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Structural and lithological characteristics of the Bayankhongor Ophiolite Zone, Central Mongolia

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Abstract: The mechanism of continental growth of Central Asia is currently debated between models invoking continuous subduction–accretion, or punctuated accretion due to closure of multiple ocean basins. Ophiolites in Central Asia may represent offscraped fragments in an accretionary complex or true collisional sutures. The Bayankhongor ophiolite, a NW–SE-striking sublinear belt 300 km long and 20 km wide, is the largest ophiolite in Mongolia and possibly Central Asia. We present results of the first detailed structural and lithological study of the ophiolite. The study area is divided into four zones: Baidrag complex, Burd Gol, Bayankhongor, and Dzag zones. The Archaean Baidrag complex comprises tonalitic granulites and metasediments. The Burd Gol zone is a metamorphosed sedimentary and igneous mélange. The Bayankhongor zone contains the dismembered ophiolite forming a serpentinite mélange. The Dzag zone consists of asymmetrically folded chlorite–mica schists resembling meta-turbidites. The structure is dominated by steeply dipping, NE directed thrusts and NE-vergent folds. We suggest the Bayankhongor ophiolite marks the closure of an ocean separating two microcontinents: the Baidrag complex with the Burd Gol accretionary complex to the south, and a northern continent that forms the basement for the Hangai region. Subduction was towards the SW with NE-directed ophiolite obduction onto a passive margin represented by the Dzag zone.

Keywords: Mongolia, ophiolites, plate tectonics, Central Asian orogenic belt.

Central Asia is a collage of continental blocks, ancient island arc terranes, subduction complexes and fragments of oceanic crust that amalgamated during the late Precambrian, Palaeozoic and Mesozoic. Şengör *et al.* (1993) produced a regional tectonic synthesis of the basement geology of Western China, Kazakhstan, Mongolia and parts of Russia utilizing existing published information, and proposed a mechanism for continuous continental growth through subduction accretion and arc collision. They suggested that a subduction zone existed along the southern margin of the Angara craton (Fig. 1, inset) throughout the Palaeozoic era and that a vast complex of arc and subduction–accretion material including offscraped ophiolitic fragments accumulated in front of seaward-migrating magmatic fronts. In contrast, Coleman (1989) and Hsü *et al* (1991) identified distinct ophiolite belts in northwestern China, which they interpreted as discrete suture zones separating different Palaeozoic blocks. These models differ in that the former invokes steady state subduction–accretion over a prolonged period of time, whereas the latter favours punctuated accretion by collision and closure of multiple ocean basins now marked by ophiolitic sutures. Mossakovsky *et al.* (1994) proposed a model for Central Asia whereby the early stages of continental growth were dominated by arc development and accretion and the late stages by collision of accreted continents. In order to understand how the bulk of the continent of Asia was formed, it is essential to work out the tectonic significance of the Central Asian ophiolites and their role in the continental accretion process.

Mongolia presents an exceptional opportunity to examine this problem because it lies centrally within this collage (Fig. 1, inset) and contains some of the best preserved Palaeozoic ophiolitic rocks in Central Asia with over 60 reported separate occurrences (Fig. 2). Despite their abundance, few Mongolian ophiolites have been studied using modern structural techniques and important questions remain regarding their internal structures, mechanism of emplacement and overall tectonic significance. Here we present results of a detailed structural study of the Bayankhongor ophiolite, the longest continuously exposed ophiolite belt in Mongolia and possibly all of Central Asia.

Regional geology

The basement geology of Mongolia comprises tectonostratigraphic terranes between the major Precambrian cratonic blocks of Angara, North China and Tarim (Fig. 1; Şengör *et al.* 1993; Zorin *et al.* 1993; Mossakovsky *et al.* 1994; Dobretsov *et al.* 1995). These terranes form gently curving, NW-SE striking belts in the west and south of Mongolia and a less ordered mosaic pattern in the central and northern provinces around the Hangai region (Fig. 1; Mossakovsky *et al.* 1994; Zorin *et al.* 1993). A generally accepted concept is that accretion progressed southwards through time (Mossakovsky & Dergunov 1985; Şengör *et al.* 1993; Mossakovsky *et al.* 1994; Dobretsov *et al.* 1995). This interpretation has traditionally led to the basement geology being divided into three belts according to their time of accretion: the Baikalian, Caledonian and Variscan (Mossakovsky & Dergunov 1985; Mossakovsky *et al.* 1994). However, some workers are reluctant to use divisions that refer to European orogenic events and which are poorly constrained by existing age data. Another problem is

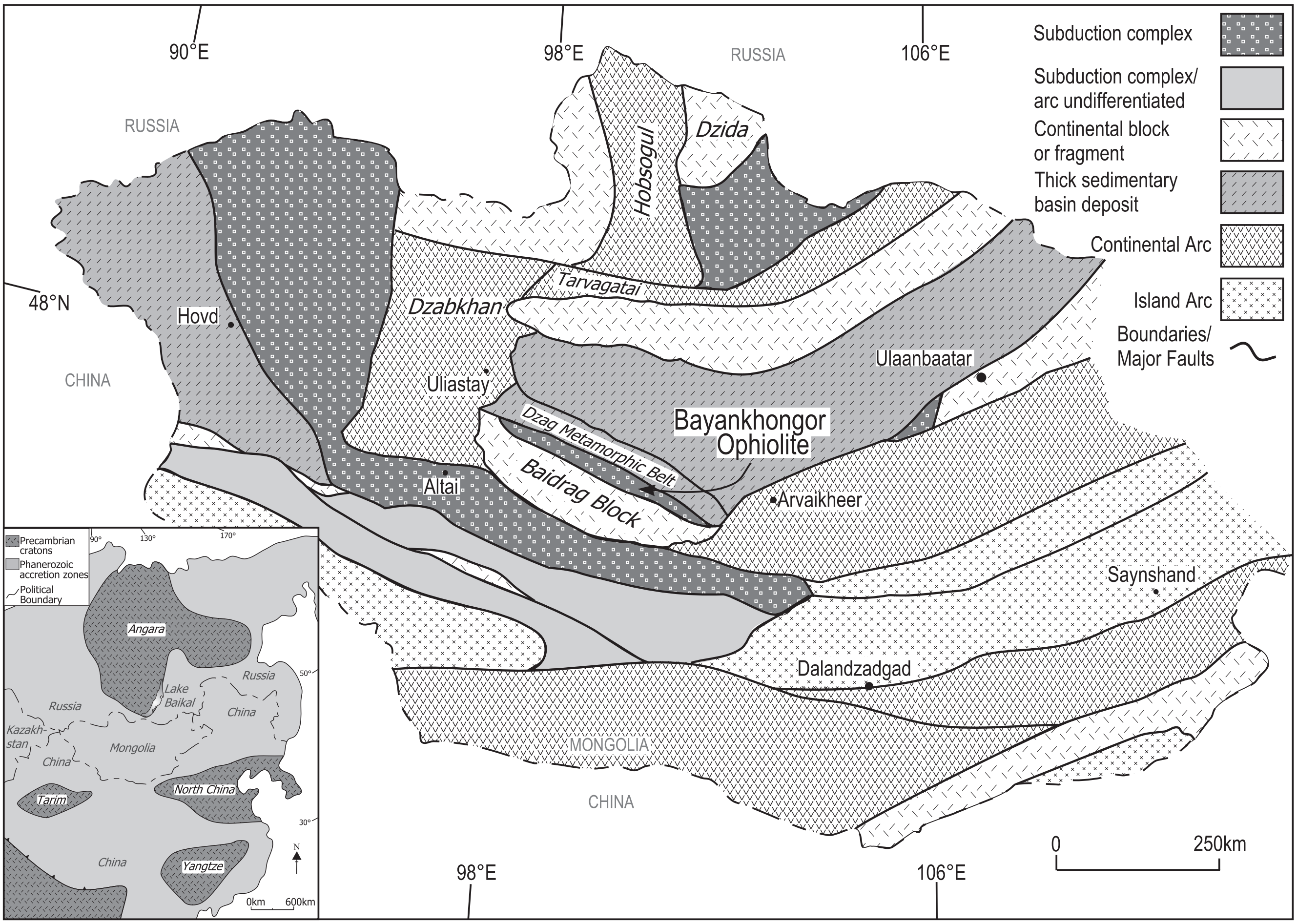

Fig. 1. Major terranes of central and western Mongolia from Dorjnamjaa *et al.* (1998). Position of the Bayankhongor ophiolite zone is indicated. Inset map shows Mongolia's position in Central Asia and locations of major Precambrian cratons.

that past studies have tended to identify all high-grade metamorphic terranes in Mongolia as Precambrian without supporting isotopic evidence (e.g. Barsbold & Dorjnamjaa 1993). Thus some authors have interpreted disparate regions containing crystalline basement (Baidrag, Dzabkhan, Tarvagatai, Hobsogul and Dzida blocks) to be part of a larger Precambrian terrane called the Tuva–Mongolian microcontinent (Fig. 1; Mossakovsky & Dergunov 1985; Şengör *et al.* 1993; Zorin *et al.* 1993; Mossakovsky *et al.* 1994; Dobretsov *et al.* 1995; see Lamb & Badarch 1997 for more discussion). However, Didenko *et al.* (1994) suggested that these blocks are separate units which were brought together during the Palaeozoic and this model is partly supported by recent U–Pb zircon dating of samples from the northern section of the Tuva–Mongolian microcontinent located in Tuva, south Siberia by Kozakov *et al.* (1999*a*, *b*) who showed that the earliest deformation in the basement rocks here occurred in the early Cambrian around 536 ± 6 Ma rather than in the Precambrian as previously assumed. However, despite these results, there are some proven Precambrian continental blocks in Central Mongolia such as the Baidrag massif which lies to the SW of the Bayankhongor ophiolite zone (Fig. 1) and which has yielded U–Pb zircon ages of 2646 ± 45 Ma and 1854 ± 5 Ma (Mitrofanov *et al.* 1985; Kozakov 1986; Kotov *et al.* 1995). From cross-sections compiled from a geological and geophysical transect across Central Mongolia, Zorin *et al.* (1993) suggested that continental crust, probably Precambrian in age, is also present below the thick sedimentary cover of the Hangai region to the NE of the Bayankhongor ophiolite. Kovalenko *et al.* (1996) published an array of Sm–Nd model ages from Phanerozoic granites in the Hangai region, which range from T_{DM}=1058 Ma to T_{DM}=2154 Ma. Because the granites have negative ε_{Nd} values, Kovalenko *et al.* (1996) argue that they are sourced from melting of continental crust below the Hangai region whose minimum age is given by the model ages.

The Bayankhongor ophiolite zone (Figs 1 & 2) is situated on the southern side of the Hangai mountains which formed during regional Cenozoic doming (Windley & Allen 1993; Barry & Kent 1998; Cunningham 1998). The ophiolite forms a NW–SE-striking sub-linear zone approximately 300 km long and up to 20 km wide (Figs 1 & 2) exposed continuously from just west of the town of Dzag to just east of Bayankhongor City (Fig. 2b). Uplift and erosion along the southern flank of the dome has resulted in good exposure of the ophiolite belt. Previous lithological mapping enables a four-fold tectonic subdivision of the region from south to north: the Baidrag complex, Burd Gol mélange, Bayankhongor zone and Dzag zone (Fig. 1; Teraoka *et al.* 1996; Tomurtogoo *et al.* 1998).

The Archaean Baidrag complex, composed of tonalitic gneiss, granulite and amphibolite, with minor marble and quartzite, has been interpreted as a microcontinental block (Mitrofanov *et al.* 1985; Kozakov 1986; Kozakov *et al.* 1997).

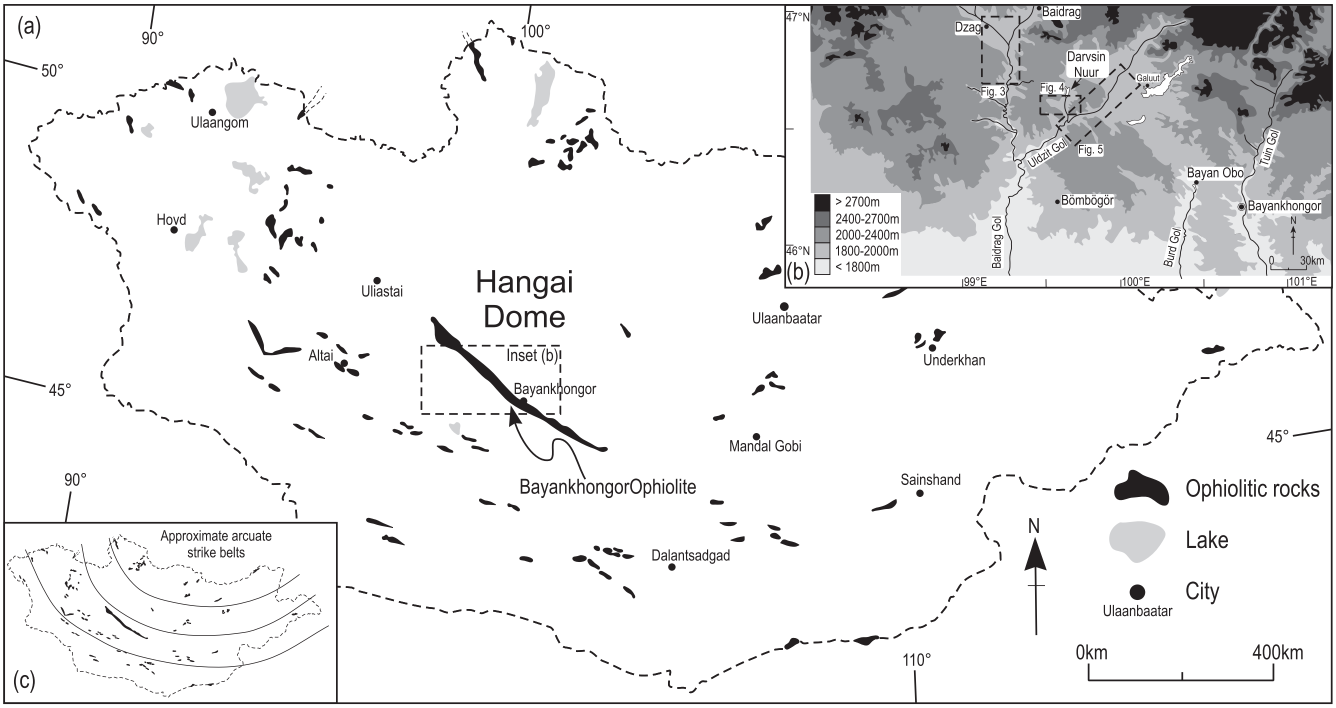

Fig. 2. (**a**) Ophiolite occurrences in Mongolia. The Bayankhongor ophiolite is the largest in the region. (**b**) Topography of the Bayankhongor area. Locations of transects and Figures 3–5 shown. (**c**) Map showing general structural trends of basement rocks in Mongolia.

The Burd Gol zone is a tectonic mélange containing lenses of sedimentary and igneous rocks cut by abundant quartz veins. From palaeontological dating of stromatolites in limestone lenses, Mitrofanov *et al.* (1981) suggested that the Burd Gol mélange has a late Precambrian age. Within the mélange, metamorphic grade increases towards the north. North of the Burd Gol zone there is a small area of interbedded marine mudstone and limestone which reportedly contain Carboniferous fossils (Dergunov *et al.* 1997).

The Bayankhongor zone contains three sub-units, here named the Delb Khairkhan mélange, ophiolite mélange and Haluut Bulag mélange. The Delb Khairkhan mélange lies to the south of the ophiolite and contains sedimentary and volcanic rocks of Precambrian to Ordovician age (Ryantsev 1994; Dergunov *et al.* 1997). The ophiolite mélange is composed of a complete ophiolite stratigraphy (Moores 1982), dated at 569 ± 21 Ma (Sm–Nd hornblende and whole-rock isochron on gabbro; Kepezhinskas *et al.* 1991) dismembered into blocks enclosed within a serpentinite matrix. The Haluut Bulag mélange is dominantly sedimentary with lenses of bedded limestone, sandstone, siltstone, and locally vesicular basalt, enclosed in a matrix of pelitic schist.

The Dzag zone consists of asymmetrically folded chlorite–mica schists that locally contain relict sedimentary features suggesting they are meta-turbidites.

Transect data

In the summers of 1997 and 1998, three cross-strike geological transects were carried out through the Bayankhongor ophiolite (including Delb Khairkhan and Haluut Bulag mélanges) and adjacent Dzag and Burd Gol zones (Figs 3–5). The transects along the Baidrag Gol south of Darvsin Nuur and along the Uldzit Gol, were chosen because of the deep incision and excellent exposure created by these river systems (Fig. 2b). Fieldwork focused on documenting stratigraphic and metamorphic relations, internal structures and structural evolution of the ophiolite and adjacent lithological units. Reconnaissance was also carried out in other areas within the Bayankhongor Zone in order to gain a wider understanding of along-strike variations and to fully characterize the Dzag and Burd Gol zones.

Major lithotectonic units

The study area is divided into six major lithotectonic units: Burd Gol mélange, Carboniferous sedimentary rocks and volcanic sequence, Delb Khairkhan mélange, ophiolitic rocks, Haluut Bulag mélange, and Dzag Zone which are juxtaposed along NE–SW-trending, NE-vergent thrust faults (Figs 3–5). In this section we describe the important lithological characteristics of each unit.

Burd Gol mélange

The contact of the Burd Gol mélange with the Baidrag block to the south is observed SW of the town of Bömbögör (Fig. 2b, N46°16.962′, E99°32.360′), where granitic gneisses of the Baidrag block are overlain unconformably by a series of thick quartzites and sandstones which comprise the southernmost section of the Burd Gol mélange. The foliation in the Baidrag gneisses dips steeply NW and the Burd Gol mélange rocks dip shallowly NE. Detailed descriptions of the Archaean Baidrag complex can be found in Kozakov (1986) and Kozakov *et al.* (1997). A few kilometres NE of the contact, the Burd Gol mélange becomes more mixed with lenses of sedimentary and igneous lithologies enclosed in a black schist matrix. Andesitic dykes, which cut the foliation are dismembered and surrounded by a matrix of graphitic schists. A more detailed study

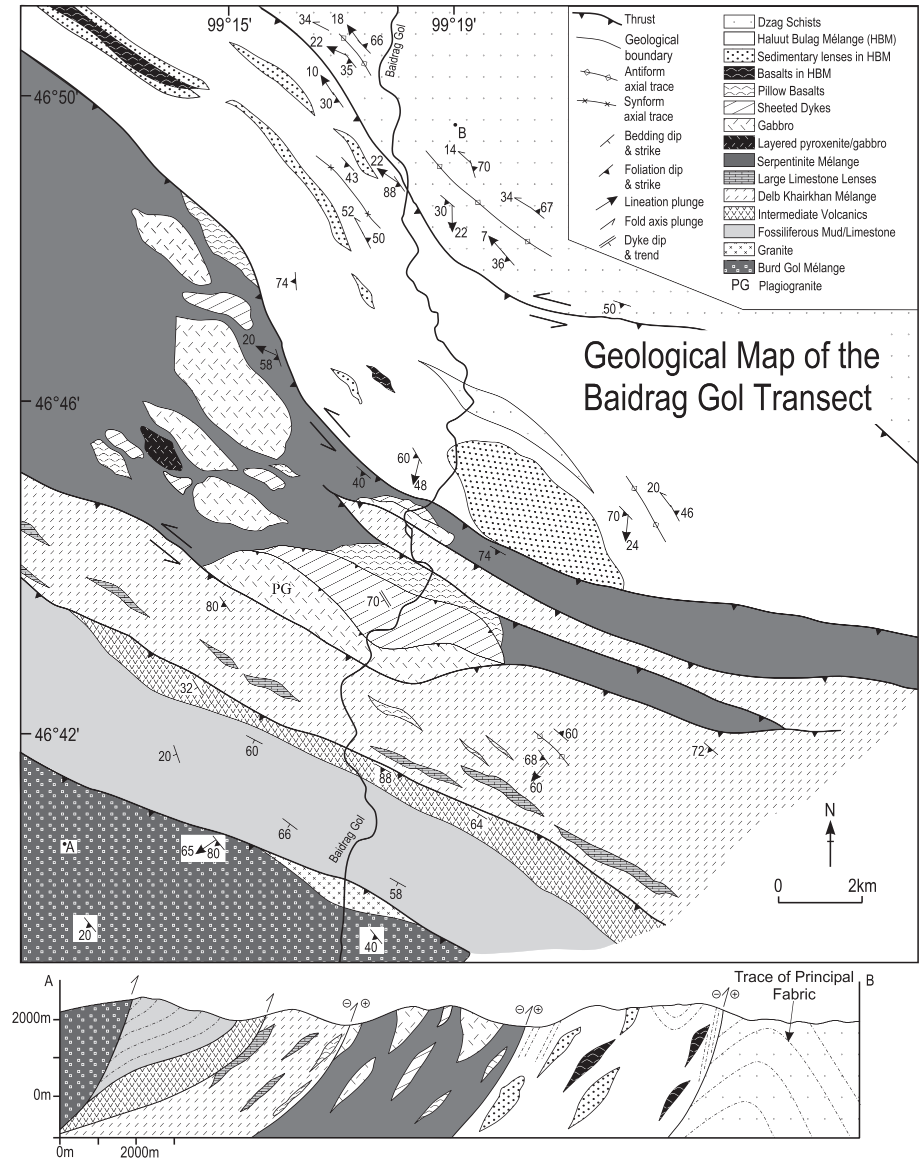

Fig. 3. Geological map and cross section of the Baidrag Gol (*River*) transect. See Figure 2b for location.

of the Burd Gol mélange was carried out to the NW of Bömbögör (Fig. 2b, N46°19.785′ E99°36.017′) where numerous, variably oriented quartz veins up to 4 m wide cut the mélange. The veins are locally gold-bearing (Komarov *et al.* 1999). Teraoka *et al.* (1996) obtained a K–Ar age of 699 ± 35 Ma from muscovite from the black schists. To the north of these black schists, many igneous and sedimentary lenses several hundred metres across are enclosed in a black schist matrix. The sedimentary lenses are composed of limestone, sandstone, siltstone, mudstone, shale, chert and well-bedded calci-turbidite. These lenses contain internal deformation which appears to have formed before incorporation into the mélange matrix, because proximal blocks of the same lithology contain dismembered folds. Igneous lithologies include basalt, gabbro, dolerite, andesite and rare rhyolite.

The Uldzit Gol transect contains particularly good exposures of the Burd Gol mélange that demonstrate that the mélange matrix is metamorphically zoned with classic Barrovian facies (Fig. 5). Over a distance of approximately 6 km, grades increase northwards reaching amphibolite facies at the thrusted contact with the Carboniferous sedimentary rocks. This is indicated by metamorphic assemblages that contain cleavage forming biotite and biotite porphyroblasts up to 1 cm in size in the south whereas northwards, the schists become garnet–biotite–muscovite-bearing with abundant euhedral, syntectonic garnets (5 mm), and then staurolite–muscovite–biotite schists. The staurolites form 1 cm wide and up to 3 cm long euhedral porphyroblasts. These are the highest-grade assemblages observed in this study, but Dergunov *et al.* (1997) reported sillimanite and Komarov *et al.* (1999) reported kyanite and sillimanite from the same unit. Possible kyanite pseudomorphs were observed, but contact metamorphism, caused by a local granite intrusion, may have overprinted any higher-grade metamorphic assemblage. Takahashi & Oyungerel (1997, 1998) determined K–Ar ages ranging from 551 Ma to 467 Ma on biotite and muscovite from granite plutons in the Uldzit Gol area, which they interpreted to represent the crystallization age. However, because these granites are tectonically foliated, we suggest that the younger ages may be due to younger metamorphic events. Local amphibolite bodies and mélange schists near the granite intrusion, contain a contact overprint texture with 5–10 cm acicular

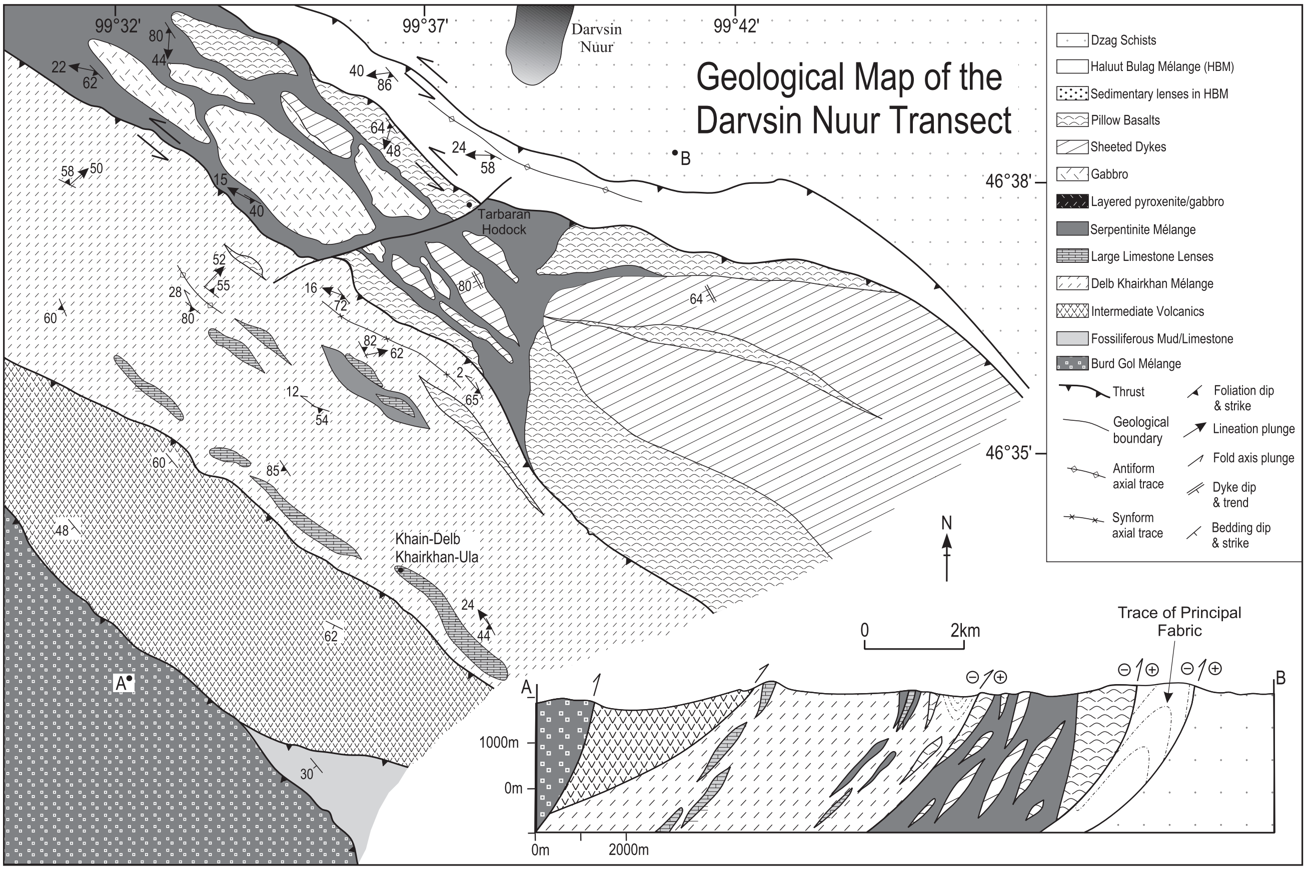

Fig. 4. Geological map and cross section of the Darvsin Nuur (*Lake*) transect. See Figure 2b for location.

bow-tie hornblende crystals overprinting the primary schistosity. The amphibolites form sheet-like bodies but it is unclear whether they were originally lava flows or dykes since they are dismembered and surrounded by the pelitic schists of the mélange.

Carboniferous sedimentary rocks and volcanic sequence

To the north and NE of the Burd Gol mélange, there are interbedded green Carboniferous fossiliferous marine mudstones and limestones (Figs 3–5), which contain abundant, well-preserved brachiopods, bryozoans, crinoids and corals (Tungalag 1996; Dergunov *et al.* 1997). The sedimentary rocks are well bedded and dominated by mudstones with beds 2–5 m thick. The limestone beds vary from a few centimetres to about 3 m thick and occur locally and discontinuously. These are the youngest known rocks in the study area.

The Carboniferous sedimentary rocks lie unconformably on (Fig. 3), or in thrust contact with (Figs 4 & 5), a sequence of extrusive volcanic rocks and minor sedimentary rocks which have been variously assigned to the Ordovician (Dergunov *et al.* 1997) or Devonian periods (Tungalag 1996) based on palaeontological evidence and correlation with similar units elsewhere. The volcanic strata consist of sheet-like flows of andesite, dacite, basalts, and trachybasalts that are interbedded with agglomerates and tuffs. There are also small intrusive bodies of quartz–plagioclase porphyry. Dacites and agglomerates are the most abundant lithologies. The agglomerates contain 2–5 cm angular fragments of nearly all other volcanic rocks, enclosed in a fine groundmass dominated by plagioclase. Individual flows vary in thickness from about 1 m to 15 m. Stratigraphically above these volcanic and plutonic rocks is a thin conformable sequence (5–10 m) of volcanogenic conglomerate and sandstone.

Delb Khairkhan mélange

The Delb Khairkhan mélange contains mixed lenses of igneous and sedimentary rocks enclosed in a matrix of pelitic schist. Along the southern boundary of the mélange in the Baidrag Gol and Uldzit Gol transects, igneous rocks seemingly derived from the volcanogenic sequence to the south, consisting of quartz–plagioclase porphyry, dacite and volcanogenic conglomerates and sandstones are included in the mélange. On the north side of the mélange near its contact with the ophiolitic sequence, lenses of gabbro, dolerite and pillow basalts several hundred metres long and 20–30 m wide resemble those in the ophiolite (Figs 3 & 4). In addition to the volcanogenic sedimentary rocks, there are lenses of limestone, quartzite, shale and sandstone. Along the contact with the volcanic rocks there is a prominent ridge of limestone that continues in en-echelon segments along strike to the east for several hundred kilometres (Figs 3–5). The ridge limestone is interbedded with shales and mudstones, bedding dips SW and the unit has a maximum thickness of around 1 km. Similar limestones occur as smaller lenses throughout the mélange.

The ridge limestones contain abundant well-preserved stromatolites. These stromatolites have been identified as *Conofiton gargantuous* by Boishenko (1979) and interpreted as late Precambrian in age (Riphean stage in Russian terminology).

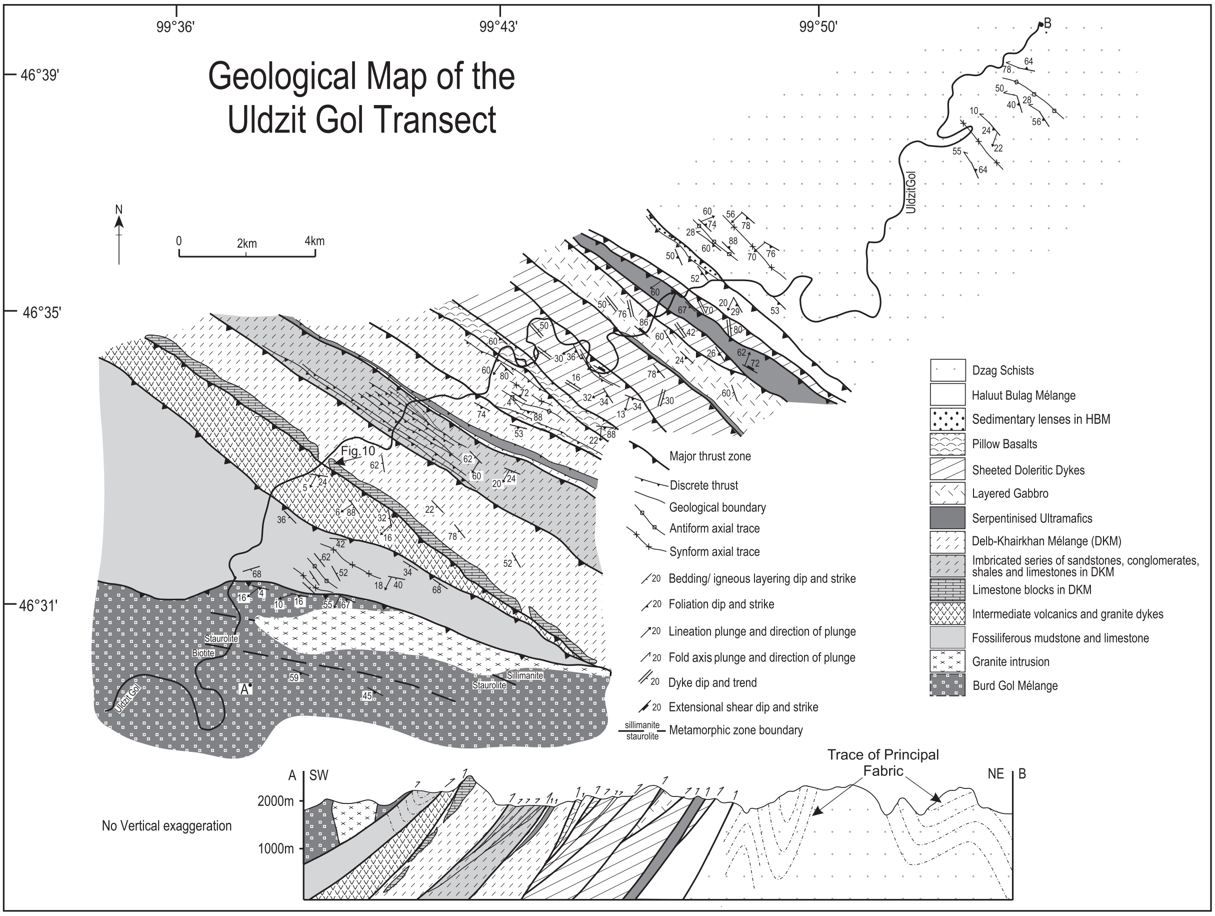

Fig. 5. Geological map of the Uldzit Gol transect. See Figure 2b for location. Note that the Delb Khairkhan mélange is subdivided into smaller lithological groups to highlight the imbricate structure that occurs where mechanically weak matrix is subordinate to rigid coherent blocks. This structural relationship is unique to this transect.

Ophiolitic rocks

The ophiolitic rocks comprise a complete ophiolite stratigraphy (Moores 1982): i.e. ultramafic cumulates, gabbro, sheeted dykes, pillow lava and local chert and limestone. However, the ophiolite is dismembered into blocks, which vary in the completeness of their internal stratigraphy (Figs 3–5). These blocks are enclosed in a matrix of sheared, serpentinized ultramafic rocks and thus the entire sequence constitutes another mélange. The composition of the mélange varies along strike. In the NW, the sequence is dominated by blocks of gabbro, poorly preserved pyroxenite and pillow basalt surrounded by serpentinite, whereas in the SE it is dominated by pillow basalt and sheeted dyke lenses (Figs 3–5). In the east of the Darvsin Nuur transect and throughout the Uldzit Gol section, the mélange has less serpentinite matrix and is dominated by thrust imbricated blocks of upper ophiolite stratigraphy (Figs 4 & 5).

Gabbro blocks (Fig. 6a) have metre-scale compositional layering (pyroxenite to leucogabbro) and crystal size layering on tens of metre scale. Generally (with the exception of local pyroxenite-dominated bodies; Fig. 3) gabbro lenses are derived from the top of the cumulate section near the sheeted dyke transition because numerous doleritic dykes and sills crosscut cumulate layering. The dykes consistently strike between 280° and 300° and dip steeply NE. One gabbro block (PG on Fig. 3) located on the southern boundary with the Delb Khairkhan mélange in the Baydrag Gol transect contains several plagiogranite dykes 1–1.5 m thick discordant to the cumulate layering of the gabbro.

On the eastern bank of the Uldzit Gol, a gabbro block has graded layers that become particularly leucocratic reaching near-anorthositic compositions. Kepezhinskas *et al.* (1991) produced a Sm–Nd whole rock and mineral isochron age of 569 ± 21 Ma for this unit, which they interpreted to be the crystallization age.

The sheeted dyke complex is very well preserved and demonstrates clear dyke-in-dyke relationships (Fig. 6b). There are two different types of dykes in the study area, plagiophyric and aphyric (Ryantsev 1994; Dergunov *et al.* 1997). The plagiophyric dykes are on average 2–3 m wide and are characterized by large (3–5 cm) plagioclase phenocrysts, which are concentrated in the centre of the dykes. The aphyric variety are around 1 m wide and have a more typical doleritic composition and texture. In addition, the aphyric dykes are often slightly discordant to the plagiophyric ones suggesting that they may be derived from a different generation of magma.

The boundary between the sheeted dykes and pillow lavas is tectonic (Figs 3–5), and because of shearing, the pillow basalts are locally poorly preserved. Aphyric (Fig. 6c) and plagiophyric pillow basalts are present and are mineralogically and texturally similar to the sheeted dykes. These similarities suggest that dykes intruding the pillow section represent the feeding conduits for successive flows. Multiple flows are

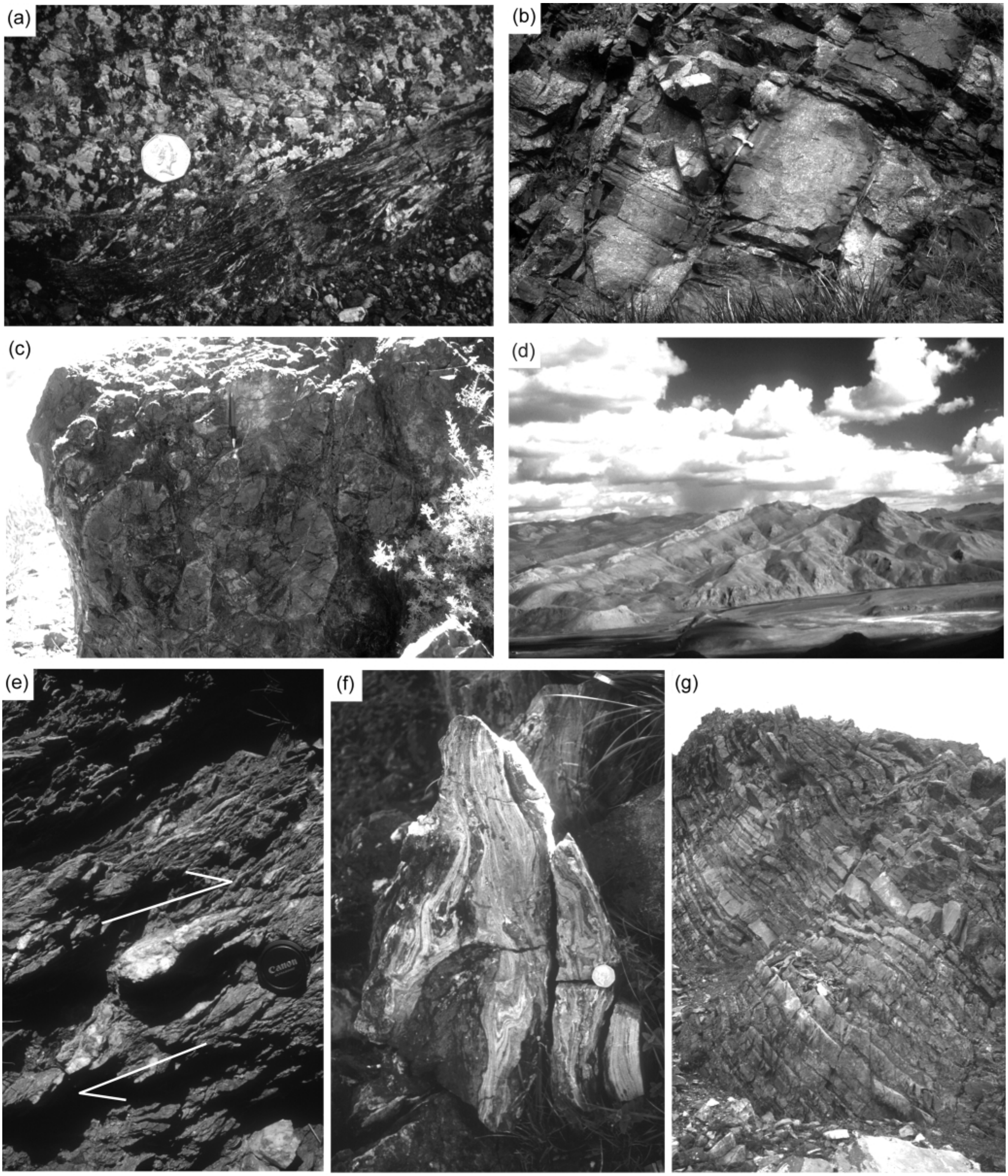

Fig. 6. Photographs illustrating typical lithologies of major tectonic units. (**a–c**) Ophiolitic rocks: (**a**) gabbro with a small ductile shear zone, (**b**) sheeted dykes (**c**) aphyric pillow basalt, (**d**) View looking east of bedded sedimentary rocks in the Haluut Bulag mélange. The darker rocks in the centre are interbedded basaltic lavas, (**e**) View looking NW of asymmetric calcite boudin in the Dzag zone suggesting top-to-the-NE shear. (**f–g**) Burd Gol mélange: (**f**) SE view of deformed limestone surrounding fragments of basalt, (**g**) calc-turbidite beds looking SE.

separated by zones of pillow breccia. The pillow lavas show considerable hydrothermal alteration with epidote veining and epidotization of some pillows.

On the western bank of the Uldzit Gol (Fig. 5; N46°33.640′, E99°43.625′) outcrops of well-preserved pillow basalts contain inter-pillow limestone and chert, and are locally overlain by bedded black chert and limestone. This is the only location where bedded sedimentary rocks were observed to be in direct contact with the pillow basalts. Neither the cherts nor the limestones were found to contain fossils, but Ryantsev (1994) reported lower Cambrian sponge spicules from the same unit.

Haluut Bulag mélange

The Haluut Bulag mélange is dominated by sedimentary lithologies. However, these lithologies are different from those of the Delb Khairkhan mélange, suggesting that the constituent lithologies of the two mélanges formed in different environments. The Haluut Bulag mélange contains lenses of limestone, sandstone, chert, tuff, minor acid volcanic material, and vesicular basalt. The basalts have a different composition to that of the ophiolite pillow basalts, that are enclosed in a pelitic matrix, which is itself lithologically heterogeneous. The matrix varies in composition from black shale to carbonate mudstone and quartzose siltstone. The matrix is metamorphosed to low-grade phyllite that surrounds coherent lenses that are commonly intensely fractured and internally brecciated.

Some very large kilometre-scale blocks within the mélange in the Baidrag Gol transect, contain interbedded basalt, mudstone and limestone, with a shallow NE dip (Fig. 6d). These large blocks dominate the NW margin of the mélange for 12 km along strike at the contact zone with the Dzag zone.

Dzag zone

The Dzag zone is composed of highly deformed pelitic and psammitic schists of lower greenschist grade containing rare 0.5 m wide layers of limestone. The composition of the schists varies slightly with higher muscovite contents occurring in the south immediately below the thrusted contact with the Haluut Bulag mélange.

Less metamorphosed fine-grained interbedded siltstones, sandstones and shales contain rounded quartz grains and preserved sedimentary structures and resemble slightly metamorphosed turbidites. Cleavage generally overprints and obscures primary bedding. However, approximately 5 km to the north of the town of Dzag (Fig. 2b), outcrops of the Dzag schists contain reasonably preserved pebbles of sandstone and siltstone despite penetrative cleavage development. Reconnaissance to the north of Dzag showed that the Dzag schists continue northeastwards over a cross-strike width of at least 10 km consisting of chlorite–muscovite schists in which the amount of chlorite relative to muscovite increases, in a northwards direction, away from the thrust contact to the south.

Kurimoto *et al.* (1998) obtained a K–Ar date of 453.9 ± 9.1 Ma on white mica from a locality on the east side of the Baidrag Gol (N46°45.93′, E99°26.98′) close to the contact between the Dzag zone and the Haluut Bulag mélange and produced a second date of 447.4 ± 9.0 Ma from a second sample of Dzag schists near Bayan Obo village (N46°19.88′, E100°14.50′). They interpreted these dates to represent an Ordovician regional metamorphic event.

Structural characteristics

Despite the general continuity of lithotectonic units in the study area, the structural architecture of the Bayankhongor zone is complex and changes along strike. In this section we describe detailed structural observations from each of the three transects from west to east followed by observations made during reconnaissance mapping in areas to the east near Bayankhongor City.

Baidrag Gol transect

Burd Gol mélange. The foliation in the matrix of the Burd Gol mélange dominantly dips shallowly (between 20° and 40°) south to SW but is locally folded into gentle NE-vergent asymmetric folds. The folding becomes more intense and foliation in the matrix dips more steeply (80°) towards the unit's northern contact which is a thrust fault that places the mélange over Carboniferous marine mudstones to the north (Fig. 3).

Carboniferous sedimentary rocks and volcanic sequence. Bedding in the Carboniferous rocks dips moderately to the SW (40–60°; Fig. 3) and contains evidence of brittle fracturing and brecciation. In this transect, the contact between the Carboniferous strata and the volcanic sequence appears to be an unconformable sedimentary contact (Fig. 3).

The dip of flows in the volcanic sequence varies from about 60°SW to sub-vertical close to the contact with the Delb Khairkhan mélange to the north (Fig. 3). A weak shear fabric occurs preferentially along the chilled margins between successive flows and is most strongly developed near the thrusted contact between the volcanic rocks and the Delb Khairkhan mélange to the north. The foliation dips steeply to the SW, has a down-dip lineation, and C–S fabrics suggest top-to-the-NE shearing i.e. the volcanic sequence has been transported over the Delb Khairkhan mélange to the north (see cross section in Fig. 3).

Delb Khairkhan mélange. The structure of the Delb Khairkhan mélange is very complex. Foliation in the matrix generally dips between 40° and 80°SW, but locally is vertical or dips steeply NE. Foliation generally strikes NW–SE, but is locally deflected around more competent lenses that are elongate parallel to strike. Small-scale folds of the foliation with fold axes trending NW and axial planes dipping SW occur locally (Figs 3 & 7).

Quartz and chlorite stretching lineations show two major trends, either down dip to the SW or sub-horizontal plunge to the west or NW, i.e. along strike (Fig. 7). SW lineations are most common. Asymmetric quartz boudins and rotated lithic clasts observed parallel to SW-trending lineations suggest top-to-the-NE movement, whereas shear sense where sub-horizontal lineations predominate is top-to-the-SE or sinistral sense. Within the pervasively sheared mélange matrix, there are discrete zones of more concentrated shearing and brittle crushing. These high strain zones are marked by 20–30 m wide belts in which the matrix rocks have been fractured to form gouge-like clay, which contains a sub-vertical fabric. Slickensides trend around 285° with a near horizontal plunge. C–S fabrics parallel to the slickensides again suggest top-to-ENE movement. The boundary of the Delb Khairkhan mélange with the ophiolite is complex in this transect; it has an 'S' shaped map view (Fig. 3), reflecting repetition caused by thrust imbrication.

Ophiolitic rocks. The ophiolitic mélange in the Burd Gol transect contains many large blocks and some near complete sections of ophiolite stratigraphy (Fig. 3). The largest blocks are at least 4 km long, and 2 km wide (Fig. 3) and the smallest are centimetre scale. Most of the larger blocks are composed of

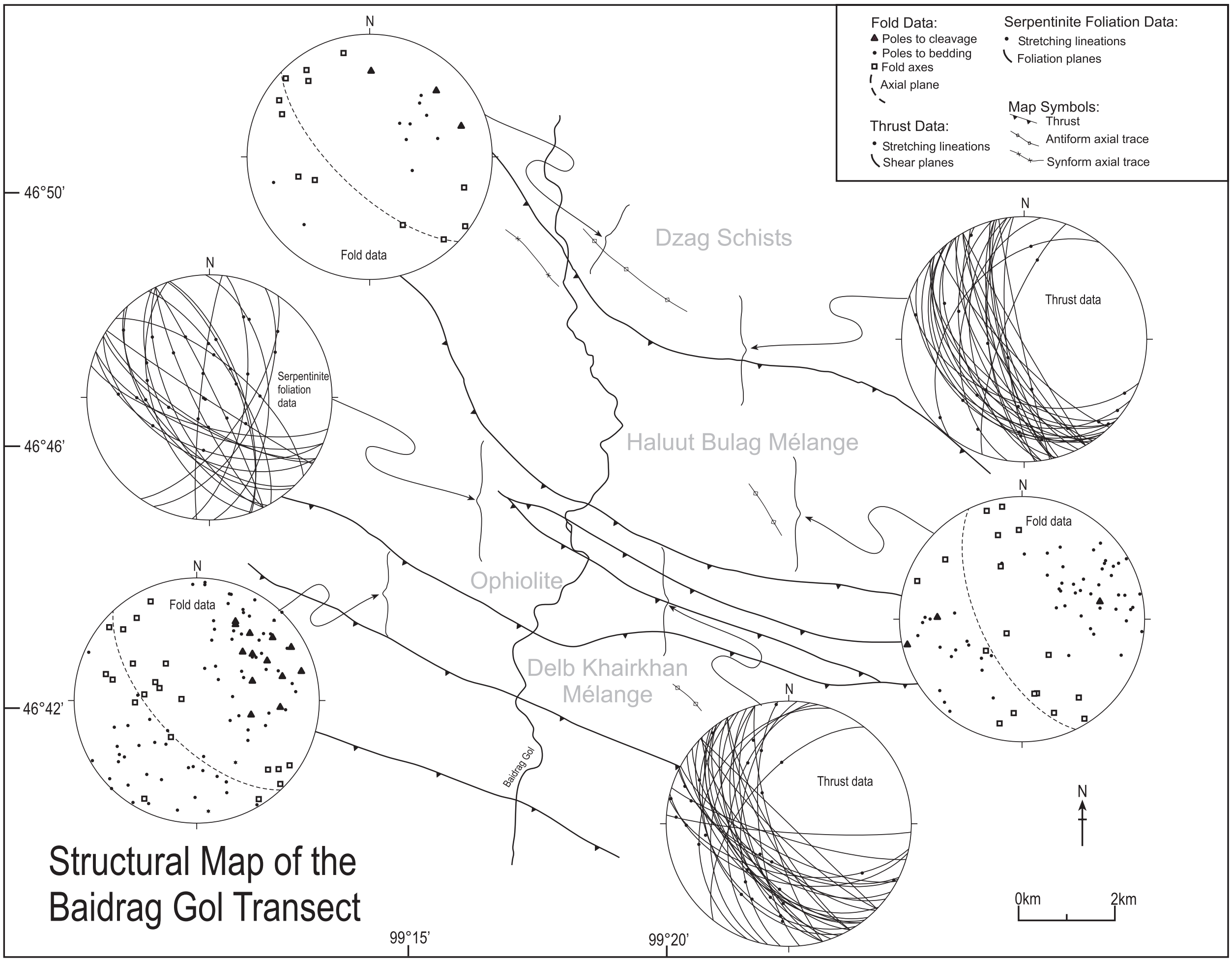

Fig. 7. Structural data from the Baidrag Gol transect. Fold data indicate SW-dipping axial planes consistent with NE-vergent thrusting. Shallow stretching lineations to WNW or NW, shown on thrust data plots, are consistent with shear sense criteria which suggest a sinistral strike slip component to the deformation. Foliation in the serpentinite mélange dips SW and ENE dips about a vertical axis due to fabric divergence around rigid lenses in the mélange, rather than folding. Lower hemisphere, equal area stereoplots. Refer to Figure 3 for lithological relations.

gabbro with cumulate layering dipping gently to the SW, but the dip direction is inconsistent in smaller blocks suggesting that these have been rotated during shearing.

A more complete ophiolite section crosses the Baidrag Gol (Fig. 3), the lowest unit is gabbro which contains an increasing number of doleritic dykes towards the north, culminating in local occurrences of sheeted dykes. However, the boundary between the gabbro–dyke unit and the sheeted dyke complex is tectonic (dipping SW) with the gabbro thrust over the sheeted dykes (Fig. 3). Although the general stratigraphic sequence has remained intact, the boundaries between units are sheared.

The sheeted dykes have trends consistent with dykes in the gabbro of between 280° and 300°, and dip to the SW (Fig. 3). Local shearing, with a SW dipping foliation, along the chilled margins of some individual dykes has produced internal breccias distorting the dyke-in-dyke relationships.

The serpentinite matrix forms low-lying easily eroded topography. The foliation in the serpentinite matrix dips steeply (60–90°) to the SW or NE fanning around a vertical axis along strike. We interpret this to be due to the foliation diverging around rigid lenses as no evidence for folding was observed (Figs 3 & 7). Lineations are difficult to detect; the few that were observed are generally expressed by chlorite accumulations on shear surfaces and record variable directions (Fig. 7).

The overall width of the serpentinite mélange is variable along strike in the Baidrag Gol transect. Towards the west, the width of the belt increases to more than 15 km (Fig. 3). However, to the east the width narrows to about 1–2 km.

The contact between the serpentinite mélange and the Haluut Bulag mélange to the north is not well exposed due to low topography and grass cover. However, it is probably tectonic because foliation intensity increases towards the contact.

Haluut Bulag mélange. The matrix structure of the Haluut Bulag mélange is dominated by a well-developed SW-dipping shear fabric (Fig. 7) that is locally folded into NE-vergent asymmetric folds (Fig. 7), and a second weak cleavage is developed axial planar to these folds. Locally, the fold hinges become rotated due to development of minor orthogonal shears in the matrix causing it to be broken into blocks. Chlorite and biotite stretching lineations on the foliation planes trend either down-dip to the SW or oblique to the west and NW. C–S fabrics, rotated quartz clasts and asymmetric boudins in shear zones suggest top-to-the-NE shear sense consistent with that documented previously in the Delb Khairkhan mélange.

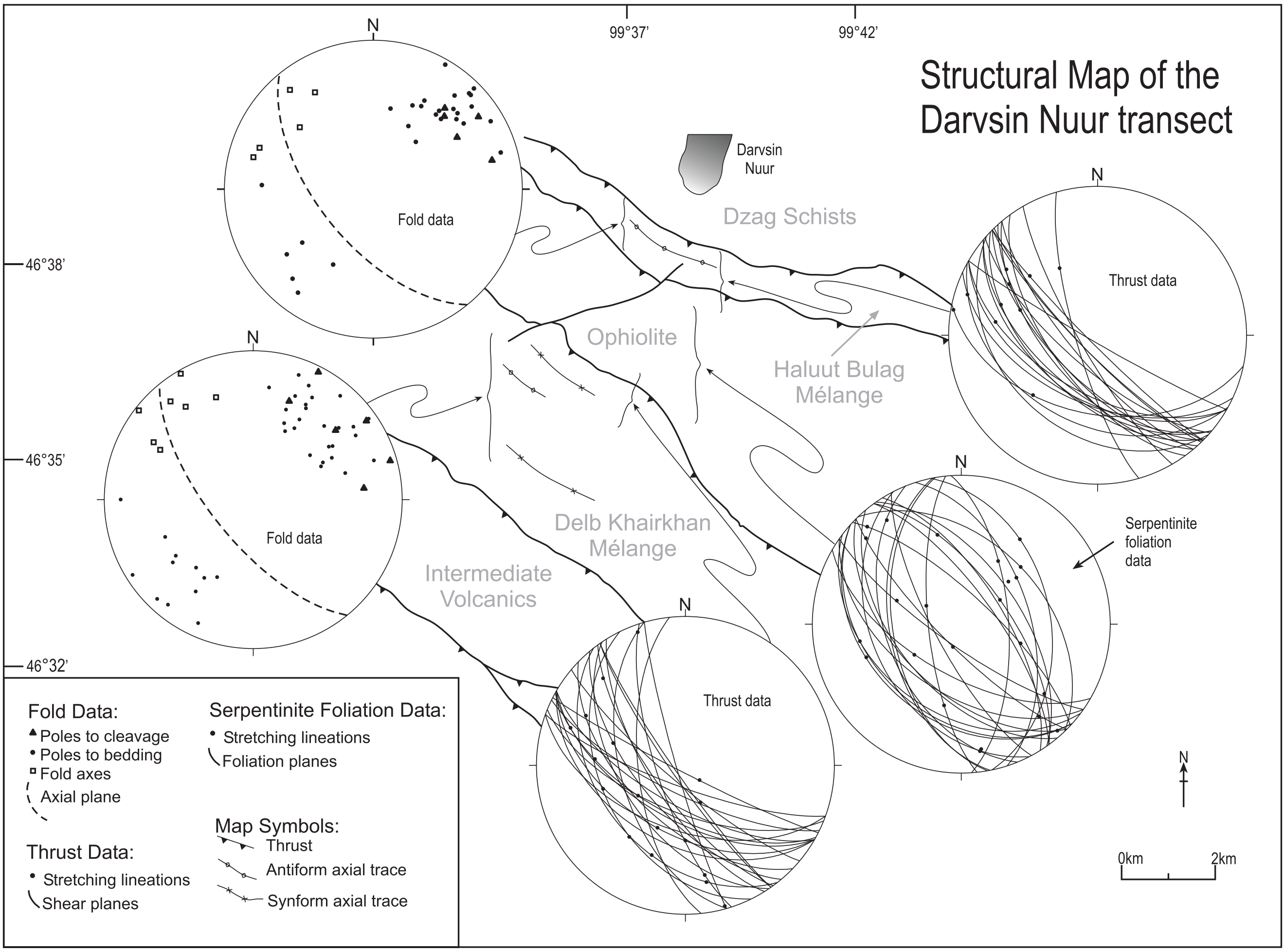

Fig. 8. Structural data from the Darvsin Nuur transect. SW-dipping thrust fabric and axial planes of folds are consistent with NE-vergence. Foliation in the serpentinite mélange is steep and fans about a NW–SE vertical axis. Lower hemisphere, equal area stereoplots. Refer to Figure 4 for lithological relations.

Dzag zone. The contact between the Haluut Bulag mélange and the Dzag zone to the north is exposed in only one locality on the western bank of the Baidrag Gol near its junction with the Dzag Gol (Fig. 3, N46°49.688′, E99°16.989′). There, the rocks of the Haluut Bulag mélange are thrust over the Dzag zone along a thrust fault which dips between 50° and 80° to the SW (Figs 3 & 7). The fault zone is about 20 m thick and contains internally imbricated slices of the Dzag schists. The cleavage is deformed into asymmetric NE-vergent folds (Fig. 7). Minor fold axes have consistent shallow plunges to the NW, and a weak SW-dipping second cleavage is axial planar to the hinge zones. Abundant thin calcite and quartz veins cut the schists, and have been boudinaged and rotated parallel to the first cleavage. Lineations are not well developed in the contact thrust zone with the Haluut Bulag mélange, but those that are detectable suggest slightly oblique slip in a WSW–ENE direction. Shear sense indicators such as boudinaged veins (Fig. 6e) suggest top-to-the-NE shearing which is consistent with the NE vergence of folds of the first cleavage. Immediately to the north of this locality, outcrop exposure ends and grass covered plains obscure the geology around the town of Dzag (Fig. 2b).

Darvsin Nuur transect

Burd Gol mélange. The Darvsin Nuur transect is located approximately 40 km SE along strike from the Baidrag Gol transect (Fig. 2). In the Darvsin Nuur transect, the Burd Gol mélange is poorly exposed due to grass cover. However, the rocks that are exposed are dominated by pelitic schists with a penetrative schistose foliation that dips SW at approximately 40–60°. The northern margin of the mélange is marked by a thrust contact with both the Carboniferous sedimentary rocks and extrusive volcanic sequence (Fig. 4).

Carboniferous sedimentary rocks and volcanic sequence. The Carboniferous sedimentary rocks crop out in the SW of the transect area and increase in thickness towards the SW (Fig. 8). Bedding dips about 30°SW. The contact between the Carboniferous rocks and the volcanic sequence is unexposed.

The volcanic sequence is poorly exposed over a 5 km width but extends along strike to the NW and SE. Flows of basalt and dacite strike NW–SE and have a variable dip between 40° and 60°S or SW (Fig. 4). Locally developed sub-vertical ENE–WSW striking shear zones record dextral shear sense based on asymmetry of boudinaged calcite veins. These shear zones have a maximum width of 10 cm and are confined to the volcanic units. Near the contact of the volcanic series with the Delb Khairkhan mélange, to the north, a pervasive shear fabric is developed in the volcanic units with shear zones dipping approximately 50° to the SW. Quartz stretching lineations in the shear zones are down-dip and rotated clasts in the agglomerates suggest top-to-the-NE shearing or thrusting of the volcanic series over the Delb Khairkhan mélange (Fig. 4).

Delb Khairkhan mélange. The principal fabric in the Delb Khairkhan mélange becomes gradually steeper from 50° at the thrust contact to approximately 80° near the limestone at the summit of the Khain–Delb Khairkhan–Ula ridge (Fig. 4). The limestone is highly fractured and contains abundant calcite and quartz veins. Thin interbeds of shale dipping approximately 60°SW within the limestone have accommodated local shearing. On the north side of the ridge, there is a 300 m wide zone of shale that is deformed into NE vergent open folds with minor fold axes plunging consistently 10–30°NW (Figs 4 & 8). The area to the south of the contact with the ophiolitic rocks is a broad valley with only a few small isolated hills providing exposure of the mélange.

On the north side of the mélange there is a small block of brecciated dolomite surrounded by foliated serpentinite forming a broadly sigmoidal outcrop pattern (Fig. 4). As well as the serpentinite outcrops, there are also some pillow basalt blocks in variable states of preservation near the contact of the Delb Khairkhan mélange with the ophiolitic rocks (Fig. 4) which contain a heavily sheared phacoidal texture, with individual phacoids forming rod-like structures. The long axes of the rods have variable orientations in individual blocks suggesting rotation between blocks. The matrix schists around these blocks have a more consistent foliation that dips approximately 70–85° to the SW and in some places locally to the NE (Fig. 8). Amphibole and calcite stretching lineations on the foliation planes plunge shallowly WNW and asymmetric minor folds suggest thrust movement with a sinistral component. The contact of the Delb Khairkhan mélange with the ophiolitic sequence is not exposed, but is assumed to be tectonic due to well-developed shear fabric close to the contact zone in both the pillow lava blocks and the matrix schists.

Ophiolitic Rocks. The large gabbro block on the west side of the area in Fig. 4 (N46°37.000′ E99°35.000′), has well-developed reticulate vein networks associated with local normal-sense shear zones. Other small shear zones with ductile characteristics (Fig. 6a) are not associated with veining but are also normal sense. The normal-sense shears are confined to the gabbro block and may represent relict ocean floor faulting.

In the easternmost section, there is a very large block of pillow basalt and sheeted dyke rocks that extends into the Uldzit Gol section and has a more thrust-imbricate style of deformation (Fig. 4). The contact between the pillow basalt block and the sheeted dykes is sheared and is almost vertical but reliable indicators of shear sense were not found. The strike and dip of the dykes in this transect, and in the Baidrag Gol transect are similar, i.e. they strike NW–SE and dip 60–80°SW (Figs 3 & 4). Flows in the pillow basalts dip steeply to the SW at around 60° to 80°.

Within the serpentinite matrix, small sheeted-dyke lenses approximately 5 m in length have their long axes orientated NW–SE parallel to the strike of the serpentinite foliation, which clearly diverges around and envelops the blocks. The dominant foliation dip is to the SW consistent with that observed throughout the transect (Figs 4 & 8). Serpentine and talc stretching lineations are either down-dip, or plunge shallowly to the NE or SW. Deviations from southwesterly dips occur in zones where there are large expanses of serpentinite without coherent blocks. The foliation in such areas generally has a near vertical to NE dip, possibly related to foliation fanning around vertical (Fig. 8) Generally, it is difficult to measure foliation planes because the serpentinite contains small phacoidal bodies rather than parallel cleavage planes.

At the contact zone between the serpentinite mélange and the Haluut Bulag mélange (Fig. 4), there are highly sheared pillow basalts on the south side and highly sheared limestones and pelitic rocks on the north side. On both sides of the contact a strong penetrative foliation that dips 30–50° to the SW (Fig. 8). Chlorite and quartz stretching lineations plunge in a SW or WSW direction. C–S fabrics and asymmetric quartz boudins parallel to these lineations suggest top-to-the-NE or top-to-the-east directed shear consistent with the general directions observed in the Baidrag Gol Transect.

Haluut Bulag mélange. The Haluut Bulag mélange is significantly thinner in the area of Darvsin Nuur than in the Baidrag Gol transect, reaching less than 2 km maximum outcrop thickness.

Cleavage planes in the mudstone, dip shallowly SW near the contact with the serpentinite mélange, but steeply NE towards the Dzag zone in the north. It appears therefore that the foliation is folded into a large NE-vergent open fold (Figs 4 & 8). Foliation is more strongly developed in the mudstones near the contact with the Dzag zone, suggesting a tectonic contact (Figs 4 & 8) but the actual contact is unexposed.

Dzag zone. There is very poor exposure of the Dzag lithologies in this transect area due to low topography around Darvsin Lake.

Uldzit Gol transect

Burd Gol mélange. The overall structure of the Burd Gol mélange is extremely complex with variable foliation strike and dip. As well as pervasive shearing within the matrix there are local areas of more concentrated shear. In the high strain zones, a near vertical penetrative foliation strikes NW–SE, and rocks have suffered intense brittle deformation and internal brecciation producing 5 m wide zones of clay gouge material. In one high strain zone, shearing has produced ductile mylonitic fabrics in limestone surrounding fragments of basalt (Fig. 6f). Away from the high strain zones large lenses of undeformed sedimentary rocks (Fig. 6 g) are enclosed within the pelitic schist matrix. Near to the contact with the Carboniferous rocks to the north, the foliation in the mélange matrix becomes more uniform dipping to the SW. The contact is a thrust fault (Fig. 5) marked by a clear topographic break striking NE–SW. The pelitic schists and amphibolites in the Burd Gol mélange above the fault have a well developed cleavage dipping 4°–20°SW (Figs 5 & 9). Biotite and amphibole lineations on the cleavage plane plunge consistently SW or WSW (Figs 5 & 9). C–S fabrics and rotated staurolite porphyroblasts within the matrix schists suggest top-to-the-NE movement.

Carboniferous sedimentary rocks and volcanic sequence. Directly beneath the thrust contact with the Burd Gol mélange in the footwall, Carboniferous limestones are mylonitized and the mylonitic fabric is folded into tight isoclinal folds inclined slightly to the NE. Fold axes plunge shallowly NW. The degree of mylonitization diminishes to the north of the contact, where after 30 m the rocks lack shear fabrics and folds are more open in character (Figs 5 & 9).

Near the northern contact with the volcanic sequence, the Carboniferous sedimentary rocks have a weak cleavage that

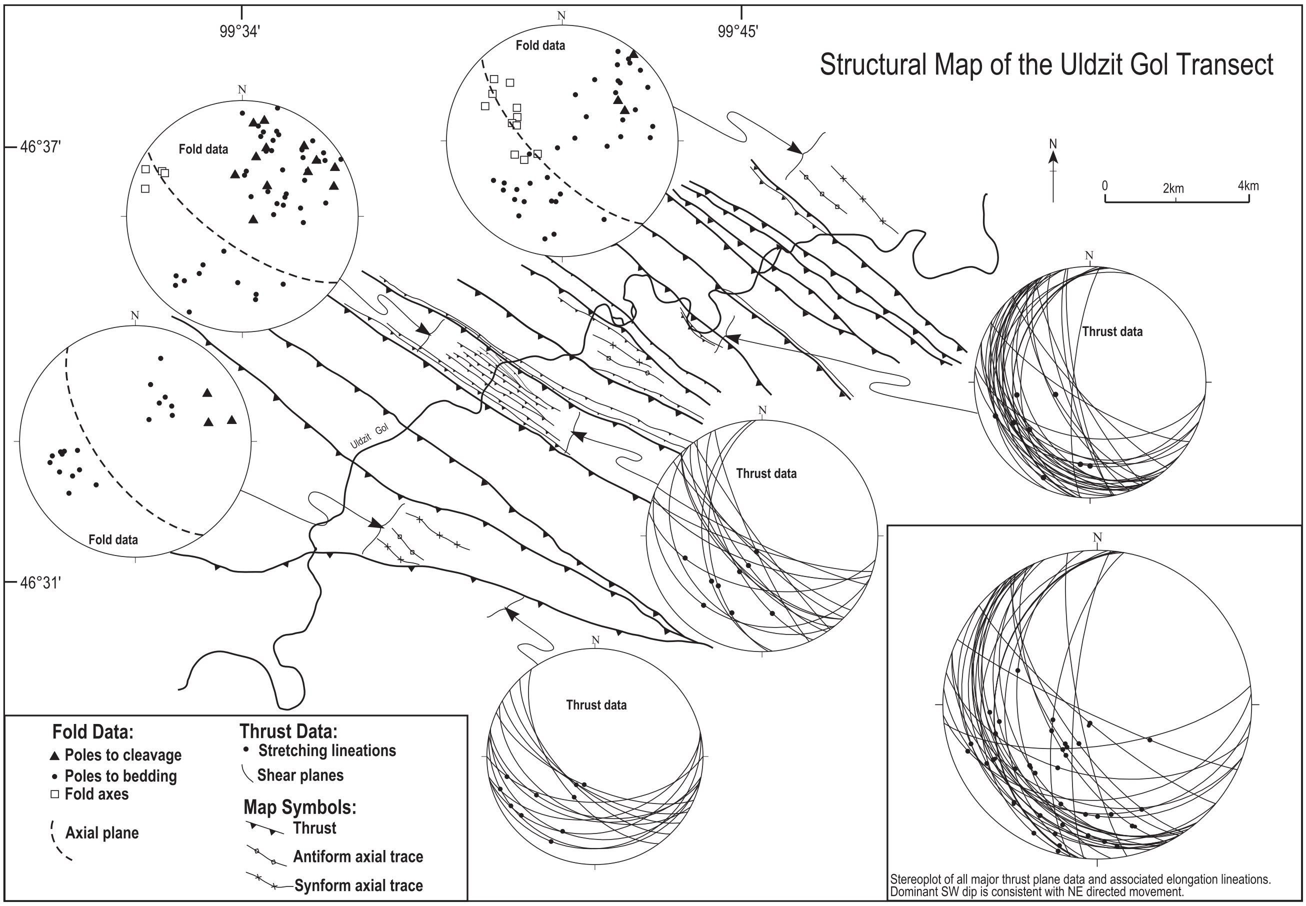

Fig. 9. Structural data from the Uldzit Gol transect. SW-dipping axial planes of folds and dominant SW-dipping thrust fabric suggest NE-vergent thrusting in the area. Lower hemisphere, equal area stereoplots. Refer to Figure 5 for lithological relations.

dips steeply SW and is accompanied by brecciation of the mudstones. The volcanic rocks immediately on the north side of the contact are also foliated with the same dip and strike. The actual contact is not exposed and there are no reliable shear sense indicators, but it appears likely that the Carboniferous rocks have been thrust over the volcanic units based on the evidence for NE transport of the Burd Gol mélange and the NE-vergent folding within the Carboniferous rocks (Figs 5 & 9).

On the northern side of the volcanic sequence, the rocks are weakly foliated with foliation dipping to the south or SW (Fig. 5). Down-dip quartz stretching lineations and C–S fabrics suggest top-to-the-north or NE, or thrusting of the volcanic and Carboniferous rocks over the Delb Khairkhan mélange to the north (see cross-section Fig. 5).

Delb Khairkhan mélange. In this transect, the mélange is divided into two compositional and structural zones. The southern zone is lens-dominated and highly imbricated by thrusting with very little pelitic matrix (Fig. 5, cross-section), whereas the northern section near the ophiolite is dominated by a pelitic matrix. Figure 10 shows a view across the imbricate zone looking NW. The northern and southern zones are separated by a zone of concentrated shearing (Fig. 5, N46°34.000′, E99°39.000′), in which the matrix rocks have suffered intense brittle deformation and internal brecciation. This shear zone marks a metamorphic divide because the matrix rocks on the north side are more recrystallized with a greater abundance of muscovite and sericite defining the principal foliation. The dominant dip of the foliation is to the SW and there are some minor folds with axial planes that dip SW and quartz stretching lineations also plunge SW consistent with overall NE transport (Figs 5 & 9). Near the contact between the Delb Khairkhan mélange and the ophiolite, the foliation is more strongly developed suggesting a non-exposed tectonic contact.

Ophiolitic rocks. Immediately to the north of the Delb Khairkhan mélange is a block of aphyric pillow basalt that has pervasive SW dipping foliation. Small, locally developed shears dip north and contain C–S fabrics and offset veins that suggest normal shear sense. Surrounding these shears are zones of carbonate alteration and copper mineralization. Since the normal-sense shears are confined to the pillow basalts we suggest that these structures may be relicts of ocean floor faulting.

SW-dipping foliation becomes more pervasive to the north, close to the contact with a block of sheeted dykes, suggesting a sheared contact. Sub-horizontal chlorite stretching lineations plunge WSW or ESE, and rotated plagioclase phenocrysts parallel to the WSW lineation suggest top-to-ENE shearing. The sheeted-dyke complex to the north has a total thickness of approximately 2.5 km but is actually composed of two sheeted-dyke blocks juxtaposed along a large thrust fault which has caused the dyke rocks to have a strong shear fabric throughout an area 100 m wide (Fig. 5). The dykes strike NW, consistent

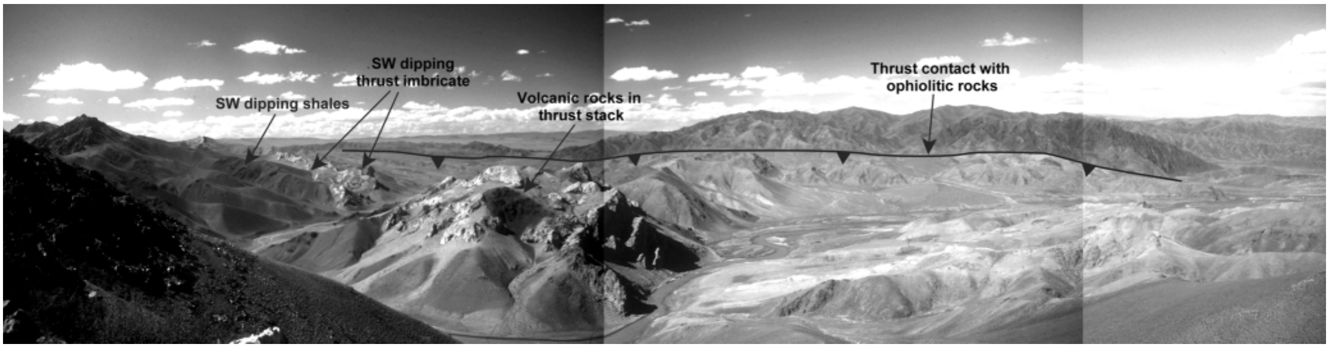

Fig. 10. Composite panoramic photograph looking NW across the Delb Khairkhan mélange to the thrust contact with the ophiolitic rocks in the Uldzit Gol Transect. Note that topography at the thrust contact with the ophiolitic rocks reflects resistance to erosion (see Fig. 3 for viewpoint location).

with those observed in the other two transects, but in contrast they dip NE.

A large gabbro body to the north contains several dykes intruded along NNE dipping shears in the gabbro body. The dykes have been boudinaged into a series of sigmoidal lenses enclosed in mylonitized gabbro. Rotation of phenocrysts in the gabbro and C–S fabrics in the dykes suggests that the shears are normal sense. Locally dykes form complex reticulate networks, which end abruptly in shear zones that offset the dykes suggesting normal shear sense. The normal shears are confined to the gabbro block and do not extend into the surrounding serpentinite mélange.

The northernmost section of sheeted dykes at the contact with the Haluut Bulag mélange has a prominent foliation which dips steeply to the SW.

Haluut Bulag mélange. On the west side of the Uldzit Gol, the Haluut Bulag mélange is very thin and is composed of only a single massive limestone block. On the eastern side of the Uldzit Gol, the mélange widens and is dominated by pelitic schists with small lenses of sandstone and siltstone. Foliation in the schists dips variably to the SW (Fig. 9). Near the contact with the Dzag zone, schistosity becomes steeper (up to 80° to the SW) and more pervasive (Fig. 9).

Dzag zone. The foliation of the schists in the Dzag zone immediately north of the contact, is folded and kinked into open, NE vergent asymmetric folds (Figs 5 & 9). Chlorite stretching lineations on the foliation plane plunge SW (Figs 5 & 9) and asymmetric boudinaged calcite veins viewed parallel to the lineation direction suggest top-to-the-NE shearing, consistent with the general shear directions recorded throughout the transect (see cross-section Fig. 5).

Reconnaissance observations near Bayan Obo and Bayankhongor City

Reconnaissance studies were carried out to assess whether the structural observations made in the three transect areas continue along strike to the SE.

Near Bayan Obo village (Fig. 2b) the same lithotectonic units of the Delb Khairkhan mélange, ophiolite zone and Haluut Bulag mélange were found but without the Carboniferous sedimentary rocks or volcanic sequence. The structures in the three mélange units are consistent with those observed in the transect zones, i.e. a SW-dipping foliation and top-to-the-NE shear sense. However, the sub-linear arrangement of units breaks down near Bayankhongor City, where it becomes difficult to discern individual mélange units. Sporadic outcrops of ophiolite lithologies are surrounded by shale and limestone. Unfortunately, the degree of exposure is very poor making it impossible to carry out detailed structural investigations. Delor *et al.* (2000) produced an Ar/Ar age of 484 ± 5.9 Ma of hornblende from a foliated pillow basalt collected just SW of Bayankhongor City which was interpreted as the age of metamorphism.

The Dzag schists to the north of Bayankhongor City have slightly different structural characteristics with foliation commonly dipping steeply NE. However this is variable along strike and because the average dip value is approximately 80° this variation could simply be the result of steep cleavage fanning.

Discussion

The above data show that all three transects share structural and lithological similarities that can be extrapolated over the entire 300 km strike length of the ophiolite zone. The main subdivisions of the Burd Gol and Delb Khairkhan mélanges, ophiolitic rocks, Haluut Bulag mélange and Dzag zone can be traced continuously along strike (Fig. 11). In contrast, the Carboniferous marine sedimentary rocks and the volcanic series are less continuous and occur only locally in the transect areas (Fig. 11), but not along strike to the east as shown by reconnaissance investigations. Moreover, the Carboniferous sedimentary rocks are discontinuous within the individual transect areas (Fig. 11) and have experienced less intense deformation than the other lithological units as the beds have only been tilted to the SW or gently folded without penetrative cleavage development.

Mitrofanov *et al.* (1985) and Komarov *et al.* (1999) suggested that the Burd Gol mélange represents a passive margin sequence. Although bedded sedimentary rocks in unconformable contact with the Baidrag block could constitute a passive margin environment, we believe that the highly mixed and structurally complex rocks adjacent to the ophiolite zone constitutes a subduction accretion complex. The Burd Gol mélange is also the most highly metamorphosed unit locally containing amphibolite grade staurolite and kyanite schists. The increase in metamorphic grade towards the contact with the ophiolite could be because deeper sections of the accretionary wedge are exposed along the thrust contact, or that the contact itself represents the site of the original subduction zone and locus of highest pressure metamorphic assemblages. The

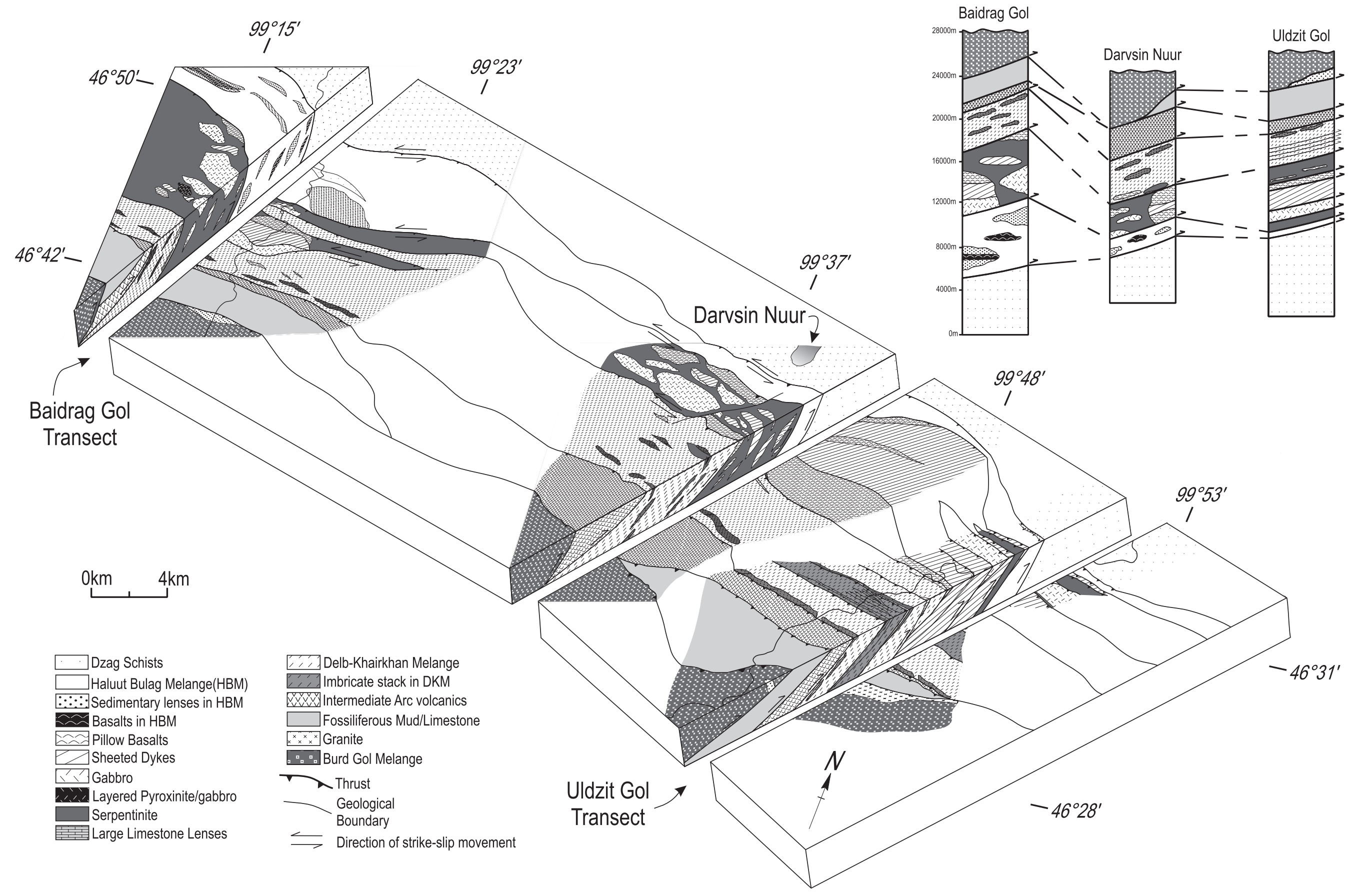

Fig. 11. Block diagram illustrating interpreted along-strike linkage of lithological units and major faults within the Bayankhongor ophiolite belt. Continuity of units and structures in unmapped areas is interpreted from geomorphic relations and aerial photograph analysis. Schematic columns represent correlation of tectonic stratigraphy between transect areas. Dotted tie lines represent interpreted correlations between boundaries along strike. Note discontinuous nature of the Carboniferous mudstones and the changes in thickness of other units.

abundant quartz veins within the mélange are probably products of dewatering of sedimentary rocks and dehydration of subducting oceanic crust similar to those described from modern accretionary environments such as Nankai in Japan (Agar 1990; Maltman *et al.* 1992).

All three mélanges that make up the Bayankhongor ophiolite zone (Delb Khairkhan, ophiolite, and Haluut Bulag mélanges) contain similar lithologies, in which lenses of competent rocks are enclosed within a less competent matrix. Generally, the lenses are largely undeformed, whereas the matrix has absorbed most of the strain and consequently has a well-developed foliation. The foliation consistently dips steeply (50–80° on average) to the SW (Figs 7–9). In addition, stretching lineations developed within the foliation plane trend uniformly to the SW or WSW–ESE (Figs 7–9), and shear sense indicators consistently suggest top-to-the-NE or ESE. It is possible that thrusting was directed first to the NE and then there was a change in stress field conditions to produce the ESE-directed strike-slip movement indicated by the shallow lineations. However, both lineation orientations are defined by chlorite and quartz which deform ductiley at low temperatures (<400°C), thus both directions of movement may have been synchronous and deformation may have been partitioned between NE-directed thrusting and sinistral strike-slip displacements in an overall transpressional regime. However, with the present data it is impossible to conclude definitively whether this is the case or if deformation was partitioned in time. The fact that folding in the Dzag zone is consistently NE-vergent might suggest that the ESE strike-slip zones are a more localized feature within the ophiolite zone. We suggest that combining the overall thrust movement with a strike-slip component is a mechanism by which mélanges can be created that have complexly mixed lithological lenses, but within clearly defined boundaries i.e. only ophiolitic rocks in the serpentinite mélange. Thus internal divisions are mixed, but original facies boundaries are commonly retained (Fig. 11). An exception to this is within the Delb Khairkhan mélange where ophiolitic lenses such as pillow basalts and serpentinite (Figs 3 & 4) are included in the sediment-dominated mélange, presumably due to localized mixing along the contact where a sinistral strike-slip component of deformation has occurred. There are some slight differences in the style of deformation of the mélange units along strike. The most notable example is in the Uldzit Gol Transect where the Delb Khairkhan and serpentinite mélanges contain an imbricate thrust stack instead of a pervasively sheared mélange (Fig. 5). This is probably because where imbrication has occurred, the mélanges contain less mechanically weak matrix and accommodate shortening by discrete thrust motion between more rigid lenses.

Lithological variations within the Delb Khairkhan mélange suggest that the mélange is derived from different tectonic environments. The large limestone lenses that locally contain stromatolites, and sandstone and conglomerates suggest a shallow water environment, whereas the fine muds and siltstones which comprise the protolith for the matrix schists suggest deeper water environments. Together, these rocks may represent sediments from the trench of a subduction zone with the limestones and sandstones being shed from the top of the accretionary wedge and the pelitic rocks of the mélange matrix representing pelagic mudstone scraped from the ocean floor.

The Dzag schists to the north of the ophiolite zone have previously been interpreted as part of an accretionary wedge (Dergunov *et al.* 1997). We believe that thick and lithologically monotonous chlorite mica schists, may have once been clastic turbidites and more likely represent a deep-water passive margin or more specifically continental rise sequence than an accretionary wedge. In addition, the Haluut Bulag mélange which is composed dominantly of limestone lenses in a pelagic matrix also contains vesicular basalts suggesting subaerial eruption. These rocks may have been shed from a continental margin to the north onto the continental rise as debris flows and subsequently incorporated into the mélange during obduction of the ophiolite.

Previously, there has been disagreement over the direction of obduction of the ophiolite and the vergence of structures. Tomurtogoo (1989, 1997) suggested that the ophiolite was thrust to the SW based mostly on inferred dip of stratigraphic units, whereas Kopteva *et al.* (1984), Ryantsev (1994) and Dergunov *et al.* (1997) recognized SW-dipping faults and suggested NE-directed thrusting based on the palaeontological age of the units available. We agree with the latter opinion based on the evidence presented here of consistent SW-dipping structures and shear sense indicators which suggest NE or ENE movement.

The ophiolite contains a complete igneous stratigraphy of serpentinized ultramafics, gabbro, sheeted dykes and pillow lavas, as described by Moores (1982). We interpret the rocks to have formed at a spreading centre based on the stratigraphic relations, presence of sheeted dykes, and relict normal faults that presumably formed during sea-floor spreading. What remains unclear is whether the rocks formed in an open ocean or a marginal back-arc basin associated with a subduction zone. The discovery of limestone in spaces between pillow basalts suggests that the ophiolite formed in an environment above the carbonate compensation depth, but conversely, local occurrences of chert suggest a deeper water environment. As there are no other sedimentary rocks in direct contact with the ophiolite and since dismemberment makes it difficult to determine how thick the ocean crust was, we cannot draw any more substantive conclusions. The only current published geochemical data available on the ophiolitic lithologies are in Kepezhinskas *et al.* (1991) which ambiguously show some MORB characteristics together with indications of a modified source, possibly a plume. The evidence for a shallow water environment shown by the interpillow limestones suggests that this was not a normal Atlantic-type ocean basin. A more detailed environmental model requires a better geochemical database.

The chronology of deformation in the area is complex and the age of obduction of the ophiolite remains controversial. Deformation occurred in the Burd Gol mélange as early as 699 Ma (Teraoka *et al.* 1996) which implies that subduction was occurring from at least this time, well before the obducted ophiolitic rocks were formed at 569 ± 21 Ma (Sm–Nd mineral and whole rock isochron; Kepezhinskas *et al.* 1991). Dates relating to metamorphism of the Dzag schists cluster around 450 Ma (K–Ar method on white micas; Kurimoto *et al.* 1998) and combined with the Ar/Ar age of 484 Ma (Delor *et al.* 2000) from the ophiolite itself suggests that obduction may have occurred around this time. However, this age could equally relate to post obduction metamorphism. The inclusion of the Carboniferous sedimentary rocks within the thrust imbricated succession may suggest that deformation was continuous until post Carboniferous times. However, since the sediments are less penetratively deformed than the other units, we suggest that these represent an overlap assemblage, deposited after major deformation associated with ophiolite obduction and mélange deformation in the Bayankhongor area. Post-Carboniferous reactivation of the Bayankhongor zone may be related to late Palaeozoic tectonic events in southern Mongolia (Hendrix *et al.* 1996; Lamb & Badarch 1997; Höck *et al.* 2000), but the actual extent of these deformational events in the Southern Hangay region is poorly resolved. Work in progress will hopefully lead to more precise dating and will allow a more detailed evolutionary history to be developed.

Because the area is dominated by sedimentary mélanges, it could be suggested that Şengör *et al.*'s (1993) model of a vast accretion complex applies to this area. Moreover, the occurrence of andesitic dykes intruding the Burd Gol mélange and the intermediate volcanic sequence to the north (Fig. 11), could be interpreted to represent incipient arc formation, built on top of the accretionary wedge which is a prominent feature of the Şengör *et al.* (1993) model. However, an implicit part of their model is that the accretion zone has a continuous history, therefore ophiolites represent offscraped fragments within the complex rather than discrete sutures. It seems unlikely that an ophiolite fragment 300 km long would remain intact and unmixed with the rest of the rocks in an accretionary wedge. In addition, other small ophiolite occurrences less than 300 km to the east and west suggest that the ophiolite extends further along-strike (Fig. 2). Moreover, current work in Tuva (southern Siberia) by Pfänder *et al.* (1999) has identified ophiolite occurrences also dated at 569 ± 1.0 Ma (Pb/Pb on single zircon) suggesting that these ophiolites may be genetically related to the Bayankhongor ophiolitic rocks. Also, growing evidence for a continental block beneath Hangai (e.g. Sm–Nd model ages of Kovalenko *et al.* 1996) suggests that the Bayankhongor ophiolite marks a collisional suture between the Baidrag and Hangai continents.

Our preferred interpretation is that the Bayankhongor ophiolite represents a suture marking the position of a now inactive subduction zone between the Baidrag block to the south, and the Dzag zone to the north. Subduction was to the SW based on the dominant polarity of thrusting with the Burd Gol mélange representing an accretionary wedge built up against the Baidrag continental block to the south. The ophiolite was obducted in a northeasterly direction over the Dzag zone which may have been part of a passive margin of a continent located beneath the sedimentary cover of the Hangai region. Future work along strike is needed to establish whether the ophiolite belt can be traced into neighbouring regions and therefore constitutes one of the major suture belts of Central Asia.

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