



Organic petrology of subbituminous carbonaceous shale samples from Chalāw, Kabul Province, Afghanistan: Considerations for paleoenvironment and energy resource potential

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ABSTRACT

Neogene (?) subbituminous carbonaceous shale deposits from Chalāw, Afghanistan, were investigated through organic petrology techniques and standard coal analyses to determine paleoenvironment and potential for resource utilization. The Chalāw deposit, approximately 30 km southeast of Kabul, currently is exploited for brick making and domestic heating and cooking. Three multiple-bench channel samples of the mined bed at Chalāw were collected and evaluated. The presence of significant huminite (ranging from 0.2 to 59.0 vol.%, mineral-inclusive basis) is suggestive of a terrestrial lignin-rich precursor plant material. Measured reflectance values of 0.38–0.55% indicate subbituminous rank. This rank suggests burial depths of approximately 1500 m and maximum temperatures of approximately 50 °C. Structured liptinite macerals generally are absent except for some fluorescing morphologies interpreted to be poorly-preserved root cork suberinite. Sponge spicule bioliths including gemmoscleres and megascleres are common. These petrographic observations, in addition to high mineral matter content (33 to >95 vol.%), medium to high sulfur content (2.1–11.5 wt.%, dry basis; db), and the presence of common gastropod? shell fragments and an aragonite-needle chalk bed are consistent with, but not directly indicative of, a marginal marine or estuarine mangrove depositional environment. However, additional data are necessary to confirm this hypothesis and deposition in a freshwater environment cannot be ruled out at this time.

Commercial-scale development and utilization of the Chalāw deposit as a thermal fuel resource may be possible using a fluidized bed combustion system which could accept the low-quality mine product currently produced. Samples examined herein contain high-ash yield (45–90 wt.%, db), high total moisture content (17–39 wt.%), low calorific value (980–6860 Btu/lb, m,mmf), and have poor agglomerating properties (FSI = 0), consistent with fuels utilized in fluidized bed combustors. However, delineation of the extent of the deposit through field investigation will be necessary to make a quantified resource estimate for mine planning.

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1. Introduction

The U.S. Geological Survey (USGS) is conducting a cooperative coal and associated mineral fuels assessment of Afghanistan in collaboration with the Afghan Ministry of Mines and Industries (SanFilippo, 2005). The current program began in 2004 and to date has included the collection and analysis of approximately one-hundred-fifty coal and rock samples. Objectives of the assessment include determination of the quality, quantity, and distribution of Afghanistan's coal and associated mineral fuel resources (e.g., carbonaceous shales), as well as indigenous capacity building through training of Afghanistan

Geological Survey (AGS) staff and development of infrastructure in Kabul to facilitate and sustain future assessment activities.

Most of the known coal deposits in Afghanistan are found in Jurassic strata, which are in the northern part of the country and generally far removed from the major population centers. Approximate annual production historically has been on the order of 200,000 tonnes produced from semi-mechanized mines operated by the government (Bose, 1979). Current production has slightly exceeded this level but mostly is from non-mechanized small-scale exploratory adits. At the present, coal utilization in Afghanistan primarily is for the firing of bricks and for domestic heating and cooking purposes. There is no coal-fired electrical generating capacity installed in Afghanistan (most electricity is from hydropower) and no functional rail transportation.

The Chalāw deposit examined herein is located in the Kabul Basin about 30 km southeast of central Kabul (Fig. 1) at an elevation of

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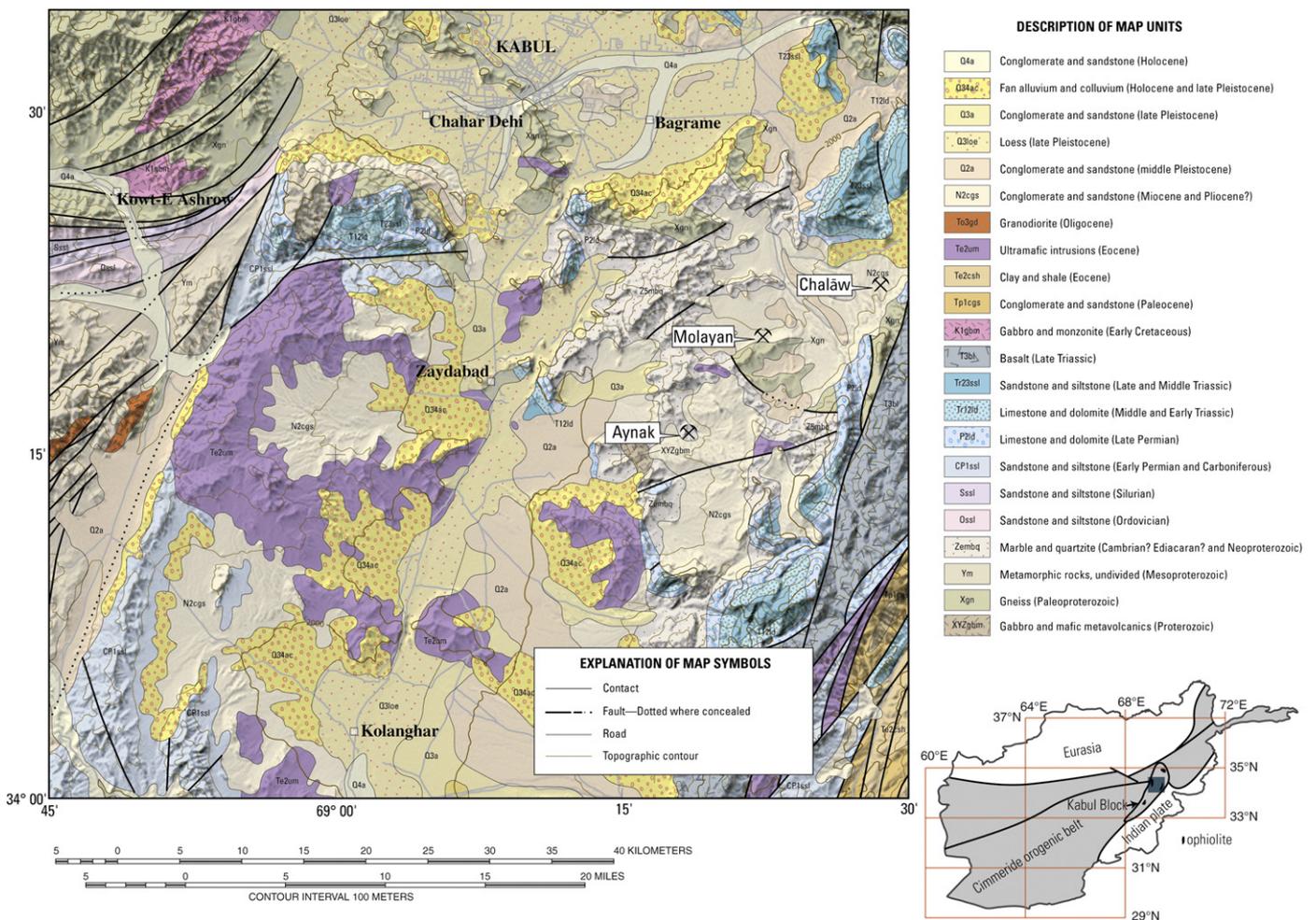


Fig. 1. Geologic map of the Chalaw area. Modified from Bohannon and Turner (2005), which is an adaptation of the original map of Abdullah and Chmyriov (1977). The Lataband Series (which includes the N2cgs unit hosting the Chalaw deposit) originally was mapped as Pliocene by Abdullah and Chmyriov (1977). However, subsequent work in the area by vertebrate paleontologists (Brunet et al., 1984; Sen, 2001), and geologic mapping work in progress (Bohannon, in press) indicates that rocks equivalent to the N2cgs unit may range in age from Miocene to Pliocene. We do not consider the stratigraphic position of the Chalaw deposit to be definitively known. The location of Molayan is approximate and derived from Fig. 1 of Brunet et al. (1984). The area of the geologic map is shown (rectangle in the index map) with respect to the political boundaries of Afghanistan and regional crustal elements (Eurasia, Indian plate, Cimmeride orogenic belt, Kabul Block).

approximately 2460 m above sea level. The carbonaceous shales at Chalaw are hosted in Neogene (?) basin-fill and fan deposits that blanket the Kabul Basin (Bohannon and Turner, 2005; Doeblich et al., 2006). These nearly horizontal strata were mapped as part of the Lataband Series (Abdullah and Chmyriov, 1977) and are attributed to deposition occurring during Tertiary subsidence (Menessier, 1968). Precise chrono- and/or biostratigraphic ages for the Chalaw strata are not available. The most likely age is Miocene and/or Pliocene considering proximity and stratigraphic similarity to nearby vertebrate sampling localities (Brunet et al., 1984), and based on molluscan faunas described by Menessier (1968). However, because detailed geologic mapping in the area has never been undertaken, we do not consider the stratigraphic position of the Chalaw deposit to be definitively known.

Lataband Series rocks generally are considered to be correlative with the Upper Miocene to Pleistocene Siwalik strata occurring on the Potwar Plateau in Pakistan and in the Himalayan foothills of India, which are >300 and >1000 km distant, respectively (e.g., Abbasi and Friend, 2000; Basu, 2004; Nelson, 2005). Lataband Series rocks near Chalaw are described as terrestrial sediments including conglomerates, sands, and clays, interpreted to represent channel-fill and floodplain deposits (Sen, 2001). Thin (~1 m) limestone beds occurring in the Lataband Series were interpreted as lacustrine deposits by Sen (2001). Mammalian faunas from the nearby Molayan

vertebrate locality are indicative of open grassland to savannah type environments from a relatively dry climatic era (Brunet et al., 1984).

The Miocene–Pliocene strata which host the Chalaw deposit unconformably overlie Permian–Mesozoic limestones and Proterozoic crystalline basement of the Kabul Block (Fig. 1), a fault- and ophiolite-bounded tectonic element of uncertain provenance (e.g., Treloar and Izatt, 1993; Badshah et al., 2000). The presence of ophiolites at the margins of the Kabul Block has led most workers to infer that it was a peri-Gondwanan microcontinental fragment surrounded by oceans and emplaced against Eurasia near the Cretaceous–Paleocene boundary (e.g., Tapponnier et al., 1981; Sengör, 1984; Treloar and Izatt, 1993; Gnos et al., 1997). Alternatively, Beck et al. (1996) hypothesized that the Kabul Block represented a leading element of the Indian Plate that was displaced southwestward and extruded during India–Eurasia collision in the Tertiary.

Historical reconnaissance reports on the mineral resources of Afghanistan suggested that coal beds in the Neogene rocks of the Kabul Basin may be relatively widespread (Drummond, 1841). However, the extent of the mined carbonaceous shale bed in the area of Chalaw was not delineated in the current study due to security and time constraints; anecdotal reports from local residents indicated that the deposit is limited to the immediate area around the current mining operation. There is no subsurface information available however, and it is

quite possible that additional coal or carbonaceous horizons may be present above or below the mined beds.

The current mine product from Chalāw primarily is used to fire brick kilns located on the road between Chalāw and Kabul and for local home heating and cooking. The objective of this paper is to present organic petrology data and basic quality analyses for preliminary considerations on the paleoenvironmental conditions of deposition, and to better characterize the Chalāw deposit as a potential commercial-scale fuel resource.

2. Methods

2.1. Sample collection

Chalāw samples include three benched channels through the mined interval, which were collected according to ASTM D4596-09 (ASTM, 2009a) from three different adits at the mine location. The channels were divided into benches based on visual appearance (Fig. 2) for a total of 18 samples (Table 1), one of which did not contain enough material for petrographic analysis (KBL-CHLW-3/06-U3.6p). A run-of-mine sample collected from bags stacked in an adit entrance also was analyzed (Table 1; sample KBL-CHLW-3/06-A2-ROM).

Channel samples 5/05 and 3/06-L are laterally equivalent although sampled in different adits (within 200 m of one another); channel sample 3/06-U was collected from a locality stratigraphically above the location of samples 5/05 and 3/06-L in a third adit (within 100 m of sample 3/06-L), and is separated from samples 5/05 and 3/06-L by a laterally persistent aragonite-needle chalk bed (sample KBL-CHLW-3/06-R-1, Table 1). Where sampled, the 3/06-U interval is dropped by a normal fault so that it is horizontally adjacent to the strata from which the 5/05 and 3/06-L samples were taken (Fig. 2). The chalk sample was collected at the entrance of the adit which is shown in Fig. 2.

The samples were collected from the active mine faces and as such reflect the best possible material available for collection. However, the deep weathering profile of the region may negatively impact quality analysis of some of the samples. For example, secondary gypsum formed in the near-surface environment may boost the volatile matter determination in the proximate analysis.

2.2. Organic petrographic analyses

Samples were prepared for incident light analysis according to ASTM D2797-07 (ASTM, 2009b). Determinations of mean random (R_o) huminite reflectance were conducted according to ASTM D2798-

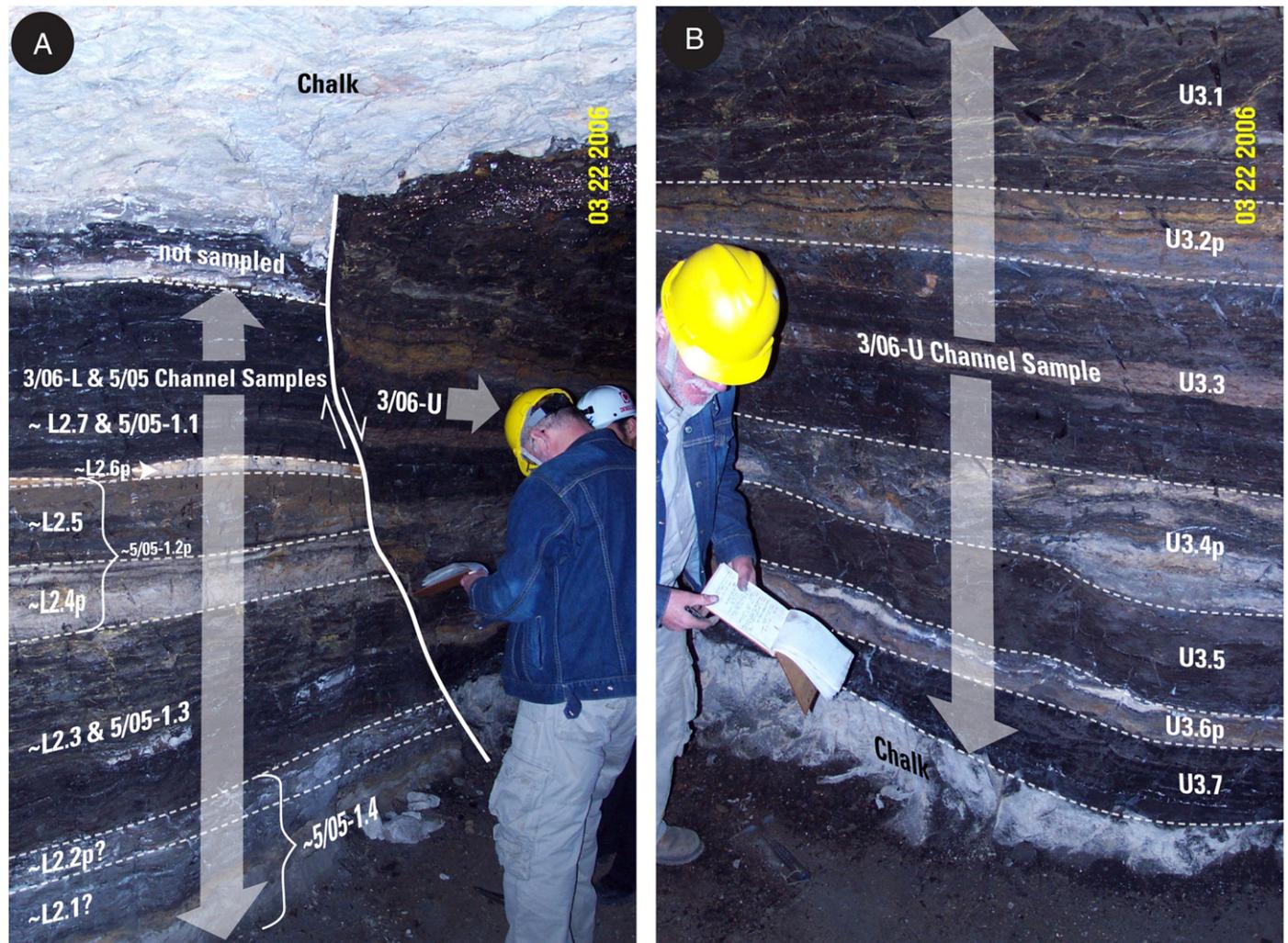


Fig. 2. Photographs from inside a Chalāw mine adit showing normal fault, channel bench divisions for the 3/06-U sample, and approximate channel bench divisions for the 5/05 and 3/06-L samples. The chalk sample (KBL-CHLW-3/06-R-1; Table 1) was collected at the entrance to this adit. (A) Approximate bench divisions for the 5/05 and 3/06-L channel samples (which were collected in other adits). The correlations with the sampled adits are not definite; in particular, the lowermost bench shown in (A) is more organic-rich where sampled in the other adits (samples L2.1 and 5/05-1.4). Sample series 3/06-U, which is faulted in from above on the normal fault shown in (A), was collected from this adit at a location approximately 3 m beyond the men on the right side of the photograph. (B) Bench divisions for channel sample 3/06. Note that the adit roof chalk in (A) is now the adit floor in (B) due to displacement on the normal fault.

Table 1
Petrography of Chalaw carbonaceous shale samples on a vol.% mineral-inclusive basis. See footnote for explanation of abbreviations.

Sample ID	Huminite		Total huminite		Inertinite			Total inertinite			Liptinite		Total liptinite		Ro (%)	Sample type
	Thickness (cm)	Telohuminite	Detrohuminite	Fusinite	Semifusinite	Macrinite	Funginite	Inerto-detrinite	Suberinite	Resinite	Alignite	Mineral	Sponge spicule			
KBL-CHLW-5/05-1.1	60	23.4	12.7	8.2	9.4	0.4	0.1	5.2	23.2	0.4	X	40.0	0.4	0.42	Carb. shale	
KBL-CHLW-5/05-1.2p	15	1.0	1.0	0.8	1.6	X	X	1.4	3.8	X	X	94.2	X	0.46	Carb. shale	
KBL-CHLW-5/05-1.3	53	8.4	12.4	8.2	4.8	X	X	7.2	20.2	0.4	X	58.2	0.3	0.42	Carb. shale	
KBL-CHLW-5/05-1.4	60	34.0	15.0	2.8	3.2	0.1	0.1	2.4	8.6	0.7	X	40.2	1.6	0.45	Carb. shale	
KBL-CHLW-3/06-U3.1	45	3.0	2.2	X	3.0	X	X	0.6	3.6	X	X	91.2	X	0.55	Carb. shale	
KBL-CHLW-3/06-U3.2p	15	0.2	X	1.0	6.4	X	X	4.0	7.4	X	X	92.4	X	0.44	Carb. shale	
KBL-CHLW-3/06-U3.3	53	7.9	8.2	4.2	11.8	0.1	X	4.0	20.1	X	X	63.8	X	0.51	Carb. shale	
KBL-CHLW-3/06-U3.4p	20	0.2	X	0.6	3.4	X	X	X	4.0	X	X	95.8	X	0.52	Carb. shale	
KBL-CHLW-3/06-U3.5	27	7.0	3.6	2.8	5.4	0.4	X	1.8	10.4	X	X	79.0	X	0.55	Carb. shale	
KBL-CHLW-3/06-U3.6p	15	na	na	na	na	na	na	na	na	na	na	na	na	na	Carb. shale	
KBL-CHLW-3/06-U3.7	22	13.4	15.1	4.6	18.6	X	0.1	8.6	31.9	X	X	39.6	X	0.49	Carb. shale	
KBL-CHLW-3/06-L2.7	35	24	6	36.6	6.7	10.1	0.1	0.1	3.5	20.5	X	42.8	X	0.42	Carb. shale	
KBL-CHLW-3/06-L2.6p	5	2.0	1.6	0.2	1.4	X	X	0.8	2.4	X	0.2	93.6	0.2	0.37	Carb. shale	
KBL-CHLW-3/06-L2.5	14	3.4	3.8	2.0	2.6	X	X	1.8	6.4	X	X	86.0	0.4	0.48	Carb. shale	
KBL-CHLW-3/06-L2.4p	18	1.0	0.8	1.0	1.8	X	X	1.6	4.4	X	X	93.8	X	0.46	Carb. shale	
KBL-CHLW-3/06-L2.3	44	8.8	10.6	6.7	8.9	0.4	0.1	6.9	23.1	0.6	X	55.8	1.1	0.46	Carb. shale	
KBL-CHLW-3/06-L2.2p	8	14.5	17.9	32.4	7.2	X	X	5.7	18.2	0.2	X	49.2	X	0.42	Carb. shale	
KBL-CHLW-3/06-L2.1	33	43.9	15.1	2.5	2.7	X	X	0.4	5.6	1.7	X	33.1	0.5	0.49	Impure coal	
KBL-CHLW-3/06-A2-ROM ^a	na	29.5	10.7	1.5	4.1	0.2	0.1	3.0	8.8	1.6	X	48.0	1.2	0.47	Carb. shale	
KBL-CHLW-3/06-R-1 ^a	na	na	na	na	na	na	na	na	na	na	na	na	na	na	Chalk	

X = not present; na = not analyzed.

^a Evaluated for diatoms.

09 (ASTM, 2009c). Samples were analyzed for organic composition in incident light according to a modification (500 counts vs. 1000) of ASTM D2799-05a (ASTM, 2009d). Maceral nomenclature for the inertinite maceral group is according to the International Committee for Coal and Organic Petrology (ICCP, 2001). Although random reflectance values for several of the samples are slightly higher than 0.5%, the huminite nomenclature (Šýkorová et al., 2005) is used for all samples herein. Nomenclature for the liptinite group is according to Taylor et al. (1998). Sponge spicules are present in channel samples 5/05 and 3/06-L and were included in the point count; they are tabulated as part of the vol.% mineral category in Table 1.

Diatoms were processed from the run-of-mine and chalk samples (Table 1), using 35% hydrogen peroxide, 15% hydrochloric acid, 70% nitric acid. Residues were returned to a neutral pH between steps. The sample material was dried on cover slips and mounted in Naphrax. Microfossils were counted at 500× and, if necessary, identified at 1000×. Diatoms and chrysophyte cysts were identified using standard references (Krammer and Lange-Bertalot, 1991a,b; Snoeijns, 1993; Snoeijns and Vilbaste, 1994; Snoeijns and Potapova, 1995; Duff et al., 1995; Snoeijns and Kasperovičienė, 1996; Sims, 1996; Krammer and Lange-Bertalot, 1997a,b; Snoeijns and Balashova, 1998).

2.3. Proximate–ultimate and Rock-Eval analyses

The samples were analyzed for proximate (D3172-07a), ultimate (D3176-89), equilibrium moisture (D1412-07), calorific values (D5865-07a), free swelling indices (D720-91), ash fusion temperatures (D1857-04), forms of sulfur (D2492-02), fluorine (D3761-96), and grindability indices (D409/D409M-09) in a commercial laboratory (Geochemical Testing, Somerset, Pennsylvania) according to ASTM methods and procedures (ASTM, 2009e). SO₃ in ash was determined in USGS laboratories by ASTM D6349-08 (ASTM, 2009e). Samples also were analyzed by Rock-Eval pyrolysis and LECO Carbon Analyzer for total organic carbon (TOC) in a commercial laboratory (Humble Geochemical Testing, Inc.) according to the methods described in Barker (1974), and Espitalié et al. (1977).

3. Results and implications

3.1. Petrographic analyses

Mean random huminite reflectance (R_o) values range from 0.38 to 0.55% and average 0.47% generally indicating subbituminous rank (Teichmüller, 1987; ISO, 2005). According to the survey of Barker and Pawlewicz (1986), these reflectance values correspond to a maximum temperature of approximately 50 °C. Assuming an average surface temperature of 5–15 °C and a typical continental geothermal gradient of 20–25 °C/km (e.g., Klett et al., 2006), this suggests approximate maximum burial depths of 1500–2000 m for the Chalaw deposit.

It is generally believed that reflectance values of interior areas of vitrinite and/or huminite are not significantly impacted by surficial weathering (e.g., Chandra, 1958; Lo and Cardott, 1995; Copard et al., 2004). Therefore, reflectance is the preferred rank-indicating parameter used in the characterization of the Chalaw deposit.

Mineral matter content determined by petrographic point count (performed for eight samples) and calculated from sulfur content and ash yield data according to ASTM D2799-05a ranges from 34 to 96 vol.%.

Diatoms were rare and poorly-preserved (fragmentary) in the two samples that were evaluated (Table 1 and Fig. 3). None of the species present are age diagnostic. With the exception of *Aulacoseira granulata* and *Melosira varians*, all species are benthic, and were observed attached to either sediment or macrophytes. All diatom species and chrysophyte stomatocysts observed in the two samples are found in freshwater environments.

The volume of organic material in most of the Chalaw samples is subordinate to that of mineral matter content. The organic material that

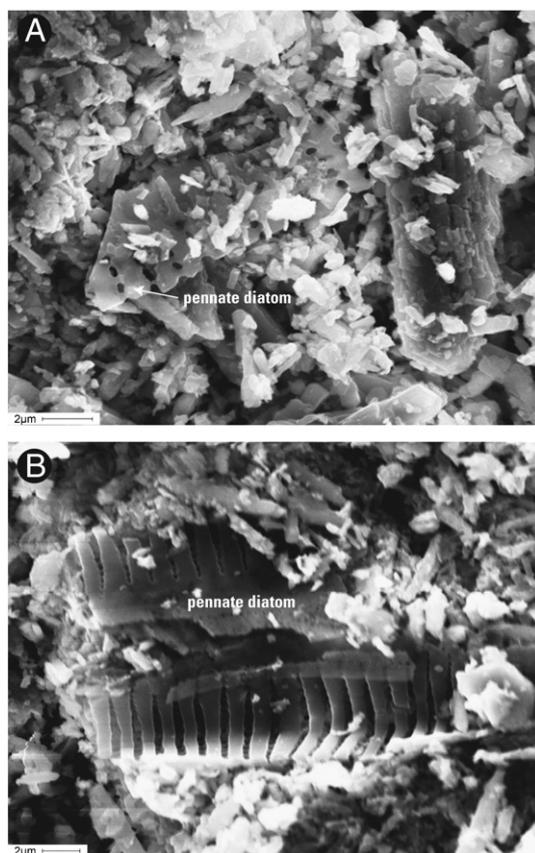


Fig. 3. Scanning electron microscope (SEM) photographs of pennate diatoms in the Chalāw chalk bed (sample KBL-CHLW-3/06-R-1; Table 1). The remainder of the material in the photographs is aragonite, as identified via X-ray diffraction. (A) Part of a pennate diatom. (B) Central part of a pennate diatom, possibly of the genus *Navicula*, fractured along the raphe. SEM photographs courtesy of Harvey Belkin, USGS.

is present is dominated by huminite group macerals, ranging from 0.2 to 59 vol.% on a mineral-inclusive basis (Table 1 and Fig. 4). Inertinite content ranges from 2.4 to 32 vol.%, dominated by semifusinite (max. 19 vol.%). Liptinite content ranges from 0.0 to 1.7 vol.% and is dominated by what we interpret as root cork suberinite (max. 1.7 vol.%). Apart from cutinite noted in only one sample, structured liptinite macerals other than suberinite (e.g., sporinite) are absent from the Chalāw samples.

3.2. Proximate–ultimate and Rock-Eval analyses

All but one of the Chalāw samples are classified as carbonaceous shale based on ash yield (Table 2) according to the ASTM definition, wherein carbonaceous shale contains >50 wt.% ash yield on a dry basis (db) (ASTM, 2009f). The lowermost bench of the 3/06-L channel (Fig. 4) contains 45 wt.% ash yield (db) and is classified as impure coal. Sulfur content for all samples is medium to high (2.1–11.5 wt.%, db). The 3/06-U series samples primarily contain sulfate sulfur (Table 3), possibly as a result of pyrite oxidation and secondary gypsum formation in the modern weathering environment; sulfur in the 3/06-L and 5/05 channel samples primarily occurs as pyritic and organic sulfur. Equilibrium moisture values range from 15 to 34 wt.% and average 22.5 wt.%, suggesting an approximate rank of subbituminous (Teichmüller, 1987), consistent with the rank determined via reflectance.

Calorific content ranges from 980 to 6860 Btu/lb on a moist, mineral matter-free basis (m,mmf) indicating lignite A–B rank by the ASTM D388-05 classification (ASTM, 2009g). However, weathering and oxidation of the organic material in the Chalāw samples may contribute to a reduction in measured calorific values (e.g., Berkowitz, 1989). In addition, calorific content determinations may be unduly

influenced by the high mineral matter content of the samples and the dehydration of clays and other water-bearing minerals during calorimetry. High F values (Table 3) in some samples also support the idea that volatile halides present in the mineral matter content may interfere with calorimetry of the organic material. In particular, F values in the 5/05 channel sample are high relative to published ranges for coals, soils, and shales (Swaine, 1990).

Data from Rock-Eval pyrolysis are compiled in Table 4. T_{\max} values range from 403 to 439 °C and the R_o values calculated from T_{\max} range from 0.1 to 0.7% with an average of 0.39% ($R_o \text{ Calc.} = 0.0180 * T_{\max} - 7.16$ from Jarvie et al., 2001). No correlation was observed between T_{\max} and measured R_o values. However, since calculated R_o values bracket the range of measured R_o values, and the average values generally are similar (0.39% calculated vs. 0.47% measured), the Rock-Eval T_{\max} data are interpreted to corroborate the rank of the Chalāw deposit as subbituminous.

Thermal distillate (S1) and pyrolysis output (S2) range 0.9–5.4 and 0.4–50.3 mg hydrocarbons per g rock (Table 4), respectively, and do not display consistent relationships with organic composition (Table 1). Rather, S2 values are correlated with TOC ($r^2 = 0.84$; samples with low S2 interpreted to be most affected by modern weathering in the 3/06-U series fall off of the trendline) and dry ash yield ($r^2 = 0.72$), indicating broad similarities in organic composition across all of the samples. S2 values generally are lower than those reported for coal samples of similar reflectance (Mukhopadhyay, 1989), and lower than the range reported for coal samples (50–250 mg/g; Bordenave, 1993, p. 242). Low S1 values are compatible with the low thermal maturity of the samples and broadly similar to thermal extraction data from similar rank Tertiary coal samples (Mukhopadhyay, 1989). Lower average S1 values in the 3/06-U series samples also indicate oxidation in the weathering environment.

Low Hydrogen Index values of 12–148 (mg hydrocarbon per g organic carbon) are consistent with the dominance of Type III organic matter (terrestrial huminite) indicated by petrographic point count (Table 1). S3 and Oxygen Index values are highest in the 3/06-U samples, consistent with the other analytical parameters (e.g., higher sulfate sulfur and lower pyritic sulfur, calorific value, S1 and S2 values) that suggest oxidation in the modern weathering environment.

Total organic carbon (TOC) values of course show a strong negative correlation with ash yield (db) ($r^2 = 0.91$), and strong positive correlation with C (db) determined from ultimate analyses ($r^2 = 0.99$). TOC also is positively correlated with vol.% huminite ($r^2 = 0.93$), and vol.% huminite plus inertinite ($r^2 = 0.96$) determined from petrographic analyses.

4. Discussion

4.1. Chalāw paleoecology – mangrove community?

In the carbonaceous shale samples from Chalāw, the absence or relative scarcity of the liptinite macerals (Table 1) that typically are found in humic coals (i.e., sporinite, cutinite and resinite) may suggest a slightly alkaline depositional environment hostile to the preservation of liptinite (e.g., Taylor et al., 1998). This may be indicative of a marginal marine or estuarine setting such as a mangrove community that would experience alkaline conditions above the sediment interface in the aerobic tidal zone. The presence of significant huminite content (ranging from 0.2 to 59.0 vol.%, Table 1) suggests a lignin-rich precursor plant material and the typical preservation of terrestrial (woody) vegetation. This is consistent with a mangrove community, which generally does not contain abundant cellulose-rich and lignin-poor herbaceous vegetation such as grasses, sedges, or ferns (e.g., Woodruffe, 1995). Refractory roots from below the sediment interface are interpreted to be the primary contributor to mangrove peat growth (e.g., Spackman et al., 1966; Cohen and Spackman, 1977), rather than the less abundant above-ground woody twigs, or leaves which may be removed by macrofauna (e.g., mangrove crabs) (Middleton and McKee, 2001).

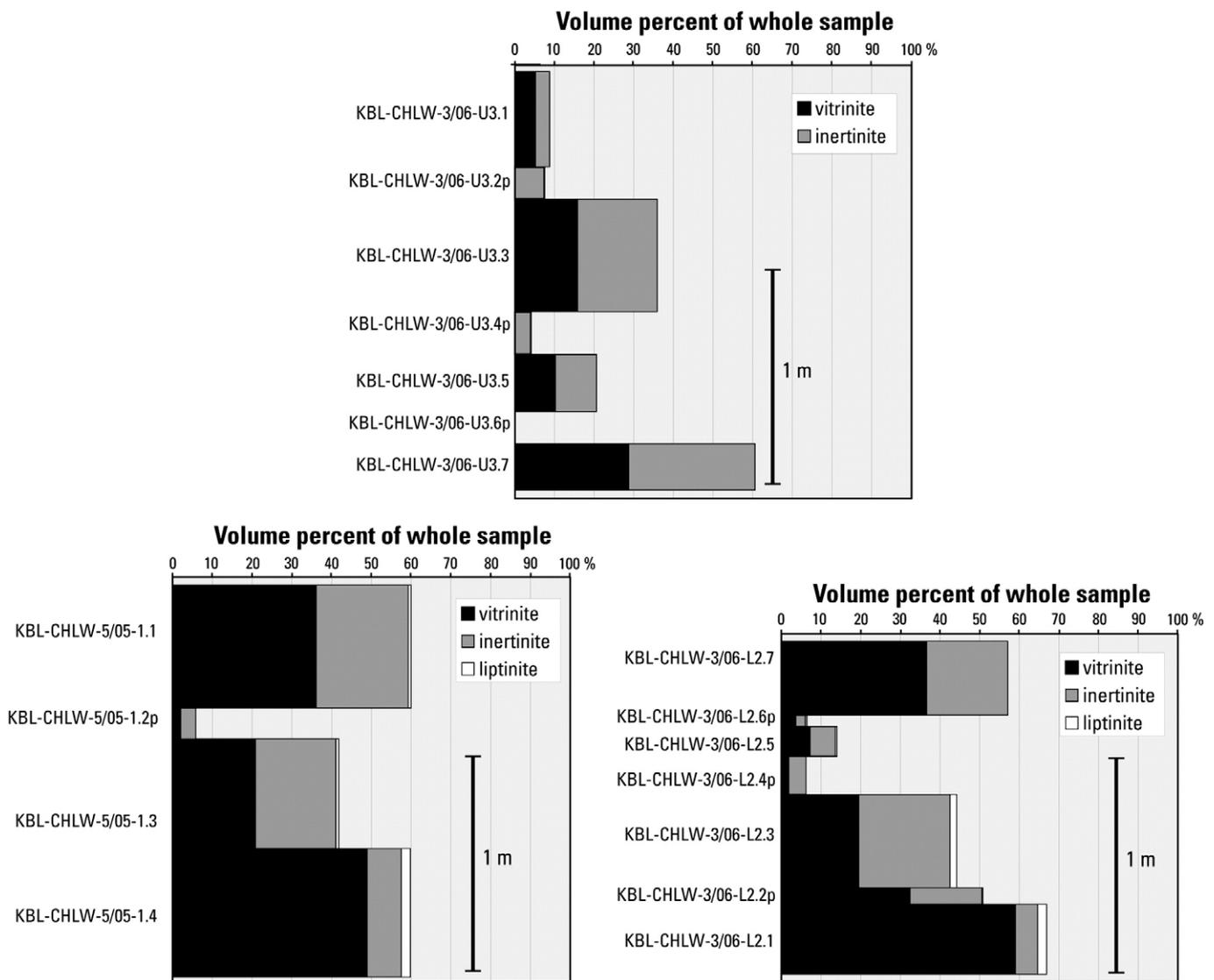


Fig. 4. Diagram showing organic composition of the three Chalaw channel sample benches.

Huminite content generally exceeds inertinite content in the more organic-rich Chalaw samples (samples with mineral matter <50 vol. %) from the 5/05 and 3/06-L channel series (Table 1). In these samples, telohuminite content is greater than detrohuminite (with the exception of parting sample 3/06-L2.2p), suggesting processes which may have favored the preservation of humic vegetation such as plant roots. Roots may have been preserved by anaerobic, slightly acidic (?) conditions which limited bacterial activity below the sediment interface. Mangrove soil pH has been documented as acidic with values of 5–7 in studies by Wakushima et al. (1994) and Ukpong (2007). Potential preservation of root material as telohuminite in the 5/05 and 3/06-U samples is in contrast to the most organic-rich sample from the overlying 3/06-U channel series, wherein the ratio of telohuminite to detrohuminite is approximately one-to-one (Table 1, Fig. 4), implying processes which favored the mechanical and chemical destruction of vegetation.

Huminite in the 5/05 and 3/06-L channel benches sometimes contains internal reflections and is weakly fluorescent (Fig. 5A–B). This may be representative of tannin impregnation via the collapse and gelification of tannin-filled cell lumens or may suggest putrefaction of the precursor vegetation in anaerobic conditions (e.g., Taylor et al. 1998). Tannin impregnation may have helped to preserve some lignin-rich tissue in the presumably neutral to slightly basic pH environment that would be present above the sediment interface in

the near-shore mangrove community (e.g., Staub and Cohen, 1979; Taylor et al., 1998). A gradation between dark huminite with internal reflections to bright huminite without internal reflections was observed in several instances, suggesting localized oxidation. R_o values (Table 1) for the 5/05 and 3/06-L samples are slightly lower and HI values (Table 4) are slightly higher than for the 3/06-U samples. In general, huminite is free of internal reflections and does not display fluorescence in the 3/06-U samples, and pyrolysis values (S1 and S2, Table 4) are lower. This indicates the possibility of weathering of the 3/06-U samples which do show petrographic signs of surficial oxidation and desiccation (Fig. 5C).

The 5/05 and 3/06-L channel samples both are characterized by relatively high contents of huminite in their basal benches, separated from an upper huminite-rich bench by a mineral matter-rich parting (Fig. 4 and Table 1). The petrographic compositions of the top benches of channel samples 5/05 and 3/06-L are virtually indistinguishable (Fig. 4 and Table 1), implying significant lateral continuity in organic content at the mine location (the samples were collected from approximately 200 m apart). The 3/06-U channel benches all are characterized by high mineral matter content except for the basal bench which is approximately 60 vol.% organic matter with equal proportions of huminite and inertinite. Overall, inertinite constitutes a greater proportion of the organic material in the 3/06-U sample when compared to the 5/05 and 3/06-L samples. This may suggest more frequent wind- or water-borne

Table 2

Proximate–ultimate and calorific value data (dry basis, db) for carbonaceous shale samples from Chalāw, Afghanistan. SO₃ in ash on an as determined basis. SO₃-free corrected ash on an inherent moisture basis (calculated using total moisture). Calorific value also reported on a moist, mineral matter-free basis (CV m,mmf). See footnote for explanation of table abbreviations.

Sample ID	RM wt.%	ADL wt.%	Moist wt.%	EM wt.%	Ash	SO ₃ wt.%	SO ₃ -free Ash wt.%	VM wt.%	H wt.%	C wt.%	N wt.%	S wt.%	CV Btu/lb	^a CV m, mmf Btu/lb	ASTM rank
KBL-CHLW-5/05-1.1	5.55	25.92	30.03	na	52.28	7.09	33.99	25.38	1.75	33.50	0.71	2.88	5620	6162	ligB
KBL-CHLW-5/05-1.2p	3.98	14.37	17.78	na	90.01	1.43	72.95	8.90	0.08	3.81	0.23	2.06	566	1876	ligB
KBL-CHLW-5/05-1.3	5.22	19.90	24.08	na	67.01	6.49	47.57	21.48	0.92	21.78	0.62	3.53	3629	5558	ligB
KBL-CHLW-5/05-1.4	7.01	24.86	30.13	na	52.05	9.16	33.04	28.94	1.71	33.32	0.67	3.58	5542	5953	ligB
KBL-CHLW-3/06-U3.1	4.31	17.76	21.30	16.09	83.34	4.74	62.48	16.63	1.17	6.73	0.44	2.19	906	1984	ligB
KBL-CHLW-3/06-U3.2p	11.60	11.75	21.99	na	89.60	33.96	46.16	20.19	0.99	3.45	0.23	11.52	111	nc	nc
KBL-CHLW-3/06-U3.3	6.43	23.68	28.59	18.87	71.35	9.41	46.15	25.39	1.44	15.89	0.72	2.65	2202	3008	ligB
KBL-CHLW-3/06-U3.4p	7.73	12.85	19.59	16.32	88.02	19.38	57.06	18.51	na	na	na	5.81	102	nc	nc
KBL-CHLW-3/06-U3.5	5.78	25.89	30.17	25.48	75.84	8.89	48.25	23.36	1.48	13.55	0.54	2.89	1908	2632	ligB
KBL-CHLW-3/06-U3.6p	8.35	12.43	na	na	na	21.23	na	na	na	na	na	na	na	nc	nc
KBL-CHLW-3/06-U3.7	8.64	33.15	38.93	33.89	51.47	22.82	24.26	38.22	2.06	30.70	0.98	3.65	4406	3554	ligB
KBL-CHLW-3/06-L2.7	4.56	25.49	28.89	22.06	54.82	8.32	35.74	27.11	2.48	30.90	0.86	3.00	5087	5830	ligB
KBL-CHLW-3/06-L2.6p	1.68	17.63	19.01	na	68.32	5.84	52.10	27.78	na	na	na	2.35	632	977	ligB
KBL-CHLW-3/06-L2.5	2.43	17.41	19.42	15.19	86.73	4.12	67.01	11.81	1.08	5.62	0.61	3.18	944	2414	ligB
KBL-CHLW-3/06-L2.4p	2.63	14.65	16.89	na	89.90	1.63	73.50	9.08	1.05	2.74	0.30	2.84	574	1858	ligB
KBL-CHLW-3/06-L2.3	4.58	17.50	21.28	21.77	65.14	4.82	48.81	20.57	1.98	22.31	0.79	3.67	3627	5931	ligB
KBL-CHLW-3/06-L2.2p	3.69	18.09	21.11	22.65	60.41	9.34	43.21	31.03	2.04	24.83	0.77	2.79	3735	5443	ligB
KBL-CHLW-3/06-L2.1	4.78	22.42	26.13	29.27	44.98	12.74	29.00	31.66	3.09	37.67	0.83	3.67	6426	6863	ligA
KBL-CHLW-3/06-A2-ROM	4.15	21.57	24.82	25.70	59.14	9.19	40.37	25.95	2.42	27.16	0.72	3.35	4509	5933	ligB ^{app}
KBL-CHLW-3/06-R-1	na	na	na	na	na	na	na	na	na	na	na	na	na	nc	nc

RM = residual moisture; wt.% = weight percent; ADL = air-dried loss; Moist = total moisture; EM = equilibrium moisture; Ash = ash yield; VM = volatile matter; CV = calorific value; m,mmf = moist, mineral matter-free; Btu/lb = British thermal units per pound; lig = lignite; na = not analyzed; nc = not calculated; app = apparent.

^a Calculated using total moisture.

deposition, or desiccation and oxidation of the surface and upper portions of the precursor peat during deposition of the 3/06-U sediments. Fusinite interpreted to be carbonized root cortex preserving angular cell wall junctions (e.g., Cohen et al., 1987) is common (Fig. 5D).

The structured liptinite macerals which are present in the Chalāw samples are interpreted to be poorly-preserved root cork suberinite (Fig. 5E–F). This maceral primarily is found in the 5/05 and 3/06-L channel samples (Table 1). The presence of suberinite would be consistent with the preservation of the anchoring plant roots of a mangrove community wherein the substrate occurs in persistently waterlogged and anaerobic conditions and primary oxygen transfer occurs through the above-water aerial root system (e.g. Tomlinson, 1994). Rarely, serrated edges suggestive of leaf cutin are present. However, the relative infrequency of definitive serrated-edge cutinite

in the Chalāw samples may be a result of the mulching of leaves by mangrove crabs (e.g., Middleton and McKee, 2001; Skov and Hartnoll, 2002; Koch et al., 2005). Removal by tidal action and/or rapid microbial decay in the slightly alkaline and aerobic surface environment also could result in poor leaf preservation. Numerous studies cited in Middleton and McKee (2001) have documented poor leaf preservation in mangrove peat accumulations. Wooller et al. (2007) also noted a declining abundance of leaves with depth in a red mangrove-dominated peat and an absence of leaves below 730 cm peat depth.

The absence of sporinite indirectly suggests a plant community with reproductive systems based primarily on mechanisms other than spore dispersal. This observation is consistent with a viviparous mangrove community wherein reproduction occurs via growth of a

Table 3

Forms of sulfur, ash fusion temperatures (reducing atmosphere), and associated quality parameters for carbonaceous shale samples from Chalāw, Afghanistan. Forms of sulfur and fluorine content on a dry basis. See footnote for explanation of table abbreviations and text for listing of ASTM standards used for analysis.

Sample ID	Forms of sulfur			Fluorine ppm	Ash fusing temperature (°C)					
	Sulfate (%)	Pyritic (%)	Organic (%)		Init.	Soft.	Hemi.	Fluid	HGI	FSI
KBL-CHLW-5/05-1.1	0.12	0.90	1.86	984	1170	1200	1250	1320	107	0
KBL-CHLW-5/05-1.2p	0.23	1.70	0.12	1540	1240	1300	1370	1440	na	0
KBL-CHLW-5/05-1.3	0.19	2.12	1.21	1128	1150	1170	1300	1350	105	0
KBL-CHLW-5/05-1.4	0.13	1.01	2.44	772	1140	1160	1170	1360	93	0
KBL-CHLW-3/06-U3.1	1.90	0.17	0.12	228	1150	1200	1230	1290	na	0
KBL-CHLW-3/06-U3.2p	11.20	0.17	0.16	244	1150	1170	1180	1190	na	0
KBL-CHLW-3/06-U3.3	2.14	0.12	0.39	22	1180	1200	1200	1220	138	0
KBL-CHLW-3/06-U3.4p	5.70	0.09	0.02	238	na	na	na	na	na	0
KBL-CHLW-3/06-U3.5	2.42	0.25	0.23	203	1150	1200	1290	1430	na	0
KBL-CHLW-3/06-U3.6p	na	na	na	18	na	na	na	na	na	na
KBL-CHLW-3/06-U3.7	3.33	0.14	0.17	214	1170	1180	1180	1240	na	0
KBL-CHLW-3/06-L2.7	0.04	0.02	2.94	247	1150	1160	1190	1270	na	0
KBL-CHLW-3/06-L2.6p	0.63	1.30	0.42	129	na	na	na	na	na	0
KBL-CHLW-3/06-L2.5	0.54	2.39	0.25	298	1180	1210	1270	1380	na	0
KBL-CHLW-3/06-L2.4p	1.17	1.55	0.11	454	1200	1270	1290	1420	na	0
KBL-CHLW-3/06-L2.3	0.71	1.60	1.36	259	1150	1190	1290	1380	91	0
KBL-CHLW-3/06-L2.2p	0.51	0.99	1.28	272	1150	1170	1180	1200	na	0
KBL-CHLW-3/06-L2.1	0.29	0.65	2.73	167	1170	1170	1180	1220	na	0
KBL-CHLW-3/06-A2-ROM	0.35	1.37	1.63	293	1160	1180	1180	1330	90	0
KBL-CHLW-3/06-R-1	na	na	na	na	na	na	na	na	na	na

ppm = parts per million; Init. = initial; Soft. = softening; Hemi. = hemispheric; HGI = Hardgrove grindability index; FSI = free swelling index; na = not analyzed.

Table 4
Rock-Eval and LECO total organic carbon data for carbonaceous shales from Chalāw, Afghanistan. See footnote for explanation of table abbreviations.

Sample ID	TOC	S1	S2	S3	T_{\max} (°C)	HI	OI	PI
KBL-CHLW-5/05-1.1	30.58	4.11	39.66	8.95	411	130	29	0.09
KBL-CHLW-5/05-1.2p	3.57	0.22	0.50	1.52	403	14	43	0.31
KBL-CHLW-5/05-1.3	19.74	1.89	22.65	5.35	428	115	27	0.08
KBL-CHLW-5/05-1.4	29.28	3.27	40.96	8.53	415	140	29	0.07
KBL-CHLW-3/06-U3.1	5.68	0.74	1.91	6.38	417	34	112	0.28
KBL-CHLW-3/06-U3.2p	3.49	0.12	0.43	2.62	435	12	75	0.22
KBL-CHLW-3/06-U3.3	12.72	1.14	4.85	10.63	427	38	84	0.19
KBL-CHLW-3/06-U3.4p	3.11	0.11	0.56	2.49	429	18	80	0.16
KBL-CHLW-3/06-U3.5	10.18	2.55	14.60	12.02	422	143	118	0.15
KBL-CHLW-3/06-U3.6p	na	na	na	na	na	nc	nc	nc
KBL-CHLW-3/06-U3.7	25.34	0.61	7.74	15.81	439	31	62	0.07
KBL-CHLW-3/06-L2.7	27.91	3.47	35.14	8.52	412	126	31	0.09
KBL-CHLW-3/06-L2.6p	4.79	0.50	6.83	1.93	422	143	40	0.07
KBL-CHLW-3/06-L2.5	5.71	0.09	0.82	1.94	418	14	34	0.10
KBL-CHLW-3/06-L2.4p	3.61	0.26	0.91	1.44	406	25	40	0.22
KBL-CHLW-3/06-L2.3	20.58	2.67	22.23	7.37	417	108	36	0.11
KBL-CHLW-3/06-L2.2p	20.78	2.12	25.82	7.93	418	124	38	0.08
KBL-CHLW-3/06-L2.1	34.45	5.36	50.31	12.28	413	146	36	0.10
KBL-CHLW-3/06-A2-ROM	24.32	3.61	35.90	8.55	416	148	35	0.09
KBL-CHLW-3/06-R-1	na	na	na	na	na	nc	nc	nc

TOC = wt.% total organic carbon; S1, S2 = mg hydrocarbons/g rock; S3 = mg CO₂/g rock; HI = hydrogen Index (S2*100/TOC); OI = Oxygen Index (S3*100/TOC); PI = Production Index (S1/(S1+S2)); na = not analyzed; nc = not calculated.

propagule which still is attached to the parent plant (Cameron and Palmer, 1995). The propagule is a live root which drops into the water for dispersal when it is mature. Alternatively, absence of sporinite could be due to dispersal in the water column or poor preservation under oxidizing, neutral-basic pH conditions in the above-ground mangrove environment. Absence of resinite is interpreted to suggest the infrequent occurrence or poor preservation of waxes, fats, resins, and latexes, gums, etc., in the precursor plant community. This is consistent with poor preservation of above-ground wound resins, and the absence of resin- and fat-rich seeds which are replaced by propagules in the viviparous mangrove plant.

The presence of sponge spicule bioliths (Table 1) is consistent with a mangrove environment wherein sponges could be anchored to the hard substratum afforded by mangrove roots and trapped sediment (e.g., Rützler, 1988; Ellison, 1996), although spicules also are noted from freshwater swamp environments (e.g., Warwick et al., 1997). In some cases, spicules are intimately associated with telohuminite, suggesting a physical attachment of the spicule to the huminite precursor root? material. Spicule gemmoscleres are present (Fig. 5G–H) but megascleres are far more common (Fig. 5I–J). Sponge spicules are not present in the chalk or in benches of the 3/06-U channel sample collected from above the chalk bed.

Based on the petrographic observations made herein, the paleoecology of the Chalāw deposit could be interpreted as consistent with the precursor vegetation and characteristics present in a mangrove community, although freshwater deposition cannot be ruled out. However, if the Chalāw deposit is interpreted to be from a mangrove environment, this implies the existence of a variable salinity, anoxic environment on a tidally-inundated estuarine or marine shoreline, in a tropical or subtropical latitude (e.g., Tomlinson, 1994; Hogarth, 2007). High mineral matter content of the Chalāw samples (34 to >95 vol.%) also is consistent with a mangrove environment wherein roots impede water flow in the intertidal zone and increase sediment deposition (Kenig et al., 1990). Dominance of inorganic material in the Chalāw samples could be interpreted to represent proximity to a terrigenous sediment source, for example an estuarine or marine shoreline environment. Organic-rich layers in modern mangrove peat have been interpreted as representing periods of relatively fast vegetation growth, whereas

mineral matter-rich layers are interpreted as periods of inundation by sediment-laden water or representative of the desiccation and decay of vegetation (Cameron and Palmer, 1995).

Several other observations also are consistent with the paleoenvironmental interpretation of the Chalāw strata as a mangrove community. For instance, the presence of the aragonite-needle chalk bed between the L and U sample series (Figs. 2A–B, 5K and 6A) is consistent with comparison to modern-day southwestern Florida where a coralline mud buries mangrove peat (Spackman et al., 1966). In Tobacco Range of the Belize barrier reef a modern mangrove community is associated with *halimeda*-rich sand and mud (Woodruffe, 1995). However, marine chalk could form over a freshwater peat environment with a sufficient change in base level.

Medium to high sulfur content (2.1–11.5 wt.%, Table 2; avg. 3.6 wt.%, db) is consistent with a marine or brackish influence (Spackman et al., 1966; Casagrande et al., 1977), and the frequent presence of pyrite (Fig. 6B) and pyritized shell fragments (Fig. 6C–D) is consistent with a subaquatically deposited mangrove peat (e.g., Cameron and Palmer, 1995). Peat deposited in freshwater environments typically contains low sulfur content (<1.0 wt.%; e.g., Casagrande et al., 1977; Spratt et al., 1987).

The low abundance, fragmentary nature of the diatom flora, and environment suggested by other proxies (e.g., high sulfur content and high mineral matter content) may suggest that the diatoms observed in the two samples that were evaluated were transported from upstream freshwater environments. The maximum in-ground temperature of 50 °C suggested by R_0 values is similar to the temperature at which opaline silica is mobilized (Pisciotta, 1981; Isaacs, 1982); however, the fragmentary nature of the individual frustules (Fig. 3) may suggest mechanical disaggregation during transportation.

4.2. Alternative interpretations and future research directions

If the Chalāw shales were deposited in a mangrove environment, an estuarine or marginal marine connection is implied for the Kabul Block during the Miocene–Pliocene, an observation which has significant tectonic implications and which requires close and critical examination. However, despite the observations and preliminary interpretation presented herein, the petrographic and other evidence that supports a mangrove paleoenvironment at Chalāw is not inconsistent with other types of paralic plant communities that could occur in close proximity to mangrove, for example, cabbage palm or cypress. Previous workers have concluded that Lataband Series rocks and their equivalents were deposited in terrestrial intermontane basins (Brunet et al., 1984; Abbasi and Friend, 2000; Sen, 2001; Basu, 2004; Nelson, 2005), wherein a freshwater swamp environment could occur with the same characteristics as reported herein for the Chalāw strata. Therefore, additional data are necessary to invalidate or better support further interpretation of the precursor plant community. For instance, palynological analyses probably are the best tool available to unequivocally establish the identity of the original vegetation (e.g., Willard et al., 2001). In addition, biomarker analyses may better constrain the types of precursor material present. Studies by Koch et al. (2003, 2005) and Basyuni et al. (2007) identified pentacyclic triterpenol compounds taxaxerol, β -amyrin, germanicol, lupicol, and betulin, and the sterol β -sitosterol, among others, as tracers for mangrove leaves and sediments. Biomarkers may also be a tool by which to better constrain the paleosalinity of the depositional environment, and to better distinguish a marine from a terrestrial freshwater signature. Mineralogical and geochemical studies to identify the inorganic phases and differentiate a terrestrial versus marginal marine (e.g., glauconite, high B concentrations) environment also are necessary. Planned and ongoing work on the Chalāw samples as part of the USGS Afghanistan coal resource assessment will utilize these and other types of analytical techniques, e.g., nuclear magnetic resonance spectroscopy, to better constrain and guide our interpretations of the paleoenvironment.

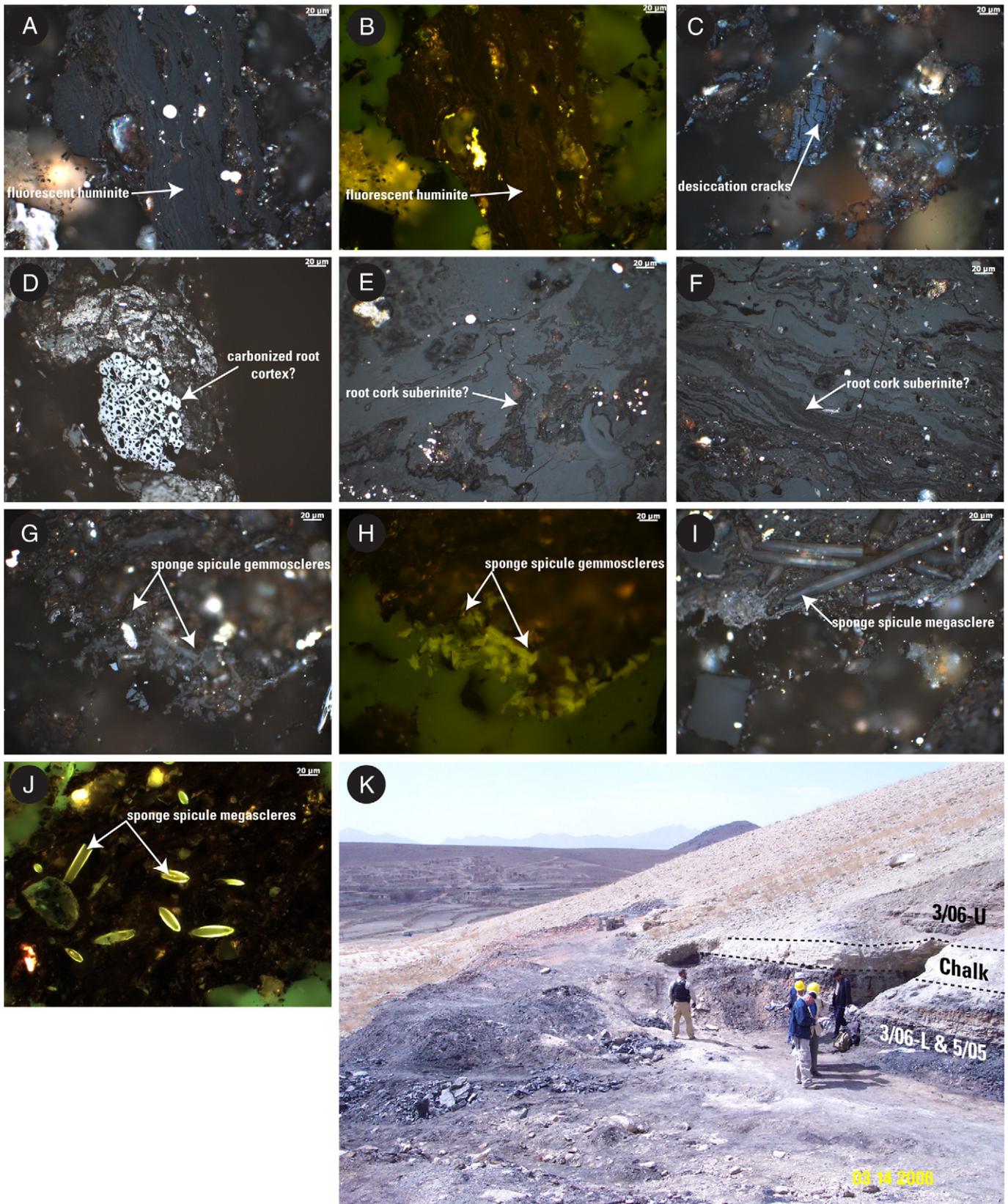


Fig. 5. (A) Dark fluorescent huminite in sample KBL-CHLW-3/06-L2.7 showing reddish internal reflections. (B) Same field of view as (A) under blue light illumination. (C) Desiccation cracks in huminite in sample KBL-CHLW-3/06-U3.5. (D) Carbonized root cortex aerenchyma? (fusinite) preserving angular cell wall junctions in sample KBL-CHLW-3/06-U3.7. (E) Root cork suberinite? in sample KBL-CHLW-3/06-L2.1. (F) Root cork suberinite? in sample KBL-CHLW-5/05-1.4. (G) Spicule gemmoscleres in sample KBL-CHLW-3/06-L2.1. (H) Same field of view as (G) under blue light illumination. (I) Spicule megascleres in sample KBL-CHLW-3/06-A2-ROM. (J) Spicule megascleres in sample KBL-CHLW-3/06-A2-ROM under blue light illumination. (K) Outcrop photograph of aragonite-needle chalk bed between the L and U channel sample series. Photomicrographs A, C–G, and I under white light illumination, oil immersion, 500× magnification.

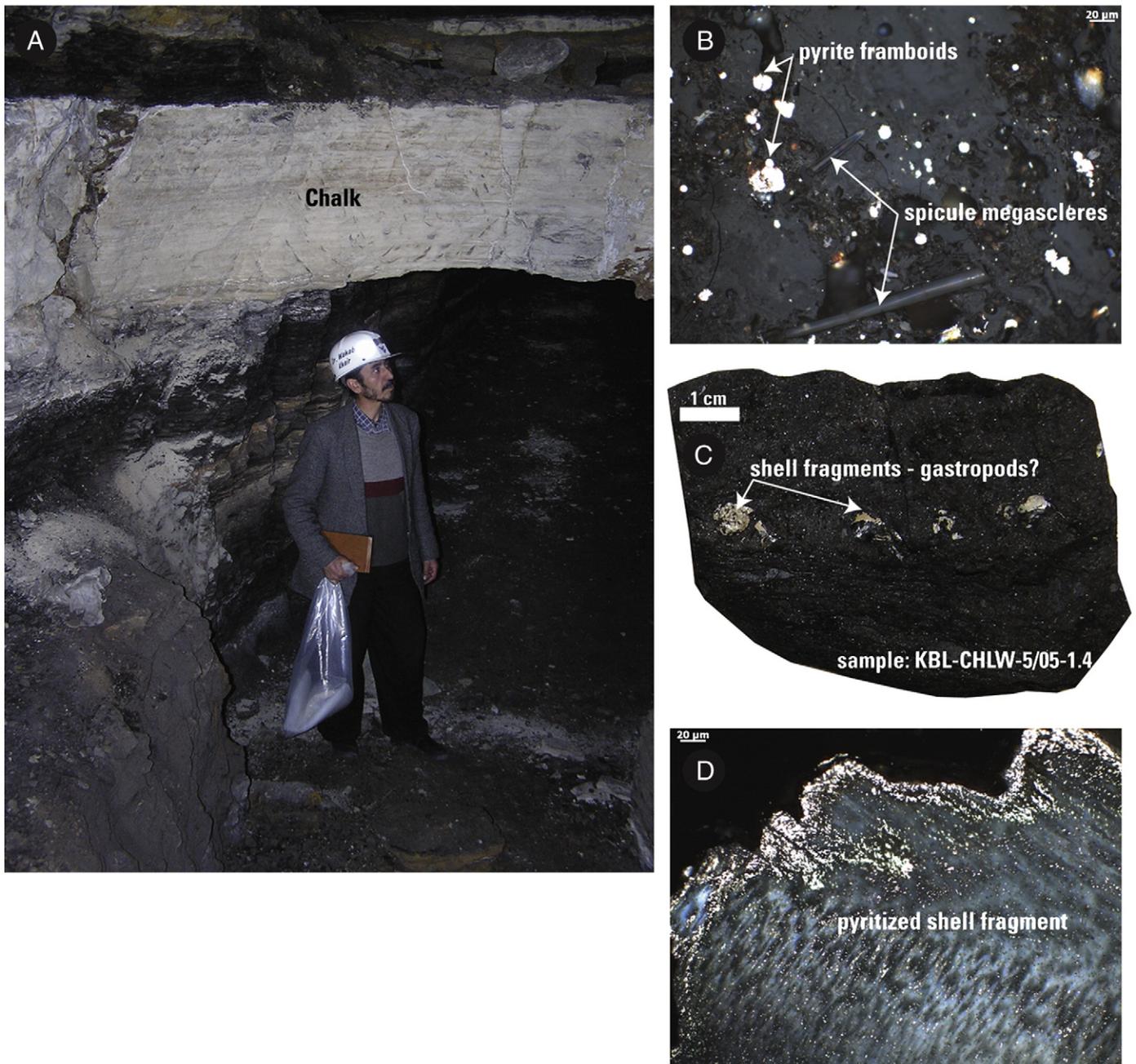


Fig. 6. (A) Adit photograph of aragonite-needle chalk bed between the L and U channel sample series. (B) Photomicrograph of pyrite framboids in sample KBL-CHLW-3/06-L2.1. Spicule megascleres are present. (C) Pyritized shell fragments (gastropods?) in hand sample KBL-CHLW-5/05-1.4. (D) Photomicrograph of pyritized shell fragments in sample KBL-CHLW-3/06-L2.2p. Photomicrographs B and D under white light illumination, oil immersion, 500× magnification.

4.3. Energy resource potential

The world-class Aynak copper deposit is hosted in Proterozoic rocks approximately 15–20 km west–southwest of Chalāw (Fig. 1), one of a series of important stratiform copper deposits occurring within the Kabul Block (Afghanistan Geological Survey, 2005). At Aynak, copper resources are estimated at approximately 30 million tonnes (Peters et al., 2007), and the Afghanistan government has contracted with a Chinese consortium for the development of this resource (Page, 2008; Library of Congress, 2008). However, development will require power for mine operations and for extractive metallurgy. Jurassic coal deposits in the north of the country represent a viable fuel resource for mine operations; however, these coal resources are hundreds of km distant and there is only one improved road southward towards Kabul for coal transport. There are no railroads in Afghanistan for coal transportation

and no installed coal-fired electric capacity. Chronic energy shortages affect Kabul and only about ten percent of Afghanistan's population has access to electricity (Energy Information Administration, 2006). Plans to build transmission lines to import electricity are in progress; however, the existing hydroelectric capacity in the country is in need of rehabilitation and currently is underutilized (Library of Congress, 2008).

Better understanding of the potential thermal fuel resources present at Chalāw could lead to use of the deposit to produce electricity. For example, a turn-key fluidized bed combustion (FBC) unit could be fueled by Chalāw carbonaceous shale for electricity generation in support of Aynak mine operations or milling, as well as for general public consumption. The ash yield, moisture and sulfur content, and calorific value of the Chalāw samples (Table 2) are appropriate in comparison with thermal fuels utilized in modern fluidized bed combustors (e.g., Oka, 2004).

Lack of agglomerating properties (FSI = 0, Table 3) also may help to decrease defluidization and blockage effects in a fluidized bed combustion application (e.g., Gray and Lowenhaupt, 1989; Brown et al., 1996). However, accurate determination of free swelling index values may be negatively impacted by high mineral matter content. High grindability indices (HGI = 90–108, Table 3) may suggest relative ease in potential milling of the mine product for utilization. Low ash softening temperatures (1160–1300 °C, Table 3) may suggest potential slagging and fouling tendencies in a conventional pulverized fuel combustion application, but this concern might be irrelevant at the lower temperatures of FBC (e.g., Habiger, 1996). Moreover, ash fusion temperatures are very similar to Powder River Basin subbituminous coals used in combustion applications (e.g., Stultz and Kitto, 2005).

The coal-quality data presented herein suggest that the Chalāw deposit may be a viable resource for commercial-scale development. Further field investigations and drilling would help to better delineate the extent and quantity of the Chalāw resource and improve mine planning. The stratigraphic and geographic distribution of the carbonaceous shale deposit is not known and it is possible that better quality beds may be present in other areas or horizons.

5. Summary and conclusions

A subbituminous carbonaceous shale deposit mined at Chalāw approximately 30 km southeast of central Kabul, Afghanistan, currently is exploited to fire local brick kilns and for domestic use. Petrographic and other characteristics of three channel samples collected from the mined carbonaceous shale bed at Chalāw are suggestive of a mangrove precursor peat. These characteristics include the absence of liptinite macerals except for what is interpreted herein as root cork suberinite, presence of shell fragments and sponge spicules, high mineral matter and sulfur content, and the presence of an adjacent aragonite-needle chalk. The inferred mangrove depositional environment implies a variable salinity, tidally-inundated estuarine or marginal marine setting in a tropical or subtropical latitude for Chalāw strata. This depositional environment interpretation is inconsistent with previous work that interpreted equivalent strata in Afghanistan as deposited in terrestrial intermontane basins. However, a freshwater depositional environment cannot be ruled out with the current data and additional work including palynological and/or biomarker analyses is necessary to support or invalidate a mangrove interpretation of the depositional environment.

Quality analyses of the Chalāw samples suggest that the deposit could be utilized as a thermal fuel resource in a fluidized bed combustion unit. This may allow rapid commercial-scale development of the world-class stratiform copper deposit at Aynak and/or for power generation for public consumption; however, delineation of the physical extent of the Chalāw deposit through field investigations would be helpful in evaluating this prospect.

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