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A Review of the Non-metallic Industrial Minerals of Mongolia: The Impact of Geological and Geographical Factors on their Formation and Use

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Abstract

Mongolia is one of the countries of the Asian continental interior rich in ore and non-metallic deposits. Non-metallic commodities of high-unit and high-place value commodities are found throughout the country. Some reference types are discussed in this paper: (1) feldspar-quartz pegmatites; (2) graphite-bearing skarns; (3) contact-metamorphic marbles; (4) igneous and sedimentary gemstone deposits; (5) coarse-grained aggregates (alluvial-fluvial); (6) fine-grained aggregates (fluvial-aeolian); (7) arenaceous-argillaceous byproducts of coal mining; (8) and argillaceous deposits. (Paleo)geography and climate were decisive for the accumulation (e.g., clay and sand deposits) and alteration (e.g., calcareous and gemstone deposits) of many of the non-metallic deposits. The recent geographical and climatic situation is responsible for the poorly developed infrastructure and especially affect the high-value commodities. Acquisition of digital data in the field is a must in a country of the continental interior of Eurasia, in order to save time and space for the transport of samples to accelerate data acquisition. A portable IR mineral analyzer (PIMA) is essential in exploration for industrial minerals and its applicability may be rated as follows, in order of decreasing applicability for different commodities: (1) carbonates, (2) sulfate-bearing rocks, (3) argillaceous rocks, (4) clay-bearing arenaceous rocks, and (5) rocks abundant in alumosilicates/ framework silicates.

Introduction

MONGOLIA IS THE fifth largest country in Asia in terms of land area, covering 1,566,000 km^2. A great deal of its 2.4 million inhabitants lives in and around the capital Ulaanbaatar (Jargalsaikan, 1998). The country is landlocked within the heart of Asia, a situation it shares with many countries such as Kazakhstan, one of its western neighbors that is known for its mineral wealth. This extraordinary geographic position is a key factor for the extremely continental climate with a long, cold winter and a short, hot summer. Climate and geology have both a decisive effect on the life in Mongolia. Copper, gold, and molybdenum are stable commodities of the metal sector, whereas fluorite and coal dominate the non-metallic sector (Marinov et al., 1997). Non-metallic deposits other than fluorite have, however, gained only modest attention, and little is known in the outside world about the origin and production of industrial minerals and construction materials. Non-metallic deposits have been briefly touched upon in compilations of mines and deposits in Mongolia (e.g., Jargalsaikan, 1998; United Nations, 1999). Textbooks or encyclopediae such as those by Kuzvart (1984), Carr and Herz (1989), Mathers and Notholt (1994), and Harben and Kuzvart (1996) contain little data on Mongolia's non-metallic deposits. Almost all unpublished reports in the archives are written in Russian or Mongolian, and thus often inaccessible to foreigners. The aim of this paper is to shed some light on a hitherto unknown field of the geology of industrial minerals. Emphasis is placed on the extent to which sedimentology and

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geography have influenced the formation, alteration, and use of non-metallic commodities in Mongolia, a country synonymous for many people with the largest steppe in the world and dinosaurs roaming an area that is today known as the Gobi Desert.

Sedimentological investigations were supplemented by mineralogical studies and combined with geographic studies, covering the entire spectrum from paleogeographic, palaeoclimatologic, morphoclimatic, and socio-geographic analyses. The aim is to present a full picture of some important types of non-metallic deposits in Mongolia from their primary emplacement through the stages of redeposition under varying morphoclimatic conditions, up to the stage of exploration and exploitation. Using terms coined by petroleum geologists, this approach may be called a "facies analysis," covering the entire pathway of concentration from the "source rock" to the "host rock." The study attempts to provide distinctive criteria useful in evaluating particular rock series in the various fields of geology of non-metallic deposits. These criteria may also be transferred to neighboring countries such Kazakhstan or Uzbekistan. Similar "facies studies," were conducted elsewhere by Tiercelin et al. (1992) and by Dill (1994) and Dill et al. (2001). The mineralizations and rock sequences under consideration are located across central Mongolia, along a transect from the northern mountain taiga to the desert steppe of the Gobi (Fig. 1). Studies were centered around sand and argillaceous rocks in the eastern Mongolian steppe at Baganuur and the Gobi Desert, and focused particularly on calcareous and graphite-bearing rocks in the mountainous taiga south of Choevsgoel (Khuvsgul) Nuur, near Tsagaan Chuluut, feldspar-quartz pegmatites located about 170 km west of Ulaanbaatar, and gemstone deposits in the western Mongolian steppe (Fig. 1).

Geological Setting and Geographic Overview

As part of the Central Asian fold belt, a series of E-W–striking arcs have developed from the Precambrian to the Permian (Marinov et al., 1973; Badarch et al., 2002). These fold belts are fringed by the Siberian craton in the north and by the Sino-Korean and Tarim cratons in the south (Kampe, 1997; East Eurasian Geological Seminar, 1998; United Nations, 1999) (Fig. 2). Throughout the Mesozoic, tectonic reactivation triggered intense volcanic activity and basin subsidence, mainly in the southern parts of the country. The formation of the platform cover dates back to the Mesozoic–Paleogene, when the synclines that are filled with continental sediments subsided (United Nations, 1999). Large areas in the south are underlain by Cretaceous and Tertiary platform sediments (Marinov et al., 1973) with a great variety of landforms that obtained their morphology mainly by the continental climatic conditions. 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 to 10°C and that the average annual precipitation lies between 100 and 400 mm (Hilbig, 1995). The northernmost area under consideration is located near the Choevsgoel Nuur which 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. 3). According to the map of vegetation zones by Hilbig, the majority of the study area forms part of the mountain forest steppe, which passes northward into what is called the taiga and toward the south into the steppe *sensu stricto*, giving way to the desert steppe further south and to desert proper near the Chinese-Mongolian border (Fig. 3).

Low-relief surfaces may be encountered at different altitudes cutting across basement rocks of different lithologies. These erosional surfaces were interpreted in terms of ancient peneplains (Fig. 4A). In the lowland, the usually very unstable steppe fluvial drainage systems are characterized by interconnected braided channels in a fluvial floodplain (Fig. 4B). Toward the south channel abandonment, unconfined flow patterns, and shortage of water become an ever-increasing problem for herdsmen and miners alike (Fig. 5). Geomorphology and hydrology have a significant influence on whether a deposit can be worked in these parts of the continental interior.

A geographic overview of Mongolia must also address the infrastructure of the country, which is still under development. Railroad and communications systems are confined to a narrow zone stretching from Ulaanbaatar toward the southeast, where the railway line crosses the border into China near Zamyn uud (Fig. 1). In the opposite direction, another railway line connects Ulaanbaatar with towns in southeastern Russia. Erdenet and Baganuur, two major cities in Mongolia, are connected by

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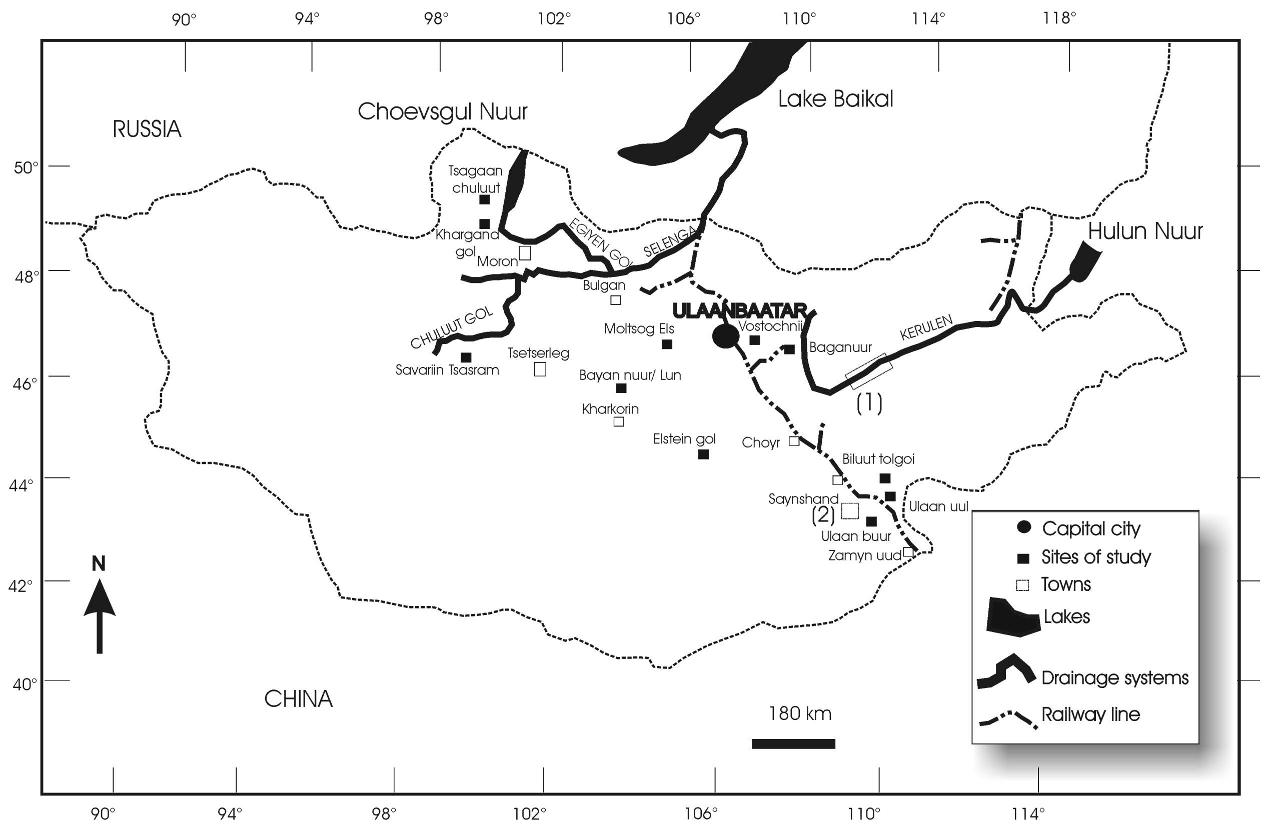

FIG. 1. Index map showing the study areas and major cities in Mongolia. Boxed areas marked with Arabic numerals denote the position of drainage systems of the Kerulen (Kherlen) River (1) and the study site for Quaternary deposits in the Gobi Desert (2).

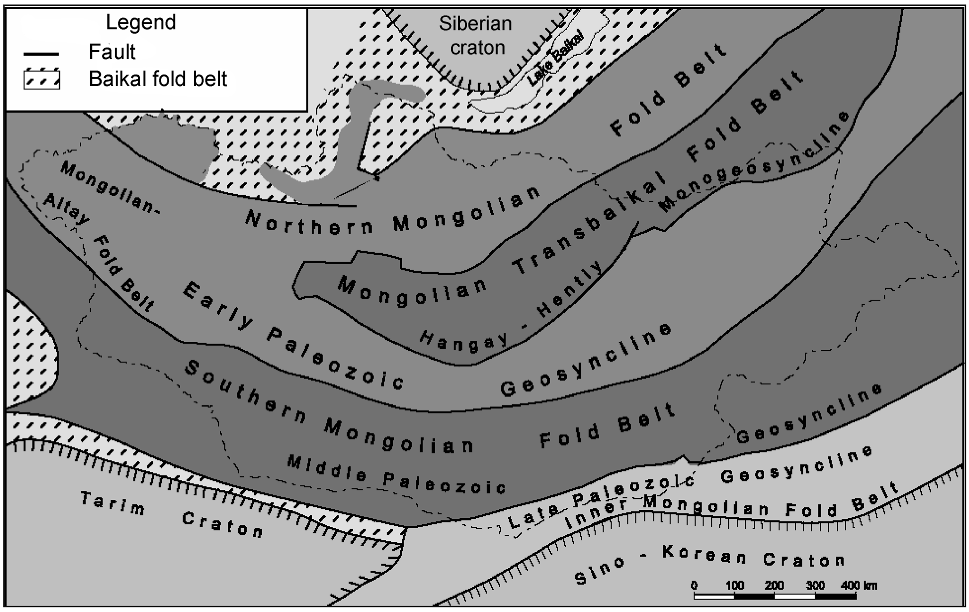

FIG. 2. Regional geological units of Mongolia (Kampe, 1997).

a branch rail line with the trunk railway mentioned above. The remaining parts of the territory in the far east and west are rather isolated and are not yet connected with the capital either by train or by paved country roads. The latter type of road occurs only in the immediate surroundings of the major cities. They grade into unimproved roads and tracks that criss-cross the steppe in various directions.

Field and Laboratory Techniques

Field work involved the common measures of large-scale mapping, sampling, and cross sectioning. Laboratory-based mineralogical investigations included examination of thin and particulate sections for heavy mineral concentrates and X-ray diffraction analysis (XRD). In the field, grain size analysis was carried out with a sliding caliper and hand lens. In the laboratory, grain size measurements were then refined by sieving analyses. Major and minor elements were analyzed using XRF. To comply with the poor infrastructure and minimize the shipping expenses for samples, as many digital data as possible were captured in the field and saved on laptop. Cross sections were surveyed by means of a hand-held magnetometer (Kappameter) and a gamma spectrometer (Fig. 6A). These geophysical methods have been discussed at length in various textbooks (e.g., Miall, 2000) and their applicability proven for correlation and interpretation of the depositional environments in many field studies. Analyses with a portable infrared mineral analyzer (PIMA), involving acquisition and first-hand interpretation of data, was carried out with a laptop in the field. PIMA was set up for analysis in a base camp. The power supply may be provided by car battery or a power pack connected to the local power supply system if available. We measured directly rock and core samples as well as loose rock material or powdered samples through Petri dishes. The system was calibrated to wave length and reflectance for routine data acquisition (Fig. 6B). The principles of IR spectrometry are well known, and IR-based analytical methods have been applied in various fields of geosciences for a long time (Herrmann et al. 2001). When a rock is illuminated by an IR-light source, certain wavelengths of the light are absorbed by the rock-forming minerals as a result of sub-molecular vibrations. Bending and stretching of molecular bonds in a mineral are especially strong in phases containing hydroxyl $((OH)^{-})$ and carbonate $((CO_3)^{2-})$ complexes (Fig. 6B). The spectrometer measures the reflected radiation from the surface of rocks and minerals in the short-wavelength infrared (SWIR) from 1300 to 2500 nm (Fig. 6B). Mineral identification is based on the

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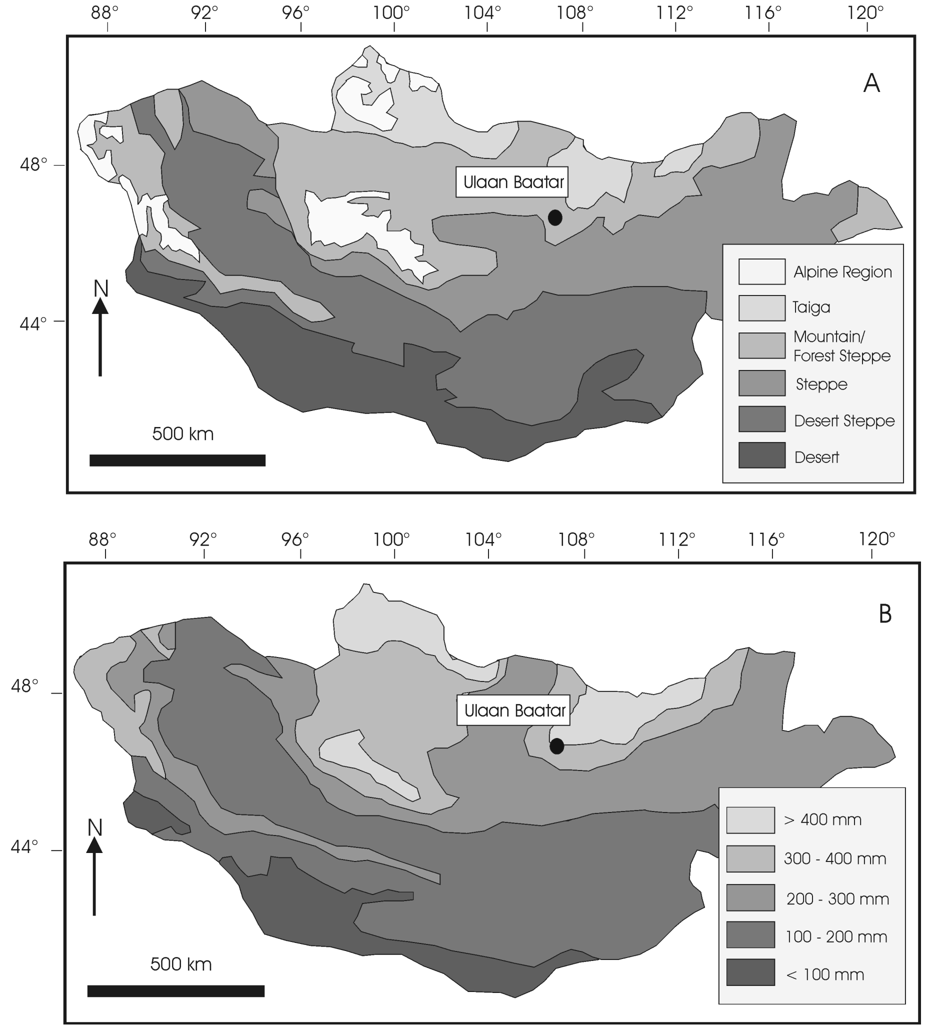

FIG. 3. Vegetation zones (A) and annual precipitation maps (B) of Mongolia (from Hilbig, 1995).

characteristic spectral signature of the various mineral groups such as phyllosilicates, calcareous minerals, and sulfates.

Besides this more sophisticated approach of capturing digital data, traditional and proven methods were applied in the field to preconcentrate samples and save money by “hammer-and-laptop techniques.” Panning of stream sediments was carried out during the study of placers. It was followed by magnetic separation and heavy liquid separation with tetrabromethane or sodium polywolframate in the laboratory (Fig. 7).

Pegmatite Deposits

Location and case history

The Bayan nuur and the Lun pegmatite fields are located 170 km west of Ulaanbaatar (Fig. 1). Several pegmatite deposits of the Bayan nuur and the Lun pegmatite fields were under exploration in the late 1980s. Based upon the data reported by Baljinnyam et al. (1993) the Bayan nuur–Lun pegmatite field contains reserves of 4.254.000 tons of K feldspar and 2.407.000 tons of quartz. Of the numerous pegmatite deposits, the major deposits Shagait-uul and

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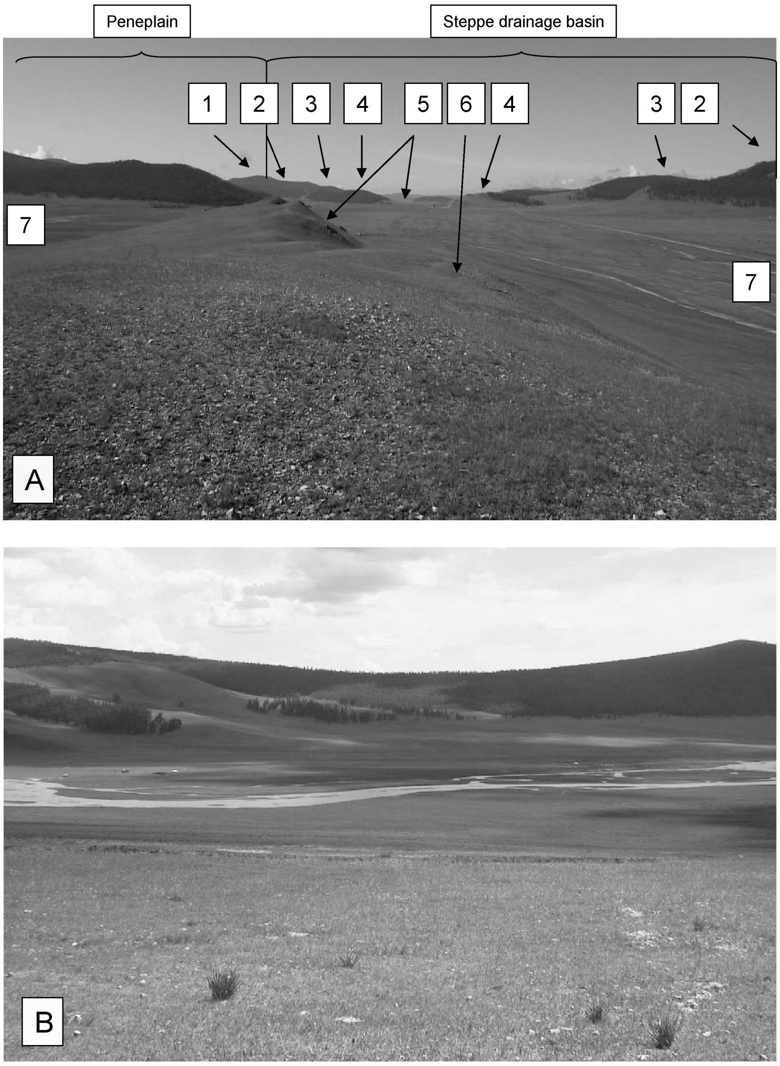

FIG. 4. Overview of geography and drainage systems in the northern steppe regions. The region was investigated for its marble, graphite and aggregate deposits. A. Cross section through a steppe river drainage basin. Alluvial channels (5–7) and strath terraces (2–4) of the Egiin gol (river) south of Choevsgul Nuur. The number "1" marks the level of the ancient peneplain and the edge of the steppe river drainage system. B. Braided river drainage system typical of the taiga and mountain forest steppe south of Choevsgul Nuur.

Zakhiin-tsohio were investigated in more detail and taken as a case in point for the pegmatite mineralization in the Bayan nuur–Lun field. The Bayan nuur–Lun pegmatite field is located as follows: 104°30'/47°50'–104°45'/47°50'–104°30'/47°40'–104°45' /47°40'.

Geographic and geological setting in the Bayan nuur–Lun region

The pegmatite deposits are located in a zone transitional between the mountain steppe and steppe proper (Fig. 3). The landscape is very monotonous and characterized by smooth hills and wide

FIG. 5. Overview of geography and drainage systems in the southern steppe regions. The area was investigated for its clay and aggregate deposits. Poorly confined flow in the desert steppe following a heavy downpour. Flow direction is marked by the arrowhead. The individual streams branch in fan-shaped drainage systems that they were not able to fill completely following the episodic precipitation. The levees marked by the white stippled lines demarcate previous flow regimes of higher strength.

V-shaped valleys, that are dry during most of the year (Fig. 8A). In places, the bare bedrock is exposed at slope angles greater than 35°. Some flat-topped hillocks covered with boulder fields and named tors *sensu* Anderson (2002) stand out from the grassland. These geomorphological forms on flat hilltops and the cliffs are helpful in the localization of the various pegmatite bodies at an altitude of between 1200 and 1400 m a.m.s.l.

A great variety of metamorphic rocks of Neoproterozoic age was recognized in the basement complex in the Bayan nuur–Lun region. In the Shagait-uul area, the bedrock is composed mainly of black biotite gneiss, granite gneiss, and amphibolites, belonging to the Middle Oortsog metamorphic complex (Fig. 8B). In the Zakhiin-tsokhio area, gneisses prevail in the southern part of the study area, grading toward the north into biotite schists and amphibolites. In the Shagait-uul area, the pegmatites roughly strike in an E-W direction and dip almost vertically (Fig. 8E). Their average thickness is ~20 m, and their maximum thickness measures 140 m. Pegmatite bodies may be traced over a distance of as much as 400 m. They display a pronounced zonation with an endocontact zone and granitic pegmatite at the margin, giving way to graphic and blocky pegmatites in the center (Figs. 8C–8E). All pegmatitic bodies are crosscut by swarms of aplite and quartz veins trending approximately in a NW-SE direction. Unlike Shagait-uul, in the Zakhiin-tsokhio area, the pegmatite bodies are conformable and unconformable to the foliation of the host rocks (Fig. 8F). Zonation and the average strike are similar to Shagait-uul; the dip angle of 30° N is, however, much lower than at Shagait-uul.

Mineralogical and chemical compositions

The mineralogical and chemical compositions of the Shagait-uul and Zakhiin-tsokhio pegmatites are given in Table 1. In the endocontact zone of the pegmatite, plagioclase prevails over K-feldspar and quartz, whereas in the core zone of the pegmatite the K-feldspar has significantly increased over plagioclase and quartz contents. Biotite, muscovite, almandine-enriched garnet, magnetite, and schoerl are present as minor constituents. Quantification of these accessory minerals did not reveal any preferred concentration of these minerals in one or the other structural zone of the pegmatites (Figs. 8E–8F). Only in the Zakhiin-tsokhio pegmatites, the tourmaline content may, locally, attain a volume of as much as 50% of the graphic pegmatite. Tourmaline

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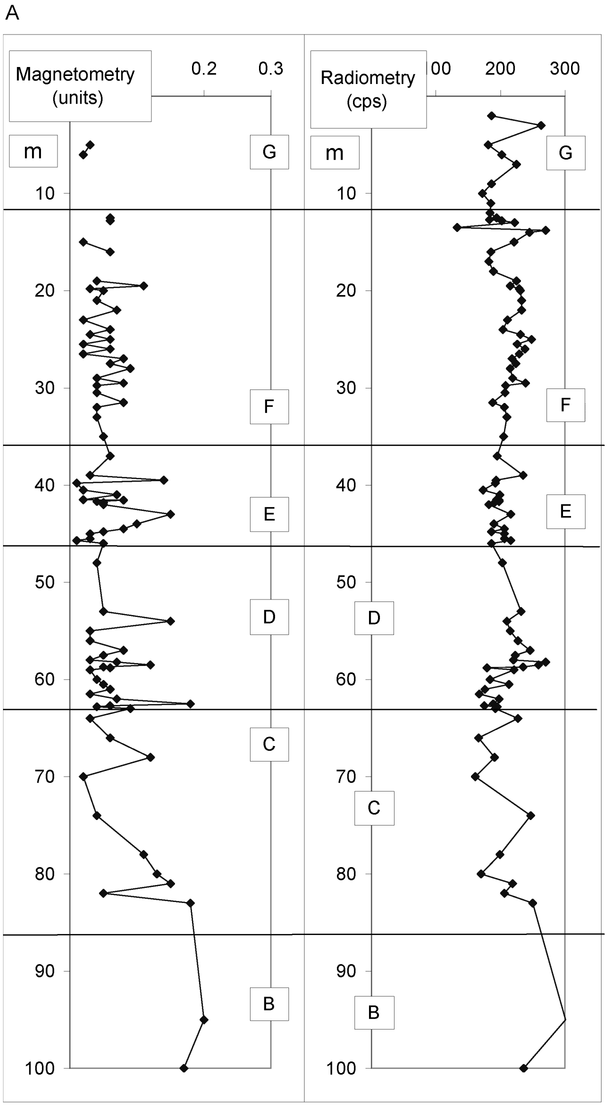
FIG. 6. Capture of digital data in the field, e.g., for fine-grained aggregates and clay mineralization of interseam and roof sediments in the Baganuur lignite openpit. A. Magnetic susceptibility and gamma radiation. Magnetic susceptibility (dimensionless units) and natural gamma radiation (total counts/second = cps) are plotted as a function of lithology (for more detail, see individual sections of the reference cross section in Fig. 16). B. Facing page. Survey graphs of Lower Cretaceous sediments, using a Portable Infrared Mineral Analyzer (PIMA). Legend: 1 = characteristic shortwave-infrared absorption features in (hull quotient) spectra of some common phyllosilicates found in Baganuur (modified from Herrmann et al., 2001) to illustrate the variation of IR-sensitive components (e.g., AlOH) through time in the Cretaceous sediments; 2 = infrared spectra measured at various depths of the reference cross section in the Baganuur open pit lignite mine (for more detail, see the individual lithological sections of the reference cross sections in Fig. 16).



is also found in association with muscovite and garnet in some of the quartz veins intersecting the pegmatite. The largest crystal size of K-feldspar was found in the blocky pegmatite, with crystals attaining as much as 0.5 m. A special type of pegmatite is reported from the Zakhiin-tsokhio, where pegmatite veins are strongly enriched in muscovite and where the mineral zonation is very much different from the overall mineral association in the Bayan nuur–Lun region (Table 1). K-feldspar decreases toward the core of the pegmatite, whereas the contents of quartz and muscovite increase, resulting in quartz-muscovite veins with only little feldspar. Plagioclase shows an inward-increasing trend in the pegmatites. This is the only site in the pegmatite province where crystals of beryl were found in the zone of graphic pegmatite. The average chemical compositions of the pegmatites do no significantly differ from each other, and qualify these pegmatites as quartz-bearing K-feldspar pegmatites (Table 1).

Marble and Graphite Deposits

Location and case history

In the Choevsgoel region, sparry limestone and marble are widespread. The major marble deposit is the Tsagaan Chuluut deposit (N 50°21'48", E 99°46'19") about 100 km northwest of Moron (Figs. 1 and 9). This site is reached from Ulaanbaatar by two-day ride on more than 680 km of jeep roads through steppe and mountain taiga. The marble deposit was discovered in 1983 by the Duch gol Geological Party, which was mapping the area at a scale of 1:50,000. In the aftermath of this campaign, drilling, sampling, and mapping at a scale of 1:10,000 was carried out in an area measuring 0.4 km^2 (Chuluunbat and Olzbaatar, 1986).

Several graphite deposits are also known near Tsagaan Chuluut. A maximum carbon content of

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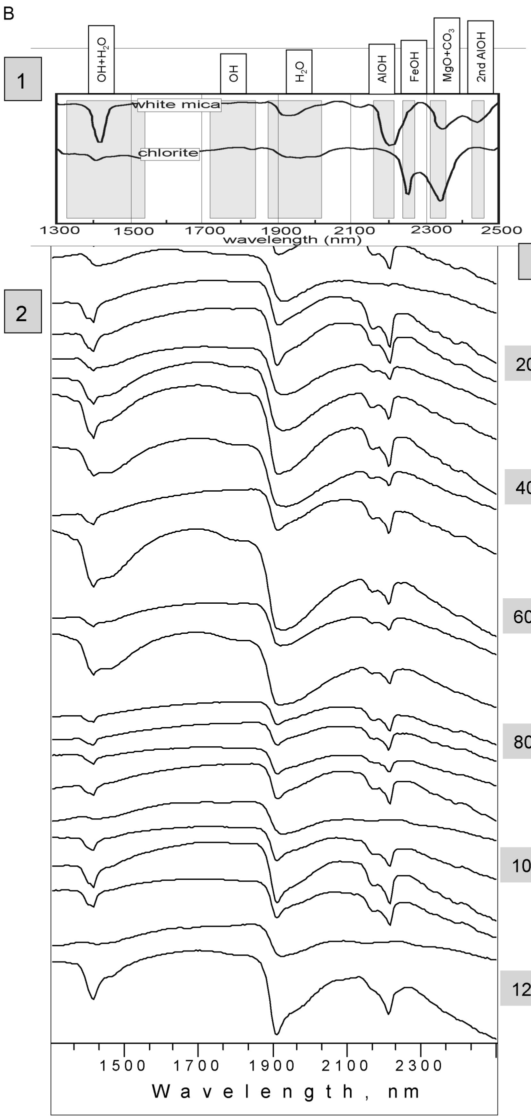

almost 60% was reported from the Khargana gol deposit (N 50°23'30", E 100°2'00"), 13 km southeast of the Khatgal sum center (Fig. 10) (United Nations, 1999). The Itge Naidvar deposit in the area has a much lower carbon content, ranging between 1.13 and 12.41% carbon. The first documentary evidence of graphite in this region goes back to the early 1930 when Yaxnotov (1931) calculated the graphite reserves in the area. His calculation yielded 320 tons for Khargana gol as category A, 15,000 tons as category B, and 60,000 tons as category C_1. A detailed lithological map was presented by Chilkhaajav et al. (1982).

Geographic and geological setting in the Tsagaan chuluut region

At approx. 2300 m elevation, the basement rocks south of Lake Choevsgoel are truncated by a low-relief surface (Fig. 4A, morphodynamic generation 1). Only a few isolated hillocks such as those in the environs of Tsagaan chuluut stand out from this plateau (Fig. 9A). They were quarried for marble. Surface drainage has carved out wide, trough-shaped valleys and V-shaped gullies at an altitude of between 1800 and 1900 m.

The calcareous rocks are part of the Choevsgoel Series, which is subdivided into an upper Khesen Formation and a lower Khoridal Formation (Fig. 9). The whole thickness of the upper subformation is 1220 m, whereas the lower subformation reaches a thickness of as much as 1940 m in the study area.

Calcareous rocks in the Choevsgoel aimag are flasered, displaying various tints of grey and white (Fig. 11B). Limestones of the Khesen Formation were assigned an Early Cambrian age of formation (Badarch, 2003). Massive and spotted dolomites or dolomite-bearing limestones alternate with silicified siltstones. In places, oncolites are visible in the sparitic limestone. The Khoridol Formation is lithologically very similar, yet contains some bituminous limestones and siltstones with archaeocyathids. The Cambrian carbonate sequence was intruded by Middle Devonian medium- to fine-grained leucocratic biotite granites that, locally, possess a more porphyritic texture. Less widespread are aplitic dikes and porphyritic granites that intersected the calcareous country rocks. This Middle Devonian igneous activity in the Tsagaan chuluut area gave rise to a

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FIG. 7. Concentration of heavy minerals near the Shavryn Tsaram gemstone deposit using a wooden Mongolian-style pan.

contact-metamorphic aureole in the exocontact of granite intrusions, measuring 400 to 500 m in width. The marble is exposed to about 70% over a length of approximately 1200 m; the remainder is covered by Quaternary sediments. Studies focused on the marble at Tsagaan chuluut revealed a workable calcareous sequence that is composed of three concordant marble layers very much different from each other in color and crystal size: (1) upper horizon rock: black to grey, fine- to medium-grained, average thickness 30 m (max. 47 m); (2) middle horizon: light grey to white, medium-grained, average thickness 46 m (max. 86 m); (3) lower horizon: black to grey, medium-grained, average thickness 42 m (max. 61 m).

The marble horizons strike between 230° and 260° and dip southwest at an angle of between 18° and 35°. In their topmost part the marble layers were subject to an intensive karstification, the lower boundary of which reaches a depth of as much as 15 m, with an average depth of supergene alteration standing at 6 m. The study area is transected by numerous faults striking at various angles (Fig. 9). Chemical analyses have shown an increase of the MgO content in the marble toward the fractures.

Mineralogical, chemical and petrophysical data of the marble

Chemical analyses given in Table 2 classify the calcareous rocks as “dolomitic limestones” and “calcitic dolomites,” using the triangular plot of Leighton and Pendexter (1962). In the upper horizon it is a dolomitic limestone with fine-grained calcite falling in the particle size range 0.09 to 0.5 mm. Accessory minerals are tremolitic amphibole, phlogopite, muscovite, chlorite, and pyrite. The middle horizon consists almost completely of calcite and hence may be called a “limestone” according to Leighton and Pendexter (1962). Calcite forms a coarse-grained granoblastic texture with crystals in the size range 0.4 to 1.3 mm (max. 2.6 mm). The lower horizon closely resembles the upper horizon with respect to its mineralogical assemblage. PIMA studies and hand lens examination showed that smectite, illite, kaolinite, quartz, chalcedony, and goethite line fracture planes and, thereby, may considerably reduce the durability and hardness of the marble, decreasing its aesthetic value (Fig. 11B). The alteration minerals mentioned above become more abundant toward the present-day topographic

TABLE 1. Average Mineralogical Compositions of Pegmatites in the Shagait uul and Zakhin Tsokhio Areas, in wt%

Minerals	Endocontact	Granite-pegmatite	Graphic pegmatite	Blocky pegmatite	Quartz-muscovite vein
			Pegmatite, Shagait uul area		
K-feldspar	18.2	60.4	51.7	54.3	–
Plagioclase	54.5	10.2	14.7	14.4	–
Quartz	24.7	28.6	31.2	30.6	–
Biotite	1.4	0.8	1.1	0.7	–
Muscovite	–	–	0.4	–	–
Garnet	0.4	–	0.4	–	–
Tourmaline	–	–	0.2	–	–
Magnetite	0.8	–	0.3	–	–
			Pegmatite, Zakhiin tsokhio area		
K-feldspar	44.6	68.3	55.7	60.1	–
Plagioclase	31.3	3.4	12.3	10.9	–
Quartz	21.5	26.8	28.4	28.1	–
Biotite	1.3	0.7	0.6	–	–
Muscovite	0.6	0.5	2.1	0.9	–
Garnet	–	0.3	0.7	–	–
Tourmaline	0.3	–	0.1	–	–
Magnetite	0.5	–	0.1	–	–
			Muscovite-pegmatite vein in Zakhiin tsokhio area		
K-feldspar	–	39	32	10	9
Plagioclase	–	26	34	32	18
Quartz	–	24	29	41	40
Biotite	–	2	1	–	–
Muscovite	–	8	13	16	33
Garnet	–	1	1	–	–
Tourmaline	–	–	1	1	–
Beryl	–	–	1	–	–

Oxides	Shagait uul	Zakhiin tsokhio
	Microcline, Bayan nuur-Lun pegmatite field (mass %)	
SiO_2	64.8	65.08
Al_2O_3	17.84	17.54
Tot FeO	0.18	0.21
CaO	0.12	0.41
K_2O	1.32	13.4
Na_2O	2.74	3.36

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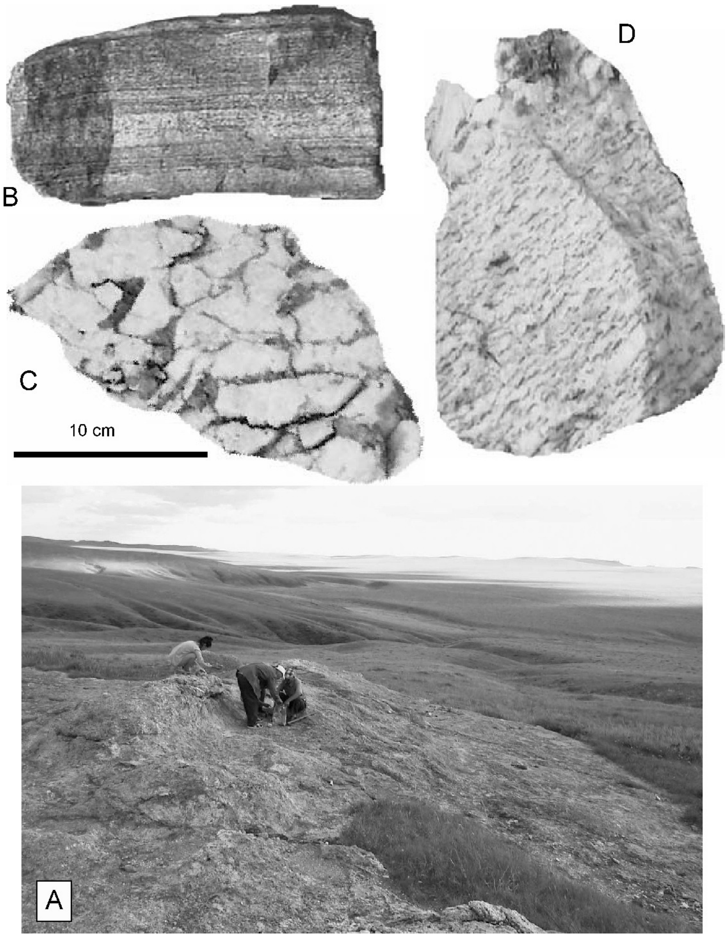

FIG. 8. Pegmatites in the Bayan nuur and Lun area. A. Unvegetated flat-topped hill in the vast grassland of the steppe proper marks the outcrop of the Zakhiin-Tsokhio pegmatite. B. Well-banded amphibolite at Zakhiin-Tsokhio. C. Blocky pegmatite of the central facies at Zakhiin-Tsokhio. D. Graphic pegmatite of the marginal facies at Zakhiin-Tsokhio. E. (facing page) Shagait uul pegmatite in plan view. F. Zakhiin-Tsokhoi pegmatite in plan view.

surface. The rock strength is low to moderate and varies from 842.9 to 853.6 kg/cm^2 in the black variety to 591.5 to 646.6 kg/cm^2 in the white marble. Water absorption is less than 0.25 % and proves the rock to be a frost-resistant dimension/ornamental stone. The abrasion resistance falls in the range of 1.1 to 2.2 g/cm^2.

Geographic and geological setting in the Khargana gol region

The Khargana gol deposit lies on the left bank of the Khargana gol (River) in a wide trough-shaped valley of the Choevsgoel mountain taiga, with patches of open forest covering the ridges (Fig. 12). Morphology and geology are very much like that recorded for the Tsagaan chuluut marble deposit. The lithologies of the Khesen (thickness in the area: 425 to 1040 m) and Khoridol (thickness in the area: 100 to 630 m) formations were already described for the Tsagaan chuluut deposit. Only one subformation, the Ukhaa tolgoi subformation, a clastic series of Early to Middle Cambrian age, adds to the geological record in the Khargana gol area, as it is not present in the Tsagaan chuluut region. Early to Middle Devonian intrusives are more diverse than in Tsagaan chuluut, and are subdivided into three facies. Arranged in decreasing order of their abundance, the following igneous rock associations

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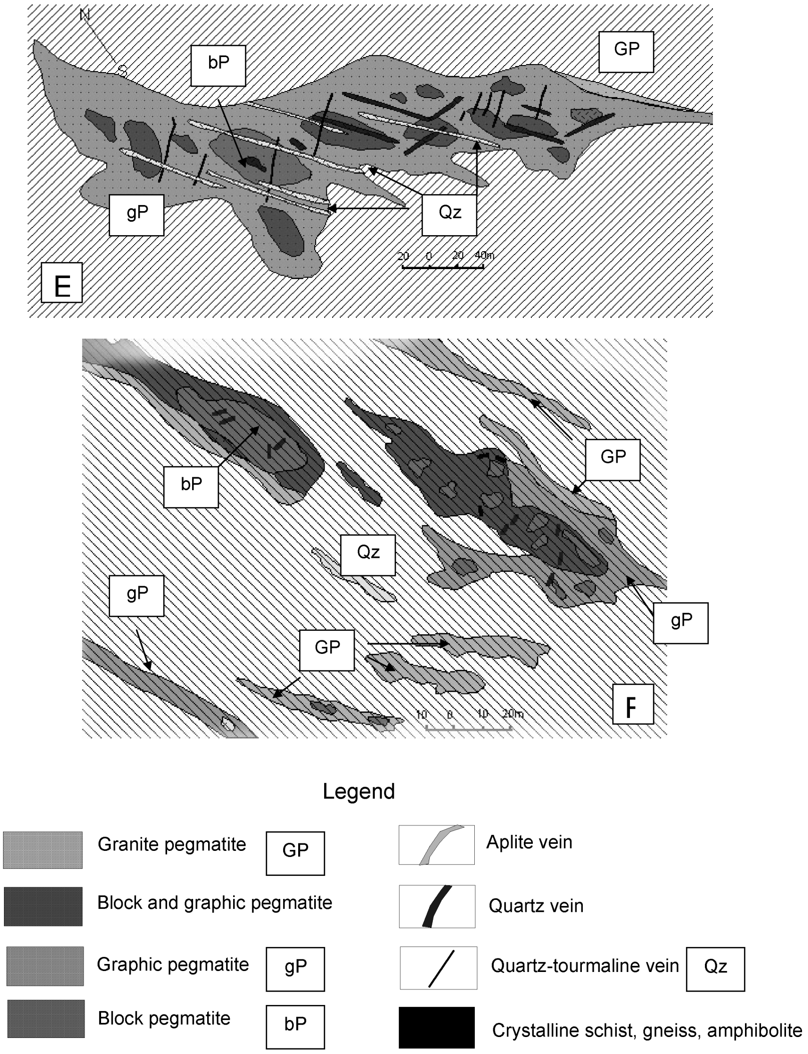

Fig. 8. *Continued.*

occur: (1) syenite–quartz syenite; (2) granite-granodiorite-adamellite; and (3) nepheline syenite (Fig. 10). The chemical composition of the syenite from the region is indicated in Table 3. The contact zone between the Lower Cambrian sparry limestone and the Devonian coarse-grained syenite stock is sharp and mineralized with graphite (Fig. 12). The calcareous host rocks of graphite may be traced over a distance of 600 m in a northwesterly direction and measure ~100 m in thickness (Fig. 12). Three different zones mineralized with graphite were mapped around the intrusive complex and are as follows: (1) pyroxene-olivine-carbonate zone; (2) carbonate zone; (3) serpentine-carbonate zone.

Mineralogy of the graphite deposit

Graphite is hosted by an almost pure limestone of up to 95% calcite and little dolomite. The pyroxene-olivine-carbonate alteration zone developed along fractures that host graphite flakes attaining a size of between 0.008 to 0.2 mm (Fig. 12). The carbonate zone consists of up to 70% pyroxene and 30% calcite, with graphite present only as an accessory mineral. The serpentine-carbonate zone is

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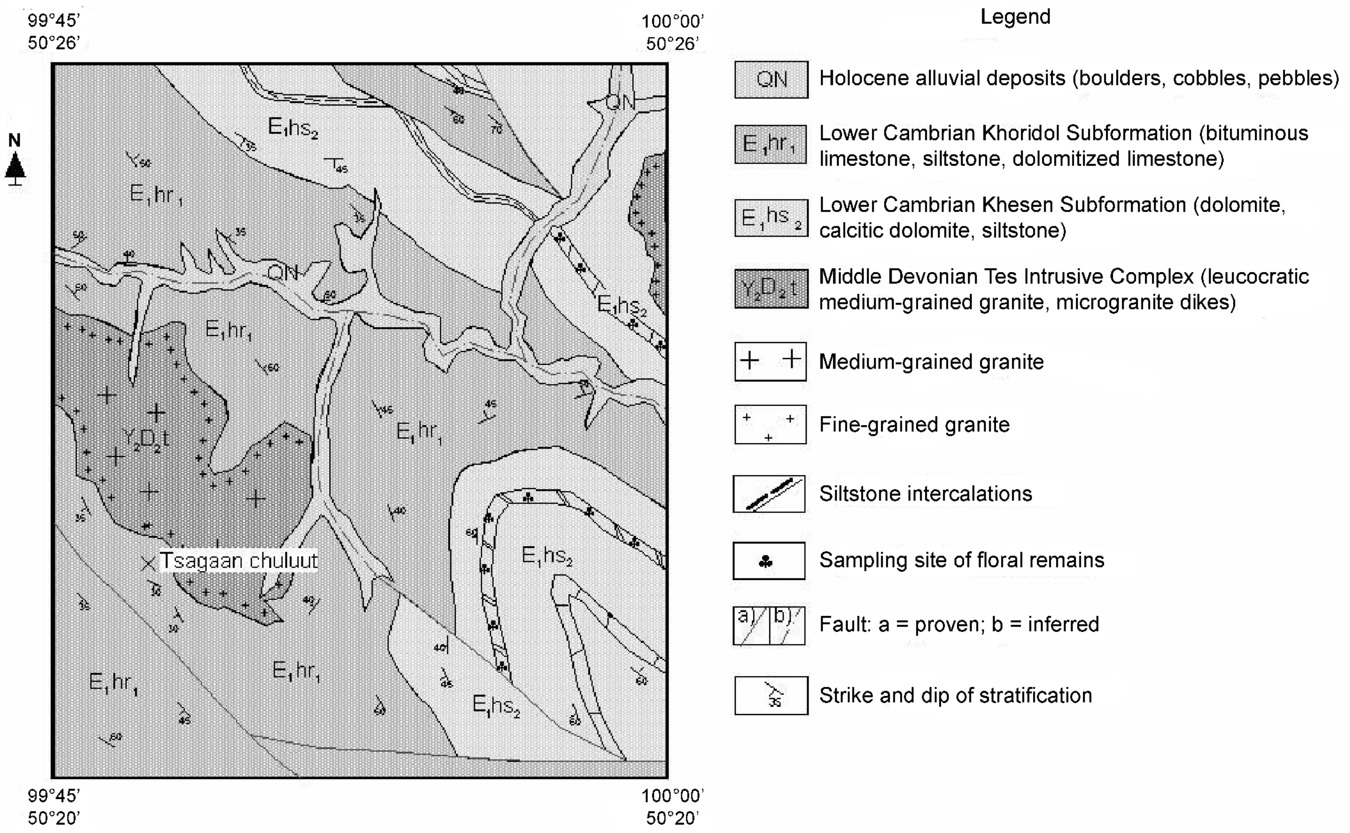

Fig. 9. Geological map of the Tsagaan chuluut marble deposit.

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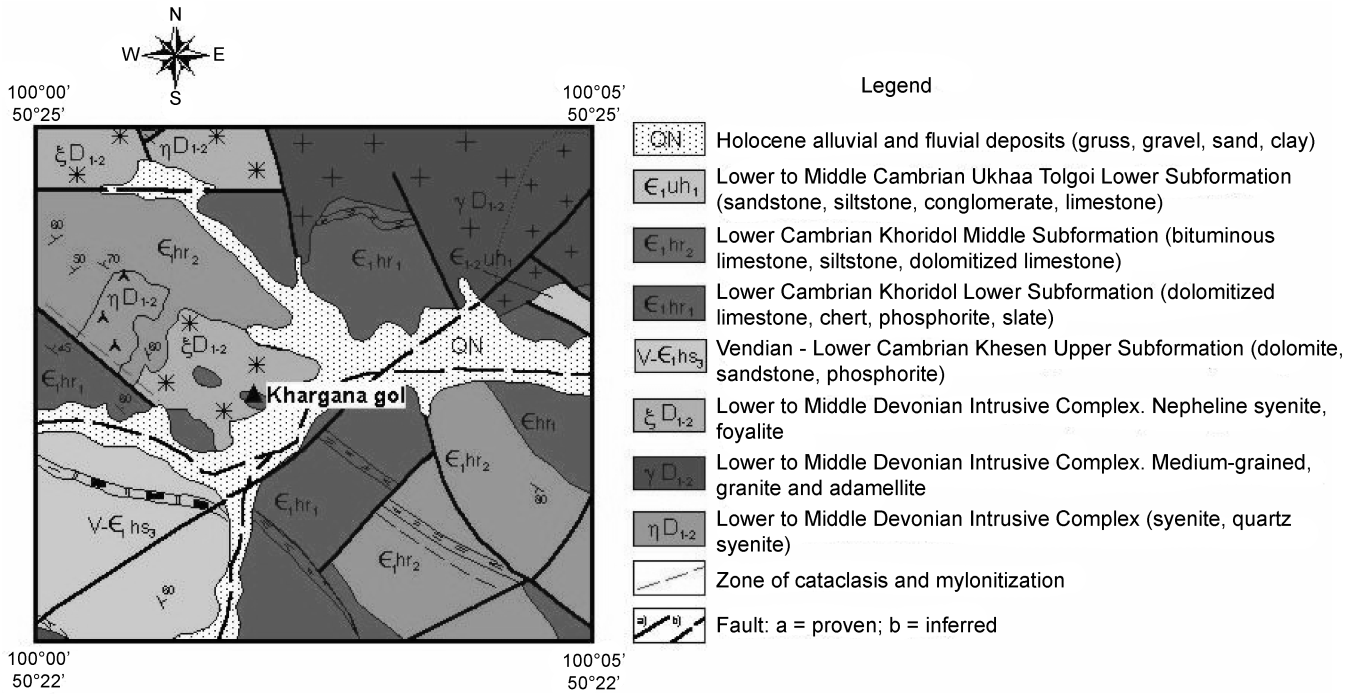

Fig. 10. Geological map of the Khargana gol graphite deposit.

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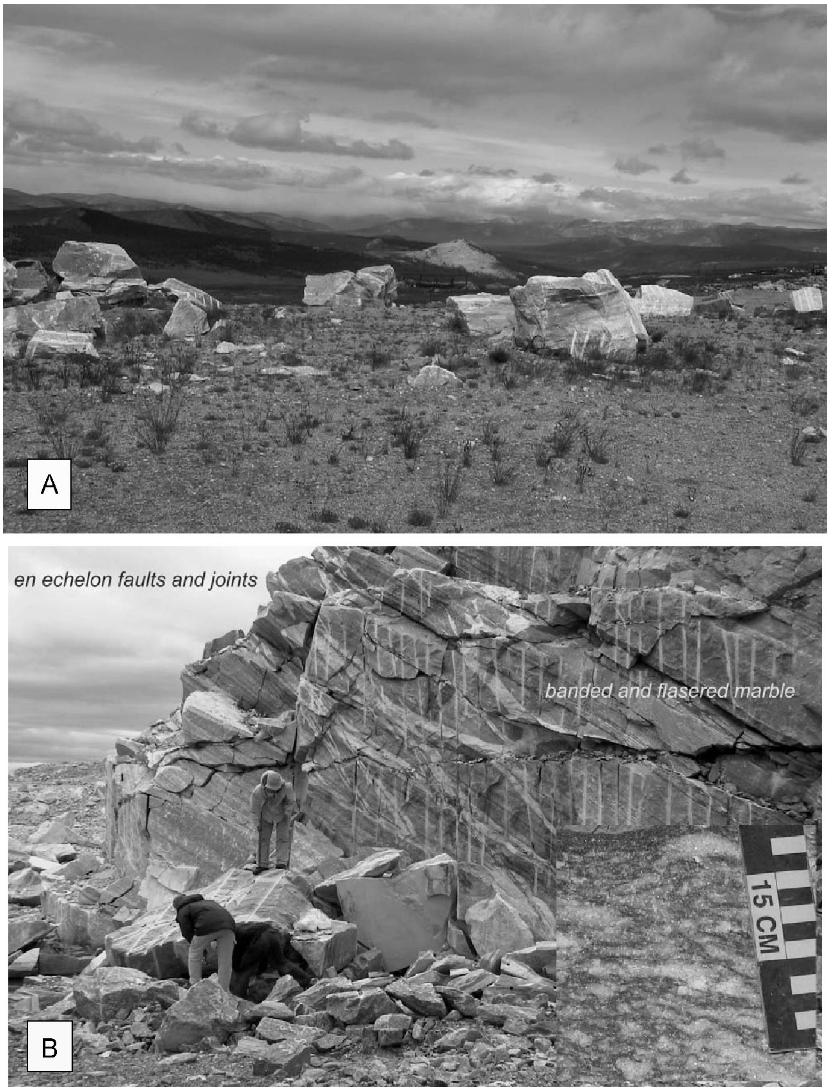

Fig. 11. A. Close-up view of the Tsagaan chuluut limestone plateau with some blocks exploited in a nearby quarry. The view is facing westward over ridges and hills cored by contact-metamorphic limestone, which due to their resistance to weathering stand out from the peneplain. B. Wall of a quarry at Tsagaan chuluut showing the flasered marble intersected by numerous veins each rimmed by an alteration halo. The inset at lower right gives a close-up view of the flasered marble.

composed of serpentine totaling as much as 40 wt%. Carbonate is present in quantities of up to 75% calcite, whereas the graphite content is less than 5%. The graphite occurs in lenses, infills fractures, and is unequally distributed in the alteration zone, with graphite bodies attaining a total length of between 0.2 and 14 m and a width of between 0.02 and 0.8 m. In the graphite lenses, the graphite content is 96 to 100%. Minor impurities are calcite, quartz, and goethite. The carbon tenor lies between 56 and 58%, the ash content between 15 and 40%. The chemical composition of the ash consists of SiO_2 (58.72 wt%), Al_2O_3 (11.84 wt.%), Fe_2O_3 (7.44 wt%), FeO (1.12 wt%), CaO (8.83 wt%), MgO (3.75 wt%), $K_2O + Na_2O$ (7.54 wt%), Ni (33 ppm), Co (6 ppm), Cu (90 ppm), and Pb (4 ppm). Detailed

TABLE 2. Chemical Composition and Classification of Marble Layers in the Tsagaan chuluut area (wt%)

		Element content, in wt%						
No. of sample	Lithology	SiO_2	Fe_2O_3	FeO	CaO	MgO	CO_2	LOI
1	Calcitic dolomites	5.22	6.27	0.18	33.82	16.83	41.88	8.06
2	Calcitic dolomites	2.98	0.07	0.33	38.39	16.99	44.25	4.16
3	Dolomitic limestones	5.42	0.07	0.08	43.86	5.71	41.13	7.58
4	Dolomitic limestones	2.22	0.09	0.29	48.96	4.18	42.08	3.04
5	Dolomitic limestones	1.86	0.29	0.29	46.84	5.71	39.35	3.48

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investigations of some samples for their sulfur and nitrogen contents gave values in the range 0.003% and 0.006% for S and 0.027% and 0.031% for N. SEM analyses showed different generations of graphite. Generation-I forms uneven laminated graphite schists with flakes of ~50 µm. The outward appearance is rather massive. Generation-II graphite developed along veinlets parallel to the schistosity of the graphite schist. These platy crystals are coarser than the flakes of generation-I and grew perpendicularly to the stratification inward from the selvages of the veinlets.

Argillaceous Deposits

Location and case history

Argillaceous lithologies were investigated in the Gobi desert steppe within close range of the railway line connecting Ulaanbaatar with the port city of Tienshin, China (Fig. 1). Other access to argillaceous rocks is provided by the numerous opencast mines under operation for hard coal and lignite in Mongolia, the largest of which is situated near Baganuur (Fig. 1). All three geological periods, the Late Carboniferous/ Late Pennsylvanian and Permian periods, the late Jurassic through early Cretaceous periods, and the late Paleocene and Eocene epochs, are known for the vast accumulation of peat and formation of coal that have resulted in coal measures and widespread argillaceous-arenaceous interseam sediments in Mongolia (Stach et al., 1982; Diessel, 1992). The clastic interseam and roof rocks of the coal deposits are currently stripped off, dumped, and mainly used for backfill. The largest opencast mine currently in operation in Mongolia is Baganuur, with reserves totaling to 600 million metric tons and an average caloric value of 3900 kcal/kg (Kampe, 1994; Jargalsaikan, 1998). It is located about 110 km east of the capital Ulaanbaatar (Fig. 1).

In the southeastern Gobi Desert, vast badlands exist near the Chinese border. The terrain is made up of several red hills that rise to a height of about 30 m above the desert plain and cover several square kilometers (Fig. 13). The Ulaan buur and Ulaan uul study areas are located in the southeastern Gobi, at N 44°23'33", E 111°06'48" and N 44°28'36", E 111°07'17", respectively (Figs. 1 and 14). The area has been mapped at a small scale by the Mongolian Geological Survey, but has not been investigated for argillaceous rocks yet. A railway station is located in the sum (county administrative) center of Erdene (Fig. 14).

Interseam sediments at Baganuur lignite mine

Geological setting. The Baganuur Basin is among the rift or pull-apart-basins that subsided at the Jurassic–Early Cretaceous time boundary (Berriasian) in East Asia. Three coal seams, the major seam as much as 38 m thick, are intercalated between clastic rocks of Early Cretaceous age. The host syncline extends about 8 km across in NNE-SSW direction. The environment of deposition and the paleoecology of this intermontane basin was only recently studied by a German-Mongolian study group (Dill et al., 2004) (Figs. 15 and 16). Based on the distribution of fining- and coarsening-upward sequences and the organic matter, the basin fill has been subdivided into seven depositional units: A = fluvial-swamp; B = fluvial-lacustrine; C = deltaic-fluvial; D = fluvial; E = fluvial-deltaic-lacustrine/ floodplain (?), F = lacustrine-deltaic-swamp; G = swamp-fluvial (Fig. 16).

Lithology and clay mineralogy. The lithology and mineralogy of the coal-bearing strata were investigated along an E-W transect extending about 120 m

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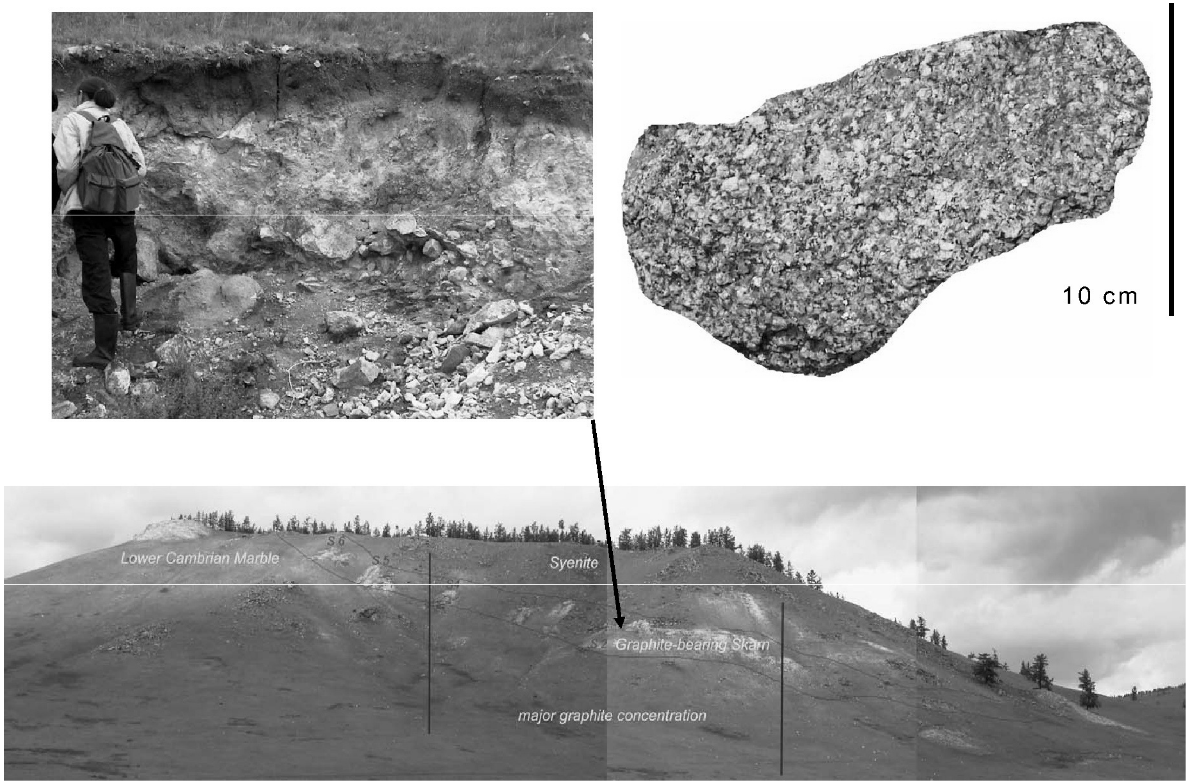

Fig. 12. Panoramic view of the contact between the Devonian syenite and the Lower Cambrian marble on the left bank of the Khargana gol. The labels S1 through S6 mark the trenches in the graphite-bearing skarn. The zone where the graphite concentration attains its highest level is bounded by two vertical bars. In the close-up view of trench S1 a lens of graphite (dark) is seen in contact with the pyroxene skarn (white). A specimen of the syenite is shown at the upper right.

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TABLE 3. Chemical Composition and Classification of Host Rocks in the Khargana gol Area, wt%

No.	Lithology	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
1	Syenite	57.26	0.80	18.58	0.56	4.09	0.15	1.60	5.28	4.60	5.58	0.31	0.76
2	syenite	56.82	0.86	17.73	2.75	2.77	0.09	1.40	3.89	5.20	6.18	–	1.37

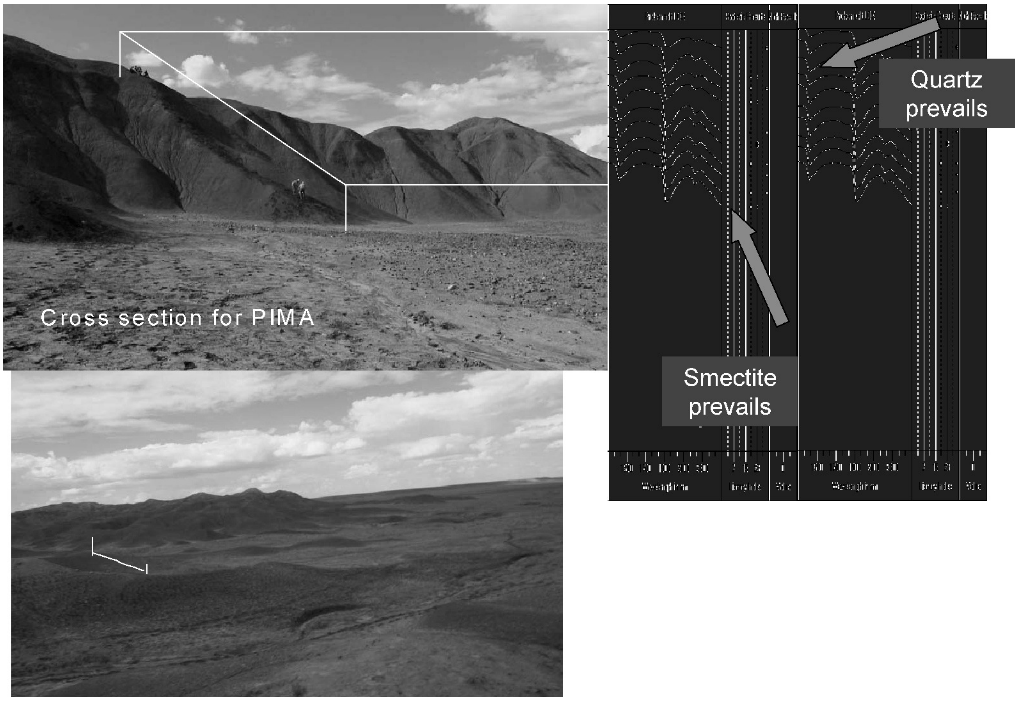

FIG. 13. The Ulaan uul smectite-bearing clay deposit represents a new discovery during the 2001 field campaign using a PIMA for mineralogical cross-sectioning. The white transect in the overview down left gives the position of the PIMA profile.

across the open pit from the footwall seam through the Quaternary fluvial overburden (Fig. 16). In addition to the routine field work involving mapping and sampling, a cross section was also subject to a continuous geophysical survey using a kappameter and a gammaspectrometer (Fig. 6A) and a mineralogical survey using a PIMA (Fig. 6B).

The magnetic susceptibilities of sedimentary rocks are a direct response to the amount of magnetite present in the rock. Magnetite is abundant in coarse-grained fluvial sediments of lithofacies associations C, D and E. Fe oxide, which is very stable and not highly susceptible to weathering and attrition throughout transport, was used as a measure of the amount of basic detrital material deposited into the basin, and can also be taken as a means to locate placer-type accumulations of heavy minerals (Fig. 6A).

The scintillometer enables geologists to identify host rocks abundant in K-bearing silicates (mica, alkaline feldspar) and/or Th- and U-bearing heavy minerals. The contents of Th- and U-bearing heavy minerals are low in the interseam sediments at Baganuur. Therefore the gamma readout is a direct measure of K-bearing silicates present in the sediments. Potassium-bearing minerals are very homogeneously distributed throughout the entire cross section (Fig. 6A). Unlike the gamma log, the

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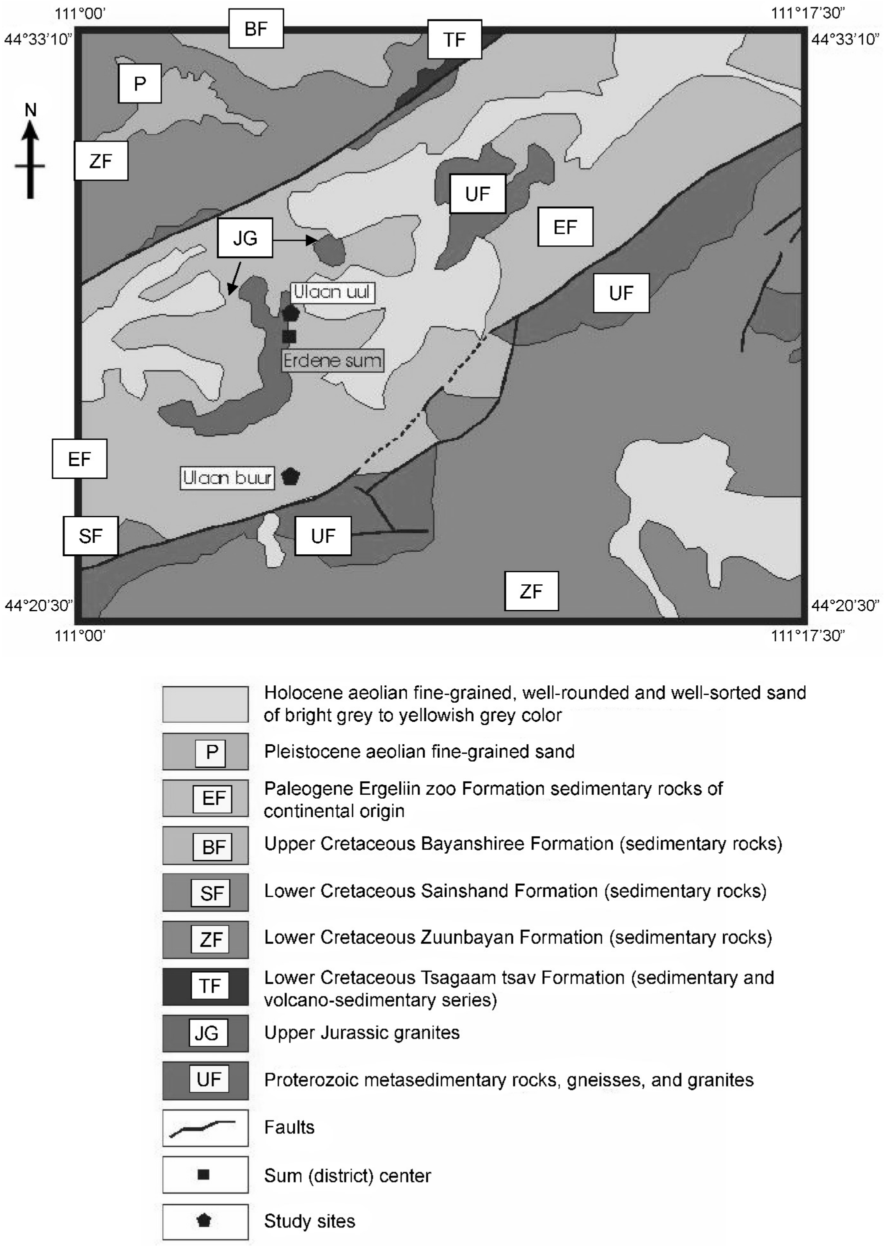

FIG. 14. Geological setting in the environs around the district center of Erdene and the locations of Ulaan uul and Ulaan buur.

susceptibility log reflects a decreasing-upward trend with R^2 = 0.4829. Based upon that reading, one may assume that magnetite decreases in the younger sediments.

The PIMA readout is very complex, and reflects the great variety of sedimentary rocks encountered in this section. Quartz and feldspar (albite-oligoclase, microcline) are the major minerals in the

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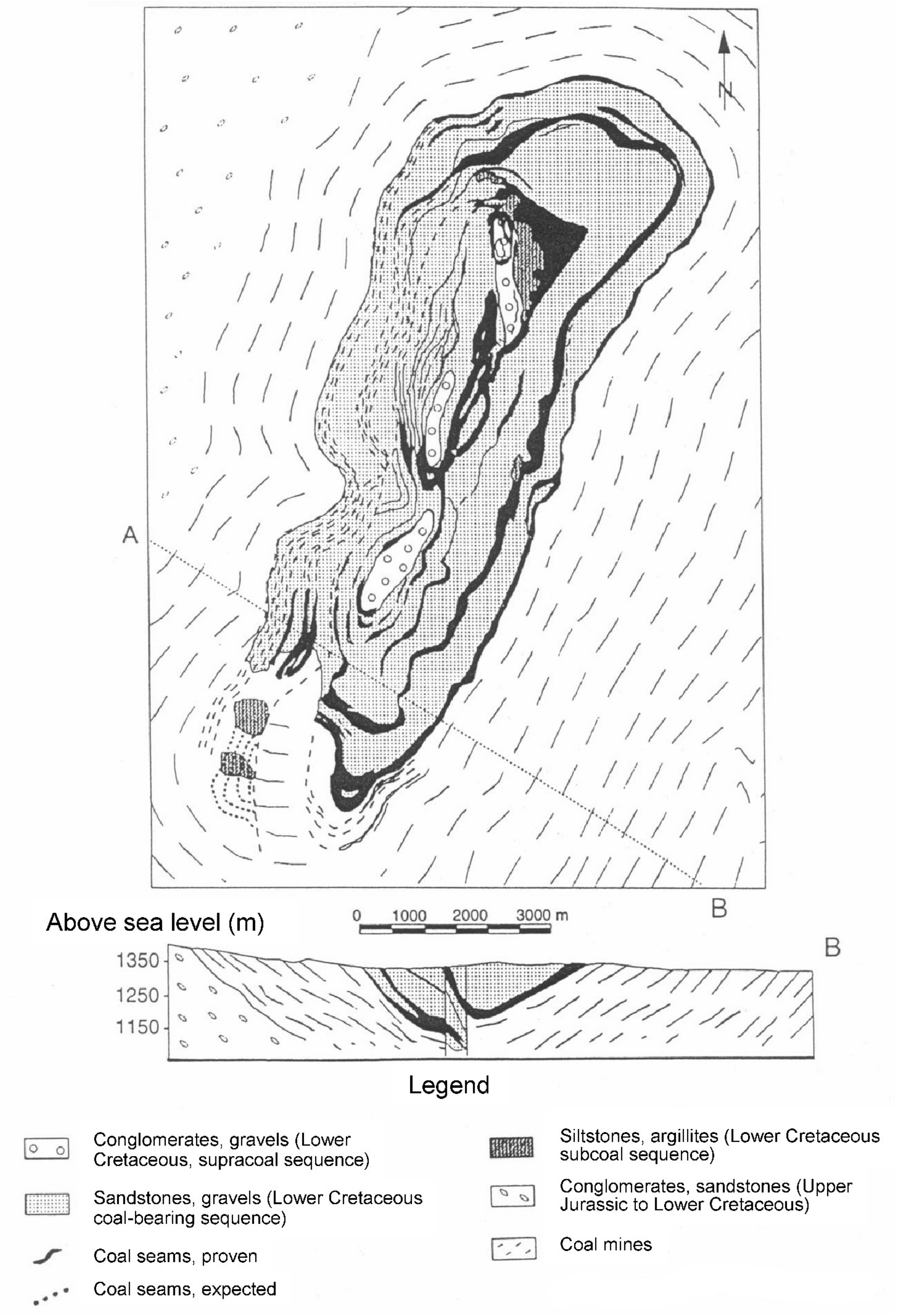

FIG. 15. Map showing the Baganuur lignite deposit and associated rocks and a cross section in the southern part of the basin (after Jargalsaikhan, 1998).

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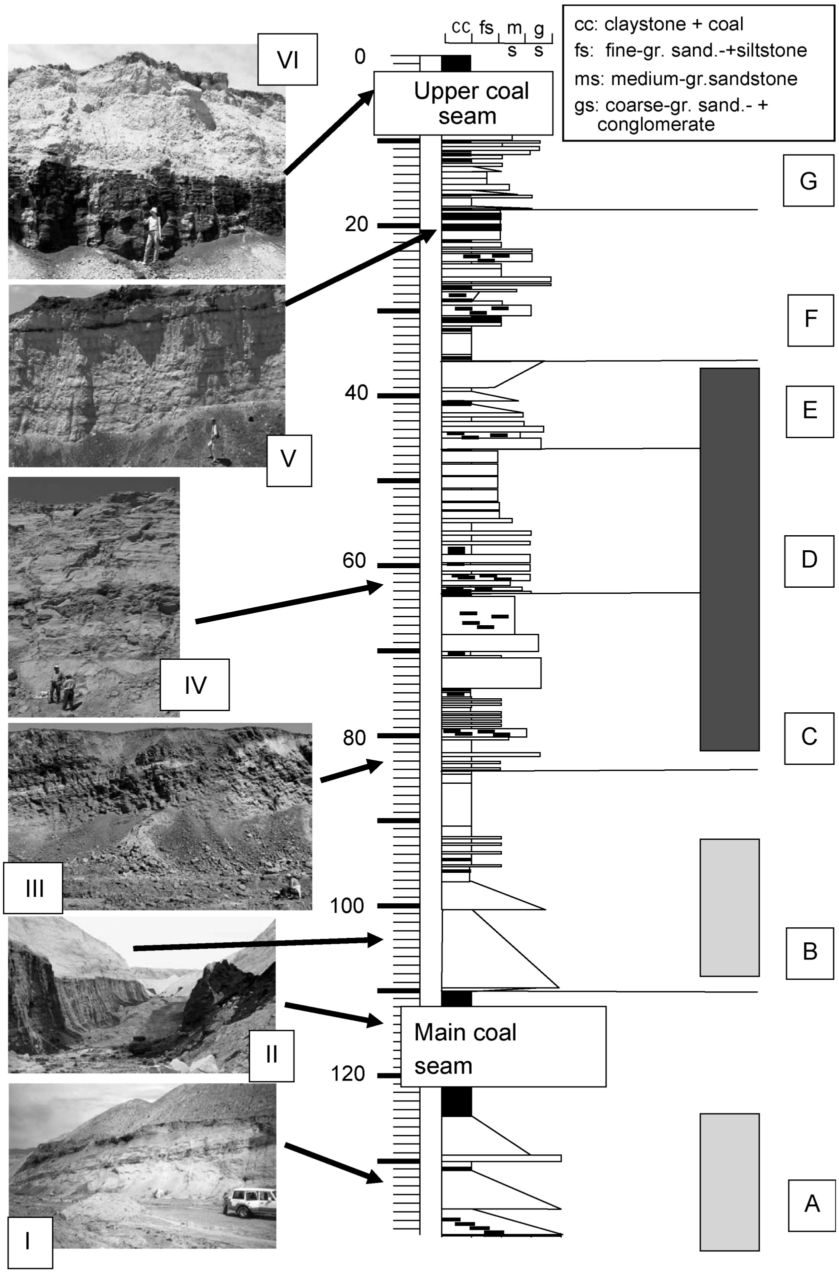

FIG. 16. Caption on facing page.

sandstones. Thus the majority of clastic rocks may be designated as arkosic arenites using the sandstone classification scheme of Pettijohn et al. (1973). Terrigenous clastic rocks with elevated contents of lithoclasts (granitic igneous rocks, glass shards) are called lithic arkose or lithoclast-bearing feldspar arkose. In the siltstones and mudstones, kaolinite-group phyllosilicates predominate. Second in abundance among sheet silicates are smectite-group phyllosilicates (nontronite). Mica-group phyllosilicates (illite, muscovite, and chloritized biotite) are ubiquitous, and occur in the arenaceous

FIG. 16. (*facing page*) Reference cross section through the Lower Cretaceous coal-bearing series at Baganuur, Mongolia. The capital letters A–G on the right-hand side of the diagram denote the stratigraphic units referred to in the text. The close-up views coded with Roman numerals on the left provide an overview of the lithology of the various units. Legend: I. FU sequences composed of coarse-grained to conglomeratic arkosic arenites at the base gradually convert into fine sand towards the top. The siliciclastics are overlain by lignite seams, each with a gradual transition into the underlying sand and a sharp erosional contacts towards the overlying basal conglomerates. Environment: Meandering fluvial drainage system with point bar and swamp deposits. II. Lignite seam. The bench is bounded toward the right (west) by the face of the main coal seam, which is overlain by clastic material of roof- and interseam sediments. Environment: Poorly drained (back)swamps evolved from a meandering fluvial drainage system. III. Dark siltstones abundant in plant debris and alternating with fine-grained strata. Parallel bedding and parallel lamination are common in these heterolithic sediments. Environment: Deposits of a fluvial-dominated delta. The delta sediments prograde over fluvial to lacustrine sediments. IV. Coarse- to medium-grained arkosic arenites on dark grey silty claystones, siltstones, and silty sandstones. Environment: Transition from a deltaic to a fluvial regime. V. Coarse- to fine-grained arkosic arenites. In the uppermost part a small coal seam is intercalated between the siliciclastics. Environment: Lacustrine-deltaic regime is characterized by distal splays, poorly drained swamps and bayfill deposits. VI. The upper coal seam unconformable overlain by sand and gravel of Quaternary age. Environment: Braided river drainage system over periglacial deposits (see coarse-grained aggregates). Sediments of Formation G developed in fluvial swamps. The red vertical bar denotes the stratigraphic units suitable for coarse ceramic material, the bright blue bar the stratigraphic units containing feldspar sands.

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as well as argillaceous sediments in Baganuur (Fig. 6B). Siderite is the only non-silicate mineral among the rock-forming minerals. Pyrite and chalcopyrite are sparse. Heavy minerals include apatite, garnet, anatase, zircon, brookite, epidote, sphene, and tourmaline. In Figure 17, the chemical compositions of units A through G of the Baganuur sediments are shown as mean values and listed together with mean values for Ulaan uul and Ulaan buur, of the southeastern Gobi (see the following section).

Argillaceous rocks at Ulaan uul and Ulaan buur

Geological setting. The oldest rocks in the region are metasedimentary rocks, gneisses, and granites of Proterozoic age. They are overlain by Lower Cretaceous sedimentary rocks that provide the upper boundary on a NE-SW–striking graben filled with continental sediments of the Ergeliin zoo Formation, and Late Jurassic granites; Holocene aeolian fine-grained sediments rest on the eroded basement rocks (Fig. 14). The sedimentary rocks near Ulaan buur closely resemble stratigraphically equivalent units at Ulaan uul. At both locations, pronounced rusty red rock colors and a coarsening-upward grain size variation are evident.

The rocks of at Ulaan uul are fine-grained and very monotonous in their outward appearance (Fig. 13). A close-up view of the rocks at Ulaan buur delivers a picture very much different from what has been described from Ulaan uul. The rock series consists of coarse-grained to conglomeratic lithic arenites.

Lithology and clay mineralogy. The major difference between the redbed sequences at Ulaan uul and Ulaan buur is grain size. Lithologically and mineralogically, both occurrences are very much alike. A PIMA survey was carried out along a traverse in the field from the footslope to the top of one of the “red hills” (Fig. 13). Not surprisingly, the stack of spectra obtained during this measurement is very monotonous, reflecting the outward appearance of the red hills. Only the uppermost spectrum in the stack of IR graphs suggests a change in the mineralogical and chemical compositions of the red argillites. A quick-look interpretation in the field led to the identification of quartz, smectite, carbonate minerals, and feldspar. Follow-up refinement of these data in the lab with XRD yielded mica, dolomite, and chlorite in addition to the minerals already identified in the field.

Primary and Secondary Gemstone Deposits

Location and case history

About 20 sites have to date been explored in Mongolia for gemstones. The Mongolian gemstone occurrences were subdivided into three categories according to their end use and application: (1) faceted cut stones; (2) cabochon cut stones; and (3) ornamental and craft stones (United Nations, 1999). In 1975 and 1976, exploration was carried out in the Tariat district for gemstones to produce faceted cut stones. During this campaign, the Shavryn Tsaram gemstone deposit was discovered in the Khangai

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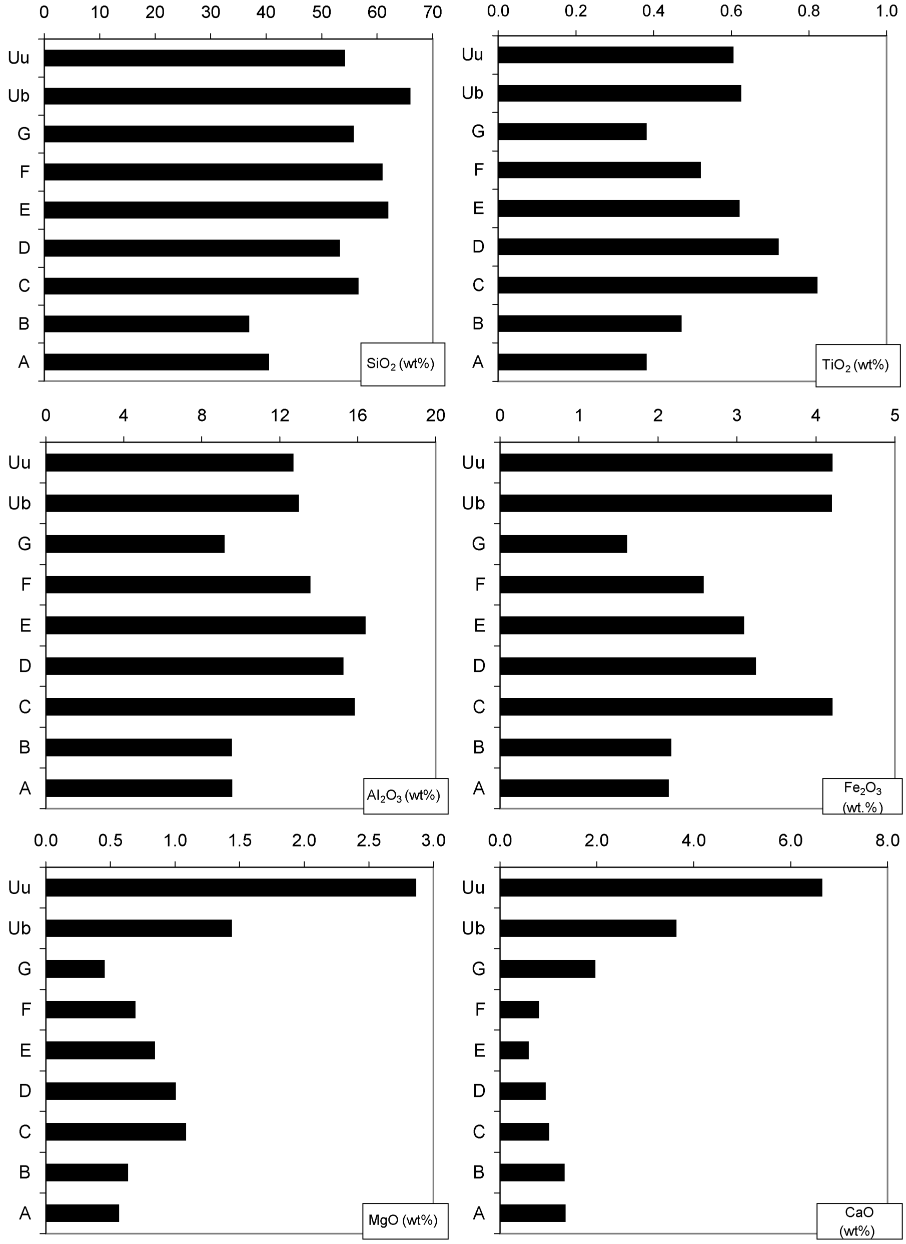

FIG. 17. Caption on facing page.

Mountain belt at N 48°2'19", E 99°53'11" (Figs. 1, 18A–18B). The exploration campaign, which began in the mid-1970s turned into an exploitation phase for garnet in 1981. Opencast mining was mainly focused on the poorly consolidated sedimentary rocks that spread across a high-altitude plateau. During the most recent campaign, the basic volcanic rocks hosting gemstones as well as the apron of gravel- to silt-sized material around them were investigated. Field work was not restricted to the

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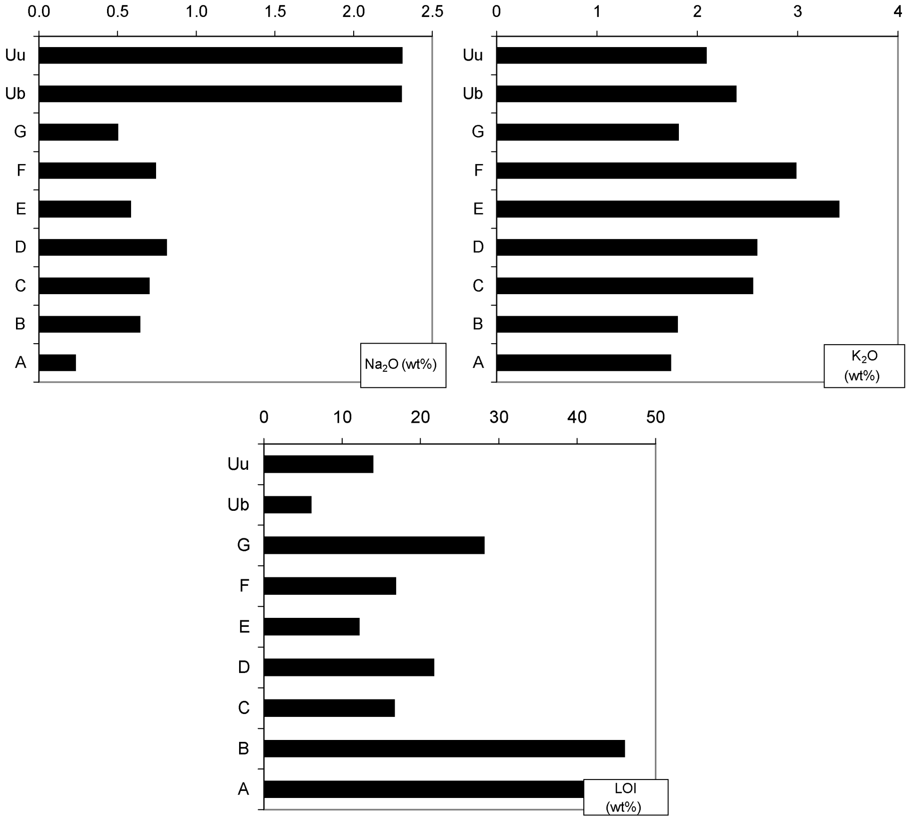

FIG. 17. Chemical composition of argillaceous deposits. Abbreviations: Uu =Ulaan uul; Ub = Ulaan buur; A through G = formations in Baganuur (see Fig. 16)

clastic dispersion aureole in the immediate surroundings of the basic volcanics, but also involved stream sediment sampling of creeks from their reaches incised into the clastic dispersion aureole around the volcanics downstream to their confluence with the trunk river of the Chuluut gol drainage system (Fig. 19).

Geographic and geological setting

The study area lies at an altitude of between 1800 and 2800 m. Gemstone mineralizations were located on a low-relief, high-altitude plateau 2350 m elevation, with a large outcrop on a slope gently dipping toward the south. From the west, creeks of the Chuluut gol drainage system are incised into the high-altitude mountain plateau and drain the mountainous area (Fig. 20). The creeks flood only periodically and join the Gichgeniin gol, a tributary of the Chuluut gol, at about 2000 m elevation. The primary host rock is exposed over an area measuring 600 m × 350 m. Coarse-grained epiclastic/pyroclastic material debouches at the footslope of a hillock, constituting a fan-shaped accumulation, which widens toward the southwest, and stretches over 3500 m with a maximum width of 400 m (Fig. 20).

The Khangai Mountains are the most prominent feature in the study area. The ridge was uplifted and superimposed on the Mongolian Plateau, a plateau characterized by a remarkable basin and range topography (Ufimetsev, 1990). The oldest strata in the study area were dated as Upper Proterozoic. They constitute a series of black and grey metamorphosed shales, sandstones, marble, and quartzite. The major part of the study area is made up of basement rocks belonging to the Lower Paleozoic Zag Series. It consists of shales and clastic sediments running the gamut from siltstone to conglomerate (Figs. 18A and 18B). The Tariat Formation, which is

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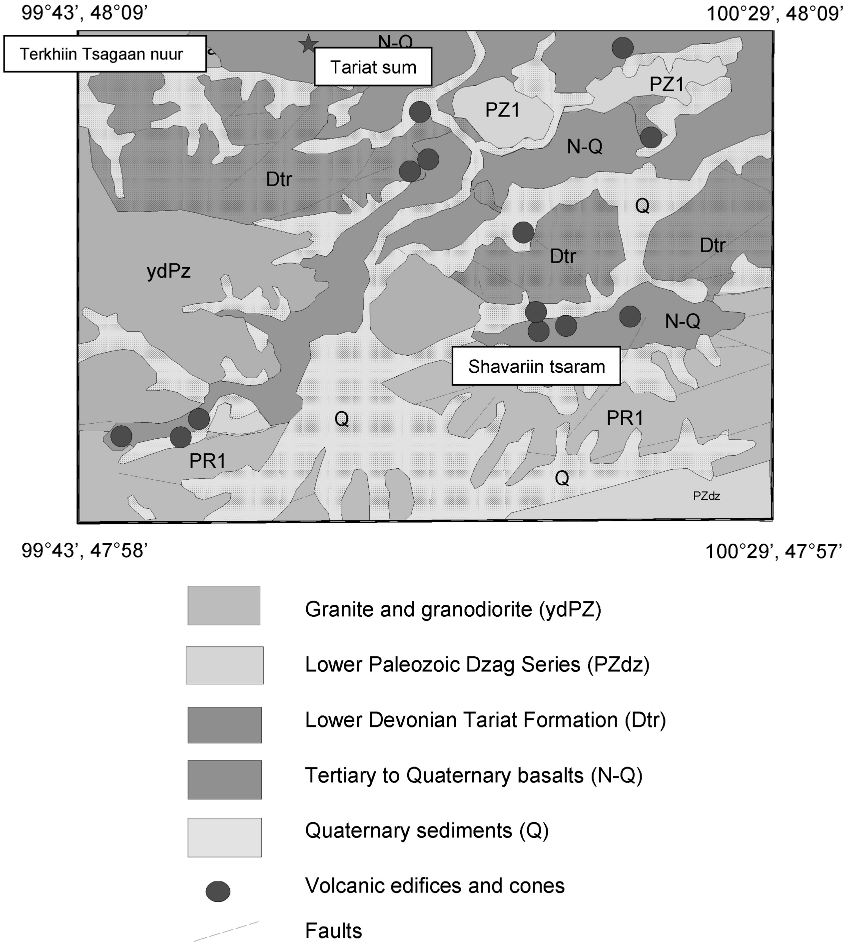

FIG. 18. The Shavryn Tsaram gemstone deposit. Sketch map showing the geological setting of the Tariat region and position of the Shavryn Tsaram gemstone deposit.

assigned a lower Devonian age, overlies the Zag Series. In some places in the study area granites, plagiogranites, and diorites were intruded into Upper Proterozoic rocks. The Cenozoic featured extensive volcanism in the area under consideration, and a great variety of sedimentary rocks were deposited in lakes, river channels, alluvial fans, and aeolian deposits (Fig. 21). The continental sediments all formed during the Quaternary. Alkali basaltic volcanism in the Hangai dome lasted from the Late Tertiary to the Holocene (Fig. 21).

Petrography of the primary host rocks

The volcanic-hosted gemstone deposit occurs in a mushroom-shaped body of alkaline basanites and olivine basalts (Fig. 22). The gemstones are accommodated by a dark tuffaceous breccia representative of a diatreme pipe facies. The matrix of the basanite consists of dark volcanic glass (70 to 75%). Some rocks at Shavryn Tsaram are remarkable for their trachytic fluidal texture. Olivine phenocrysts are key to the categorization of the volcanic rock. In contrast to olivine, plagioclase, clinopyroxene, and magnetite are rather fine-grained and, thus, difficult to identify in the dark vitreous matrix. Accessory minerals include ilmenite, apatite, zircon, chromium spinel, and graphite. Igneous inclusions reach a size of as much as 3 cm and contain garnet, pyroxene, olivine, biotite, and sanidine.

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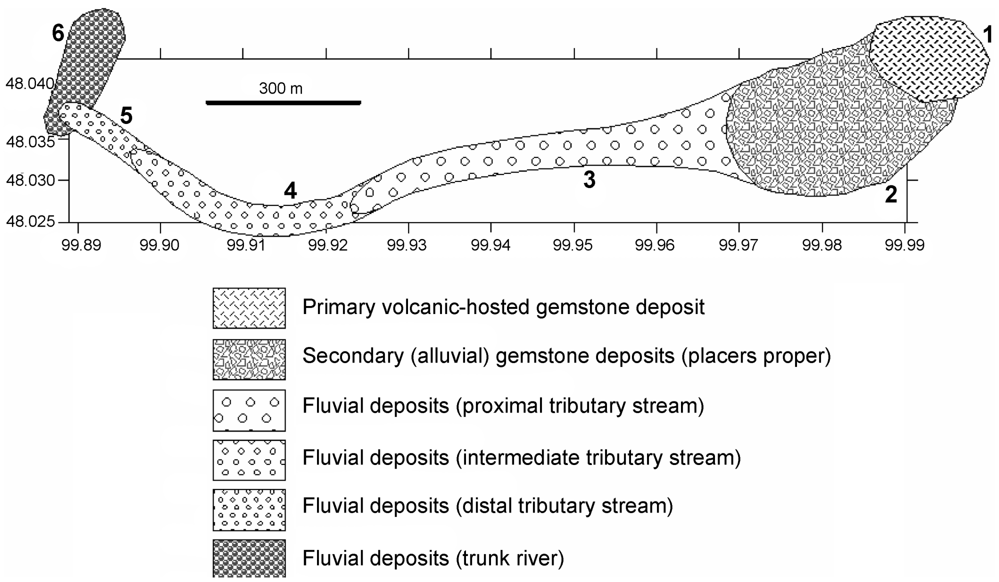

FIG. 19. Longitudinal section from the primary gemstone deposit (1) to the main river channel (Chuluut drainage system) in the Shavryn Tsaram area.

Pyrope-enriched garnet is a solid solution of pyrope 66–78%, almandine 13–21%, and grossular 11–13%. The subhedral olivine in the breccia falls in the range Fo 88 to Fo 92 (Kopylova et al., 1995).

Petrography of the placer deposits

About 0.5 m below ground, matrix-supported gemstone conglomerates were exposed in trenches on the plateau at 2350 m elevation. Angular clasts measuring up to 3 cm in size are disseminated in a silty matrix or were concentrated in several discrete seams as much as 15 cm thick (Fig. 23). Flat-lying bedsets of matrix-supported conglomerates extend for several hundreds of meters across the plateau (Fig. 20, areas 2 and 3). The seams are monotonous and do not show any lateral facies change in the area under consideration. The lithological contact between the seam and its roof rock is gradational; no grading was observed within the individual seams, but grain sorting is fairly good. Downstream, the alluvial placer deposits pass into fluvial deposits of the tributary stream and eventually join the trunk river deposits.

The minerals in the placer seams were identified with the unaided eye as garnet and minor olivine (Fig. 23). Unlike the conglomeratic placer deposits, the identification of discrete minerals in the sand-sized stream sediments is fraught with difficulties and was left for in-depth investigation in the laboratory. Mineralogical analyses of the assemblage in the laboratory led to the discovery of alkaline feldspar as another major component and minor constituents such as pyroxene (augite, chromium diopside, bronzite, hypersthene, enstatite), amphibole, ilmenite, phyllosilicates (biotite, chlorite), epidote, zircon, tourmaline, kyanite, apatite, monazite, sphene, rutile, spinel (black spinel, chromium spinel), and magnetite.

The sequence of lithoclast assemblages reveals a marked decrease in volcanites and pyroclasts away from the basic host rocks. A drop in volcanites accompanies a jump in clasts from the crystalline bedrock. This change in the lithoclast association also left its imprints on the heavy mineral suites. Forsterite-enriched olivine rapidly disappears downstream in the small rivulets. Grains of fayalite-enriched green olivine are present in the heavy mineral separates further downstream. Olivine grains are strongly corroded and coated in parts with limonitic crusts. Titanite is the prevailing mineral in the narrow creeks draining the plateau toward the west. The roundness of garnet megaclasts does not significantly increase during transport. Epidote (pistacite) is common in all heavy mineral separates. Other minerals such as orthite, spinel, or monazite occur only sporadically.

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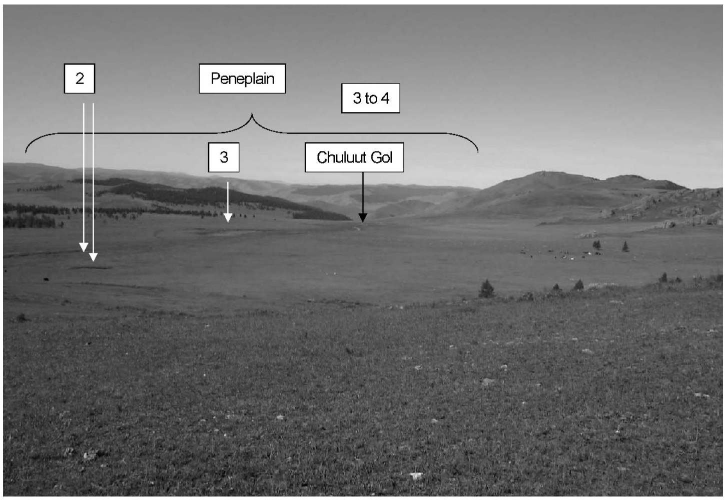

FIG. 20. View from the Shavryn Tsaram primary gemstone deposit westward across the peneplain. The placer deposit/secondary gemstone deposit are in a large mountain valley that narrows toward the west in a V-shaped valley and eventually ends up in the Chuluut gol (see black arrowhead). The white arrows denote shallow open cuts operated for gemstone placers, with the number 2 denoting the proximal placer and 3 denoting the upstream parts of the distal placer. The numbers "3 to 4" mark areas where heavy minerals underwent reworking and dispersion in the creeks. For more information on fluvial drainage systems see also Figure 4.

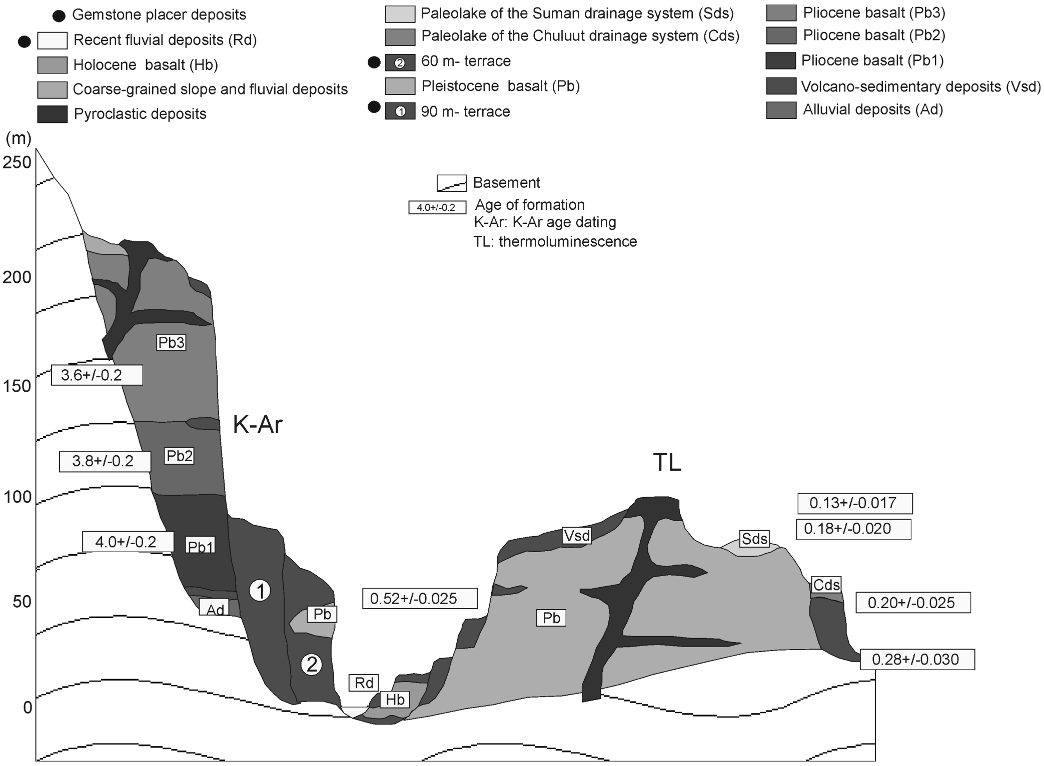

FIG. 21. Idealized cross section through the Cenozoic igneous and sedimentary rocks in the Tariat region.

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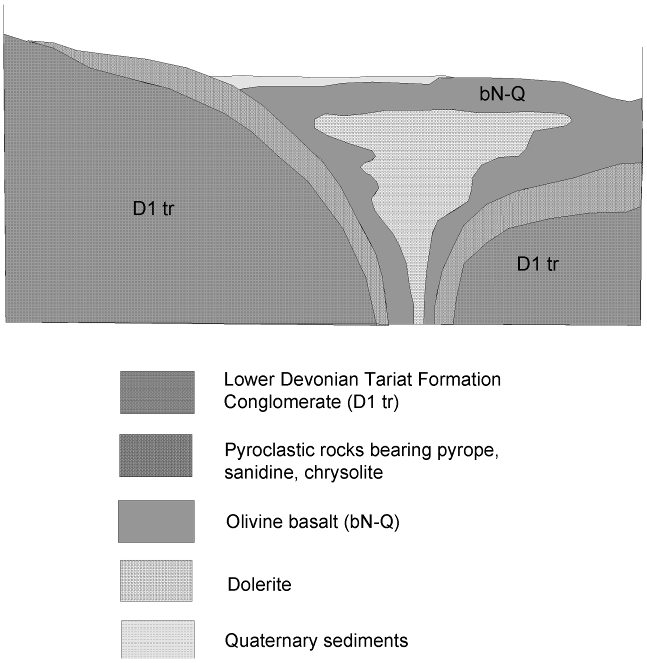

FIG. 22. Idealized cross section through the gemstone-bearing breccia pipe in the Tariat region.

Aggregate Deposits

Location and case history

Coarse-grained aggregates, which by definition comprise loose sediments and crushed rocks of particles greater than 5 mm, are fairly widespread in Mongolia. The different types of fluvial drainage systems containing coarse-grained aggregates warrant careful study because they are very much different in the various zones of vegetation across Mongolia (Figs. 4A, 4B, 5, and 24). Deposits of fine-grained aggregates, commonly called sand, are a more sensitive issue, and therefore this sort of aggregate has been under exploration and investigation in Mongolia over the past decades for different purposes, such as a construction material or glass production. In 1991/1992, a Mineral Processing Technological Center was established by United Nations Development Programme that by state order has carried out concentration tests on a laboratory scale since 1996 to improve the quality of fine-grained aggregates (Kampe, 1997). Activities like those in the Mineral Processing Technological Center demonstrate that the country, despite the ubiquitous nature of clastic rocks, is in urgent need of detailed geological and mineralogical investigation into fine-grained aggregates to guarantee good quality along with large quantities. Various drainage systems and four sites at Moltsog els, Biluut uul, Vostochnii, and Elstein gol were investigated for fine-grained aggregates (Fig. 1, Table 4).

Geomorphological and geological setting

Almost 80% of the lithofacies types observed in deposits of steppe river drainage systems are gravel-dominated, and considered as potential sites to exploit coarse-grained aggregates. Coarse-grained clastic rocks occur in all study areas from the northern mountain taiga to the desert steppe. All fluvial deposits are conspicuously undernourished with respect to sand-sized particles. In most places gravelly sediments alternate with silty sediments (Fig. 25). The main flow in the drainage systems of the mountain taiga and steppe is confined to a few active highly-sinuous channels (Fig. 24/I, zone A) which are closely associated with numerous abandoned channels in a fluvial floodplain (Fig. 24/I, zone A). Some are interconnected-braided, but others are preserved only as isolated oxbows. They are the sites of coarse aggregate deposits. The entire fluvial system is typically very unstable. Tributaries are scarce and only periodically active in zone B

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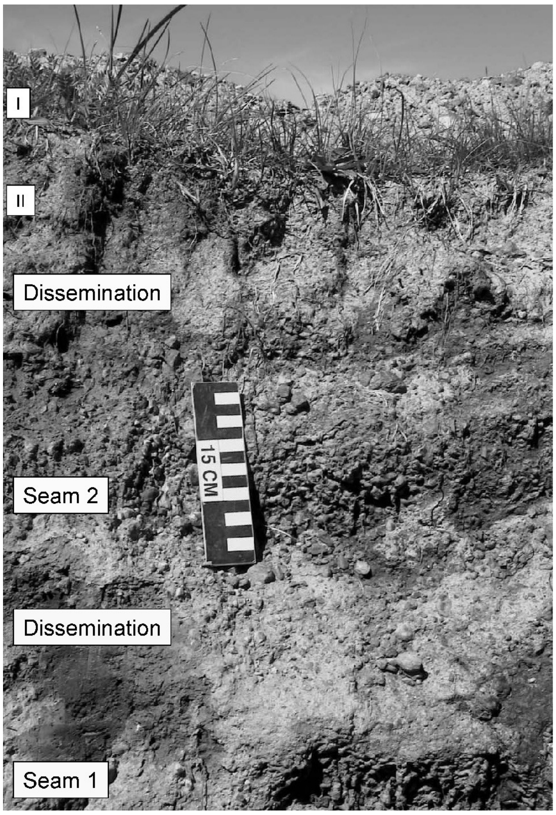

FIG. 23. Cross section through the secondary gemstone deposit at Shavryn Tsaram (Fig. 19, area 2). Different stages of sheet flooding with heavy minerals disseminated in a muddy matrix (Dissemination). Flow strength attains its peak in sediment bulking during which discrete pyrope seams (Seam) were emplaced. The top stratum consists of thin steppe pioneer soil (I).

(Fig. 24/I). Branched channels run almost perpendicular to the trunk river and contribute much to the load of the perennial streams during intensive rainfall snowmelt. An overall picture of the fluvial drainage systems can only be drawn based on aerial images covering in this case study the upper reaches of the Kerulen River (Figs. 1, 24/I). Detailed interpretation of stereopairs of aerial photographs has proven to be a useful tool in the reconnaissance for industrial minerals in different types of drainage systems (Green et al., 1994). The method was also applied to give a 2-D view of the drainage systems under consideration.

In the desert steppe, ephemeral streams are only able to transport and deposit bedload (Fig. 24/II). These intermittent streams discharge into flats extending along the ridges or into circular bowl-shaped depressions called pans. The terminology of these geomorphic features mostly depends on the language used (Rosen, 1994). An active river system as it was recorded from Zone A in the northern parts of the country does not exist in the desert steppe (Fig. 24/II).

Deposits of fine-grained aggregates have to be searched for outside these drainage river systems. Different lithofacies types may be recorded for fine-grained aggregates. The sands are diverse in structure, geometry/geomorphology, and the type of rocks with which they are associated.

In the mountain forest steppe between Bulgan and Moron, sand sheets, attaining a few decimeters to one meter in thickness, are patchily distributed on river terraces. The sand sheets sit about 6 to 10 m above the floodplain of the recent fluvial drainage system. Isolated, rippled sand sheets, which measure about 1 km^2 each, are sparsely vegetated.

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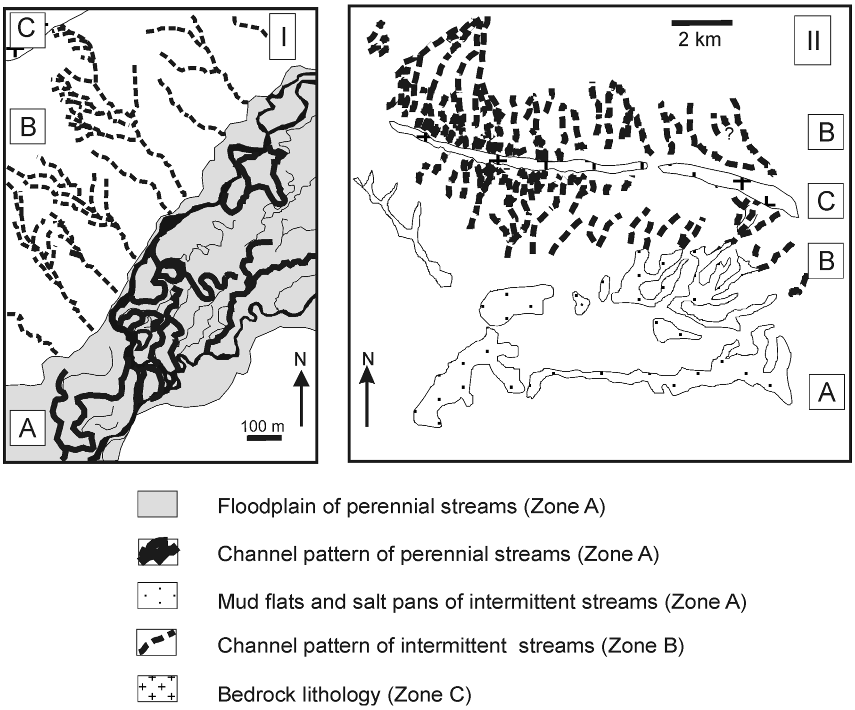

FIG. 24. Coarse-grained aggregate deposits of Quaternary age in steppe drainage systems redrawn from aerial images. For location of maps (I) and (II) see Figure 1. Zones A to C describe the various parts of the stream systems, referred to in the text. I. The drainage system is typical of the vegetated areas of the steppe (mountain forest steppe to steppe proper). II. The drainage system is typical of the non- or poorly vegetated parts used to be encountered in the desert steppe.

Ripples form a sequence from straight-crested to catenary.

In the steppe west of Ulaanbaatar, large dune fields occur. East of the capital, in the same vegetative zone, the relief of the sand accumulations is much lower than in the west. In the eastern plain, sands more than 2 m thick are covered with grass (Fig. 26A). The largest dune fields along the NNW–SSE transect through the various vegetation zones were found in the desert steppe south of Erdene, where dunes stand out from the flat-lying interdune sediments by several tens of meters (Fig. 26B). The interdune sediments are sparsely vegetated with shrubs, while the dunes are barren.

Sedimentary petrography of aggregate deposits

The cumulative frequency curves of grain size distribution classify these arenaceous sediments as medium-grained, moderately well to well-sorted sands. The various deposits studied for fine-grained aggregates are quite similar (Fig. 27). Grain sorting is better in sand deposits from the desert steppe than in deposits in the steppe proper. 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 that was elaborated by Pettijohn et al. (1973), the sands plot in the field "lithic arenite" (Table 4).

Mineral associations identified under the petrographic microscope corroborate the chemically based classification. Quartz prevails, and alumosilicates (e.g., microcline, orthoclase, albite-oligoclase and chessboard albite) are second in abundance. The feldspar contents may increase in some sands so that they have to be termed feldspar arenites rather than lithic arenites. Among the heavy minerals, green tourmaline, green amphibole, brown biotite, titanite, and zircon predominate. Lithoclasts that have been derived from gneissic, granitic, and basaltic source rocks contribute to the lithology of these sands.

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TABLE 4. Chemical Composition of Sand Deposits in Central Mongolia, wt%

Location	Coordinates	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Moltsog els	N 47°50'25", E 105°53'53"	82.86	0.192	8.57	0.97	0.02	0.28	0.943	2.64	2.087	0.021
Biluut tolgoi	N 44°17', E 111°11'	84.09	0.153	8.06	0.76	0.04	0.16	0.349	1.71	3.446	0.031
Vostochnii	N 47°45'30", E 107°32'19"	77.68	0.145	12.2	0.72	0.018	0.16	0.947	3.43	3.527	0.029
Elstein gol	N 47°47'36", E 107°29'59"	77.7	0.081	12.42	0.57	0.014	0.12	0.953	3.6	3.514	0.023

FIG. 25. Beds of fine-grained siliciclastics (II) are intercalated among gravel beds (I). Suspended load is filling the abandoned channels and infiltrating the gravel of the longitudinal bars. The cross section cuts through the sediments of an intermittent stream. The thin steppe soil is coded III.

Geological and Geographic Impacts on the Formation of Industrial Minerals

Origin of pegmatite deposits in western Mongolia

At the end of differentiation of a granitic magma, the build-up of water in the residual magma and emanation differentiation may gave rise to rare metal granites and pegmatites. Numerous examples are known, for example, from the Variscan orogen (Mücke et al., 1990; Scaillet et al., 1996; Webster et al., 1997). Late-stage differentiation processes have not played a significant role during the formation of the pegmatites in the Bayan nuur-Lin sun field, where beryl is sporadic and is the only mineral that results from concentration of rare elements. Based upon their segregation in different zones (Table 1), the pegmatites are called zoned pegmatites, *sensu* Bilal et al. (2000). Based on their intercalation with metamorphic rocks, these pegmatites have much in common with metapegmatites, sensu Glodny et al. (1998), which were emplaced along with regional metamorphism of Precambrian rocks. The segregation in the Mongolian pegmatites did, however, not reach the level typically observed in granite pegmatites, where large feldspar crystals as much as one

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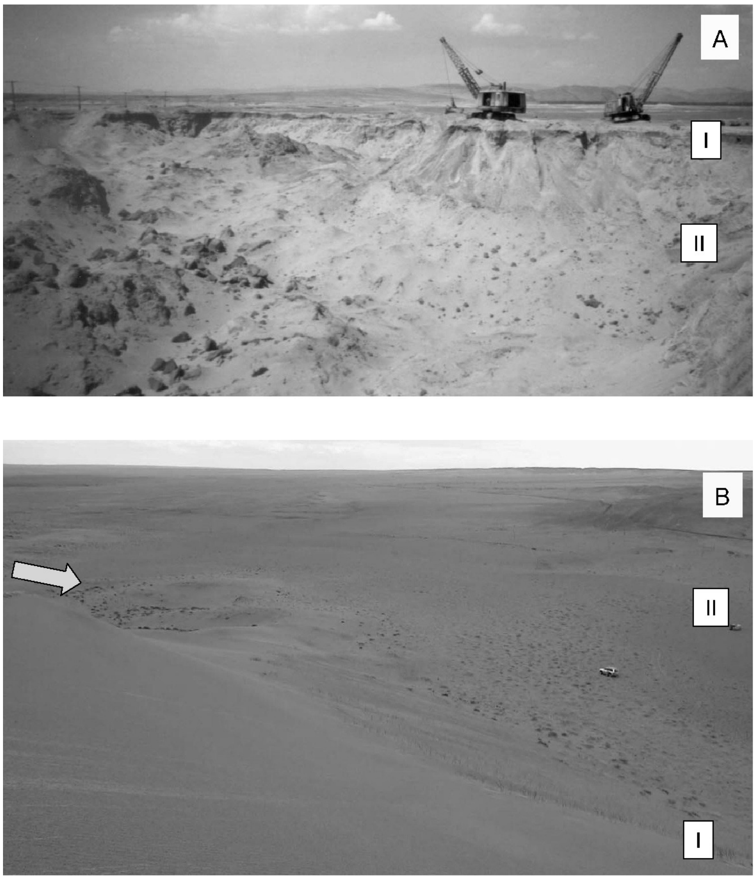

FIG. 26. A. Large open pit operation in the dune fields and sand sheets near Vostochnii operated for fine-grained aggregates. The sand flats (II) are blanketed by steppe soil and grassland (I). B. Parabolic dunes and transverse dunes in the desert steppe near the railway line from Ulaanbaatar to China. See Landrover for scale (II) and the railway track snaking uphill in the background.

meter may be extracted by simplified mining or hand sorting. Beryl is very scarce in the pegmatites under study and locally may be identified also in pegmatitic mobilizates unrelated to a granitic parent magma. The same holds true for the graphic intergrowth of feldspar and quartz which is not exclusive to granite-related deposits (Uebel, 1983). The studied pegmatites are transitional between granitic metapegmatites and pegmatitic mobilizates that come into being during retrograde metamorphism, leading to unzoned pegmatitic schlieren with albite in excess of orthoclase but without any rare-element minerals (Dill 1979).

Schmidt and Dandar (1995) studied fluid inclusions in feldspar formed during the early stages of Mongolian pegmatite emplacement. They found an average temperature of homogenization of as much as 675°C, and determined the pressure of pegmatite formation to be 350 Mpa. The average NaCl content in the solution is less than 10%. These data agree well with data reported elsewhere. Physico-chemical investigations centered around these pegmatitic mobilizates and their metabasic country rocks (banded amphibole gneisses) were also carried out by Okrusch et al. (1990, 1991) in the northeast Bavarian Basement, Germany. The country rocks studied in Germany are lithologically equivalent to the metabasic rocks shown in Figure 8B and the maximum temperature of formation was determined to be 620 ± 30°C. Based upon white mica that crystallized interstitially to the framework silicates of the pegmatites, a temperature of formation higher

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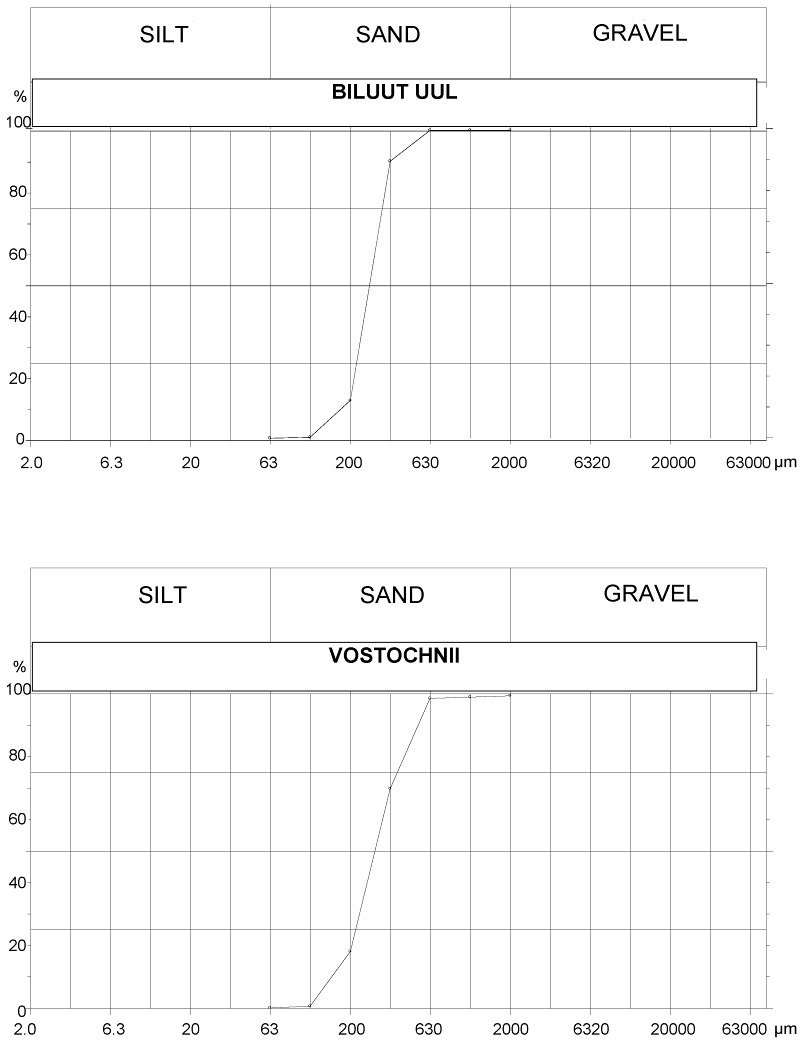

FIG. 27. Cumulative frequency curves of impeded (vegetated) aeolian sands (Vostochnii) from the steppe proper and unvegetated aeolian sands from the desert steppe (Biluut uul).

than 400°C may be inferred for the quartz-feldspar association. The structural conformity between these pegmatitic mobilizates and the enclosing country rocks suggest that pegmatitization accompanied deformation of the country rocks.

The pegmatites are exposed in the steppe. Locally, they are covered only with a thin veneer of pegmatitic boulders but without regolith indicative of supergene alteration of their primary mineral assemblage. The coarse-grained nature of the pegmatitic rocks rendered difficult any attack through meteoric fluids on the feldspar. Even semi-humid climatic conditions, under which peneplains in present-day central Africa used to form, and palaeoclimates of similar type during the Cenozoic in Mongolia, monomineralic coarse-grained feldspar rocks show a rather good preservation potential and stand out as "blockmeers," tors, or form riffles and humps in the regolith (Fig. 28). In rocks containing finer-grained alumosilicates or granitic schlieren, the situation is different and small-scale regolithization may be observed. The geographic/climatic

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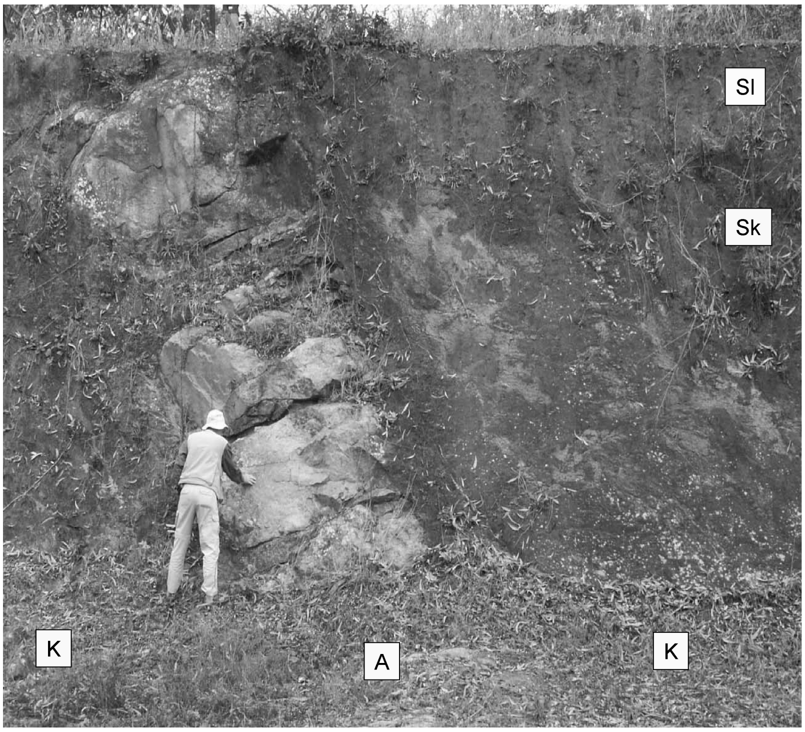

FIG. 28. Resistance of pegmatitic dikes to weathering under semi-humid conditions in present-day central Africa (Malawi). These weathering conditions are supposed to have prevailed during the recent geological past in Mongolia as well. Migmatitic gneiss (K) is more susceptible to weathering than the feldspar-quartz dike (A) producing a weathering mantle of saprock (Sk) and saprolite (Sl) (lithofacies Vb) several meters thick. The steeply dipping dike is preserved almost intact and stands out as a ridge in the regolith. The meteoric fluids easily penetrated the metamorphic rocks along the planes of foliation, which are very narrowly spaced and almost vertical.

impact on the formation of the (meta)pegmatitic mobilizates in the Asian continental interior is almost nil (Table 5).

Origin of marble and graphite deposits in northern and Central Mongolia

From the Vendian through the Early Cambrian, calcareous rocks developed on a large shelf in the Choevsgoel region/basin (Badarch et al., 2002; Badarch, 2003). The environment was not an overall inhospitable habitat, otherwise trilobites and gastropods would not have been able to survive at the bottom of the Early Cambrian sea. Skeletal remains of these arthropods and mollusks are present in several beds of these calcareous series. Interbeds strongly enriched in dolomite were obviously deposited in a more landward position, where evaporation was high. Much has been written on evaporite-bearing sediments in coastal sabkhas by Shearman (1966), Kinsman (1969), Kendall (1979), Sheppard et al. (1992), Alsharhan and Kendall (2002), and literature cited therein. These studies were focused on the well known southern coast of the Arabian Gulf. This part of the Vendian through Lower Cambrian shelf with stratabound dolomite may be interpreted as some sort of a paleosabkha. The climate during that time was arid to semiarid in the area under study. Fine-grained clastic rocks are intercalated among the carbonate rocks. They formed in an environment quite different from that of the calcareous rocks, in lagoons or in a shallow intrashelf basin below wave base in a more distal position relative to the dolomite. In this setting, bituminous matter was formed and fine-grained material settled out of suspension to give rise to some pelagic mud- and siltstones. The physicochemical conditions that favor precipitation of bituminous matter, now present in the marble as

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TABLE 5. Synopsis: Geology, Geography, Evaluation, and End Use of Commodities

Type of deposit	Location	Igneous and metamorphic impact on origin of deposit	Paleogeographic and climatologic impact on origin of deposit	Morpho-climatic impact on alteration of deposit	Climatological impact on exploration/exploitation of deposit	Infrastructural impact on exploration/ exploitation of deposit	Geographic zone	End usage
Feldspar-quartz deposits	Bayan nuur Lun sun	(Meta)pegmatitic mobilizates	No impact	No impact	Moderate to strong	Moderate	Mountain forest steppe to steppe proper	Ceramic raw material
Graphite deposits	Khargana gol, Itge Naidvar	Contact metasomatic	Shelf-(paleo)sabkha	Little impact (bleaching of fine-grained graphite)	Very strong	Strong	Taiga	Graphite of medium to high quality
Calcareous (marble) deposits	Tsagaan chuluut	Contact metamorphic (regional metamorphic)	Shelf-(paleo)sabkha	Karstification related to peneplanation	Very strong	Very strong	Taiga	Dimension-building stones
Arenaceous-argillaceous deposits	Baganuur	No impact	Alluvial-fluvial-poorly-drained swamp	Glacio-fluvial	No impact (as byproduct of open-cast coal mining)	Little to no impact	Steppe proper	Ceramic raw material (low quality)
Argillaceous deposits	Ulaan uul, Ulaan buur	No impact	Alluvial-fluvio/ deltaic-ephemeral lacustrine	Calcretization	No impact	Little to no impact	Desert steppe	Ceramic raw material and adsorbents
Coarse-grained aggregates	Kerulen River, unnamed drainage systems in the Gobi	No impact	Alluvial-fluvial	Glacio-alluvial-fluvial	No impact	Little to no impact	Mountain forest steppe to desert steppe	Construction raw material
Fine-grained aggregates	Moltsog els, Biluut uul, Vostochnii, Elstein gol, Buduun tolgoi	No impact	(Fluvio)-aeolian	(Fluvio)-aeolian	Moderate	Strong to moderate	Mountain forest steppe to desert steppe	Construction raw material and special sand (e.g. glass sand)
Gemstone deposits	Shavryn Tsaram	Explosive volcanism of alkaline affiliation forming pipes and diatremes	No impact	Alluvial-fluvial (elluvial) placer	No impact	No impact	Mountain forest steppe	Jewelry and abrasives

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graphite streaks, and minor pyrite may best be described as moderately reducing or dysaerobic (Fig. 11B). This paleogeographic scenario may be applied also to the Khargana gol area, where the shelf (basin) environment may, however, be called euxinic due to the accumulation of organic matter now present as graphite.

Regional metamorphism transformed these limestones into flasered sparry limestones and marbles. Some sort of "protore" formation took place during this stage of lithogenesis. Devonian igneous activity was, however, the most relevant process for the marble and the graphite deposits to develop in the Tsagaan chuluut and the Khargana gol area, respectively.

In Tsagaan chuluut, contact metamorphism attributed to Devonian granite intrusions gave rise to the hornblende-hornfels facies and converted limestones to marble deposits. Tremolite in some marble may have developed according to the following reaction (Skippen, 1974):

$$\text{5 dolomite} + \text{8 quartz} + H_2O = \text{tremolite} + \text{3 calcite} + 7\ CO_2\,.$$

In the Khargana gol area, the granite-related contact metamorphism was rather moderate, whereas the syenite-related contact metasomatism was of higher grade, giving rise to various skarn-type alteration zones with pyroxene being the marker mineral for the highest grade recognized in the area. It may be correlated with the pyroxene-hornfels facies and the mineralization described according to the following reaction (Rice 1977):

$$\text{tremolite} + \text{3 calcite} + \text{2 quartz} = \text{5 diopside} + 3\ CO_2 + 2\ H_2O.$$

The estimated formation temperatures for the mineral assemblages in the marble can be bracketed between 350° and 400°C for the tremolite zone. The skarns may have formed at somewhat higher temperatures. Due to the open system during the recrystallization of the calcareous rocks, the physicochemcial conditions cannot be determined in the same way as for the contact metamorphism. The crystallinity of graphite is only discernible under the microscope, and consequently the commercial term "amorphous graphite" may be used for this soft black earthy material. From the mineralogical point of view this term is a misnomer, because graphite is not amorphous but of fine crystal size. This early generation of fine-grained graphite is equivalent to the carbon in the flasered marble in the Tsagaan chuluut area, and was the result of early contact metamorphism or regional metamorphism of organic material that primarily accumulated together with the carbonate on the marine shelf during Vendian through Early Cambrian times (see paleogeography).

The second generation of graphite is a highly crystalline, flaky graphite occurring in veinlets. Because we did not analyze carbonaceous matter for its isotope composition, the precise source of the carbon in the veins cannot be determined with certainty. From its outward appearance and crystallinity, this graphite comes close to Sri Lankian graphite, even if it does not match the Sri Lankian deposits with respect to the size of the deposit (Dissanayake, 1994). Based on its structural and textural characteristics, we posit early magmatic deposition of graphite transitional to skarn-type mineralization. The various skarn minerals in different zones support the idea of intertonguing of igneous and contact metasomatic processes. The mineralization is akin to mineralizations described from the Botogol deposit in eastern Russia (Fogg and Boyle, 1987). The graphite supposedly formed as early as the syenite. Wickham et al. (1995) investigated the Mongolian–Transbaikalian granite belt that was related to development of a large Paleozoic orogenic province. The province incorporated a vast territory of southern Siberia (Russia) and northern Mongolia. Syenite magmas in this belt crystallized at rather high temperatures >940°C, whereas the near-liquidus temperature of the peralkaline granite was lower, 760–790°C (Litvinovsky et al. 2002). Similar temperatures may be assumed for the igneous-related deposits of industrial minerals in the Choevsgoel region, of northern Mongolia.

Origin of argillaceous deposits

The depositional environments in Baganuur and the southeastern Gobi Desert are rather similar. In Baganuur and in the Gobi, fluvial, deltaic, and lacustrine sediments were laid down (Figs. 13 and 16). The paleogeographic setting in Ulaan buur is very much like that in Ulaan uul. Both redbed sequences were interpreted as a prodelta in the lower part, being overlain by delta-front sediments. Concluding from the grain size distribution, the conglomeratic facies at Ulaan buur is representative of the proximal part of a continental delta, whereas at Ulaan uul fine-grained sediments were laid down in more distal position. In their topmost part delta

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plain sediments and calcretes developed (Fig. 13). The physicochemical and hydrological conditions encountered in Baganuur and at Ulaan uul and Ulaan buur, however, are very different. In Baganuur, a grey rock color representative of poorly drained swamps predominates. The paleogeography is indicative of a perennial drainage system under humid conditions (Fig. 16). In the Gobi desert steppe, redbeds are the predominating rocks. They attest to arid to semiarid conditions and to streams episodically draining mud flats during the Paleogene (Fig. 16). This has some consequences for the type of phyllosilicates present in each working area. Slightly acidic meteoric fluids provoked kandite-group minerals (kaolinite, halloysite) to develop in Baganuur, whereas more alkaline fluids gave rise to smectite-group minerals in the deposits of the Gobi Desert. The palaeoclimate throughout the Early Cretaceous and Eocene, respectively, were key during formation of these contrasting assemblages of phyllosilicates.

The Baganuur interseam sediments consist of kaolinite-bearing clays alternating with arenaceous rocks that contain feldspar spanning the full range from unaltered crystals through feldspar pseudomorphosed by kandite-group minerals. Weathering and post-depositional clay mineral transformation contributed both to a depletion of arenaceous rocks in labile silicates, such as feldspar, and to the formation of kaolinite. Humic acids issuing from the swamps (coal seams) were, however, less effective than in nearshore marine basins such as the Cologne Basin, Germany, where these solutions contributed much to the formation of a mature, clean quartz sand underneath the coal seams, useful for special end usages. The fluvial fining-upward sequences at Baganuur, ranging in grain size from conglomerates to siltstones, formed a natural barrier (sealing horizon) in the footwall rocks of the coal seams that prevented large-scale per-descensum fluid migration necessary for early diagenetic kaolinization (Fig. 16). The content of organic matter and thermal maturation reactions in the coals (peat) could have little chemical effect on their substrates during pedogenesis and burial. A sort of (self)sealing effect in the substrate was detrimental to widespread and pervasive kaolinization at Baganuur.

Origin of gemstone deposits

Cenozoic volcanism in the Mongolian Plateau is considered to represent hotspot volcanism (Zonenshain et al., 1991). Typical features for the basaltic rocks suggestive of a hotspot and continental rift volcanism are the tectonic control of volcanism by grabens and the variation of the chemical composition from transitional-alkali to truly alkaline character. Garnet–two pyroxene granulite, garnet pyroxenite, and garnet peridotite xenoliths from the pyroclastic facies of the volcanic center in the Tariat depression yields a geothermal gradient for the region of 900°C to 1050°C at 45 km depth. Gemstones were emplaced primarily by an explosive volcanic process as indicated by the breccia pipes. The source rock is more akin to what was defined by Scott-Smith and Skinner (1984) as a lamproite than a kimberlite.

The depositional environment of the gemstone placer deposits may be constraint as follows. Poor roundness of the clasts in the seams is a direct response to the very short distance of transport (Fig. 23). The short-distance transport could not have been conducive to good sorting of the clasts. The very homogeneous particle size in the placer reflects the original size during crystallization in the magma rather than the result of subsequent comminution during transport. The bedsets lack internal structures. There are no cross-cutting bedforms.

Channels or scouring are totally missing. A coarsening-upward trend in the grain size variation suggests deposition under conditions of sheet flow and is supposed to be the result of episodic, intense flow processes. The placer sandwiched between the fine-grained clastics required a substantial amount of water at a certain time, which may have been provided by subglacial meltwater floods (Kor and Cowell, 1998). These hyperconcentrated flows/sediment bulking of the lithofacies were reworked, and accumulated gemstones proximal to the primary gemstone deposit (area 2) (Figs. 19, 20, and 23). Deposition fades out in low-concentration, unconfined flows off the primary gemstone deposit in a wide mountain valley (areas 2 and 3) (Fig. 19 and 20). The placer minerals eventually were dispersed in sediments that were deposited in the creeks and small rivers of the Chuluut Gol drainage system (Fig. 21). The secondary or placer-type gemstone deposits are of roll-ore type that tend to form close to the primary deposit with extensive eluvial outwash being involved in the concentration of the metallic or non-metallic commodities (Dill, 1985).

Heavy minerals of moderate chemical and mechanical stability such as garnet are present in the alluvial placers (Morton, 1984; Dill, 1995, 1998). The comminution of olivine cannot be accounted for by the short-distance transport alone.

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Disintegration of volcanic parent material occurred under chemical conditions which produced abundant 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 placer sediments.[2] Redeposition of heavy and light minerals took place under less intensive chemical weathering in the aftermath of this peneplanation as the climate cooled.

Origin of coarse- and fine-grained aggregate deposits

In view of the geomorphological position, the deposits of coarse-grained aggregates occur along the passage from the midslope through the footslope into the present-day channel system (slope angle 0–35°). Although the slope angles govern the position of the coarse-grained aggregates, the gravel-fines ratio governs the workability of the deposit (Fig. 25). The lithofacies implies a wide range of depositional modes, indicating all stages of a sudden, flash-flood type of sediment dispersal in form of hyperconcentrated sheets, debris flows in steeper slope positions, and channelized flows along the thalweg (Fig. 4B). It began with creep and solifluction/gelifluction on hillslopes, gave way to unconfined mass flows, and finished in a channelized flow of the ephemeral (zone B) and perennial stream (zone A) systems (Fig. 4, 5, and 24).

Grain size variation, sorting, and grain morphology of fine-grained aggregates leave no doubt that the aggregates are aeolian in origin. In the steppe proper, sand sheets and complex parabolic dunes exist, largely covered with shrubs and grass (Fig. 26A). In the desert steppe, parabolic, complex barchanoid ridge dunes and transverse dunes form the equivalent dune association (Fig. 26B).

All aeolian depositional forms described from the various parts of the steppe are impeded dunes. They suggest a constant wind direction and some are still active as shown by the shifting sand. Their shape is strongly influenced by the moisture and 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 role in the accumulation of sands, especially in the steppe proper. Small plants and grass constitute the most frequent obstacle, which cause wind deceleration and lead to a baffling effect for wind transport. Parabolic dunes, the outward appearance of which has been reshaped through time by rain-splash erosion and soil formation, are fossil dunes which were supposed to have been emplaced during the late or postglacial period (Grunert et al. 2000). Another factor constraining the evolution of the various aeolian depositional forms is the limitation in the sand source or areas of deflation.

Another group of sand accumulations named parabolic dunes, although less widespread than barchanoid ridge dunes and transverse ridge dunes, evolved in the desert steppe as it passes into the desert proper (Fig. 26B). Several slip faces along the windward side classify them as compound barchanoid ridge dunes (Embabi and Ashour, 1993). They have been studied in the neighboring Taklimakan Desert by Chinese geoscientists as to their migration rates and morphometry in relation to the local wind regime (Zhibao Dong et al., 2000). If parabolic dunes are part of the dune field, they are older and form a marginal facies relative to the barchanoid ridge dunes, thereby reflecting a period of time of higher humidity.

Meteoric fluids percolating through these wind-blown sediments were only moderately acidic. Otherwise heavy minerals such as amphibole, pyroxene, and biotite would not have survived under conditions of chemical weathering. Apatite, which might be expected in view of the granitic lithoclasts contained in the dune sands, was removed from the heavy minerals suite of the aeolian deposits. According to the experimental data of Nickel (1973), apatite dissolution is more rapid than that of amphibole in groundwater of pH 5.6. A loss of apatite by dissolution took place during alluvial storage on the floodplains and backswamps, as well as in the channel facies that sourced the aeolian deposits as they fell dry during the summer season. So neutral to mildly acidic conditions are supposed to have occurred during deposition of sand.

Geological and Geographic Impacts on Exploration and Use of Industrial Minerals

Metamorphic and magmatic industrial minerals from the taiga through the steppe proper

Segregation into lithofacies zones is well developed in the pegmatites under study (Figs. 8E and

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[2] For the mode of formation of peneplains as a fluvial/erosional surface or etchplain truncating all rock types of different resistance, see among others Summerfield (1996) and Coltori and Ollier (2000) (Fig. 28).

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8F), but separation of quartz from feldspar did not follow this trend (Figs. 8C and 8D). The pegmatite may be used as raw material for ceramic goods from the mineralogical and chemical point of view. Hand sorting of minerals cannot be done economically, and wet separation in the dry steppe is not an easy task. Drilling, blasting, and secondary breaking is necessary for the hardrock feldspar-quartz intergrowths. Geology and geography/climate in the continental interior both have not worked in favor of any subsequent use. Nepheline syenite, the driving force for the contact metasomatism in the Khargana gol graphite deposit might be used as a non-metallic raw material, although it is somewhat remote and thereby difficult to develop (Mommsen, 1988; Potter, 2001) (Fig. 10). Flake-graphite mineralizations were produced in Khargana gol, although to a limited extent, and dimension stones may be quarried at Tsagaan chuluut. Metamorphic processes have led to high-quality raw materials.

Although the graphite, apart from some moderate bleaching, was left almost unaffected by meteoric fluids, the marble deposit was affected in its near-surface parts by climatic conditions during the Cenozoic. Limestones are more susceptible to alteration by *per descensum* meteoric fluids than skarn deposits. Karstification is moderate, but cannot be neglected on the vast peneplain of Tsagaan chuluut when it comes to an assessment of the economic potential of the marble. Supergene alteration has affected the uppermost parts of the limestones, and faults acted as conduits for meteoric fluids so that they could also alter deeper parts of the marble (Fig. 11B).

The quality and the aesthetic value of the marble look promising, as is the case with the petrophysical characteristics of the calcareous rocks. The economic potential and use of this ornamental stone are predominantly controlled by post-metamorphic tectonic disturbances and vein-type mineralization. En echelon faults and criss-crossing joints may limit the workable size of the marble blocks to such an extent that the marble cubes cannot be sawn economically. Secondary supergene mineralization that developed along these fractures also has a negative impact on the quality of the marble. Away from the ancient peneplain truncating the basement rocks, the impact of this type of alteration may become negligible. On the other hand, the low-relief geomorphology is unfavorable for a quarry designed to excavate to greater depth. Blocks of up to 3 m^3 were exploited in quarries but now are abandoned. Reserves are good but the infrastructure is poor. This is valid also for the neighboring graphite deposits in the area. Judging by the examination of trenches and outcrops, those "ore shoots" within the graphite-bearing exocontact of the syenite delivering graphite of superior quality are small and very remote under present infrastructural circumstances, so as to be non-competitive with the producers in Sri Lanka, in Madagascar, or neighboring China (Harben and Kuzvart, 1996). Adverse climatic conditions in this northernmost part of Mongolia, close to the taiga, set limits to the period of mining operations for non-metallic commodities and the poor infrastructure raises obstacles for economic exploitation in the Choevsgoel and Bayan nuur–Lun areas.

Argillaceous deposits from steppe proper through desert steppe

The current climatic conditions in the steppe and the desert steppe are of lesser significance than in the mountain taiga (see the sections on graphite and marble) when it comes to the exploration or exploitation of the argillites investigated near Baganuur and Erdenet (Figs. 1 and 3A). Both deposits are close to the major railway line (Fig. 1). Judging by the mineral assemblage and chemical composition, formations C, D, and E of the coal-bearing series at Baganuur are of interest as raw materials for coarse ceramics; formations A and B can only be used as feldspar sands (Fig. 16). No discrete kaolin beds of workable size were identified in open pits (Figs. 6B and 16). This is a fact that is critical for the commercial utilization of interseam and roof sediments of the coal-bearing sequences. The Al_2O_3 content is at the lower end of ball clays, and the SiO_2 content is relatively high due to the framework silicates and quartz in the arenaceous interbeds (Fig. 17). An alternative to the present backfill, the clastic rocks may be quarried selectively with large fixed-arm excavators and stockpiled throughout the current operation for subsequent use. Inasmuch as the geological situation is very simple and predictive, the above method of exploitation may be applied. These sediments may be taken as feedstock for coarse ceramic products, provided the mineral composition of the various layers of interseam sediments is known and can easily be monitored throughout the ongoing mining operation. Quarrying is a byproduct, as in many other lignite opencast mines elsewhere, and the resources are enormous. As opposed to many other sites in Mongolia, these kaolinite-bearing clays are close to the site of poten-

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tial consumption. They may easily be delivered to the consumer by freight train. The railway connection is also an asset for the Ulaan uul argillaceous raw material. Moreover it may easily be exploited by shovels and excavators, as the badlands rise straight from the flat-lying desert steppe (Fig. 1 and 13). In contrast to the Baganuur mine with its kaolinitic interseam sediments, bentonitic clays occur in the Gobi Desert. In Ulaan buur, the content of coarse-grained lithoclasts and relic framework silicates rule out economic use. The fairly high Fe content in Ulaan uul is somewhat detrimental, and qualifies the argillaceous raw material as a bentonitic clay of low quality.

Gemstone deposits in the steppe proper

The overall features of the basic source rocks, moderate trace-element contents of Cr and Ni, the presence of sanidine instead of leucite, and a K_2O/Na_2O ratio of far below 5 qualify the area as moderately prospective for diamond-bearing "lamproitic" rocks (Table 2). Titanite, a very widespread Ti-bearing mineral in the heavy mineral suite of stream sediments, reflects some sort of "natural disclaimer" for diamonds to be abundant in the basic source rocks. Ultrabasic host rocks of diamonds concentrate Ti in perovskite, titaniferous amphibole, and phlogopite as well as in ilmenite but not in titanite.

The average size range of garnet is 2 to 10 mm, whereas olivine (peridot) rarely reaches as much as 3 mm. The annual production of garnet is about 250 kg, and the output of peridote does not exceed 2 kg. Peridot could not be ground mechanically due to its small grain size. Garnet can be exploited and manufactured. In three breccia pipes, 73 crystals of diamonds measuring 0.75 × 0.75 mm were said to be found. The economic figures for garnet are 1764 gr/m^3, peridot 80 gr/m^3, and sanidine 4 gr/m^3. Garnet is the mineral of economic interest. With the heavy mineral distribution in mind, the economic potential of the area for diamonds is considered as moderate.

Diamond-bearing kimberlites of the Siberian craton are invariably located above high-density rock masses. All known fields originated by Late Paleozoic–Early Mesozoic within-plate magmatism controlled locally by rift structures (Kaminsky, 1972; Moralev and Glukhovsky, 2000).

Climatic conditions during the Late Cenozoic that were detrimental to the quality of marble in Tsagaan chuluut were essential for the release of placer minerals from their basic source rocks in Shavryn Tsaram and for their reconcentration around the volcanic edifices and in the drainage system of the Tariat region. Gemstone commodities of high unit value do not suffer from the infrastructural situation in the western steppe in the same way as commodities of high place value (e.g., marble, feldspar, quartz).

The hydrology and depositional environments of the mountain/forest steppe and steppe proper are the most ideal sites for alluvial and fluvial placer deposits, mainly for gold, tin/cassiterite, and gemstones (Zhamsrandorzh and Diachov, 1996). Gold is among the stable products of Mongolia. Numerous large-scale and artisanal mining operations exist across the country, with Au grades reported to be as high as 11,800 mg/m^3 (Ar Chuluut) and reserves amounting to as much as 41,000 kg (Kampe, 1997). Placer deposits in Mongolia are classified according to the Russian scheme as alluvial, diluvial, proluvial, eluvial, glacial, and technogenic. The pay zones of the placer deposits occur mainly at the base of gravel bars, at different levels/terraces immediately above bedrock. The conditions and the formation of these placers through the interplay of fluvial and glacial processes were studied by Kotov et al. (1989).

Aggregate deposits from the mountain forest steppe to the desert steppe

Fine-grained aggregates in the desert steppe belong to what might be called renewable deposits; equivalent deposits in the steppe proper are impeded aeolian dunes and sand sheets or fossil landforms. They may also be distinguished from each other by their cumulative grain size distribution curves (Fig. 27). This is especially true for the Buduun tolgoi deposit located near the trunk railway line in the Gobi. Moltsog els and Vostochnii have the advantage of being located near sites of consumption in the capital, Ulaanbaatar. As far as the use of fine aggregates in concrete, asphalt for roads, and mortars is concerned, the material can be sold "as extracted." As far as filter sand or glass sand is concerned, the granulometric composition looks promising but the chemical and mineralogical compositions do not (Table 4).

The Quaternary morphoclimatic situation does not foster the development of high-quality, fine-grained aggregates. Large-scale quarrying for coarse-grained aggregates is difficult unless attention is paid to the fluvial dynamic of steppe river drainage systems.

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First and foremost, the environment of deposition of the Central Asian steppe shows a conspicuous bimodality in grain-size distribution. Not surprisingly, there is a fairly good supply of coarse-grained aggregates such as gravel and cobbles for construction, and the production of concrete derived from braided stream fluvial drainage systems in the steppe and mountain steppe, but a significant shortage exists for sand-grade aggregates. By sieving and crushing gravelly fluvial sediments from fluvial deposits, these shortcomings in the supply of finer grained aggregates can be minimized but not overcome.

These Quaternary continental depositional environments record periodic and episodic climatic changes, which is characterized in the Central Asian region by the highest degree of seasonal contrast on Earth. 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 to 10°C, and the mean annual precipitation lies between 100 and 400 mm (Hilbig, 1995). As a result, physical weathering is very strong, but chemical weathering is moderate. This is the major reason for the conspicuous grain-size bimodality and why fine-grained aggregates did not get depleted of their mafic heavy minerals and light alumosilicates to give a quartz sand exceeding 98 wt% SiO_2. The abundance in alumosilicates and in heavy minerals that have been derived from basic source rocks are both detrimental to any use to produce high-quality glass sand (Harben and Kuzvart, 1996). Another climatic effect relates to the exploitation of the raw material; a very short and dry summer and a long, harsh winter restrict the opencast operations to a few months per year.

Conclusions

Non-metallic commodities of high unit and high place values occur in Mongolia throughout the country. Some sites investigated during this campaign may be brought into the reaches of economic use mainly for infrastructural reasons. The current climate and the resultant vegetation zones are one factor underlying the poorly developed infrastructure. The negative aspects of climate and infrastructure becomes evident especially for high–place value commodities that may be exploited only in the narrow zone along the NW-SE trunk railway line (e.g., Ulaan uul). Commodities of higher value than ceramic raw materials fall outside the field of economic use, generally because of limited reserves, such as the graphite deposits, and the very adverse climatic conditions, especially in the northern forest steppe and taiga. The overall geology of several E-W fold belts being squeezed between two major cratons to the north and south reveals a very patchy distribution of lithological units and deposits (Zonenshain, 1972). Shortage of water and the extremely continental climate, with high daily and annual temperature fluctuations and low precipitation, are further liabilities to exploitation. High–unit value commodities in primary deposits and placers that are related to them in both space and time are most attractive. The presence of heavy mineral concentrations is favored by intensive physical weathering during lengthy regimes of continental climate that provided and preserved clastic aureoles around the various source rocks.

Capture of digital data in the field is a must in a vast country in Asia's continental interior with poorly developed infrastructure, in order to save time and space for the transport of samples. Geophysical devices such as a gamma spectrometer and magnetometer have proven to be very efficient tools in exploration for industrial minerals (Fig. 6). Especially, the handheld magnetometer offers numerous possibilities to trace layers and beds (clay, sand) or identify placer accumulations in bars scattered across a fluvial drainage system (gemstones). The applicability of a portable IR spectrometer in exploration for industrial minerals is useful, in order of decreasing applicability, for the following commodities: (1) carbonates; (2) sulfate-bearing rocks, (3) argillaceous rocks; (4) clay-bearing arenaceous rocks; (5) rocks abundant in alumosilicates/framework silicates. By using PIMA in the field, the number of samples taken during field work can be reduced by 50 percent in some sites with argillaceous and clay-bearing arenaceous rocks.

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