7(g). MICROBIAL MAT SEDIMENTARY STRUCTURES AND THEIR RELATION TO ORGANIC-CARBON BURIAL IN THE MIDDLE NEOPROTEROZOIC CHUAR GROUP, GRAND CANYON, ARIZONA, USA

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The mudstones of the Kwagunt Formation of the Chuar Group display a wide range of sedimentary and geochemical attributes that indicate burial of organic carbon was mediated, if not controlled, by benthic microbial mats. We also observed that the sedimentary structures were not randomly distributed, but occurred in two commonly recurring associations that correspond with two modes in the relation between organic-carbon and silt content: a positive relation with silt content proportional to weight % total organic carbon (TOC), and an inverse relation with silt content proportional to 1/weight % TOC. These facies associations support the previously reported interpretation of a higher energy, 'shallower-water' setting (based on coarse-grained lithofacies; e.g., Vidal and Ford, 1985; Reynolds and Elston, 1986; Reynolds et al., 1988; Cook, 1991; Dehler et al., 2001) as well as an additional lower energy, more distal, 'deeper-water' environment.

The Kwagunt Formation (~500 m thick, Figure 7(g)-2A) accumulated in a relatively shallow rift embayment near the northwestern margin of the equatorial region of Laurentia during the Middle Neoproterozoic (800–740 Ma). Previous work suggests that deposition occurred in relatively shallow marine waters, not deeper than 100 m, based upon the common occurrence of desiccation features, rippled thin sand beds, dolomite and sandstone bedsets and the interpretation of 'ripples' in mudstones (Dehler et al., 2001). Variations in base level and climatic wetness are thought to have been rapid and possibly glacio-eustatic based on observations of commonly occurring sharp, conformable transitions from black shale to dolomite. Deposition is interpreted to have occurred in an intra-cratonic rift embayment, possibly silled like the Black Sea (Cook, 1991), or in a half-graben (Seeley and Keller, 2003). We observed previously unreported sedimentary structures that reveal abundant evidence of microbial mat features during the course of our detailed analysis of the mudstone facies and stratigraphy, as part of an integrated study of the biogeochemical system of the Chuar Group (Junium and Bohacs, 2005). Previous work concentrated on the coarser grained lithologies, with 75% of facies description concentrated on 20% of the outcrop interval (Dehler et al., 2001). Our samples were collected from the Awatubi and Walcott Members of the Kwagunt Formation in the Nankoweap Butte area, Arizona in 1986, by researchers from Exxon Production Research Company (Figure 7(g)-1). In all, the fine-grained strata can be divided into five facies based on lithology, bedding, physical and biogenic sedimentary structures, and bulk, molecular, and isotopic organic geochemical attributes (Junium and Bohacs, 2005). Sedimentary structures observed that indicate microbial-mat influence include: (1) wavy, crinkly, anastomose or discontinuous laminae; (2) desiccation features and roll-up structures; (3) fenestral laminae; (4) 'pustular' or wavy surfaces; (5) pseudo-cross-laminae; (6) mica flecks adhered to inferred mat surface; (7) graded beds with carbonaceous caps; (8) pyrite associated with carbonaceous laminae (Figures 7(g)-2, -3). These all accord with features deemed diagnostic of microbial mats

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by Schieber (1999, 2004). Fragments of microbial filaments have been observed in pulverised, acid-digested samples from the area (Vidal and Ford, 1985), but the microbial mat features that are common in hand specimen have not been reported.

Molecular geochemical analyses reveal even-over-odd preferences in *n*-alkane distributions and possible monomethyl-alkane series. These results support previous findings of quaternary-branched-diethylalkanes and monomethyl-alkane series (Hieshima and Pratt, 1991; Logan et al., 1999b; Kenig, 2000) – geochemical features interpreted by those workers as indications of sulphide-oxidising bacteria and benthic microbial mats. Figure 7(g)-3F shows the well-developed even/odd predominance in the C20–C26 *n*-alkanes with C20 being the most abundant compound. This geochemical character is seen in modern and ancient examples with microbial mat structures (Logan et al., 1999b; Kenig, 2000). Similar characteristics have been reported from other proven Precambrian organic-rich rocks: Centralian Superbasin, Australia (Logan et al., 1999b), Nonesuch Formation, USA (Hieshima and Pratt, 1991), and from Late Precambrian oils from eastern Siberia (Fowler and Douglas, 1987). Other molecular characteristics indicate significant, but variable amounts of planktonic algal input: dominance of C27 steranes, hopane/sterane ratios of 1 to 2, pristane/phytane ratios between 0.7 and 1.4, and extended isoprenoids (Peters et al., 2005).

Pseudo-cross laminated structures, carbonaceous lenses, crinkly, silty, anastomosing and discontinuous laminae are found in facies interpreted to have accumulated in more distal, quieter, ‘deeper’ water (Figures 7(g)-2B to -2D). This facies also tends to have TOC contents greater than 4% and an inverse relation between silt content and TOC. These intervals have the even/odd *n*-alkane carbon number predominance of the rest of the Kwagunt Formation, but they show a much stronger planktonic-algal (normal-marine microbial) signature with high concentration of shorter chain *n*-alkanes (Figure 7(g)-2E).

Fenestral laminae, roll-up features and pustular surfaces, indicative of mat desiccation, are more common in regions interpreted to have been deposited in higher-energy, more proximal, ‘shallower-water’ settings (Figures 7(g)-3A to -3E). TOC content in this facies tends to be less than 3% and is positively correlated with silt content. Its geochemical character is the most common throughout the Chuar Group (Figure 7(g)-3F) and shows significant input of organic matter associated with microbial mats (e.g., as seen in other formations by Logan et al., 1999b and Kenig, 2000).

These observations of microbial-mat features and distributions integrated with the full range of physical and geochemical data, indicate that the depositional setting of the Kwagunt Formation varied systematically along a depositional gradient. It ranged from more distal, quieter, relatively clear but ‘deeper-water’ areas with intermittent sediment transport and significant planktonic algal input along with patchy benthic microbial mats, to more proximal reaches. These higher energy, ‘shallower-water’ areas also had relatively clear water but were intermittently exposed subaerially and benthic microbial mats were widespread. These findings demonstrate the power of a fully integrated approach that includes careful consideration of the finer-grained strata to provide detailed insight into depositional conditions at this critical time in Earth history.

Figures

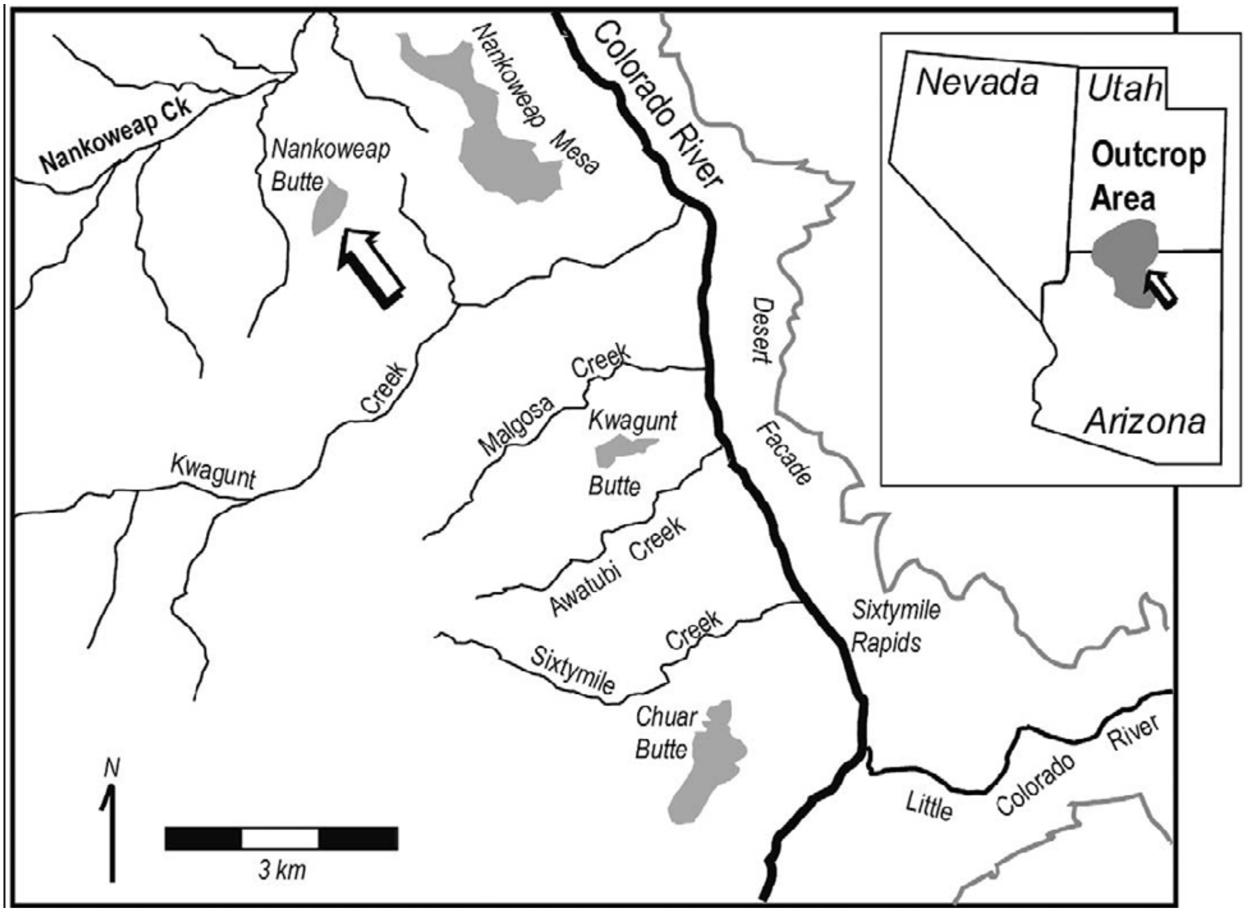

Figure 7(g)-1: Location of outcrop pictured in Figure 7(g)-2.
The outcrop is located around Nankoweap Butte, west of the Colorado River between Nankoweap and Kwagunt Creeks, approximately 9.8 km upstream of the confluence with the Little Colorado River, Grand Canyon National Park, Arizona (arrow: 36.26316◦ N, 111.88376◦ W, WGS84).

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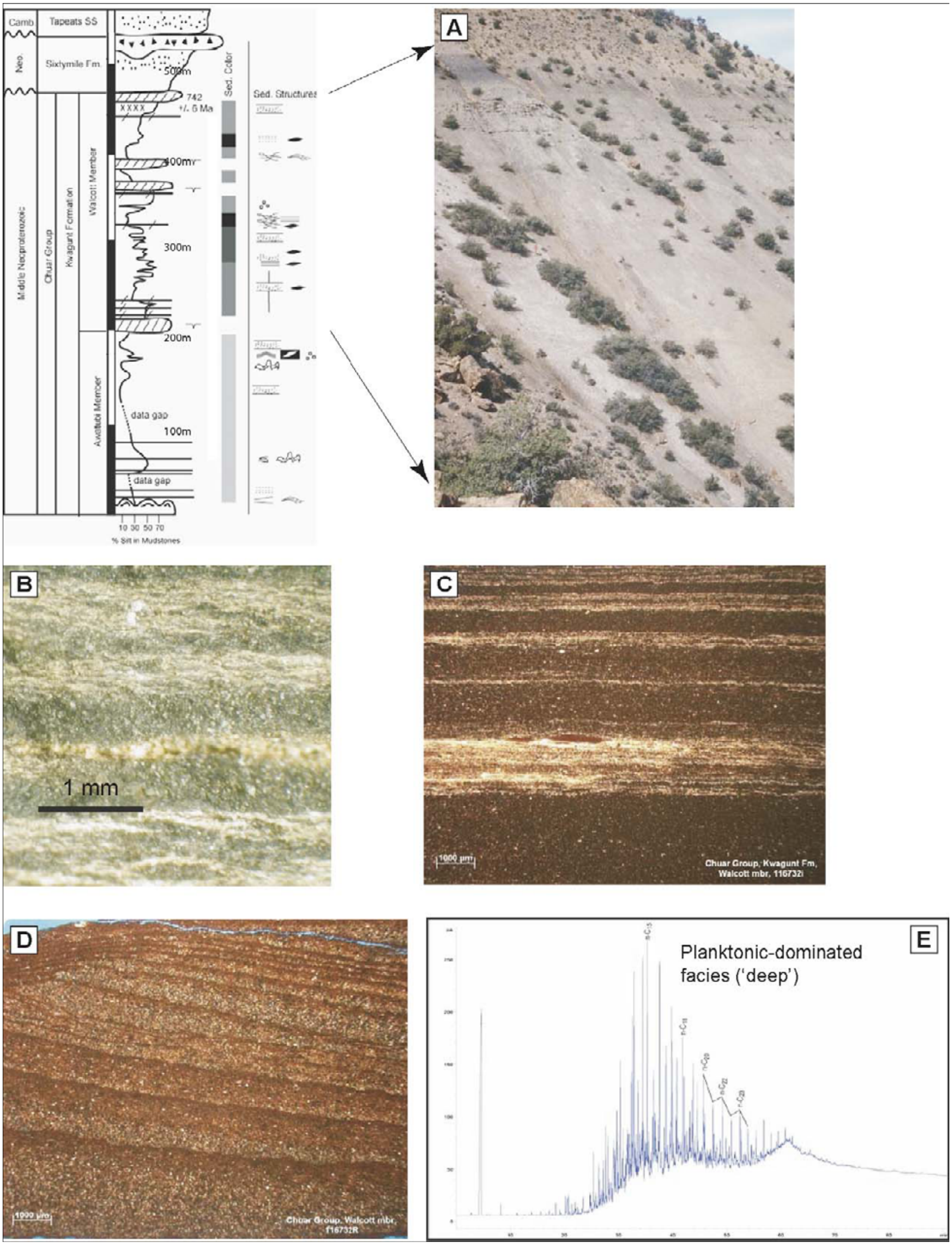

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Figure 7(g)-2:
(A) Vertical profile of Kwagunt Formation at the Nankoweap Butte measured section showing vertical stacking of lithology, rock colour, silt content, and sedimentary structures. Fenestral laminae, roll-up structures, and pustular surfaces (facies association B) are more common in the basal third. Pseudo cross-bedding, carbonaceous lenses, crinkly, silty, anastomosing and discontinuous laminae (facies association A) occur most commonly in the darker, more silt-lean portions of the upper two-thirds of the section. (B) Hand sample showing anastomose and discontinuous laminae in very dark grey, silt-bearing, clay-rich mudstone of the Walcott Member, Kwagunt Formation (from approximately 323 m on the measured section in Figure 7(g)-2A). These structures are interpreted to record potentially chemosynthetic microbial mats and relatively distal and quiet-water conditions. (C) Thin section detail of anastomose and discontinuous laminae in black, organic-matter-rich, clay-dominated mudstone of the Walcott Member (~418 m on measured section). Organic-carbon content is 9.8%, comprising both benthic microbial and planktonic algal input. These structures are interpreted to record possibly chemosynthetic microbial mats in relatively distal and quiet bottom conditions. This bedding style is probably analogous to the 'striped shales' described by Schieber (1986) and shown in other examples in this volume (see Chapter 5 and Sections 7(b), 7(c)). (D) Thin section image of pseudo-cross-bedding in dark grey, clay-bearing, silt-rich mudstone with black carbonaceous laminae atop inclined graded beds (from ~398 m on measured section). These structures indicate intermittent transport of sediment over a microbial mat-covered substrate (see Schieber, 2004). (E) Gas-chromatograph trace of solvent-extracted organic matter from sample shown in Figure 7(g)-2C. The high concentration of shorter chain *n*-alkanes indicates a dominance of organic matter derived from planktonic algae/photosynthetic protests, whereas the even/odd distribution in the higher carbon-number *n*-alkanes portrays significant content of microbial-mat organic matter, both consistent with a more distal depositional setting.

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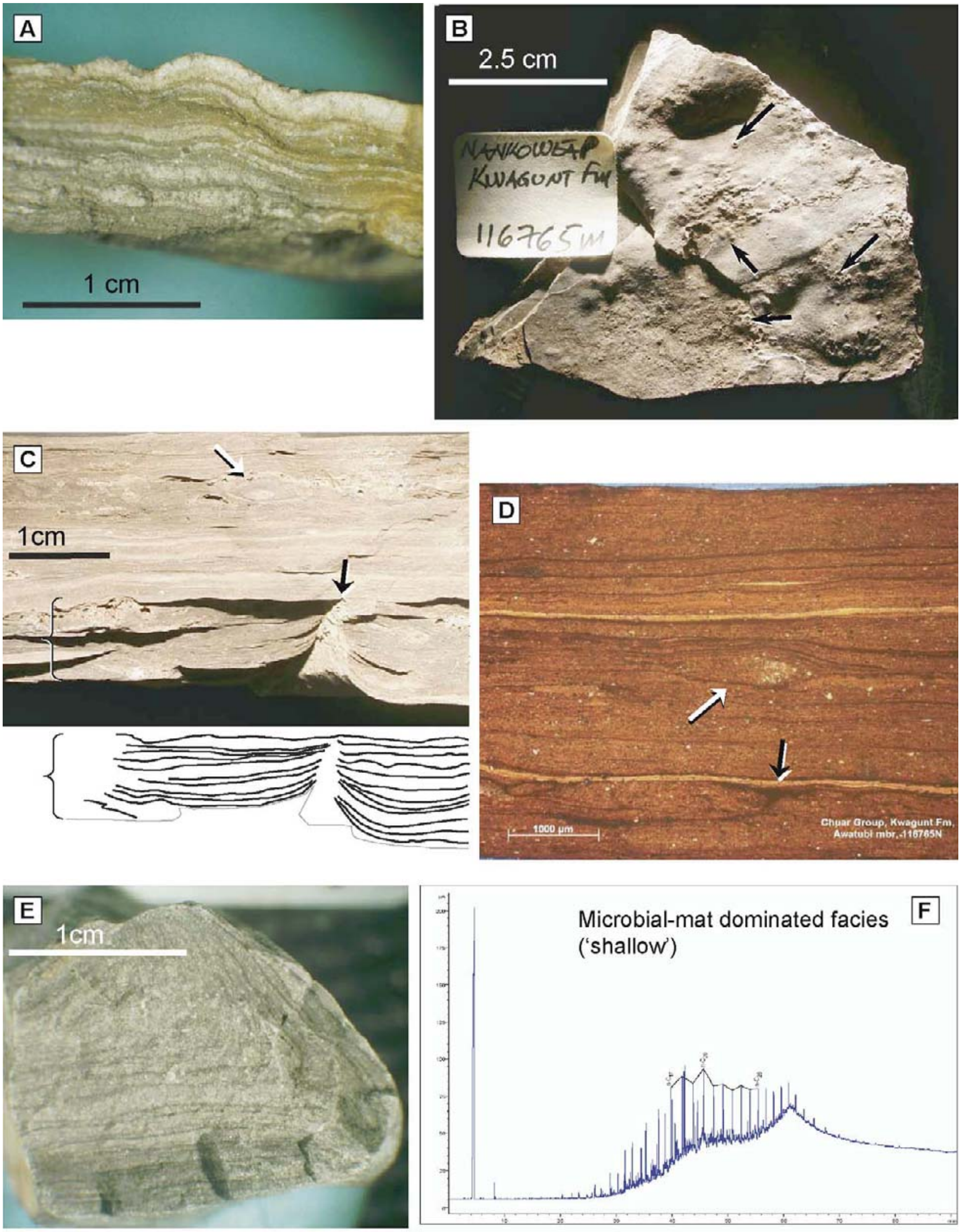

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Figure 7(g)-3:
(A) Hand specimen of wavy and crinkly carbonaceous and silty laminae in a grey silt-bearing, clay-rich mudstone from the Awatubi Member, Kwagunt Formation (from approximately 62 m on the measured section in Figure 7(g)-2A). These laminae are interpreted to record microbial-mat (probably photosynthetic) accumulation under intermittent clastic sedimentation in relatively shallow water. (B) Bedding-plane view of hand specimen with welldeveloped pustular surface structures at several stratigraphic levels in dark grey, clay-bearing, silt-rich mudstone with black carbonaceous laminae, from the Walcott Member (~173 m on measured section). Arrows indicate pustules, including several 'popped' pustules. Pustular surfaces arise from gas bubbles trapped below cohesive microbial mats and can form in emergent and submergent conditions (see discussion in Schieber, 2004). (C) View of fenestral laminations on surface perpendicular to bedding (white arrow) and upturned laminae terminating at a vertical surface interpreted as a desiccation crack (black arrow). Line drawing below shows convergent geometry of laminae at several levels, indicating intermittent development of upturned laminae (contrast with consistently parallel pattern of laminae observed in simple desiccation cracks). Specimen is a grey-brown, silt-bearing, clay-rich mudstone with common carbonaceous laminae from the Awatubi Member (~161 m on measured section). Both structures are interpreted to represent sedimentation among microbial mats under intermittent subaerial exposure. (D) Thin section detailed image of fenestral lamination (white arrow) and abruptly discontinuous laminae probably related to desiccation (black arrow) in hand specimen described in Figure 7(g)-3C. The very thin and dark laminae are interpreted to be remains of microbial mats. (E) View of vertical face of roll-up structure in a medium grey, clay-bearing siltstone with common to abundant carbonaceous laminae, from near the base of the Awatubi Member (~60 m on measured section). Roll-up structures probably represent microbial mat mediated sediment accumulation under more prolonged subaerial exposure and subsequent high-energy bottom conditions (see discussion in Schieber, 2004). (F) Gas-chromatograph trace of solvent-extracted organic matter from dark grey, clay-bearing mudstone with abundant carbonaceous laminae from the upper portion of the Awatubi Member (~175 m on measured section). Total organic-carbon content is 1.8%. The well-developed even/odd distribution in the C20–C26 *n*-alkanes and peak abundance of C20 *n*-alkane indicate organic matter is dominantly from microbial mats.

References

Cook, D.A., 1991, Sedimentology and shale petrology of the upper Proterozoic Walcott Member, Kwagunt Formation, Chuar Group, Grand Canyon, Arizona. M.S. Thesis, Northern Arizona University, 158 pp.

Dehler, C.M., Elrick, M., Karlstrom, K.E., Smith, G.A., Crossey, L.J., Timmons, J.M., 2001, Neoproterozoic Chuar Group (~800—742 Ma), Grand Canyon: a record of cyclic marine deposition during global cooling and supercontinent rifting. Sedimentary Geology v. 141-142, p. 465-499.

Fowler, M.G., Douglas, A.G., 1987 Saturated hydrocarbon biomarkers in oils of late Precambrian age from Eastern Siberia. Organic Geochemistry v. 11, p. 201-213.

Hieshima, G.B, Pratt, L.M., 1991, Sulfur/ carbon ratios and extractable organic matter of the middle Proterozoic Nonesuch Formation, North American Midcontinent Rift. in Walter M R (editor), Special issue; Proterozoic petroleum, Precambrian Research v. 54, p. 65-79.

Junium, C., and Bohacs, K.M., 2005, Sedimentary, petrographic, and geochemical evidence for benthic microbial mats and a refined mudstone stratigraphy for the Neoproterozoic Kwagunt Formation, Chuar Group, Grand Canyon. Geological Society of America and Geological Association of Canada Earth System Processes 2 conference, Calgary, Canada, Paper 8-1.

Kenig, F.C., 2000, $^{16}C_{29}$ homologous series of monomethylalkanes in the pyrolysis products of a Holocene microbial mat. Organic Geochemistry v. 31, p. 237-241.

Logan, G.A., Calver, C.R., Gorjan, P., Summons, R.E., Hayes, J.M., Walter, M.R., 1999, Terminal Proterozoic benthic microbial mats and their environmental significance. in Ninth annual V. M. Goldschmidt conference, LPI Contribution LPI-CONTRIB-971, p. 176.

Peters, K. E.; Walters, C. C.; Moldowan, J. M., 2005, The Biomarker Guide, Volume 2: Biomarkers and Isotopes in Petroleum Exploration and Earth History, Second Edition. Cambridge University Press, Cambridge, 1132 pp.

Reynolds, M.W., Elston, D.P., 1986, Stratigraphy and sedimentation of part of the Proterozoic Chuar Group, Grand Canyon, Arizona. Geological Society of America Abstracts with Program 18, p. 405.

Reynolds, M.W., Palacas, J.G., Elston, D.P., 1988, Potential petroleum source rocks in the Late Proterozoic Chuar Group, Grand Canyon, Arizona. USGS Circular 1025, p. 49-50.

Schieber, J., 1999, Microbial mats in terrigenous clastics; the challenge of identification in the rock record. in: Hagadorn, J.W., Pflueger, F., Bottjer, D.J., (editors) Unexplored microbial worlds. Palaios v. 14, p. 3-12.

Schieber, J., 2004, Microbial mats in the siliciclastic rock record: a summary of diagnostic features. in Eriksson, P.G., Altermann, W., Nelson, D., Mueller, W.U., Catuneanu, O., Strand, K., (editors), The Precambrian Earth: Tempos and events. Developments in Precambrian Geology, Elsevier, p. 663-672.

Seeley, J.M., Keller, G.R., 2003, Delineation of subsurface Proterozoic Unkar and Chuar Group sedimentary basins in northern Arizona using gravity and magnetics; implications for hydrocarbon source potential. AAPG Bulletin v. 87, p. 1299-1321.

Vidal, G., Ford, T.D., 1985, Microbiotas from the Late Proterozoic Chuar Group (northern Arizona) and Uinta Mountain Group (Utah) and their chronostratigraphic implications. Precambrian Research v. 28, p. 349-389.