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Geomorphological studies along a transect from the taiga to the desert in Central Mongolia—evolution of landforms in the mid-latitude continental interior as a function of climate and vegetation

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Abstract

Variations of drainage systems in the central Mongolian steppe was investigated along a N–S transect covering all zones of vegetation and precipitation from the taiga to the outer reaches of the Gobi Desert. Geomorphological studies supplemented by sedimentological, mineralogical (heavy minerals, lithoclasts) and chemical analyses (arenaceous deposits) resulted in the delineation of five lithological groups which were subdivided into 23 rock types using rock strength, geomorphological forms/geometry, lithology, clast size, sorting, stratification, rock contacts and grain shape. To demonstrate the relationship between landforms and the climatic as well as morphological processes, a process-product approach was taken and eight rock type associations were established. The transport regime along the slopes is characterized by mass flows that pass upslope into solifluction/gelifluction sheets and soil creep. Towards the thalweg, mass flows grade into coarse-grained gravel deposition of highly sinuous and braided fluvial streams. On vegetated high-altitude peneplains and mid-slopes, as well as scarcely vegetated desert steppe plains, unconfined flow prevails over confined flow. Arenaceous deposits of aeolian origin gave rise to dune fields and sand sheets. Chemical weathering is moderate in the steppe of the continental interior and the pH value of meteoric fluids is straddling around neutral. Due to the intermediate position of the steppe between polar and warm deserts, salt efflorescence and calcretes came into being. The major characteristics of the steppe depositional environments will be discussed and summarized in order to provide a key for the interpretation of paleosteppe settings in the ancient sedimentary record.

Keywords: Geomorphology; Sedimentology; Taiga; Steppe; Desert; Mongolia

1. Introduction

Mongolia covers an area of 1,566,000 km^2 with only little more than 2 million inhabitants (Jargalsaikan, 1998) (Fig. 1). Throughout the Mesozoic and the Cenozoic, basins subsided into the basement rocks, especially in the southern parts of the country (Marinov et al., 1973). Quaternary beds have been under investigation in Mongolia for many years. These continental depositional environments record in an excellent way periodic and episodic climatic changes in this central Asian region which is characterized by the highest degree of seasonal contrast on Earth. Considering the global distribution of morphoclimatic zones of Tricart and Cailleux (1972), the study area in Mongolia forms part of the dry continental zone. Attribution to this morphoclimatic zone means that the average annual temperature is in the range of 0–10 °C and the mean annual precipitation lies between 100 and 400 mm (Hilbig, 1995). The northernmost area under consideration lies close to the periglacial zone with average temperatures well below the freezing point and an annual precipitation of more than 400 mm according to the data reported by Hilbig (1995)- (Fig. 2). According to the map of vegetation zones drafted by Hilbig (1995), the majority of the area under consideration forms part of

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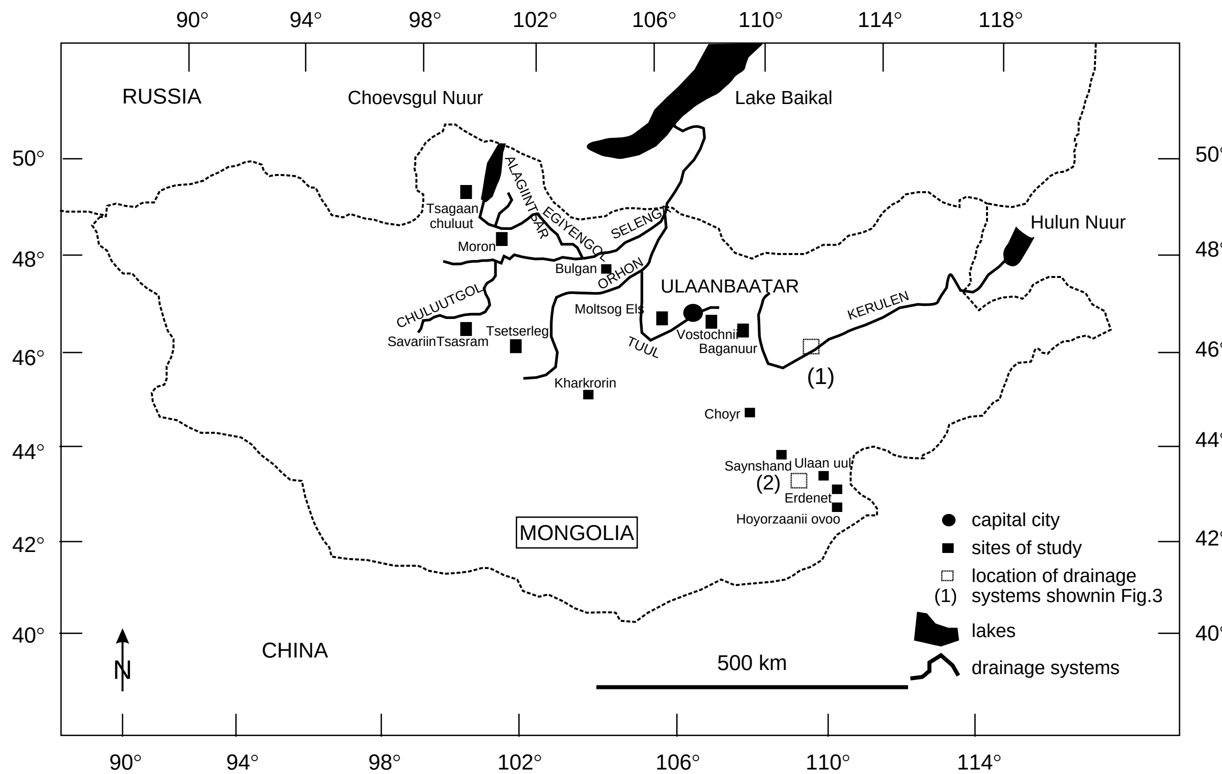

Fig. 1. Index map is to show the sites of study, fluvial drainage systems and lakes referred to in the text or in figures elsewhere in the paper. The framed areas and numbers in brackets denoting the reference drainage systems in Fig. 3 are not to scale but only for siting the study areas: (1) mountain forest steppe to steppe s.s. and (2) desert steppe.

the mountain forest steppe which passes northward into what is called the taiga and towards the south into the steppe *sensu stricto* which gives way further south to the desert steppe (Fig. 2).

The fluvial drainage systems have attracted much attention and were therefore intensively studied by many geoscientists (Schumm, 1977; Bristow and Best, 1993; Miall, 1996; Galloway and Hobday, 1996). Sedimentological studies have been conducted in numerous modern and ancient sedimentary environments. The steppe, however, a mid-latitude region which is transitional between the desert and the taiga across Central Asia, has attracted only little attention as far as the drainage systems and landforms are concerned. Only lakes were the target during some research operations (Grunert et al., 2000; Williams et al., 2001; Peck et al., 2002). Some papers have been published on the climatic evolution, dealing mainly with the interplay of glaciation and lake-level fluctuation in this central Asian region which has been secluded for so long (Lehmkuhl, 1998- see further literature thereunder). An overview of the drainage system in this area has not been given so far and a transect covering the various landforms of the steppe has not yet been worked through. Central Mongolia, showing the highest degree of seasonal climatic contrast on Earth, is an excellent study area for any investigation of steppe rivers. A north-south transect through Central Mongolia covers all zones of climate and vegetation and, thus, yields a full picture of the various types of the steppe and the various rock types which characterize its drainage systems (Table 1). Geographic studies focused on the present-day landforms and their sedimentary structures may help create a picture as close as possible of the paleogeography of continental depositional environments in ancient deposits (Table 1).

2. Methodology

At different sites along a N–S transect, the various terrigenous steppe deposits were investigated as to their sedimentological textures, structures and lithological compositions (Table 1). For an overview of the steppe drainage system in plan view, aerial images were used to sketch the drainage systems of the steppe, but are not shown in figures due to the poor reproduction (Fig. 3). Five lithological groups have been established based upon their grain-size variation (Table 1). In the field, grain size analysis was carried out with a sliding caliper. In the laboratory, grain size measurements were then refined by sieving analyses. The rock properties were described by the unaided eye or under the petrographic microscope using common schemes and comparison charts: Selby (1987)—rock strength, Illenberger (1991)—grain morphology, Jerram (2001)—sorting, Collinson and Thompson (1982)—fabric variations.

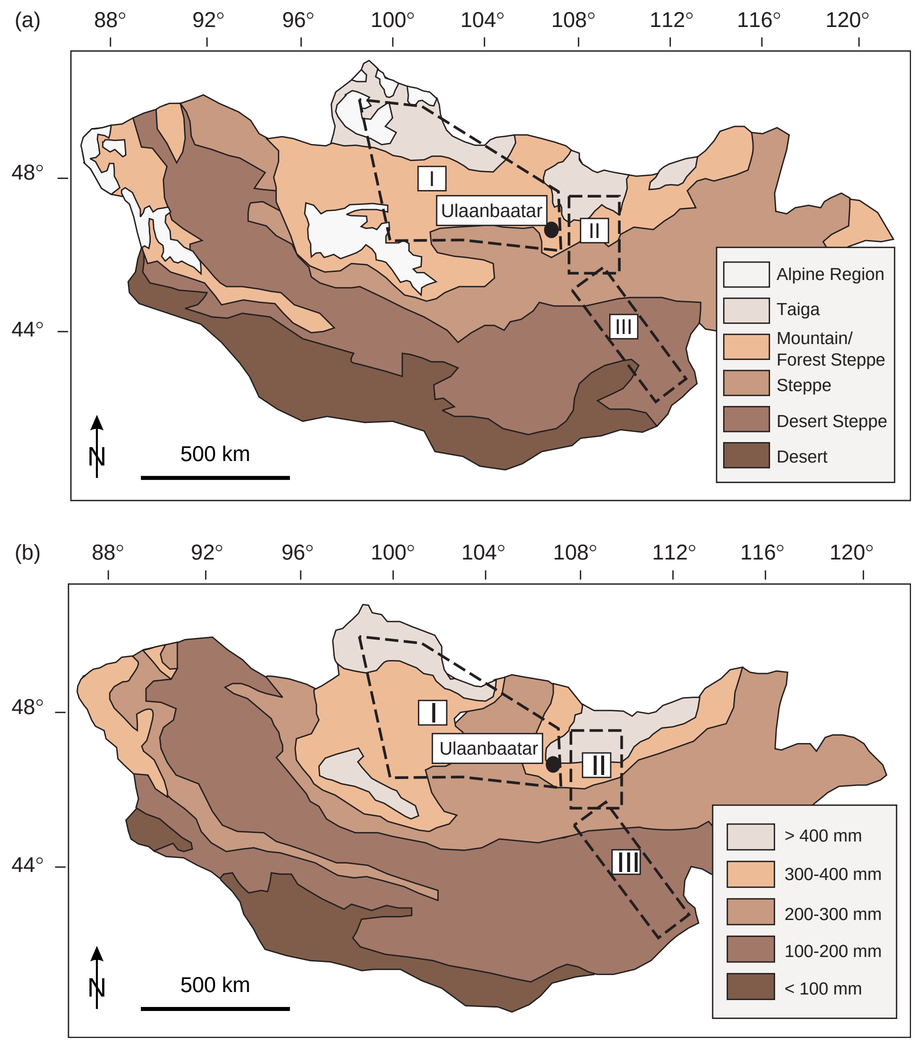

Fig. 2. Vegetation zone (a) and annual precipitation (b) maps of Mongolia (from Hilbig, 1995). The study areas I to III along the transect from the taiga to the desert are shown by the framed areas.

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. Chemical data reported in this study are based on conventional X-ray fluorescence analysis.

3. The position of the drainage systems—the steppe rivers in plan view

Three working areas (I to III), covering all zones of vegetation and precipitation in Mongolia, are outlined in Fig. 2. In study area I, it is the upper reaches of the Selenga—Egiyen Gol fluvial drainage systems that offer a great variety of textures and structures along the river banks and gullies (Fig. 3). The Egiyen Gol fluvial system starts from the Choevsgoel Nuur and flows into the Selenga River which discharges its load into Lake Baikal beyond the border in Russia (Fig. 1). Further to the south, the Orhon and Chuluut Gol drainage systems have also been considered during this study. In study area II, the Kerulen River empties into the Hulun Nuur, a lake situated in the Chinese border zone (Fig. 1). Study area III provides an overview of the drainage systems operative in the desert steppe, where no large, well defined drainage systems evolved.

The main flow in the drainage systems of areas I and II is confined to some active highly-sinuous channels (Fig. 3—zone A—bold-faced channels) which are interconnected with numerous abandoned channels in a fluvial floodplain (Fig. 3—zone A—slim channels). These abandoned channels have shifted fairly vigorously. Some of them are braided, others are preserved only as isolated oxbows. Levees and crevasse splays are absent in the drainage systems. The whole fluvial system is usually very unstable. Tributaries are scarce and active only on a periodical basis in zone B. The branched channels run almost perpendicular to the trunk river and contribute much to the load of

Table 1
Lithological variation and landforms in the Central Mongolian Steppe

Lithological group	Rock type	Intact rock strength	Geomorphological form/geometry	Mineralogy—sedimentology/clast size/sorting	Stratification/fabric/rock contacts	Grain shape	Inferred processes of formation, depositional environment and landforms	Vegetation zone
I	Ia	strong to very strong	low—relief surface, vegetated plateaus, platforms	igneous, metamorphic rocks, sedimentary rocks (indurated)	Primary structures and textures well preserved	n.d.	peneplains, strath terraces (erosional), entrenched drainage systems (e.g. meander belts)	taiga to steppe s.s.
	Ib		low- relief surface, non-vegetated plateaus, mesas			n.d.	etchplain or etched surfaces with tafoni weathering	desert steppe
	Ic	moderately strong to weak	no surface expression, mostly covered with sediments of lithological groups II to V. If exposed formation of gentle hillslopes or in flat-lying areas passing into patterned grounds	unconsolidated to loose sediments, saprolite or saprock on top of rock type Ia	contorted stratification, ice wedges gradual	n.d.	poorly to (un)consolidated bedrocks, saprock and saprolite altered by permafrost resulting in patterned grounds	mountain forest steppe to steppe s.s.
II	IIa	strong to moderately strong	fan several tens of meters thick which may coalesce to aprons extending laterally extent over hundreds to thousands of meter along the bedrock channel, bluffs of ephemeral streams or fault escarpment	monomict to polymict gravel/$\varnothing_{max.}$ mostly over 0.25 m/poor	Massive/clast-sp.	angular	rock fall fed through rills gullying into the top-slope, scree or talus slopes (locally little slide near the scarp)	mountain forest steppe to desert steppe
	IIb	moderately strong to weak	bed, gravel lag 0.3 to 0. 5 m thick on top of the bedrock, lateral extension (?) overlain by conglomerates as much as 5 m thick in the study area	oligomict to polymict/ $\varnothing_{max.}$ 15 cm//moderately to moderately well sorted	Massive/clast-sp. to matrix-sp., disk-shaped and rotlike clasts orientated into vertical position, FU in places/ erosive and gradual contacts, undulating bounding surface towards the roof sediments	subrounded to subangular, spheres to discs dependant on bedrock lithology	channel floor lag deposits, locally altered by permafrost (grading towards the top into mudflows/glacial till)	mountain forest steppe to steppe s.s.

	IIc		beds to fans up to 0.5 m in thickness, bedsets measuring up to several tens of meters in alluvial terraces, lateral extension (?)	oligomict to polymict/ $\varnothing_{max.}$ 15 cm/moderately to moderately well sorted	Massive to crudely bedded/clast-sp., imbrication (a(t)b(i)-fabric)/ gradual contacts (rarely erosive)	subrounded to subangular spheres to discs dependant on bedrock lithology, distance of transport and age of deposition	debris flows to longitudinal bars (turbulent flow, inertial bedload)	taiga to steppe s.s.
	IId		beds up to 0.5 m in thickness, bedsets up to several tens of meters in alluvial terraces, laterally extending across the floodplain		horizontally bedded/ clast-sp., imbrication (a(t)b(i)-fabric)/erosive and gradual contacts	well rounded to subangular spheres to discs dependant on bedrock lithology	fluvial processes producing longitudinal gravel bars and bedforms and channel fill deposits	mountain forest steppe to steppe s.s.
	IIe		lobes and ramps up to 1 m in thickness, lateral extension of individual beds some tens of meter, lateral extension of bedset units of floodplain-width	oligomict to polymict/ $\varnothing_{max.}$ 10 cm/moderately to moderately well sorted	crudely cross-bedded/ clast-sp., imbrication (a(t)b(i)-fabric)/erosive contacts	rounded to subangular spheres to discs dependant on bedrock lithology	fluvial processes producing transverse bedforms and causing accretion in channel fill deposits	
	IIf		gravel veneer less than 0.2 m thick, covering the entire floodplain	oligomict to polymict/ $\varnothing_{max.}$ 10 cm	clast-sp. pebbles scattered across the floodplain without any grain contact	subrounded to subangular	wind-cutting and faceting altering fluvial gravel into ventifacts	steppe s.s. to desert steppe
III	IIIa	weak	foot of slope, terracettes, trough-shaped-layers 0.2 m thick and up to 6 m wide	mono- to oligomict,/ $\varnothing_{max.}$ 3 cm/well to poorly sorted	massive to crudely bedded/locally FU and CU, clast-sp. to matrix-sp.,/top gradual, sharp undulating bounding surface at the base (subtype also with gradational base)	subrounded to subangular	deposition of channel fills and clast rich debris flow that are transitional into longitudinal gravel bars and bedform (unconfined → confined flow)	mountain/forest steppe to steppe s.s.
	IIIb			mono- to oligomict,/ $\varnothing_{max.}$ 7 cm/well to poorly sorted	massive to crudely bedded/CU (rarely FU), clast-sp/top and base gradational	subrounded to subangular	longitudinal gravel bars and bedforms with gravel overpassing and surface armoring transitional into solifluction/ gelifluction sheets	
	IIIc	weak	midslope to foot of slope, terracettes, more than 0.4 m thick	mono- to oligomict,/ $\varnothing_{max.}$ 15 cm/poorly sorted	massive/matrix-sp., disorganized fabric to imbrication (a(p)a(i)-fabric)/top and base gradational	subangular to angular	debris flows (subtype mud flow) developing from solifluction/gelifluction sheets	
	IIId	weak to moderately strong	topslope/creep slope, lobes and sheets several hundred meters wide and up to 3.5 km long, approx.3 m thick	heavy minerals and lithoclasts of intermediate to labile stability, mono- to oligomict,/ $\varnothing_{max.}$ 3 cm/moderately well-sorted	horizontally bedded/ matrix-sp./top and base gradational	angular to (subrounded)	sheet flows leading to different types of hyper (proximal) and low-concentration flows	mountain/forest steppe

(*continued on next page*)

Table 1 (*continued*)

Lithological group	Rock type	Intact rock strength	Geomorphological form/geometry	Mineralogy—sedimentology/clast size/sorting	Stratification/fabric/rock contacts	Grain shape	Inferred processes of formation, depositional environment and landforms	Vegetation zone
	IIIe	strong to moderately strong	midslope, footslope, incised valleys, rills and gullies, lobes several 10 m thick and 100 m wide, lateral extension several kilometers	poly- to oligomict/$\varnothing_{max.}$ 100 cm/poorly sorted	massive to crudely bedded/matrix-sp to clast - sp., CU to disorganized fabric/top and base gradational,	angular to (subrounded)	polycyclic giant (debris) mass flows	desert steppe
	IIIf	moderately strong to weak	lobes and fan-shaped sheets a few tens of cm thick and hundreds to thousands of m wide	mono- to oligomict/ $\varnothing_{max.}$ 10 cm,/poorly sorted	crudely bedded/clast-to matrix-sp., (a(t)b(i)-fabric), desiccation cracks/ top and base gradational,	subrounded to subangular	unconfined to poorly confined flows in form of stream- to flashfloods result in badlands with rockwash, proximal fans with discontinuous levees and distal gravel scree with ventifacts	desert steppe
	IIIg	strong to moderately strong	lobes several km across and several tens of meters thick	Oligomict/$\varnothing_{max.}$ 10 cm,/poorly sorted	massive to crudely bedded/clast-to matrix-sp., in places a(p)a(i) fabric/top and base gradational	subrounded to subangular	debris flows deposition with laminar to turbulent flows	desert steppe
IV	IVa	weak to very weak	dunes grading into sand sheets on river terraces and floodplains covered with grassland. The arenaceous deposits are, locally, scarcely vegetated	fine-gr. to medium-gr. sand, quartz, feldspar, stable to intermediate heavy minerals goethite, lithoclasts (oligo- to polymict)/well to moderately well sorted	massive to cross-bedded, ripple cross lamination with straight-crested through catenary current ripples	subangular to well rounded	aeolian deposition leading to sand sheets and complex parabolic dunes (?). Sand sheets may, in places, pass into loess.	(mountain/forest steppe) to steppe s.s.
	IVb		dunes grading into sand sheets on scarcely vegetated plains. The arenaceous deposits are devoid of vegetation and soil			well rounded	aeolian deposition leading to parabolic dunes, barchanoid ridge dunes, transverse dunes and sand sheets	desert steppe
V	Va	weak to very weak	tabular layers, lenses or blankets normally 0.1 to 0.3 m thick extending across the floodplain	gray to brown silt and finesand	massive to crudely bedded/top sharp or gradual, base gradual	n.d.	deposition of suspended load filling abandoned channels and spreading across the floodplains	mountain forest steppe to steppe s.s.
	Vb		tabular layers some tens of cm thick extending across the floodplain and alluvial terraces	black to dark gray silt to finesand carbonaceous matter, plant debris	massive to crudely bedded/top sharp and base gradual, intensively rooted	n.d.	deposition of fine-grained material in an aquatic environment of fluctuating water level fosters growth of shrubs and the development of swamp and fluvial marsh deposits	steppe s.s.

Vc		some tens of decimeters (max. 50 cm in the areas under study)	dark gray to brown silt to finesand with carbonaceous matter and, in places, calcareous concretions	massive/(top and) base gradual, intensively rooted	n.d.	paleosols, incipient soil and steppe soils such as chestnut soils/castanozems/ustolls passing into xerosols (see rock type Vd)	mountain forest steppe to steppe s.s.
Vd	moderately strong	encrustations, coatings, blankets patchily distributed on various parent rocks, infiltration into parent rocks down to a depth of between 1 to 2 m	calcite, goethite detrital minerals in the study area plagioclase, orthoclase, illite-muscovite/clay- to silt-sized (cement minerals)	matrix- to grain-sp, desiccation cracks and fissures	xeno- to hypidiotopic	calcretes	desert steppe
Ve	weak to very weak	blankets, thickness greater than 0.2 m several square kilometers	mud to fine sand halite, gypsum, mirabilite, soda ash	massive to vaguely bedded/desiccation cracks	n.d.	mud flats around perennial and ephemeral lakes, deflation residues	mountain forest steppe to steppe

n.d., not determined; sp., supported; FU, fining upward; CU, coarsening upward). *Lithological group,* Grain size-based field classification of rocks in the Mongolian Steppe; *Rock type*, Coding referred to in the text and figures; *Intact rock strength*, Rock strength according to Selby (1987); *Geomorphological form/geometry*, Morphology, including thickness and aereal extension; *Mineralogy-sedimentology/clast size/sorting*, Mineralogical and textural variations. Sorting according to Jerram (2001); *Stratification/fabric/rock contacts*, Structural variation with fabric classifications (Collinson and Thompson, 1982); *Grain shape*, Grain shape according to Illenberger (1991); *Inferred processes of formation, depositional environment and landforms*, Interpretation; *Vegetation zone*, Occurrence of rock type types in relation to the present-day vegetation zones according to Hilbig (1995).

the perennial streams during intensive rainfall or melting of snow. Further away from the active drainage system, flat-topped basement rocks gradually merge into the rugged relief of the hinterland (Zone C) (Fig. 3).

In the desert steppe, the bedrock lithology is exposed in ridges, rounded and flat-topped hillocks (Fig. 1 and 3b—Zone C) from which ephemeral streams make their way downslope (Zone B). These intermittent streams discharge into flats extending along the ridges or into bowel-shaped depressions called pans.

4. Lithological group I—the bedrock of the steppe river drainage system

4.1. Description

In the northern part of area I, the bedrock of fluvial deposits is mainly composed of metasedimentary and igneous rocks of Palaeozoic age (East Eurasian Geological Seminar, 1998; Tomurtogoo, 1996), while Tertiary volcanic rocks dominate the southern part. In study areas II and III, fluvial deposits mainly rest upon Mesozoic clastic rocks (East Eurasian Geological Seminar, 1998). The lithological group I has been subdivided into three rock types, according to their intact rock strength and vegetation cover (Table 1).

Rock type Ia. Rock type Ia occurs in landforms which have a low relief surface covered with grassland. At approx. 2300 m a.s.l. (above sea level) the basement rocks south of Choevsgoel Nuur are truncated by a low-relief surface. Surface drainage has carved out wide, trough-shaped valleys and in some places deprived the calcareous and igneous rocks of their thin blanket of weathering loam and soil (Fig. 4). Most of the toeslopes are soil-mantled. On both sides of the present-day floodplain along the Egiyen Gol, several strath terraces developed in Paleozoic bedrocks (Figs. 3 and 5—Zone B). A peculiar type of rock type Ia developed in the Chuluut Gol drainage system. It starts off as shallow gravel-dominated steppe river (see rock type IId), occupying a wide floodplain and ends up in a deep canyon incised into flat—lying plateau basalts of Pliocene to Holocene age.

Rock type Ib. Towards the south (study area III), the flat-lying, low-relief landscape becomes gradually deprived of its vegetation. Boulders are scattered across the low-relief landscape or the bedrock lithology pierces the thin cover of gravel (rock type IIIf). Gaping-mouth caves occur in the granitic rocks north of Erdenet, Gobi. The rock debris are rounded to subrounded (Table 1).

Rock type Ic. Rock type Ic is evolved mainly in sandstones, carbonaceous clastic rocks and coal, or in rocks covered by a thick regolith (Migon and Thomas, 2002). Near Baganuur (area II), an undulous bounding surface developed between the Lower Cretaceous lignite seam and the overlying Quaternary coarse-grained sediments (see also rock type IIb) (Fig. 6). Convulsion of stratification is intensive. The beds show some sort of

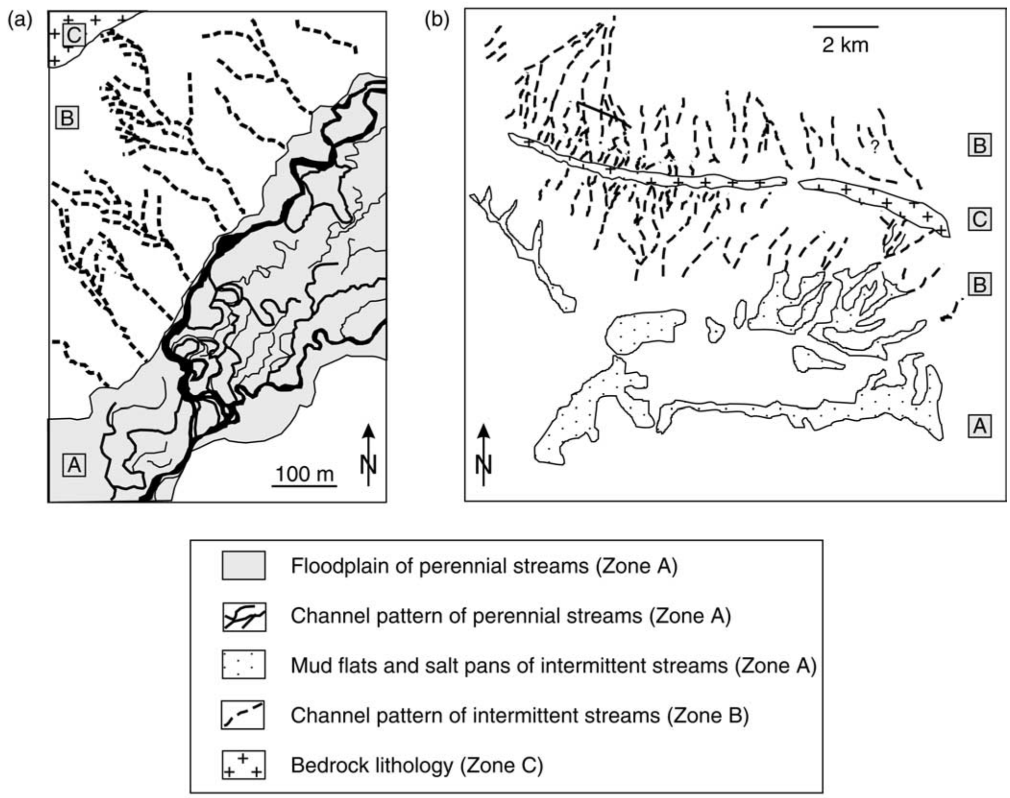

Fig. 3. Steppe drainage systems redrawn from aerial images. For location of maps (a) and (b) see Fig. 1. Zones A to C describe the various parts of the stream systems, referred to in the text. The drainage system in map (a) is typical of the vegetated areas of the steppe (mountain forest steppe to steppe s.s.). The drainage system in map (b) is typical of the non- or poorly vegetated parts, a representative of which is the desert steppe (Gobi). The line thickness used in map

recumbent folds in the loosely packed saprock (Fig. 7). Another surface expression of rock type Ic is the patterned grounds (Fig. 8).

4.2. Interpretation

Rock type Ia. The low-relief surfaces truncating the basement rocks in the hinterland of the Egiyen Gol are interpreted as peneplains. Different erosion surfaces—called by German geomorphologists 'Piedmonttreppen'—developed through different phases of peneplanation. Many papers considering especially the climatic impact on formation of this low-relief erosional plain have been published (Phillips, 2002; Twidale, 2002—further literature cited in these papers). The relic peneplain was dissected by trough-shaped valleys which are occupied by small intermittent streams (Zone B). The slopes in the tributary valleys with slope angles of 20° (locally more than 65°) were classified as 'fall face' and 'transportational midslope', using the process-related classification scheme of Dalrymple et al. (1968). Where the trunk rivers formed cut banks in Paleozoic limestones, gradients of as much as 90° developed in the rock slope. The strength and direction of the wind and the exposure of the slopes to sunlight impacted on thaw and frost and controlled the slope stability and angle (Fig. 4). The most spectacular response to fluvial processes during the Quaternary is the set of strath terraces which developed at various levels (Fig. 5). The slope of these terraces is steepened by undercutting of river channels. The edge of the drainage basin, measuring several kilometers, is marked by the peneplain '1' and the oldest strath terrace '2' (Fig. 5). The age and the most-likely pattern of the drainage systems which worked their way down the gently tilted low-relief surfaces described above may be constrained by the fluvial evolution in the Tsetserleg area. The highly sinuous Chuluut Gol has already been flowing through this valley during

Fig. 4. Upper reaches of a valley oriented westward and occupied by an ephemeral river (Fig. 3–Zone B) that incised into the relic peneplain near Tsagaan Chuluut and flows into the Egiyen Gol (Fig. 5). Transition between bedrock channels and alluvial channels. Rock type: Ia, Vc.

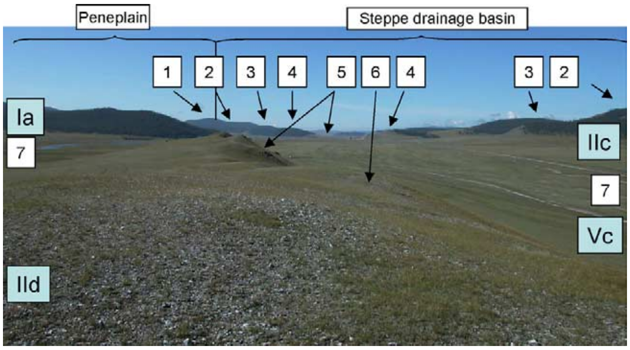

Fig. 5. Cross-section through the steppe river drainage basin. Alluvial channels ('5–7') and strath terraces ('2–4') of the Egiyen Gol trunk river south of Choevsgul Nuur. '1' marks the level of the ancient peneplain and the edge of the steppe river drainage system. Rock type: Ia, IIc, IId, Vc Morphodynamic generations: '1' to '7'.

pre-Holocene time. Its channel system was entrenched into the basalt and its drainage shape inherited from the precursor river pattern. Downcutting was very rapid and no terraces developed. Differences in the resistance to weathering were very low in the volcanic bedrock. Rock composition and the interplay of fluvial erosion led to the development of a nearly vertical cliff. Mass movements restored the toeslope to an angle at which the system is almost stable and fluvial erosion and denudation have reached equilibrium.

Rock types Ib. In the desert steppe, stripping of the weathering mantle exposed an etchplain with shallow depressions separated by water divides. The hollows encountered in the boulders and pinnacles of bedrock are named tafoni (Twidale, 2002). It is still an enigmatic feature with a number of hypotheses put forward for their formation (Goudie and Viles, 1999; Taylor and Mitchell, 2000). Salt weathering and organic activity, leading to a local enhancement of acidity, appear to be the most likely processes in this case (Summerfield, 1991).

Rock type Ic. The soft-sediment deformation in rock types Ib was caused by cryoturbation under periglacial conditions following the criteria for identification by Brodzikowki and Van Loon (1987) and Ballantyne (2002). Repeated thaw and frost have caused contortion of the original structures in the soft bedrocks (Figs. 6 and 7). In places, scouring may be recognized at the interface bedrock—or saprock—overburden (Fig. 6). Patterned grounds in the steppe are the product of various processes. Cryogenic and aeolian processes have led to some sort of thaw lakes in the flat-lying, finer-grained interdune sediments near Vostochnii (Fig. 8). These thermokarst features are related to melting of ground ice in the subsurface, resulting in the formation of small, shallow, isolated ponds filled with water and fined-grained material. Desiccation and salt cracking occur as these ponds dry out during the short summer period and the chipped rock flakes become subjected to deflation. Since ground-ice phenomena are crucial for the built-up of patterned grounds, these landforms are attributed to rock type Ib.

5. Lithological group II—gravel-dominated deposits of steppe drainage systems

5.1. Description

Almost 80% of the rock types observed in steppe river drainage systems found along the transect from the northern taiga to the desert steppe are gravel-dominated (Table 1, Fig. 1). Lithological group II has been subdivided into six rock types, mainly for textural and structural reasons (Table 1).

Fig. 6. The Upper Coal Seam in the Baganuur open pit. The toplayers and beds of the Lower Cretaceous lignite were pushed and contorted at the base of the Quaternary overburden by thaw-and-freezing processes. Rock type-IIb gravel are overlain by fluvial deposits of rock type IId-e and by a thin blanket of steppe soil. Rock type: Ia, Ib, IIa, IId-IIe, Vc.

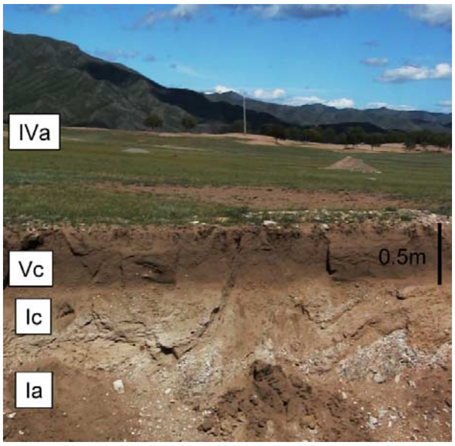

Fig. 7. Cryogenic structures are widespread in the bedrock of alluvial terraces south of Bulgan (Ic). The saprock grades through a thin layer of aeolian deposits into a brown steppe soil (Vc). In the background white sand sheets and dunes, in places, stripped of their vegetation and soil blanket may be identified between the trees and the power line pylons in the background. Rock type: Ia, Ic, Vc, IVa.

Rock type IIa. Rock type IIa deposits are exceptional in terms of clast size, exceeding 0. 25 m in diameter, as well as for highly angular grain shapes (Table 1). In area I, dislodged fragments of Cenozoic volcanic rocks constitute a wedge-shaped apron along the cliff of Chuluut Gol Canyon. The scree covers the footslope of the cliff of a volcanic platform. Due to the low cohesion, the threshold slope angle of the scree may reach 45°. Boulders of the scree are scattered across the river channel. In the desert steppe, rock type IIa is only poorly represented near Erdenet, Gobi Aimag, where layered basalts and red beds of lower Cretaceous age form a bluff above the floodplain of an ephemeral drainage system. The apron of coalescing fans is poorly developed and its particle size is much smaller than in equivalent sediments from Chuluut Gol.

Rock type IIb. In the plains around Baganuur, a veneer of gravel occurs between the bedrock and the overlying fluvial sediments. The grain-supported gravel beds of the Kerulen drainage system rest on top of the Early Cretaceous lignite seam, the stratification of which is strongly contorted just beneath this unconformity (Figs. 6 and 9). The unstratified gravel deposits attain a thickness of as much as 0.5 m and, locally, display a fining-upward grain-size trend. Near the base of the coarse-grained deposits, platy gravels are oriented with their long axes in an upright position. Imbrication is rare. Upward, the layer grades into mud-supported gravel.

Fig. 8. Patterned grounds developed on a large dune field near Vostochnii. The aeolian deposits form a low to moderate relief (IVa). The larger dunes may easily be distinguished by their bright color from the dark granite bluffs to be seen at the skyline and from the finer-grained sediments sparsely covered with grassland in the fore-ground (Ic). The patterned grounds on interdune sediments closely resemble thermokarst phenomena. Rock type: Ic, IVa.

Fig. 9. Frost sorting has put clasts in the floor lag at the interface between the Upper Coal Seam in the Baganuur open pit and the Quaternary rock type—IIb deposits with their long axis into vertical position. The gravel pass upwards into glacial (?) sediments. Rock type: Ic, IIb.

Rock type IIc. The Egiyen Gol drainage system created a series of terraces near the outlet of the Choevsgoel Nuur (Fig. 5). The lower two terraces are all covered with coarse-grained deposits or completely made up of gravelly sediments (Fig. 5—levels 5 and 6). Higher up in the hierarchy, only strath terraces have been preserved, attesting to previous fluvial activity (Fig. 3—Zone C) (see rock type Ia). The maximum clast size of rock type IIc deposits lies between 100 and 150 mm, and the mean clast size ranges from 10 to 30 mm. The lithological composition of gravel changes significantly downstream. Paleozoic crystalline limestones exposed along the river have contributed much to the clast assemblage in the area of Tsagaan Chuluut. The roundness of pebbles and cobbles may be described as subrounded and their fabric is mostly clast-supported. Imbrication of clasts is common. Erosive contacts at the base of gravel layers are rare. The tributaries of the Egiyen Gol are not much different from the trunk river as to grain size distribution (max. clast size: 150 mm, mean: 20 mm), but very much with respect to their clast petrography (Figs. 10 and 11).

Rock type IId. Rock type IId is different from rock type IIc in terms of grain shape and structure (Table 1, Figs. 5, 6, 11 and 12). Bedding and roundness have improved in deposits of rock type IId relative to rock type IIc. Erosional contacts are widespread. Rock type IId occurs downslope of rock type IIc.

Rock type IIe. Arcuate forms evolved in channels of rivers in the western steppe around convex, gravely river banks (Fig. 13). The gravel deposits locally form cohesive gently dipping ramps on the downflow side of the channel or are composed of sets of smaller banks. A crude planar

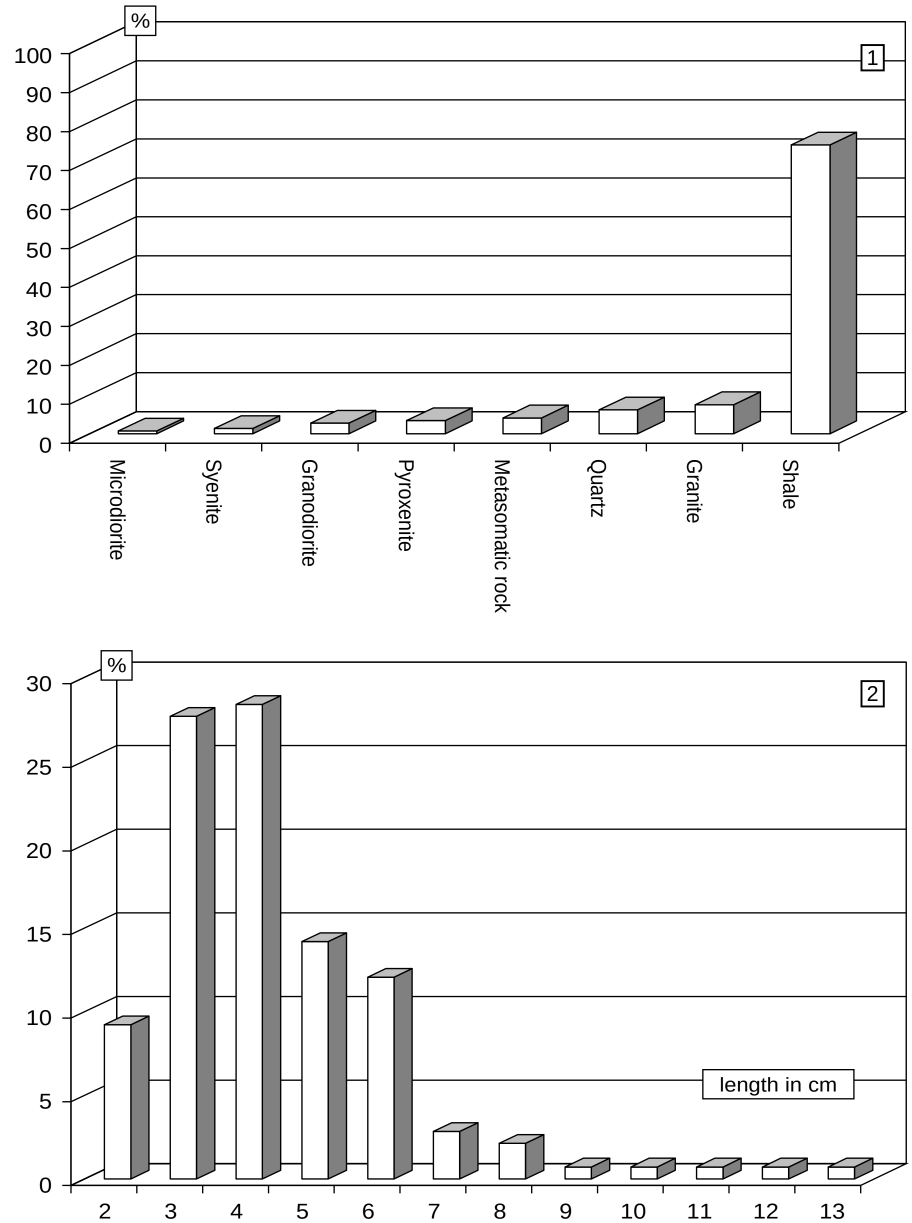

Fig. 10. Histograms illustrating the clast petrography (1) and grain-size variation (2) in sediments of rock types IIc-IId from the Egiyen Gol drainage system. Rock type: IIc, IId.

cross-bedding may be observed. The concave part of the channel is bordered by a steep vegetated bank.

Rock type IIf. This rock type occurs as isolated blocks or pebbles on top of sparsely or non-vegetated parts of rock types IIc and IId in the vast river floodplains of the trunk rivers. The grains are facetted and polished so as to be ranked as 'subrounded' to subangular'.

5.2. Interpretation

Rock type IIa. Rock type IIa originated from gravitational processes operative along bedrock channels in the mountain/forest steppe–steppe vegetation zone. The type of movement is mainly fall, and to a lesser extent slide *sensu*

Fig. 11. Clast assemblage of bar sediments in the Egiyen Gol drainage system near Choevsgul Nuur. Rock type: IId, IIe.

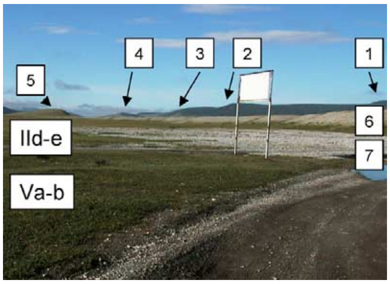

Fig. 12. Alluvial terraces south of Choevsgul Nuur in an intermittent tributary stream of the Egiyen Gol. Rock type: IId, IIe, Va, Vb Morphodynamic generations: '1' to '7'.

Varnes (1978) and Coussot and Meunier (1996), forced by the incision of the river channel that provokes a lateral release in confining pressure. The resultant talus slope is fed through rills gullying into the topslope. Removal of underlying support by the river during periods of high floods and the rock fall determine the slope stability and the angle of slope. Coniferous trees, which line up at the foot of the talus along the river bind soil and contribute to the slope stability. In the desert steppe, rock fall does not produce extensive talus slopes. The balance between supply and removal, both of which control the evolution of talus slopes, is negatively influenced by a supply of fine-grained material over gravel. Fine-grained material has a lower threshold angle than coarse-grained material and is rapidly washed out.

Rock type IIb. The gravel is arranged in an almost upright position by thawing and freezing processes. Relict permafrost structures are widespread at the interface between the bedrock and the basal channel lag. Contorted beds, particularly widespread in soft bedrock sediments underneath the fluvial deposits and local ice wedges, are produced by cryoturbation. Rock type IIb grades upward into a mud-supported gravel which were reworked by fluvial processes of the Kerulen drainage system.

Rock type IIc. The deposits are representative of debris flows (turbulent flow of inertial bedload), following the criteria by Miall (1996). Periodically abrupt changes in the flow regime are evidenced by the bimodal grain size distribution and the structures observed in the

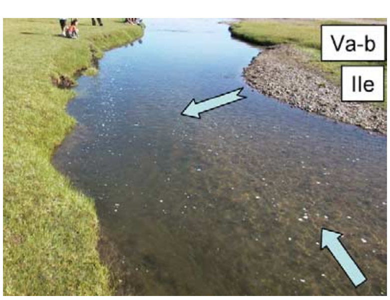

Fig. 13. Transverse bedforms in a steppe drainage system near Tsetserleg. The flow direction (see arrow head) is away from the observer and the bed accretion indicated by the double-arrow works its way from right to left. For scale see children playing at the channel banks (upper edge of figure). Rock type: IIe, Va, Vb.

fluvial deposits (Table 1). The gravel deposits created an open-space fabric, which was locally infiltrated by the silty and muddy fines of rock type Va. The roundness of clasts in the longitudinal bars of the modern Egiyen Gol River (modern floodplain/level 7—angular) ranks lower than the roundness of clasts in the residual bars on the terraces of levels 5 and 6 (well rounded) (Fig. 12). The variation in grain shape observed in the trunk river is a function of the distance of transport. Angular calcareous debris have been eroded immediately from the bedrock underlying the present-day floodplain (level 7), whereas rounded clasts of older terraces have been derived from a provenance far off with a variegated lithology (Fig. 10). The oldest gravel assemblages were sourced from a provenance area enriched in silicates, mainly metapelites and metapsammites. The clast petrography becomes the more variegated as a comparison is made between the first-order (Egiyen Gol) and second-order rivers (Alagiin Tsar River). The nearness of the Alagiin Tsar River to the source area and the periodical flow yielded a clast assemblage texturally and compositionally less mature than in the trunk river (Fig. 10). Moreover, in the drainage systems under consideration, the roundness is strongly dependant on the rock type. In the Alagiin Tsar River, a second-order stream in the Choevsgul Nuur-Egiyen Gol drainage system, the granitic and pegmatitic pebbles and cobbles are 'rounded' whereas the metabasic clasts fall in the category subangular (Fig. 11).

Rock type IId. According to Miall (1996), this rock type reflects formation of gravel bars, bedforms and channel fill deposits which were found in the study area I in the modern flood plain (level 7) and on the alluvial terraces (levels 6 and 5) (Fig. 5). With respect to texture and structure, the deposits resemble those recorded by Nemec and Postma (1993) as longitudinal bars from shallow, braided rivers.

Rock type IIe. Large accretionary bench-and-channel deposits evolved in steppe drainage systems (Fig. 13). They coat the inclined parts of some of the longitudinal gravel bars and bedforms that were categorized among rock types IIc and IId. The accretionary/erosional deposits with scour pool at depth are fairly unstable deposits. They were obviously produced during a relatively short period of time. Following the suggestions of Miall (1996) these deposits are considered representative of transverse bedforms.

Rock type IIf. Gravels described in the previous paragraphs from bar deposits underwent abrasion, taking a fine polish through sandblast actions of windblown sand. Ventifacts are common on fluvial deposits in the southern part of area I, II and the northern part of area III.

6. Lithological group III—mixed-load deposits of steppe drainage systems

6.1. Description

Lithological group III, found in all study areas, encompasses the mixed-load deposits of steppe river

Fig. 14. Alternating beds of flow types near Moron. Hyperconcentrated flow (rock type—IIIa) in proximal position with a sharp erosional surface at the base is overlain by cogenetic debris flow deposits. Rock type: IIIa, IIIc.

drainage systems. The abundance in fine-grained material has two consequences for the sedimentary fabric and the position of the sediments. First, the sediments are called matrix-supported. Secondly, the sediments, in general, formed on the colluvial footslopes marginal to the drainage system, far off the present-day thalweg. Lithological group III has been subdivided into seven rock types (Table 1).

Rock type IIIa. The structure of rock type-IIIa deposits was well exposed in a drainage system near Moron (Figs. 14–16). The main architectural element of rock type IIIa is a trough filled with coarse-grained debris that display a pronounced CU grain-size variation (Table 1). A sharp undulous bounding surface exists at the base of the trough. The contact between the layer on top and the filling of the trough is transitional with respect to the fine-grained matrix sediments but abrupt with regard to the clasts ($Ø_{mean}$ = 3 cm). An overall clast-to matrix-supported fabric of the subrounded pebbles (monomictic to oligomictic clast community) may be recognized. Only in a few places, bedding was recognized within the troughs (Fig. 15). There are also laterally very extensive gravel beds which have neither an erosive contact at the base nor any grading within the bed itself (Fig. 16).

Rock type IIIb. This rock type resembles rock type IIIa. A pavement of larger angular gravel evolved, however, on top of the individual gravel beds of rock type IIIb (Fig. 17). Stacked patterns of crudely stratified slope deposits of this sort can be identified at many outcrops.

Fig. 15. Two discrete layers (1, 2) of a well-bedded flow (rock type IIIa) in distal position with a sharp erosional surface at the base are overlain by cogenetic debris flow deposits. Rock type: IIIa, IIIc.

Fig. 16. Horizontally bedded deposits of rock type IIIa with no erosional bounding surfaces. Rock type: IIIa.

Rock type IIIc. On the mid- and upper footslopes, the sediments of rock type IIIb almost imperceptibly merge into deposits of rock type IIIc. Downslope the roundness of clasts increases in the gravel deposits, and the overall clast size (as much as 15 cm) also decreases. Towards the edge of the drainage system, bedding becomes vague and the coarse-grained deposits take a massive appearance. The upper boundary between rock types IIIc and Ic on the slope is marked by the upper edge of the main scarp. Downslope, the sediments of rock type IIIc fade out in lobes, creating discontinuous terracettes. The platy metapelitic clasts found in these lobes show a crude longitudinal imbrication.

Rock type IIId. Rock type IIId is not linked with a drainage system. Rock type IIId was studied on a low-relief, sparsely vegetated, plateau which truncated olivine basalts of Tertiary age in the environs of Savariin tsaram, where primary gemstones deposits were explored during the recent past (N 48° 02′ 34″-E 99° 59′25″) (Fig. 18). Matrix-supported conglomerates with angular clasts up to 3 cm large and disseminated in a silty matrix are concentrated in several discrete seams as much as 15 cm thick (Fig. 19). The flat-lying bedsets of the conglomerates extends some 100 m across the plateau (Table 1). No lateral facies change exists in the area under consideration. The rock contacts between the seams and their roof rocks are gradational. Within the seam, no grading is observed but grain sorting is fairly good. The minerals identified at outcrop are pyrope, little olivine and some alkaline feldspar.

Fig. 17. Coarsening-upward (see wedge widening upward) and surface armoring in clast-supported gravels evolving from matrix-supported gravel at the base. Rock type: IIIb.

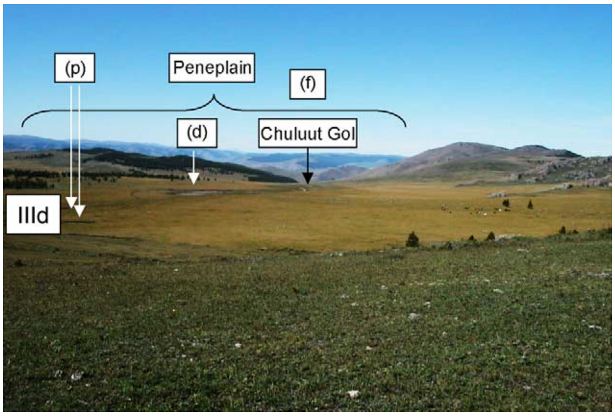

Fig. 18. A view from the Savariin Tsaram primary gemstone deposit towards the west over the peneplain which cuts across Pliocene basaltic rocks. The low-reliefed landscape developed at an altitude of 2300 m. The placer deposit/secondary gemstone deposit and rock type-IIId deposits, respectively, are located in the foreground, in a large mountain valley which narrows towards the west in a V-shaped valley and eventually ends up in the Chuluut Gol (see black arrowhead). The white arrows denote shallow open cuts operated for gemstones placers (proximal placer (p) and distal placer (d)). (f) marks reworking and dispersion of heavy minerals in the creeks (Fig. 2a—zone B) and fluvial deposits (Fig. 2a—zone A) of the Chuluut Gol drainage system. Rock type: IIId.

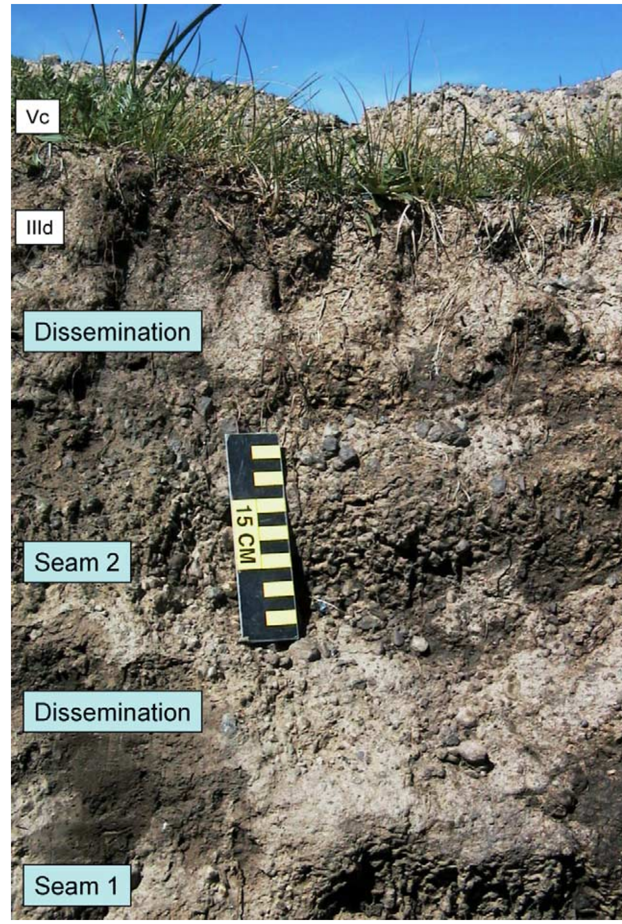

Fig. 19. A profile typical of rock type IIId in the secondary gemstone deposit at Savariin Tsaram. Different sheet-flooding deposits, each of which starts off with heavy minerals disseminated in a muddy matrix. The flow strength attained its peak in sediment bulking during which discrete pyrope seams amenable to open cast mining were emplaced. Rock type: IIId, Vc.

Rock type IIIe. The largest grain size observed in sediments of drainage systems in the Mongolian steppe was encountered in boulder conglomerates spread across a plain in front of an escarpment near Erdenet (area III). Due to the low rainfall, vegetation is confined to a few shrubs growing on the foothills of the lobes of the boulder conglomerates (Fig. 2). Several phases of mass movement may be deduced from the crude bedding and the marked stacking pattern of the CU successions. The individual layers are massive and their clast roundness is very poor (Table 1). Rain splash erosion and slope wash is intensive due the lack of a stabilizing blanket of soil and vegetation, respectively. The oligo- to polymict deposits of rock type IIIe are not connected with a perennial or ephemeral drainage system.

Rock type IIIf. At the foot of badlands and on almost all sparsely vegetated plains of the desert steppe being tilted at an angle of less than 5°, thin planar sheets or lobes of mud-supported gravel lags developed (Fig. 20). Often, it is only a veneer of residual gravel that is left behind from a more coherent cover with rock type-IIIf deposits (Fig. 20). The sediments of rock type IIIf get winnowed through time and deprived of their fines. The layers are fan-shaped, contain lobes and are terminated by discontinuous paired gravel levees (Fig. 21). The gravels are subrounded to subangular and used to be arranged in an a(t)b(t) fabric (Fig. 22).

Rock type IIIg. Rock type IIIg comprises beds of coarse-grained sediments which are transitional between matrix-supported and clast-supported conglomerates (Table 1). They form lobes which amalgamate to aprons along fault escarpments in the Gobi desert steppe and they contain abundant goethite, giving the rock a reddish brown tint.

Fig. 20. Unconfined stream- and flash-flood deposits spread across the plains of the desert steppe. The unvegetated badlands with gullies are subject to strong slope-wash and rain-splash erosion. The fine-grained material was derived from the unvegetated hills built up of loose grains of fine-grained quartz, feldspar, mica and smectite. The coarse-grained clasts in the foreground (1) have been reworked from the topstratum of the hills which consists of an older generation of rock type- IIIf gravel (2) and calcretes (Vd) case-hardening the summits of the hillocks and providing, in places, some shelter to fine-grained red beds against erosion. Rock type: Ib, IIIf, Vd.

Fig. 21. Poorly confined flow in the desert steppe following a hefty downpour. Flow direction is marked by the arrow head. The individual streams branch in a fan-shaped drainage system which they were not able to fill completely during this episodical precipitation. The levees covered with a few shrubs and marked by the white stippled lines in the figure for better recognition demarcate previous flow regimes of higher strength. Rock type: IIIf.

The sediments are only vaguely bedded. Their poorly rounded pebbles and cobbles tend to have an a(p) fabric.

6.2. Interpretation

Rock type IIIa. The inverse grading and the stack of CU sequences attest to an abrupt strengthening of the flow regime in these channels, whereas the FU sequences attest to a waning of floods. These deposits were emplaced under conditions of relatively high sediment supply and water discharge. The lithosomes with FU sequences are held to be bar gravels and channel lags. In terms of flow processes, rock type-IIIa deposits indicate unconfined flows altering into confined flows (Friend, 1983). The regime is interpreted as transitional between a debris flow and a fluvial bed load transport in accordance with studies carried out elsewhere by Todd (1989). Graded hyperconcentrated flows as they were described from the study area were recorded from many alluvial environments of deposition (Melis et al., 1997; Sohn et al., 1999). Flows in Fig. 14 show the sediments laid down in a proximal location and flows in Fig. 15 in a distal position relative to the source area. The stacking pattern of rock type IIIa in Fig. 16 displaying a strong grain size variation of alternating gravel and silt points to abrupt changes in the flow regime of the drainage system. Imbrication is absent. It is held to be a sequence of flat bars which developed in a shallow gravelly braided river close to the edge of the main/present-day floodplain where it interfingers with debris flow deposits (Nemec and Postma, 1993; Siegenthaler and Huggenberger, 1993).

Fig. 22. Gravel orientation in a poorly confined rock type-IIIf drainage system in the aftermath of an episodic flashflood. The rose diagram gives the orientations of the long axes of pebbles. The ball-point pen and arrowhead point in flow direction. Rock type: IIIf.

Rock type IIIb. Rock type IIIb deposits are longitudinal gravel bars and bedforms which were altered by some sort of gravel overpassing and surface armoring. Nemec and Postma (1993) recorded such a CU trend from the central parts of longitudinal bars. These crudely bedded layers and lobes marginal to rock type IIIa suggest solifluction. Stratification patterns and sedimentary properties similar to those of rock type IIIb were observed in coarse-grained deposits by Van Steijn et al. (1995). According to these authors slow movement during the dry seasons, dominated by frost creep, causes thick stony fronts and layers.

Rock type IIIc. These deposits resulted from debris flows in regions of steep slopes or cliff-talus slope systems. Matrix-supported conglomerates with either disorganized fabric or poorly developed longitudinal imbrication form terraced hillslopes near Ulaanbaatar (Fig. 23). These mixed deposits are typical of vegetated areas in the mountain/forest and steppe *sensu stricto* (Coussot and Meunier, 1996) and reflect ‘impeded forms of cohesive debris/mud flow deposition’. Extensive biogenic creep may facilitate and trigger such slope processes (Butler, 1995). The population of burrowing rodents in the Mongolian steppe is very dense. Large-scale and small-scale changes in the state of H_2O such as deglaciation in the mountain ranges and attendant periglacial phenomena as well as seasonal meltwater discharge were a forcing effect on the mass movements. Degradation of low-lying permafrost contributed to debris flow movement (Zimmermann and Haeberli, 1992). The turbate structures in the debris flow proper, and their

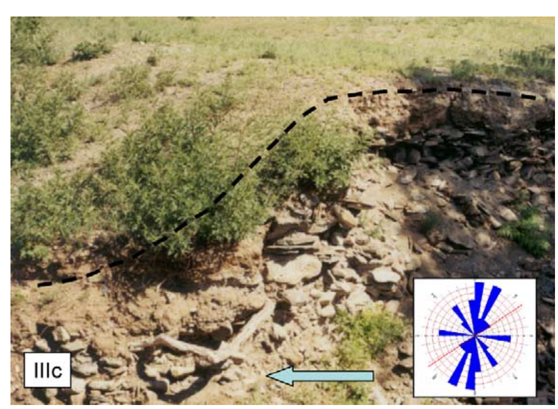

Fig. 23. Profile of a slope terracette caused by a debris flow of rock type IIIc in a gorge feeding debris into the Tuul River south of Ulaanbaatar. The platy metapelites are arranged in a shingle-like fabric with prevalently longitudinal imbrication. The arrowhead denotes the current direction; the rose diagram gives the orientations of the long axes of pebbles. Rock type: IIIc.

association in time and space with rock type IIIa characterized by channel-fill deposits, point to downslope flow deceleration and dewatering (Fig. 23).

Rock type IIId. The source for the gravelly sediments of rock type IIId is located in the nearby volcanic bedrock. Poor roundness of clasts is a direct response to the very short distance of transport. On the other hand, the short distance of transport could not have significantly sorted the clasts. The very homogeneous particle size, especially in the placer seams, cannot resulted from transport. The particle size in the placer reflects the original size during crystallization in the magma rather than abrasion during transport. The lack of internal structures in the bedsets, missing cross-cutting bedforms, channels or scouring and a coarsening-upward trend in the grain sizes suggest deposition under conditions of sheet flows. The placer sandwiched between the fine-grained clastics required a substantial amount of meltwater at a certain time which may have been provided by subglacial meltwater floods (Kor and Cowell, 1998). These hyperconcentrated flows/sediment bulking of rock type IIId reworked and accumulated gemstones proximal to the primary gemstone deposit (Fig. 18(p)). They fade out in low-concentration unconfined flows off the primary gemstone deposit in a wide mountain valley extending at high-altitude (Fig. 18(d)).

Rock type IIIe. Poor sorting, inverse grading in some places and large protruding clasts observed in the pebble-boulder conglomerates are indicative of deposition by debris flows, following the results of Johnson (1984). Strong grain interaction such as collision and friction may be interpreted from the clast-supported texture in some layers. Crude bedding was produced by stacking of several debris-flow surges, obviously triggered by episodic tectonic pulses and resultant uplift along the fault zone. Parallel alignment of some clasts suggests that the mass flow underwent laminar shearing (cf. Enos, 1977).

Rock type IIIf. Streamfloods and flashfloods caused by episodic downpours were responsible for cobble- and pebble-enriched deposits in the desert steppe. The upper-flow-regime bedforms developed from slope wash, leaving behind unvegetated badlands with their hillslopes carved by rills and gullies (Fig. 20). At the foot of the topographic highs, the flow fans into sheet-like tabular bedsets and branches into very shallow channels a few centimeters deep but several meters wide, or fades out immediately in sheets of unconfined flow (Fig. 21). As the flood abates, the silty matrix quickly dries out as marked by numerous desiccation cracks and the fine-grained material is blown off by the wind. Paired discontinuous gravel levees denote previous stages of flooding (Fig. 21). The lack of a(p)a(i) fabric and grading is an argument against en masse deposition by frictional freezing and shows that a lot of simple traction was involved in the transport of sediments (Collinson and Thompson, 1982; Postma et al., 1988; Todd, 1989) (Fig. 22).

Rock type IIIg. The coarse-grained red bed deposits of rock type IIIg reflect various types of debris flow deposition much different from many of the coarse-grained deposits mentioned previously by their a(p)a(i) fabric. While a(t)b(i) orientation indicates a rolling movement or traction current, gravel arranged in the present way 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.

7. Lithological group IV—arenaceous deposits in steppe drainage systems

7.1. Description

Arenaceous deposits at Vostochnii, Moltsog Els, Moron, Bulgan and near Saynshand are not much different as to their mineralogical and chemical compositions (Table 2). Therefore they were treated together as far as their sedimentological and lithological characteristics are concerned. These arenaceous sediments are medium-grained and moderately well to well-sorted sands. The particles are mostly well-rounded. Some grains did not achieve such a perfect shape and have to be categorized as subangular. In the classical diagram log SiO_2/Al_2O_3 vs. log Na_2O/K_2O, which was elaborated by Pettijohn et al. (1973), the sands plot in the field 'lithic arenite' (Table 2). The mineral association consists of quartz, microcline, orthoclase, albite-oligoclase and chessboard albite. In some sands, the feldspar contents increased so that their host rocks have to be termed feldspar—rather than lithic arenites. Among the heavy minerals, green tourmaline, green amphibole, brown biotite, sphene and zircon predominate. Their lithoclasts have been derived from gneissic, granitic and basaltic source rocks.

Rock type IVa. In the mountain forest steppe sand sheets, attaining a few decimeters to 1 m in thickness, are patchily distributed on river terraces (Figs. 1 and 7). The isolated rippled sand sheets, each sparsely vegetated, measure about 1 km^2. Their ripple index is around 7.5 and their individual ripples form a sequence from straight-crested to catenary forms. In the steppe, west of Ulaanbaatar, large dune fields are covered in places with grassland.

Rock type IVb. The largest dune fields were found during this field campaign in the desert steppe south of Erdenet, where dunes stand out from the flat-lying interdune sediments by several tens of meters. The interdune sediments are scarcely vegetated with shrubs whereas the dunes themselves are barren. Only on the foothills of the dunes, a few blades of feather grass (*Stipa*) are able to resist the permanent westerly winds (Fig. 24).

7.2. Interpretation

There is no doubt that the deposits of lithological group IV were emplaced by aeolian processes. All aeolian landforms described from the steppe belong to the group of impeded dunes. They suggest a constant wind direction

Table 2
Chemical composition of arenaceous deposits of rock type IV

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Pb	Sr	Zn	Zr	TOC	Si/Al	Na/K
Max	84.09	0.19	12.42	0.97	0.04	0.28	0.95	3.60	3.53	0.03	563.00	33.00	11.00	185.00	11.00	76.00	0.05	1.02	0.10
Mean	80.58	0.14	10.31	0.76	0.02	0.18	0.80	2.85	3.14	0.03	439.75	26.00	9.00	154.50	9.25	58.00	0.03	0.90	−0.05
Min	77.68	0.08	8.06	0.57	0.01	0.12	0.35	1.71	2.09	0.02	325.00	20.00	4.00	117.00	6.00	28.00	0.02	0.80	−0.30

Max, maximum content: mean, mean value, min: minimum content; TOC, total organic carbon content; Si/Al, log (SiO_2/Al_2O_3); Na/K, log (Na_2O/K_2O) according to Pettijohn et al. (1973).

Fig. 24. A close-up view of the slip-face of a transverse dune. Blades of feathergrass are swirling around under the westerly wind and produce semicircle-shaped marks in the sand which may be used, when fossilized, as casts for the determination of the paleowind direction.

(Fig. 24). Their shape is strongly influenced by the moisture and the roughness of underlying bedrock and interdune sediments and by the resultant type and density of vegetation. Disrupted airflow, and obstacles such as downwind vegetation clumps play an important part in the accumulation of sands, especially in the steppe s.s. Another factor putting constraints on the evolution of the various aeolian depositional forms is limitation of the sand source or areas of deflation.

Rock type IVa. Not all of the detrital material found in these aeolian deposits achieved perfect roundness indicative of mature aeolian sands. The angularity of grains is indicative of a short distance of transport. The sand sheets show poorly-developed current ripples whose crests run almost parallel to the flow direction of the drainage system nearby, from which the sand has been blown out as the floodplains dried. According to Manighetti and Carter (1999), lower to intermediate wind strength may be deduced from the ripple pattern of the aeolian deposits under consideration in the Mongolian steppe. Small plants and grass cause wind deceleration and lead to a baffling effect for wind-transport. The interdune deposits are fine-grained, organic-rich sediments. Organic matter has had a decelerating effect on sand transport, yet was not incorporated to a large extent in the active sand sheet nor able to form a topsoil on the sand sheets. Paleosols buried throughout the accumulation of sand were not spotted in the dunes under study. Therefore the total organic carbon content (TOC) in the arenaceous deposits is very low (Table 2). Below the sand sheets under study, a finer-grained, dark brown massive material frequently came to rest upon the cryoturbated bedrocks (Fig. 7). Parabolic dunes are fossil dunes which might have been emplaced during the late or postglacial period (Grunert et al., 2000).

Rock type IVb. Parabolic dunes evolve in the desert steppe as the latter passes into the desert, proper. The slip face direction and the marks produced by the feather grass at the foot of the dunes indicate accretion by wind from the west–northwest (Fig. 24). Several slipfaces along

Fig. 25. Beds of fine-grained siliciclastics (Va) are intercalated among rock type IId sediments which show a pronounced imbrication (see arrowhead for flow direction). Suspended load is filling the abandoned channels and infiltrating the gravel of the longitudinal bars in a tributary of the Selenga drainage system. The profile shows sediments of an intermittent stream. Note also the hole which was burrowed by some of the rodents densely populating the Mongolian steppe. Rock type: IId, Va, Vc.

the windward side classify them as compound barchananoid ridge dunes (Embabi and Ashour, 1993). Parabolic dunes, as part of a dune field, are older and form a marginal facies of the barchanoid ridge dunes thereby reflecting a period of higher humidity.

8. Lithological group V—fines in steppe drainage systems

8.1. Description

Fine sand and mud make up the majority of sediments of lithological group V. Although genetically different from the siliciclastics, chemical sediments are also assigned to lithological group V that in turn has been subdivided into five rock types (Table 1).

Rock type Va. Gray and brown, fine-grained sediments which attain a thickness of as much as 0.3 m are often interbedded with gravel (Fig. 25) or rest on gravel bars and bedforms (Fig. 26). The argillaceous rocks are massive with gradational contacts towards their under- and overlying gravel beds and make up a vast part of the fluvial drainage system.

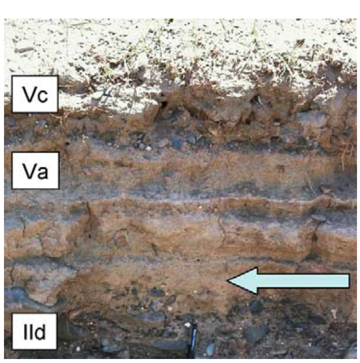

Fig. 26. Floodplain sediments (Va) exposed in the cutbank of the river Orhon near Kharkrorin. Rock type: IId, Va, Vc.

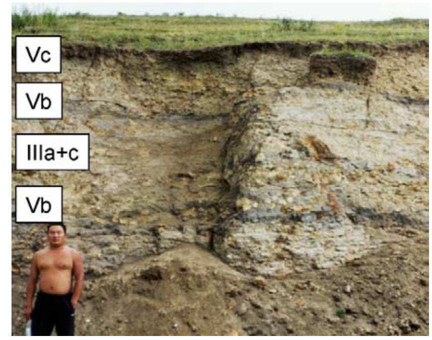

Fig. 27. Alternating rock type III and V sediments at outcrop in an alluvial terrace of the Kerulen River east of Baganuur. The thin layers enriched in carbonaceous material are swamp deposits under and overlain by flow deposits delivered partly by slope processes, partly by the Kerulen River. Vc is a representative of the most recent pedogenic processes in this steppe. Rock type: IIIa, IIIc, Vb, Vc.

Rock type Vb. In contrast to the fines of rock type Va, Vb deposits are dark gray to black, indicating the presence of abundant organic matter. Where overlain by sediments, the contact is sharp, where exposed on the present-day floodplain the fines are densely vegetated with various species of aquatic plants or blanketed by grassland and intensively rooted (Fig. 27).

Rock type Vc. The various deposits on the floodplain of the present-day drainage system and on the deeply weathered bedrock use to be topped by a massive chestnut-brown layer of silt to fines (Fig. 7). It is mostly blanketed by grassland, scattered bushes and open forests (e.g. taiga). Calcareous concretions may, in places, be spotted in the rock type.

Rock type Vd. Tertiary and Cretaceous siliciclastics near Ulaan uul and Hoyor zaanii ovoo in the desert steppe are coated with calcareous encrustations several centimeters thick (Fig. 28). The calcareous cement minerals are xeno- to hypidiotopic, *sensu* Friedman (1965). Plagioclase, orthoclase and illite-muscovite constitute the mineral assemblage of the parent rock and are infiltrated and cemented by calcite. Goethite is another cement mineral, but is present in lesser amounts than carbonate.

Fig. 28. Calcite-bearing duricrusts (calcretes s.s.) coating sandstones of Paleogene age in the desert steppe at Hoyor zaanii ovoo. Rock type: IIIf, Vd.

Rock type Ve. Vast flats composed of brownish gray, fine sand and silt and sparsely covered with vegetation are found around lakes in the mountain forest steppe and steppe, proper. The deposits show a great variety of textures, are vaguely bedded, and the surface of the fines is cut by numerous desiccation cracks. Halite, mirabilite, gypsum and soda ash are abundant (United Nations, 1999).

8.2. Interpretation

Rock type Va. The rock type Va reflects channel abandonment and suspended load settling in a stagnant water pond. The suspended load infiltrates the interstices of coarse-grained siliciclastics in braided streams (Fig. 26). It is representative of floodplain sediments (Brackenridge and Hagedorn, 1992).

Rock type Vb. Deposition of fine-grained material in an aquatic environment of fluctuating water level fostered the growth of shrubs and the development of vegetated swamps and fluvial marshes.

Rock type Vc. The rock type stands for pedogenic processes which brought about typical steppe soils or castanozems in the vegetations zones north of the steppe *sensu stricto*. (Fig. 2). The topmost position in the lithological profiles, the very homogeneous textures and traces of rooting point to in situ formation of these rocks.

Rock type Vd. Rock type Vd may be called a calcrete sensu Wilson (1983). It developed when saturated pore water was drawn to the surface by evaporation and capillary forces. The lack of roots and its massive texture contradict any idea of a pedogenic calcrete. The lack of dolomite and other evaporite minerals along with the good preservation of framework- and sheet silicates in the parent rock are convincing arguments for moderate chemical weathering and for a pH value of meteoric fluids near neutral to mildly alkaline conditions (Königsberger et al., 1999).

Rock type Ve. Rock type Ve bridges the gap between the steppe drainage systems and true lacustrine sediments, which are not treated in this study. The close-basin lakes under consideration are situated in the mountain forest steppe and the steppe, proper. Today laminated silts cropping out in lake terraces bear witness of these highstands as well as large lake plains covered with fines that gently dip towards the lake. These nearshore mudflat sediments are seasonally flooded and became sites of evaporative concentration and salt precipitation during dry periods.

9. Discussion

9.1. Lithological variation and weathering

Weakening of the rock strength by chemical weathering is moderate in the study areas. The regolith on top of the bedrock (rock type Ic) is evidence of a weathering residue on a relict landscape. The petrographical diversity in the catchment area of the fluvial drainage systems was well preserved in the fluvial clast assemblages in group II under the climatic conditions and resultant physical weathering of the vegetations zone from the taiga to the steppe *sensu stricto* (Fig. 2). The subarctic climatic conditions in the northern Mongolian grassland with a temperature range of 45 °C and precipitation exceeding more than 400 mm/year are accountable for the moderate chemical weathering. The most conspicuous result is the close association of stable and unstable lithologies in the clast communities of the river bed load (Academy of Sciences, 1990). Since there was no inflicting damage to the clasts of rock types IIc to IIe other than transport and attrition in steppe rivers, the clast assemblages are a direct mirror image of the erosion of the source rocks in the hinterland (Dill, 1995). Another good marker for the weathering rate and the simulation of acidification during pedologic processes is the heavy-mineral assemblage. *Heavy minerals* of moderate chemical and mechanical stability such as garnet are present in the debris flows of rock type IIId (Morton, 1985; Dill, 1995, 1998). Disintegration of volcanic parent material occurred under chemical conditions which produced a lot of fine-grained material but did not eradicate garnet. Late-Pliocene to early Pleistocene (?) chemical weathering and climatic conditions favorable for peneplanation produced the parent material for rock type IIId (Fig. 18). The formation of peneplains is discussed herein, for the various models of formation the reader is referred to Summerfield (1996). Re-deposition took place under less intensive chemical weathering in the aftermath of this peneplanation as the climate turned cooler.

The aeolianites were systematically investigated for their accessory minerals to give a clue as to the weathering and climatic conditions operative during deposition of the steppe sediments. The meteoric fluids percolating through these wind-blown sediments were only moderately acid. Otherwise heavy minerals such as amphibole, pyroxene and biotite would not have survived. Apatite which might be expected in view of the granitic lithoclasts observed in the dune sands was removed from the heavy minerals suite of the aeolian deposits. According to the experimental data of Nickel (1973), apatite is dissolved more rapidly than amphibole in groundwaters at a pH of 5.6. A loss of apatite by dissolution took place during alluvial storage on the flood plains, backswamp as well as the channel facies. So neutral to mildly acidic conditions are supposed to have occurred throughout the time of emplacement of these terrigenous depositional environments. The equivalent marker minerals among the *light-mineral* assemblage to constrain the pH of the meteoric fluids are carbonate minerals. Depletion of rock type Vc sediments in CO_2 by organic growth and elevated temperature along with a steady decrease in rainfall towards the desert steppe attest to a slight increase in alkalinity of the meteoric fluids and induced calcite precipitation. Fine Ca-aggregate laminae observed in sections through deposits of steppe lakes are the product of seasonal changes (Peck et al., 2002).

9.2. Evaporation and salinity

The rate of evaporation in continental environments can be concluded from the presence of calcite in duricrusts (rock type Vd). Salt is concentrated in and around many lakes. The marginal facies of these lakes which cover large areas in the mountain/forest and the steppe proper is dealt with under rock type Ve. The mineral composition is made almost exclusively of halite (>90%) with subordinate amounts of hydrohalite, carnallite, epsomite, gypsum and trona (Kampe, 1997). Such efflorescences are a common phenomenon of zones showing a long-term or seasonal strong aridity. They occur in polar and warmer desert environments. The great variability in salt types and marked differences reflect mainly the nature of inputs into the drainage systems (Goudie and Cooke, 2002). For the steppe environment under study, we invoke the formation of natural cryogenic brines which were investigated in detail by Starinsky and Katz (2003). There calculation leading to the cryogenic brine model deals with the minerals mirabilite and hydrohalite, which they claim to be repeatedly dispersed by the advance and retreat of the ice sheet, dissolved by melt water or eroded during post-glacial uplift, leaving almost no traces in the geological record. This is not the case in the Central Mongolian Steppe where numerous salt concentrations with mirabilite are well preserved.

9.3. A synopsis-climate-and morphology-related rock type associations

Fig. 29 illustrates the relationship between rock types and the climatic as well as the morphological processes.

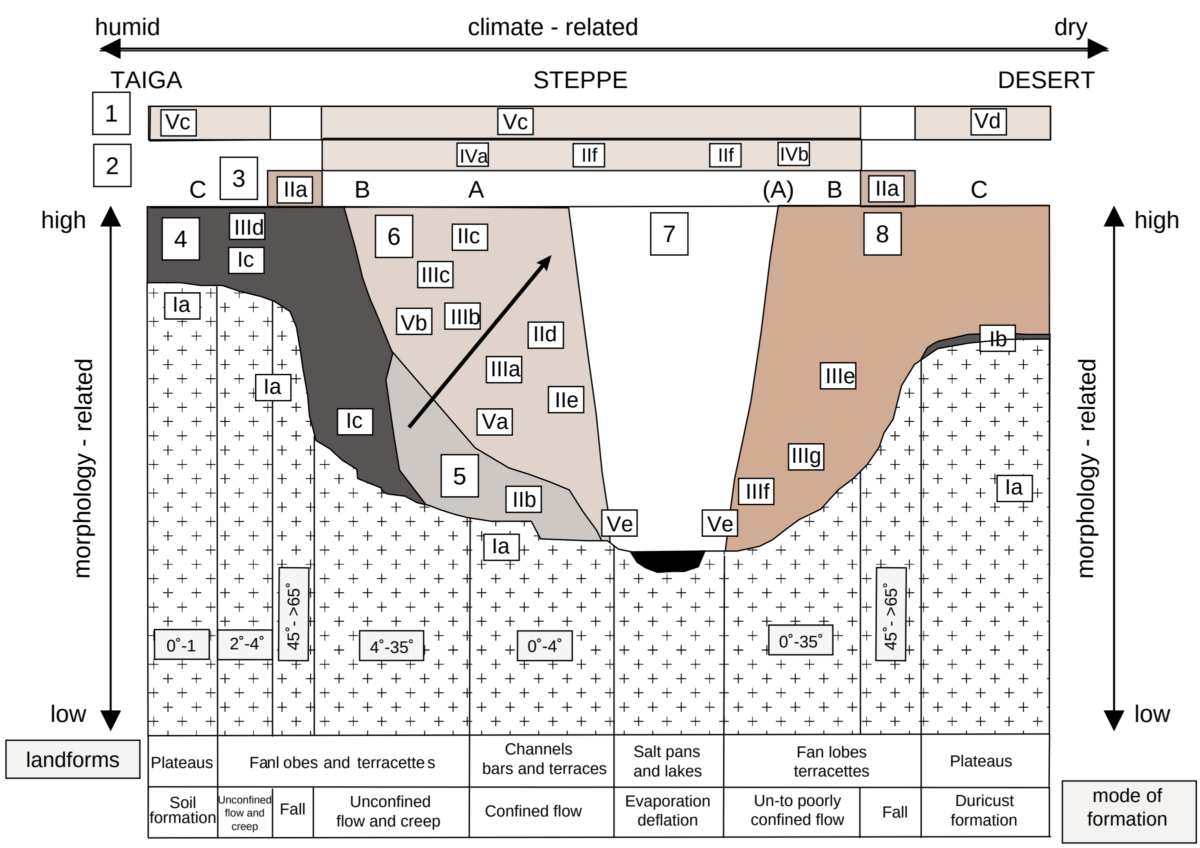

Fig. 29. Synoptic overview of climate- and morphology-related rock type associations along a transect from the taiga (humid) to the desert (dry). The slope model has been modified from Dalrymple et al. (1968). 'high' means high-altitude mountains, 'low' means lowlands. The rock types have been grouped into eight rock type associations given Arabic numerals in squares. Rock type associations 1 and 2 are strongly controlled by the climate, association 3 is exclusively controlled by the slope angle or morphology-related and associations 4 through 8 are controlled by the climate and the morphology. The landforms (e.g. channels…) resulting from the climate- and morphological-related modes of formation (e.g. unconfined flow and creep….) are shown along the *x*-axis. Landforms and mode of formation may both be correlated with the slope model given above. The zonation given by the capital letters A, B and C along the *x*-axis on top of the diagram allows for a comparison with the drainage systems illustrated in plan view in Fig. 3. Rock type association: (1) Pedogenic sequence, (2) aeolian sequence, (3) rock fall, (4) regolithization, cryogenic alteration, exhumation and redeposition of the etched plain through flow processes, (5) fluvio-glacial flow deposition and cryogenic alteration, (6) mass flow to fluvial depositions in vegetated terrain, (7) evaporation and deflation, (8) mass flow to fluvial depositions in non-vegetated terrain. Arrow in rock type association 5 and 6 denotes decrease in cohesion during flow and deposition.

The modes of formation, the resultant landforms and deposits in the steppe, are shown along the x-axis of the diagram (Fig. 29). For the steppe eight rock type associations have been established (Table 1).

Rock type association 1 is representative of the *pedogenic sequence* (Fig. 29—Vc to Vd). It is truly climate-related. Pedogenic processes are operative on all geomorphic features, excluding landforms with steep slopes, and on all kinds of parent rocks (rock type I). The transition from chestnut soils/castanozem/ustolls in the mountain/forest steppe through xerosols into calcitic calcretes of the desert steppe is a clear climate-related change—climatic catena—caused by increasing temperatures and a reduced rate of precipitation (Figs. 7 and 29). The change in soil types has been described in a cross plot by Scheffer and Schachtschabel (1976) as a function of temperature (5–17°) and precipitation (350–100 mm). The pH values of the various soil types are said to be >7.

The distribution of aeolian depositional forms is a function of vegetation and humidity (rock type association 2—*aeolian sequence*). Reconstruction of the paleoclimate during the last 14,000 years in Central Asia shows a clear trend of higher lake stands and stronger monsoon. Vice versa shrinkage phases of the lake and higher aridity went along with reactivation of sand dune formation (Chen-Tung et al., 2003). Barchanoid dunes and transverse ridge dunes used to be more frequent in areas of low precipitation than complex parabolic dunes. Silt and sand were blown out of mudflats (rock type Ve) unprotected by vegetation. Morphology and landforms exert some control on the formation of rock type association 2 (IVa-IIf-IIf-IVb) by the source area (e.g. mudflats of rock type Ve) and also by the selectivity for certain depocenters. High-altitude plateaus and steeply dipping slopes are spared from such aeolian accumulations (Fig. 29).

Rock type association 3, represented only by a single rock type IIa (*rock fall*), is restricted to cliffs and thus held to be a morphology-related mass movements. In the mountain/forest steppe and steppe s.s. this sort of slope development is found in regions with neotectonic movements and volcanic activity, lasting until the Holocene. In the parts of the desert steppe under consideration the endogenous processes of structural and igneous activities mentioned above are less powerful to give rise to rock type association 3.

Rock type association 4 (Ia-Ib-Ic-IIId) is both morphology- and climate-related and reflects the incipient phases of steppe/plain formation on a low-reliefed predecessor landscape. The *regolith* of rock type Ic was preserved only in the vegetated parts of the steppe on a flat-lying topography. In the desert steppe, however, the bedrock was stripped of its weathering mantle. Rock type Ib is the *exhumed low-reliefed predecessor landscape*. Conical and rounded landforms with weathering pits suggest more intensive chemical weathering, a stronger impact of organic acids on rock disintegration and humidity fluctuating on a wider range than in the present-day steppe. It is supposed to be a weathering residue or a *relict etchplain* that came into existence during the Plio-Pleistocene when wetter conditions existed relative to the present-day steppe climate (Devjatkin and Murzaev, 1989). The IIId *sheetfloods* developed on a high-altitude mountain platform under humid, but colder, conditions than during the formation of the regolith as the chemical weathering has almost come to a halt (see heavy minerals) (Figs. 18 and 19). The rock type Ic is also the substrate where the *permafrost structures were preserved* (Fig. 6).

Deposits of rock type association 5 evolved in large morphological depressions and a more-reliefed landscape, yet at a lower topographic level than rock type association 4 (Fig. 29). The dip angles of the erosional surfaces which the sediments of rock types IIId (0–1°) and IIb (0–4°) rest upon are very low (Fig. 29). Rock type association 4 is representative of creep and unconfined flow, whereas association 5 is *transitional between unconfined and confined flow*. This transitional process happens during the initial stages of steppe river drainage systems in a periglacial environment (Fig. 29, Table 1). Reworked glacigenic material is common and the *impact of permafrost is recognizable* all around (Figs. 6 and 9). Paraglacial rock-slope debris and weakening of the rock during formation of rock type association 4 provide a significant source for the sediments of association 5. Rock type association 5 is confined to soil-mantled vegetated parts of the steppe and has no equivalent in the desert steppe. All that furnish evidence that the sedimentological processes during rock type association 5 are currently no longer operative in the steppe drainage systems.

Rock type 6 encompasses processes ranging from *mass flows through fluvial deposition* (Figs. 4–6, 14–17, 23). These flow processes are operative along the passage from the midslope through the footslope into the present-day channel system (0–35°) (Fig. 29). The various rock types developed as a function of slope angle and thus rock type association 6 is morphologically related. Aside of this morphological parameter, the *gravel-fines ratio* plays a fundamental part in the evolution of this rock type association (Table 1, Fig. 29-arrowhead). In particular, rock types IIIa through IIIc are genetical connected, indicating all stages of a sudden and flashy sediment dispersal in the form of hyperconcentrated sheet, debris and channelized flows. It starts off with creep and solifluction/gelifluction, gives way to unconfined mass flows and ends up in a channelized flow of the ephemeral (zone B) and perennial stream (zone A) systems (Figs. 3, 14–17). The availability of fine-grained debris is decisive as to whether catena IIc-IId-IIe or catena IIIc-IIIb-IIIa and eventually Vb and/or Va come into being. The key to how rock type association 6 develops is governed to some extent by the intensity of rock type associations 4 and 5 in the area, both of which are sourcing rock type association 6 in the *vegetated or soil- and regolith-mantled landscape*. Precipitation and vegetation have an accelerating and a hampering effect, respectively, on the flow processes in rock type association 6 (for precipitation and vegetation see Fig. 2). According to Köppen's (1923) classification scheme the northern and higher mountainous parts belong to the Dw climate (cold snowy forest with dry winter) while the lower and southern parts belong to the dry climates coded Bs (dry during summer). The current continental climatic conditions are dominated by the Siberian high, whereas the summer is dominated by the Asian low. The continental climate is reflected by annual temperature changes of about 45° with limited precipitation mainly during the summer months of June to August (Academy of Sciences, 1990). The recent climatic variation in the steppe has a direct impact on the geomorphological processes of rock type association 6 by providing periodically run-off water and extreme temperature contrasts.

Rock type association 7 resulted from a lowering of the lake-level thereby exposing mudflats in the environs of saline lakes to *deflation* and provoking strong *evaporation*.

Rock type association 8 is a poor representative of what has been discussed in rock type association 6 as *mass flows to fluvial depositions* (Figs. 20–22). In the *non-vegetated area* of the desert steppe, a catena from IIIe through IIIg into IIIf evolves. Flow is unconfined to poorly confined. It takes place on an episodic to periodic basis. There are thick fan lobes in the proximal facies close to the escarpment and thin layers and gravel lags in the distal facies.

10. Summary and conclusions

The steppe environment is a siliciclastic-dominated continental environment of deposition occurring between the polar and warm deserts. Its ancient analogs may be identified based upon the following characteristics:

1. Conspicuous bimodality in the grain-size distribution.
2. Sand-sized material is patchily distributed and subject to strong lateral and facial variations.
3. Fine-grained (carbonaceous) interbeds are large in their extension but thin
4. Paleosols are monotonous in their vertical built-up with calcite occurring disseminated in concretions or as massive duricrusts dependant on the zone of vegetation/-precipitation.
5. Evaporites occur in thin layers together with argillaceous matter and may, locally, display a variegated mineral association of chlorides, sulfates and carbonates of Ca, Mg and Na.
6. Placer deposits of metallic and non-metallic commodities are abundant and dependant on the source area.
7. Sedimentary deposits are immature with respect to texture and composition.
8. Directional sedimentary structures in coarse-grained deposits are unimodal but subject to very strong changes through time (fluvial and mass flow). In arenaceous deposits, patterns indicative of the paleocurrent are more persistent through time (wind direction).

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Different Transcriptions

1	Selenga	Selenge
2	Egiyen gol	Eg gol
3	Choevsgoel	Khuvsgul
4	Orhon	Orkhon
5	Baikal	Baigal
6	Kerulen	Kherlen
7	Alagiin tsar	Alagyn tsar
8	Saynshand	Sainshand

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