7(j) Benthic microbial mats as an oil shale component: Green River Formation (Eocene) of Wyoming and Utah

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The lacustrine Green River Formation (Eocene) of Wyoming, Utah, and Colorado (Fig. 7(j)-1) is best known for its fish fossils and its oil shales (Bradley, 1964; Surdam and Stanley, 1979; Roehler, 1990; Russel, 1990; Ferber and Wells, 1995). It contains extensive horizons of carbonaceous shale (Fig. 7(j)-2) with high contents of organic matter and kerogen, and is considered one of the largest oil shale deposits of the world (Tuttle, 1991). In most publications the organic matter is presumed to have originated from planktonic organisms (Bradley, 1964), yet the possibility of benthic microbial mats has been considered (Smoot, 1983; Schieber, 1999). The lakes in which the Green River Formation accumulated were, at times quite shallow (Surdam and Wolfbauer, 1975; Bohacs et al., 2000) and it is therefore conceivable that at certain periods portions of the lake bottoms were colonized by photosynthetic or non-photosynthetic microbial mats.

Smoot (1983) considered the possibility of a microbial mat origin for the Green River oil shales, based on the observation of eroded and transported oil shale intraclasts and the lack of soft sediment deformation (loading) beneath silt ripples overlying oil shale beds. The latter observation suggested that the organic-rich layers that were to become future oil shale beds were cohesive at the time of deposition. This is a behaviour one would more readily associate with a microbial mat than with a simple organic bottom ‘muck’. Though these observations are most intriguing, Smoot (1983) mentioned this issue only in passing and did not provide any illustration of the observed features.

The following considerations are based on personal observations from field work and thin section study of Green River Formation shales from the various sub-basins in which it accumulated (Fig. 7(j)-1). Surveying these oil shales on the hand specimen scale it is clear that not all organic-rich beds were created equal (Fig. 7(j)-3). Some oil shale beds are finely laminated with wavy, continuous laminae (Fig. 7(j)-3A and -3D), whereas others show a more discontinuous lamina style (Fig. 7(j)-3C), and yet others are homogenous and lack lamination altogether (Fig. 7(j)-3E). Whereas the finely laminated type (Fig. 7(j)-3A and -3D) can persuade one to consider a microbial mat origin, such a case is more difficult to make for the discontinuous lamina style (Fig. 7(j)-3C), and quite implausible for the homogenous type (Fig. 7(j)-3E). The wavy lamina style of laminated oil shale beds (Fig. 7(j)-3A and -3D), however, is a weak argument for a microbial mat origin because it could be an artifact of compaction around lenses of detrital or diagenetic dolomite (Schieber, 1999).

Further insights into the origin of the laminated oil shale beds come from shale beds with abundant streaks of carbonaceous material that measure from a few millimetres to several centimetres in size (Fig. 7(j)-3B) and appear to be fragments of laminated oil shale as seen in Fig. 7(j)-3A and -3D. These fragments were transported as discrete particles and show soft deformation and even overfolding. Such features suggest that these fragments had internal cohesiveness, an unlikely behaviour for settled organic-rich bottom muds, but one that is

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consistent with a mat bound surface sediment. In keeping with interpretations of cohesive organic-rich fragments in other mudstone units (Chapter 5), it is therefore assumed that the carbonaceous streaks in Fig. 7(j)-3B represent eroded and transported mat fragments. By extension, this also implies a microbial mat interpretation for laminated oil shales as seen in Fig. 7(j)-3A and -3D.

Examining oil shale samples under the petrographic microscope also indicates multiple modes of origin. At this magnification level, samples from laminated oil shales show continuous wavy laminae of organic material (Fig. 7(j)-4A, B, and C) that are a few microns to tens of microns in thickness. This is a feature that is consistent with microbial mats, a conclusion that receives further support from the observation of transported fragments that indicate internal cohesiveness (Fig. 7(j)-4E).

In contrast, the oil shale samples pictured in Fig. 7(j)-4D, F, and G lack continuous laminae and contain discrete organic particles that are dispersed in a clay and dolomite matrix. These are from oil shale beds with homogenous appearance (Fig. 7(j)-3E) and the organic particles are most readily interpreted as phytoplankton remains that settled to the bottom. In the case of Fig. 7(j)-4F and G there is considerable resemblance to shales elsewhere in the rock record that contain abundant compressed remains of spores, pollen, and algal cysts (cf. Taylor et al., 1998).

The laminated organic intervals in Fig. 7(j)-4A, -4B, and -4C are at first glance very similar to what has been described as “lamalginites” from other lacustrine oil shales (Taylor et al., 1998), yet the organic laminae in the Green River examples show considerably more lateral persistence than the laminae of ‘normal’ lamalginites, a property that one would expect in case of a continuous microbial cover of the sediment surface. It is hard to imagine how accumulation of land- or plankton-derived organic particles could have produced such a structure. The presence of detrital lenses and particles within these laminated organic intervals furthermore indicates a benthic origin, rather than deposition from mid-water mats (Dickman and Artuz, 1978; Dickman, 1985). In conjunction with the cohesive behaviour demonstrated by eroded and transported fragments of this laminated material, and bearing in mind the frayed edges of these fragments that imply strength in the lamina plane (Chapter 5), it is plausible to interpret finely laminated oil shale intervals as the deposits of benthic microbial mats.

Comparable organic-rich beds with wavy laminae have been reported from other lacustrine successions and were likewise interpreted as the result of benthic microbial mats (Hutton et al., 1980; Gibling et al., 1985a, b; Goth, 1990; Wuttke and Radtke, 1993; Goth and Schiller, 1994). Oschmann (2000) described texturally very similar layers from the Kimmeridge Clay, a marine black shale of Jurassic age. Yet, although microbial mats are clearly capable of producing organic-rich shale beds in lacustrine and marine successions, the above observations show that the assessment can not be made uncritically. In the Green River Formation at least, there seem to be fundamentally two pathways that lead to formation of oil shale beds: (1) accumulation of abundant planktonic organic matter in the bottom sediments, or (2) buildup of organic matter through the growth of benthic microbial mats. The former process led to formation of homogenous oil shale beds, and the latter resulted in finely laminated oil shales. In both cases very low net sedimentation rates were an additional prerequisite. The photos in Fig. 7(j)-4 also show that laminated oil shales generally have higher concentrations of organic matter than the homogenous type, possibly a suggestion that autotrophic rather then heterotrophic bacteria were involved in mat formation (heterotrophic bacteria would have reduced the amount of organic carbon).

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Figures and Captions: Chapter 7(j):

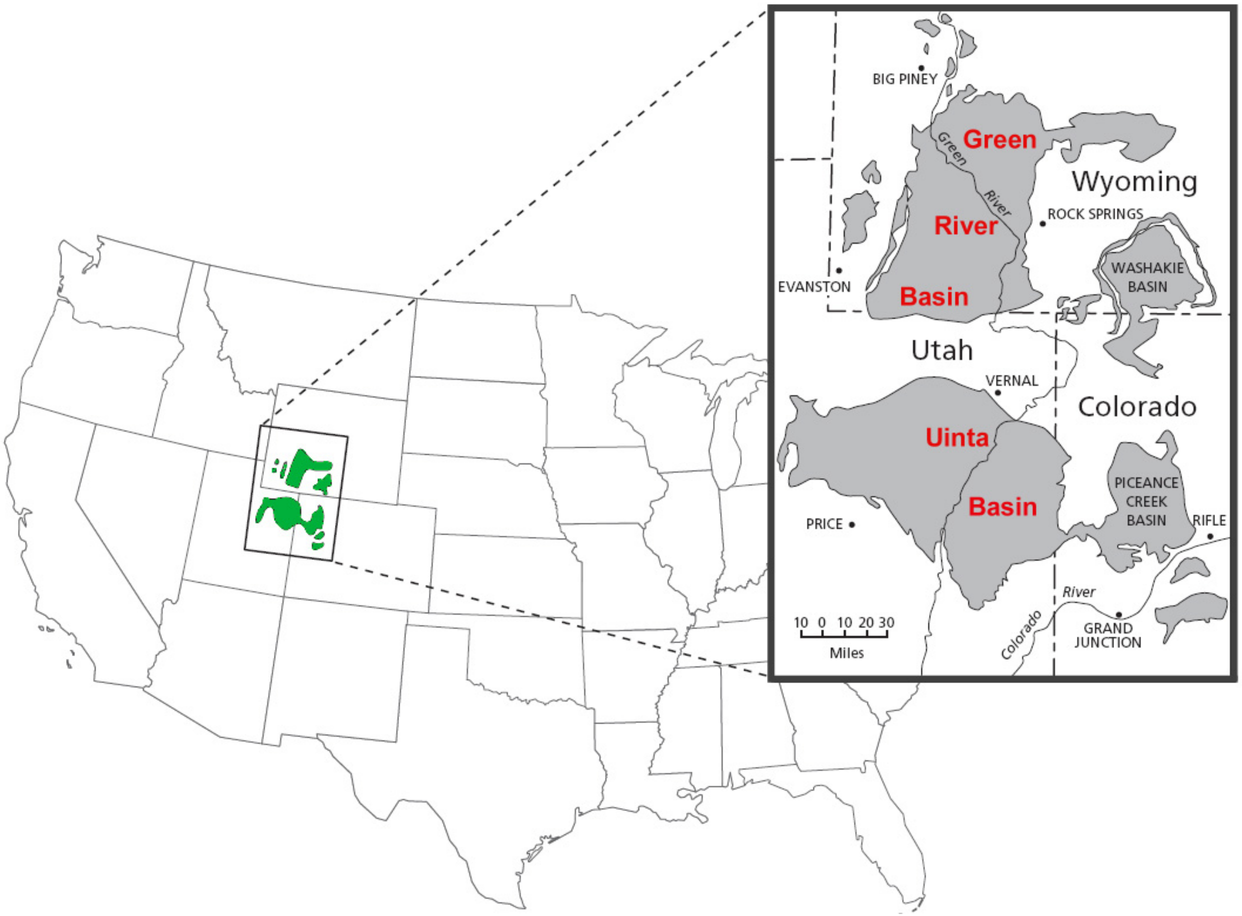

Fig. 7(j)-1: location map:

Location of the Green River Formation in North America. Inset shows location of individual depocentres. Wilkins Peak oils shales shown in this contribution come from the Green River Basin ofWyoming, and samples of Parachute Creek oil shale come from the Uinta Basin of Utah. Figure adapted from Smith (1980).

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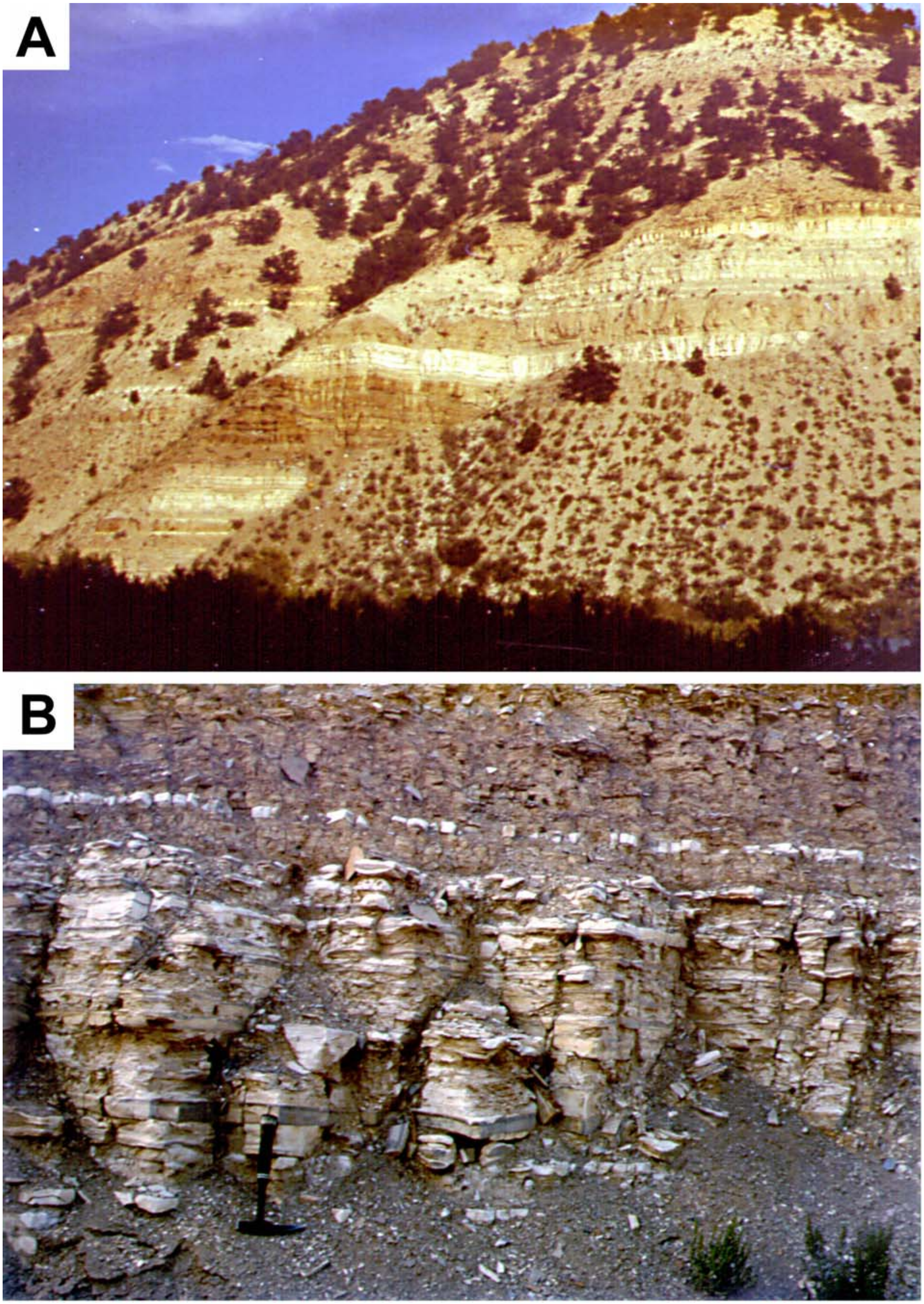

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Fig. 7(j)-2: outcrop views of Green River Formation oil shales:

(A) A slope exposure of the Parachute Creek Member of the Green River Formation, south of Duchesne, Utah, along US Highway 191. Shows cyclic deposition of strata. Whitish-pale coloured intervals are rich in oil shale beds. Although fresh oil shale samples look dark brown to black because of an abundance of organic matter and kerogen, outcrop oxidation of organic matter leaves behind the light coloured mineral matrix and gives the rocks a very different appearance.

(B) Outcrop photo of one of the whitish-pale oil shale intervals from (A). The lightest, almost white ledge-forming beds are most strongly enriched in organic matter. These beds show wavy internal laminae that may have formed as benthic microbial mats. If a sample is cracked with a hammer, it is seen that the rock turns dark brown to black just a few millimetres below the weathering surface. Its resistance to weathering (ledge-former) is due to its “water-proofed” (by kerogen) nature. Hammer for scale is 32 cm long.

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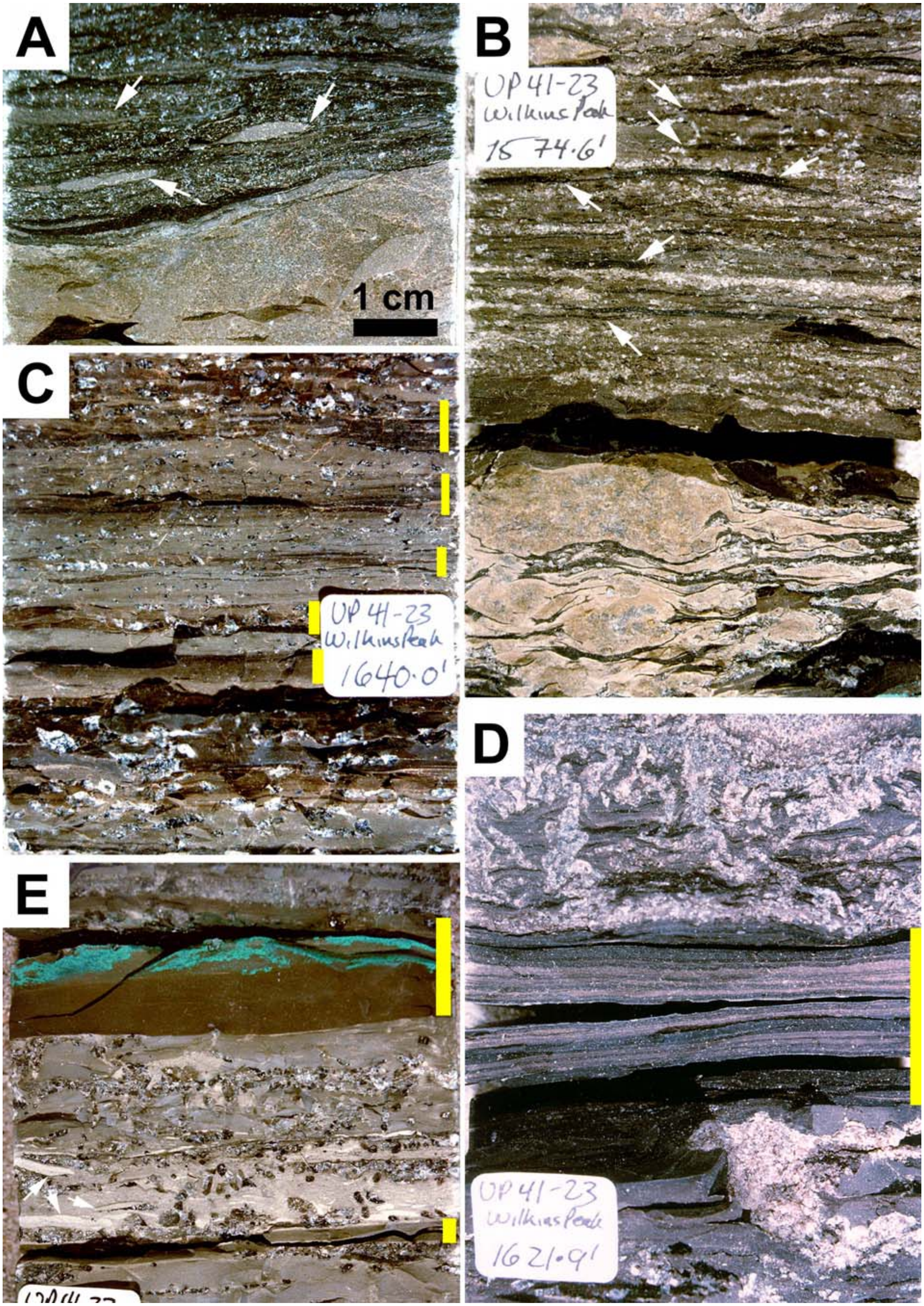

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Fig. 7(j)-3: Views of diamond drill core from the Wilkins Peak Member of the Green River Formation (core diameter 55 mm): (photos kindly provided by Dr. Kevin Bohacs (Exxon Research Lab; scale bar in (A) applies to all other core pictures in this figure)

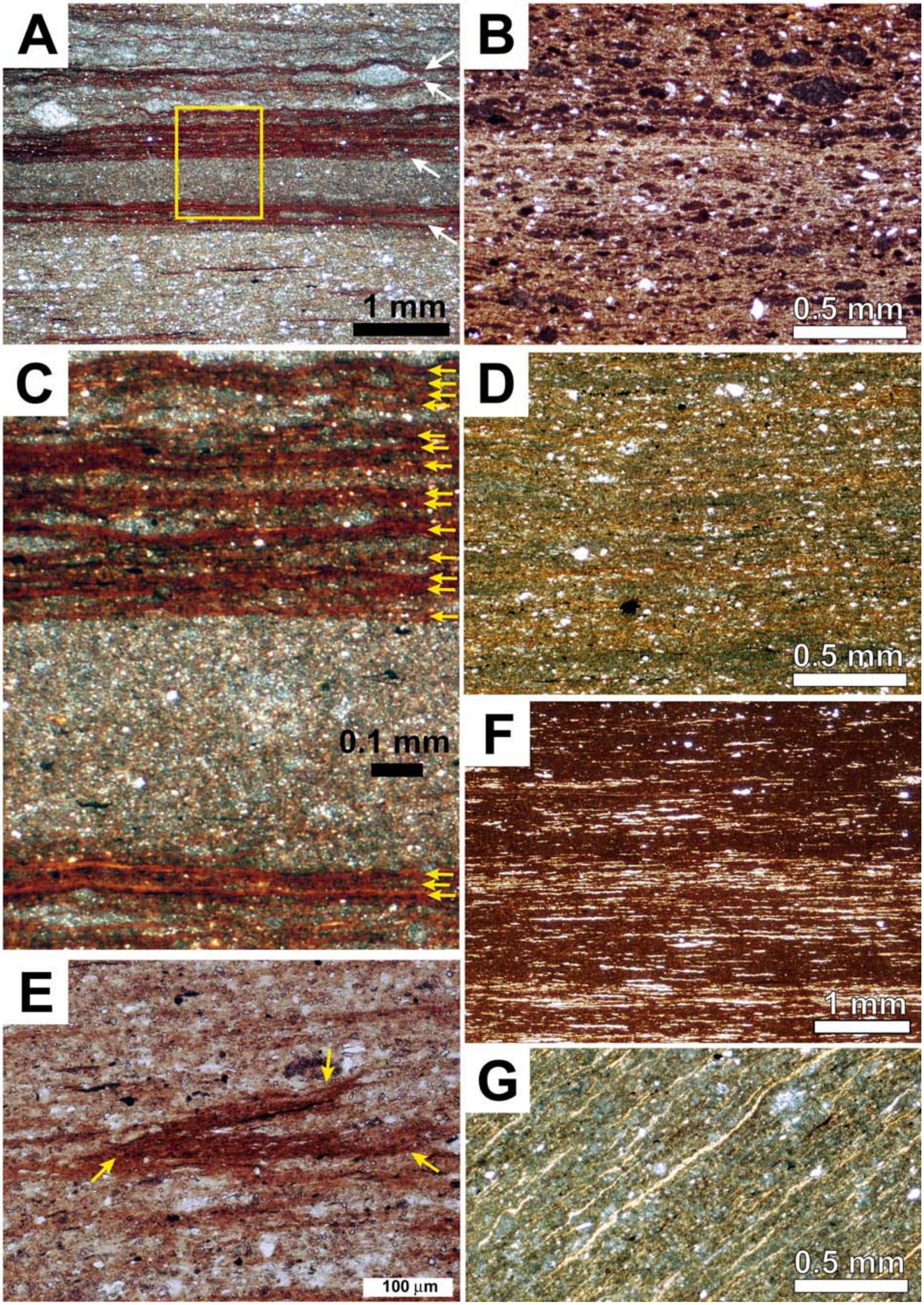
(A) Wavy laminated carbonaceous oil shale (dark laminae) in upper half of image, above a dolomite bed below. Small crystals of dolomite and other diagenetic minerals are sprinkled through the carbonaceous laminae. Small lenses of dolomite between carbonaceous laminae (arrows) accentuate wavy appearance, but carbonaceous laminae are also wavy-crinkly at a much smaller wave length. These are potential microbial mat layers.

(B) The upper two thirds of the photo show gray mudstone with dark streaks (arrows) that are aligned parallel to bedding. The latter are of the same material that forms the dark laminae in (A). The whitish grains are lacustrine evaporite minerals, such as trona, shortite, northrupite, etc. Because “normal” organic-rich bottom muds do not have much internal cohesion, they would be dispersed by erosion and mixed with detrital components before re-deposition. In contrast, the streaks suggest that they were transported as individual particles. Thus, the interpretation here is that these streaks represent eroded and transported mat fragments. The lower third of the photo shows an oil shale layer with abundant growth of early diagenetic trona (light coloured) that destroyed the original fabric.

(C) This photo shows an oil shale interval with abundant gray mud interbeds, particularly in the upper half. The alternation of gray shale beds with intervals that contain brownish (kerogen-rich) laminae (marked with yellow bars), bears some resemblance to Proterozoic striped shales. The whitish and clear (dark) grains are lacustrine evaporite minerals.

(D) Oil shale interval with abundant intergrowth of lacustrine evaporites (trona, light-pinkish colour). The early diagenetic growth of these minerals completely disrupts the original oil shale fabric. The layer in the middle was not affected and shows wavy carbonaceous laminae (dark) that alternate with wavy-lenticular dolomite laminae. This is potentially a microbially laminated interval.

(E) An oil shale with two kerogen-rich intervals (marked with yellow bars) interbedded with gray shale. As in previous images, the latter contain scattered lacustrine evaporite minerals that grew during early diagenesis. The oil shale beds are rather homogenous and do not show a wavy-crinkly internal lamination. The sediment interval between the two marked oil shale beds appears graded. It has dolomite rip-up clasts (white arrows) and dolomitic sand (lighter colour) in the base and the clay content increases upwards (as it gets darker). This could be interpreted as an event deposit related to flash floods that entered the lake basin.



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<u>Fig. 7(j)-4: Photomicrographs of various Green River oil shale samples</u>:

(A) Dolomitic oil shale (Wilkins Peak Member) with well defined kerogen-rich (brownish) intervals (arrows). Kerogen-rich intervals consist of brownish laminae that are continuous on the thin section scale. The kerogen-rich intervals in turn are continuous at the hand specimen scale, and may be traced in outcrop for several metres in fresh exposures. These are the layers that were interpreted as microbial mat deposits in Fig. 7(j)-2.

(B) Another Wilkins Peak oil shale with well defined continuous laminae. Tiny dolomitic lenses produce wavy laminated appearance.

(C) Enlarged portion of Fig. 7(j)-4A (marked with yellow box on (A)). Shows that individual laminae (marked with yellow arrows) are from ten to tens of microns thick and continue at approximately constant thickness. The wavy nature of these laminae is due to small lenses of dolomite.

(D) Lean dolomitic oil shale (Parachute Creek Member) with discontinuous brownish kerogen streaks. The latter do not appear to be concentrated in certain intervals, but are rather randomly distributed. In hand specimen this type of oil shale is homogenous rather than laminated, as for example in Fig. 7(j)-3E.

(E) Eroded piece of organic material that was deformed and folded over during transport. It appears to have been derived from erosion of organic-rich layers like those shown in Fig. 7(j)-4A, -4B, and -4C. Deformation and folding implies internal cohesive strength and is suggestive of a microbial mat origin. Parachute Creek Member, Piceance Basin, Colorado.

(F) Green River oil shale from Uinta Basin in Utah. Shows discontinuous yellow organic streaks of variable length. Some horizons contain a larger concentration of these streaks.

(G) Low grade dolomitic oil shale from the Wilkins Peak Member. Rotated forty degrees for better contrast. This shale also contains discontinuous yellow organic streaks of variable length.

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