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A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia

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Abstract

We present a new terrane synthesis for Mongolia that incorporates geological, geochemical and geochronological data from more than 60 years of Mongolian, Russian and joint international studies. Forty-four terranes are distinguished and classified into cratonal, metamorphic, passive margin, island arc, forearc/backarc, accretionary complex, or ophiolitic types. New detailed stratigraphic columns for all terranes are presented which summarize the geological evolution of each terrane. Our analysis reveals that small Precambrian cratonic blocks in the Hangay region acted as a central nucleus around which Paleozoic arcs, backarc/forearc basin assemblages, associated subduction complexes and continental slivers were accreted. The temporal and spatial order of accretion and amalgamation was complex and probably not simply from north to south with time. The timing of terrane accretion is partly constrained by sedimentary overlap assemblages and post-amalgamation intrusive complexes. The main stages of amalgamation occurred during the Neoproterozoic, Cambrian–Ordovician, Devonian, Pennsylvanian–Permian and Triassic. The arcuate trends of terranes around the central Hangay region provide the first-order structural grain for Mongolia. This crustal anisotropy has played a major role in controlling the geometry and kinematics of all subsequent Phanerozoic deformation and reactivation of structures in the region, including the Cenozoic development of the Altai and Gobi Altai. Our results provide the most detailed synthesis to date of the basement geology of Mongolia which should provide an important crustal framework for interpreting the Phanerozoic tectonic evolution of a large part of Central Asia. In addition, our synthesis allows the economic resources of Mongolia to be placed in a modern tectonic context.

Keywords: Mongolia; Terranes; Central Asian Orogenic Belt; Altaids

1. Introduction

The vast territory of Mongolia lies in the heart of the Central Asian Orogenic Belt, one of largest provinces of Phanerozoic continental growth on Earth. The Central Asian Orogenic Belt is fringed by the Precambrian Siberian Craton in the north and by the Tarim and Sino-Korean Cratons in the south (Fig. 1 inset). Several different summaries, syntheses and models have been proposed to explain the tectonic development of Mongolia and surrounding regions involving closure of small ocean basins by multiple subduction, obduction of ophiolites, accretion and collision of island arcs and microcontinents, and formation of multiple suture zones (Ruzhentsev and Pospelov, 1992; Mossakovsky et al., 1994; Didenko et al., 1994; Buchan et al., 2001a). In contrast, Sengör et al. (1993) envisaged continuous, oceanward migration of a single subduction zone and strike-slip stacking to create the entire Altaid collage.

Traditionally, the territory of Mongolia is subdivided into a northern and southern domain. The northern domain is usually classified as a 'Caledonian' orogen and the southern domain as a Hercynian (or Variscan) orogen. These domains are separated by the so-called Main Mongolian Lineament—an approximate regional topographic and structural boundary separating dominantly Precambrian and Lower Palaeozoic rocks to the north, from dominantly Lower to Upper Palaeozoic rocks to the south (Amantov et al., 1970; Marinov et al., 1973) (Fig. 1). McKerrow et al. (2000) redefined the Caledonian orogeny and suggested that the term Caledonian be used only for those regions such as the northern Appalachians, British Isles, Scandinavia, etc, where continental deformation occurred during the closure of the Iapetus Ocean. Thus the terms Caledonian and Hercynian are inappropriate as a time indicators for the Central Asian Orogenic Belt, however, the basic two-fold subdivision for

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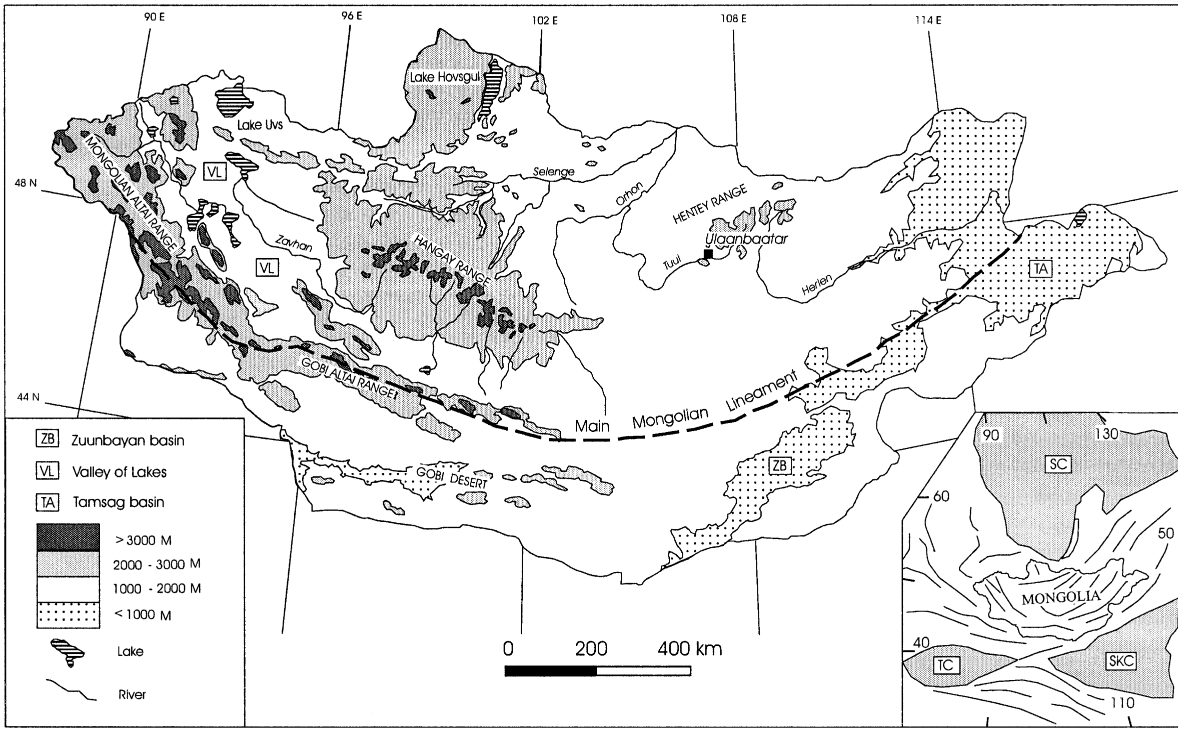

Fig. 1. Simplified topographic map of Mongolia. The Main Mongolian Lineament is a traditionally defined and approximate topographic and structural boundary separating dominantly Precambrian and Lower Palaeozoic rocks to the north from dominantly Upper Palaeozoic rocks to the south. Insert map shows location of Mongolia, approximate structural trends, and neighbouring Precambrian cratons. SC—Siberian Craton, TC—Tarim Craton, and SKC—Sino-Korean Craton.

Mongolia into a northern and southern domain is still applicable.

The northern domain contains scattered outcrops of metamorphic rocks of Precambrian and Lower Paleozoic age, Neoproterozoic ophiolites, and Lower Paleozoic island arc volcanics and associated volcaniclastic sediments. In this domain, there are many granitic rocks of various ages and compositions, Devonian to Carboniferous sediments, and Permian volcanic–plutonic belts with associated marine and non-marine sediments.

The southern domain is dominated by Lower to Middle Paleozoic arc-related volcanic and volcaniclastic rocks with fragments of ophiolites and serpentinite melanges. Along its northern margin there are distributed Silurian and Devonian fossil-rich 'reef' limestones, associated with terrigenous and volcaniclastic rocks. Pennsylvanian to Permian volcanic rocks are widespread. In the southeast there are Permian limestones and turbidites, and minor volcanic rocks that are interpreted as fragments within a suture zone between the Altaid collage and Manchuride Orogenic Belt (Sengör and Natal'in, 1996). The eastern parts of both domains are intruded by numerous Mesozoic rare metal granite plutons and are overlapped by Upper Jurassic to Cretaceous non-marine volcanic and sedimentary rocks.

More than 60 years of geological investigations in Mongolia including 25 years of joint Mongolian–Russian research and 10 years of Mongolian-western research have resulted in many publications, including over 50 specialized transactions and 3 comprehensive volumes on the geology of Mongolia. During the past decade, several workers have attempted to interpret the basement geology of Mongolia in terms of a collage of tectonostratigraphic terranes (Coleman, 1994; Tomurtogoo, 1997; Badarch and Orolmaa, 1998; Byamba and Dejidmaa, 1999; Tomurtogoo et al., 2000). 'Terrane' analysis of Mongolia and adjacent regions was also carried out as part of an international project 'Mineral resources, metallogenesis, and tectonics of Northeast Asia' (1996–2002) conducted by US Geological Survey and collaborating agencies of Russia, Mongolia, China, Japan and South Korea (Nokleberg et al., 1999). The first author of this paper (G. Badarch) participated in this joint project and worked on the completion of the regional terrane and overlap assemblage maps, and interpretations of the metallogeny and tectonic history of Mongolia.

In this paper, we present a new and more refined terrane map with accompanying stratigraphic columns for each terrane. Our study draws from analysis of new stratigraphic, geochronological, and sedimentological data derived from published and unpublished maps, published literature, and our own field results. This study differs from previous work in that we present for the first time, detailed stratigraphic columns for all terranes and have incorporated all known geochronological data into our analysis. Our objective is to present an up-to-date synthesis of the main stratigraphic and

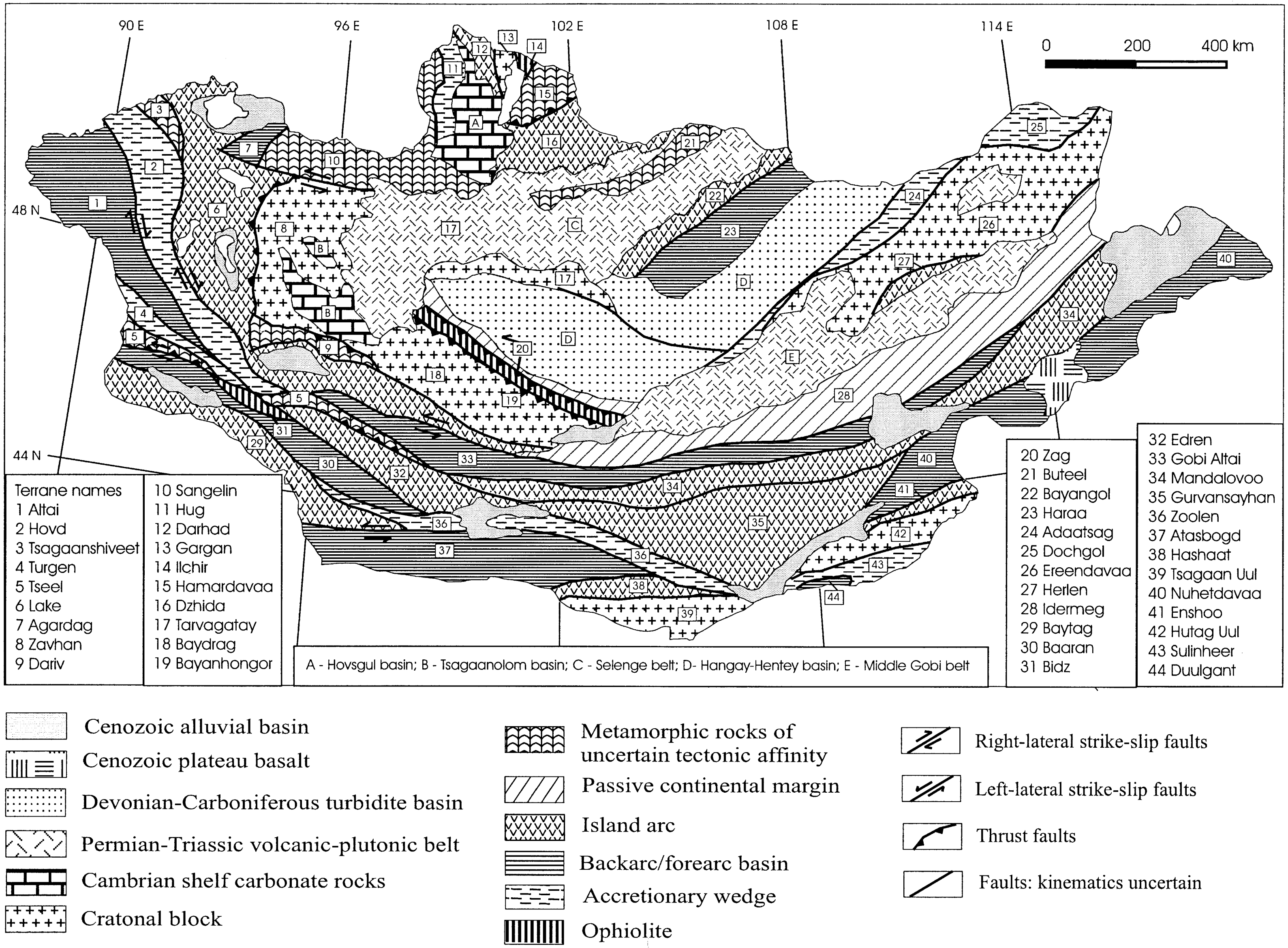

Fig. 2. Tectonostratigraphic terrane map for Mongolia. Some terranes continue into neighbouring countries, however, we have not attempted to define individual terrane limits beyond the Mongolian political border. All individual terranes are discussed in text and corresponding stratigraphic columns are shown in Figs. 4–11.

structural characteristics of the terranes and provide a basic crustal framework for workers interested in understanding the Phanerozoic tectonic evolution of Mongolia.

2. Methods

In this study, we use the term terrane as originally defined by Coney et al. (1980), Jones et al. (1983), Howell et al. (1985) and Nokleberg et al., 1994 as: a fault-bounded assemblage or fragment that is characterized by a distinctive geologic history that differs from that of adjacent terranes. Each terrane contains distinctive sedimentary, volcanic, plutonic and/or metamorphic rocks which differ from neighbouring terranes in their petrological, geochronological and/or isotopic characteristics. Some terranes also have unique palaeontologic or palaeomagnetic signatures. Boundaries of terranes are fault zones that in some cases, were reactivated during subsequent tectonic events. Some terrane boundaries are concealed by younger cover rocks, intrusions, and alluvial sediments and are located only approximately.

The geology of Mongolia is subdivided into 44 terranes (1–44) which are genetically classified into the following types: cratonal, metamorphic, passive continental margin, island arc, backarc/forearc basin, accretionary wedge and ophiolitic (Fig. 2). For the purposes of description the terranes have been numbered geographically; terranes lying to the north of the Main Mongolian Lineament are numbered, from west to east 1–28, terranes to the south of the lineament are numbered from west to east 29–44. This numbering system is given in Fig. 2. We describe briefly the stratigraphy, structure and plutonic rocks of each terrane and their overlap assemblages, identified by the number shown in Fig. 2. We present the stratigraphy according to recently proposed IGC stratigraphic nomenclature (Remane, 2000). The stratigraphy of each terrane (Fig. 3) is summarized in a stratigraphic column, identified by its number. The column also indicates the time span from terrane formation to final accretion (Figs. 4–11). No attempt is made to define terranes within neighbouring countries. However, because some Mongolian terranes continue into neighbouring countries, we have incorporated terrane-specific information from those countries in our study.

We are cognizant of past debate concerning the merits of regional terrane analysis (Sengör and Dewey, 1990). However, we believe that the method is applicable and useful for continental regions such as Mongolia where large Precambrian cratons are absent and numerous disparate tectonic blocks have accreted and amalgamated. We have used a conservative approach in our classification, but recognize that with further research, some terranes will be modified, combined, or reclassified. Nevertheless, our results provide the most detailed synthesis to date of the basement geology of Mongolia which should provide an important crustal framework for interpreting the Phanerozoic tectonic evolution of a large part of Central Asia. In addition, our synthesis allows the economic resources of Mongolia to be placed in a modern tectonic context.

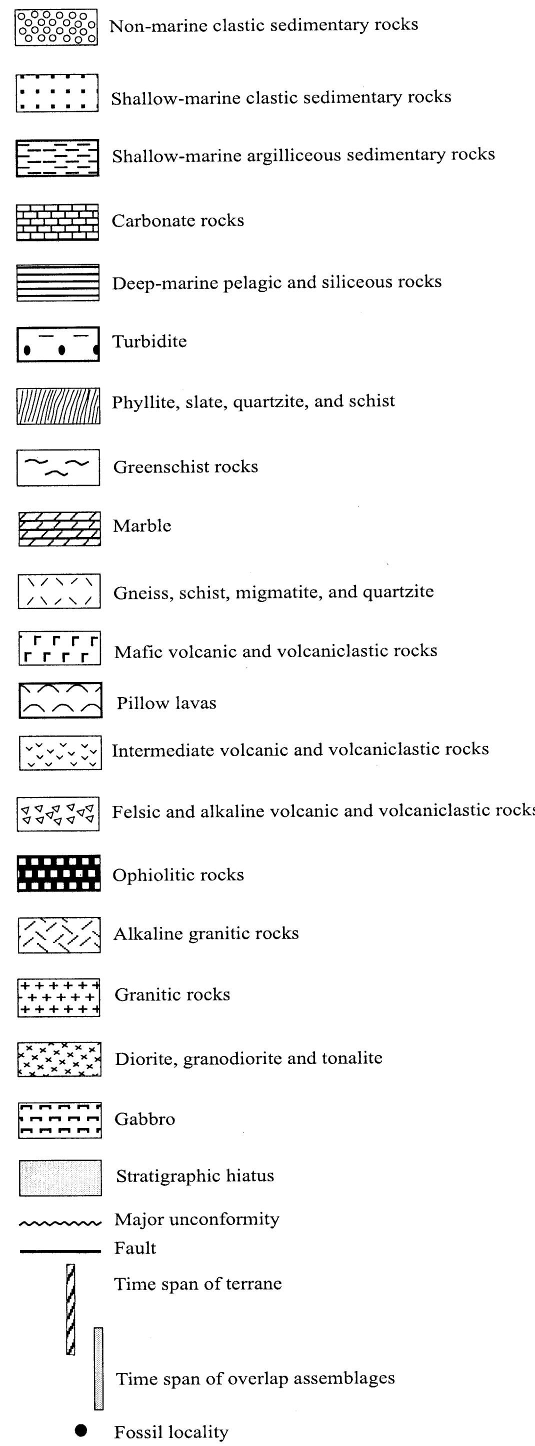

Fig. 3. Legend for stratigraphic columns for all Mongolian terranes (Figs. 4–11).

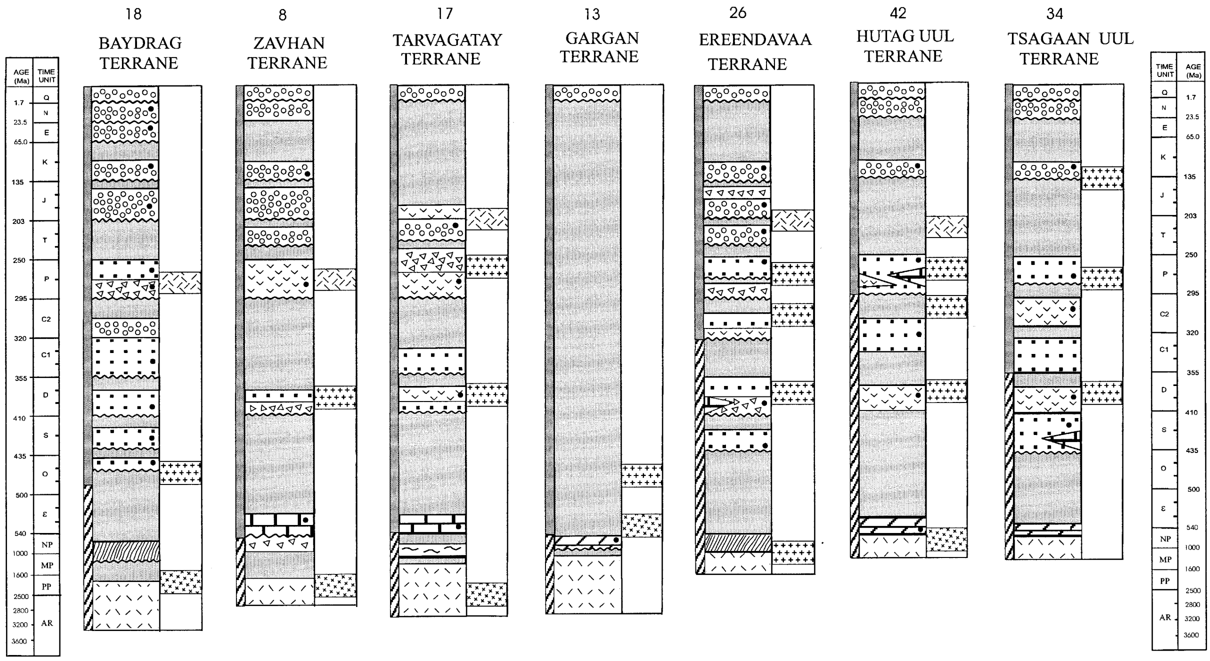

Fig. 4. Stratigraphic columns for Mongolian cratonal terranes. See Fig. 3 for legend.

3. Terrane descriptions

In the following sections, we describe the geology of 44 separate terranes which fall into seven genetic categories.

3.1. Cratonal terranes

The cratonal terranes are seven separate blocks that contain mainly Archaean–Proterozoic metamorphic complexes, and Neoproterozoic metasedimentary, volcanic and greenschist rocks. Five cratonal terranes are in the northern domain and two in the southern domain.

The Baydrag Terrane (18) is located southwest of the Bayanhongor Ophiolite and is mainly composed of the Baydrag and Bumbuger metamorphic complexes (Figs. 2–4). The former contains Archaean tonalitic gneiss (U–Pb zircon age of 2650 ± 30 Ma), granulite and amphibolite, and minor quartzite (Kozakov et al., 1997; Mitrofanov et al., 1985; Kozakov et al., 1999a). The Bumbuger Complex comprises schist, gneiss, marble, quartzite, and charnockite intruded by granite and granodiorite dykes (U–Pb zircon ages of 2364 ± 6, 1854 ± 5 Ma; Kotov et al., 1995). A granulite facies enderbitic gneiss, derived from a dioritic protolith has an emplacement age of 2409.1 ± 0.4 Ma and a granulite facies peak metamorphic zircon age of 1839.8 ± 0.6 Ma (Kröner et al., 2001). Both complexes are overlain unconformably by pebbly sandstone, quartzite and dolomite of probable Neoproterozoic age (K–Ar muscovite age of 699 ± 35 Ma; Teraoka et al., 1996). The northeastern boundary of the terrane is an assumed thrust fault along the southern edge of the Bayanhongor Ophiolitic Terrane (Buchan et al., 2001a). The western boundaries with the Dariv and Zavhan terranes are obscured by post-accretion granite plutons and Mesozoic cover. The overlap complexes of the terrane include Upper Ordovician coral limestone, conglomerate and sandstone, Silurian graptolitic shale, Devonian to Permian volcanic and volcaniclastic rocks with marine fossils, and Jurassic–Cretaceous clastic sediments. The post-accretion plutonic complexes are Ordovician granite and leucogranite dated by a Rb–Sr isochron at 469 ± 9 Ma (Oyungerel and Takahashi, 1999) and Permian diorite and granite.

The Zavhan Terrane (8) to the east of the Lake Island Arc Terrane (Figs. 2–4) is a composite terrane, and can be subdivided into at least three separate fault-bounded zones, (Makarychev, 1988; Burashnikov, 1990; Tomurtogoo, 1997), which from west to east are the Urgamal, Hutul and Hungui (Zavhan–Mandal) zones. The Urgamal Zone contains epidote–amphibolite and greenschist facies metamorphosed calc-alkaline basalt, andesite, stromatolitic limestone, and quartzite that contains fragments of ultramafic and mafic rocks. There are many granite plutons, including a granite-gneiss dome, which has a Pb–Pb zircon age of 1868 ± 3 Ma (Burashnikov, 1990). The Hutul Zone consists of a structurally imbricated assemblage of basalt, andesite and volcaniclastic rocks, metamorphosed to greenschist and amphibolite facies. There are also several bodies and thrust sheets of ultramafic rocks and gabbro. The Hungui Zone is dominated by gneiss, migmatite, amphibolite, quartzite, and schist in its lower part, and interbedded multi-colored rhyolite, basalt, andesite, tuff, and volcaniclastic rocks in its upper part (Zavhan Formation). The felsic volcanic rocks have yielded Pb–Pb zircon ages of 850 ± 2 and 750 ± 3 Ma (Burashnikov, 1990). The relationship between the lower

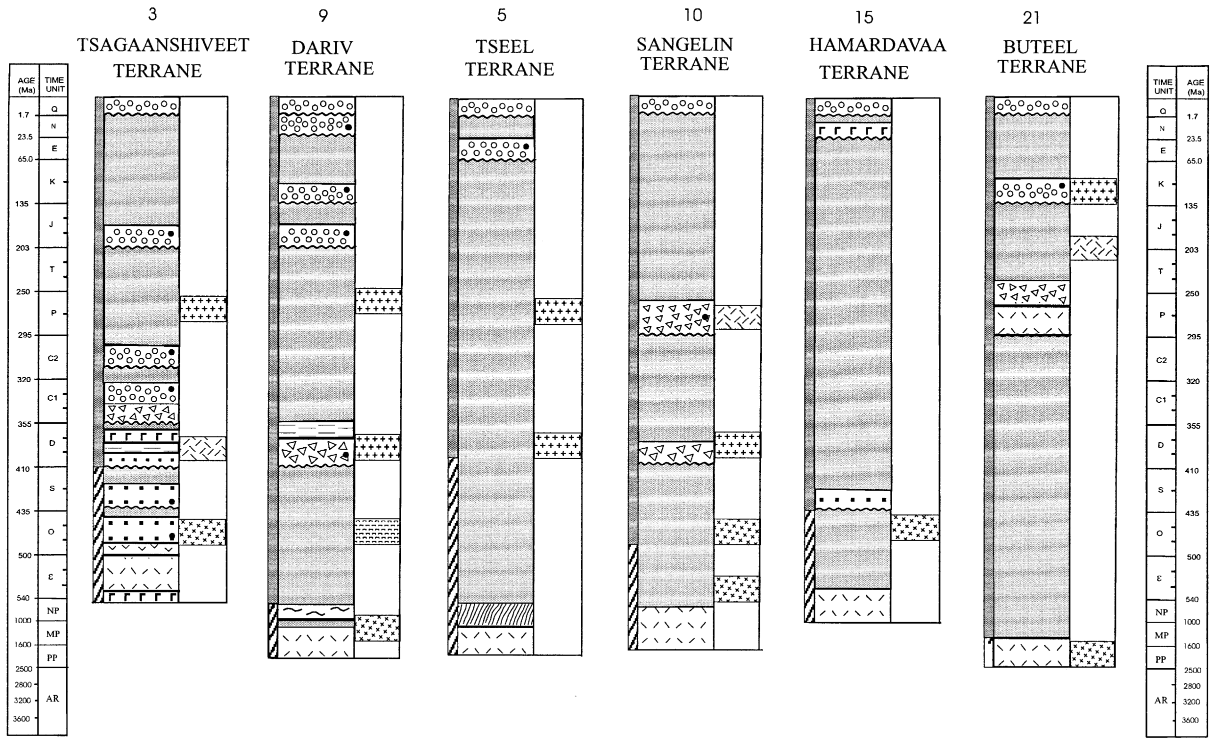

Fig. 5. Stratigraphic columns for Mongolian metamorphic terranes. See Fig. 3 for legend.

and upper parts are not well constrained, but Makarychev (1988) described an unconformity and conglomerate at the base of the upper section. Within the Hungui Zone, there are also fragments of ultramafic and mafic rocks of unknown tectonic affinity. The Zavhan Terrane (8) is overlain by the Tsagaanolom Basin containing Neoproterozoic–Lower Cambrian conglomerate, sandstone, argillite, diamictite, dolomite, limestone with phosphatic horizons, and Devonian to Cretaceous non-marine volcanic and sedimentary rocks (Khomentovsky and Gibshir, 1996; Lindsay et al., 1996). The terrane is intruded by Devonian and Permian granite plutons.

The Tarvagatay Terrane (17) occurs in the northern Hangay area and consists of early Precambrian gneiss, migmatite, amphibolite, and schist, intruded by anorthosite plutons, and Neoproterozoic greenschist facies metamorphosed volcaniclastic rocks (Figs. 2 and 3). The oldest radiometric ages available so far from the Tarvagatay Terrane (17) are Pb–Pb zircon dates of ca 3050 Ma from anorthosite (Mitrofanov et al., 1985). The terrane is overlain by Neoproterozoic–Lower Cambrian stromatolitic limestone and volcaniclastic rocks, Devonian and Mississippian conglomerate and sandstone containing marine fossils, andesite, dacite, tuff, and Permian volcanic–plutonic rocks of the Selenge Belt, and Middle Triassic–Lower Jurassic non-marine clastic and volcanic rocks. Post-accretion Devonian to Triassic granite plutons cut the terrane. Ilyin (1990), Kovalenko et al. (1996a,b), Zorin et al. (1993) and Buchan et al. (2001a) suggested that continental crust, presumably of Precambrian age is present in this terrane, probably extending to the south under a thick sedimentary cover in the Hangay region.

The Gargan Terrane (13) occurs north of Lake Hovsgul and extends into Russia (Figs. 2 and 4). It is made up of mainly Precambrian granite-gneiss, amphibolite, and schist overlain by Neoproterozoic marble, quartzite, chert, metasandstone, and mudstone. In Russia, the gneiss has a Rb–Sr isochron age of 3153 ± 57 Ma (Aktanov et al., 1992) and a U–Pb zircon age of 2 Ga (Khain et al., 1995). Recently, Kuzmichev et al. (2001) have recognized that the Gargan Block is overthrust by the Dunzhugar island arc ophiolites and intruded by tonalite plutons. The tonalites are dated by Rb–Sr isochron 812 ± 18 Ma and by U–Pb zircon at 785 ± 11 Ma (Kuzmichev et al., 2001). The terrane is also cut by Ordovician granite plutons (Khain et al., 1995).

The Ereendavaa Terrane (26) is located in northeastern Mongolia and extends into Russia and NE China (Figs. 2–4). It consists of Paleoproterozoic gneiss, amphibolite, schist and marble, overlain by Neoproterozoic black schist, metasandstone, siltstone, limestone, and minor conglomerate and volcanic rocks intruded by Precambrian and Devonian granite and leucogranites. In Russia, biotite granite and leucogranite were dated by U–Pb zircon at 740 ± 20 Ma and Rb–Sr isochron at 850 Ma, respectively (Bibikova et al., 1979). The Neoproterozoic schists are unconformably overlain by Silurian clastic sediments containing *Tuvaella gigantea* sp. brachiopods, Devonian andesite, rhyolite, tuff, volcaniclastic rocks, conglomerate, sandstone and minor fossiliferous limestone (Zonenshain, 1972; Gordienko, 1987). The post-accretionary complexes include Carboniferous and Permian volcanic and marine sedimentary rocks of the Middle Gobi volcanic–plutonic Belt (Fig. 2) and Triassic to Jurassic non-marine sediments. Permian, Upper Triassic–Lower Jurassic granite plutons intrude the terrane.

The Hutag Uul Terrane (42) is located in southeastern Mongolia and extends to the east into Inner Mongolia, China (Figs. 2–4). It consists of Precambrian gneiss, schist, migmatite, marble, quartzite, stromatolitic limestone, metasandstone, Devonian basalt, andesite, dacite, tuff, volcaniclastic rocks, minor pillow lavas, coral-bearing limestone, and Pennsylvanian volcaniclastic rocks (Suetenko and Lkhasuren, 1973; Byamba, 1996; Badarch and Orolmaa, 1998). The gneiss is exposed in the Xilinhot area, Inner Mongolia and has a Sm–Nd isochron age of 1025 ± 41 Ma (Xu et al., 1996). The terrane is intruded by subduction-related tonalite, diorite, and granodiorite of presumed Devonian and Carboniferous age. However, in its eastern continuation in Inner Mongolia, China, similar plutonic rocks have a U–Pb zircon age of 310 Ma (Baolidao Suite, Chen et al., 2000). The post-accretion complexes include Permian marine sedimentary and volcanic rocks, and granite plutons. The REE–carbonatite-hosted Lugingol Alkaline Pluton with Rb–Sr isochron ages of 222–244 Ma is located within the terrane (Munkhtsengel and Iizumi, 1999).

The Tsagaan Uul Terrane (39) occurs in the southernmost part of Mongolia and consists of Neoproterozoic granite-gneiss, quartzite, marble, stromatolitic limestone, and metasandstone, unconformably overlain by fossil-rich Silurian limestone, sandstone, siltstone, Lower Devonian basalt, andesite, tuff, sandstone, and siltstone. These rocks are intruded by Middle-Upper Devonian granite and granodiorite (Figs. 2–4). Garnet-bearing aplite within the gneiss has a Pb–Pb zircon age of 770 Ma (Kozakov, 1986). 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). The terrane is overlain by Carboniferous and Permian volcanic and sedimentary rocks. Post-accretion Permian and Upper Jurassic–Lower Cretaceous plutonic complexes intrude the terrane. The southeastern margin of the terrane is bordered by the Onch Hayrhan metamorphic core complex that has Ar–Ar biotite ages of 129–126 Ma for augen gneiss, and mylonite (Webb et al., 1999).

3.2. Metamorphic terranes

High-grade metamorphic terranes have traditionally been regarded as early Precambrian blocks. However, new geochronological data indicate that high-grade metamorphism in these terranes occurred mainly in the Palaeozoic, not the Precambrian, and the metamorphic complexes contain thrust stacks with widely varying lithologies suggesting that crustal shortening has juxtaposed rocks which originally

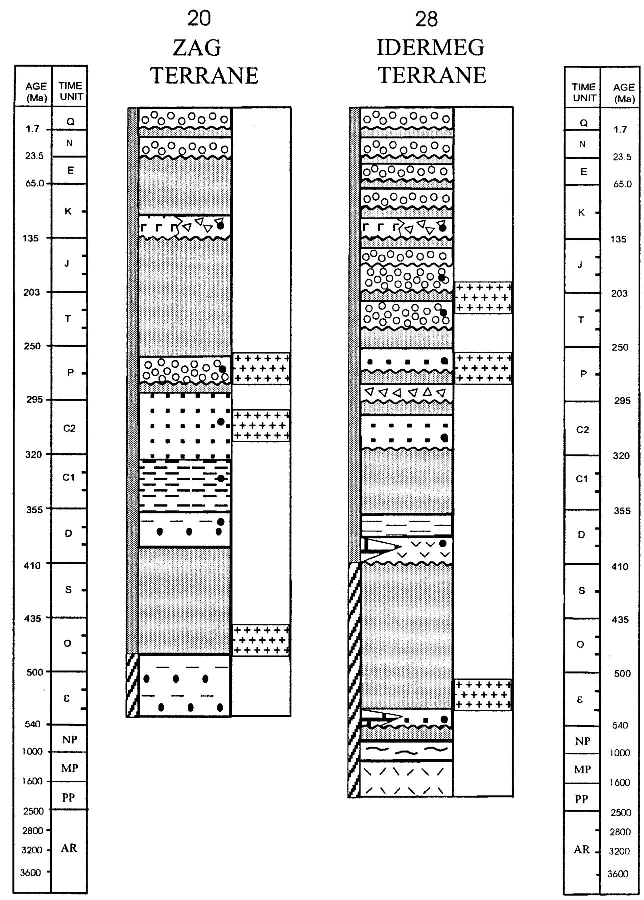

Fig. 6. Stratigraphic columns for Mongolian passive continental margin terranes. See Fig. 3 for legend.

formed in different tectonic settings (Bibikova et al., 1992; Kozakov et al., 1999a–c; Salnikova et al., 2001). We distinguish six metamorphic terranes, five in the northern domain, and one in the southern domain.

The Tsagaanshiveet Terrane (3) was originally described by Dergunov et al. (1980) and occupies a small wedge-shaped area on the eastern side of the northwestern end of the Mongolian Altai Range (Figs. 2 and 5). It is composed of Neoproterozoic–Lower Cambrian volcanic rocks, Palaeozoic (?) gneiss, amphibolite, migmatite, schist, quartzite, and metasandstone intruded by diorite and granodiorite (K–Ar age of 456 ± 23 Ma; Gavrilova, 1975), and Ordovician and Silurian andesite, tuff, sandstone, siltstone, and minor limestone with brachiopods, *T. gigantea* sp. (Figs. 2 and 5). The stratigraphy and protolith age of the metamorphic rocks are not well understood, although Demin and Demin (1993) reported a single U–Pb detrital zircon date of ca 1820 Ma from a gneiss. The terrane is overlain by Devonian and Carboniferous volcanics, sedimentary rocks and Jurassic redbeds. The post-accretion plutonic rocks include Middle Devonian and Permian subalkaline and alkaline granites (Volochkovich and Leontyev, 1990).

The Dariv Terrane (9) forms east–west trending uplifted blocks between the Zavhan and Lake terranes, previously described as the Dariv and Gobi Altai Precambrian massifs (Makarychev et al., 1986; Dergunov, 1989; Khain et al., 1995; Kheraskova et al., 1985). The terrane contains a mixture of metamorphic assemblages, some of which might be cratonic fragments, others have unknown affinity. The terrane contains Proterozoic tonalite, gneiss, garnet amphibolite, migmatite, graphitic marble, quartzite and Neoproterozoic greenschist-grade volcanic and sedimentary rocks intruded by diorite and plagiogranite (Figs. 2 and 5). A granite-gneiss contains a 1715 Ma zircon xenocryst and has an emplacement age of 1127.2 ± 12 Ma (Kröner et al., 2001). The gneiss is intruded by the Neoproterozoic (?) Shargyngol Dyke Complex, which has continental rift geochemical signatures (Burashnikov and Ruzhentsev, 1993). Overlap assemblages include Devonian rhyolite, tuff, volcaniclastic rocks and Jurassic conglomerate and sandstone. The terrane is intruded by Ordovician gabbro and diorite and Devonian and Permian granite plutons.

The Tseel Terrane (5) includes several scattered blocks, located on the southern margin of the Mongolian Altai and northwestern side of the Gobi Altai ranges and extends into northwest China to the west (Figs. 2 and 4). It is composed of polymetamorphosed and polydeformed tonalitic gneiss, amphibolite, schist with relics of granulite, and syntectonic granodiorite and granite dated by U–Pb zircon at 370 and 385 Ma, respectively (Mitrofanov et al., 1981; Kozakov, 1986; Bibikova et al., 1992). The protolith age of metamorphic rocks and granulite–amphibolite facies metamorphism is uncertain. Kozakov (1986) obtained Pb–Pb zircon ages ranging from 250 to 1120 and 2200 Ma from gneiss. The Gashuun Nuur basic dyke complex (Sm–Nd ages of 320, 321 Ma; Baykova and Amelin, 1994) and Permian granites intrude these rocks.

The Sangelin Terrane (10) is located to the northwest of the Hangay Range and extends into Russia (Figs. 2 and 5). The terrane contains highly deformed and metamorphosed rocks of the Erzin, Moren and Naran complexes which were previously considered as Archaean–Proterozoic basement and cover strata (Mitrofanov et al., 1981). The Erzin complex consists of gneiss, marble and quarzite metamorphosed to low-pressure granulite facies. The Moren complex contains gneiss, bimodal volcanic rocks, quartzite, metasandstone, and marble metamorphosed to amphibolite facies. The Naran Complex (presumed cover strata) is composed of marble, schist, felsic volcanic rocks, quartzite, limestone and metasandstone containing Neoproterozoic macrofossils (Mitrofanov et al., 1981). Recent metamorphic and geochronological studies by Kozakov et al. (1999a,b) and Salnikova et al. (2001) indicate that synmetamorphic granodiorite and tonalite plutons within the Moren and Erzin complexes have U–Pb zircon ages of 536 ± 5.7 and 494 ± 11 Ma, respectively, and post-metamorphic granosyenite from the Naran Complex has a U–Pb age of 497 Ma. Based on these data, the authors conclude that these complexes were tectonically juxtaposed prior to 497 Ma and metamorphosed together to amphibolite facies. The terrane is overlain by Devonian, Permian felsic volcanic rocks and is intruded by Ordovician, Devonian, and Permian granite plutons.

The Hamardavaa Terrane (15) occurs northeast of Lake Hovsgul and extends into Russia (Figs. 2 and 5). It is composed of Precambrian (?) gneiss, schist, amphibolite, marble, and quartzite metamorphosed to granulite and amphibolite facies and synmetamorphic plagiogranite and granodiorite plutons (U–Pb zircon age of 481 ± 5 Ma, Kotov et al., 1997). The terrane is thrust southwards over the Dzhida Island Arc Terrane (16) and is overlain by Silurian marine sedimentary rocks.

The Buteel Terrane (21) occurs along the northern side of the Selenge River and consists of gneiss, migmatite, amphibolite, schist, quartzite and marble, intruded by pegmatite and diabase dykes (Figs. 2 and 5). The strongly deformed and mylonitized gneiss has a Pb–Pb zircon age of 275 Ma (Kröner et al., 2001). However, Bibikova et al. (1993) published a U–Pb zircon age of 1.9 Ga for the granulite metamorphism of similar rocks in Russia. The terrane is intruded by Triassic to Lower Cretaceous granite plutons (K–Ar biotite ages of 89–129 Ma; Koval and Smirnov, 1983). Zorin et al. (1997) suggested that the terrane and its northeastern continuation in Russia are Cretaceous metamorphic core complexes related to continental extension (K–Ar biotite ages of 110–140; Kozubova et al., 1980).

3.3. Passive continental margin terranes

The passive continental margin terranes comprise mainly Neoproterozoic–Lower Palaeozoic shelf carbonate–quartzite sequences and deep-marine sediments overlain by Devonian–Carboniferous and Permian volcanic and sedimentary rocks. The basement for these thick sedimentary successions is either poorly exposed or of unknown terrane affinity. We distinguish two passive continental margin terranes in the northern domain (Figs. 2 and 6).

The Zag Terrane (20) is located northeast of the Bayanhongor Ophiolite and consists of the Zag Schists and Haluut Bulag Unit (Figs. 2 and 6; Buchan et al., 2001a). The former is composed of highly deformed pelitic and psammitic schists of lower greenschist grade containing rare 0.5 m wide layers of limestone. Less metamorphosed, fine-grained interbedded siltstone, sandstone and shale contain rounded quartz grains and resemble slightly metamorphosed turbidites. Chlorite–muscovite schists are reported as having K–Ar muscovite ages of 439.9 ± 9.1 Ma and 447.4 ± 9.0 Ma (Kurimoto et al., 1998). The Haluut Bulag Unit contains lenses of limestone, sandstone, chert, tuff, minor felsic volcanic material and vesicular basalt which have been intensively deformed and telescoped into a tectonic melange (Buchan et al., 2001a). The matrix is black

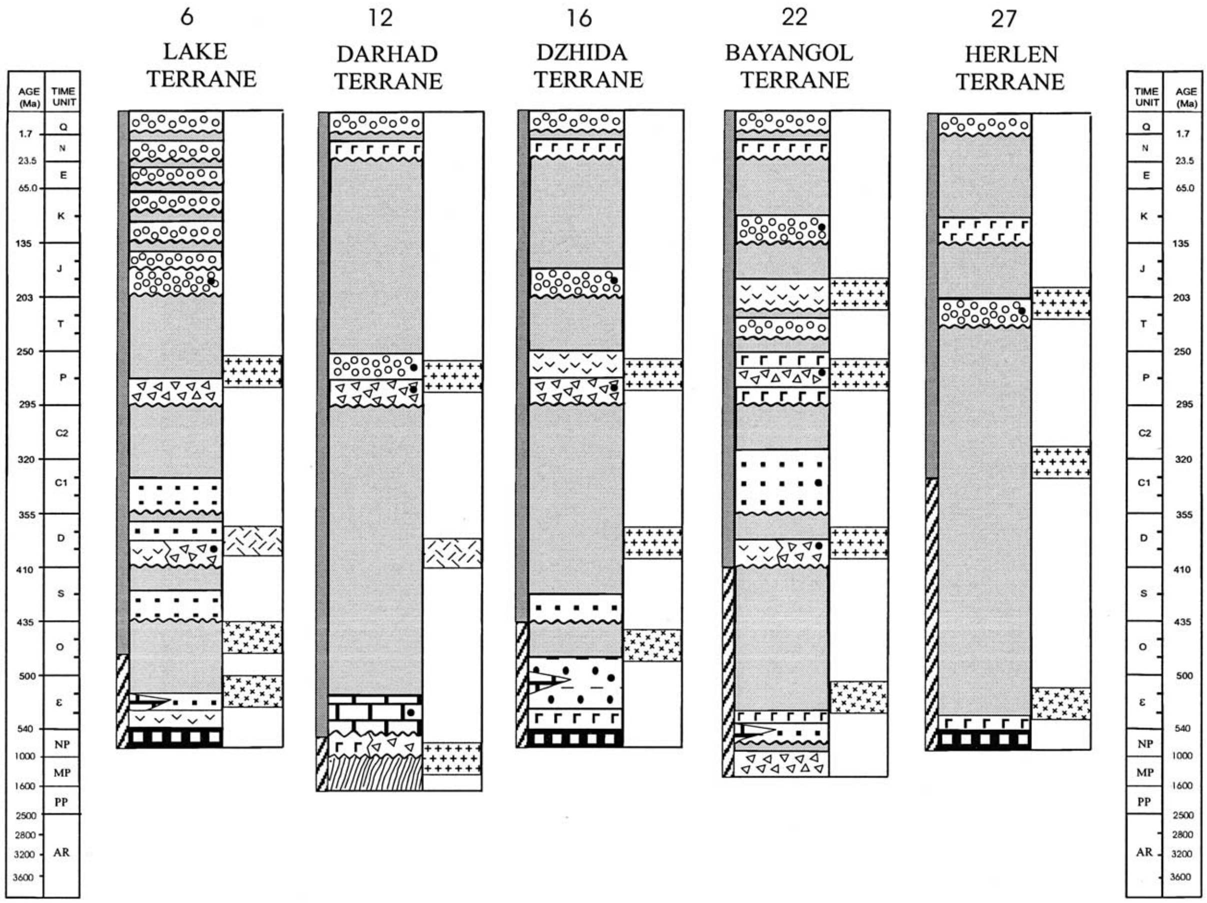

Fig. 7. Stratigraphic columns for island arc terranes of the northern domain of Mongolia. See Fig. 3 for legend.

shale, carbonate mudstone and quartzose siltstone metamorphosed to low-grade phyllite facies. The Zag Schists and Haluut Bulag Melange are dominated by a well-developed SW-dipping shear fabric, NE-vergent asymmetric folds, and NE directed overthrusts. The protoliths for the Zag Schists are interpreted as deep water passive margin sediments that were overthrust by the Haluut Bulag Melange and the overlying Bayanhongor Ophiolite (Buchan et al., 2001a). The terrane is overlain by Devonian–Carboniferous Hangay–Hentey sediments and Permian sedimentary rocks, and is intruded by Ordovician (?), Carboniferous and Permian granites (Kurimoto et al., 1997).

The Idermeg Terrane (28) occurs in eastern Mongolia and consists dominantly of marble, quartzite, conglomerate, sandstone, and limestone containing archeachyathes and stromatolites that are believed to be Neoproterozoic to Cambrian in age (Figs. 2 and 6; Amantov, 1966; Byamba et al., 1990). These rocks were deposited on crystalline basement rocks including gneiss, amphibolite, schist, and phyllite and are intruded by Middle-Upper Cambrian granite plutons (Marinov et al., 1973). The post-accretionary complexes include Devonian to Permian and Triassic–Jurassic volcanic and sedimentary rocks, and minor limestone. These rocks are intruded by Permian and Triassic–Lower Jurassic granite plutons.

3.4. Island arc terranes

The island arc terranes are widely distributed in western and southern parts of Mongolia and consist mainly of intact or dismembered ophiolites, tholeiitic to calc-alkaline volcanic and volcaniclastic rocks intruded by diorite and granodiorite plutons (Fig. 2). There are eleven island arc terranes, five in the northern domain and six in the southern domain. Ophiolites in the northern domain are typically Late Neoproterozoic in age, and the age of island arc and seamount volcanic rocks is thought to be Lower -Middle Cambrian. The ophiolites and island arc volcanic rocks have been interpreted as fragments of the Palaeoasian ocean and island arc systems (Zonenshain and Kuzmin, 1978; Tomurtogoo, 1989; Dergunov, 1989; Ruzhentsev and Mossakovskiy, 1996). The island arc terranes of the southern domain contain fragments of dismembered ophiolites, melanges, and island arc volcanic and volcaniclastic rocks which are generally interpreted to be derived from Middle to Late Palaeozoic ocean basin deposits and island arc sequences (Ruzhentsev et al., 1985; Ruzhentsev and Pospelov, 1992; Lamb and Badarch, 1997).

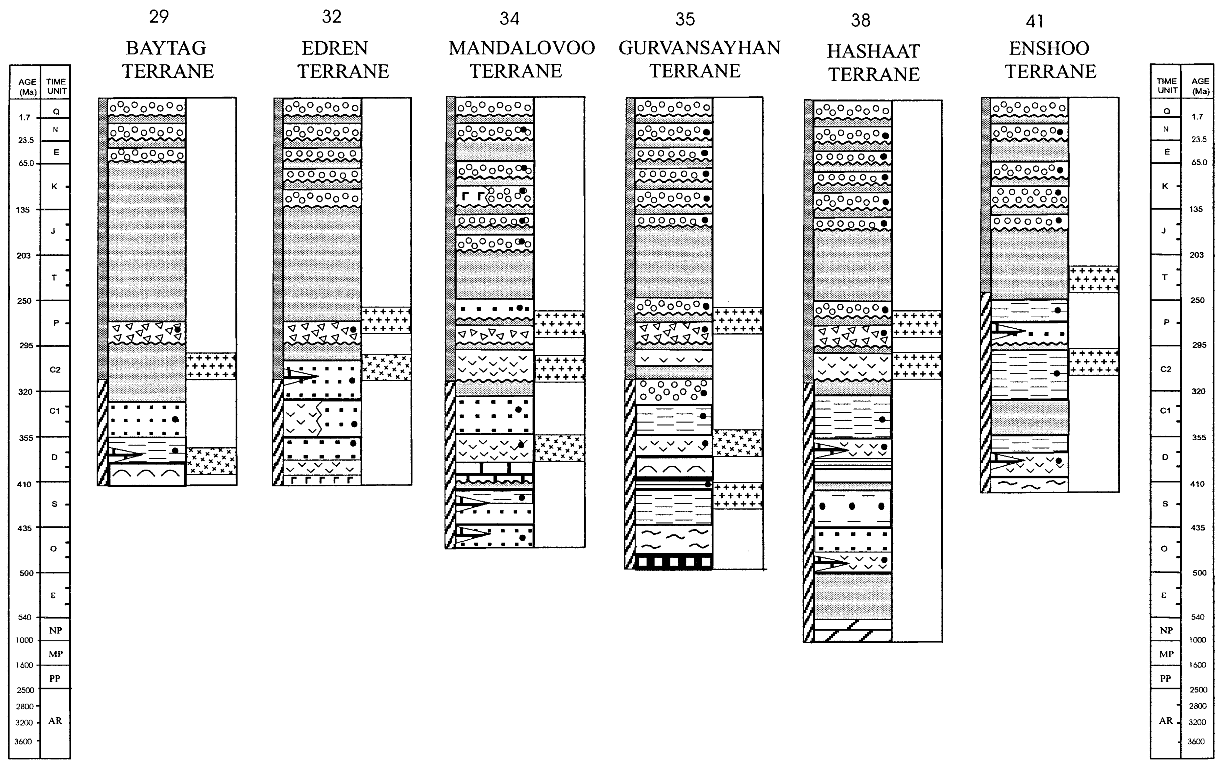

Fig. 8. Stratigraphic columns for island arc terranes of the southern domain of Mongolia. See Fig. 3 for legend.

The Lake Terrane (6) occurs mainly in the Valley of Lakes, east and northwest of the Mongolian Altai and Gobi Altai ranges, respectively (Figs. 1, 2 and 7). The terrane consists mainly of Cambrian island arc volcanic rocks containing fragments of ophiolites. The ophiolites commonly contain a complete stratigraphy, including peridotite, layered gabbro, sheeted dykes, pillow lavas and deep marine red chert (Zonenshain and Kuzmin, 1978; Ruzhentsev and Burashnikov, 1995). The ages of the ophiolites have recently been dated for the Hantayshir (568 ± 4 Ma, U–Pb zircon), Dariv (573 ± 6 Ma), Seriin Nuruu (527 ± 43 Ma, Sm–Nd; Kovalenko et al., 1996a,b), and Geriin Nuruu complexes (522 ± 13 Ma, Sm–Nd; Kovalenko et al., 1996a,b). The Dariv Ophiolite is overlain by undeformed sandstone which contains detrital zircons dated at 479.6 ± 1.0 Ma (Kröner et al., 2001). The island arc rocks are represented by calc-alkaline basalt, andesite, rhyolite, tuff, volcaniclastic rocks, minor conglomerate, limestone with archeachyathes and trilobites, and granodiorite, granite, and granosyenite plutons. The plutonic rocks are correlated with those in Tuva region of Russia, which have U–Pb zircon ages of 489.4 ± 2.6 and 512 ± 4 Ma (Kozakov et al., 1999b; Pfänder et al., 2000). Large clasts of granite and quartz–porphyry from conglomerate in the Dariv Range have Pb–Pb zircon ages of 492 ± 1.0 and 539.7 ± 1.0 Ma, respectively (Kröner et al., 2001). These data suggest that the Lake Island Arc was formed on Late Neoproterozoic oceanic crust and developed during the Cambrian to Early Ordovician. Post-accretion assemblages include Silurian, Devonian and Mississippian marine sedimentary and volcanic rocks, Permian, Jurassic and Cretaceous clastic sediments, Ordovician quartz diorite, granodiorite and granite (U–Pb zircon ages of 451–464 Ma; Kozakov et al., 1999b,c), Devonian alkaline plutons (U–Pb zircon and Rb–Sr isochron ages of 380–390 Ma; Kovalenko et al., 1995) and Permian subalkaline granite plutons.

The Darhad Terrane (12) extends from west of Lake Hovsgul into Russia and consists of Neoproterozoic calc-alkaline basalt, andesite, dacite, rhyolite, tuff, conglomerate, sandstone, siltstone, dolomite and limestone, intruded by riebeckite granite (Figs. 2 and 7). The volcanic rocks and coeval alkaline granite have a Rb–Sr isochron age of 718 Ma and K–Ar age of 740 Ma, respectively (Buyakaite et al., 1989; Ilyin, 1990; Konnikov et al., 1994). Granite clasts from a conglomerate have K–Ar ages of 823 Ma (Ilyin, 1990). The terrane is overlain by mainly Neoproterozoic–Lower Cambrian carbonate rocks of the Hovsgul Basin and Permian molasse, and is intruded by Devonian and Permian subalkaline granite plutons.

The Dzhida Terrane (16) is located in the eastern Hovsgul area and extends into Russia (Figs. 2 and 7). It is composed of several thrust sheets containing Neoproterozoic dismembered ophiolite, melange with olistostromes and Cambrian–Lower Ordovician tholeiitic to calc-alkaline island arc and oceanic island basalt, andesite, rhyolite, tuff, volcaniclastic rocks, and minor archeaocyathic limestone intruded by Ordovician granodiorites (Al'muhamedov et al., 1996; Tomurhuu, 1999). Post-accretion assemblages include

Silurian, Devonian and Permian volcanic and sedimentary rocks and Devonian and Permian granite plutons. The northern boundary of the terrane with the Hamardavaa Block is not well constrained, but assumed to be a south-directed thrust. The overall structure of the terrane is dominated by steeply dipping SE-directed thrusts and SE-vergent folds.

The Bayangol Terrane (22) occurs in the northern Hentey Range (Fig. 1) and extends into Russia (Figs. 2 and 7). The terrane consists of Neoproterozoic metamorphosed dacite, rhyolite, minor andesite, tuff, sandstone, stromatolitic limestone and overlying Neoproterozoic–Lower Cambrian conglomerate, cross-bedded sandstone, and minor stromatolitic limestone. The terrane is intruded by Cambrian, Devonian diorite and granodiorite plutons and overlain by Devonian and Carboniferous intermediate to felsic volcanic and shallow-marine sedimentary rocks, and Permian to Jurassic non-marine clastic sedimentary and volcanic rocks. Post-accretionary plutons of Devonian, Permian, and Upper Triassic–Lower Jurassic age intrude the complex. The structure of the terrane is dominated by top-to-the-southeast thrust faults and NE-trending shear zones, sinistral strike-slip faults, and upright and overturned folds.

The Herlen Terrane (27) occurs as a narrow fault-bounded lens up to 25 km wide and 200 km long between the Ereendavaa and Idermeg terranes (Figs. 2 and 7). It consists of Neoproterozoic–Lower Cambrian dismembered ophiolite, melange, tholeiitic basalt, andesite, tuff, chert, volcaniclastic rocks, minor archeacyathic limestone, and Lower Palaeozoic granodiorite and granite plutons (Palei and Juravleva, 1978; Agafonov and Stupakov, 1983). The terrane is overlain by Triassic and Jurassic non-marine sediments and intruded by Carboniferous and Upper Triassic–Lower Jurassic granite plutons. The overall structure of the terrane is characterized by northwest-directed imbricated thrust sheets which contain fragments of ophiolite, volcanic rocks, and Middle–Upper Triassic sedimentary rocks (Zonenshain, 1972).

The Baytag Terrane (29) occurs in southwestern Mongolia and extends into the eastern Junggar region of China (Figs. 2 and 8). It consists of Lower Devonian tholeiitic basalt, andesite, tuff, volcaniclastic rocks, Middle–Upper Devonian volcaniclastic sandstone, siltstone, chert, minor limestone containing conodonts, corals and brachiopods, Mississippian fossiliferous limestone and coal-bearing mudstone (Ruzhentsev et al., 1992b). The western continuation of the terrane in China contains the Armantai Ophiolite which has Sm–Nd isochron age of 479 ± 27 Ma (Baofu et al., 1999). The post-accretion complexes include Permian felsic volcanic rocks and Pennsylvanian (Late Carboniferous) granite and granosyenite plutons. The overall structure of the terrane is extremely complex with imbricated thrust stacks, melanges, high strain zones, and open to isoclinal folds.

The Edren Terrane (32) occurs between the Tseel (5) and Baaran (30) terranes (Figs. 2 and 8) and contains two distinct sequences (Ruzhentsev and Pospelov, 1992; Suetenko et al., 1988; Lamb and Badarch, 1997). The northern (Huvin Har) sequence consists of Devonian metamorphosed thin-bedded argillite, sandstone, minor chert, fossiliferous limestone, volcanic rocks and Carboniferous conglomerate, sandstone and limestone intruded by Permian alkaline granite plutons. These rocks have experienced intense brittle deformation, shearing and upright folding. On the northern margin of the terrane, the folds suggest dextral strike-slip displacement between adjacent blocks. The southern (Edren) sequence is dominated by Devonian and Mississippian volcaniclastic rocks, volcanic breccia, tuff, chert, clastic sediments, minor limestone, basalt and andesite (Yarmolyuk and Tikhonov, 1982). The major- and trace-element chemistry of Devonian basalts suggests an arc origin (Lamb and Badarch, 2001). The terrane is overlain by Permian felsic volcanic rocks and intruded by Carboniferous and Permian diorite, granodiorite and leucogranite plutons. The terrane is imbricated by thrust faults, and has experienced intense brittle–ductile deformation and greenschist-grade metamorphism.

The Mandalovoo Terrane (34) is a narrow and long belt in the northern part of the southern Mongolian domain, which extends to the east into NE China (Figs. 2 and 8). It consists of a deformed stratigraphic succession of Ordovician to Carboniferous volcanic and sedimentary rocks (Eenjin, 1983; Suetenko et al., 1984; Lamb and Badarch, 1997). Specifically, the terrane contains Ordovician and Silurian sandstone, argillite, fossiliferous limestone, Lower–Middle Devonian conglomerate, sandstone, shallow-marine fossil-rich limestone containing brachiopods (*T. gigantea* sp.), felsic tuff, Upper Devonian pillow basalt, andesite, tuff, volcaniclastic sandstone, chert, Mississippian (Lower Carboniferous) marine sedimentary rocks and Devonian diorite and granodiorite plutons. Geochemical data from pillow lavas indicate that the basalts were erupted in a subduction zone setting (Lamb and Badarch, 2001). Paleomagnetic studies suggest that the Devonian volcanic arc was near the paleoequator and drifted 40° northwards and was rotated 75° clockwise (Didenko, 1992). Post-accretion assemblages include Pensylvanian–Permian volcanic and sedimentary rocks, and granite plutons, and Jurassic–Cretaceous clastic rocks.

The Gurvansayhan Terrane (35) occurs in the central part of the southern domain, south of the Mandalovoo Terrane (34) (Figs. 2 and 8). The terrane is bordered by the Zoolen accretionary wedge in the southwest, whereas its southeastern boundary is obscured by the Zuunbayan Basin (Fig. 1). The terrane is composed of dismembered ophiolite, melanges, Ordovician–Silurian greenschist facies metamorphosed sandstone, argillite, chert, volcaniclastic rocks, Upper Silurian–Lower Devonian radiolarian chert, tholeiitic pillow basalt, andesite, tuff, Middle Devonian–Mississippian volcaniclastic rocks, chert containing Frasnian conodonts, and minor olistostrome with coral limestone clasts (Zonenshain et al., 1975;

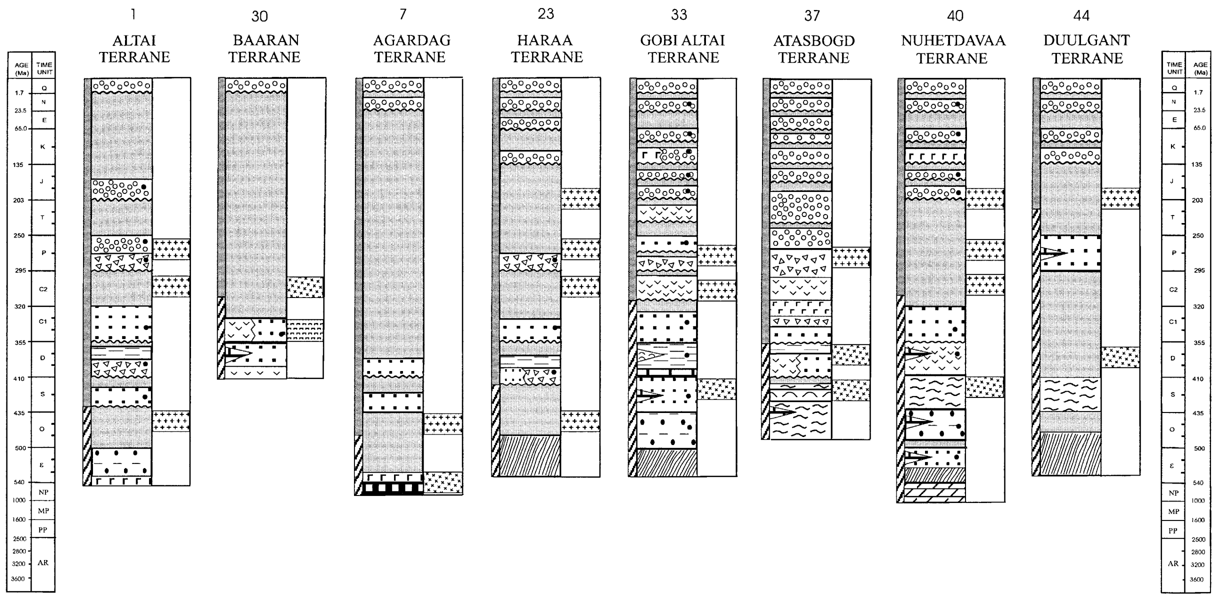

Fig. 9. Stratigraphic columns for Mongolian backarc/forearc terranes. See Fig. 3 for legend.

Eenjin, 1983; Ruzhentsev et al., 1985; Voznesenskaya et al., 1986). The major- and trace-element characteristics of Devonian basalt indicate volcanism in an arc environment (Ruzhentsev and Pospelov, 1992; Lamb and Badarch, 2001. The terrane contains porphyry copper deposits, such as Tsagaan Suvarga and Oyu Tolgoi. The Tsagaan Suvarga porphyry copper ore has an Ar–Ar sericite age of 364.9 ± 3.5 Ma (Lamb and Cox, 1998), and a Re–Os ages of 370.4 ± 0.8 Ma for molybdenite (Watanabe and Stein, 2000). The Oyu Tolgoi hypogene copper–gold deposit, located on the southeastern margin of the terrane has a K–Ar biotite age of 411 ± 3 Ma for K–silicate alteration (Perelló et al., 2001). The structure of the terrane is complex and dominated by imbricate thrust sheets, dismembered blocks, melanges, and high strain zones. There are several melange zones containing blocks of pillow lavas, fossiliferous limestone, sandstone, gabbro, diabase dykes, and amphibolite. Within the terrane there are widely distributed Pennsylvanian post-accretion syenite plutons which have K–Ar biotite ages of 307 ± 4 Ma at Oyu Tolgoi, and a monzonite dyke at Tsagaan Suvarga has an Ar–Ar mica age of 313 ± 2.9 Ma (Lamb and Cox, 1998; Perelló et al., 2001). On the southeastern margin of the terrane is located the Hanbogd riebeckite–rich orbicular granite pluton, which has yielded K–Ar ages of 287 ± 2 Ma (Kovalenko and Yarmolyuk, 1995). The terrane is overlain by Carboniferous, Permian, Jurassic and Cretaceous volcanic and sedimentary rocks.

The Hashaat Terrane (38) occurs between the Atasbogd (37) and Tsagaan Uul (39) terranes of southern Mongolia and extends to the southwest into China (Figs. 2 and 8). It consists of Precambrian marble, quartzite, metasandstone, Ordovician–Silurian greenschist facies metamorphosed andesite, tuff, limestone lenses, volcaniclastic turbidite, Devonian pillow basalt, andesite, gabbro, chert, volcaniclastic rocks containing brachiopods, Mississippian marine conglomerate, sandstone, chert, and siltstone (Ruzhentsev and Badarch, 1988; Badarch and Orolmaa, 1998). Ordovician to Carboniferous island arc volcanic rocks, and fragments of ophiolite occur along the southwestern continuation of the terrane in China (Wu, 1993). Overlap assemblages include Pennsylvanian, Permian, Jurassic and Cretaceous volcanic and sedimentary rocks, and granite plutons.

The Enshoo Terrane (41) occurs between the Nuhetdavaa (40) and Hutag Uul (42) terranes of southeastern Mongolia and extends to the east into Inner Mongolia, China (Figs. 2 and 8). It consists of variably metamorphosed and sheared gneiss, quartzo–feldspathic schist, Devonian calc-alkaline basalt, andesite, dacite, tuff, volcaniclastic rocks, and minor limestone containing brachiopods, corals and bryozoans, Carboniferous shallow-marine sedimentary and volcanic rocks, Permian andesite, dacite, tuffaceous sandstone, siltstone, shale, limestone containing cold water forms of fusulinids (Monodiexodina) and brachiopods (Pavlova et al., 1991; Ruzhentsev et al., 1992a). The Hegenshan Zone of Inner Mongolia, China, which is the eastern continuation of the Enshoo Terrane (41) contains a Devonian ophiolite, which has dunite, gabbro, sheeted dykes, tholeiitic pillow basalt, radiolarian chert, and coral limestone (Tang, 1990). The geochemistry and chromite mineralogy of these ophiolitic rocks are consistent with formation in an arc or backarc setting (Robinson et al., 1999). The Enshoo Terrane (41) is overlain by Jurassic to Cretaceous volcanic and sedimentary rocks, and intruded by Carboniferous and Triassic granodiorite, alkaline and leucogranite plutons.

3.5. Backarc/forearc basin terranes

The backarc/forearc basins contain dominantly Lower Paleozoic thick volcaniclastic and sedimentary successions, and minor slivers and melanges of ultramafic and volcanic rocks. These terranes are mainly distinguished by their proximity to island arcs, by their composition and thickness of basin sediments, and by their geochemical signatures of volcanic rocks (Watanabi et al., 1994; Lamb and Badarch, 1997, 2001; Pfänder et al., 2000). We have distinguished eight backarc/forearc basin terranes, three in the northern domain, and five in the southern domain.

The Altai Terrane (1) is located in the western Mongolian Altai Range and extends to the west into Russia and China (Dergunov et al., 1980; Dobretsov et al., 1995). It predominantly contains a thick metamorphosed Cambrian (Ordovician?) succession of clastic and volcaniclastic rocks and intermediate-mafic volcanic rocks (Figs. 2 and 9). The succession is intruded by calc-alkaline diorite, granodiorite, and granite plutons, that yield K–Ar ages of 400–456 Ma (Gavrilova, 1975). Within the sequence there are blocks, slivers and melanges of basalt, andesite, tuff, and minor limestone lenses of presumed Neoproterozoic age. The terrane is overlain by Silurian, Devonian and Mississippian volcanic and shallow-marine sedimentary rocks and intruded by Upper Devonian, Carboniferous and Permian granite plutons (Dergunov et al., 1980; Gavrilova, 1975). The Cambrian sedimentary rocks have long been suspected to be of passive continental margin affinity (Zonenshain, 1972), however, Watanabi et al. (1994), Mossakovsky and Dergunov (1985) and Byamba and Dejidmaa (1999) argued that the Cambrian sequence was deposited in a forearc/backarc basin or island arc tectonic settings based on their identification of volcaniclastic sedimentary units. Our reconnaissance study of the terrane in 2000 indicated that the terrane contains a high proportion of thrust-imbricated metabasites, suggesting that the rocks were deposited in an arc-proximal setting and later deformed and metamorphosed to greenschist grade.

The Baaran Terrane (30) occurs in the western part of the southern domain and extends to the west into China (Figs. 2 and 9). It consists mainly of Devonian volcaniclastic sandstone, siltstone, chert, and minor latite, shoshonite, tuff, coral limestone, sills of gabbro and diorite, Mississippian sandstone, siltstone, trachyandesite, quartz latite, trachydacite, tuff, chert and fossiliferous limestone (Ruzhentsev et al., 1992b). These rocks are intruded by Carboniferous granite, monzonite, granosyenite plutons and small intrusions of picrite, and picritic dolerite (Gavrilova, 1975; Izokh et al., 1990). The terrane is dominated by thrust sheets, greenschist metamorphosed, mylonitized high-strain zones, and tectonic melanges.

The Agardag Terrane (7) is located east of Lake Uvs and extends into Tuva, Russia, where it is better constrained by Pfänder et al. (2000). It consists of Neoproterozoic ophiolite, Lower Cambrian conglomerate, sandstone and limestone overlain by Silurian and Devonian shallow-marine sedimentary rocks (Figs. 2 and 9). The northeastern continuation of the terrane in Tuva contains southeast-directed thrust sheets composed of serpentinite melange, massive and layered gabbro, plagiogranite, sheeted dykes, massive, pillow basalts, Cambrian conglomerate and limestone. The plagiogranite has a Pb–Pb zircon age 569 ± 1 Ma, and trace element data from basalt and gabbro suggest that they were derived from depleted mantle and formed in a island arc/backarc basin (Pfänder et al., 2000).

The Haraa Terrane (23) occurs in the northern Hentey Range and extends into the Transbaikal region, Russia (Figs. 2 and 9). It consists of Cambrian–Lower Ordovician greenschist metamorphosed sandstone, siltstone, argillite, phyllite, schist, and minor conglomerate and tuff intruded by granite and granodiorite (K–Ar age of 420 Ma; Marinov et al., 1973). The overlap assemblages are Silurian, Devonian, Mississippian and Permian volcanic and sedimentary rocks. Devonian, Carboniferous, Triassic–Lower Jurassic granite and leucogranites intrude the sequence (Kotlyar et al., 1998).

The Gobi Altai Terrane (33) is a long and narrow belt, located along the northern margin of the southern domain and extends to the east into China (Figs. 2 and 9). It consists of Cambrian (?) greenschist facies metamorphosed sandstone, mudstone, tuff, and minor volcanic rocks, Ordovician to Silurian sandstone, argillite, shallow-marine fossiliferous limestone, minor conglomerate, olistostrome, Devonian–Mississippian conglomerate, sandstone, siltstone, fossiliferous limestone, pillow basalt, andesite and tuff, overlain by Pennsylvanian, Permian–Triassic volcanic and sedimentary rocks (Suetenko et al., 1984; Tsukernik et al., 1986; Ruzhentsev et al., 1987; Lamb and Badarch, 1997). The Ordovician–Silurian sandstones are mostly mature and quartzose, however, uppermost Silurian conglomerates contain plutonic and volcanic clasts (Lamb and Badarch, 1997). Slivers and lenses of serpentinite and gabbro are present within the Cambrian to Silurian rocks. The terrane is intruded mainly by Carboniferous and Permian granites and locally by Silurian and Devonian plagiogranites.

The Atasbogd Terrane (37) is located in the southwestern Gobi desert area and extends westward into the northeastern Tien Shan region of China (Figs. 2 and 9). The terrane consists mainly of Ordovician, Silurian greenschist facies metamorphosed sandstone, siltstone, argillite, phyllite, chert, quartzite, minor marble, pillow basalt, Devonian conglomerate, sandstone, siltstone, andesite, dacite, rhyolite, tuff, breccia, radiolarian chert, and rare fossiliferous limestone lenses (Ruzhentsev, 1985; Badarch, 1990). On the southwesten margin of the terrane, there are Ordovician–Silurian rocks intruded by granite plutons and disconformably overlain by Devonian conglomerate, sandstone, ash tuff, siltstone, and limestone lenses containing brachiopods (Ruzhentsev, 1985). The post-accretionary assemblages

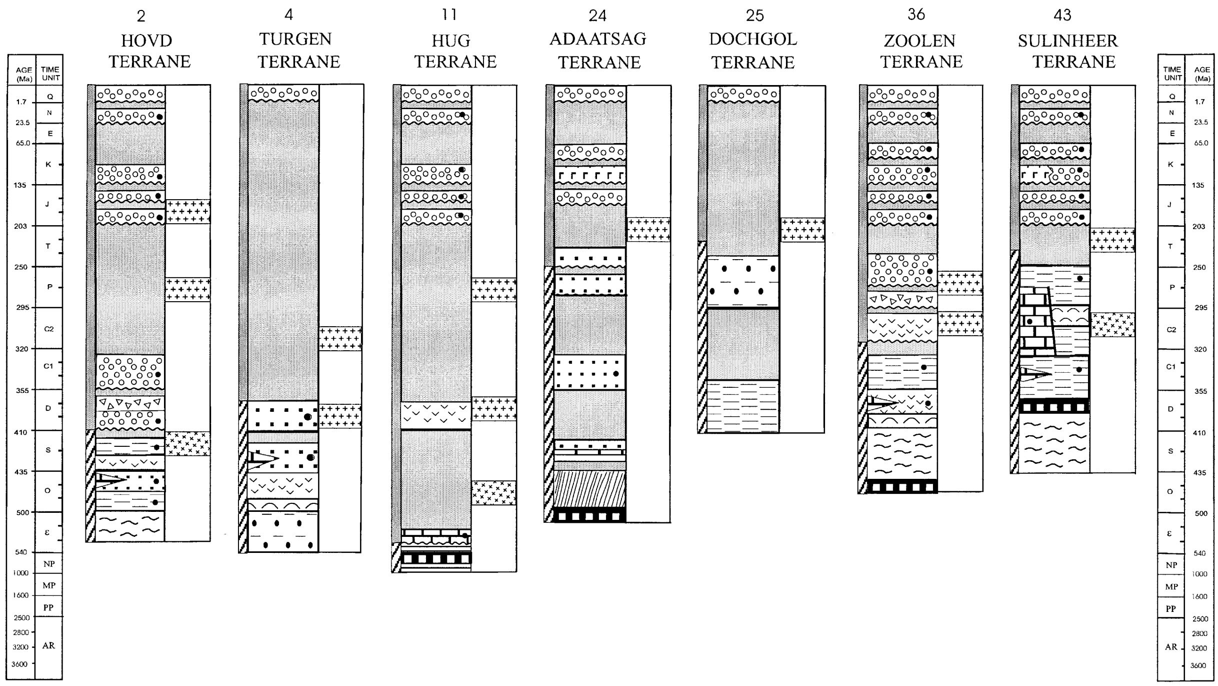

Fig. 10. Stratigraphic columns for Mongolian accretionary wedge terranes. See Fig. 3 for legend.

are Mississippian shallow marine sedimentary rocks, Pennsylvanian–Lower Permian basalt, andesite, rhyolite, tuff, volcaniclastic rocks, Upper Permian-Lower Triassic non-marine clastic rocks containing plant remains and tetrapods, and Middle Triassic–Lower Jurassic alluvial and lake sediments of the Noyon Syncline (Yarmolyuk, 1978; Gubin and Sinitza, 1993; Hendrix et al., 1996). The terrane is intruded by Devonian, Carboniferous and Permian granodiorite and granite plutons.

The Nuhetdavaa Terrane (40) is a narrow northwest trending belt near the Mongolia–China border area of eastern Mongolia (Figs. 2 and 8). The terrane is composed of Neoproterozoic gneiss, schist, quartzite, stromatolitic marble, Cambrian sandstone, siltstone, minor conglomerate, olistostrome, Ordovician–Silurian sandstone, siltstone, argillite, phyllite, minor conglomerate, coral limestone, Devonian basalt, andesite, volcaniclastic rocks, and minor coral limestone overlain by Mississippian shallow-marine sedimentary rocks (Suetenko and Lkhasuren, 1973; Badarch and Orolmaa, 1998). There are Silurian granite, granodiorite (K–Ar ages of 419–435 Ma, Marinov et al., 1973), and Carboniferous, Permian and Triassic–Lower Jurassic granite plutons. The eastern continuation of the terrane corresponds to the Dong Ujumqin Belt of China which contains volcanic and sedimentary rocks (~490 Ma), lenses of limestone with brachiopods (*T. gigantea*) and corals (Tang, 1990; Nan and Guo, 1992).

The Duulgant Terrane (44) is located in the southeastern Mongolia–China border area, south of the Sulinheer accretionary wedge terrane (43) and extends into Inner Mongolia, China (Fig. 2 and 9). It consists of Cambrian–Ordovician (?) schists, metasandstone, phyllite, tuff, quartzite, and minor marble, Silurian volcaniclastic sandstone, tuff, and chert, Permian marine sediments intruded by Devonian (?) diorite and granodiorite plutons (Ruzhentsev et al., 1989). The overlap assemblages include Cretaceous clastic rocks and Triassic–Lower Jurassic leucogranite plutons.

3.6. Accretionary wedge terranes

The accretionary wedge terranes are represented by narrow linear belts of highly deformed, metamorphosed rocks containing melanges, thrust sheets, and slivers of serpentinite, gabbro, fragments of ophiolitic rocks, and rare high-pressure schists (Figs. 2 and 10). There are five accretionary wedge terranes in the northern domain, and two in the southern domain.

The Hovd Terrane (2) occurs on the eastern margin of the Mongolian Altai Range (Figs. 2 and 10). It consists of Cambrian predominantly greenschist facies metamorphosed sandstone, siltstone, phyllite, tuff, Ordovician conglomerate, sandstone, argillite, graptolitic shale, fossiliferous limestone, and Silurian basalt, diabase, tuff, sandstone and graptolitic shale (Dergunov et al., 1980; Rozman, 1986). These rocks are intruded by gabbro, diorite, granodiorite and plagiogranite plutons (K–Ar ages of 456–440 Ma; Gavrilova, 1975). The complex occurs as fault-bounded disrupted blocks, thrust sheets, and tectonic slivers. In some places, there are melanges containing ultramafic rocks, gabbro and diabase. Our recent work in the Altai region indicates that this terrane contains polydeformed, greenschist–amphibolite facies metamorphosed volcaniclastic and sedimentary rocks, which are deformed by southwest-directed thrust faults. Overlap assemblages include Devonian and Mississippian volcanic and sedimentary rocks and Permian Jurassic subalkaline granite plutons intrude the terrane.

The Turgen Terrane (4) is located in the southern Altai Range and extends into China (Figs. 2 and 10). It is composed of Cambrian turbidite, Ordovician, Silurian–Devonian sandstone, siltstone, argillite, phyllite, and minor pillow basalt, andesite, and fossiliferous limestone intruded by Devonian and Carboniferous granite plutons (Dergunov et al., 1980). These rocks occur within southwest-directed thrust sheets and slivers separated by melange zones.

The Hug Terrane (11) occurs in the western Hovsgul area, east of the Sangelin Terrane (10) and extends into Russia (Figs. 2 and 10). The terrane consists of the Shishged Ophiolite and Neoproterozoic high-pressure metamorphic schists. The Shishged Ophiolite contains dunite, harzburgite, minor lherzolite, wehrlite, clinopyroxenite, layered gabbro, plagiogranite and diabase. The high-pressure rocks (Hug Series) are tholeiitic metabasalt, tuff, chert, metasandstone, phyllite, schist, and minor dolomite. The terrane contains early high-pressure assemblages with crossite, actinolite, winchite and late greenschist grade assemblages with chlorite, sericite, and epidote. The high-pressure metamorphism has a Rb–Sr isochron age of 829 ± 23 Ma, and late greenschist grade metamorphism is dated by Rb–Sr at 640 ± 20, and 624 ± 52 Ma (Sklyarov et al., 1996). The overall structure of the terrane is dominated by east-directed thrust sheets and melanges involving Lower Cambrian carbonate rocks. The terrane was originally covered by Neoproterozoic–Lower Cambrian shelf carbonate rocks of the Hovsgul Basin and intruded by post-collisional Ordovician diorite and granodiorite (Rb–Sr isochron age of 491 ± 25 Ma; Sklyarov et al., 1996) and Devonian alkaline and subalkaline granite plutons.

The Adaatsag Terrane (24) is a narrow and linear belt located in the southern Hentey Range and extends to the northeast into Russia (Figs. 2 and 10). It consists of Ordovician (?) schist, quartzite, metasandstone, phyllite, chert, metavolcanic rocks, Silurian coral limestone, melange, and fragments of ophiolite including layered gabbro, metabasalts and ultramafic rocks (Tomurtogoo, 1997; Parfenov et al., 1999). The sedimentary and volcanic rocks are highly deformed and metamorphosed to greenschist and amphibolite grade. Within the northeastern continuation of the terrane in Russia, these volcanic rocks correspond to MORB and OIB type (Gusev and Peskov, 1996). At the western end of the terrane, the ophiolite fragments contain dunite, harzburgite, pyroxenite, MORB-type tholeiitic pillow basalt, diabase dykes, melange with blocks of serpentinite, gabbro, basalt, limestone and quartzite, and thrust sheets of Silurian coral limestone and sandstone imbricated with Mississippian shallow marine sedimentary rocks. The northeastern part of the terrane is overlain by Middle-Upper Triassic sandstone, and siltstone with ammonites. These rocks are intruded by Triassic–Lower Jurassic rare metal granite plutons (Zonenshain, 1972).

The Dochgol Terrane (25) is located in the northeastern Mongolia–Russia border area and consists of deformed, metamorphosed Devonian to Triassic marine sedimentary, and minor volcanic rocks (Figs. 2 and 10). The Devonian–Carboniferous strata consist of sandstone, siltstone, argillite, phyllite, chert with lenses of limestone, and volcanic rocks. In Russia, these rocks contain greenschist-grade metamorphosed basalt, and glaucophane schists intruded by gabbro and diorite (Dobretsov et al., 1989; Zorin, 1999). The Permian–Triassic strata consist of sandstone, siltstone, phyllite, minor conglomerate and tuff. To the northeast in Russia, basalts, andesites and tuffs are intruded by layered gabbro and tonalite dated by Rb–Sr at 196 ± 7 Ma (Rutshtein, 1992). The Dochgol Terrane (25) is intruded by Late Jurassic–Early Cretaceous leucogranite plutons. The Dochgol (25) and Adaatsag (24) terranes both define the western end of the Mongol–Okhotsk suture (Zorin, 1999; Parfenov et al., 1999).

The Zoolen Terrane (36) forms a narrow belt in the central part of the southern Mongolian domain (Figs. 2 and 10). It consists of thrust sheets, tectonic slivers and melanges that contain Ordovician to Devonian tholeiitic pillow basalt, andesite, tuff, metasandstone, argillite, chert, minor limestone, olistostromes metamorphosed to greenschist facies, and Mississippian marine conglomerate, sandstone, and siltstone. There are many fragments of peridodite, serpentinite, gabbro, diorite, diabase and highly deformed, mylonitized and metamorphosed rocks (Zonenshain et al., 1975; Suetenko and Lkhasuren, 1973; Ruzhentsev et al., 1985). The overall structure of the terrane is characterized by imbricated thrust sheets, disrupted blocks and late strike-slip displacements. The post-accretion assemblages include Pennsylvanian–Permian non-marine volcanic, sedimentary and plutonic rocks, and Jurassic molasse.

The Sulinheer Terrane (43) is located south of the Hutag Uul Block in southeastern Mongolia–China border area (Figs. 2 and 10). It consists of fragments of ophiolite, melange, Mississippian clastic rocks, limestone, Pensylvanian–Lower Permian fusulinid-bearing limestone, Upper Permian clastic rocks, and lenses of limestone containing brachiopods and bryozoans (Ruzhentsev et al., 1989; Pavlova et al., 1991). The melange contains blocks of tholeiitic pillow basalt, tuff, radiolarian chert, and massive limestone. On the northern margin of the terrane there is Silurian–Devonian mylonitized gneiss, amphibolite, marble, quartzite, schist, metasandstone, argillite, chert, metavolcanic rocks intruded by gabbro, diorite, granodiorite and overlying Permian clastic rocks and limestones (Badarch, 1990). The muscovite–biotite schist and mylonite have Ar–Ar mica ages of 271–208 Ma (Webb, personal

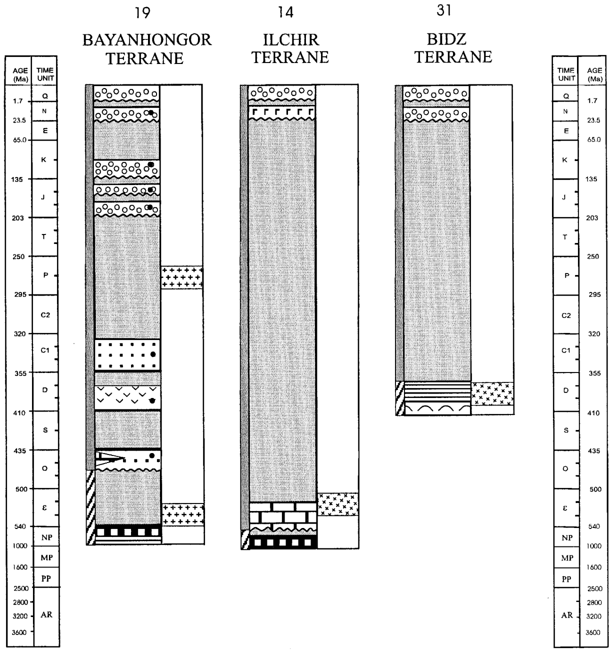

Fig. 11. Stratigraphic columns for Mongolian ophiolitic terranes. See Fig. 3 for legend.

communication, 1999). Fragments of ophiolitic rocks are exposed mainly near the Mongolia–China border area and consist of serpentinite, dunite, and minor gabbro cut by multiple quartz veins. In China, this terrane contains pillow basalt, tuff, chert, and limestone (Wang and Liu, 1986). A whole-rock Sm–Nd isochron age of 403 ± 27 was obtained for ophiolitic rocks from this terrane in China (Bao et al., 1994). The terrane is overlain by Jurassic–Lower Cretaceous clastic sedimentary rocks and intruded by granodiorite and granite plutons. In adjacent areas of Inner Mongolia, similar granite plutons (Halatu magmatic suite) have been dated by Rb–Sr isochron at 230 Ma (Chen et al., 2000).

3.7. Ophiolitic terranes

The ophiolitic terranes are the Bayanhongor (19) and Ilchir (14) terranes in the northern domain and the Bidz Terrane (31) in the southern domain. These terranes contain dominantly ophiolitic rocks and subordinate melanges that are disrupted by thrusting and strike-slip displacements.

The Bayanhongor Terrane (19) is the largest ophiolite in Mongolia and is located on the southwestern side of the Hangay Dome (Figs. 2 and 11). The terrane includes the Burd Gol Zone, Bayanhongor Ophiolite and Delb Khairkhan Melange of Buchan et al. (2001a). The Bayanhongor Ophiolite comprises a complete ophiolite stratigraphy of serpentinized ultramafic cumulates, gabbro, sheeted dykes, pillow lava and local chert, and limestone. A gabbro within the ophiolite complex has a Sm–Nd hornblende and whole-rock isochron age of 569 ± 21 Ma (Kepezhinskas et al., 1991). However, the ophiolite is dismembered into blocks enclosed in a matrix of sheared and serpentinized ultramafic rocks. 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 Burd Gol Zone is a tectonic melange containing lenses of sedimentary and igneous rocks enclosed in a black schist matrix and cut by abundant quartz veins. The black schists have a K–Ar muscovite age of 699 ± 35 Ma (Teraoka et al., 1996). The sedimentary rocks are sandstone, siltstone, mudstone, shale, chert, limestone and thin-bedded calc-turbidite. The igneous rocks include basalt, gabbro, dolerite, andesite, and rare rhyolite. The Delb Khairkhan Melange lies to the south of the ophiolite and contains mixed lenses of igneous and sedimentary rocks enclosed in a matrix of pelitic schist. On the northern side of the melange there are pillow basalts, and minor limestone, quartzite, shale and sandstone and lenses of gabbro and dolerite. New geochronological data from granites that intrude the Bayankhongor Ophiolite suggest that the ophiolite was obducted by thrusting in a collisional event which lasted from 540 to 450 Ma (Buchan, personal communication, 2001). The overall structure of the Bayanhongor Terrane (19) is dominated by NE-directed thrusting and ESE-directed sinistral strike-slip displacements (Buchan et al., 2001a). Post-accretion assemblages consist of Ordovician, Devonian, Mississippian, Jurassic and Cretaceous sedimentary and volcanic rocks intruded by Permian granites.

The Ilchir Terrane (14) is located between the Gargan and Hamardavaa blocks, north of Lake Hovsgul and extends to Russia (Figs. 2 and 11). The terrane comprises a Neoproterozoic dismembered ophiolite complex containing dunite, harzburgite, gabbro, pillow lava, boninite dikes, siliciclastic flysch with olistostrome that was covered by Neoproterozic–Lower Cambrian carbonate rocks of the Hovsgul Basin and later intruded by Ordovician granite (Belichenko et al., 1988a; Sklyarov et al., 1994; Parfenov et al., 1995).

The Bidz Terrane (31) occurs in a narrow sliver which extends for one hundred kilometres along the northern side of the Baaran Terrane (30) (Figs. 2 and 11). It consists of tholeiitic pillow basalt, tuff, chert, sandstone, siltstone, argillite, and minor thin layers of limestone, intruded by gabbro and diorite. The age of the volcanic and sedimentary rocks is presumed to be Ordovician to Devonian (Ruzhentsev et al., 1992b). Major and rare element data suggest that these basalts are MORB-type and formed at an oceanic ridge (Ruzhentsev et al., 1992b). On the eastern margin of the terrane there are quartz–chlorite–sericite schists containing lenses of igneous and sedimentary rocks. The overall structure is dominated by SW-directed thrust faults, and high-strain shear zones. The Bidz Terrane (31) may be displaced fragments of oceanic crust formed adjacent to an Ordovician (?) island arc identified to the west in the Chinese Altai (He and Han, 1991; Windley et al., 1994).

4. Discussion

The cratonal, metamorphic and passive continental margin terranes were previously interpreted as either parts of the so-called Tuva–Mongolian (or Central Mongolian) Massif (Mitrofanov et al., 1981; Gordienko, 1987; Ilyin, 1990; Tomurtogoo, 1997), fragments of Gondwana (Didenko et al., 1994), or Pre-Altaid continental crust (Sengör et al., 1993; Sengör and Natal'in, 1996). The Tuva–Mongolian Massif is essentially a terrane amalgam in northern and central Mongolia which has previously been defined as having Precambrian basement with granulite–amphibolite grade metamorphosed rocks and Mesoproterozoic–Cambrian sedimentary cover (Mitrofanov et al., 1981; Gordienko, 1987; Tomurtogoo, 1997). The true shape and dimensions of the Tuva–Mongolian Block are unclear and new geological and geochronological data are needed to define its boundaries. Kozakov et al. (1999a,b) reported geochronological data from the Sangelin Block (10; Fig. 2) which traditionally has been regarded as part of the Tuva–Mongolian Massif and suggested that metamorphic assemblages such as the Erzin, Moren and Naran complexes are thrust stacks which formed during early Cambrian amalgamation and were metamorphosed to amphibolite and granulite facies around ca 536–494 Ma (Kozakov et al., 1999a,b; Salnikova et al., 2001). These data cast doubt on whether the Sangelin Terrane (10) should be regarded as part of the Tuva–Mongolian block and also show that the Sangelin block is significantly different in its geological and metamorphic evolution from the Zavhan Terrane (8).

Other cratonal, metamorphic and passive margin terranes located in central and southern Mongolia were previously interpreted as a contiguous oroclinally bent Pre-Altaid continental block framing the Hangay–Hentey Basin (Fig. 2; Sengör et al., 1993; Sengör and Natal'in, 1996). However, according to our proposed terrane subdivision (Fig. 2) this supposed oroclinally bent block is divisible into at least six cratonal, metamorphic and passive margin terranes, that each possess distinctive internal stratigraphy, plutonic rocks, and/or metamorphic history thus meriting their separation as distinct terranes. For example, the Baydrag Terrane (18) contains proven Archaean basement and Neoproterozoic sedimentary cover which is absent in the Zavhan (8) and other terranes. In contrast, the Zavhan Terrane (8) is characterized by Neoproterozoic rift-related volcanic rocks and carbonate cover rocks containing diamictite horizons (Lindsay et al., 1996). The Tarvagatay cratonal terrane (17) is distinguished from neighbouring basement terranes by its Archaean–Proterozoic ages of anorthosite plutons and Sm–Nd model ages of granitic rocks ranging from $T_{DM} = 1085$ Ma to $T_{DM} = 2154$ Ma (Mitrofanov et al., 1985; Kovalenko et al., 1996a,b). Kovalenko et al. (1996a,b) also suggested that Precambrian continental crust underlies the basin deposits of the southern Hangay region based on negative Nd values and Sm–Nd model ages of Palaeozoic and Mesozoic granitoids. Buchan et al. (2001a) also suggested that the Zag sequence was deposited on a passive margin to a continental block that is largely concealed by Devonian–Carboniferous cover sediments in the Hangay region. Therefore, the basement block which underlies the southern Hangay region may be a southern continuation of the Tarvagatay Block.

The Ereendavaa Terrane (26) contains cratonic basement rocks with unique stratigraphic and plutonic assemblages which distinguish it from the Idermeg Terrane (32). The latter is interpreted to be a passive continental margin sequence deposited on basement rocks of possible cratonic affinity. The distinction between these two terranes is also made because the Herlen Terrane (27) lies in between and is interpreted as a suture zone containing ophiolitic and island arc volcanic rocks.

The Tsagaan Uul (39) and Hutag Uul (42) cratonal terranes in southern Mongolia are distinguishable from neighbouring terranes by their Precambrian basement and because they contain Silurian–Devonian strata which lack brachiopod (*Tuvealla*) fossils of Siberian affinity (Rong et al., 1995), which are found in other terranes containing Silurian strata (including cratonal terranes) in Mongolia. This suggests that the Tsagaan Uul (39) and Hutag Uul (42) terranes have a different paleogeographic affinity from terranes to the north and northwest.

The metamorphic terranes of Mongolia contain metamorphosed and deformed sedimentary, volcanic and/or plutonic rocks that are not easily assigned to a single tectonic environment or period of tectonism. Radiometric dating of granite-gneiss from the Buteel Terrane (21) and foliated granite and basic dykes from the Tseel Terrane (5) give Permian and Devonian ages, respectively (Kröner et al., 2001; Bibikova et al., 1992; Baykova and Amelin, 1994). U–Pb zircon ages of granitic rocks from metamorphic complexes of the Sangelin (10), Hamardavaa (15) and Tseel (5) terranes suggest that granulite and amphibolite facies metamorphism took place during the Cambrian to Ordovician, possibly in the Devonian (Bibikova et al., 1992; Fedorovskii et al., 1995; Kotov et al., 1997; Kozakov et al., 1999a). Some of these terranes may contain tectonic slivers of Precambrian rocks however, their origin and protolith ages are not well constrained (Kozakov, 1986; Kröner et al., 2001).

The island arc, backarc/forearc and accretionary wedge terranes of Mongolia have previously been interpreted as fragments of Palaeozoic island arc systems, turbidite basins, passive continental margins, or fragments of the Tuva–Mongolian continental arc (Ruzhentsev et al., 1985; Gordienko, 1987; Ruzhentsev and Pospelov, 1992; Sengör et al., 1993; Sengör and Natal'in, 1996; Didenko et al., 1994; Mossakovsky et al., 1994; Lamb and Badarch, 1997; Tomurtogoo, 1997). Sengör and Natal'in (1996) showed three island arc units of early–middle Cambrian age within Mongolia which coincide with the Hovd (2), Dzhida (16) and Agardag (7) terranes. However, within the Hovd unit, these authors describe a Middle Cambrian–Lower Ordovician accretionary complex, unconformably

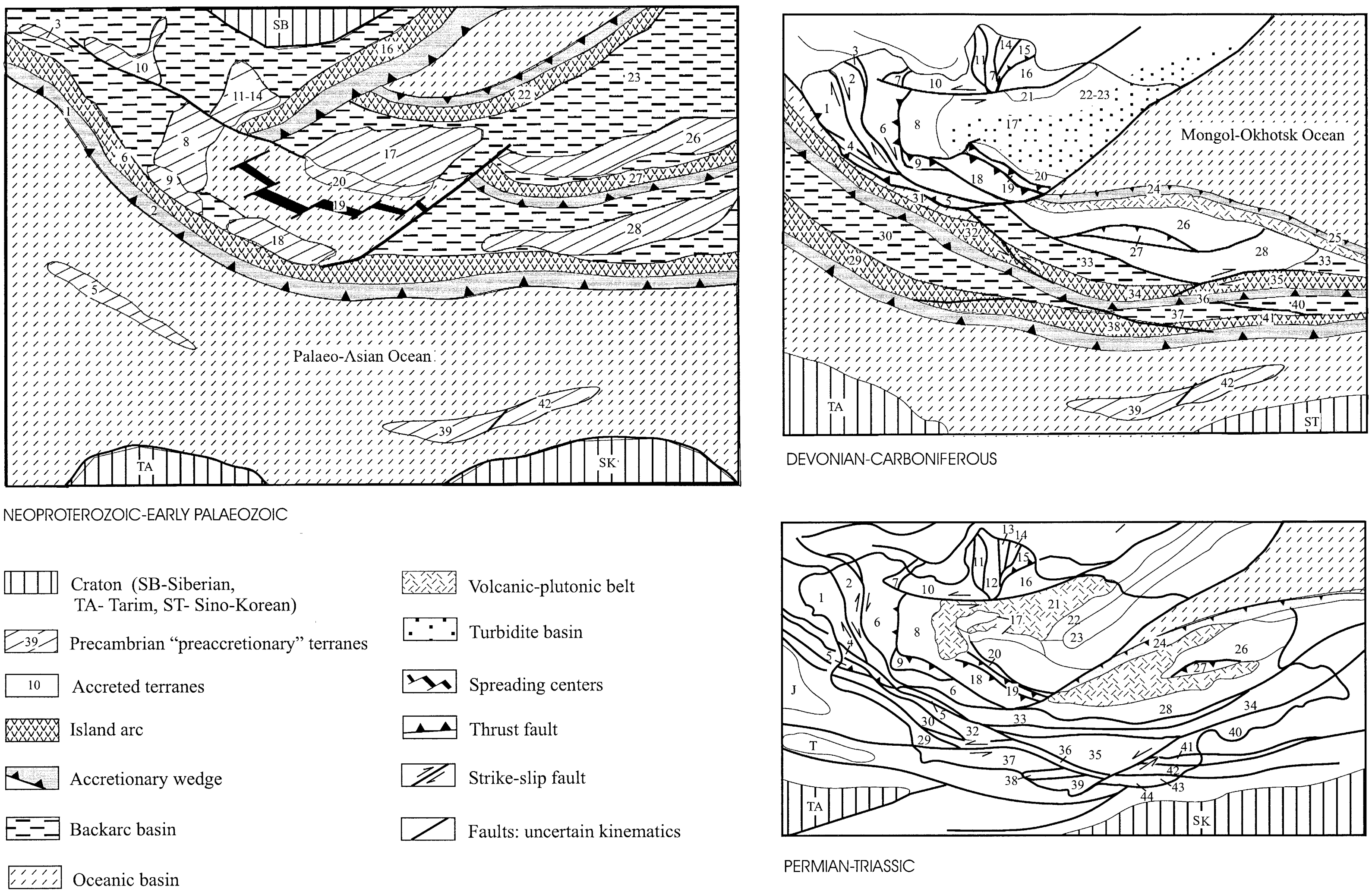

Fig. 12. Simplified three-stage evolutionary model of terrane accretion and amalgamation in Mongolia and neighbouring regions. See text for discussion. Terrane numbers are same as in Figs. 2 and 4–11.

overlain by Ordovician to Devonian sedimentary and volcanic rocks. According to Dergunov et al. (1980) and Volochkovich and Leontyev (1990), and unpublished geological maps compiled by Mongolian geologists, the major unconformity occurs at the base of the Devonian, not in the Ordovician. Because the oldest basement rocks are accreted sediments and volcanic rocks, we interpret the Hovd unit as an accretionary wedge terrane and not as an 'ensimatic arc'. The Hantayshir Ophiolite within the Lake Terrane (6) was previously combined with the Precambrian Dariv metamorphic block by Sengör and Natal'in (1996). However, new geochronological and geochemical data from ophiolitic complexes in the Lake Terrane (6) indicate that they have similar ages and chemistry to the Hantayshir Ophiolite and associated volcanic rocks (Dergunov et al., 1980; Kovalenko et al., 1996a,b; Windley et al., 2000; Kröner et al., 2001; Buchan personal communication). The ophiolitic rocks of the Lake Terrane (6) are interpreted to have formed in an island arc environment during ca 573–527 Ma (Khain et al., 1995; Kovalenko et al., 1996a,b; Kröner et al., 2001).

The Gobi Altai (33), Mandalovoo (34), Baaran (30), Baytag (29), Zoolen (36), Edren (32), Gurvansayhan (35) and Nuhetdavaa (40) terranes correspond to the South Mongolian unit of Sengör and Natal'in (1996) which contains Ordovician–Silurian turbidite sequences and Devonian–Carboniferous island arc and accretionary wedge complexes. The oldest island arc terrane within Sengör and Natal'in's (1996) South Mongolian unit is the Gurvansayhan Terrane (35) which contains Ordovician–Devonian volcanic rocks with the oldest volcanic rocks found along the southern margin (Perelló et al., 2001). This suggests that Palaeozoic accretion of younger rocks may not have been progressively southwards in southern Mongolia as previously suggested by Sengör and Natal'in (1996).

The backarc/forearc terranes of Mongolia are distinguished mainly by the presence of thick sequences of volcaniclastic sedimentary rocks and subordinate volcanic rocks. We tentatively consider that the Agardag (17), Baaran (30), and Gobi Altai (33) backarc basins were formed adjacent to the Lake (6), Baytag (29) and Mandalovoo (34) island arcs, respectively. However, the paleotectonic position of the Altai (1) and Haraa (23) backarc/forearc terranes is unclear.

The Bayanhongor (19), Bidz (31) and Ilchir (14) ophiolitic terranes of Mongolia are interpreted as fragments of oceanic crust, upper mantle and overlying sedimentary rocks. The Bayanhongor Ophiolite formed in a spreading centre within an ocean basin and was later obducted onto the Zag passive margin terrane and itself overthrusted by the Baydrag cratonal block (Buchan et al., 2001a). Structural data from the Bayanhongor Terrane (19) suggest that the Bayanhongor Ophiolite marks a collisional suture zone between the Baydrag and Hangay Precambrian blocks (Buchan et al., 2001a). In contrast, the structural evolution and age of the Bidz and Ilchir ophiolitic rocks are poorly known and their paleotectonic position remains unclear.

Post-accretion assemblages are widely distributed among the terranes of Mongolia and include sedimentary basins, volcanic–plutonic belts and plutonic rocks of various ages which stitch terrane boudaries. These post-accretion complexes provide important constraints on timing of terrane amalgamation and orogenic events that have affected the terranes. The tonalites which cut the Gargan Block and correlative rocks in adjacent Russia are dated at 790 Ma by Kuzmichev et al. (2001) and comprise the oldest igneous complexes that stitch terranes together in the region.

The Hovsgul and Tsagaanolom basins contain mainly Cambrian shelf carbonate rocks which were deposited after amalgamation of the Zavhan (8), Tarvagatay (17), Gargan (13), Ilchir (14) and Hug (11) terranes, which they overlie (Ilyin, 1990). New geochronogical data from granites and foliated pillow basalt of the Bayanhongor zone (Delor et al., 2000; Windley et al., 2001), dated schists from the Zag Terrane (8) (Kurimoto et al., 1998) and identification of Ordovician clastic sedimentary rocks in South Hangay indicate that amalgamation of the Baydrag (18), Zag (20), Bayangol (22) and Haraa (23) terranes occurred during early Cambrian to Middle Ordovician time. Synchronous amalgamation of the Lake (6), Sangelin (10), Zavhan (8), and possibly Dariv (9) terranes is partly supported by similar ages of metamorphism (ca 536–489 Ma,) in these terranes and by post-collisional granite plutons dated at ca 451–464 Ma (Kovalenko et al., 1995; Kozakov et al., 1999c). Devonian volcanic, plutonic and sedimentary rocks are widely distributed in the Mongolian Altai and post-date amalgamation of the Altai (1), Hovd (2) and Tsagaanshiveet (3) terranes.

Pennsylvanian–Permian volcanic and plutonic rocks occur in most terranes south of the Main Mongolian Lineament, suggesting amalgamation was completed by Pennsylvanian–Permian time in that region (Yarmolyuk, 1978). In central Mongolia, the tectonic significance of the Hangay–Hentey overlap basin (Fig. 2) is controversial. The Hangay–Hentey Basin is interpreted as either an accretionary wedge (Zorin, 1999; Parfenov et al., 1999), or part of the Mongol–Okhotsk oceanic gulf that developed from Neoproterozoic to the late Permian (Fig. 12; Sengör and Natal'in 1996). Alternatively, Gordienko (1987) suggested that this basin formed within an Andean type continental margin, associated with northward subduction of the South Mongolian paleoocean floor. Ruzhentsev and Mossakovskiy (1996) suggested the basin is a post-orogenic successor basin which formed on Caledonian basement of the northern Mongolian domain. This is supported by the presence of Devonian and Carboniferous shallow marine sedimentary rocks with possible rift-related bimodal volcanic rocks overlying the basement of the Tarvagatay (17), Haraa (23), Bayangol (22), Zag (20), Bayanhongor (19) and Adaatsag (24) terranes surrounding the Hangay–Hentey Basin (Kotlyar et al., 1998).

Kovalenko and Yarmolyuk (1990) suggested that the

Selenge and Middle Gobi volcanic–plutonic belts (Fig. 2) were formed in continental rift zones because they contain subalkalic bimodal volcanic rocks. Alternatively, Zorin (1999) and Parfenov et al. (1999) interpreted these belts as the Andean type continental margin or transform margin of the Mongol–Okhotsk ocean basin. Despite many suggestions for the existence of the Mongol–Okhotsk ocean basin within Mongolia, there is still no consensus on the polarity of subduction during closure, how far west the ocean extended, and the exact location of its suture.

Amalgamation of the Enshoo (41), Hutag Uul (42), Sulinheer (43) and Duulgant (44) terranes of southeastern Mongolia occurred more recently, as indicated by the occurrence of Triassic plutons which intrude all four terranes (Munkhtsengel and Iizumi, 1999; Chen et al., 2000) and the existence of Permian to Triassic mylonitic shear zones, and greenschist-grade metamorphism (Lamb et al., 1999). This amalgamation is also recorded by overlapping Middle Triassic to Lower Jurassic sedimentary rocks of the Noyon foreland basin which overlies the Atasbogd Terrane (Hendrix et al., 1996).

Although we distinguish 44 separate tectonostratigraphic terranes in Mongolia, we can make several general statements regarding the crustal evolution of the region. There appears to be a cratonic nucleus in central Mongolia around which younger terranes accreted. This cratonic block is a combination of different cratonal and metamorphic terranes around which arcs and related subduction complexes, ophiolites and basins sediments collided and amalgamated (Fig. 12). The accretion history was complex and we believe more age control and structural data are needed to confirm Sengör et al.'s (1993) hypothesis that migration of magmatic fronts was progressively to the south and west from the central Hangay region. For example, we identify at least 4 separate arc terranes in southern Mongolia (Lamb and Badarch, 1997), however, there is no simple north-to-south progression of volcanism in these terranes, and in the Gurvansayhan Terrane (35), existing age data suggest south-to-north accretion (Perelló et al., 2001). In general, interpretation of the polarity of subduction within closing ocean basins now marked by ophiolitic and accretionary terranes is only supported by structural data for a few regions. For example, in the southern Hangay region, ocean closure and terrane accretion in the Bayanhongor Ophiolite Zone involved northeastward-directed overthrusting and therefore presumably southwestward dipping subduction (Buchan et al., 2001a). However, in the western Altai region, our field results suggest structural vergence within the basement rocks is dominantly to the west, suggesting eastward dipping subduction beneath the Altai Terrane (1). Between these two areas in the Valley of Lakes (Fig. 1), the structural history is unresolved. Much more detailed structural work will be needed to document the regional vergence of structures, temporal progression of terrane accretion and amalgamation, original structural significance of terrane boundaries, and the importance of strike-slip displacements between terranes.

The arcuate trends of terranes around the central Hangay region provide the first-order structural grain for Mongolia. This crustal anisotropy has played a major role in controlling the trends and kinematics of all subsequent Phanerozoic deformation in the region, including the Cenozoic development of the Altai and Gobi Altai (Cunningham, 1998). Reactivation of older structures including terrane boundaries is suspected to play a major role in localizing active deformation and uplift in the Altai, Gobi Altai and Hangay regions (Cunningham et al., 1996, 1997).

5. Conclusions

Our synthesis of the basement geology of Mongolia allows for the distinction of cratonal, metamorphic, passive continental margin, island arc, backarc/forearc, acretionary wedge and ophiolitic terranes which differ from each other by contrasting stratigraphy, magmatism, metamorphic events and tectonic history. The timing of terrane accretion is partly constrained by sedimentary overlap assemblages and post-amalgamation intrusive complexes. The main stages of amalgamation occurred during the Neoproterozoic, Cambrian-Ordovician, Devonian, Pennsylvanian–Permian and Triassic. This study shows that a terrane perspective remains a useful and objective method of regional tectonic analysis for the basement geology of Mongolia. Future work on all aspects of Mongolia's basement geology is needed to further refine the three-dimensional architecture of Mongolia's crust and its evolution through time.

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