whole rock sections under a reflected light microscope (*e.g.*, Stasiuk *et al.*, 1991). Organic microfacies are particularly useful in the evaluation of kerogen origin and method of preservation, for interpreting paleoenvironments and paleoecology, and for recognizing fine-scale variations and cyclicity in ancient paleobiological and paleodepostional systems. Microscopic analysis of organic matter provides answers to questions centered around the nature, distribution, preservation, and significance of organic matter in sediments and rocks.

ORIGIN OF ORGANIC-RICH SEDIMENTS AND SEDIMENTARY ROCKS

Large anomalous amounts of "unoxidized," well-preserved organic matter in non-coal lithologies such as carbonate mudstones or siliciclastic shales, are generally considered by geologists to have accumulated within restricted paleoenvironments where oxygen levels were very low (*e.g.*, sub-oxic to anoxic) and primary bio-productivity provided an adequate supply of organic matter (*e.g.*, Demaison and Moore, 1980) (Fig. 1). Several other secondary factors that influence the overall total organic carbon content (% TOC) and kerogen quality in sedimentary rocks include sediment texture-grain size, water depth, rate of allochthonous organic matter supply and sedimentation rate (*e.g.*, Tyson, 1987). Despite geological dogma stating anoxia as the main controlling factor influencing organic matter preservation, considerable debate continues as to what primarily controls the accumulation of large quantities of organic matter in sediments and sedimentary rocks. Two competing hypotheses presently exist (see Tyson, 1995): one which argues for preferential preservation of organic matter primarily as a function of bottom water anoxia (*e.g.*, Demaison and Moore, 1980); the other for the overall importance of higher biological productivity and carbon flux (Calvert, 1987; Pederson and Calvert, 1990; Calvert *et al.*, 1992), such as in regions of oceanic upwelling (Parrish, 1982).

Based on organic geochemical and organic petrographic evidence, three processes are currently considered viable mechanisms to explain or account for effective organic matter preservation and kerogen formation (see de Leeuw and Largeau, 1993). The first is an older, "classical model" which proposes that organic matter is subjected to very early diagenetic fragmentation and degradation followed by recondensation into insoluble geopolymers (Tissot and Welte, 1984). The second is a selective preservation process which results in preferential accumulation of resistant biomacromolecules derived from cell walls of cyanobacteria, greenalgae, and other microalgae (*e.g.*, Largeau *et al.*, 1984; Tegallar *et al.*, 1989), or from resistant biomacromolecules of spores, pollen, and waxy cuticular coverings of leaves and needles derived from vascular plants (*i.e.*, angiosperms and gymnosperms (see Brooks, 1971 and de Leeuw and Largeau, 1993). The third process proposed for kerogen formation and preservation involves sulphur vulcanization of certain biological compounds, such as lipids (Sinninghe-Damste *et al.*, 1988) or carbohydrates (Van Kamm-Peters, *et al.*, 1998), thereby forming sulphur-enriched kerogens. Of all three of the above processes, selective preservation and vulcanization "pathways" are generally considered more important than the recondensation "pathway" (see de Leeuw and Largeau, 1993). The dominant process in a particular depositional setting is fundamentally linked to the nature of the original biomass (*e.g.*, resistant biomacromolecules in cell walls *versus* non-resistant molecules such as low molecular weight lipids), the degree of microbial alteration and the susceptibility of the biomass to react with inorganic constituents in the depositional environment.

CHARACTERIZATION OF DISPERSED ORGANIC MATTER

Organic geochemistry and organic petrology are the two principal disciplines in geology which study and characterize the nature and origin of organic matter in sedimentary rocks at the molecular and microscopic level, respectively. As a result of the relationship which exists between the biogeochemical origin of organic matter and its hydrocarbon potential, organic geochemistry and optical microscopy of kerogen have historically been used to predict what type of hydrocarbons were generated, where, and, with additional burial history and kinetic information, when the hydrocarbons were generated within organic-rich strata (see Tissot and Welte, 1984; Rullkötter, 1993).

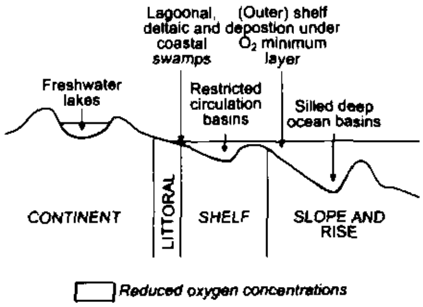

Figure 1 Generalized cross-section from continent to ocean illustrating depositional environments where reduced oxygen concentrations may occur, and thus govern the accumulation of abundant kerogen and hydrocarbon source rocks in geological paleoenvironments; note the diagram exhibits high vertical exaggeration (modified from Brooks, 1987).

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[1] Macerals (see Bustin *et al.*, 1983) are the individual, microscopically recognizable organic components of coal or other sedimentary rocks (*e.g.*, plant spore components are defined as sporinite macerals); macerals are analogous to minerals in rocks like sandstone.

Organic Geochemical Characterization of Kerogen and DOM

Rock-Eval[2] pyrolysis and elemental analysis are the two most commonly used techniques for grossly assessing the organic geochemical nature, origin, and hydrocarbon potential of kerogen in sediments and sedimentary rocks (*e.g.*, Tissot and Welte, 1984; Tyson, 1995). These bulk characterization methods use the quantity of organic carbon, hydrogen, and oxygen within kerogen as the basis for classifying, assessing petroleum potential, and interpreting the origin of organic matter (*e.g.*, lacustrine algal, marine phytoplanktonic or coaly terrestrial origin; Fig. 2a). For example classical Type I and Type II kerogens have high H/C ratios and low O/C ratios as defined by elemental analysis, and high hydrogen indices and low oxygen indices as defined by Rock-Eval pyrolysis[2,3] (Fig. 2). Microscopically, Type I and Type II kerogens most commonly comprise some combination of well-preserved to degraded lacustrine or marine microalgae and cyanophyte cell walls, terrestrial waxy to resinous plant cuticles, spores or resins, and structureless amorphous organic matter. As a result of their elemental chemical composition, Type I and II kerogens typically generate sulphur-lean crude oils upon geological burial and heating (thermal maturation). However some kerogens may become enriched in sulphur through vulcanization of algal-derived organic matter during very early diagenesis (*e.g.*, lipid vulcanization; Sinninghe-Damste *et. al.*, 1988), and as a consequence, these Type I/II kerogens generate sulphur-rich heavy bitumens and crude oils. Classical Type III kerogens have low H/C ratios and high O/C ratios relative to Types I and II (with corresponding low hydrogen indices and high oxygen indices; Fig. 2), and normally contain a combination of terrestrial, wood- and lipid-derived, "coaly" DOM. Type III kerogen preferentially generates gas during catagenesis. In exceptional cases where Type III kerogen is enriched in resinous components (*i.e.*, resinite macerals or resinite-impregnated vitrinite), naphthenic and aromatic crude oils can be generated during thermal maturation (Snowdon, 1991).

Bulk geochemical techniques such as Rock-Eval are commonly used in conjunction with molecular and/or microscopic characterization to determine the character and origin of DOM in sedimentary rocks. Gas chromatography and gas chromatography-mass spectrometry analysis of organic solvent soluble[4], saturated and aromatic hydrocarbons (*e.g.*, normal alkanes, biomarkers[5]) and nitrogen-, sulphur-, and oxygen-bearing resin and asphaltene carbon compounds recovered from kerogens, generally can provide substantial information about primary precursor organisms and the degree of subse-

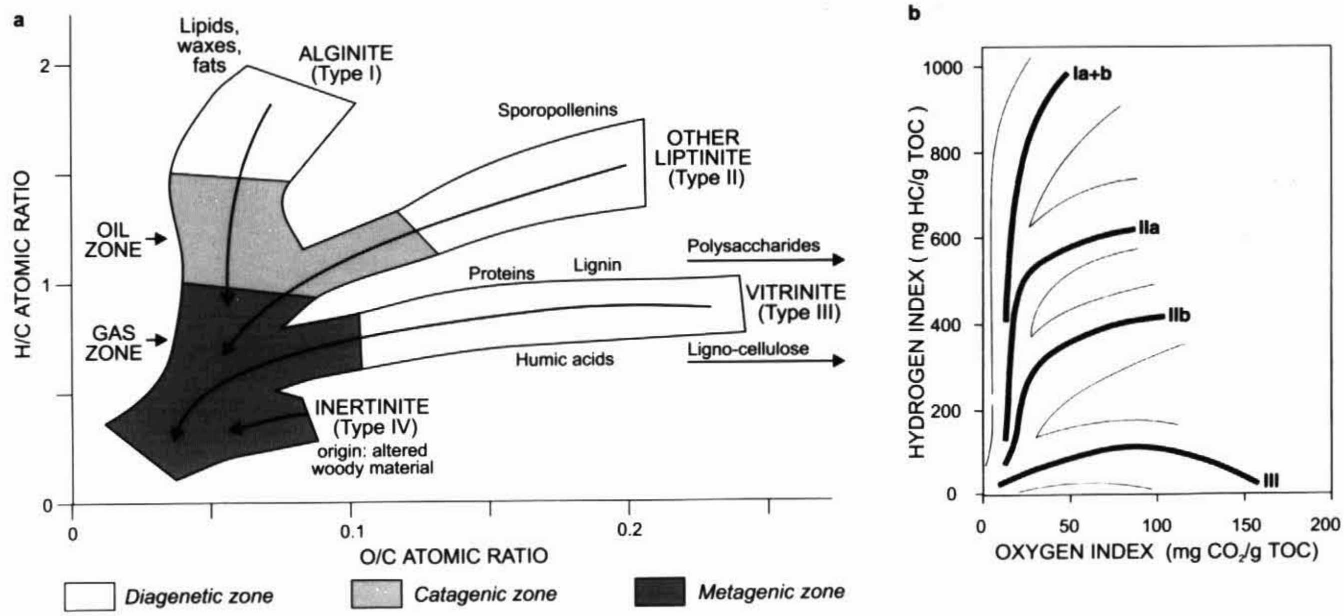

Figure 2 (**a**) A van Krevelen diagram illustrating the most common origins for maceral groups and kerogen types I to IV and their comparative H/C and O/C ratios. The changes in the general elemental composition with increasing geothermal alteration (*i.e.*, from diagenesis to catagenesis and metagenesis) are a consequence of liquid and gaseous hydrocarbon generation (modified from Brooks, 1987). (**b**) Pseudo van Krevelen diagram showing hydrogen and oxygen indices from Rock-Eval pyrolysis for different kerogen types and their evolutionary pathway from early diagenesis (starting from right side of pathway) to metagenesis (from Delvaux *et al.*, 1990, *in* Tyson, 1995).

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[2] Rock-Eval® pyrolysis (see Tissot and Welte, 1984) of powdered rock monitors and determines the amount (weight per cent) of volatile hydrocarbons, volatile kerogen, and organic and inorganic oxygen liberated/generated with increasing temperature from ~250 °C to >650 °C. Rock-Eval Hydrogen Indices are determined from the amount of hydrocarbons (HC) produced during pyrolysis in mgHC/gTOC; Oxygen Indices are calculated from the amount of Organic CO$_2$ in mgCO$_2$/gTOC.

[3] Elemental analysis of carbon (TOC = total organic carbon), hydrogen and oxygen are determined on a mineral free kerogen concentrate.

[4] Solvent used during extraction is usually 50% dichloromethane + 50% pentane mixture.

[5] Biomarkers (*e.g.*, steranes derived from steroids; triterpanes derived from triterpenoids) are defined as biologically derived molecular "fossils" of individual organic compounds; these are used for determining source organisms in kerogen, bitumen and oil and their degree of geothermal-burial alteration.

quent biological, and geothermal-burial alteration (*e.g.*, Tissot and Welte, 1984; Peters and Moldowan, 1993; Engel and Macko, 1993).

Incident Light Microscopic Characterization of Dispersed Organic Matter: *Organic Petrology*
Most microscopic characterization of DOM is currently conducted using either palynology-based transmitted light microscopy (*e.g.*, Combaz, 1980; Traverse, 1988; Tyson, 1995) or organic petrology-based incident light microscopic methods (*e.g.*, Stach *et al.*, 1982; Taylor *et al.*, 1998; Potter *et al.*, 1998). Other imaging techniques such as transmission electron microscopy (*e.g.*, Largeau *et al.*, 1990) and confocal laser scanning fluorescence microscopy (*e.g.*, Stasiuk, 1999) can also provide valuable information to supplement conventional microscopic characterization methods.

The majority of kerogen within fine-grained sedimentary rocks typically occurs as semi-solid to solid, microscopically discernible constituents, which are defined as macerals by organic petrologists using incident light microscopy (*e.g.*, Teichmuller and Ottenjann, 1977; Mukhopadhyay *et al.*, 1985) (Table 1). In the broadest sense, two types of macerals occur in sedimentary rocks: 1) primary macerals which are derived directly from terrestrial and marine organic matter deposited during sedimentation (*e.g.*, resistant microalgae cell walls), or formed through alteration and polymerization-condensation reactions during very early diagenesis (*e.g.*, amorphous organic matter); and 2) secondary macerals (*e.g.*, solid bitumens) which are formed in the geological subsurface environment through thermal alteration of primary macerals. Only primary macerals are discussed in this paper.

Macerals are characterized and classified according to their optical properties and their morphology in white and under ultraviolet or blue incident light (*e.g.*, Bustin *et al.*, 1983; Robert, 1988). Conventionally they are sub-divided into three main groups: a vitrinite group, a liptinite group, and an inertinite group (Table 1; for details of origin, classification etc. *see* Bustin *et al.*, 1983 and Taylor *et al.*, 1998).

Huminite and vitrinite[6] macerals (hereafter vitrinite; Fig. 3a,b) are mainly derived from woody lignin, or tannin-enriched components of terrestrial and marginal marine land plants (*e.g.*, gymnosperms, sedges, angiosperms; Stach *et al.*, 1982) and in some instances algal precursors (*e.g.*, Stasiuk, 1993). In the diagenetic, to catagenetic, to early metagenetic zones[7] of thermal maturation (see Tissot and Welte, 1984) the vitrinite group macerals have an intermediate or "grey level" reflectance (Fig. 3b), and are characterized by intermediate H/C and O/C ratios relative to the

Table 1 Maceral classification of DOM using the maceral concept (see also Stach *et al.*, 1982; Bustin *et al.*, 1983; Potter *et al.*, 1998; Taylor *et al.*, 1998). For further subdivision of the huminite/vitrinite and inertinite groups in this table see above references. ICCP = International Committee for Coal Petrology (1971).

Maceral Group (after ICCP)	Maceral	Maceral Variety
Huminite/Vitrinite[6]	see Figure 3	
Inertinite	see Figure 3	
Liptinite	sporinite cutinite resinite suberinite fluorinite chlorophyllinite	
	amorphinite	hebamorphinite fluoramorphinite matrix bituminite
	alginite	*Botryococcus* *Pila-Rheinshia* *Tasmanites* *Leiosphaeridia* filamentous *Gloeocapsomorpha* dinoflagellates
	acritarchs	
Zooclast (informal group)	scolecodont graptolite chitinozoan foraminifera conchostracan	

Figure 3 (facing page) Photomicrographs of vitrinite, inertinite and zooclast maceral groups taken using white (a-i, m-o), and ultra-violet and blue (j-l), incident light, using oil immersion objectives; scale bar on o applies to all images. **a.** Vitrinite showing cell structure of vascular woody plant; **b.** Grey reflecting vitrinite (V) and higher reflecting "white" inertinite (I) macerals; viewed perpendicular to paleodepositional bedding plane. **c.** White-reflecting Inertinite fusinite maceral derived from wood combusted at a high temperature during igneous intrusion. **d.** Inertinite (I) fusinite maceral derived from thermal alteration of a plant spore. **e.** Inertinite (I) fusinite maceral derived from filamentous algae. **f.** Chitinous, bulbous microfossil with morphology similar to chitinozoan (C). **g.** Spiny chitinozoan (courtesy Dr. F. Goodarzi). **h.** Graptolite (G) showing the fusellar structure of the periderm in cross-polarized light. **i.** Phosphatic maceral probably derived from marine fish remains. **j.** Chitinous maceral similar to fish bone. **k.** Chitinous conchostracan microfossil (C) probably derived from brine shrimp-like organism. **l.** Tooth-like scolecodont maceral derived from annelid worm; **m.** Marine radiolarian-like siliceous, opalline (arrows) microfossil. **n.** Carbonate microfossils derived from calcareous green microalgae shells (coccoliths) embedded within a grey-reflecting bitumen (courtesy Dr. C.L. Riediger). **o.** Chitinous linings of planktonic bivalve microfossils (ostracods).

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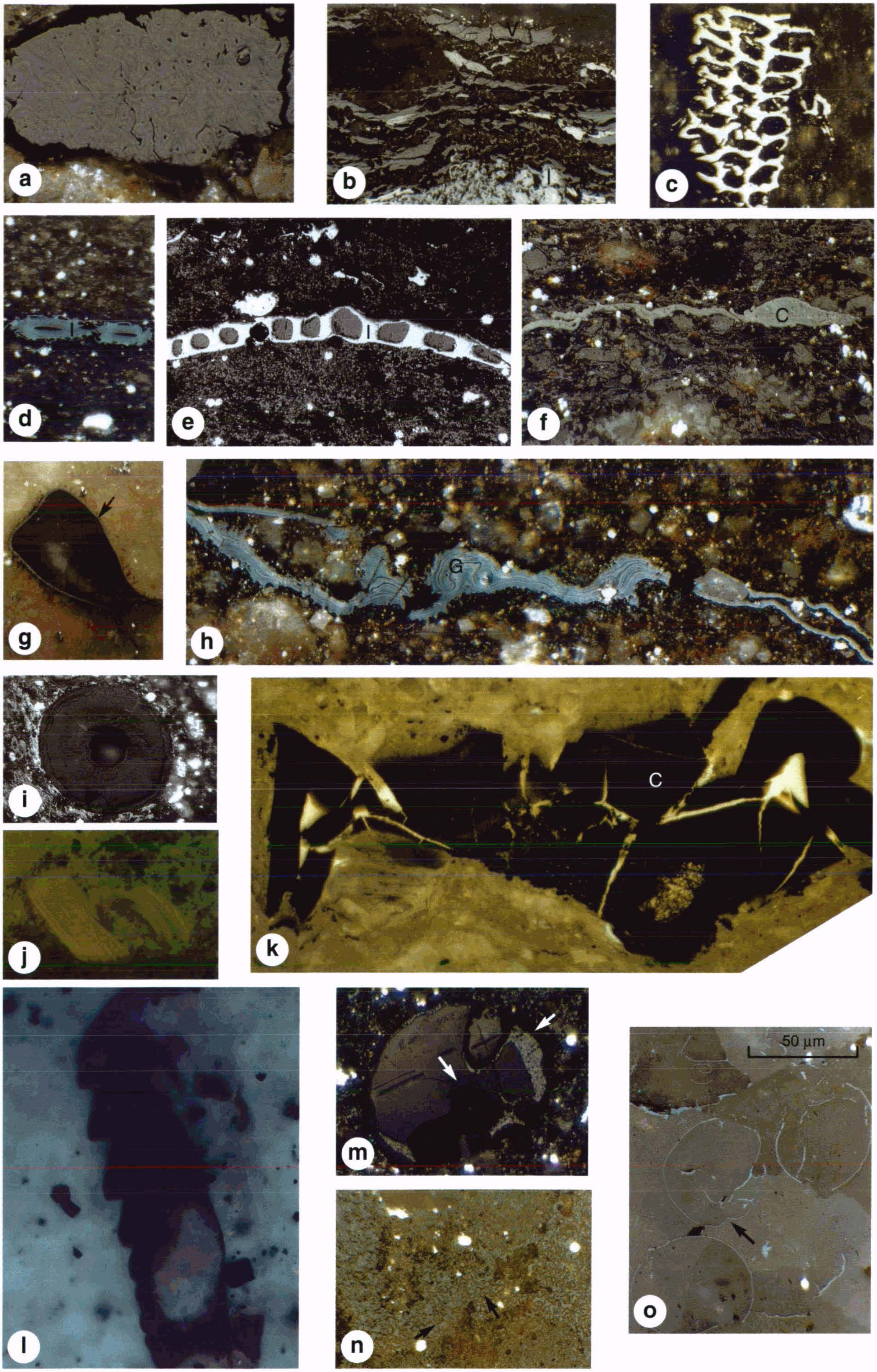
[6] At low levels of thermal maturity (vitrinite reflectance in oil, %Ro <0.50) or in low rank coals (brown, lignite and some sub-bituminous coals) woody macerals are classified as huminite. At higher levels of thermal maturity and coalification, the term vitrinite is used.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other two maceral groups (Fig. 2).

Liptinite macerals are derived from either microalgae constituents to form unicellular (Fig. 4a,b) and colonial (Fig. 4c,e,h) alginites, dinoflagellates (Fig. 4f) and acritarchs (Fig. 4g), or from waxy, lipid and resinous higher plant constituents to form macerals such as sporinites (Fig. 4d, i-k), cutinites (Fig. 4l, o), and resinites (Figs. 4m, n). In the diagenetic, to catagenetic, to early metagenetic zone, the liptinite macerals are the lowest reflecting of the three maceral groups, generally exhibit autofluorescence[8] during ultraviolet- or blue-light irradiation, and are characterized by the highest H/C ratios and lowest O/C ratios (Fig. 2).

Inertinite macerals are mainly derived from organic matter that was partially to extensively oxidized in the paleoenvironment either through transport and reworking, combustion, or fungal and microbial decay (Fig. 3b-e), although shallow subsurface bacterial-related alteration must also play a role in producing inertinite macerals (Taylor *et al.*, 1998). In the diagenetic, to catagenetic, to early metagenetic zone of thermal maturation the inertinite group of macerals are the highest reflecting with the lowest H/C and highest O/C ratios (Fig. 2).

A fourth, informal group of macerals, commonly termed **Zooclasts**, are also present in sediments and sedimentary rocks (Table 1) (see Taylor *et al.*, 1998; Potter *et al.*, 1998). These are mainly derived from the remains of benthic and planktonic, chitinous, "bony," calcareous or siliceous organisms including chitinozoa (Fig. 3f-g), graptolites (Fig. 3h), fish (Fig. 3i, j), concostrachen (*e.g.*, brine shrimp; Fig. 3k), scolecodonts (Fig. 3l), radiolaria (Fig. 3m), coccoliths (Fig. 3n), ostracods (Fig. 3o), among others.

Macerals within any of the groups described above can be further subdivided into maceral varieties based on morphological criteria, optical criteria or genetic affinity to existing organisms (*e.g.*, see alginite macerals in Table 1; Stasiuk, 1994). By combining a detailed approach to maceral classification and analysis of the spatial and vertical distribution of macerals and maceral assemblages, *organic facies and organic microfacies* can be defined within sediments and sedimentary rocks, potentially providing a genetic and temporal basis for evaluating paleodepositional and paleoecological systems.

Organic Facies and Microfacies: Concepts

Lateral and vertical variations in the type and quality of organic matter within sediments and sedimentary rocks can occur at three levels or scales: (i) at a basin scale, where variations are interpreted as a response to different tectonic or basinal settings (Huc, 1988), (ii) at a sequence scale, where variations are interpreted as a response to sedimentary cycles (*e.g.*, Leckie *et al.*, 1990; Chow *et al.*, 1995) and; (iii) at a microscopic scale, where vertical variations in DOM can potentially preserve daily, to decadal, to millenial, to longer term time scale cycles and changes (*e.g.*, Stasiuk *et al.*, 1991; Bertrand and Lallier-Verges, 1993; Lallier-Verges *et al.*, 1993; Stasiuk *et al.*, 1994; Fowler and Stasiuk, 1995). At the first two scales, *i.e.*, basinal and sequence, the distribution of DOM is described and interpreted in terms of *organic facies* (of; *e.g.*, Jones, 1987). At the microscopic level, spatial variations in DOM distribution are described and interpreted in terms of *organic microfacies* (*e.g.*, Stasiuk *et al.*, 1991). From a petroleum exploration perspective, organic facies (and to a lesser extent organic microfacies) are used primarily to predict the occurrence and quality of hydrocarbon source rocks as a function of paleoenvironment (Tyson, 1995). From a paleoecological and paleoclimatic perspective, organic facies and microfacies offer the potential to identify short-term and long-term variations or cycles (*e.g.*, Lallier-Verges *et al.*, 1993).

Rogers (1980) was the first to define organic facies on the basis of "organic matter type, its source, and paleodepositional environment" (see Tyson, 1995). Peters *et al.* (1981) later expanded the definition of organic facies, stating that the "concept is based on: (i) the type of organisms and biomass, (ii) the paleodepositional environment and; (iii) the conditions prevailing during early diagenesis." Over the past two decades, a variety of geochemical and petrographic parameters have been used to characterize and define organic facies variations, and to a lesser degree organic microfacies variations, within and between potential hydrocarbon source rock units and Recent sediments, particularly as they apply to paleodepositional environment, sequence stratigraphy and sedimentary cycles, source rock quality and hydrocarbon generation thresholds and the chemistry of generated hydrocarbons (*e.g.*, Jones, 1987; Tyson, 1995). Most commonly, organic facies are defined by using the covariance between bulk geochemical

Figure 4 (facing page) Photomicrographs illustrating liptinite group macerals which constitute an important component of kerogen or dispersed organic matter in sedimentary rocks. All except m and r (taken in white light) were taken under ultra-violet and blue, incident light; scale bar on q applies to all images. **a.** Prasinophyte unicellular alginite (*Leiosphaeridia*) derived from green (chlorophyte), marine microalgae, viewed parallel to bedding plane. **b.** Prasinophyte unicellular alginite (*Tasmanites*; T) viewed perpendicular to bedding plane. **c.** Multicellular, marine coccoidal alginite (*Gloeocapsomorpha prisca*). **d.** sporinite from nearshore marine setting. **e.** Coccoidal *Botryococcus* alginite in lacustrine marl. **f.** Marine dinoflagellate alginite maceral. **g.** marine spiny acritarch alginite maceral. **h.** *Botryococcus* alginite (B) with sporinite (S) in lacustrine marl (courtesy Dr. F. Goodarzi). **i-k.** land plant-derived, sporinite macerals. **l.** Cross-section through a conifer needle sheathed by yellow fluorescing serrated cutinite (C). **m, n.** Conifer-derived resinite (R) macerals in white (m) and blue (n) light. **o.** Cutinite maceral viewed in a section parallel to "leaf" surface showing cell structure. **p.** Brown fluorescing amorphinite (A) in fine-grained marine carbonate (viewed perpendicular to bedding). **q.** Red-fluorescing amorphinite deposited in a near-shore, saline intertidal to lagoonal paleoenvironment. **r.** Low-reflecting, smooth to granular amorphinite(A) associated with abundant framboidal pyrites (P) from epicontinental marine black shale.

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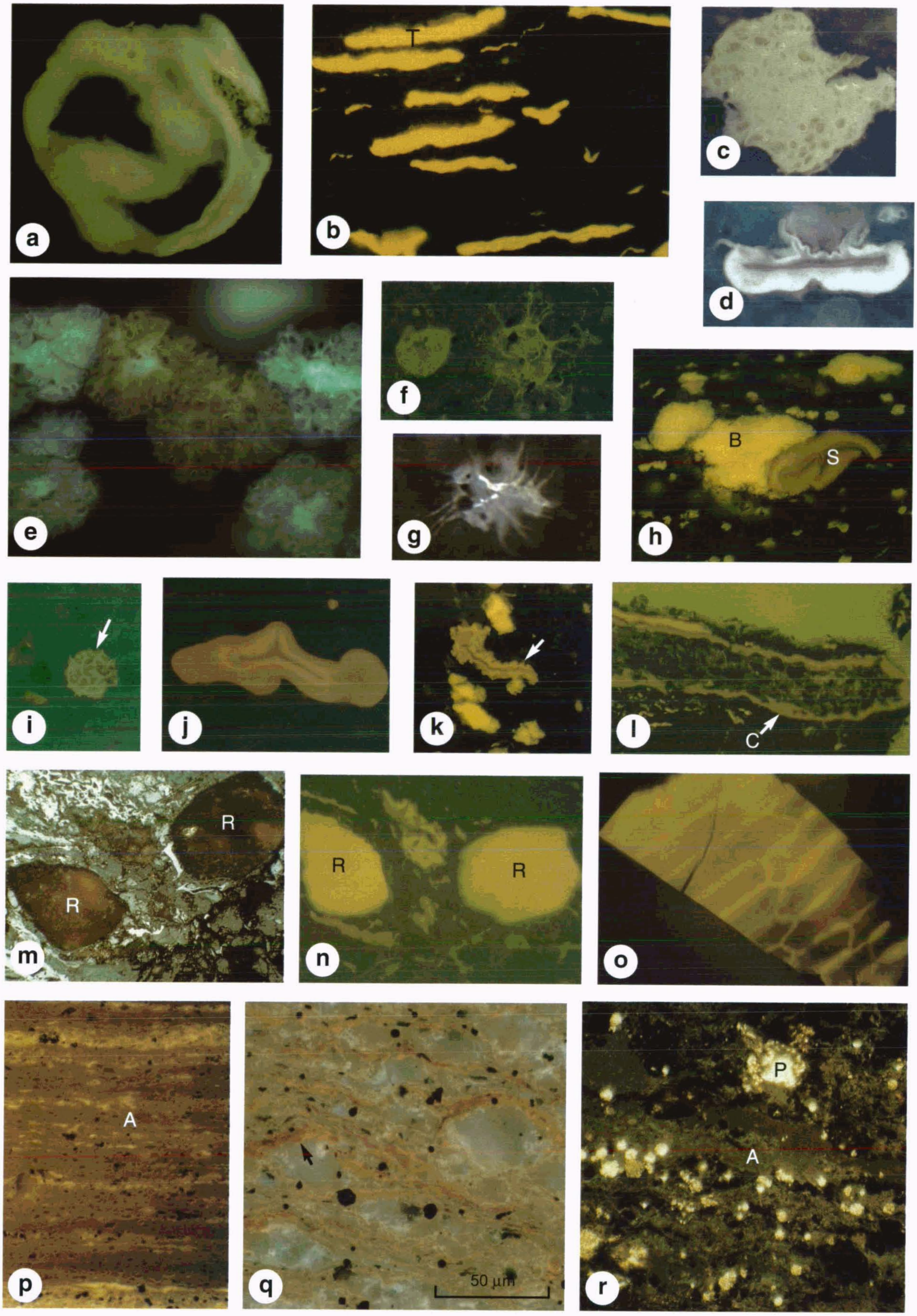
[7] **Diagenesis** is the first stage of sedimentary burial evolution under low temperatures; it is characterized by microbial destruction of proteins and carbohydrates, the significant loss of water, carbon dioxide and ammonia and the conversion of organic matter into kerogen. Biogenic methane is the most important hydrocarbon produced during this stage. **Catagenesis** is an intermediate stage of burial evolution that follows diagenesis. Liquid petroleum is generated in the early stage whereas "wet gas" and condensate are generated at later stages. **Metagenesis** is the last stage of thermal alteration of kerogen with respect to hydrocarbon generation forming mainly "dry" methane gas.

[8] Liptinite macerals are auto-luminescent, or fluorescent, when irradiated with ultra-violet or blue light; *i.e.*, they give off an energetic "glow" in the visible light region. Most of the fluorescence from liptinites comes mainly from molecules with conjugated bond systems (aromatics, substituted aromatics, isoprenoids, carotenoids and polyenes) "surrounded by a matrix" of unsaturated molecular structures.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(C, H, O and S) and microscopic data (maceral or palynomorph composition; *e.g.*, Jones, 1987; Tyson, 1995; Follows and Tyson, 1998). Figure 5 and Table 2 illustrate and summarize the bulk chemical, pyrolysis, and microscopic criteria of seven organic facies relative to sedimentary environments for a siliciclastic *basinal to fluvial-deltaic paleodepositional* system (after Jones, 1987; compiled by Tyson, 1995).

Microscopically, organic facies and organic microfacies can be defined using two methods: 1) incident light microscopy using macerals and maceral assemblages (*e.g.*, Mukhopadhyay *et al.*, 1985; Taylor *et al.*, 1998; Potter *et al.*, 1998) and 2) transmitted light microscopy using palynomorph and phytoclast assemblages (*palynofacies*; *e.g.*, Combaz, 1964; Tyson, 1995). This paper describes and illustrates the former method and its applications to evaluating paleoenvironmental and paleoecological systems. In addition, examples of image analysis from organic-rich laminites are used to illustrate the potential importance of this method for studying rocks of this nature. One advantage of reflected light microscopy over transmitted light microscopy (*i.e.*, palynology-based) for maceral and organic microfacies analysis is that whole rock samples rather than kerogen concentrates are used, thus preserving fine-scale temporal relationships as well as

Table 2 Summary of gross chemical, pyrolysis (Rock Eval), and microscopic criteria and characteristics of classical organic facies of Jones, 1987 (from Tyson, 1995).

Organic Facies	H/C at % $VR_0 \cong 0.5$	Pyrolysis yield HI	Pyrolysis yield OI	Dominant Organic matter		Sedimentary structure
A	≥ 1.45	> 850	10 - 30	Algal; amorphous	A	Laminated
AB	1.35 – 1.35	650 – 850	20 – 50	Amorphous; minor terrestrial	AB	
B	1.15 – 1.35	400 - 650	30 – 80	Amorphous; common terrestrial	B	Well bedded to laminate
BC	0.95 – 1.15	250 – 400	40 – 80	Mixed; some oxidation	BC	Poorly bedded
C	0.75 – 0.95	125 – 250	50 – 150	Terrestrial; some oxidation	C	Poorly bedded to bioturbated
CD	0.60 – 0.75	50 – 125	40 – 150+	Oxidized; reworked		
D	≤ 0.6	< 50	20 – 200+	Highly oxidized; reworked	D	Massive, bioturbated

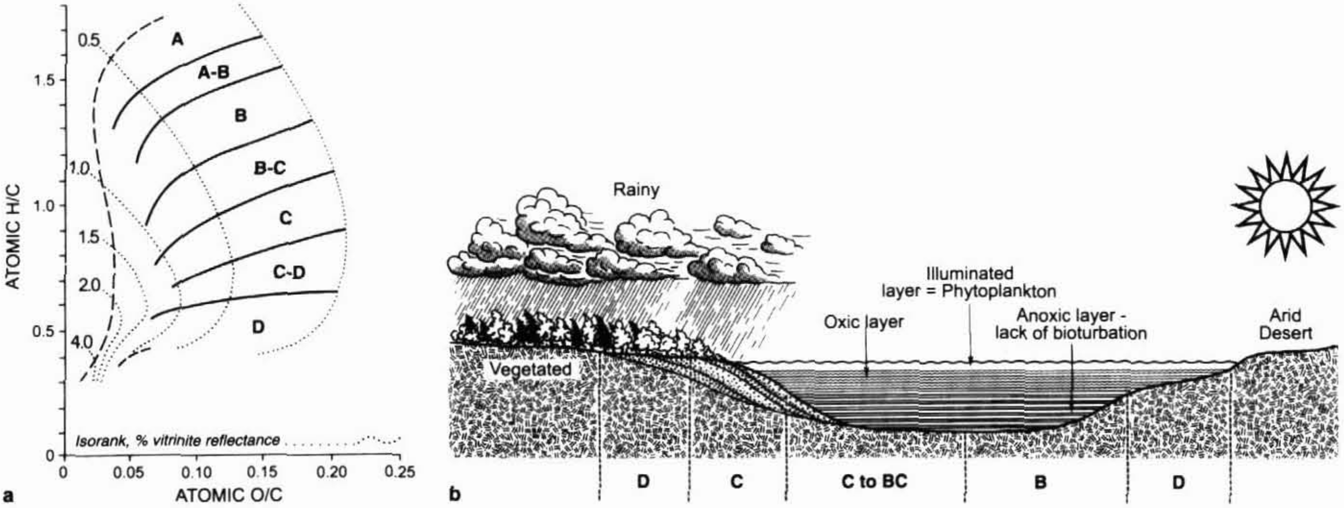


Figure 5 Organic facies defined for a basin to deltaic-fluvial, siliciclastic depositional system expressed as H/C and O/C fields on a van Krevelen diagram (**a**) and placed within the context of their paleodepositional environment (**b**) (after Jones, 1987, from Tyson, 1995).

organic-inorganic microtextures such as those produced by algal mats (*i.e.*, stromatolites). Concepts of organic facies and microfacies are illustrated in the following examples from the Western Canada Sedimentary basin.

ORGANIC MICROFACIES FROM WESTERN CANADA SEDIMENTARY BASIN

During Late Ordovician and Middle Devonian time in Western Canada, organic-rich, potential hydrocarbon source rocks were deposited throughout the region within a variety of tectonic and paleodepositional settings (*e.g.*, Wardlaw and Reinson, 1971; Davies and Ludlam, 1973; Stoakes *et al.*, 1987a,b; Chow *et al.*, 1995; Osadetz and Snowdon, 1995). Organic microfacies from shallow water, subtidal carbonates of the Upper Ordovician Yeoman Formation in southeast Saskatchewan, and organic microfacies from marine to marginal marine carbonates, shales and evaporites of the Middle Devonian Elk Point Group in Alberta and Saskatchewan, record variations in macerals and maceral assemblages, and paleoenvironmental and paleoecological systems over short and long periods of geological time.

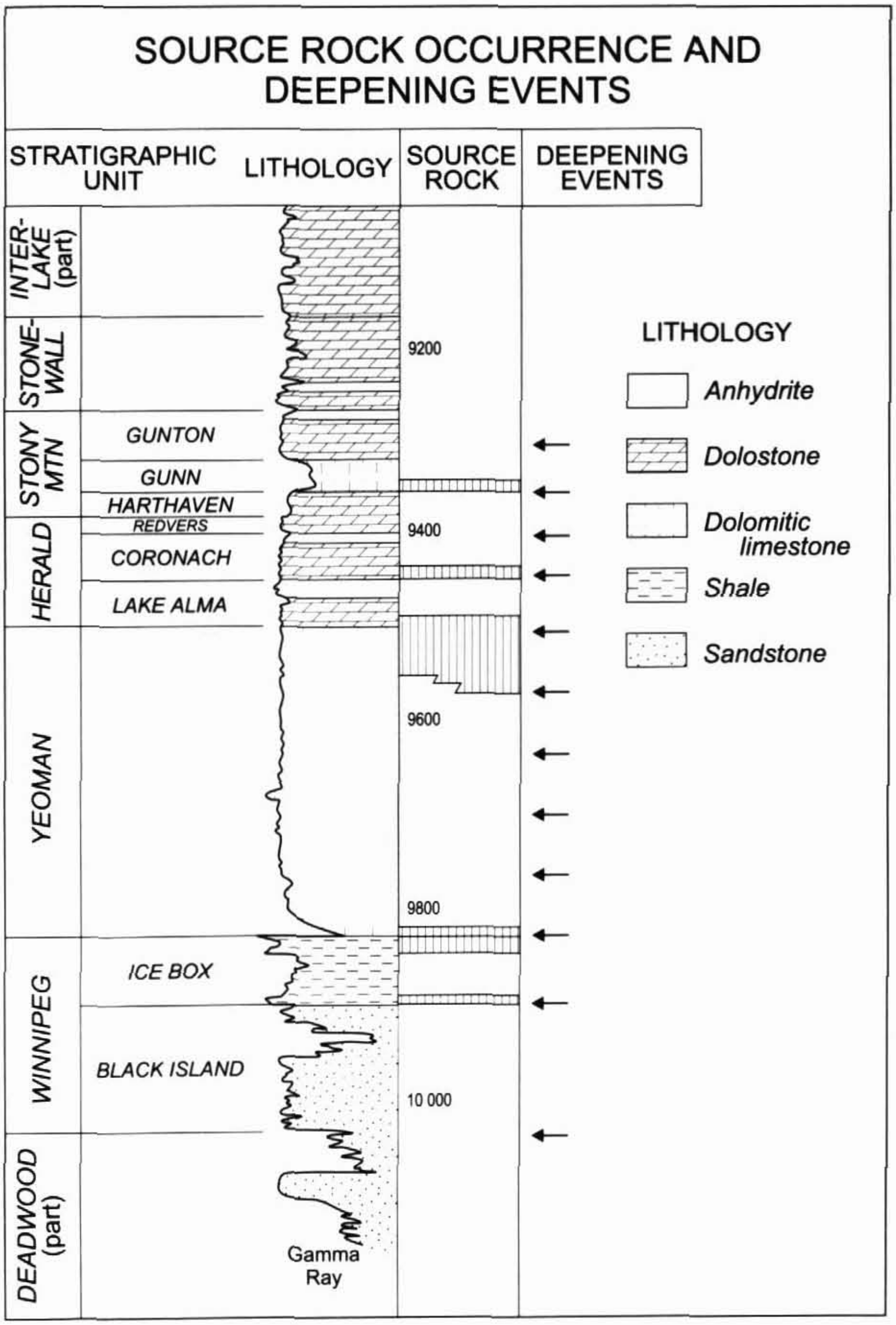


Figure 6 Stratigraphy of Ordovician strata (Winnipeg to Stony Mountain). Hydrocarbon source rocks in the Yeoman Formation consist of *G. prisca* alginite organic microfacies (after Osadetz *et al.*, 1989; see Mossop and Shetson, 1994 for details of regional stratigraphy).

Upper Ordovician Source Rocks, Williston Basin

***Gloeocapsomorpha prisca* Alginite Marine Hydrocarbon Source Rocks**

The first example of organic microfacies is from variably bioturbated to laminated, dolomitic wackestones to lime mudstones of the Upper Ordovician Yeoman Formation of southeastern Saskatchewan (Fig. 6). The host carbonate sequence was deposited in a broad, shallow water epicontinental seaway characterized by a gradually sloping ramp profile resembling the modern Trucial coast area of the Persian Gulf (Stoakes *et al.*, 1987a). Several hydrocarbon source rock zones in the Yeoman Formation have exceptional potential for oil generation and many are characterized by very high total organic carbon contents (up to 35 % TOC), and very high hydrogen indices (up to 1000 mg hydrocarbon/g Organic carbon) and low oxygen indices (Type I kerogen; Osadetz *et al*, 1989; Fowler *et al.*, 1998). Macerals in the Yeoman Formation are characterized by a preponderance of *Gloeocapsomorpha prisca* coccoidal alginite. Similar *G. prisca*-enriched hydrocarbon source rocks of Cambrian and Ordovician age (referred to as kukersites) are known from around the world (*e.g.*, Fowler, 1992; Tyson, 1995), each characterized by a distinct organic geochemical composition with a dominance of C_{15}-C_{19} normal alkane hydrocarbons showing an odd-carbon-number predominance and very low amounts of acyclic isoprenoid biomarkers (Fowler, 1992). Their occurrence is thought to be restricted to lower Paleozoic geological periods with some workers proposing a possible late Ordovician extinction (see Fowler, 1992, p. 353). Recent investigations by Fowler and Stasiuk (1999) have, however, discovered apparent *bona fide G. prisca* alginite from Upper Devonian strata in southern Alberta, placing in doubt these previous contentions.

Much controversy has surrounded the biological origin and life habit of the *Gloeocapsomorpha prisca* precursor microalgae, leading to a large number of organic petrology and organic geochemistry studies aimed at resolving the issue. In fact, the origin of the alga has been debated by paleontologists at least since 1917 (see Wicander *et al.*, 1996). Conclusions from more recent studies of *G. prisca* differ greatly, ranging from assignment to a non-photosynthetic, prokaryotic, benthic, mat-forming organism, to a photosynthetic cyanobacteria (*e.g.*, Reed *et al.*, 1986; Foster *et al.*, 1990; Stasiuk and Osadetz, 1990) to a phototrophic, planktonic and possibly eucaryotic organism (Hoffmann *et al.*, 1987) perhaps related to the extant green algae *Botryococcus braunii* (Derenne *et al.*, 1992). By using organic microfacies analysis of maceral assemblages within the Yeoman Formation kukersites from southern Saskatchewan, Stasiuk and Osadetz (1990) and Stasiuk *et al.*, (1994) advanced the debate by identifying three distinct organic microfacies for *G. prisca* alginite, each interpreted to represent a distinct life cycle stage of the precursor alga. Definition of three marine organic microfacies in the Yeoman Formation is based on variations in size and microscopic "habit" of *G. prisca* alginite within the rock fabric.

Marine Gloeocapsomorpha prisca Organic Microfacies

Two of the organic microfacies in the Yeoman Formation consist of *Gloeocapsomorpha prisca* alginite which appears to be "floating" within a carbonate matrix. Organic microfacies Gp_{DA} (Gp is for *G. prisca*, and $_{DA}$ defines alginite variety based on size and cell wall character) and organic microfacies Gp_{DB} are characterized by disseminated A and disseminated B maceral varieties of *G. prisca* alginite, respectively, and occur dispersed within a fine-grained matrix of calcite and dolomite (Stasiuk and Osadetz, 1990; Stasiuk *et al.*, 1994). Organic microfacies Gp_{DA} consists of small (generally <5-20 µm), thin-walled, *G. prisca* alginite colonies typically consisting of no more than 12 individual cells (Fig. 7a-d). Organic microfacies Gp_{DB} is similar although it consists of larger *G. prisca* colonies (up to 100 µm) with much thicker outer cell walls (Fig. 7a, 7e-g). Prasinophyte alginites and acritarchs (Fig. 7h) derived from green microalgae are also commonly present in both organic microfacies. Scolecodonts (*e.g.*, Fig. 4l), derived from the jaw apparatus of burrowing annelid worms, and zooplankton-derived, chitinozoans (*e.g.*, Fig. 4g) are also present in these kukersites. Organic microfacies Gp_{DA} are characterized by relatively lower TOC contents and hydrogen indices relative to organic microfacies Gp_{DB} (Stasiuk and Osadetz, 1993; Fowler *et al.*, 1998).

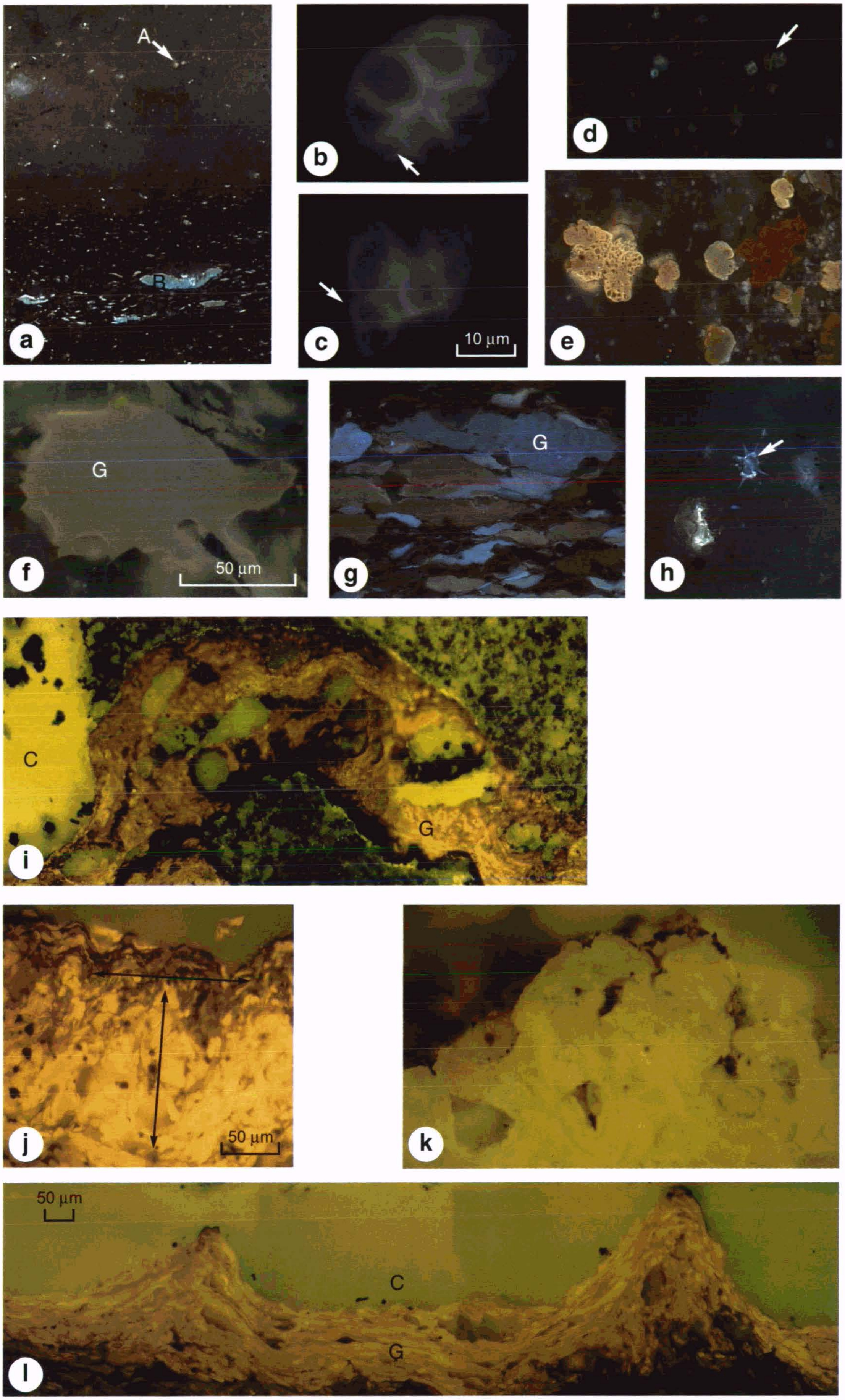
Stromatolitic organic microfacies (designated omf Gp_S) in the Yeoman Formation is also dominated by *Gloeocapsomorpha prisca* alginite macerals, however the alginite occurs very concentrated in an algal mat habit, forming micro-textures such as flat laminations, pinnacles, domes/pustules, "light response" phototactic structures and endolithic algae borings (Fig. 7i-l; Fig. 8). The best preserved microtextures in organic microfacies Gp_S are associated preferentially with hardgrounds (Fig. 7i,l). Organic microfacies Gp_S in the Yeoman have very high TOC contents, very high hydrogen indices and low oxygen indices relative to the organic microfacies Gp_{DA} and Gp_{DB} (Stasiuk and Osadetz, 1993; Fowler *et al.*, 1998). Many of the stromatolitic microtextures formed by *G. prisca* in the Yeoman Formation (Fig. 8) have distinct similarities to those of modern algal and cyanophyte stromatolites (*e.g.*, Golubic, 1976; Park, 1976; Kinsman and Park, 1976).

Gloeocapsomorpha prisca Life Cycle and Paleodepositional Model

Many existing microalgae exhibit great morphogenetic variability in response to environmental factors. For example, they may possess two or more entirely different morphologies at different stages in their life history (see Fritsch, 1958; South and Whittick, 1987). The three organic microfacies in the Yeoman Formation likely are manifestations of the life cycle of the precursor microalgae (Fig. 9a). The disseminated *Gloeocapsomorpha prisca* alginite in organic microfacies GP_{DA} displays a morphology characteristic of a coccoidal planktonic microalga within a very early stage of maturity and growth (Fig. 9a) (Padmaja, 1972). The green microalgae-derived macerals (*i.e.*, Prasinophytes and acritarchs) in this organic microfacies indicate that phytoplankton other than *G. prisca* also occupied the paleowater column and thus the paleoecological system. Burrowing worms were also present (*i.e.*, scolecodont macerals) indicating that some free oxygen was available in the sediment.

A marked change in *Gloeocapsomorpha prisca* alginite morphology and an advanced growth stage of the microalgae precursor is preserved within organic microfacies Gp_{DB}, *i.e.*, larger, thick-walled alginite which represents the transformation from an early (organic microfacies Gp_{DA}), to mature or vegetative growth stage (Fig. 9a). During this period of growth *G. prisca* likely dominated the paleowater column and paleoecological system with relatively minor contribution from unicellular green microalgae. Organic microfacies Gp_{DB} is thus interpreted to represent a monospecific algal bloom period. Subsequent to the bloom, *G. prisca* (organic microfacies Gp_S) appears to have developed stromatolites likely initiated by the microalgae sinking to the water-sediment interface (Fig. 9a,b). Microtextures in the *G. prisca* mats indicative of response to sunlight (*e.g.*, gliding and phototaxis; *e.g.*, Monty, 1976) show that the original alga was photo-

Figure 7 (facing page) Photomicrographs illustrating macerals in Upper Ordovician Yeoman Formation kukersite source rock. All photos were taken under ultra-violet and blue incident light, except b and c which were taken using confocal laser scanning fluorescence microscopy (see Stasiuk (1999); *scale on f is also for d-h; scale on c is also for b; scale on j is also for a, i, k, l.* **a.** Image showing lamina rich in small disseminated *G. prisca* alginite (A), omf Gp_{DA} alternating with lamina rich in large disseminated *G. prisca* alginite (B), omf Gp_{DB}. **b,c.** High magnification image *G. prisca* disseminated A alginite (from organic microfacies Gp_{DA}) collected using confocal laser scanning fluorescence microscopy; note cell division, 'budding' of colony. **d.** Small colonies of thin-walled disseminated *G. prisca* alginite from organic microfacies Gp_{DA}. **e.** Thick-walled, large colonies of disseminated B *G. prisca* alginite associated with small *G. prisca* A alginite. **f, g.** Highly thickened cell walls in disseminated *G. prisca* alginites (G), almost completely obliterating the cell structure of the algal colony. **h.** Spiny acanthomorphic acritarch, probably from green microalgae. *i. Dome-shaped stromatolite* micro-texture formed by *G. prisca* alginite (G), omf Gp_S associated with carbonate hardground (C). **j.** Light response by microalgae preserved in *G. prisca* alginite stromatolite; horizontal zone (arrow) may represent night response and the vertical zone (arrow) day response growth. **k.** Algal head or pustule stromatolite microtexture preserved in omf Gp_S. **l.** Pinnacles formed by *G. prisca* alginite (G) preserving stromatolite microtexture in omf Gp_S *associated with carbonate hardground (C).*


A
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synthetic. The complete lack of calcification in the algal mats formed by *G. prisca* is characteristic of subtidal mat growth in modern environments (Round, 1981), which is consistent with the geological setting (Osadetz *et al.*, 1989).

Organic microfacies in the Yeoman Formation kukersites, Gp_{DA}, Gp_{DB} and Gp_S, undoubtedly resulted from preservation of resistant cell walls of the most dominant microalgae living in the water column and near the sediment water interface. The microscopic interlayering of the three *Gloeocapsomorpha prisca* "life cycle stages," has, in some places, preserved a record of periodicity and variability in paleodepositional and paleoecological conditions. Factors such as increases in sedimentation rates are known to effect growth and productivity in living microalgae, as does changes in water salinity, free oxygen, temperature, nutrients and photic conditions (Fay, 1983; South and Whittick, 1987) (Fig. 9b). It is not known which factor or combination of factors controlled the increase in bioproductivity of *G. prisca* during Ordovician time; this remains open to further investigation. Nonetheless it is clear that variability in paleoenvironmental conditions played an important role in initiating and controlling the growth cycles and productivity of *G. prisca*.

Why were the highly organic-rich kukersites preserved? A combination of selective preservation of resistant cell walls and anoxia likely controlled the formation of these high quality oil-prone hydrocarbon source rocks in the shallow subtidal paleoenvironment during Ordovician time. Considering that the kukersites occur as relatively thin zones (cms to tens of cm) interbedded with bioturbated lime mudstones containing macerals and macrofossils indicative of normal, oxygenated marine conditions (*e.g.*, scolecodonts and crinoids), deoxygenation of the water column fostered by *Gloeocapsomorpha prisca* algal blooms (see Chow *et al.*, 1995) must have further enhanced the preservation potential of the highly resistant biomacromolecular cell walls of the precursor microalgae to form such excellent hydrocarbon source rocks.

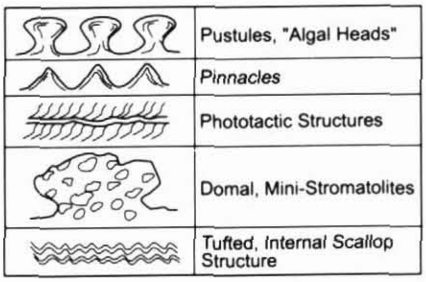

Figure 8 Summary sketch of stromatolite micro-textures formed by *G. prisca* alginite in organic microfacies Gp_S. Similar stromatolite textures have been reported from Holocene sediments in both intertidal and subtidal depositional settings.

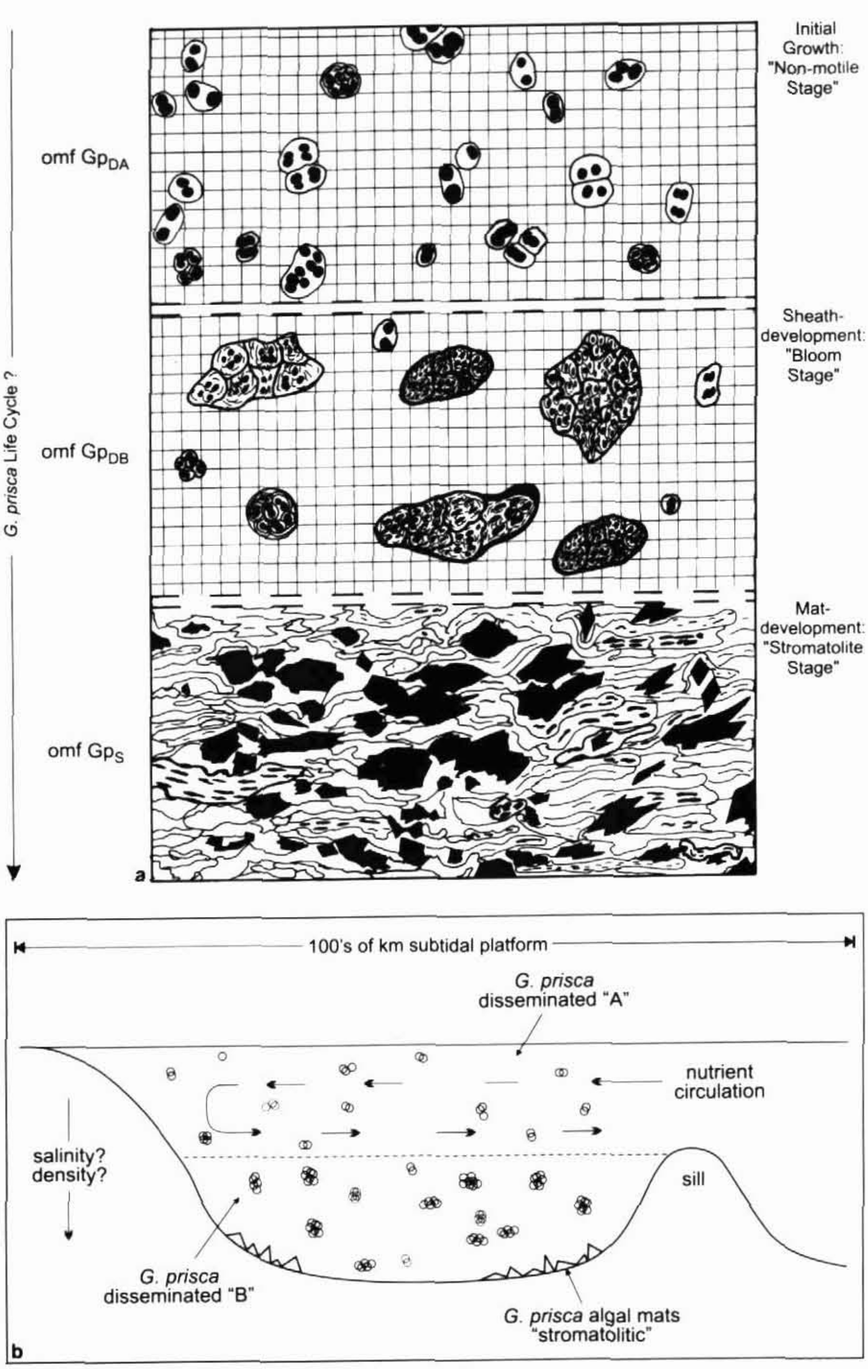

Figure 9 Model of "life cycle" (**a**) and paleodepositional setting (**b**) for *Gloeocapsomorpha prisca* alginite in Upper Ordovician Yeoman Formation hydrocarbon source rocks, Saskatchewan. In the early stage (disseminated A maceral variety; omf GP_{DA}) the alga, which consisted of ~2-12 coccoidal cells, was non-motile and planktonic. After several weeks, it is probable that *G. prisca* entered a palmella "bloom" stage (disseminated B maceral variety; omf GP_{DB}) when the alga became significantly larger through successive vegetation and agglomeration into colonies. At one, perhaps late stage, *G. prisca* formed algal mat-stromatolites (omf GP_S) on the sediment surface.

Middle Devonian Source Rocks, WCSB Elk Point Group Laminites

Middle Devonian bituminous lime mudstone laminites of the Lower Keg River Member in the La Crete Subbasin of northwest Alberta, and laminites of the Brightholme Member of the Winnipegosis Formation, Elk Point basin, west-central Saskatchewan (Fig. 10), are very enriched in kerogen with high TOC contents (up to 25 wt%; Osadetz *et al.*, 1992; Osadetz and Snowdon, 1995; Chow *et al.*, 1995). These two units are approximately time-equivalent, consisting mainly of type I to type II marine kerogen (Fig. 11) and, as for the Yeoman Formation kukersites, are also examples of the importance of high primary productivity to the formation of hydrocarbon source rocks (Chow *et al.*, 1995).

A detailed sedimentology, sequence stratigraphy and organic petrology analysis of the Lower Keg River Member hydrocarbon source rocks was completed by Chow *et al.* (1995). These laminites (generally cm's to <1 m thick) with the highest TOC contents and Hydrogen Index values (Fig. 11) occur within transgressive sequences, and probably accumulated within photic zone, anoxic waters (Clegg *et al.*, 1997) in the deepest part of a carbonate ramp setting where water depths are estimated to have been no greater than 20 to 40 m (Chow *et al.*, 1995). Interbedded with the Keg River organic-rich laminite lime mudstones are open marine wackestone carbonates containing abundant brachiopod and crinoid fossils (Chow *et al.*, 1995). Time-equivalent dolomitic shales with much lower TOC contents and Hydrogen Indices accumulated in shallower, more oxic waters within the "proximal ramp" (Fig. 11). To the west of the La Crete Subbasin, the Peace River Arch (*e.g.*, Podruski, 1988; Mossop and Shetson, 1994) was a topographic high and exposed hinterland during Keg River laminite accumulation, potentially providing a source for fine-grained detrital sediments and in particular for nutrients to be shed into the carbonate depositional Subbasin (Chow *et al.*, 1995).

Similar detailed sedimentology and sequence stratigraphic studies have not been conducted for the Brightholme Member laminites of the Winnipegosis Formation in the Williston Basin, although these rocks have been described from east-central and eastern Saskatchewan and western Manitoba. The Brightholme laminites source rocks are considered to have formed in a restricted, "basinal" setting associated with coeval reef, and carbonate buildups (Wardlaw and Reinson, 1971; Davies and Ludlam, 1973; Stoakes *et al.*, 1987b).

Marine Prasinophyte-amorphinite Organic Microfacies

Rock-Eval data (Chow *et al.*, 1995; Osadetz and Snowdon, 1995), biomarker geochemistry of solvent extracts (Osadetz *et al.*, 1992; Fowler *et al.*, 1993; Clegg *et al.*, 1997) and reflected light microscopy (Stasiuk *et al.*, 1991; Stasiuk, 1993; Stasiuk *et al.*, 1994; Chow *et al.*, 1995; Clegg *et al.*, 1997) of DOM from the Lower Keg River and Brightholme laminites reveals that both source units contain organic matter of similar biological origin. In the best pre-

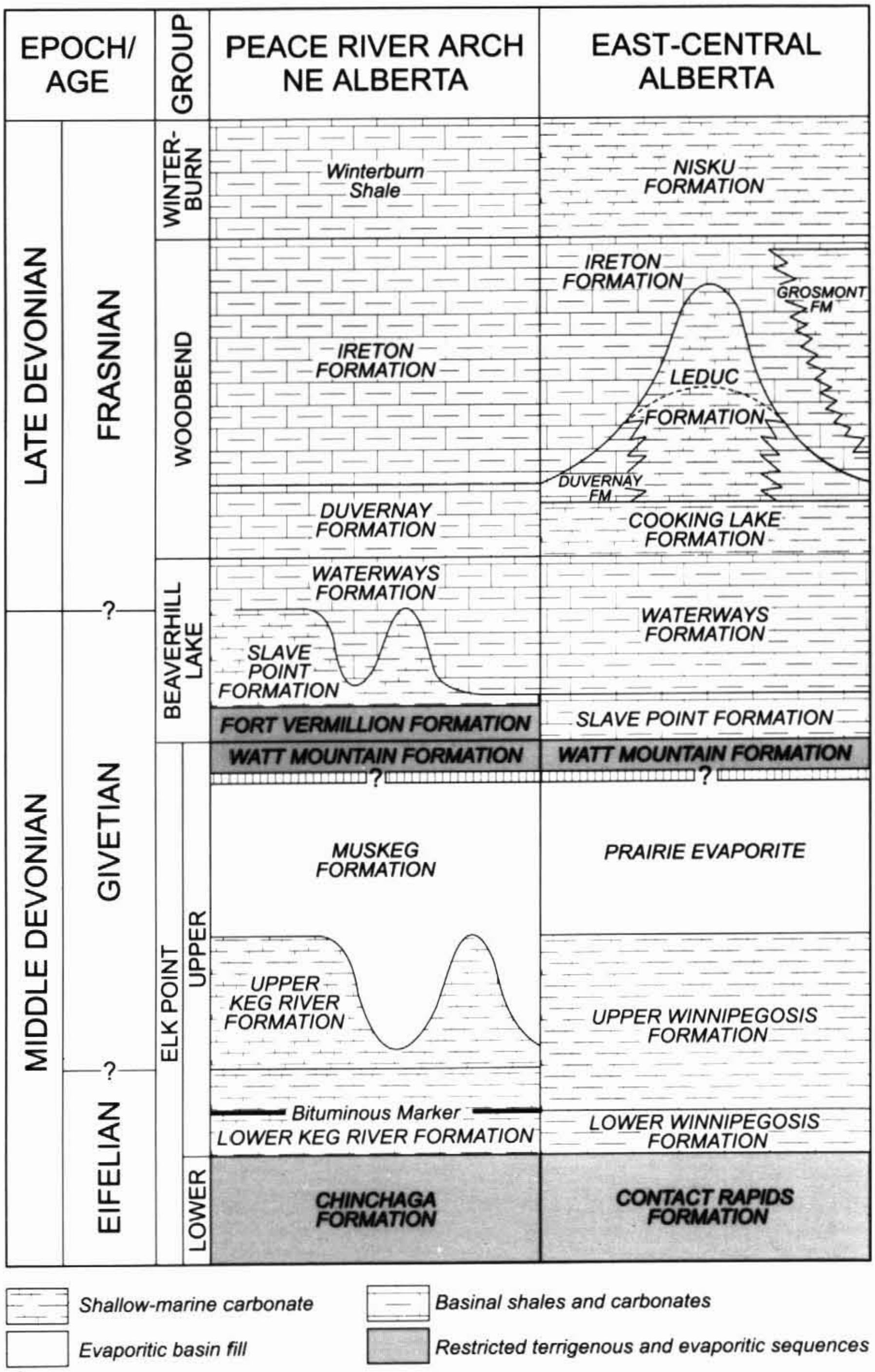

Figure 10 Stratigraphy of Devonian strata for the La Crete Subbasin, northeastern Alberta and "East Shale" basin, east central Alberta (see Mossop and Shetson, 1994 for details of regional stratigraphy).

served, and "least physically disrupted" laminites, two dominant organic microfacies can be distinguished with reflected light microscopy. Organic microfacies P_A (P for Prasinophyte; $_A$ defines alginite variety based on size and cell wall character) is very organic-rich and consists of a network of weakly fluorescing amorphinite[9] (Fig. 12a), and abundant, large (up to 350 μm in diameter), thick-walled, unicellular Prasinophyte *Leisphaeridia* and *Tasmanites* alginites (Fig. 12a-c; Table 1). Layers and lenses of abundant carbonate cricoconarid microfossils are also common in this organic microfacies (Fig. 12b,g) and within many parts of the laminites in general (Chow *et al.*, 1995). Other, secondary, but important macerals in organic microfacies P_A include round vitrinite macerals (Fig. 12d,e,f; Stasiuk, 1994; Stasiuk *et al.*, 1994) and spiny, green microalgae-derived acritarchs (*e.g.*, *Veryachium*). In contrast, organic microfacies P_B consists of a discontinuous network of amorphinite associated mainly with small (~5-35 μm), rather than large Prasinophyte alginite macerals (Fig. 11a,c) and is relatively organic-lean. Spiny acritarchs and terrestrial sporinites also occur in minor amounts.

Laminite "Algal Bloom Model"

The varve- or couplet-like lamination shown by organic microfacies P_A and organic microfacies P_B in the Elk Point Group laminites is classified as biogenic, and likely resulted from variations in biogenic flux within the paleoenvironment (*e.g.*, Kemp, 1996). The maceral composition and organic microfacies in these laminites clearly indicates that periodic, photic zone algal bloom episodes were important to organic matter preservation and hydrocarbon source rock formation (Chow *et al.*, 1995; Clegg *et al.*, 1997). Lamina enriched in small Prasinophyte alginites (omf P_B) represent preservation of early growth/immature green, phytoplanktonic microalgae (*i.e.*, marine chlorophytes probably similar to living *Pterosperma* or *Pachysphaera* algae; see Tappan, 1980) cells formed during "normal" productivity. In contrast, lamina enriched in large Prasinophyte alginites (omf P_A) represent mature, green microalgae resting cells (or **phycoma**) formed during algal bloom periods and anomalous productivity (Fig. 13). The production of large amounts of specialized, reproductive resting cells from planktonic microalgae can reflect highly stressed environments such as those incurred during algal blooms or seasonal breakdown of hydrographic stability of a stratified water column (*e.g.*, Fay, 1983; Anderson, 1994). Stressed growth conditions related to algal blooms in the Elk Point laminite paleoenvironment are also supported by the round vitrinite macerals, in this case derived from specialized reproductive resting cells, or akinetes, of filamentous microalgae or cyanophytes. Morphologically the Elk Point akinete cells are similar to those produced by living filamentous cyanophytes such as *Nostoc* and *Wollea* (Fay, 1983; South and Whittick, 1987; Stasiuk, 1994). Reproductive resting cells of microalgae and cyanophytes settle to the sediment-water interface where they can remain dormant for years if necessary, or until conditions (*e.g.*, nutrient level; extent of photic zone) in the water column return to normal. At such time the resting cells germinate and release swimming or motile cells into the water, beginning a new cycle of active reproduction.

Anoxic conditions (see Chow *et al.*, 1995; Clegg *et al.*, 1997) and enhanced preservation of microalgae-derived organic matter and high quality, oil prone source rocks in the Brightholme and Lower Keg River members appears to have been fundamentally related to episodes of high bioproductivity during Middle Devonian time in western Canada. Summerhayes (1983) has suggested that short bursts of very high bioproductivity may at times exceed an ecosystems ability to mineralize or recycle organic matter, thus leading to *preservation* by productivity. During algal bloom episodes in the La Crete and Williston subbasins, depletion of oxygen in the water column likely was accelerated by extensive bacterial respiration, and, as a consequence, fundamentally controlled the extent of photic zone anoxia (Stasiuk, 1993; Clegg *et al.*, 1997). Deoxygenation of the relatively shallow water column (~20-40 m) appears to have been so extensive that it led to massive kills of calcareous zooplankton which are now preserved as lenses and layers of cricoconarid microfossils in the laminites (Chow *et al.*, 1995). This phenomenon is not unlike the mass mortality among invertebrates and fish imposed by some modern day algal blooms in marine waters (*e.g.*, Cadee, 1992).

The obvious question which arises

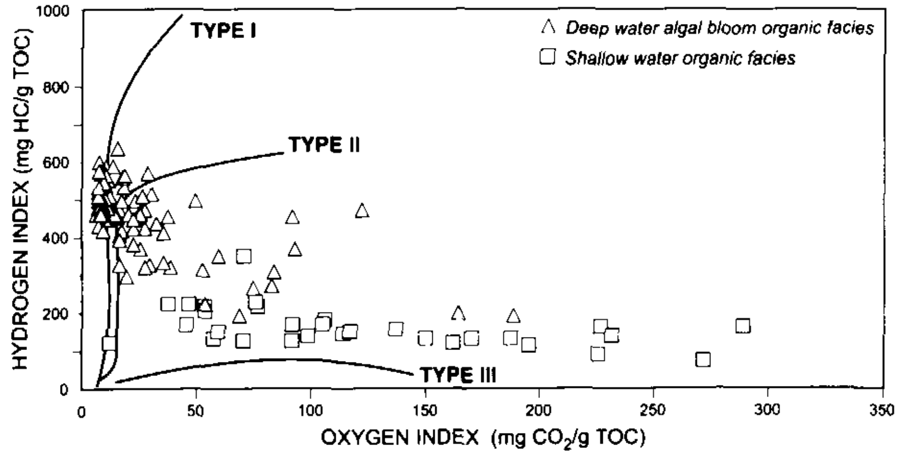

Figure 11 Plot of Rock-Eval hydrogen and oxygen indices defining kerogen types for the Middle Devonian lower Keg River Formation bituminous laminites from deep water, "distal" ramp setting consisting of kerogen-rich, well preserved algal bloom organic facies and microfacies (Type I to II kerogen), and stratigraphically equivalent, shallow water, "proximal" ramp, dolostones consisting of low amounts and poorly preserved kerogen (Type II to III kerogen); *La Crete Subbasin, Alberta*.

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[9] In reflected and transmitted light microscopy "amorphinite" is defined as a structureless maceral of indefinite shape (Fig. 4p-r). It is typically very low reflecting in thermally immature rocks. Boussafir *et al.* (1995) have shown that four types of amorphinite with different origins are present in laminites of the Kimmeridge Clay Formation: 1) bacteran walls derived from selective preservation, 2) lipids which have been vulcanized by sulphur; 3) biomacromolecular algaenans from selective preservation; 4) altered lignin.

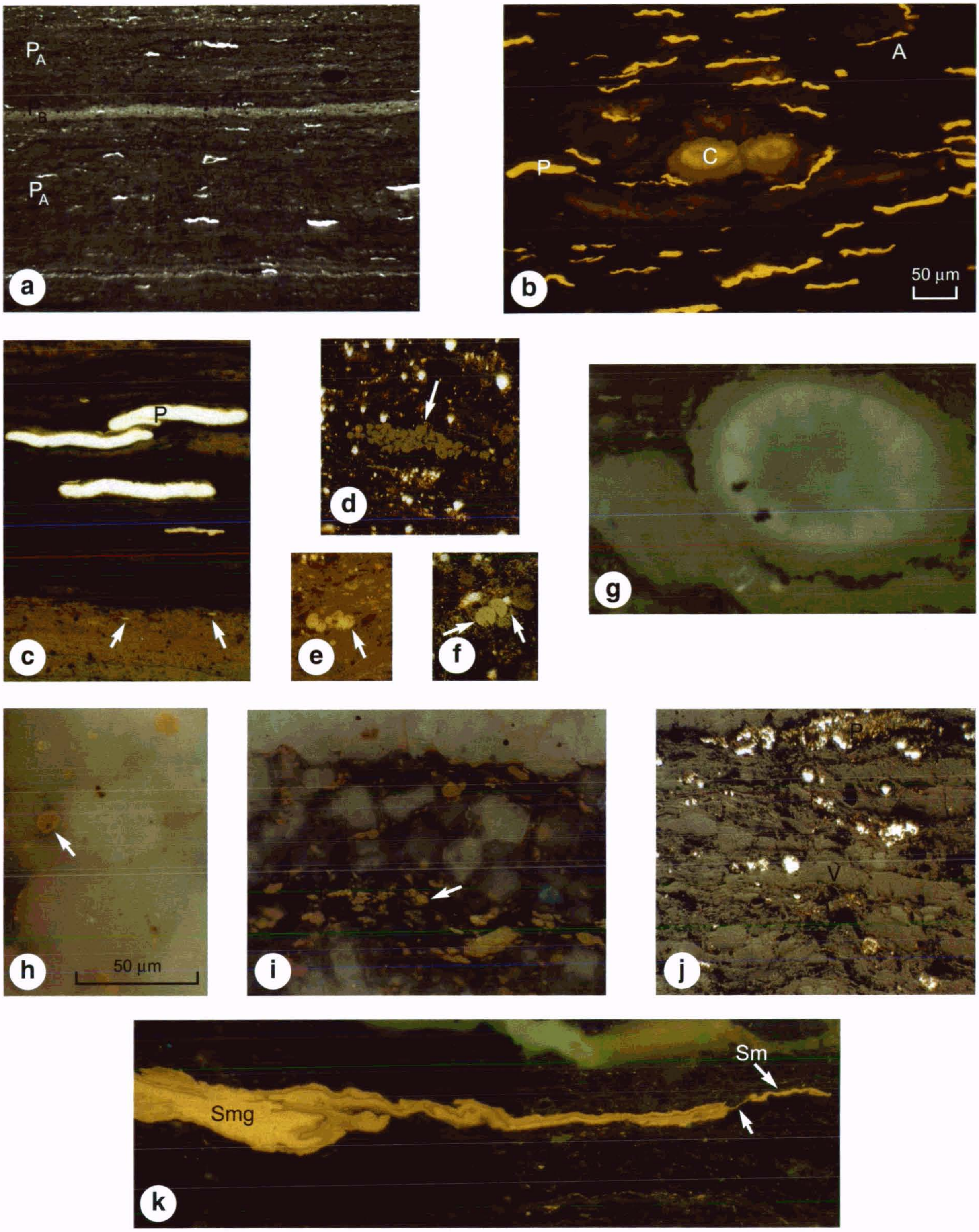

Figure 12 Photomicrographs of macerals in Middle Devonian Keg River (northwest, Alberta) and Winnipegosis (east-central Saskatchewan) formation laminites (a-g) Middle Devonian Ashern to Upper Winnipegosis formation strata, east-central Alberta (h-k). All photomicrographs were taken under ultra-violet and blue, incident light, except d-f and h which are in reflected white light; scale on b as also for a and k; scale on h is for remainder. **a.** Low magnification, perpendicular to bedding view showing alternation of thin, organic-lean lamina hosting very small Prasinophyte alginite (non-algal bloom omf **P_B**) and thick, organic-rich lamina hosting large, thick-walled Prasinophyte alginite (algal bloom omf **P_A**) **b.** Yellow fluorescing, thick-walled, Prasinophytes alginite (P) with lens of "planktonic," cricoconarid microfossils (C) and amorphinite (A) in marine algal bloom omf P_A. **c.** Close up of organic-rich laminae with yellow fluorescing marine Prasinophyte alginite (P) associated with dark amorphinite and organic-poor lamina with small Prasinophyte alginites (arrows). **d-f.** Round vitrinite group macerals derived from micro-algal special reproductive, resting or akinete cells, indicative of algal blooms (arrows). **g.** "Planktonic" cricoconarid microfossils with internal, early, "dog's-tooth," calcite cement. **h.** Very small colonies of marine, platformal, coccoidal *G. prisca* alginite. **i.** Small colonies of *G. prisca* alginite, possibly preserved as a stromatolitic omf in marine platform setting. **j.** Grey-reflecting vitrinite (V) associated with abundant framboidal pyrite (P) minerals. **k.** Yellow-orange fluorescing, land plant-derived sporinite derived from a mega-spore (Smg) shown "releasing" a microspore-derived sporinite (Sm), note attachment by thin "thread" (indicated by arrow).

from the Elk Point paleoecological and paleodepositional scenario is, "what fundamentally controlled the onset of algal blooms in these regions during Middle Devonian time?" This remains largely uninvestigated, but one possible factor which may have influenced formation of the Keg River laminites is proximity to emergent hinterlands (*e.g.*, Peace River Arch west of the La Crete Subbasin) and related influx of nutrients during fresh water run-off into the marine ramp setting, this in turn triggering *periodic and massive algal blooms* (see also Cadee, 1992; Chow *et al.*, 1995). In support of terrestrially-related runoff, Revill *et al.* (1994) have concluded that many Prasinophyte (*e.g.*, *Tasmanites*) algal blooms preserved in the geological record were associated with reduced salinity levels in littoral marine settings, mainly as a consequence of increased freshwater input.

Elk Point Group: Marine to Terrestrial Organic Microfacies

The next examples of organic microfacies are from a siliciclastic-carbonate-evaporite sequence which spans the uppermost Ashern and lowermost Winnipegosis formations of the Middle Devonian Elk Point Group in east-central Alberta (Meijer Drees *et al.*, 1995) (Fig. 10). During Middle Devonian time this region was located within a shallow water inner shelf to coastal plain setting (*e.g.*, Kent, 1994), providing an *excellent record of profound vertical* changes in paleoenvironments, kerogen type, organic facies at the centimetre-to-metre scale, and organic microfacies at the microscopic scale (Fowler and Stasiuk, 1995). At one particular location in east-central Alberta, over an interval of 27 m, kerogen type, total organic carbon contents and Hydrogen Indices vary widely ranging from 0.2% to 58%, and 50-700 mgHC·g^{-1} organic C, respectively (Fig. 14a,b). The maceral assemblages and organic microfacies from this sequence of Elk Point Group strata reflect an overall upward shallowing of depositional waters and a transition from an open marine, "oxidizing," inner platform, setting in the Ashern Formation, passing upward into brackish, coaly deposits and brackish algal, lacustrine-like laminites of the Lower Winnipegosis Formation, and finally into stromatolitic lagoonal evaporites of the Prairie Formation (Figs. 14b).

Marine Platformal, Coccoidal and Unicellular Alginite Organic Microfacies: Ashern Formation

Platformal, silty claystones and dolostones of the Ashern Formation (Meijer Drees *et al.*, 1996) are organic-lean (%TOC_{max} = 0.58) with low hydrogen, and high oxygen indices, and thus have poor potential as hydrocarbon source rocks (Fig. 14b; Fowler and Stasiuk, 1995). Such Rock-Eval characteristics clearly reflect an Ashern paleoenvironment which was adverse to either, or both, high bioproductivity and preservation of oil-prone kerogen. Despite inadequate productivity and poor preservational conditions, organic microfacies comprising small colonies (<5-15 mm in diameter) of coccoidal *Gloeocapsomorpha prisca* alginite and small Prasinophytes can still be defined in the Ashern Formation (Fig. 12i, j). The precursors to both *G. prisca* and Prasinophyte alginite were photic and planktonic in habit, and *G. prisca* in particular, is characteristic of "proximal" shallow water paleoenvironments for several Devonian formations in the Western Canada Sedimentary Basin (see Fig. 15; *e.g.*, bank margin to inner platformal, to lagoonal, to lacustrine-like paleoenvironments; Chow *et al.*, 1995; also see Obermajer *et al.*, 1997). The lack of large, *G. prisca* alginite colonies with thickened outer cell walls indicates that the precursor microalgae population likely was in a very early growth stage of development (Padmaja, 1972; South and Whittick, 1987) unrelated to an algal bloom.

Marine-influenced, Vitrinite-sporinite Coaly Organic Microfacies

Ten metres above the organic-lean marine platformal organic microfacies of the Ashern, and just above the boundary between the Ashern and the overlying Winnipegosis formations, thin organic-rich zones (1664-1665 m depth; Fig. 14b) contain up to 57.5% TOC and occur in association with stromatoporoidal carbonates (Meijer Drees *et al.*, 1995; Fowler and Stasiuk, 1995). Rock-Eval and maceral data from this zone in the Winnipegosis Formation corroborate that coaly, Type III kerogens were preserved locally in east-central Alberta during Middle Devonian time (Fowler and Stasiuk, 1995). Terrestrial macerals are dominant within this organic microfacies including vitrinite, sporinite and cutinite (see Table 1; Fig. 12h,k; Fig. 16c), indicating a substan-

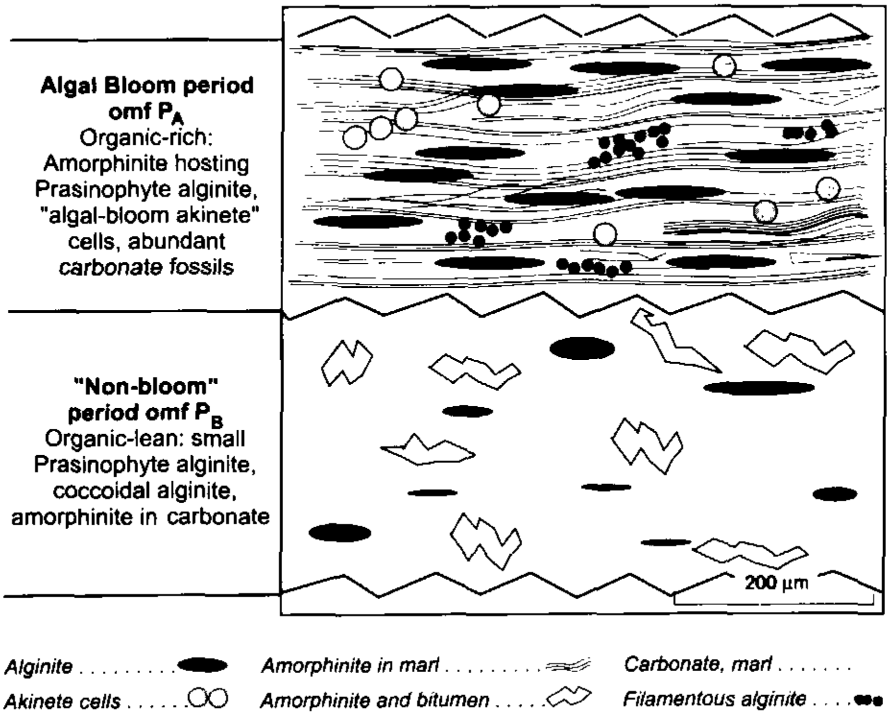

Figure 13 Cartoon illustrating maceral components and lamination of "algal-bloom" (omf P_A) and "non-bloom" (omf P_B) organic microfacies in the bituminous laminite hydrocarbon source rocks of Middle Devonian Keg River Formation lower member, La Crete Subbasin, Alberta (see also Chow *et al.*, 1995).

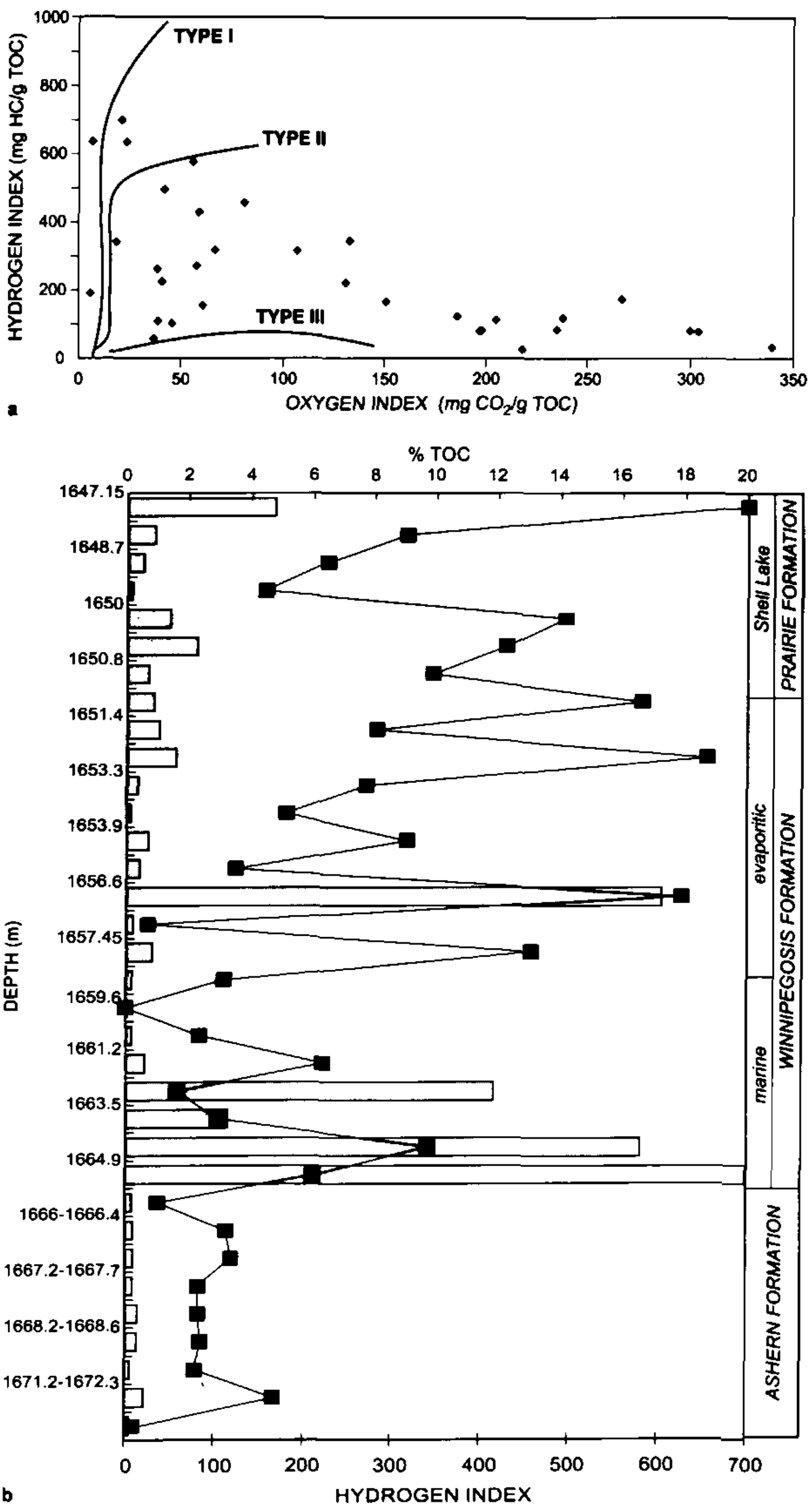

Figure 14 (**a**) Plot of Rock-Eval hydrogen and oxygen indices defining kerogen types for sequence of Middle Devonian Elk Point Group strata at 11-35-38-10W4, east central Alberta; (**b**) Vertical variation in total organic carbon contents and Hydrogen Index through Elk Point Group strata at 11-35-38-10W4 (from Fowler and Stasiuk, 1995 and Meijer Drees *et al.*, 1995); depth axis not to scale; black squares represent Hydrogen Indices and bars represent % TOC.

tial input of higher plant matter typically associated with nearshore marine to deltaic depositional settings. Coccoidal *Botryococcus* alginites also occur in this organic microfacies supporting a fresh to brackish water depositional setting such as lacustrine, back barrier, lower delta plain, or estuarine environments (*Tappan, 1980; Stach et al., 1982*). A significant marine influence on the paleodepositional setting is implied by local concentrations of abundant framboidal pyrite in vitrinite (Fig. 12j), and by the association of stromatoperoids and other carbonate marine fossils (Meijer Drees *et al.*, 1995). Despite the strong marine influence, the preservation of a megaspore "in the process of releasing" and still attached to a microspore by a delicate thread (Fig. 12k) attests to minimal transport and probable autochthonous origin of the thin coaly zone in the Winnipegosis Formation, likely within a coastal plain type of paleosetting (*e.g.*, Kent, 1994).

"Lacustrine (?)" Coccoidal Alginite-sporinite Organic Microfacies

Above the coaly horizon, within the evaporitic dolomites of the upper portion of the Winnipegosis Formation (1656.6 m depth; Fig. 14b), a thin (<2 cm), organic-rich (TOC = 16.5 %), "boghead coal" (see Stach *et al.*, 1982) zone is present. Hydrogen Indices in excess of 600 mg HC·g^{-1} organic C combined with low oxygen indices define the kerogen as Type I/II (Fig. 14), indicating that it is highly prone to generating liquid hydrocarbons during the catagenetic stage of thermal maturity (Tissot and Welte, 1984). The relative amount and size of coccoidal *Botryococcus* alginite and sporinite macerals varies vertically in the Winnipegosis laminites, forming two distinct organic microfacies (Figs. 16b, 17g). Organic microfacies B$_S$ (*i.e.*, *Botryococcus* alginite with minor sporinite) forms the thickest lamina and consists of large, thick-walled, well preserved, chlorophyte-derived *Botryococcus* alginites, and minor amounts of small sporinites set within a matrix of fluorescing amorphinite and mineral matter (Fig. 17g,h). In contrast, organic microfacies S$_B$ (*i.e.*, sporinite macerals with minor *Botryococcus* alginite), form thinner laminae and consist of abundant, large sporinites and minor amounts of small *Botryococcus* alginite colonies set within a matrix of weakly

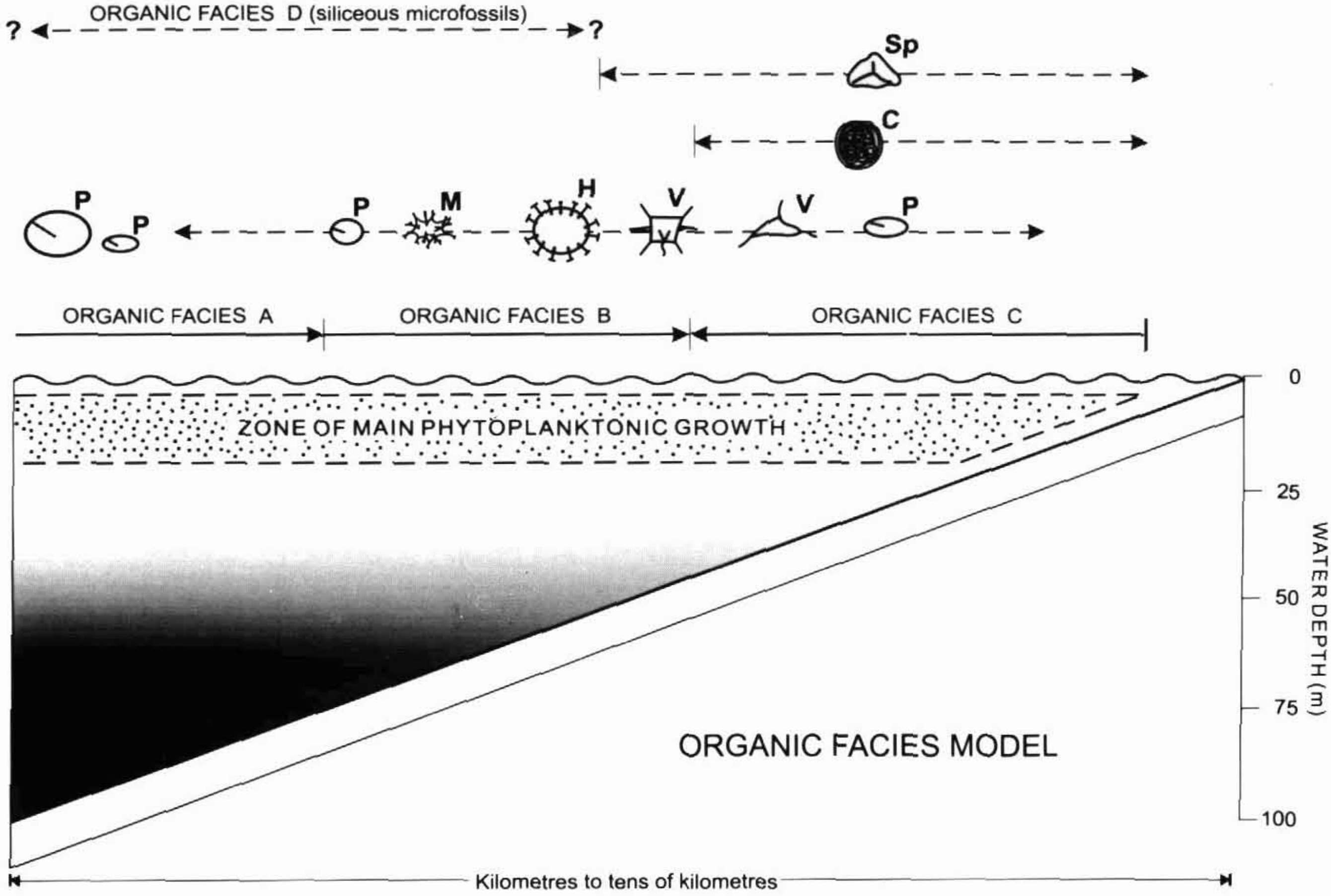

Figure 15 Maceral-based organic facies (of) model for Devonian strata in the Western Canada Sedimentary basin *(see Chow et al., 1995; see also* Obermajer *et al.,* 1997) . The distribution of alginites and acritarchs, siliceous marine microfossils (*e.g.,* radioloarian) and terrestrial sporinites (see also Dorning, 1987; Tyson, 1987) define the organic facies. Organic facies A, B and C are defined by the relative amount and type (size) of unicellular Prasinophyte alginite (*e.g.,* planktonic green algae, P), spiny acanthomorphic acritarchs (planktonic, green algae; H, M, V; *see also inshore-offshore* acritarch zonation by type in Molyneux *et al.,* 1996), coccoidal alginite (planktonic green and/or blue-green algae; C) and sporinite (land plant-derived spores and pollen; Sp). Organic facies D defines intervals containing siliceous microfossil assemblages. Organic facies A represents relatively deep water, organic facies B intermediate water depths and organic facies C, shallow water deposition. The *lateral depositional limit of organic facies D is* probably wide ranging from basinal to platformal.

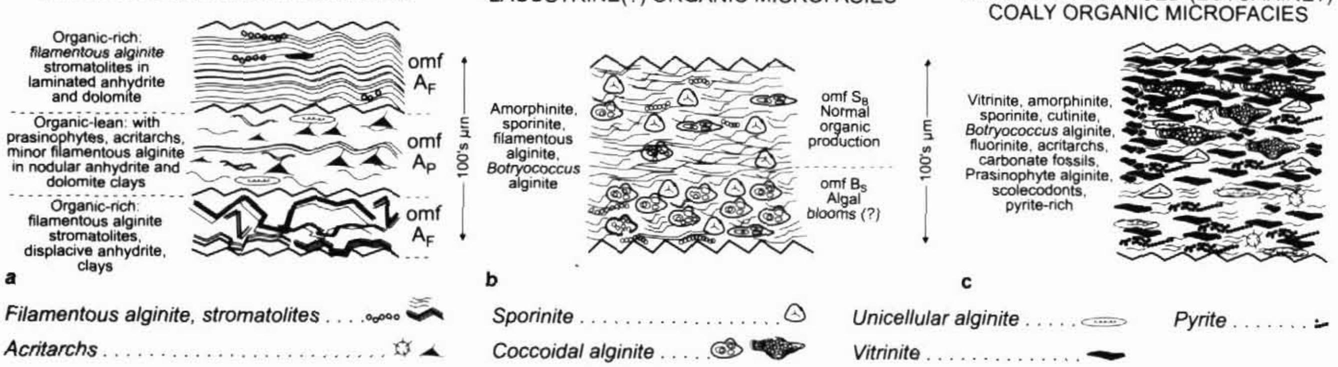

Figure 16 Cartoon illustrating macerals and their spatial relationship within coaly (**c**; Winnipegosis Formation), "lacustrine-like" (**b**; Winnipegosis Formation) and lagoonal (**a;** Prairie Formation) organic microfacies for Middle Devonian Elk Point Group at *11-35-38-10W4, east-central Alberta (see* also Fowler and Stasiuk, 1995).

fluorescing amorphinite and mineral matter (Fig. 17g).

The preservation of couplets (perhaps varves) represented as different organic microfacies and the overall dominance of *Botryococcus* alginite and terrestrial sporinite macerals in both organic microfacies strongly implies cyclical deposition under fresh to brackish water conditions such as those of lacustrine, lower delta plain or estuarine settings (Tappan, 1980; Stach *et al.*, 1982). The variation in the type and proportion of biomass contributing to the sediment (*i.e.*, sporinites *versus* alginites) and the formation of laminae defining organic microfacies B_S and organic microfacies S_B in the Winnipegosis Formation, may record "forcing phenomena" affecting bioproductivity and sedimentation in east-central Alberta during Middle Devonian time, perhaps attributable to annual- or seasonal-related chemical and physical variations in the paleodepositional environment. This is open to further study. The morphological characteristics of *Botryococcus* alginite colonies in organic microfacies B_S are interpreted to represent periods of high productivity and rapid growth, perhaps during periods of elevated salinity, which in living *Botryococcus* microalgae results in the formation of algal colonies with highly thickened, very resistant outer cell walls (Derrene *et al.*, 1992).

Saline Lagoonal, Stromatolitic Organic Microfacies

Just below major salt deposits of the Upper Member of the Prairie Formation, lagoonal anhydrites and argillaceous carbonates of the lower Prairie Formation member (1647-1650 m depth, Fig. 14b), contain several, very thin (<2 cm), organic-enriched zones with total organic carbon contents ranging from 2% to 14%, and hydrogen indices from 200 to 700 $mgHC \cdot g^{-1}$ Org C (Fig. 14b). Two amorphinite-enriched organic microfacies with very low maceral diversity characterize the most organic-rich zones in the upper member lagoonal facies (Fig. 16a). Organic microfacies A_F (*i.e.*, amorphinite with filamentous alginite) contains yellow to orange fluorescing amorphinite and minor filamentous alginite (Fig. 17a,b) with distinctive, rectangular cellular organization (Fig. 17c). Organic microfacies A_P (*i.e.*, amorphinite with Prasinophyte alginites) is similar, but in addition to amorphinite, green microalgae-derived acanthomorphic acritarchs and small Prasinophyte alginite macerals are also present (Fig. 17b,d). The amorphinite and the filamentous alginite macerals have been significantly modified in both organic microfacies as the result of very early diagenetic growth of displacive anhydrite crystals (Fig. 17b,e,f). The distinct absence of pyrite in both organic microfacies (Fig. 17a-f) refelcts a lack of Fe availability and therefore sulphur in the environment was available for very early diagenetic sulphur vulcanization of organic compounds such as lipids (Sinninghe-Damste, 1988), or carbohydrates (Van Kamm-Peters *et al.*, 1998) derived from cellulose-enriched components of algal mats[10].

Although water conditions in the lagoonal paleoenvironment of the Prairie Formation were mainly hypersaline, forming evaporitic deposits, the lamination of organic microfacies A_F with A_P implies variability in paleodepositional conditions. That is, the green, chlorophyte microalgae-derived acritarchs and Prasinophytes in organic microfacies A_P are typically indicative of normal marine conditions in Paleozoic and modern settings (Tappan, 1980; Round, 1981; Tyson, 1995; Molyneux *et al.*, 1996), suggesting periodic transport of phytoplankton from the open marine shelf into the lagoon (*e.g.*, storms), and in the process, "freshening" the lagoonal waters. By contrast, organic microfacies A_F is interpreted to have accumulated during periods of higher salinity (hypersaline ?) with an apparent low diversity of organisms within the lagoon waters reflected in low maceral varieties. Such low biological diversity in general is typical of rather hostile depositional conditions, such as those created by algal blooms, or in this case, high salinity (Fay, 1983; South and Whittick, 1987).

Image Analysis of Middle and Upper Devonian Laminites

In order to use maceral distributions in recent and ancient laminites as geochronomators to assess annual, interannual, decadal, or longer-term variability in paleodepositional, paleoecological and paleoclimate settings, data collection and basis for interpretation should include image analysis. This is a powerful method of evaluating vertical changes in quantitative parameters. Automated aquisition of digital microscopic images of laminites has been successfully applied to the study of Recent sediments, especially in the counting and measurement of varves (*e.g.*, Zolitschka, 1996).

Applied image analysis of Devonian potential hydrocarbon source rocks from the Western Canada Sedimentary Basin in Alberta can compare and contrast: a) the vertical distribution of Prasinophyte alginites from a shallow water, ramp setting in Middle Devonian Keg River Formation laminites from the La Crete Subbasin, with, b) the distribution of alginites from deep water basinal laminites deposited adjacent to a reef complex within the Upper Devonian Duvernay Formation, Alberta. Laminite zones with minimal physical disruption in lamina were selected for analysis, thus providing the best potential for detecting "cyclic or non-cyclic" maceral distribution in a vertical profile. By capturing a mosaic of digital images along a 500 μm-wide vertical strip perpendicular to laminite bedding, total number of alginites, mean area and size of alginites, and total area of alginites were calculated (*e.g.*, Fig. 18 shows Duvernay laminite results; see also Stasiuk and Pratt, 1995). Previous sequence stratigraphy, sedimentology and organic microfacies analysis have shown that preservation of DOM in the Duvernay Formation basinal source rocks was largely a function of depth-related anoxia rather than bioproductivity, as illustrated by a correspondence between TOC contents, organic facies, and depositional facies and cycles within the Duvernay laminites (see Chow *et al.*, 1995). In contrast, as described above, a combination of stratigraphic, sedimentologic and organic microfacies analysis of the Keg River laminites concluded that DOM accumulation and preservation in these strata was linked fundamentally to massive algal bloom episodes which took place in a shallow water, distal ramp setting.

The vertical distribution of total number, and mean and total area of alginites in the two Devonian laminated hydro-

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[10] This process likely plays a key role in producing a sulphur-rich kerogen type prone to generating S-enriched crude oils at anomalous low levels of thermal alteration (*i.e.*, mid-to-late diagenesis).

carbon source rocks, as defined by image analysis, supports both geological observations, and paleoenvironmental and paleoecological interpretations. For example, the overall average size and variability in average size of alginites in vertical profile for the Duvernay basinal laminites (Fig. 18b) is considerably smaller compared with the alginites in the Keg River laminites, by a factor of ~8-10. The dominance of much smaller Prasinophyte alginites in the Duvernay laminite profile, as compared with the Keg River laminite profile, records the general lack of large, mature, algal bloom-related Prasinophyte alginites in the basinal paleodepositional setting (Fig. 18).

Variations within the Duvernay Formation laminites are also recorded by the vertical distribution of the total number of alginites displaying cyclic rising and falling patterns (*e.g.*, Fig. 18a). The Duvernay laminite (Fig. 18a) forms two basal microcycles, which are overlain by a set of cyclic alginite-lean intervals followed by a set of alginite-rich intervals. What was fundamentally responsible for this cyclicity in the basinal source rocks of the Duvernay? This is open to further research, but within each of the lower cycles, approximately 20 to 25 "couplets" can be defined based on the alternation of large and small alginites. This number of "couplets" is within the range of the 22 year periodicity forced upon the earth by solar magnetic, or Hale cycles. Similar periodicities have also been reported from varved Quaternary lacustrine laminites (see Glenn and Kelts, 1991).

CONCLUSIONS AND FUTURE DIRECTIONS

Reflected light microscopy and organic petrology studies using the maceral concept, and organic microfacies analysis of whole rocks, are proving to be a tremendous asset to the genetic study of organic-rich and organic-lean sedimentary rocks, mainly with respect to organic geochemistry, sedimentology and stratigraphy studies fundamental to oil and gas exploration. Unlike other methods used for evaluating DOM, organic petrology provides direct observational data for evaluating and interpreting both recent and ancient depositional and ecological systems. Organic petrology also has the potential to act as a georecorder for detecting short to long time scale variations and cycles affecting organic matter productivity, accumulation, and preservation and destruction of organic carbon, including climatic effects. Currently, maceral and organic microfacies analysis is used almost exclusively to study ancient laminites or other types of organic-rich, fine-grained sedimentary rocks, despite the fact that the organic petrology data collection, procedures and basis for interpretation also appear to be well suited to assess more recent, Quaternary environments (*e.g.,* Pleistocene to Recent). The challenge for the future is to successfully apply this method for examining modern, organic-rich laminites, and, along with organic geochemical, sedimentological and stratigraphic studies, interpret their origin and variations with time.

To achieve these goals, microscopic studies of dispersed organic matter (DOM), will, in the future, need to include more routine use of transmission electron and scanning electron microscopy, and involve confocal laser scanning fluorescence microscopy which offers higher resolution and the ability to visualize macerals three-dimensionally (see Stasiuk, 1999). Such an integrated microscopic approach, combined with other methods such as organic geochemistry, will improve the characterization and classification of DOM, particularly for amorphous and sub-microscopic organic components.

Improvements in our understanding of the nature, distribution, preservation and significance of organic matter in the rock record are central to understanding hydrocarbon source rock distribution, and in predicting where, and under which conditions, source rocks occur. It is an added benefit that micro-

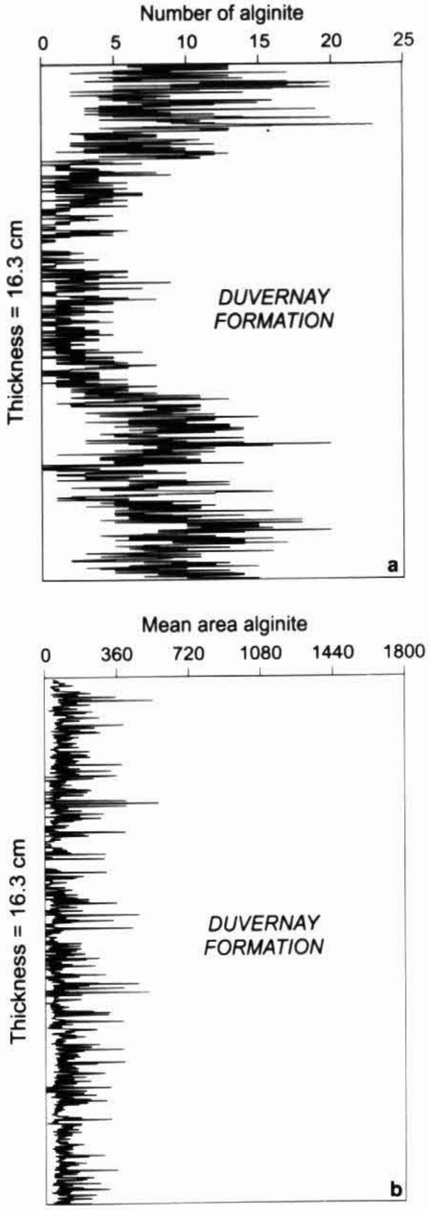
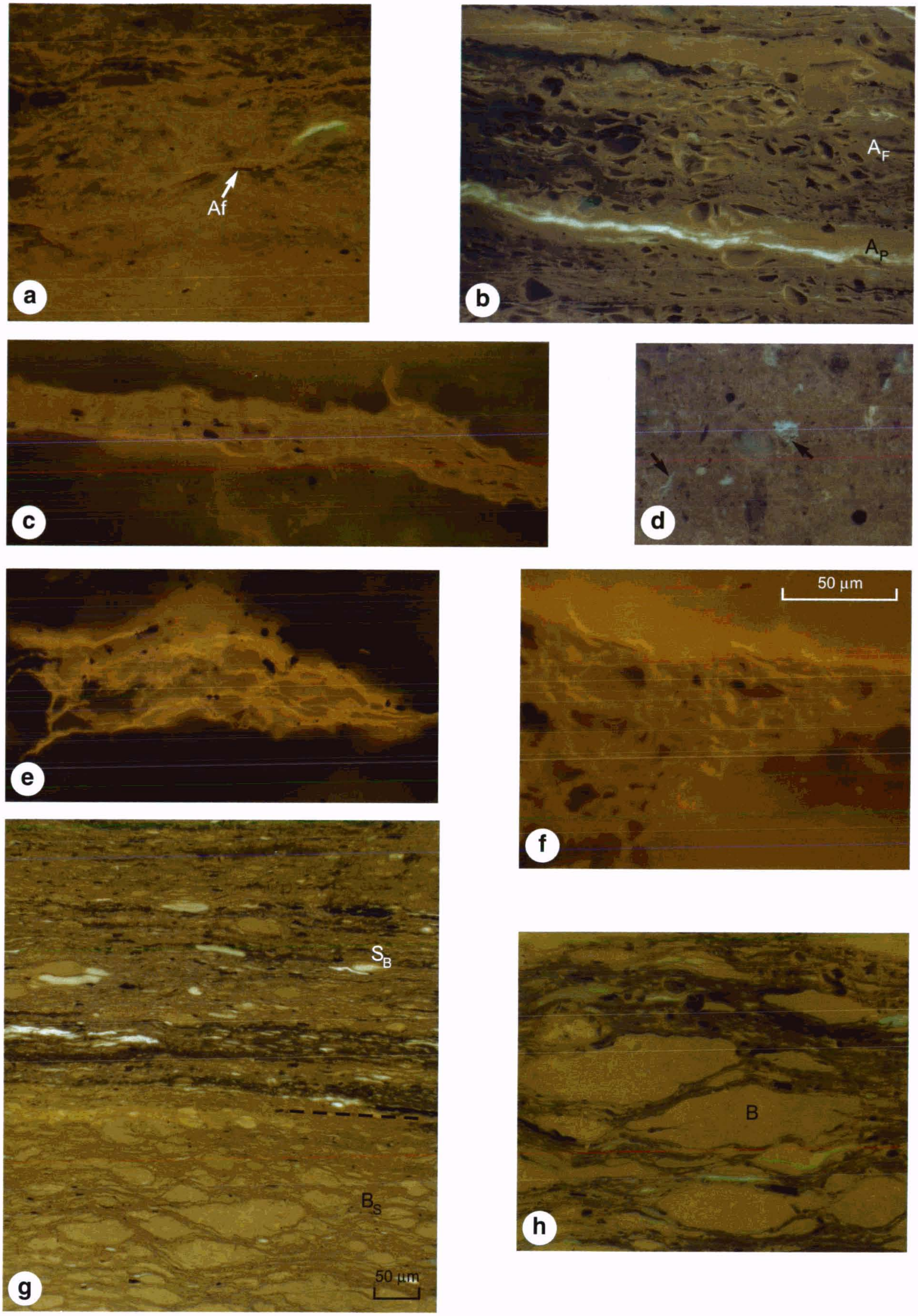


Figure 18 Image analysis profiles illustrating the vertical distribution of total number of alginites per unit area (**a**) and mean area of alginites (**b**) through 16.3 cm of well preserved, Upper Devonian Duvernay Formation laminite hydrocarbon source rocks, Redwater, central Alberta (also see Chow *et al.*, 1995 and Stasiuk and Pratt, 1995). See text for explanation.

Figure 17 (**facing page**) Photomicrographs of macerals and organic microfacies from Winnipegosis and Prairie formations in Middle Devonian Elk Point Group strata, northeastern Alberta; scale on g is also for a and b; scale on f is for remainder of images; all were taken under ultra-violet and blue, incident light. **a.** Perpendicular to bedding plane view of laminated, lagoonal, stromatolitic omf A_F consisting of filamentous alginite (Af) and amorphinite in a dolomitic anhydrite matrix. **b.** Perpendicular to bedding plane view of lagoonal, stromatolitic omf $\mathbf{A_F}$ consisting of filamentous alginite and amorphinite associated with concentration of bright fluorescing marine Prasinophyte alginite, omf A_P. **c.** Microalgae cell structure preserved in filamentous alginite in lagoonal, stromatolitic omf A_F. **d.** Marine acritarchs, indicative of "normal" sea water salinity, in lagoonal omf A_P. **e, f.** Filamentous alginite in omf A_F distorted and expanded by growth of early diagenetic anhydrite. **g.** Perpendicular to bedding plane view of lamination of omf $\mathbf{B_S}$ and omf $\mathbf{S_B}$ with the former rich in large *Botryococcus* alginite and the latter enriched in bright and dull fluorescing terrestrial sporinite. **h.** Close up of fresh to brackish water, colonies of coccoidal *Botryococcus* alginite (B) in omf B_S.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scopically derived knowledge also yields information on short or long term variations in organic productivity. Also, as noted above, there is much scope for the application of the kinds of microscopic techniques that work so well on Paleozoic organic facies and microfacies, throughout the geological column, especially to Mesozoic and younger successions.

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