Tectonics of Mongolia: The second workshop of the IGCP-480 project “Tectonics of Central Asia”

Ulaanbaatar, Central and Southern Mongolia, Mongolia,
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Introduction

Central Asia encompasses nearly a dozen countries and consists of several orogenic complexes, one of which, the Altaides, is about ~1,000 km wide and ~7,000 km long, stretching from the Ural Mountains in the west to the Pacific Ocean in the east. The last decade has witnessed the establishment of two competing tectonic hypotheses for the development of these orogenic complexes. The first views the Paleozoic–Early Mesozoic development of Central Asia as a process of continuous growth of the continental crust due to the formation of large subduction–accretion complexes. This process was synchronous to the duplication of arc and forearc fragments via large-scale strike-slip systems during subduction (Şengör et al., 1993; Şengör and Natal'in, 1996; Parfenov et al., 2003; Yakubchuk, 2004). In contrast, other workers consider that multiple frontal collisions and collapses of back-arc oceans are the main mechanism for crustal growth of Central Asia (Badarch et al., 2002; Buchan et al., 2001; Buslov et al., 2002; Dobretsov et al., 2004; Windley et al., 2007). The two competing hypothesis have distinctive predictions with regard to: (1) the basement age of metamorphic complexes in the orogenic belt; (2) the style of deformation; and (3) the paleogeographic position of major tectonic units within the orogenic belt. Recent geological studies in Central Asia have mainly focused on the geochemical features of magmatic rocks, the isotopic dating of crystalline rocks, and studies of isotope system helping to elucidate the timing of continental growth (Jahn et al., 2004b; Jahn et al., 2000; Kovalenko et al., 2004). To emphasise structural and tectonic studies and the correlation of major tectonic boundaries and units across international borders, we organized a new IGCP-480 project (<http://www.igcp.itu.edu.tr/index.html>), which started in 2005 with a workshop in Irkutsk, Russia, and following field excursions to the northwestern side of the Baikal Lake (Olkhon Zone) and to the Dzhida arc (Figure 1). Participants in the project shared their data on the geology and tectonics of Central Asia. During the field excursions they became acquainted with structural relationships of the Siberian craton with the surrounding orogens. The logical continuation of our work in 2005 was to discuss the geology and tectonics of Mongolia and examine the key tectonic relations there.

The Second workshop in Ulaanbaatar, Mongolia

The workshop was organized by the Institute of Geology and Mineral Resources of the Mongolian Academy of Sciences and the School of Geology and Petroleum of the Mongolian University of Science and Technology. Personal responsibility was taken by a team led by Professor O. Tomurtoogo and Dr. D. Tomurhuu. A member of this team, Dr. Gombosurengyn Badarch, whose contribution to the geological studies of Mongolia is difficult to overestimate, died just forty days before the opening of the Second Workshop, in consequence of which it was dedicated to his memory.

Before the opening of the workshop, the Institute of Geology and Mineral Resources published an Abstract volume (93 pages, 40 abstracts, most of which are extensive and with figures) and a Field Excursion Guidebook (41 pages) as a single book (Tomurhuu et al., 2006). The abstracts and the guidebook are posted at the Project website.

The workshop was attended by 92 scientists and students from twelve countries who made thirty oral and eight poster presentations. It was opened by the welcome address of the Vice-President of the Mongolian Academy of Sciences N. Altansukh. Then Tomurhuu characterized the personality and scientific achievements of the late Gombosurengyn Badarch to whom the workshop was dedicated. Natal'in summarized the results of the first workshop in Irkutsk, Russia, and the following field excursions to the junction between the Siberian craton and a fragment of the early Paleozoic arc (the Olkhon Zone), to the section across the Neoproterozoic cover deposits of the Siberian craton, and to the Dzhida Early-Middle Paleozoic arc. He stressed the importance of the Early Paleozoic sinistral Olkhon shear zone for understanding the nature of folding in the Patom Highland and adjacent regions of the Siberian craton. The northern polarity of the Dzhida arc conflicts with recent tectonic models (e.g. Badarch et al., 2002).

The scientific sessions covered a variety of topics on tectonics in general, the tectonics of Asia or the regional tectonics of its major areas. The greater part of the presentations dealt with the regional geology and tectonics of Mongolia and neighboring regions in China and southern Russia.

An Yin and his coauthors suggested a new structural model of the Chinese Altai, which implied a considerable (>500 km) crustal shortening and thrust-fault nature of the Irtysh strike-slip fault (Figure 1). Their model was based on the balancing of a number of cross sections. However, the validity of the application of this method to highly

Figure 1 Tectonic map of Central Asia indicating the workspace of the IGCP-480 project. Locations of past and future field transects are shown by thick solid lines. The key tectonic units and structures mentioned in the text are as follows: BD—Baidrag Continental Block; BH—Bayanhongor Zone; GH—Gorhi outcrops; GY—Gyeonggi Massif; IM—Imjingang suture; IT—Irtysh shear zone; MA—Mongolian Altay; MO—Mongol–Okhotsk Suture; OC—Ogcheon Suture; T—Tariat Cenozoic basalts; SK—Solonkr suture; SV—Selenga–Vitim magmatic belt.

strained metamorphic rocks may cause large uncertainties as some participants noted.

Tomurtogoo provided an overview of the tectonics of Mongolia dividing it into two large domains separated by the Mongol–Okhotsk suture, which he has traced to the west along the southern side of the Khangai–Khanter Zone (Figure 1). This division cast doubt on the unity of the Tuva–Mongol massif and implied a much greater length for the Mongol–Okhotsk ocean.

Rojas-Agramonte and her coauthors analyzed the ages of detrital zircons from various Paleozoic tectonic units of Mongolia trying to determine their possible source areas. The majority of zircon populations indicates locations of source areas in Siberia. At the same time zircon ages between 800–1,000 and 1,300–1,700 Ma require a source that is different from the Siberian craton and neighboring parts of Gondwanaland. Rojas-Agramonte suggested a Baltic origin for these zircons. This suggestion was opposed by some of the participants who pointed out that magmatic processes at 800–1,000 Ma are well known in the Baykalides and consequently in the Tuva–Mongol massif. Moreover, ages of 1,300–1,700 Ma are present in the eastern part of the Siberian craton.

Dorjsuren and his coauthors, Kurihara and his coauthors, and Tsukada and his coauthors presented important data on the tectonic setting of the Paleozoic rocks constituting the Khangai–Khanter Zone of Mongolia (Figure 1). They expressed a common conclusion that these rocks belong to subduction–accretion complexes. Their data were partly checked during the field excursion and will be discussed in the next section of this report.

New isotopic age determinations of granitic rocks and detrital zircons in Chinese and Mongolian Altai (MA in Figure 1) were presented by Wang and his coauthors, Cina and her coauthors, Ying and his coauthors, and Jian Ping. Demoux and his coauthors discussed the evolution of the Ordovician to Permian magmatic arcs in southern Mongolia. The subduction-related nature of these magmatic rocks is a very important issue in their study because some researchers interpret the magmatic event of this age as occurring in intra-plate tectonic settings. Similar conclusions were made on the nature of early Mesozoic granitoids and volcanic rocks in the Khangai–Khanter Zone of Central Mongolia (Bat-Ulzii and coauthors). The geochemical features of ophiolitic rocks exposed in the Bayanhongor Zone were discussed by Tomurhuu and Munkh-Erdene who have shown that ophiolites originated in a spreading center while basaltic rocks of OIB type indicate involvement of a mantle plume activity.

Studies of sedimentary basins are still not particularly popular among the Project's participants. However, they are of great importance for tectonic correlations as it was demonstrated in the presentation made by Johnson and her coauthors who had studied the Permian sedimentary rocks along the Solonker

suture (Figure 1). The absence of a large dissection of the magmatic arc on the northern side of the suture suggests a soft collision between North China (the Manchurides) and Mongolian structures. The collision was accompanied by strike-slip deformation as it was also discussed in the presentation made by Webb and her coauthors.

An excellent overview of granitic magmatism and related metallogeny was presented by Gerel and her coauthors. They had created an extensive database in GIS format, in which the disposition of granitoids of various ages was shown in a series of time-slice maps. Relevant spreadsheets provided information on the petrography, post-magmatic alteration, metamorphism, structural features, geochronology, and occurrences of mineralization.

Using Os isotopes from the Tariat Cenozoic basalts (T in Figure 1) Wang and his coauthors evaluated the ages of the subcontinental mantle. The model's ages were similar to those of the Precambrian Tuva–Mongol massif. Younger metasomatic events may have been related to the tectonic evolution of the Altai.

Other presentations discussed regions that are located outside Mongolia. Şengör discussed the evolution of the accretionary complex in Eastern Turkey where the Arabia/Eurasia collision led to slab detachment and thus the base of the subduction–accretion complex was exposed to a rising asthenosphere. This process caused the voluminous magmatism in which alkaline rocks played a significant role.

Natal'in discussed the Early–Middle Paleozoic history of tectonic units that constitute the basement of the Late Paleozoic–Early Mesozoic Silk Road arc. Stretching from the southern side of the North China Block to the Balkan Zone of Bulgaria this arc evolved along the southern margin of Eurasia accommodating the subduction of the Paleotethyan ocean. Being uninterrupted by collisions, episodes of the Early–Middle Paleozoic activity in various parts of the arc reveal a great similarity and suggest that they evolved at the margin of a single ocean.

Hegner and his coauthors presented the results of their studies in the Transbaikalian region of southern Russia. They inferred that the subduction-related signatures recorded in trace elements of the Late Carboniferous–Early Permian rocks of the Selenga–Vitim belt (SV in Figure 1) were inherited from earlier episodes of subduction. Thus, the subduction-related setting of magmatism was neglected and instead rift-related tectonic setting was suggested.

Kuzmin and his coauthors discussed the tectonic evolution of southern Siberia with a special emphasis on geology of the Dzhdida arc and the Mongol–Okhotsk fold belt. In the second part of this presentation, Kuzmin analyzed intraplate magmatism and its significance for metallogeny in the Siberian part of Central Asia and Mongolia. He has shown that the intra-plate magmatism occurred as a

recurrent process in this region, suggesting that all changes of the Paleozoic positions of the Siberian craton and surrounding structures occurred within the Afro–Atlantic hot region of the Earth.

Subduction–accretion growth of the Tasmanides in Australia was demonstrated by Glen. The presence of a Gondwanaland Block in the Central Asia orogenic collage was suggested by Golonka and Krobicki after the analysis of the stratigraphy and collision history of similar blocks exposed in Southeast Asia. Nakajima reviewed data on the Cretaceous subduction-related granitic magmatism in Japan. Chwae and Choi contested the widely accepted tectonic correlations of the Sulu belt in China with the Gyeonggi massif in Korea. Their studies of the structural trends of the Imjingang and Ogcheon suture (Figure 1) suggest that the Sulu belt in China turns to the south and its continuation should be sought in Japan.

Almost all the presentations stimulated heated discussions. One of the most important issues was the question of the preservation of original boundaries of terranes that many modern researches have tried to identify in Central Asia assuming that this methodology will assist understanding of all tectonic complexities in the region and its evolution. During a stage of 'free floating' in paleoceans, microcontinents, or exotic intraoceanic island arcs should have certain rock assemblages that formed along their periphery. Frontal collisions of these objects with Asia would have preserved or partly preserved these rock assemblages along sutures, allowing us to reconstruct the original entities. Questions about the original boundaries of terranes were repeatedly put to the proponents of terrane analysis and multiple collisions; but the audience never received clear-cut answers.

During the business meeting, the participants of the project accepted the official invitation of the Chinese national team to hold its next meeting in China in 2007. We decided to complete a transect between the Siberian and North China cratons along a single Olkhon/Dzhida–Mongolia–Inner Mongolia line. Jiang Ping and Wenjiao Xiao overruled the geology of Inner Mongolia, which was chosen as a place for the future field excursions in 2007 (Figure 1). Field excursions to this region will provide a good opportunity for the examinations of tectonic relationships relevant to the closure of the Solonker ocean separating the Altai and Manchurides (Şengör and Natal'in, 1996).

Field trips to Khangai–Khanter Zone, 30–31 July

The Paleozoic–Early Mesozoic Khangai–Khanter zone is surrounded by older continental block belonging to the Tuva–Mongol massif (Figure 1). Its tectonic nature has been a subject of discussions since the first plate tectonic synthesis of Mongolia (Zonenshain, 1973) in which this zone was interpreted as a back-arc basin filled with a

thick (10 km) pile of Paleozoic turbidites and underlain by continental crust. Şengör et al. (1993) and Şengör and Natal'in (1996) interpreted Paleozoic and Triassic rocks of the Khangai–Khanter Zone as a subduction-accretion complexes taking into consideration the ubiquitous presence of lenses of pelagic cherts in turbidites and intricate deformation of the zone. This interpretation was shared by Parfenov et al. (2003, 1999) and Zorin (1999), while other researchers assigned the zone to an unspecified turbidite terrane/terraces, viewing it as a relict of a passive continental margin (Bucham et al., 2001; Badarch et al., 2002; Jahn et al., 2004a; Tomurtogoo et al., 2005) or as a continental block overlain by a thick sedimentary cover (Herrington et al., 2005; Kovalenko et al., 2004). Note that the interpretation of the Khangai–Khanter Zone as a passive continental margin is only very recent but it seems that it has become a popular one among the Mongolians and other geologists. That is why it was important to

visit the Paleozoic rocks of the Khangai–Khanter Zone during the field-trip, and use the expertise of all of the participants of the project to check the available interpretations. The tectonic nature of the Khangai–Khanter Zone imposes constraints on our understanding of the tectonic history and timing of closure of the Mongol–Okhotsk ocean as well as the tectonic nature of magmatic belts superimposed on the Tuva–Mongol massif.

As mentioned above, recent detailed studies in a few places in the Khangai–Khanter Zone confirmed Şengör and Natal'in suggestion on the nature of the Khangai–Khanter Zone. These studies allowed one to reconstruct the oceanic plate stratigraphy of the downgoing slab in the Mongol–Okhotsk ocean, confirm its extensive width, and constrain the age of subduction to a date as young as the Carboniferous (Kurihara et al., 2006). The finding of the Permian radiolarite reported by Tomurtogoo (2005) suggests an even younger age of subduction.

We had the opportunity to observe the structural relationships between various rocks in two outcrops located about 50 km to the east of Ulaanbaatar (GH in Figure 1). The examination of oceanic cherts surrounded by sandstones (the Gorhi formation) confirmed the tectonic contacts between cherts and sandstones, which in turn imply a *mélange* type structure for the region. The second outcrop of a limestone body occurring in the Gorhi formation was more informative. The limestones contain no admixture of terrigenous material but at the same time they contain inter-layers of mafic tuffs. These observations suggest that the limestones were formed as a cap of a seamount, subsequently incorporated into the Khangai–Khanter accretionary prism. The limestones have fault contacts with pelagic cherts alternating with thin layers of siliceous shales. Similar to the previous outcrops, the cherts reveal at least two generation of folds. Unfortunately limited observations did not allow us to determine vergence that might help in the determination of the subduction direction and the accretionary prism growth.

Previously interpreted as shallow marine deposits, Carboniferous rocks exposed to the east of Ulaanbaatar turned out to be proximal turbidites according to the unanimous opinion of the participants.

During a short field-trip before the opening of the workshop Natal'in, Şengör, and Tomurtogoo observed the same composition and structural style of rocks along the Ulaanbaatar–Harhorin road. All of us had a chance to see similar structures in the Dzag Zone located to the north of the Bayanhongor ophiolites. This zone was also assigned to the Atlantic-type passive continental margins (Badarch et al., 2002; Buchan et al., 2001). Thus, the participants reached a uniform interpretation of the subduction–accretion nature of the Khangai–Khanter Zone of Central Mongolia.

Field excursions to the Bayanhongor Zone, 31 July–2 August

The Bayanhongor Zone is the most studied region of Mongolia because of its ophiolite belt, which stretches for 300 km (BH in Figure 1). In the south, the ophiolites are in tectonic contact with the Archean to Paleoproterozoic Baidrag Block (a part of the Tuva–Mongol massif) across a *mélange* zone. In the north, they have fault contacts with the Khangai–Khanter Zone. The ophiolites occur as blocks enclosed in a matrix consisting of serpentized ultramafic rocks.

We started our work with a 4 km transect (Stops 1.1–1.4) along the Altan Am gorge, formed by the eastern tributary of the Ulziit River (see Figure 8 in Tomurtogoo et al. (2006) for locations of stops mentioned in this section). This transect across a serpentinitic *mélange*, cumulate complex, sheeted dyke complex, and volcanic rocks acquainted us with all the rock types exposed in the Bayanhongor ophiolites. The sheeted dyke complex was the most interesting

Figure 2 Rocks and structures observed during the field trip. **A**—Dyke-in-dyke in the Bayanhongor ophiolites. **B**—Consistent western dips of sheeted dykes in the Altan Am Gorge, Bayanhongor Zone. **C**—Two directions of dykes in the Bayanhongor ophiolites; **D**—Steep-dipping pillow lavas showing consistent northeastern younging directions in volcanic rocks of the Bayanhongor ophiolites. **E**—Vendian–Lower Cambrian phyllonites displaying dextral shearing parallel to the strike of the Bayanhongor zone. **F**—Steep-dipping foliation in the chlorite schist with kinematic criteria indicating dextral shearing along the southern margin of the Tuva–Mongol Massif.

object. Previous studies of the Bayanhongor ophiolites have shown that volcanic rocks vary from N-MORB through E-MORB to OIB basalts suggesting their backarc (Buchan et al., 2001) or oceanic origin (Tomurhuu and Munkh-Erdene, 2006). Observations of dyke-in-dyke relationships (Figure 2A, Stop 1.4) and asymmetric chilled margins as well as the consistency of dyke trends (Figure 2B) make the latter interpretation perhaps more likely because well-defined spreading centers are uncommon in backarc basins. At the same time, some outcrops showed that the main dyke system is cut by younger dykes of different orientations (Figure 2C). Macroscopic examinations show that the dykes have similar compositions regardless of their orientation. Their crosscutting relationships may be due to stress field variations in a spreading center caused by adjustments of the plate boundary to changes of plate kinematics. The presence of three dyke generations suggest that these adjustments were rather frequent.

The dyke system reveals consistent steep dips to the west (Figure 2B), despite interruptions of the rock continuity by faults and ductile shear zones. The trends of the dykes are discordant to the NW trend of the Bayanhongor Zone. Previous study (Buchan et al., 2001) has documented a general conformity the dyke trends and the trend of the ophiolitic zone. Thus, the disconformity that we observed could be caused by local rotations of dykes about sub-vertical axes. If this is correct, strike-slip motions provide the most likely explanation. These motions may also be inferred from the abundance of sub-horizontal slickenlines in serpentinites and similar orientation of serpentine minerals. In addition, we observed several brittle reverse faults and shear zones with a top-to-east sense of shear, all dipping steeply to the west. Buchan et al. (2001) consider northeast vergent thrusting as a main mechanism responsible for the dismembering of ophiolites and the formation of the structural skeleton of the Bayanhongor Zone. If east-vergent reverse faults and shear zones are relevant to this thrusting, their minimal clockwise rotation from 'normal' orientations also suggests a dextral sense of shear, parallel with the northwestern strike of the Bayanhongor Zone. The evidence supporting this conclusion will be discussed later in this section.

In the west, the sheeted dyke complex is overlain by pillow basalts that are exposed to the north of sheeted dykes and gabbro (Stops 1.5 and 1.6). The contact is not exposed. However northwestern younging directions in steeply dipping basalts are compatible with the spatial position of the sheeted dyke complex if one considers it as a feeder system. During the further trip across the full width of the Bayanhongor Zone we observed the same northeastern younging directions in pillow lavas (Figure 2D) exposed to the south of the sheeted dykes and gabbro (e.g. Stop 1.7). This consistency casts doubt on the published structural model (Buchan et al.,

2001), according to which thrust-bounded slices of the Bayanhongor ophiolites have moderate dips to the south, preserving the original stratification. Furthermore it casts doubt on the general conclusion about the northeastward obduction of the ophiolites onto the Dzag Zone, which, as already mentioned, was previously misinterpreted as the passive continental margin of a continental block hidden beneath the Khangai-Khantey Zone (Buchan et al. 2001).

Important observations have been made in the Vendian–Lower Cambrian fine-grained rocks that we interpreted as a part of the carbonate-olistostrome deposits in the Guidebook (Stop 1.8). It turned out that these rocks are phyllonites with strong foliation and stretching lineation. They were formed from shales containing carbonate concretions. The asymmetrical shape of these concretions and S/C structure indicated dextral shearing along sub-vertical foliation planes (Figure 2E). The phyllonites are exposed to the south of the pillow basalts and their contact was interpreted as a south directed thrust (see the Guidebook). The phyllonites presented evidence of superimposed deformations. However none of them demonstrates kinematic features that are compatible with the inference about the southwest-directed tectonic transport. On the contrary, steep crenulation cleavage overprinting the main foliation and relevant asymmetric folds indicate a top-to-northeast sense of shear.

Evidence for dextral shearing parallel with the strike of the Bayanhongor Zone has been collected farther to the south (Stop 1.9), where lavas, dykes, and gabbros are exposed. These rocks have strong foliation and a weak-to-strong, gently plunging stretching lineation. In places, the steep dipping foliation is of mylonitic type and rocks have been converted into augen gneisses. The asymmetry of porphyroblasts indicated a consistent dextral sense of shear. The metamorphic grade of the mylonites was higher than the metamorphism of the phyllonites exposed at the previous stop. The top-to-northeast motions observed in the phyllonites may explain this difference in grade. Northeast-dipping normal faults were also observed in the Altan Am Gorge. These extensional structures require a special study for a proper understanding of the late episodes of the structural history of the Bayanhongor Zone.

Our discovery of dextral shearing parallel with the strike of the Bayanhongor Zone was at odds with observations made by Buchan et al. (2001). In three regions located to the west of our field trip area they had described a left-lateral shear deduced from subhorizontal lineations. We also observed sinistral shear in mylonitized gabbro exposed near the contact between the Bayanhongor Zone and the Baidrag Block (Stop 2.2, see figure 11 in Tomurtogoo et al. (2006)). In contrast to previous sites exhibiting dextral shear, ductile deformations in gabbro at Stop 2.2 occurred at a higher temperature as evidenced by the mineral composition of the

mylonites. Moreover, the mylonitic gabbro is cut by almost unstrained mafic dykes similar to dykes of the sheeted dyke complex. Red monzonitic granites (Stop 2.6) exposed 3 km to the southeast along the same contact between the Bayanhongor Zone and the Baidrag Block and yielding 540 Ma ages reveal low temperature cataclastic foliation that is very different from the foliations in the mylonitized gabbro. All of these imply that the mylonitization in the gabbro occurred within a spreading center long before the incorporation of the deformed gabbro into the Bayanhongor *mélange*.

High-temperature mylonites were also observed at Stop 3.3 to the south of Bayanhongor city, where a large block of the cumulate complex of the Bayanhongor ophiolites is exposed. Surprisingly, the serpentinitized harzburgite, dunite, and wehrlite as well as serpentinites, are not sheared and contain a small amount of slickenside surfaces, indicating a low strain of rocks. The mylonites occur in the gabbroic part of the section where they control locations of gabbro pegmatite lenses or leucocratic gabbro. The mylonites reveal a consistent dextral shear. The low-strain of the serpentinitized rocks suggests the earlier formation of the mylonites. Similar to the mylonitized gabbro of Stop 2.2 metamorphism and deformation of gabbro at the Stop 3.3 can be attributed to processes within a spreading center.

It is clear that additional structural studies are necessary to determine all aspects of the structural and kinematic history of the Bayanhongor Zone. However, its linear shape, the steep dips of the planar structures, and our limited observations, suggested that strike-slip displacements played a significant role in the formation of the general structural framework of the zone.

During the workshop, Jiang Ping and his coauthors presented new data on the isotopic ages of ophiolitic rocks from the Bayanhongor Zone. They had found that some dykes and ophiolite cumulates have ages as young as 300–240 Ma. These ages contradict the earlier age determinations of the ophiolites as Neoproterozoic (569 and 665 Ma). Jiang Ping and his coauthors also confirmed these old ages. Dating of the metamorphic fabric and the intrusions that cut the ophiolites and the *mélange* constrains the age of main deformations to between 540 and 450 Ma (Badarch et al., 2002). Thus, the newly-obtained young ages create a significant problem for the 'customary' interpretations of the the history of the Bayanhongor Zone. Unfortunately, however, Jiang Ping and his coauthors did not clarify the structural relationships between rocks yielding 'old' and 'young' ages. Besides, the sampled rocks with 'young' ages were exposed rather far from the field trip area. Intrigued by the new age determinations we decided to visit the Upper Ordovician conglomerates that form a cover for the Bayanhongor *mélange* according to previous studies.

The Upper Ordovician rocks occur in faulted contact with the Vendian–Cambrian schists and reveal no penetrative foliation. We observed the same appearance of these rocks in several separate stops, which suggests a high likelihood of their interpretation as a cover for the Bayanhongor *mélange*. At the same time discrete high-strained shear zones can exist in the Upper Ordovician rocks. The Ordovician conglomerates contain clasts of almost all rocks constituting the Bayanhongor ophiolites including mylonites. Carboniferous grey, coarse-grained sandstones containing clasts of pink K-feldspar from the red monzonitic granites (Stop 2.6) also lack penetrative foliation. Thus, the young ages obtained for the ophiolitic rocks seem suspicious from a geological point of view and rocks yielding these ages require further detailed studies.

Field excursion to the Taats River, 4 August

A well exposed section of the Precambrian rocks in the Taats River valley is an excellent place to study the geological structure and history of the Baidrag Block (BD in Figure 1). This region has been mapped by both Russian and Mongolian geologists who have recognized a number of stratigraphic units and divided the magmatic rocks into several age groups. However the vast majority of the exposed rocks are crystalline. Therefore their age determinations based on structural relationships must be checked by isotope dating. Recently a group led by Professor Kroener (Tomurtogoo et al., 2006) obtained the first zircon ages from magmatic rocks of the region and thereby better constrained ages of previously determined stratigraphic units and magmatic complexes.

According to the previous studies the basement of the Baidrag Block consists of metamorphic rocks subdivided into Paleoproterozoic and Mesoproterozoic units metamorphosed to amphibolite facies. These units are cut by Neoproterozoic granitoids and gabbro, Cambrian and late Permian granites. In the north, the Baidrag Block has a fault contact with the Neoproterozoic metavolcanic rocks of the Bayanhongor Zone yielding 597 Ma age. In the Baidrag Block, unfoliated granites yielding 537 Ma zircon age (Tomurtogoo et al., 2006) impose constraints on the age of the high-grade metamorphism and deformation. We observed these clear relationships at Stop 4.5 (see Figure 15 in Tomurtogoo et al. (2006)). Other stops showed more complicated relationships between granitic intrusions and high-grade metasedimentary rocks. Metagreywacke, quartzite, calc-silicate rocks and marbles exposed at Stop 4.3 were assigned to the Mesoproterozoic. These rocks are metamorphosed to the amphibolite facies and in places are migmatized. The foliation is well developed and has been involved in later folds. Numerous granitic dykes gently dipping to the north intrude the metasedimentary rocks. The dykes are also foliated but

their foliation may be younger than the foliation in the country rocks. Unfortunately the foliated granites have never been dated. In the southern part of the outcrop at Stop 4.3 there is a fault-bounded lens of marble that shows a later foliation and boudinage of the earlier foliated rocks. The asymmetry of the boudins and S/C structures indicated dextral shear. This deformation can be correlated with the dextral shearing that we observed in the Bayanhongor Zone.

Near the northern contact of the Baidrag Block we observed a large body of metagabbro which in places was converted into L-tectonites with subhorizontal E–W-trending lineation. In previous studies these gabbros had been assigned to the Neoproterozoic similar to metavolcanic rocks of the Bayanhongor Zone exposed nearby. Unfortunately, the kinematic aspects of the lineation in the metagabbro were not determined. However, the presence of L-tectonites near the contact with the Bayanhongor Zone provides additional evidence for the importance of orogen-parallel strike-slip motions in Central Mongolia.

Discussions of the geology of the Taats River valley stressed the necessity of dating the foliated granites that are widespread in the area. Kroener has obtained an 1,839 Ma zircon age from granite gneisses and a 579 Ma zircon age from porphyritic unfoliated granites. The granite gneisses are associated with garnet-bearing amphibolites. Their relationships with the surrounding metasediments have not been clarified. The porphyritic unfoliated granites indicate the synchronicity between subduction-accretion processes in the Bayanhongor Zone and magmatic events in the Baidrag Block.

Field excursion to the Zuun Bogd and Halbagant Range, 4–6 August

Logistic difficulties did not allow us to go to the Zuun Bogd Range where recent studies by Kroener's group have proved the existence of the Ordovician and Carboniferous arcs (or Ordovician–Carboniferous arc?) constructed atop the basement containing granitic augen gneisses yielding 957 Ma zircon age (Demoux et al., 2006). It was unfortunate that we could not discuss on the spot the tectonic nature of the Mesoproterozoic basement of the Ordovician–Carboniferous arc, which some participants considered to be an independent micro-continent that had collided with the Baidrag Block, whereas others viewed it as a continuation of the Baidrag Block, taking into account the sedimentological features of the Vendian–Lower Cambrian limestones and the similarity of the schist–quartzite rock association in the Zuun Bogd Range with Mesoproterozoic rocks in the Taats River section.

A most informative excursion along the Halbagant River (HB in Figure 1) allowed us to examine a thick early Paleozoic section of clastic rocks. A felsic dyke yielding a 441 Ma zircon age and a tectonic lens of rhyolites yielding a 482 Ma age (Kroener, unpublished

data) confirm the early Paleozoic age of the clastic rocks. These clastics consist of four units (from north to south): (1) chlorite–muscovite schists with tectonic inclusions of marble, felsic and intermediate volcanic rocks; (2) calc turbidites with admixture of the volcanoclastic material; (3) sericite schists and metasandstones with olistoliths of limestones; and (4) bedded and massive recrystallized limestones from which Silurian fossils were collected. The sedimentological features of the clastic rocks of the section imply deep water environments. The same inference was applicable to limestones observed to be alternating with cherts. The presence of olistoliths or *mélange* inclusions as well as the admixture of volcanic material in at least the two lower units suggested an accumulation of rocks in a forearc tectonic setting. Some of the participants (Natal'in, Şengör, and Tomurtogoo) believe that this arc marks the southern margin of the Baidrag Block.

The clastic section revealed a complicated structural history and requires a thorough study. For instance, a lens of tuffaceous clastic rocks containing Permian plants is incorporated into the complicated structure of the early Paleozoic rocks and suggests a rather young age for intense deformations. Their style shows a sharp contrast with that of the more simply deformed Permian rocks exposed immediately to the north of the early Paleozoic rocks.

The most remarkable aspect of the structural history of the early Paleozoic rocks is the ubiquitous occurrence of dextral kinematic criteria associated with gently plunging stretching lineation (Figure 2F). An essential component of the Şengör and Natal'in's (1996) model of tectonic evolution of the southern and western margin of the Tuva–Mongol massif (the Baidrag Block in this particular locality), these structures were discovered for the first time. None of the other recent models suggesting of multiple arc/microcontinent collisions or terrane accretions during the Paleozoic history of Mongolia imply or predict these structures.

Concluding remarks

The Second Workshop of the IGCP-480 project has shown the growing interest of geoscientists in the project. Our style of work has proved to be efficient, especially during the extensive field excursions. Geologists discuss complicated relationships usually in a 'competitive way', revealing their skill and research philosophy and providing valuable lessons for students. Regardless of the achieved consensus these discussions help the participants better understand each other and see more clearly the strengths and weaknesses of the published works.

The field excursions have shown that 'modern' styles of doing geology, in which the main method of study is sampling of rocks followed by processing of the samples using sophisticated laboratory technologies, are highly one-sided. Many problems of geo-

logical evolution of our planet cannot be solved without traditional methods of geological studies, careful and comprehensive geological mapping of the area under consideration using new developments in structural geology and sedimentology, and a comparative analysis of data from the area studied with data from other regions of the world. At present only a small fraction of the participants of the Project, as well as other geologists working in Central Asia pay sufficient attention to traditional geology. We hope very much that this issue became clear for the young geologists and students who attended the workshop and its excursions.

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