Mongolian Geoscientist no.27 p.1-7 (2005)

Tectonic overview of Mongolia

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Mongolia is principally a part of the Central Asian orogenic belt (CAOB) that extends from the Pacific coast to the Ularls. Several different summaries, syntheses and models have been proposed to explain the tectonic development of Mongolia and surrounding regions (Ruzhentsev and Pospelov; 1992, Sengör et al. 1993, 1996; Mossakovsky et al., 1994; Didenko et al., 1994; Buchan et al. 2001).

Mongolia contains tectonically most important and complicated terranes, including cratonal blocks, island arcs, accretionary wedges and ophiolite belts. Tectonic and terrane subdivision of Mongolia have been proposed by many authors (Mossakovsky et al., 1994; Tomurtogoo, 2003, 2004, Badarch et al., 2004, Parfenov et al., 2004). Since publication of our paper on terrane subdivision of Mongolia (Badarch et al., 2002) many other professional papers on this and related theme have been published (Kuzmichev et al.,2001; Buchan et al., 2002; Khain et al.,2003, Kroener et al., 2002, Parfenov et al., 2003). The modified Terrane map of Mongolia based on analysis of latest published data for Mongolia and adjacent areas of China and Russia (Fig.1).

Cratonal and metamorphic blocks, passive continental margin terranes. The cratonal blocks are the Baydrag, Zavhan, Tarvagatay, Gargan, Ereendavaa, Tsagaan Uul and Hutag Uul terranes that consist of Archean-Proterozoic metamorphic complexes and Neoproterozoic meta-supracrustal rocks (Fig. 2). The Gargan block occurs in northern Hovsgul and adjacent areas of Russia. It is composed Archean metamorphic basement (2905 Ma, Pb-Pb; Neymark et al., 1995) overlain by marble, shale, minor chert and sandstone. The Baydrag terrane has zircon ages on tonalitic gneiss of 2650 ± 30Ma, 2833 ± 35 Ma (Mitrofanov et al., 1985; Kozakov et al., 2001). Granulite facies peak metamorphic age is 1839.8 Ma (A. Kröner). The metamorphic complexes are overlain unconformably by Neoproterozoic pebbly sandstone, quartzite, and dolomite (K-Ar muscovite age of 699±35Ma; Teraoka et al. 1996). The Zavhan composite terrane contain granite gneiss (1868± 3 Ma Burashnikov., 1990) and rift-related volcanic rocks (850 and 750 Ma, Pb-Pb zircon; Burashnikov., 1990).

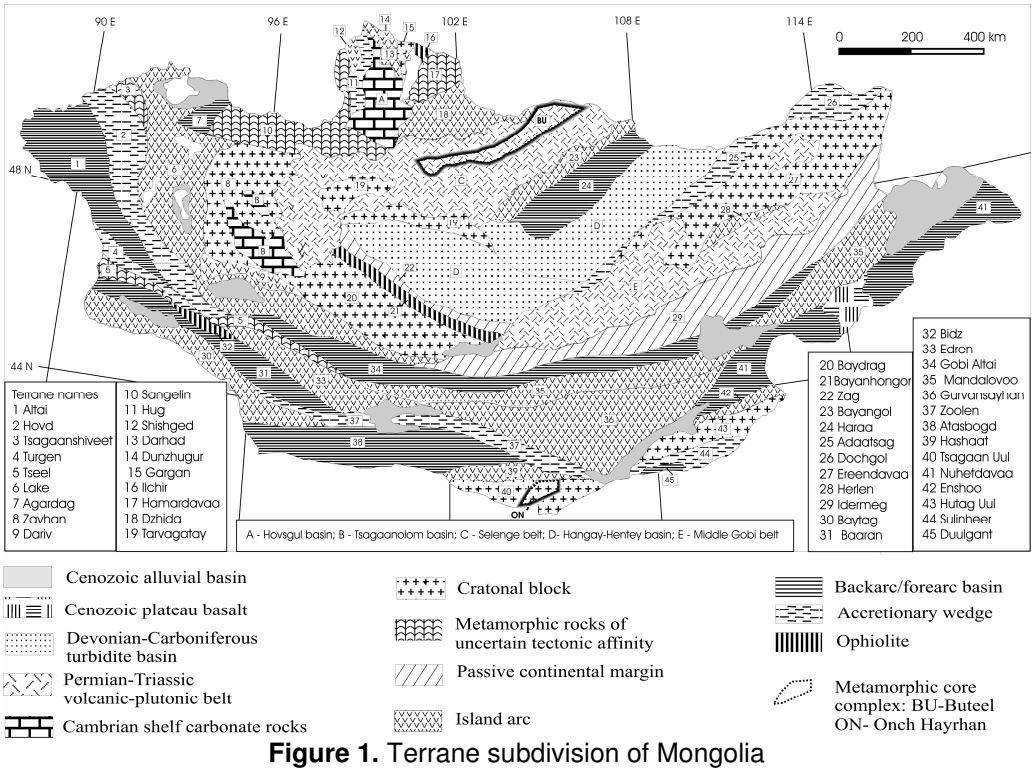

Figure 1. Terrane subdivision of Mongolia

The western margin of the terrane consists of metamorphosed accretionary complexes named as the Urgamal, Hotol and Hungui zones that consists of a structurally imbricated assemblage of basalt, andesite, volcaniclastic rocks hosted VMS deposits(Makarychev, 1988; Burashnikov 1993; QJX, 2004). In contrast to the Baydrag, the Zavhan terrane is overlain by Neoproterozoic-Lower Cambrian shelf limestone with diamictite, minor volcanic rocks (Khomentovsky and Gibsher, 1996; Lindsay et al., 1996). The Tarvagatay terrane consists of early Precambrian gneiss, migmatite, amphibolite, and schist, intruded by anorthosite (ca 3050 Ma, Pb-Pb zircon; Mitrofanov et al., 1985) and Neoproterozoic-Lower Cambrian stromatolitic limestone and volcaniclastic rocks.

The terrane extends to the northeast under Selenge belt and possibly connected with the Ikatsky terrane, Transbaikal area, Russia. The Ikatsky terrane contains early Precamrian basement, Vendian-Lower Cambrian backarc basin sediments (Belichenko, 1977, 2004). The Gargan terrane is made up of mainly Mesoproterozoic high-grade metamorphic rocks (2160Ma, U-Pb zircon; Khain et al., 1995) and overlain by Neoproterozoic and Lower Cambrian metasediments. The Ereendavaa terrane extends into Russia and NE China and consists of Paleoproterozoic and Neoproterozoic metamorphic rocks intruded by (HD- Hamardavaa, SN-Sangelin, TL- Tseel and TS- Tsagaanshiveet metamorphic blocks) by biotite granite (740± 20 Ma, U-Pb zircon) and leucogranite (850 Ma, Rb-Sr isochron, Bibikova et al., 1979). The terrane unconformably overlain by Silurian clastic sediments and Devonian volcanic rocks (Zonenshain, 1972; Gordienko, 1987). The Hutag Uul terrane consists mainly of Precambrian gneiss, schist, marble, quartzite, stromatolitic limestone, metasandstone. In the southern continuation of the terrane, in Inner Mongolia, China, the gneiss has a U-Pb zircon age of 916± 16 Ma (Wang et al., 2001).

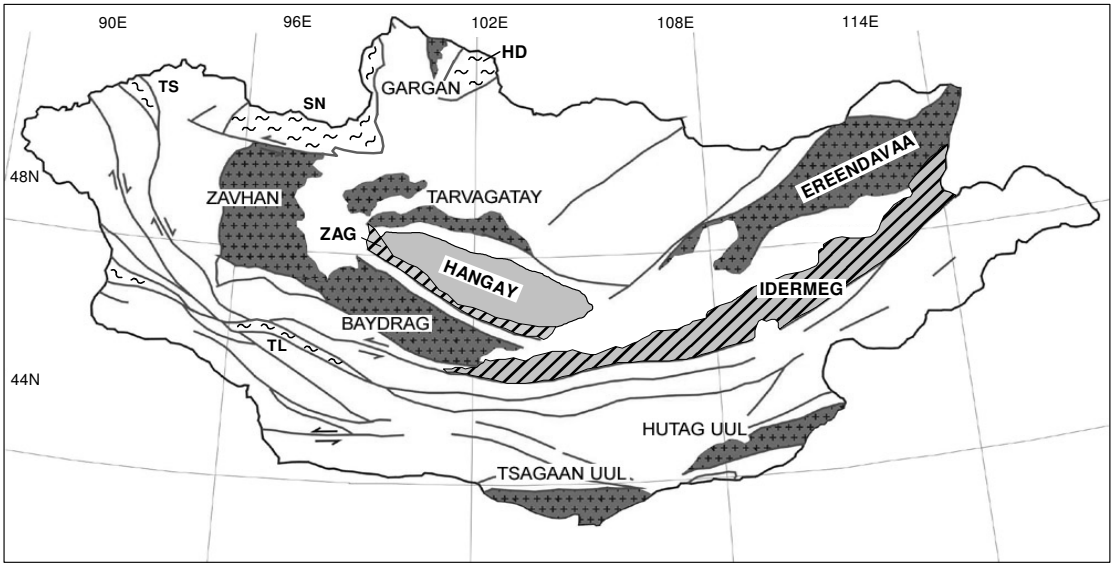

Figure 2. Distribution of cratonal, metamorphic blocks and passive continental margin

The Hangay block (hidden terrane) lies beneath Devonian-Carboniferous sedimentary cover of the Hangay region and intruded by Permian granitoids (270-250 Ma, Yarmoluk et al., 2002) The Permian granitoids have a Neoproterozoic model ages T_{DM2} = 1.4-1.1 Ga and $\varepsilon_{Nd(T)}$ – 4.4 to + 0.2 that indicate dominance of Proterozoic rocks in their source terrane (Buchan et a., 2001, 2002; Kovalenko et al., 1996, 2004; Jahn et al., 2004).

The metamorphic blocks are the Tsagaanshiveet, Sangelin, Hamardavaa and Tseel terranes. The Tsagaanshiveet terrane is composed of Neoproterozoic-Paleozoic (?) metamorphic rocks intruded by granodiorite (456 ± 23 Ma, K-Ar; Gavrilova, 1975) and Ordovician-Silurian sediments. The Sangelin terrane contains highly deformed and metamorphosed rocks of the Erzin, Moren and Naran complexes. The synmetamorphic granodiorite and tonalite plutons within these complexes have U-Pb zircon ages of 536±5.7 Ma and 494±11 Ma (Kozakov et al., 1999). The Hamardavaa terrane and its northeastern

continuation in Russia are composed of gneiss, schist, amphibolite, marble, and quartzite metamorphosed to granulite and amphibolite facies and synmetamorphic plagiogranite and granodiorite plutons (481± 5 Ma, U-Pb zircon; Kotov et al., 1997). The Tseel terrane consists of high-grade metamorphosed tonalitic gneiss, amphibolite, schist intruded by Gashuun Nuur basic dyke complex (Sm-Nd ages of 320, 321 Ma; Baykova et al., 1994) and syntectonic granodiorite and granite (370, 385± 5 Ma, U-Pb zircon, Bibikova et al, 1992). The age of granulite metamorphism (384± 2 Ma, U-Pb zircon; Kozakov et al., 2003) is consistent with the high-gradient metamorphism. The Zag and Idermeg passive continental margin terranes comprise mainly Neoproterozoic-Lower Palaeozoic shelf carbonate-quartzite sequence and deep-marine sediments. The Zag is composed of highly deformed pelitic and psammitic chlorite-mica schists (439.9 ± 9.1 Ma and 447.4 ± 9.0 Ma, Kurimoto et al., 1998). The REE element pattern and trace element spidergrams of these metapelite are almost identical to the average post-Archean shale or Phanerozoic cratonic shale (Jahn et al., 2004). The initial Sr isotope compositions for the two samples from Dzag series are 0.7030 and 0.7096, and ε_{Nd} (600 Ma)= -3.3 and - 3.1. Their Nd model ages of about 1.5 Ga indicated dominance of proterozoic rocks in their source terrane(Jahn et al., 2004). It suggests that the Dzag metasediments probably derived from a large area covering Archean-Proterozoic terranes that existed before the formation of Paleozoic island arcs. The Idermeg terrane consists of Neoproterozoic to Cambrian marble, quartzite, conglomerate, sandstone, and limestone containing archeachyathes and stromatolites (Amantov, 1966; Byamba et al., 1990). These rocks were deposited on crystalline basement rocks and intruded by Cambrian granite dated by a Rb-Sr isochron at 536 Ma. Its initial Sr isotope compositions are 0.7075 to 0.8822 (Damdinjav et al., 2003, Open-File report).

Ophiolites and mafic-ultramafic complexes. Mafic and ultramafic complexes are widespread throughout Mongolia, ranging in size from huge blocks several hundred square kilometres in area to tiny isolated slivers (Fig. 2). The Bayanhongor ophiolite is the largest ophiolite in Mongolia that comprises a complete ophiolite stratigraphy of serpentinized ultramafic cumulates, gabbro, sheeted dykes, pillow lava, chert, and limestone.

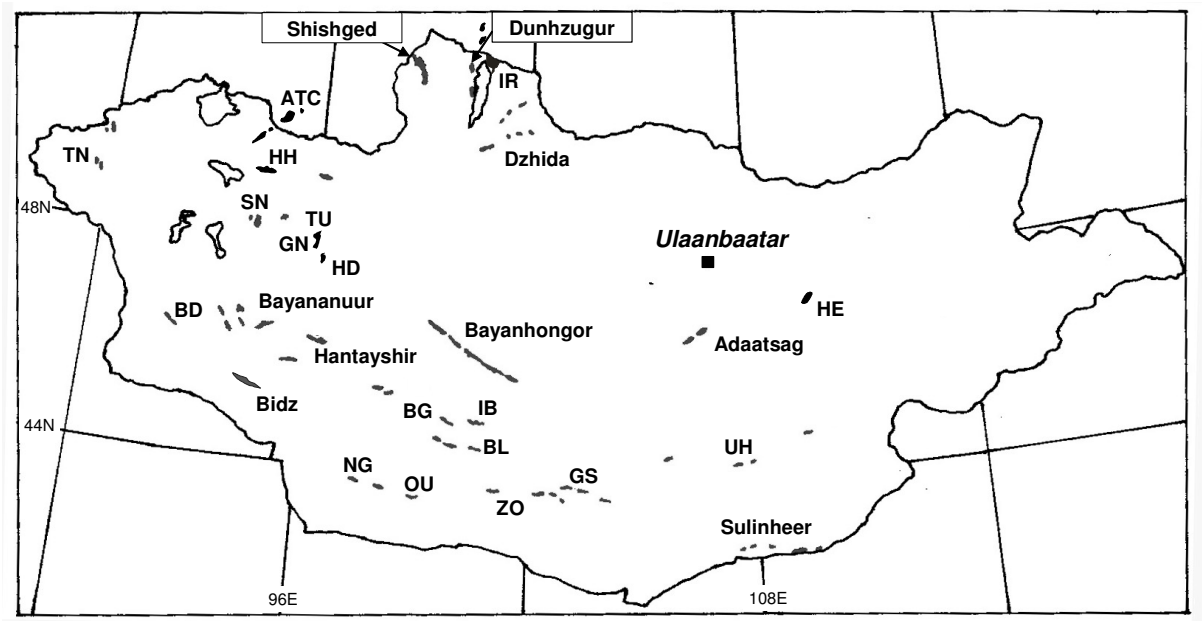

Figure 3. Distribution of ophiolite belts and mafic-ultramafic rocks (ATC- Agardagh Tes Chem; BD- Bodonch; BG- Bayangobi; BL- Bayanleg; HE- Herlen; HD- Hotol; HH-Hanhohey; GN- Geriin Nuruu; GS- Gurvansayhan; IR- Il'chir; NG- Nomin Gobi; OU- Ongon Ulaan; SN- Seriin Nuruu; TN- Tolbo Nuur; TU- Tas Uul; UH- Ulaan Hiid; ZO- Zoolen)

Gabbro has a Sm – Nd whole rock age of 569 ± 21 Ma (Kepezhinskas et al., 1991). Trace element and Nd isotope analyses show that the ophiolitic rocks vary from N-MORB through E-MORB, to within-plate tholeiites and alkaline basalts (Buchan et al., 2001b). The Hantayshir

(568 ± 4Ma, U-Pb zircon; Gibsher et al., 2001),, Bayannur (571 ± 4 and 573± 6 Ma, Pb-Pb zircon; Khain et al., 2003) and Agardagh Tes Chem (ATC, 569± 1 Ma, Pb-Pb zircon; Pfander et al., 1999) ophiolites occurs in Lake composite terranes that contains the Dariv and Agardagh subterranes. The Shishged, Dunzhugur, Il'chir and Dzhida ophiolites occur in Hovsgul area and extends into Russia. The oldest are the Dunzhugur (1019± 07 Ma, Pb-Pb zircon; Khain et al., 2002) and Shishged (800± 4 Ma, U-Pb; Kuzmichev and Kroener., 2003) ophiolites. They contain complete ophiolite sequence, including peridotite, gabbro, diabase dikes, pillow basalts, and marine sediments. The Adaatsag ophiolite in Central Mongolia contains serpentinite mélange, dunite, harzburgite, pyroxenite, wehrlite, layered and isotropic gabbro dolerite, plagiogranite dikes, basaltic lavas and oceanic sediments. A leucogabbro pegmatite dike in gabbro dated at 325.4 ± 1.1 Ma (Pb-Pb zircon; Tomurtogoo et al., 2005). The Herlen, Tolbo nuur, Bodonch ophilites are highly deformed fragments of peridotite, gabbro in mélange zones. The ophiolites exposed in Sorthern Mongolia, including Bidz, Nomin Gobi, Zoolen Gurvansayhan, Bayangobi, Bayanleg and others represent mainly Ordovician to Devonian dismembered ophiolites, slivers and serpentinite mélanges that located within an island arc sequence, accretionary complexes and backarc or forearc basin sediments. The Sulinheer (Solonker) ophiolite in southeast Gobi and adjacent areas of China consists of harzburgite, dunite, gabbroic cumulate, pillow lavas and chert overlaying by Permian clastic sediments (Ruzhentsev et al., 1989; Badarch et al., 2002; Xiao et al., 2003).

Island arcs and related basins, accretionary wedges. The island arc terranes are widely distributed in western and southern parts of Mongolia (Fig. 4). The Altai, Hovd and Turgen terranes occur in the Mongolian Altai range and and extends to the west into Russia and China. They predominantly contain a thick metamorphosed Cambrian (Ordovician?) sediments, minor volcanic rocks and syncollisional granite plutons (390-350 Ma, Demin et al., 2004; Bladimerov et al., 2001, 2002). The Lake composite terrane contains several intact ophiolites (Hantayshir, Bayannuur, Geriin Nuruu, Agardagh), calc-alkaline basalt, andesite (522± 13 Ma, Sm-Nd; Kovalenko et al., 1996) rhyolite, volcaniclastic rocks intruded by Late Camrian-Ordovician syn- and post-tectonic diorite, granodiorite, granite and covered by clastic sediments (497 Ma, Pb-Pb zircon; Kroener et al., 2001). The Shishged, Hug, Darhad, Dundzugur and Dzhida terranes are located in the northernmost part of Mongolia and extend into Russia. The Shishged terrane consists of complete ophiolite sequence (800± 4 Ma, U-Pb; Kuzmichev and Kroener., 2003) and bimodal volcanics (590± 20 Ma, Rb-Sr; Kuzmichev et al., 1994), basaltic andesite and andesite pillow lavas, pyroclastic and sedimentary rocks. The Hug accretionary wedge is composed of thrust sheets, tectonic lenses and slivers containing tholeiitic metabasalt, chert, turbidite, phyllite, blueschist containing crossite, actinolite, winchite (829 ± 23 Ma, Rb-Sr: Sklyarov et al., 1996) and sill diabase (753± 16 Ma, Kuzmichev et al., 2004). The Darhad terrane consists of Neoproterozoic calc-alkaline volcanic rocks and coeval alkaline granite (718 Ma, Rb-Sr isochron Ilyin, 1990; 740 Ma, K-Ar Buyakte et al.,1989).

The Dundzugur terrane contains intact ophiolite (1019± 07 Ma, Pb-Pb zircon; Khain et al., 2002) and island arc pillow lavas and turbidite. The Dzhida terrane contains dismembered ophiolite, Cambrian basalt, andesite, boninite, rhyolite, volcaniclastic rocks, melange, olistostrome (Al'mukhmedov et al., 1996) and arc-related gabbro and quartz diorite (506-504 Ma, U-Pb zircon, Gordienko et al., 2004). The Bayangol and Haraa terranes consist of Neoproterozoic to Ordovician metamorphosed volcanic and sedimentary rocks. The northeastern part of these terranes occur in Transbaikal region, Russia and named as the Eravna island arc terrane. It contains Meso-Neoproterozoic schist, quartzite, amphibolite, gneiss, dolomite and metasandstone, Vendian to Ordovician volcanic-sedimentary rocks that hosted SEDEX deposits. Geochemical data of an amphibolites indicates OIB and MORB type basalt (1.6 Ga to 790 Ma, U-Pb zircon; Bulgatov et al., 2004). The Herlen terrane consists of Cambrian-Ordovician dismembered ophiolite, melange, tholeiitic basalt, andesite, tuff, chert, volcaniclastic rocks, minor archeacyathic limestone, and Lower Palaeozoic granodiorite and granite plutons (Palei and Juravleva, 1978; Agafanov and Stupakov, 1983). The Adaatsag and Dochgol accretionary wedge terranes are composed of deformed, metamorphosed mélanges

containing fragments of ophiolite, arc-related volcanic and sedimentary rocks (Tomurtogoo et al., 2005; Parfenov et al., 1999).

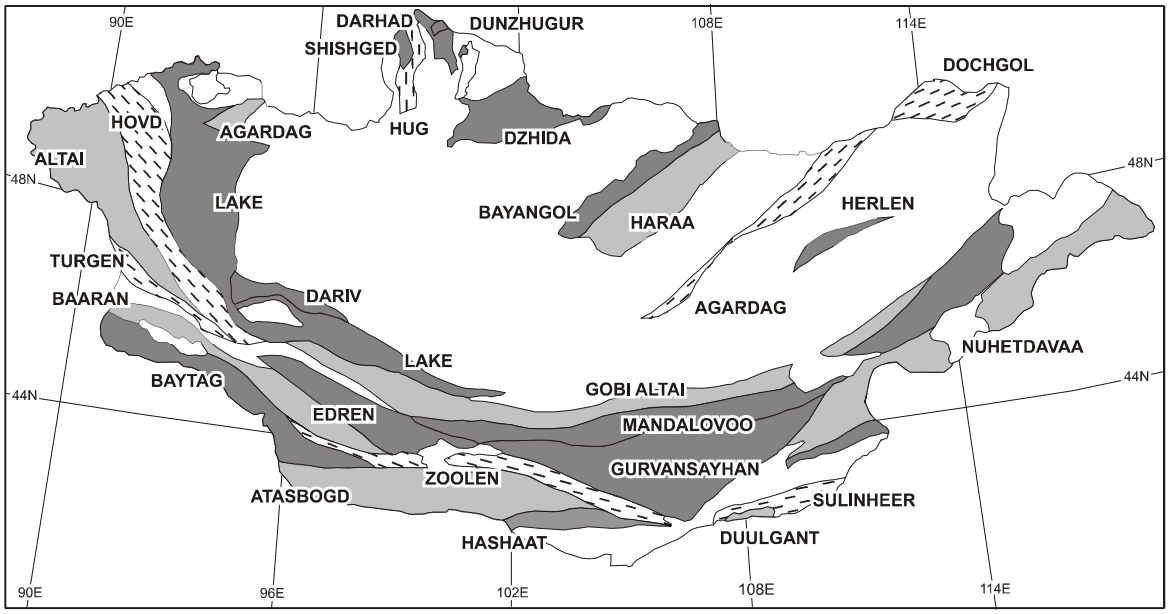

Figure 4. Distribution of Island arcs, related basins and accretionary wedges

In Russia, these rocks contain greenschist-grade metamorphosed basalt, and glaucophane schists intruded by Permian seduction-related gabbro, diorite and granite (251-263 Ma, Sorokin et al., 2004). The Baaran, Baytag, Edren and Bidz terranes consists chiefly of Devonian tholeiitic basalt, andesite, volcaniclastic rocks, Mississippian marine sediments (Ruzhentsev et al., 1992). In China, the western extension of these terranes contains the Armantai (479 ± 27 and 561 Ma, Sm-Nd, Lui et al., 1993; Jin et al., 2001) and Kalamaili (Devonian to Early Carboniferous) ophiolites and island arc volcanic rocks, forearc basin sediments (Li et al., 2003). The Gurvansayhan and Zoolen terranes are composed of dismembered ophiolite, melanges, Ordovician-Silurian greenschist facies metamorphosed sandstone, argillite, chert, volcaniclastic rocks, Lower Devonian- Mississippian tholeiitic pillow basalt, andesite, radiolarian chert, and volcaniclastic rocks and monzodiorite, monzonite, granodiorite, granite (Suetenko, 1973; Zonenshain et al., 1975; Eenjin, 1983; Ruzhentsev et al., 1985; Rhuzhentsev and Pospelov, 1992; Lamb and Badarch, 2001). The Gurvansayhan terrane is hosted porphyry Cu-Au, Cu-Mo deposits, such as Tsagaan Suvarga (364.9 ± 3.5 Ma, Ar-Ar sericite; Lamb and Cox, 1998; 370.4 ± 0.8 Ma Re-Os for molybdenite; Watanabe and Stein, 2000), Oyu Tolgoi (411± 3 Ma, K-Ar biotite, K- silicate alteration; Perelló et al., 2001) and Shuteen (321±9 Ma, Rb-Sr, diorite; Batkhishig et al., 2003). The Gobi Altai and Mandalovoo terranes consist of Cambrian (?) greenschist metamorphosed sediments, minor volcanic rocks, Ordovician to Silurian sandstone, argillite, shallow-marine limestone, minor conglomerate, olistostrome, Devonian-Mississippian conglomerate, sandstone, siltstone, fossil-rich limestone, pillow basalt, andesite and volcanoclastic rocks (Eenjin, 1983; Suetenko et al., 1984; Tsukernik et al., 1986; Lamb and Badarch, 1997, 2001, Badarch et al., 2002). The Atasbogd and Hashaat terranes are located in the southwestern part of Gobi desert and extend westward into China. The terrane consists mainly of Ordovician to Silurian greenschist facies metamorphosed sandstone, siltstone, argillite, phyllite, chert, quartzite, minor marble, pillow basalt, Devonian conglomerate, sandstone, siltstone, pillow basalt, andesite, dacite, rhyolite, chert, and rare limestone lenses (Ruzhentsev, 1985; Ruzhentsev and Badarch, 1988; Badarch et al., 2002). The Nuhetdavaa and Enshoo terranes are composed of Neoproterozoic to Cambrian (?) metamorphic rocks, Ordovician-Silurian marine succession and Devonian basalt, andesite, volcaniclastic rocks overlain by Mississippian shallow-marine sediments (Suetenko, 1973; Badarch et al., 2002). The eastern continuation of the Nuhetdavaa terrane corresponds to the Dong Ujumqin belt of China which contains volcanic and sedimentary rocks (~ 490 Ma, Tang, 1990; Nan and Guo, 1992). Along

strike to the east across the border in China the terrane consists of Hegenshan ophiolite-arc-accretionary complex (Xiao et al., 2003). The Sulinheer and Duulgant terranes occurs near the Mongolian-Chinese border area. The Sulinheer accretionary wedge consists tectonic melanges that contain blocks of mafic and ultramafic rocks, marble, blueschist (383± 13 Ma, Xu et al., 2001) and arc volcanics (Ruzhentsev et al., 1989; Pavlova et al., 1991; Badarch et al., 2002; Xiao et al., 2003). The Duulgant terrane consists of quartzite mylonite, chlorite schist, metabasalt (509± 40 Ma, Rb-Sr, Yan et al., 1989) and glaucophane schist (446± 15 and 426± 15 Ma, Ar-Ar; Zhang et al., 1987).

Discussion. The Neoproterozoic-Paleozoic tectonic framework and evolution is characterized by accretion and amalgamation of island arcs and cratonal blocks separated by intervening Paleoasian oceanic basins. In the Neoproterozoic the Dundzugur island arc was accreted to the Gargan block and intruded by the Sumsunur tonalite pluton (800 Ma, Kuzmichev et al., 2001). In Late Neoproterzoic have been formed one or more oceanic basins. The "soft" collision and ophiolite obduction started at approximately 540 Ma (Buchan et al., 2002) and the amalgamation of Cambrian island arcs and cratonal blocks, cessation of major regional deformation and metamorphism at around 450 Ma. In the Middle Paleozoic existed the South Mongolian island arc separated from Siberian continent by back-arc basin. The arc was amalgamated to the continent in late Paleozoic. The Mongol-Okhotsk ocean basin existed at least from Early Carboniferous. The ocean was closed progressively eastwards with time from the Permian to the Jurassic. The Muron left-lateral shear zone (172 Ma, Pb-Pb zircon, Tomurtogoo et al., 2005) located along the Mongol-Okhotsk suture indicates that the suture in eastern Mongolia formed at least by the mid-Jurassic.

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