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Lithofacies and fluvial–lacustrine environments of the Palaeogene Sevkhuul and Ergil members (Ergiliin Zoo Formation, South Gobi, Mongolia)

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Abstract – The clastic sequence of the Ergiliin Zoo Formation stretches along the Mongolian–Chinese border in the southern Gobi Desert, Mongolia. Its members (Sevkhuul, Ergil) exposed in the Erdene Sum region are well known for their vertebrate remains of Late Eocene and Oligocene age. Based upon field work, the continental red beds were subdivided into four units described as (I) prodelta/mud-sand flat, (II) delta front, (III) delta plain and (IV) calcretes. All sub-environments are in a fluvial–lacustrine setting. Electronmicroprobe analysis, in addition to conventional thin-section examination, was applied to shed some light on the complex mineral association made up of light minerals (quartz, plagioclase, ternary feldspar, orthoclase, smectite, illite, rare palygorskite), heavy minerals (almandine–pyrope solid solution series, zoisite–epidote s.s.s.) and abundant goethite and carbonate minerals (calcite, dolomite). Igneous rocks being exposed in the source area have contributed to the formation of carbonate minerals and Mg-bearing sheet silicates during diagenesis. Higher up on the delta plain transitional between distal alluvial and deltaic deposits, fluids emerged from the distal alluvial–fluvial deposits and formed calcareous duricrusts. Drawing conclusions from the rock colour, the mineral assemblage and the palaeoecological data, the climatic conditions may be described as alternating wet and dry seasons, closely resembling those conditions of a modern savannah.

Keywords: red beds, fluvial, lacustrine, Tertiary, Mongolia.

1. Introduction

Lithofaciesstudies and analyses of the depositional environment of sedimentary rocks in Mongolia are very scarce, especially in the southern Gobi Desert (Martinson, 1975; Devyatkin & Shuvalov, 1990; Shuvalov, 1982; Jerzykiewicz *et al.* 1993; Schmid, 1999; Johnson & Graham, 2004*a, b*). The Gobi Desert in Mongolia may for many people be synonymous with dinosaurs roaming a vast landscape which today is called the border region between China and Mongolia (Benton *et al.* 2000; Tang *et al.* 2001). Cretaceous sedimentary rocks, the renowned host strata of dinosaur remains, cover a large part of Mongolia, and some analyses of the depositional environments of these rocks may be found in Khand *et al.* (2000). Vertically upward in the stratigraphic record of the Gobi, there are some Tertiary beds rife with vertebrate remains. The Palaeogene Ergiliin Zoo Formation is well exposed along the Mongolian–Chinese border in the southern Gobi Desert, Mongolia (Fig. 1a). The sedimentary series consists of red and grey siliciclastics with a coarsening-upward grain-size trend in the study area. The thickness of the Sevkhuul and Ergil members measures 25 m each. The overall thickness of the Ergiliin Zoo Formation measures about 60 m. Studies of vertebrate remains, the first palaeontological investigations of which date back to the late 1920s, have made this stratigraphic unit very popular with palaeontologists (Berkey & Morris, 1966; Dashzeveg & Meng, 1998). Despite intensive palaeontological studies, little information is available to date on the depositional environment of the Ergiliin Zoo Formation. The lithofacies have therefore been investigated in the Erdene Sum (Sum = county) in three different study areas around Khoyor Zaany Ovoo, Ulaan Uul and Ulaan Buur, to provide a basis for an environment analysis of the Palaeogene Ergiliin Zoo Formation (Fig. 1b,c). An interdisciplinary approach has been taken, combining geological field work with mineralogy to shed some light on palaeogeographic evolution in this part of Mongolia during Early Tertiary times. Abundant faunal remains at Khoyor Zaany Ovoo give the Ergiliin Zoo Formation an edge over other red bed sequences elsewhere, which are quite similar in lithology but missing any faunal remains suitable for palaeontological dating or useful for palaeoecological interpretation.

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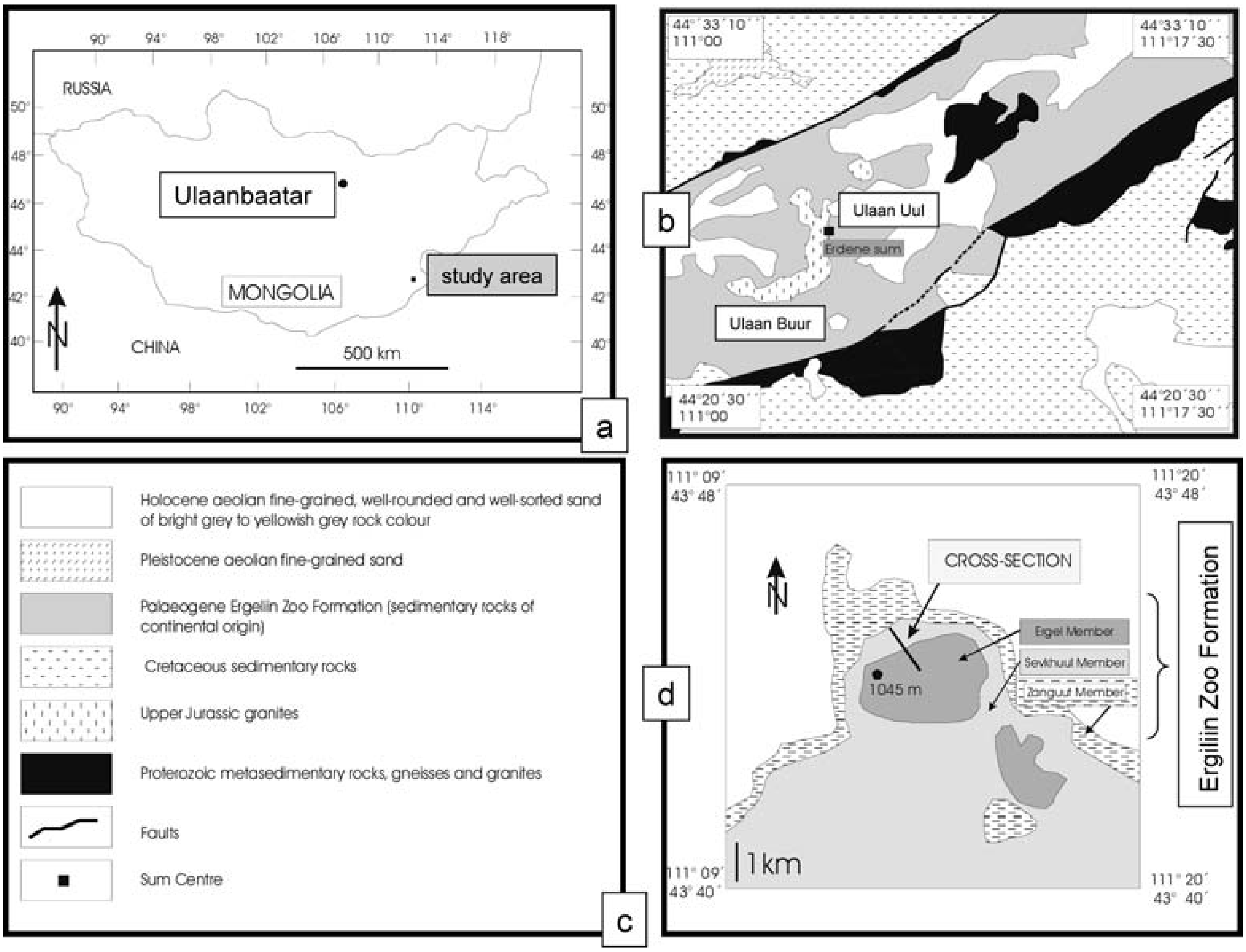

Figure 1. The position and the geological setting of the study areas. (a) Position of the study areas in Mongolia. (b) Index map to show the Ulaan Uul and Ulaan Buur study sites near Erdene Sum. (c) Legend for (b). (d) Index map to show the Khoyor Zaany Ovoo hill in SE Mongolia and its geological setting. The investigated reference section shown in Figure 2 is denoted by 'cross-section' in the geological map. Members of the Ergiliin Zoo Formation are shown in boxes with patterns identical to those on the map.

2. Geological setting

The Erdene district is located near the Mongolian–Chinese border (Fig. 1a). Jamiyandorj & Dagva Ochir (2001) and Badarch (2003) gave the most recent account of this part of Mongolia. Middle to Upper Mesoproterozoic metamorphic rocks were intruded by granites of Carboniferous age and overlain by Mesozoic and Cenozoic sedimentary rocks. The Urgun Formation consists of greenschists, plagiogneiss, meta-andesites, marbles, quartzite, granite–gneiss and amphibolites. It is unconformably overlain by the Upper Cretaceous Baruun Goyot Formation, whose age of sedimentation was determined using dinosaur eggs and bones (Badarch, 2003). Red to grey siliciclastics spanning the full grain-size range from gravel to clay make up this Upper Cretaceous series. Jurassic to Cretaceous intercontinental rift evolution has been intensively studied in the East Gobi basin to get some information on the hydrocarbon potential of this region (Traynor & Sladen, 1995; Johnson, 2004). The overlying Cenozoic rocks, which cover vast areas around Erdene, are lithologically similar and represented by the Ergiliin Zoo Formation (Fig. 1b,c). The latter series was subdivided into six members. Arranged in their stratigraphic order from bottom to top, these are the Khuvsgul, Zanguut, Sevkhuul, Ergil, Khetsuu Tsav and Shand gol members (Rojdenstvenskii, 1949; Berkey & Morris, 1966; Yanovskii, Kurochkin & Devyatkin, 1977; Dashzeveg, 1965, 1991; Dashzeveg & Meng, 1998).

3. Methodology

During the field campaign, mapping and conventional logging were carried out (Figs 1b,d, 2, 3). The cross-sections were surveyed by a hand-held magnetometer and a gamma spectrometer for stratigraphic correlation and pre-selection of samples in the field. In addition to these methods, 50 samples were analysed with a Portable Infrared Mineral Analyser to collect first-hand information in the field about the mineralogical composition of the sedimentary rocks. Laboratory-based mineralogical investigations involved examination of thin- and particulate sections for the heavy mineral contents and sedimentary textures. In addition, X-ray diffraction analysis and electron microprobe analyses were applied to get precise information on the chemical composition of rock-forming minerals. Major and minor elements of whole rock samples were analysed using X-ray fluorescence.

4. Results

4.a. Palaeontological data

Detailed palaeontological studies of the Ergiliin Zoo Formation were conducted by Dashzeveg (1965) and Yanovskii, Kkurochkin & Devyatkin (1977). A comparative study of mammalia in Kazakhstan and Mongolia was performed by Lopatin (1997). These authors reported from the Palaeogene series in Mongolia *Lophiomeryx* sp., *Emboletherium louskii* Osborn and *Hycenodon* sp. *Amynodon ihzanensis* sp. was found for the first time in the Ergil Member, and shows significant differences from species in North America and China. In the lower red argillaceous and calcareous clay beds of the Khuvsgul Member, which forms the basal unit of the Ergiliin Zoo Formation, there are no faunal or floral remains. From the Zanguut Member, underlying the Sevkhuul Member, to the Ergil Member, faunal remains have been observed in all beds, although in different quantities.

4.b. Lithological data in the Khoyor Zaany Ovoo area

The sedimentary record at Khoyor Zaany Ovoo shows the highest variability and therefore was taken as reference for the other sections with respect to lithological and biostratigraphical correlation and described in more detail than the lithologies at Ulaan Uul and Ulaan Buur (Figs 2, 3).

The fine-grained grey sandstones and siltstones of unit I at Khoyor Zaany Ovoo pass upward into medium-grained sandstone (Fig. 2). The top strata of these sequences, as thick as 0.5 m, are cross-bedded. The planar foresets and trough-shaped bedding planes of the cross-strata dip at a very low angle, have tangential bases and merge into horizontal bedding as the rocks become younger.

Grain-size variation and sedimentary structures are the major criteria for subdividing unit II into two sub-units IIa and IIb (Fig. 2). The particle size of the siliciclastics in unit IIb, spanning the range from clay to conglomerate, is much larger than that of the underlying unit IIa. The overall outward appearance of unit II is that of a coarsening-upward sequence. In Figure 4a, details of the bedding types in the finer-grained interbeds of unit II are shown. Small-scale wavy to low-angle cross-bedding is very common in unit IIb. Locally, ferruginous clay lenses are intercalated among the siliciclastics of unit IIb (Fig. 4a). Passing from unit IIa to unit IIb, a conspicuous change in the type of stratification may be observed. In the lower half, bedsets showing low-angle cross-stratification are found. They gradually develop into bedsets in the upper half showing horizontal bedding (Fig. 2). At least two different groups of clasts may be identified based on grain morphology. Group I is well rounded to rounded and consists mainly of K-feldspar and some quartz grains (Fig. 5). The grains of group II are poorly shaped and thus were classified as ‘angular to subangular’. This morphology class is made up almost exclusively of quartz.

The variable width of the lithological column in Figure 2 reflects a considerable variation in grain-size during deposition of unit III and leads to a subdivision into four sub-units IIIa to IIId. Unit III begins with conglomeratic arenites and ends in a sub-sequence composed of clay and sand (Fig. 2). Sediments of unit III also show a great variety of sedimentary structures with planar and trough cross-stratification as widespread as horizontal bedding. Particularly in unit IIIa, trough cross-bedding is a very common type of stratification with bedsets exceeding more than one metre in thickness (Fig. 4b). Many bedsets are rife with vertebrate remains, offering good conditions for palaeocurrent measurements (Fig. 6). Together with some linear orientations of vertebrate remains which are marked in the rose diagram, a total of 90 foresets in planar cross-beds and axes of trough cross-bedsets were measured. The data were statistically analysed and the results of the orientation of linear and planar sedimentary elements plotted in rose diagrams (Fig. 6). The first-order maximum of the palaeocurrent measurements in the rose diagram of unit IIIa is facing towards 45° and the second-order maximum towards 120°, with additional readings clustering around 90°. Measurements carried out in cross-bedded arenaceous rocks of unit IIId give a less complicated picture with a first-order maximum towards the northeast distinctive from the second-order maximum facing southeast (Fig. 6). Higher up in the stratigraphic sequence, complex ripple cross-lamination, wavy and lenticular bedding may be recognized in finer-grained sandstones of sub-units IIIb and IIId. Fine- to medium-grained sandstones have bedsets with climbing ripple cross-lamination alternating with horizontal plane lamination and antidunes (Fig. 4c).

Unit IV sediments are very distinct from the underlying strata, due to their heterogeneity both in composition and colour. The lower part of the unit consists of white calcareous and reddish goethite-bearing encrustations which coat the arenaceous deposits of unit III. The upper part of unit IV is formed by a veneer of gravel covering the plateau of the table mountain.

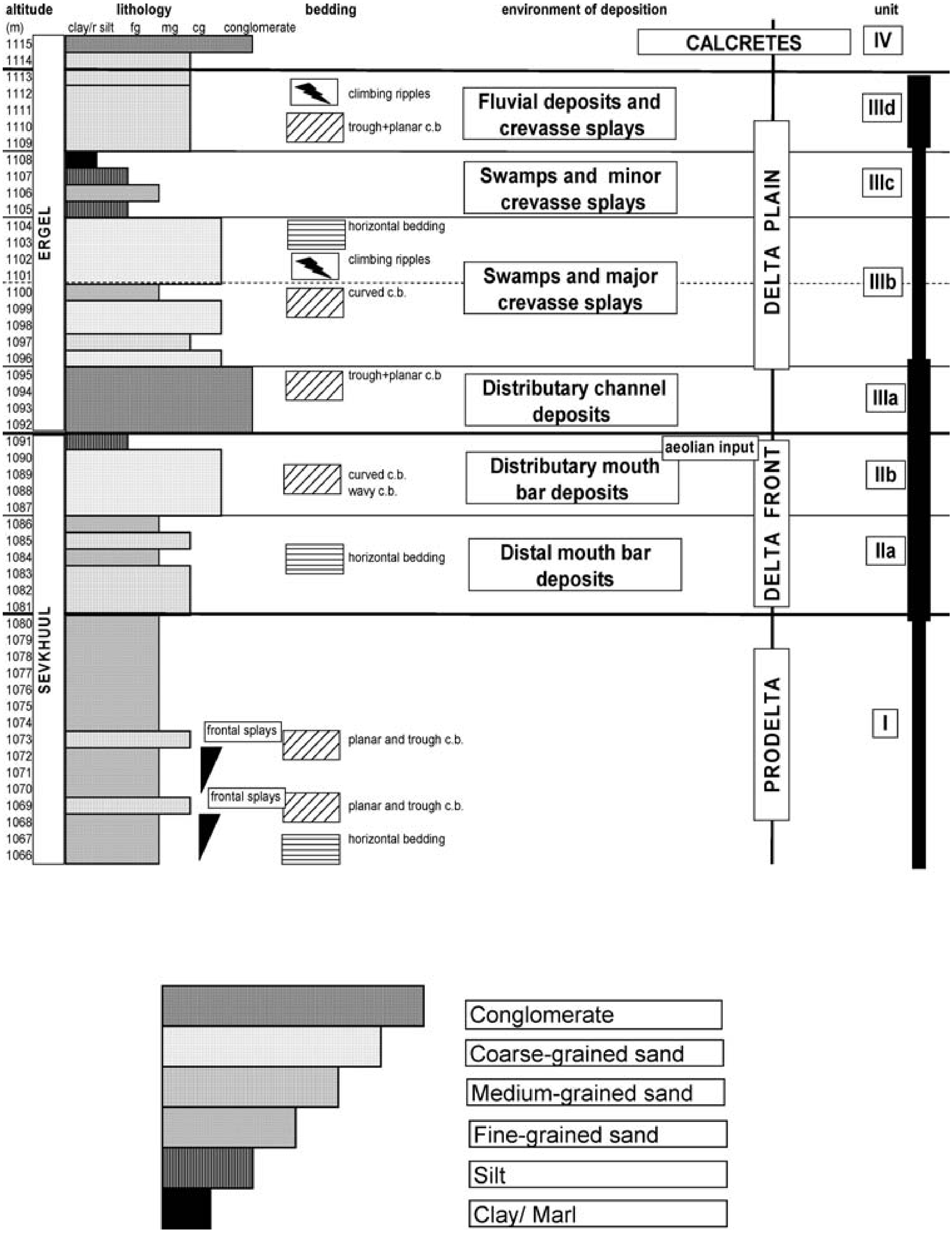

Figure 2. Stratigraphy, litholog and the environment of deposition at Khoyor Zaany Ovoo. Altitude in metres above sea level. The vertical line denotes the relative abundance of vertebrate remains in the various depositional environments.

4.c. Lithological data in the Ulaan Uul area

The outward appearance of the red bed deposits at Ulaan Uul is very monotonous. Neither the rock colour, nor the sedimentary structures and textures are helpful for the subdivision of the red bed sequence. Only grain-size variation and carbonate content have proved to be useful for a more subtle subdivision of the sequence into

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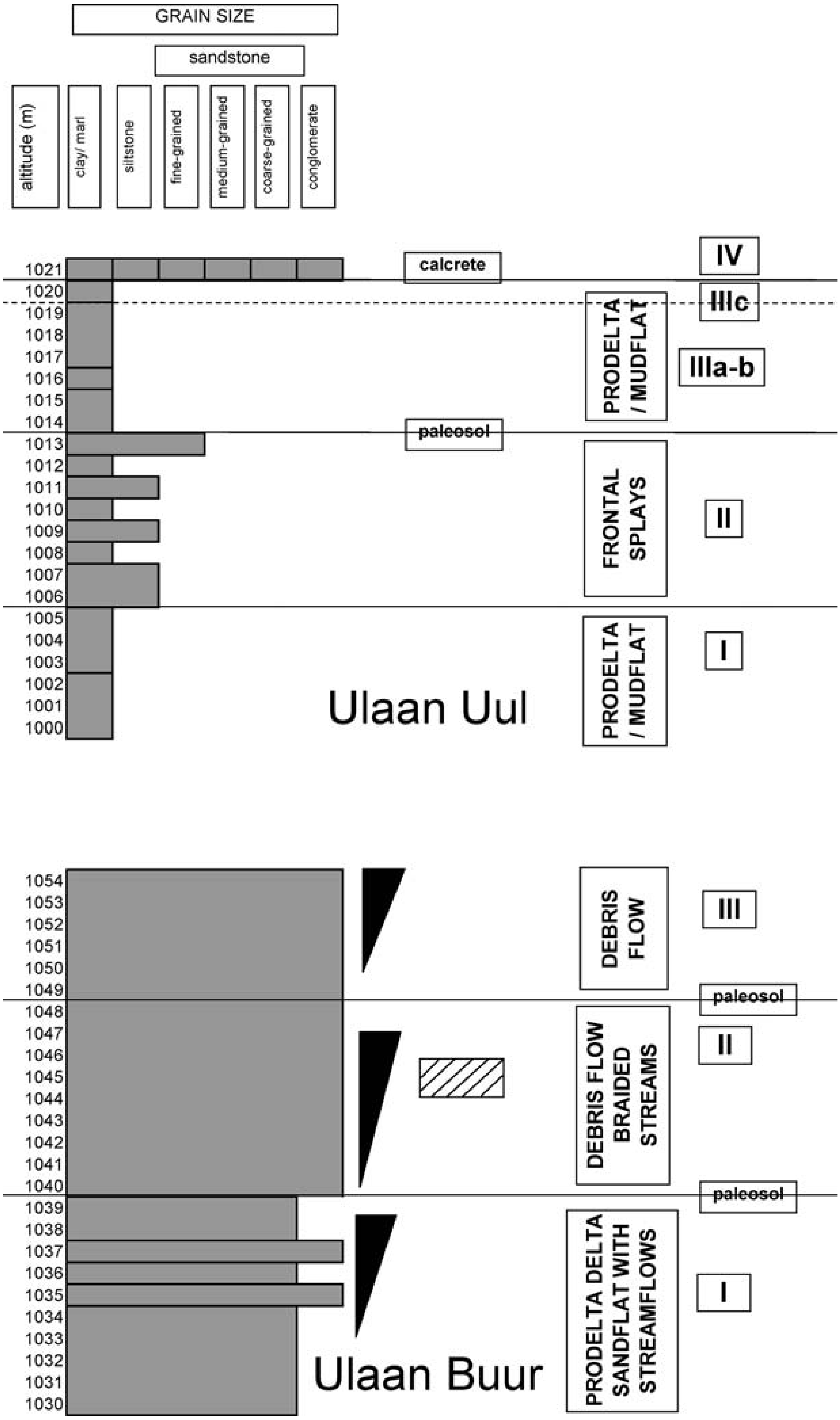

Figure 3. Lithologs and the environment of deposition at Ulaan Uul and Ulaan Buur. Altitude in metres above sea level. For legend see Figure 2. The black wedges denote fining-upward grain-size trends in each section.

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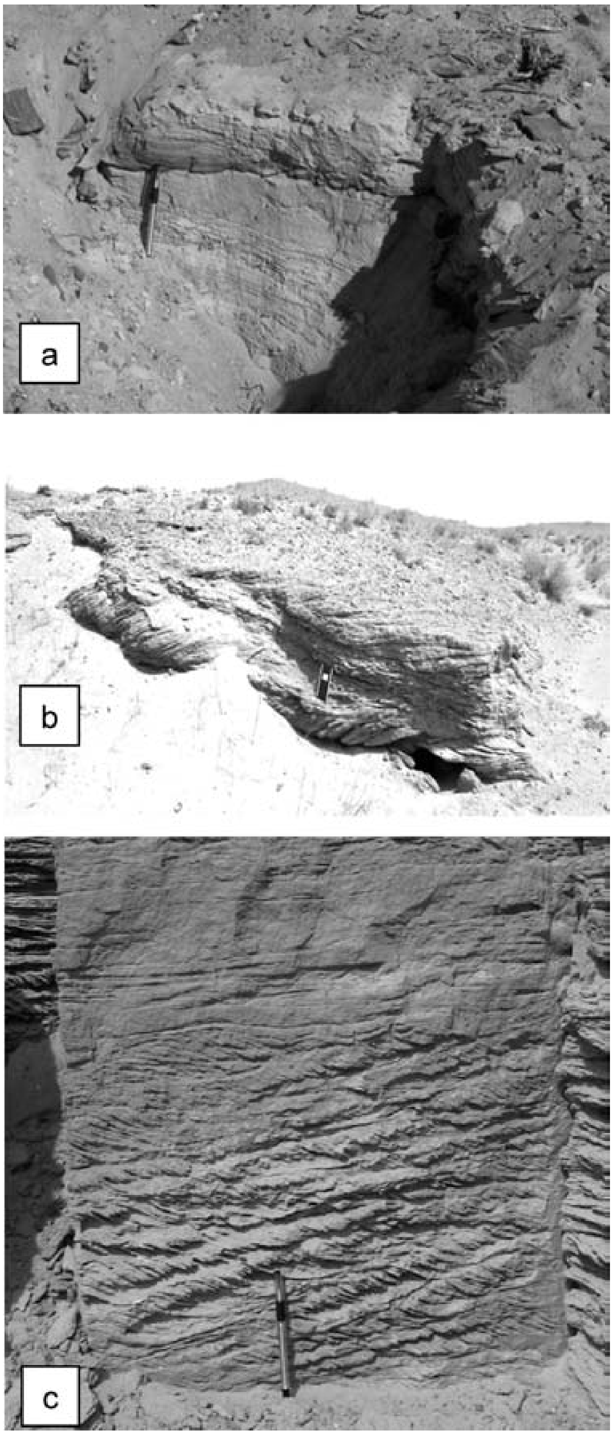

Figure 4. Lithology of the Ergiliin Zoo Formation at outcrop. (a) Fine-sand and ferruginous clay lenses are intercalated among the arenaceous siliciclastics of unit IIb. Small-scale wavy to low-angle cross-bedding is visible in the footwall sediments. Environment: distributary mouth bar deposits. Length of pen is 15 cm. (b) Planar and trough cross-stratification is widespread, particularly in unit IIIa, where trough cross-bedding is a very common type of stratification with bedsets exceeding more than one metre in thickness. The bedsets are peppered with vertebrate remains. Environment: distributary channel deposits. Height of field notebook is 20 cm. (c) Complex ripple cross-lamination, wavy and lenticular bedding may be recognized in finer-grained sandstones of sub-units IIIb and IIId. In fine- to medium-grained sandstones, bedsets show climbing ripple cross-lamination. Environment: upper delta plain–crevasse splay deposits. Length of pen is 15 cm.

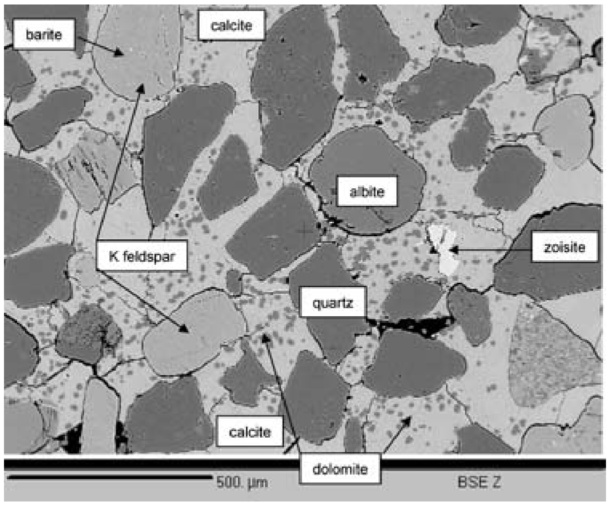

Figure 5. Electron-microprobe micrograph (back-scattered electron image). Calcareous subarkose hosting at least two different groups of detrital grains with respect to clast morphology. Group I is well rounded to rounded and consists of K-feldspar and some quartz grains. Group II is poorly shaped and classified as 'angular to subangular'. It is made up almost exclusively of quartz. Tiny ovoids of dolomite are disseminated in coarse-grained calcite.

four discrete units. The grain-size variation provides evidence for a coarsening-upward sequence which is covered by calcareous encrustation and overlain by a veneer of gravel (Fig. 3).

Unit I consists of red-brown massive mudstones; only sporadically are grains of fine sand found dispersed in these argillaceous deposits (Fig. 3). Unit II is different from the underlying stratum in its increased content of sand, its rock colour which turns into yellow and pale grey and in its poorly expressed bedding. Vertically upward in the stratigraphic column the lithological situation returns to 'normal'. The lithofacies of unit III closely resembles that of the basal unit I (Fig. 3). Unit III is only at variance with unit I in the lowermost part, where cracks, clay illuviations and microscouring may be observed, and in the uppermost part, where carbonate minerals are abundant. A thin veneer of gravel spreads across the entire sequence. Clay illuviations have already been identified near the top of unit III. Unit IV rests unconformably on unit III, and hence has to be seen as a discrete (top) stratum.

4.d. Lithological data in the Ulaan Buur area

From a distance, the sedimentary rocks in the small hills and ridges near Ulaan Buur closely resemble stratigraphically equivalent rocks at Ulaan Uul (Fig. 3). Both show a pronounced rusty red colour; however, a close-up view of the rocks at Ulaan Buur delivers a picture very different from what has been described from Ulaan Uul. It is a series of coarse-grained to conglomeratic lithic arenites to conglomerates with their angular to subangular clasts arranged in a matrix- to grain-supported fabric. Flat pebbles are imbricated

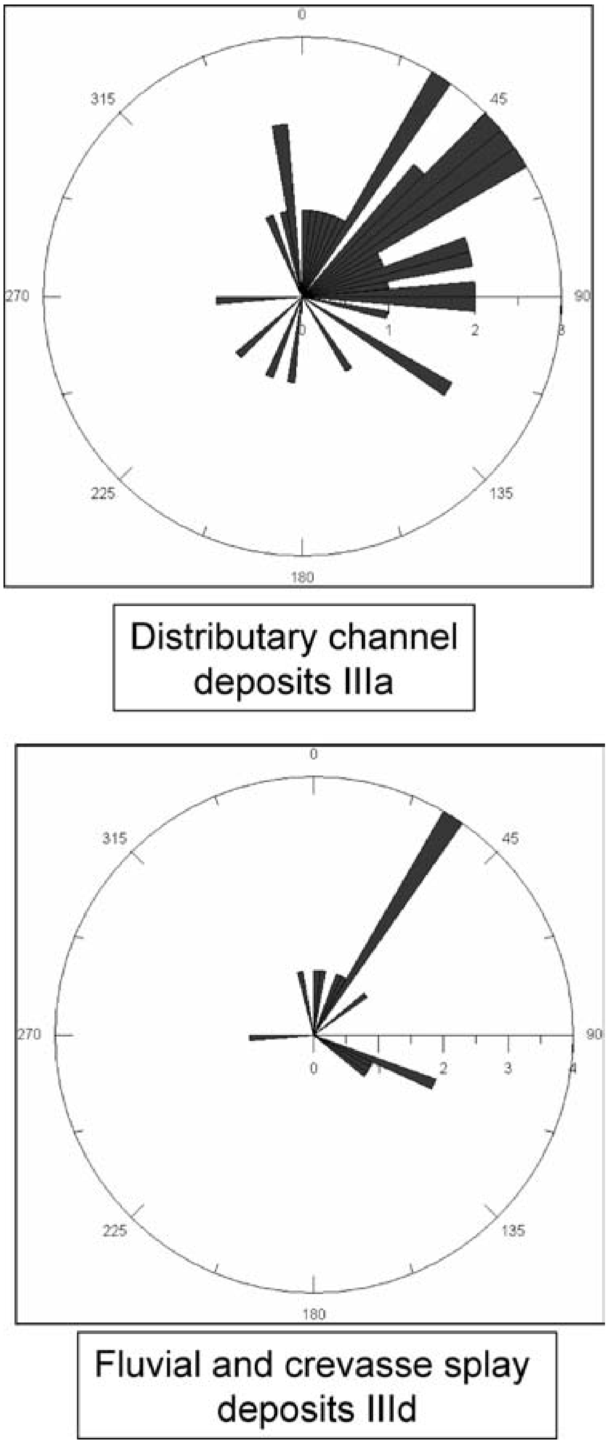

Figure 6. Rose diagrams showing the palaeocurrent direction based on measurements of cross-bedding and orientation of vertebrate remains (V) in arenaceous rocks.

with a general dip around 35° towards the north-west. Trough and low-angle cross-bedding are poorly developed and were only observed in some coarse-grained arenites near the boundary fault of the graben (Fig. 1b). The siliciclastics occur in lobes that amalgamate to aprons along fault escarpments in the Gobi Desert steppe. Because of their abundance in trivalent Fe in the form of goethite, the rocks show an overall reddish brown tint. Their poorly rounded pebbles and cobbles tend to have an a(p) fabric *sensu* Harms *et al.* (1975). The overall grain-size variation in the series shows a coarsening-upward trend, which, in context with the aforementioned stratification, allows for a subdivision of the series into three units. The units of the red beds at Ulaan Buur were coded IIa, IIb and IIIa in order to facilitate palaeoenvironmental correlation with the sections under study at Ulaan Uul and Khoyor Zaany Ovoo.

4.e. Mineralogical and chemical composition

The assemblage of sheet silicates in Khoyor Zaany Ovoo does not vary greatly across the entire section. Illite is ubiquitous, and Ca-bearing smectite occurs mainly in units I, IIIb and IIIc. The EDS spectrum of illite gives low K and Fe, some Mg and high Al. The common peaks of glycolated samples at 17 Å for smectite and 10 Å for illite corroborate the findings obtained from EMP analyses (Biscaye, 1965). Palygorskite was identified as a rare constituent among the phyllosilicates by XRD. At Ulaan Uul and Ulaan Buur, minor amounts of kaolinite were detected in addition to traces of chlorite (or vermiculite?). The almost complete shift of the 14 Å intensity towards higher d-values of the $< 2\ \mu$m fraction after being treated with glycerine indicates a dominance of smectite among the sheet silicates.

Grains of detrital feldspar are abundant, leading to the designation of most sediments as arkosic arenites and subarkoses at Khoyor Zaany Ovoo. Potassium feldspar with commonly > 90 mol. % orthoclase, makes up 13 to 24 % of the mineral assemblage of the siliciclastics. Plagioclase, with anorthite present in amounts of between 1 and 15 mol. %, makes up 6 to 10 % of the mineral assemblage (Table 1). In some K-feldspar grains, inclusions of barite were discovered (Fig. 5). A number of K-feldspar grains have an intermediate composition (Or85Ab15, Or69Ab28An3, Or62Ab37An1, Or54Ab44An2) with a fairly high Ba content of up to 1.5 wt % BaO (Table 1). Some of these alkaline feldspar solid solutions come close to what might be called a ternary feldspar *sensu* Ribbe (1983) (Table 1). Quartz is ubiquitous in all siliciclastics across the entire sequence with rounded to subrounded grains very different in size.

Grains of garnet prevail among the heavy minerals. Placer-like concentrations of garnet are common, totaling 4.2 % of the mineral assemblage. Garnet grains are up to 200 μm in size, are usually subrounded and appear unzoned in the backscattered electron images. The garnet compositions do not change throughout deposition of the Ergiliin Zoo Formation (Table 1). In terms of end-members, the garnet composition falls in the range 49–74 mol. % almandine, 16–42 % pyrope, with less than 11 mol. % andradite, and < 2.8 mol. %

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Table 1. Minimum, mean and maximum values of some light (feldspar) and heavy minerals (garnet, zoisite–epidote)

	Feldspar			Garnet			Epidote–zoisite		
Mineral	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
SiO_2	61.267	63.703	68.097	36.068	37.312	38.762	35.972	36.681	37.759
TiO_2	0.000	0.009	0.029	0	0.033	0.088	0.013	0.027	0.048
Al_2O_3	18.421	19.234	22.310	21.566	22.143	22.535	23.58	24.747	26.352
FeO(T)				27.196	28.959	34.232			
Fe_2O_3				1.622	3.606	5.235			
FeO	0.000	0.094	0.221	22.489	25.714	32.408	7.779	9.959	11.096
MnO	0.000	0.002	0.009	0.107	0.464	1.193	0.07	0.162	0.204
MgO	0.000	0.006	0.021	4.043	9.287	10.714	0.009	0.039	0.062
CaO	0.000	0.447	3.320	0.91	1.448	2.433	23.407	23.676	24.113
Na_2O	0.456	3.939	11.527	0	0.009	0.023	0	0.009	0.023
K_2O	0.201	10.597	15.859	0	0.003	0.014	0	0.004	0.008
BaO	0.000	0.476	0.743	0	0.006	0.037	0	0.008	0.027
Albite	4.187	34.337	99.027						
Anorthite	0.000	2.134	3.213						
Orthoclase	0.203	63.703	95.813						
Andradite				4.04	7.14	11.65			
Almandine				49.26	56.03	74.16			
Pyrope				16.48	35.95	42.26			
Spessartine				0	0.94	2.76			
Al/Fe							2.99	3.595	4.77
Al/Al+Fe							0.75	0.7775	0.83

Chemical data are given in wt % and end-members of solid solutions shown in the lower half of the table are given in vol. %.

spessartite. Most grains plot in a narrow range of 50–62 % almandine and 30–40 % pyrope. A small population of garnet stands out from the suite of garnet with andradite contents of between 4 and 8 %, because of its higher calculated Fe^{3+} concentrations (10–12 % andradite). Epidote–zoisite solid solution series are less abundant than garnet in the heavy mineral fraction (Fig. 5). Four of the grains analysed show very homogeneous compositions, with Al/(Al+Fe) ranging from 0.75 to 0.83 (Table 1). In addition to the major heavy minerals epidote–zoisite and garnet, which were investigated in more detail, ilmenite, zircon, tourmaline, rutile, amphibole, sphene, monazite and barite were also identified under the petrographic microscope and during electron-microprobe analyses. Monazite, sphene and barite were found to be included in K-feldspar (Fig. 5), while zircon, rutile, ilmenite and apatite form inclusions in quartz. In some dolomite clasts, amphibole and apatite grains have been seen. A common heavy mineral in units II and III is francolite. It occurs in isolated angular fragments or in bones, showing their organic tissues and textures very well preserved. Thin-section analyses of lithoclasts yielded a quite variable association of gneiss, granite, quartz mobilizates, shale, chert, silcretes and sporadic acidic volcaniclasts. The volcaniclasts are only present in the uppermost part of unit III. Although the lithoclast assemblage is varied, the association of lithoclasts does not vary significantly throughout deposition of the Ergiliin Zoo Formation. Bioclasts such as phosphatic vertebrate remains are enriched in bonebeds together with a shell hash of mollusks mainly in unit III.

Among the carbonate minerals, dolomite prevails over calcite in units I and II; it is a rare detrital component in units IIIa and IIId. Due to the elevated Mn content, part of the dolomite may be called magnesian kutnahorite or manganoan dolomite. Calcareous encrustations in unit IV are covered with a thin veneer of cobbles and pebbles. The calcareous cement minerals are xeno- to hypidiotopic, *sensu* Friedman (1965). Limonitization is widespread in all sections from units IIIa through IIId. Before goethite began coating siliciclasts, the carbonate minerals were removed from the pore space.

5. Discussion

5.a. Stratigraphy and ecology

Vertebrate remains were found across the entire section under study, predominantly in the coarse-grained arenaceous deposits of units IIa through IIIa (Fig. 2, see vertical bar). Fine-grained deposits, which were held to be swamp and mudflat deposits, are depleted in faunal remains. This is true for the red beds at Ulaan Uul, where fine-grained prodelta and delta plain deposits predominate over coarser-grained delta front deposits. On the other hand, very coarse-grained sandstones and gravelly rocks such as at Ulaan Buur did not offer a favourable habitat for mammals and reptiles to live in. These conglomeratic rocks have no good preservation potential for bones and shells. The depositional environment is too close to the mountainous hinterland, which is too inhospitable for mammals and reptiles due to lack of food and standing water bodies. A further reason for the lack of vertebrate remains lies in the high energy regime of the drainage system that might have ground away the faunal remains.

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Faunal correlation using mammal remains in the southern Gobi Desert at Khoer Dzan and Ergiliin Dzo by Meng & McKenna (1998) yielded a Late Eocene age of deposition for the sediments under study. The lowermost part exposed at Khoyor Zaany Ovoo is based on palaeontological finds attributed to the Sevkhuul Member, which was assigned a Late Eocene age. The upper half of the cross-section in the study area is equivalent to the Ergil Member, which was chronologically dated as Early Oligocene, also based on vertebrate remains (Fig. 2). Some vertebrate remains may also be useful for palaeoecological interpretation. Among the artiodactyls, the species *Lophiomeryx* was folivorous. These vertebrates lived in wooded to semi-aquatic habitats, near swamps (Blondel, 1998). The fauna is highly diverse, reflecting favourable conditions for reptiles and mammals. Comparison of ecological data with inorganic data obtained from a analysis of the host rocks leads to the taphonomic conclusion that part of the faunal remains found in the section under study were redeposited into channel-fill deposits. The distance of transport was not very long, and thus the value of the vertebrate remains for biostratigraphy not reduced. Otherwise skeletons of vertebrates could not have been preserved intact. To what extent reworking has played a part in the distribution of animal remains throughout sedimentation of the Ergiliin Zoo Formation, may be deduced from an overall correlation of its lithology and vertebrate remains. Red mudflat deposits did not offer a habitat for the animal species mentioned above (see Ulaan Uul; greenish calcareous argillaceous to arenaceous beds of the Zanguut Member were a good habitat). Upward in the stratigraphic sequence, coarser-grained calcareous siliciclastics of the Ergil and Sevkhuuk members became a more prominent host than fine-grained rocks, and hence, greater reworking of vertebrate remains may have taken place during deposition of the Ergiliin Zoo Formation.

The Ulaan Uul and Ulaan Buur sites do not cover the full stratigraphic section exposed at Khoyor Zaany Ovoo. The onset of sedimentation at Ulaan Buur took place a bit later than at Khoyor Zaany Ovoo. The brick red series at Ulaan Uul and Ulaan Buur may be correlated with the Hsanda-Go Formation. The latter was chronologically dated as Early Oligocene by means of radiometric age dating of basalts which gave an age of formation of 31.5 Ma (Schmidt, 1999).

5.b. Lithofacies and the environment analyses

A coarsening-upward grain-size trend is common to the rock sections under study, albeit very different in intensity and stacking pattern in each study site (Fig. 2). Such coarsening-upward grain-size trends have been identified in various marine and continental environments, for example, deltas prograding into the sea (Dunne & Hempton, 1984; Rasmussen, 2000), shallow marine environments (Hamblin & Walker, 1979; Park *et al.* 1995; Fürsich *et al.* 2001; Rey & Hidalgo, 2004) and submarine fans (Walker, 1979; Ito, 1998). The palaentological data presented above exclude a marine depositional environment for the Ergiliin Zoo Formation. In continental environments the prograding coarsening-upward sequences have been studied by Nemec & Steel (1984), Dill (1995), Martins-Neto (1996), Guocheng Zhang *et al.* (1998), Anadon *et al.* (1998) and Benvenuti (2003), among others. An interpretation of the depositional environments of these coarsening-upward red beds is given for each unit, based on their sedimentological textures and structures. The catena of lithofacies zones and depositional environments, respectively, is illustrated in an idealized cross-section from the source area to the basin (Fig. 7). It shows the basinal systems and the deltaic progradation of alluvial–fluvial red beds onto prodelta and mud-sand flat deposits in the foreland of a rising mountain ridge. From the moderate thickness of the section under study, small amounts of both subsidence and uplift may be inferred for the east. Gobi basin during Late Eocene and Early Oligocene times.

5.b.1. Unit I

Greenish-grey fine- to medium-grained siliciclastics show a wide lateral continuity at the foot of the Khoyor Zaany Ovoo Hill. Deposition of this rather fine-grained material took place at the edge of a low-gradient shallow basin. The grey siliciclastics were laid down on a wet mud-sand flat. The fines resulted from episodic flood discharge, as fine-grained particles were settling down from the suspension load *sensu* Vandervoort (1997). In the cross-section of Figure 2, small-scale coarsening-upward sequences or ‘microdeltas’ may be seen at 1069 m and 1073 m a.m.s.l. The coarsening-upward sequences designated as St and Sp lithofacies, using the codes by Miall (1996), may be interpreted in terms of splay channels or crevasse splay deposits (Fig. 2). Fine- to medium-grained sandstone bedsets which are well exposed in the Cretaceous St Mary River Formation have been described by Nadon (1994) in a similar way, as part of an anastomosing or meandering fluvial drainage system. The coarsening-upward sequences at Khoyor Zaany Ovoo interbedded with a fairly monotonous series of finer-grained siliciclastics represent what might be called a ‘microdelta’ and designated as frontal splays of the basal prodelta sequence using the common terminology of delta sequences. The massive mudstones of unit I in Ulaan Uul, much finer-grained than equivalent rocks at Khoyor Zaany Ovoo, are representative of a mudflat. Its site of deposition is more distal relative to the source area than at Khoyor Zaany Ovoo.

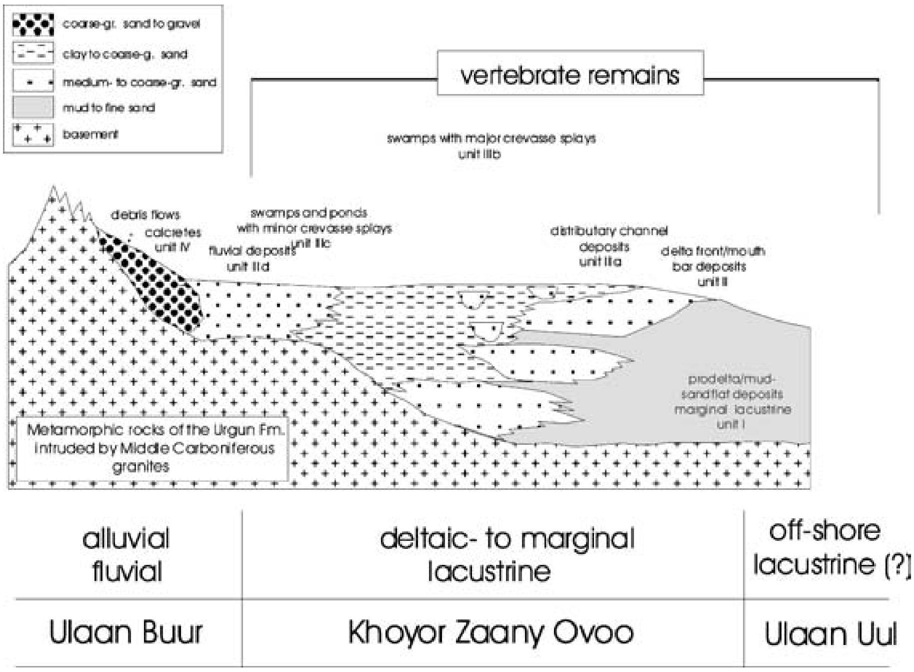

Figure 7. Cartoon showing the basinal systems in the Erdene Sum area and the delta-like progradation of alluvial–fluvial sediments onto prodelta/mud-sand flat deposits. Units referred to in the text and study sites are shown along the x-axis of the figure.

5.b.2. Unit II

The arenaceous sequence of unit II marks the onset of an extensive sediment dispersal system, minor precursors of which have already been encountered in the sedimentary sequence of unit I as frontal splays. The lithological features recognized at Khoyor Zaany Ovoo are similar to those recorded from the distal bar or delta front facies of fluvial deltas (Bhattacharya & Walker, 1992; Reading & Collinson, 1996; Roberts, 1997; Galloway, 1998; Miller & Gupta, 1999; Okazaki, Isaji & Nakzato, 2000; Lavoie, Allard & Hill, 2002). Based upon the sedimentary features recorded by these authors, the sediments of the lower sub-unit IIa are interpreted in terms of distal mouth bar deposits, while the overlying arenaceous sediments of sub-unit IIb are attributed to distributary mouth bar deposits (Fig. 4a,b). Tabular sandstones with sharp but non-erosive bases are similar to what has been described from delta-front settings. Channelized delta-front subarkoses with a great variety of cross-bedding features are interpreted as distributary mouth bar deposits (Figs 2, 4b). Considerable differences in the grain morphology originated from different modes of transport. Group II grains forming the majority of the grains have been derived from a short-distance fluvial transport, whereas the group I grains were obviously subject to aeolian transport and admixed to the fluvial deposits (Fig. 5). Aeolian deposits are typically well-rounded, well-sorted and medium-sized. The elevated K-feldspar content among group I grains is no argument against an aeolian mode of transport. Sand patches of aeolian origin are common at the landward edge of mudflats (Hofmann, Tourani & Gaupp, 2000). Unit II marks the most distal facies of an alluvial fan prograding onto the mud-sand flat. In plan view, no discrete depositional lobes were found. Amalgamation of the individual lobes gave rise to a scree-apron-type distribution of unit II along slopes of the Khoyor Zaany Ovoo hill. A close-up view of equivalent beds at Ulaan Uul and Ulaan Buur gives a similar picture but very much different as to the position relative to a potential source area. Ulaan Buur formed more proximally and Ulaan Uul more distally relative to the source area than the site at Khoyor Zaany Ovoo hill. Unit II in Ulaan Uul represents frontal splays, or in terms of a prograding alluvial fan, for the most distal stream flow deposits of an alluvial fan.

5.b.3. Unit III

The first-order maxima shown in the rose diagram showing the palaeocurrent in units IIIa and IIId reflect a single flow direction with the general trend of the fluvial drainage system towards the northeast (Fig. 2). This fluvial drainage system delivered the detrital material for the delta-like progradation. The palaeocurrent mean vectors clustering around NE were caused by the lateral movement of a highly sinuous distributary fluvial channel in unit IIIa. The changing palaeocurrent directions record the superposition of different portions of meander loops. A more stable and straight fluvial drainage system may be inferred from the rose diagram in unit IIId, where one prominent vector towards the northeast may be recognized. Both mean vectors of

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the palaeocurrent show a downstream trend towards the northeast. The wide spread from the northeast towards the southeast observed in the diagram of unit IIIa records an overall progradation towards the east at the time of deposition of unit IIIa. The second-order maximum perpendicular to the main current direction towards the southeast and another less pronounced maximum towards the north are caused by crevasse splays which from time to time broke through the levees of the main channel and spread sand-sized debris into the neighbouring ponds and swamps. Crevasse splaying became less intensive from unit IIIa through unit IIId. This is shown by the disappearance of the second- and third-order maxima from the palaeocurrent rose diagrams. The trend observed in the current ripple lamination towards the south corresponds to the second-order maximum in the rose diagram of cross-bed foresets. Ripple lamination goes along with development of the splay deposits. Note the increase in the angle of climb in Figure 4c that is evidence of a decrease in flow strength, whereas the amount of detritus settling from suspension increases. Above the reactivation surface the situation in the flow regime reversed. The flow strength increased, and antidunes and horizontal lamination evolved instead. Trough cross-bedding and current ripples, which are very much different with respect to the angle of climb, reappear in the uppermost part of unit III. The bedform structures demonstrate a very strong fluctuation in the flow regime (Baas & Oost, 1993; Reineck, Gerdes & Noffke, 1995). The arenaceous beds in unit III are interpreted in terms of crevasse splays and major channel deposits of a fluvial drainage system. Comparing the palaeocurrent orientation and intensities in the rose diagram of units IIIa and IIId, the intensity of crevassing diminishes upward and the course of the trunk river channel became more stable and straight (Fig. 2).

At Ulaan Uul the delta plain facies is represented by another fine-grained series of mudflat deposits, whereas at Ulaan Buur, proximal to the hinterland, crevasse splays and channel mouth bar deposits of a more highly-sinuous drainage system converted into braided river drainage systems and debris flows. The coarse-grained red bed deposits of units II and III in Ulaan Buur may be classified as Gmm and Gcm according to Miall (1996). Clast fabric notation uses the symbols introduced by Harms *et al.* (1975), with the symbols a, b and c denoting the long, intermediate and short axes, respectively. Indices ‘p’ and ‘t’ indicate the orientation of axes either parallel or transverse to flow direction. Index ‘i’ points to upflow imbrication of clasts. While a(t)b(i) orientation indicates a rolling movement or traction current, gravel arranged in the present way in an a(p)a(i) fabric is indicative of a dense flow with laminar shear and clast collisions in the proximal subaerial reaches of alluvial fans with little confinement of deposition.

5.b.4. Unit IV

Using the criteria recorded by Al-Sanad *et al.* (1990) and Baumhardt & Lascano (1993) the macroscopic features of these duricrusts provide evidence of a ferruginous calcrete which has been derived from groundwater fluctuation. The origin of the gravel lag on top of the table mountain is likely to have formed from late Cenozoic fluvial deposition. No calcretization may be reported from the more proximal alluvial fan deposits at Ulaan Buur.

5.c. Provenance analysis of lithoclasts and minerals

The framework composition of sandstones and siltstones does not significantly change throughout deposition of the Ergiliin Zoo Formation.

5.c.1. Lithoclasts

Lithoclast assemblages of terrigenous sediments from the Ergiliin Zoo Formation trace sources and transport paths of the sediment. Gneiss and granite among the lithoclasts point to a crystalline basement of at least medium-grade regional metamorphism, which delivered debris throughout the entire Ergiliin Zoo Formation. For a short period of time, volcaniclastic rocks were also subject to erosion in the provenance area. Another interpretation is a short-tem eruption in the region which gave rise to airfall tuffs. This event is unique. Volcanic ashes and basaltic flows are of widespread occurrence in the Cretaceous of the East Gobi Rift basin (Gerel, 1998; Halim *et al.* 1998; Johnson, 2004). Tephra fall-out was also found in the Lower Cretaceous coal field at Baganuur, Mongolia (Dill *et al.* 2004). The volcaniclasts in the Cenozoic siliciclastics are recycled from the Cretaceous underneath. Fragments of shale and chert are indicative of parent material of lower regional metamorphism than the gneissic fragments. Fragments of silcretes surrounded by dolomite attest to the formation of siliceous duricrusts prior to carbonatization.

5.c.2. Light and heavy minerals

Light and heavy mineral assemblages are very homogeneous. Quantification of the light minerals quartz and feldspar allows for a determination of the source area and an assessment of the maturity of the siliciclastics. Potassium feldspar contents in the range 13 to 24 % and plagioclase contents between 6 and 10 % of the mineral assemblage cluster in the ternary plot of Dickinson & Suczek (1979) in the field indicative of continental blocks and attest to clastic rocks of fairly great maturity. Phenocrysts of ternary feldspar have an elevated Ba abundance suggesting high-*T* crystallization (Nekvasil, 1992). Potassic silica-undersaturated mafic volcaniclasts contain typically rhomb-shaped porphyroblasts of ternary feldspar.

Detrital garnets, which are ubiquitous in the rocks under study, have proved to be useful discriminators of sandstone provenance because they show a wide range of potential compositions and are relatively stable during diagenesis (Hutchison & Oliver, 1998; Hallsworth & Chisholm, 2000). Garnet higher in pyrope contents suggests derivation from garnet-bearing metabasites, while those with lesser pyrope contents are supposed to have been derived from garnet-bearing gneisses of argillaceous origin. Zoisite–epidote intergrown in one sample with albitic feldspar furnishes clear evidence of metabasic rocks that underwent low-grade to medium-grade metamorphic conditions as a source for this type of heavy mineral. Amphibole and sphene associated with albite and epidote–zoisite support this idea. The lithoclasts and fragments have been sourced by the Middle to Upper Mesoproterozoic metamorphic rocks of the Urgun Formation where plutonic rocks extensively intruded metabasic rocks intercalated into metapsammites and metapelites (Fig. 1b). These terrains with many metabasic rocks are likely to have been the source for the Mg and Ca contained in the carbonate minerals in the Ergiliin Zoo Formation.

5.d. Diagenesis and climatic conditions

Dolomite in the prodelta facies has precipitated from meteoric-derived ground and surface water, replacing a precursor Mg-enriched calcite where saturation was reached, for example, by advanced evaporation (McQueen, Hill & Foster, 1999). Ca-enriched smectite forms together with dolomite by precipitation from hypersaline pore waters under alkaline conditions and is common to arid regimes in continental depositional environments (Weaver, 1989). The phyllosilicate assemblage changed along a transect from the basin centre towards the margin. Smectite is concentrated more basinward in the prodelta/mudflat and replaced towards the basin edge by an assemblage of smectite, mica and chlorite in braided stream drainage systems. Further towards the basin edge the phyllosilicate assemblages are barren of expandable phyllosilicates. Palygorskite may have formed by the degradation of illite under alkaline conditions, whereby the Si and Al were supplied.

Higher up in the sedimentary record, calcite becomes the most prominent carbonate mineral. The formation of large areas of sparitic calcite between the subangular siliciclastic components, notably in samples from the uppermost part of units II and III, suggests fairly long-term and stable diagenetic conditions. Goethite meniscus cement formed in a freshwater vadose hydraulic regime. An almost entirely oxidizing environment for a certain period of time during the transition from unit II into III was conducive to an alteration of dolomite and a conversion of Fe into its trivalent state.

Calcite accumulation in unit IV is a groundwater calcrete deposit, *sensu* Wilson (1983). It developed when saturated pore water was drawn to the surface by evaporation. The lack of rooting and its massive texture contradict a pedogenic calcrete.

The hydrological conditions reflected by the various carbonate minerals and the results obtained from ecological studies of the mammals and reptiles living during Early Tertiary times in the East Gobi basin suggest fluctuating dry and wet conditions during the progradation of the alluvial–fluvial deposits. These seasonal changes in humidity closely resemble those of a modern savannah. During Late Cretaceous and Paleocene times, a broad belt of aridity stretched across neighbouring China from west to east with a thick halite deposit being emplaced during the Paleocene in southern China and a more subtropical vegetation zone in northern China (Sun, 1979). Palygorskite, dolomite, Mg-enriched calcite and Ca-enriched smectite precipitated from hypersaline pore waters under alkaline conditions in a more arid regime during the Eocene Shevkhuul Member in Mongolia. The climate did not achieve conditions favourable for the precipitation of evaporites in the study area. Middle and Late Eocene evaporites were reported from China but not from the East Gobi basin (Tong *et al.* 2001). Gypsum and evaporites such as halite and mirabilite are indicators of arid and semi-arid climates. The Eocene climates in China seem to be variable with alternating humid and dry stages, but drier than in the area under study. Progressive uplift of the Tibetan Plateau had a strong impact also on the climatic conditions of the central interior in East Asia (Tapponnier *et al.* 2001). As a consequence, the humid zone was reduced during Oligocene times. Based on conifers and broadleaved deciduous forest, a warm, humid climate was deduced by Guo & Zhang (2002). Conclusively, the deltaic progradation of siliciclastic rocks at the Eocene–Oligocene boundary took place under conditions becoming more humid than in neighouring China.

6. Summary and conclusions

Siliciclastic rocks of the Ergiliin Zoo Formation formed in a lake-margin environment as alluvial–fluvial delta sediments gradually prograded basinward over mud-sand flat deposits.

Detrital heavy (e.g. zoisite–epidote s.s.s., garnet) and light minerals (e.g. plagioclase, smectite) contributed to the Ca–Mg budget in the basin and provided some Ca and Mg to the pore solution so that calcareous minerals and Mg-bearing phyllosilicates such as palygorskite and smectite could evolve. The quantity of the latter phyllosilicate reaches near-economic grade in Ulaan Uul. Marker heavy minerals point to a considerable amount of basic igneous rocks that suffered denudation in the provenance area as the Ergiliin Zoo Formation developed in the foreland. Drawing conclusions from the rock colour, the mineral assemblage and the palaeoecological data, the climatic conditions may be described as alternating wet and dry seasons, closely resembling those of a modern savannah. Towards the younger stratigraphic series the climate seems to have become more humid.

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