Zircon Ages from the Baydrag Block and the Bayankhongor Ophiolite Zone: Time Constraints on Late Neoproterozoic to Cambrian Subduction- and Accretion-Related Magmatism in Central Mongolia

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ABSTRACT

Central Mongolia represents a heterogeneous crustal domain of the Central Asian Orogenic Belt and is composed of contrasting lithotectonic units with distinct preorogenic histories. We report single-zircon evaporation and SHRIMP ages for high-grade rocks of the Neoarchean-Paleoproterozoic Baydrag block and for metaigneous rocks of the junction between the late Neoproterozoic Bayankhongor ophiolite zone (BOZ) and the Baydrag block. Zircon ages for metamorphic rocks of the Baydrag block indicate a major tectonothermal event between 1840 and 1826 Ma, coeval with the emplacement of granitic rocks at middle-crustal level dated at 1839 Ma. A granite-gneiss yielded a much younger crystallization age of 1051 Ma, the first Grenvillian age reported for this region. Together with predominantly Mesoproterozoic detrital zircon ages for a quartzite lens from the Burd Gol accretionary complex, these data attest to the heterogeneity and long Precambrian history of the Baydrag block. Crystallization ages for granite-gneisses from the northeastern margin of the Baydrag block indicate prolonged plutonic activity between 579 and 537 Ma, probably related to southward subduction of the Bayankhongor oceanic crust. A syntectonic granite vein yielded a crystallization age of 519 Ma, probably linked to accretion of the BOZ onto the northeastern active margin of the Baydrag block. Lastly, a felsic metavolcanic rock from the southeastern termination of the BOZ yielded a crystallization age of 472 Ma and suggests that punctuated volcanic centers developed during the early Ordovician in response to protracted convergence.

Online enhancements: appendix, color figure.

Introduction

The Central Asian Orogenic Belt (CAOB; Jahn et al. 2000), or Altaid Tectonic Collage (Şengör et al. 1993; Şengör and Natal'in 1996), is regarded as one of the largest areas on Earth of continental crust formation during the Phanerozoic (Şengör et al. 1993; Jahn et al. 2000; Jahn 2004). It is bounded in the north by the Siberian craton and in the south by the Tarim and Sino-Korean cratons and extends from the Ural Mountains in the west to the Pacific coast in the east (fig. 1*A*). This large orogenic system formed as a result of subduction-accretion processes within the Paleo-Asian Ocean and involved magmatic arc assemblages, ophiolitic complexes, and subordinate microcontinents (Coleman 1989; Zonenshain et al. 1990; Şengör et al. 1993; Berzin et al. 1994; Mossakovsky et al. 1994; Yakubchuk 2004, 2008; Kröner et al. 2007; Windley et al. 2007). Besides its giant size, the CAOB has an unusually long orogenic history, beginning in

Manuscript received October 12, 2008; accepted February 25, 2009.

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[The Journal of Geology, 2009, volume 117, p. 377–397] © 2009 by The University of Chicago.
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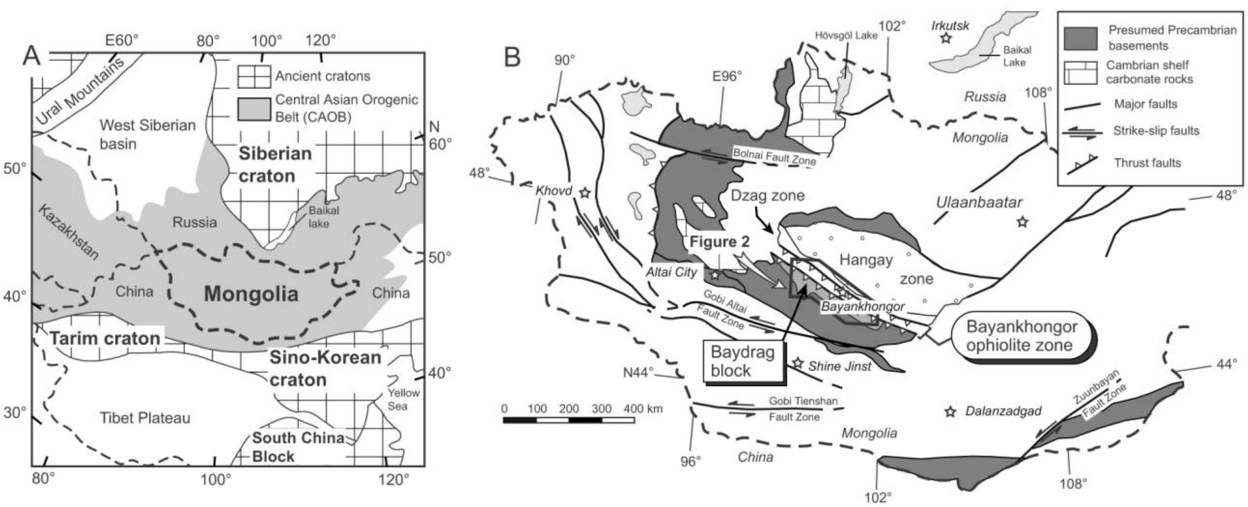

Figure 1. *A*, Outline of the Central Asian Orogenic Belt showing location of Mongolia (modified after Jahn et al. 2000). *B*, Simplified lithotectonic map of Mongolia (modified after Lamb et al. 1999; Badarch et al. 2002) showing the distribution and presumed extension of Precambrian basement and location of the Bayankhongor ophiolite zone, sandwiched between the Dzag zone and the Baydrag block. Location of figure 2 is also indicated.

the latest Mesoproterozoic (Khain et al. 2002) and terminating in the late Permian to early Triassic (Xiao et al. 2003; Li 2006; Chen et al. 2008; Zhang et al. 2008).

Several domains of high-grade rocks within the CAOB have long been interpreted as remnants of preorogenic microcontinents (Berzin et al. 1994; Mossakovsky et al. 1994). These interpretations were based mainly on geological mapping, lithological correlations, and metamorphic grade, and the paucity of precise geochronological constraints has led to many misconceptions and misinterpretations. For instance, high-grade gneisses in southern Tuva and western Mongolia, previously thought to be Precambrian in age, underwent granulite- to amphibolite-facies metamorphism between the Cambrian and the early Ordovician (Sal'nikova et al. 2001; Kozakov et al. 2002) and probably resulted from accretion/collision processes during the evolution of the CAOB. However, the presence of Precambrian magmatic rocks is relatively well documented for several high-grade crystalline complexes, such as in southern Kazakhstan (Kröner et al. 2007) and southern Mongolia (Yarmolyuk et al. 2005; Demoux et al. 2009), but the geographical extent of these domains remains uncertain. The best-studied Precambrian complex occurs in central Mongolia within the Dzabkhan microcontinent (Mossakovsky et al. 1994) and is known as the Baydrag block or terrane (fig. 1*B*; Badarch et al. 2002; Kozakov et al. 2007), which consist of a ca. 1000-km^2 nucleus, where Neoarchean to Paleoproterozoic magmatic and tectonometamorphic events are well defined by reliable radiometric ages. Considering the uncertain geographic extend and tectonic boundaries of the Baydrag crystalline complex we use the original descriptive term Baydrag block (Mitrofanov et al. 1981) instead of Baydrag "terrane" as recently proposed by Badarch et al. (2002).

Determining the timing of tectonothermal events during juxtaposition of lithotectonic units is of critical importance in establishing the amalgamation history of the CAOB. Central Mongolia is an ideally suited region to scrutinize this problem because it contains contrasting lithotectonic units (fig. 1*B*) composed of a metamorphosed turbidite-like sequence (Dzag zone), a late Neoproterozoic ophiolite (Bayankhongor ophiolite zone, BOZ), and a Precambrian basement complex (Baydrag block). We present new single-zircon evaporation and sensitive high-resolution ion microprobe (SHRIMP) ages for high-grade rocks from the Baydrag block and for metaigneous rocks from a transect across the southeastern termination of the Bayankhongor ophiolite zone and Baydrag block in central Mongolia. These ages enable us (1) to refine the tectonothermal evolution of the Baydrag block before 1.8 Ga and to elucidate its eastern extension, and (2) to reconstruct the late Neoproterozoic to Cambrian accretion history of the BOZ with respect to that of the Baydrag block.

Regional Geology and Geochronological Background of the Baydrag Block and Bayankhongor Ophiolite Zone

In central Mongolia, the southern flank of the Hangay highland is occupied by an orogenic zone that contains the late Neoproterozoic Bayankhongor ophiolite (Buchan et al. 2001; Tomurtogoo 2002; Kovach et al. 2005). This ophiolite forms a northwest-southeast-trending sublinear zone (fig. 1*B*) and is tectonically integrated within an accretionary complex developed between the Baydrag block and the Dzag zone (fig. 2*A*; Osozawa et al. 2008 and references therein). Previous lithological and structural studies have shown that the overall regional structural pattern is dominated by northwest-striking and northeast-vergent thrust faults (fig. 2*A*; Buchan et al. 2001; Osozawa et al. 2008), which enable distinguishing six major lithotectonic units described below from south to north; earlier geochronological results are summarized in table A1, available in the online edition or from the *Journal of Geology* office.

Baydrag Block. The gneissic basement making up most of the Baydrag block is subdivided into two complexes according to their lithological characteristics, namely Baidaragin and Bumbuger (fig. 3; Kozakov et al. 2007). The Baidaragin complex is primarily composed of migmatitic tonalitic gneisses, which contain lenses of amphibolite and pyroxene-bearing mafic gneisses. The Bumbuger complex is dominated by metasediments and includes an alternation of pyroxene-bearing crystalline schists and leucocratic gneisses as well as forsterite-bearing marbles, quartzites, garnet-biotite schists, and leucocratic pyroxene-bearing gneisses. All rocks underwent amphibolite- to granulite-facies metamor-

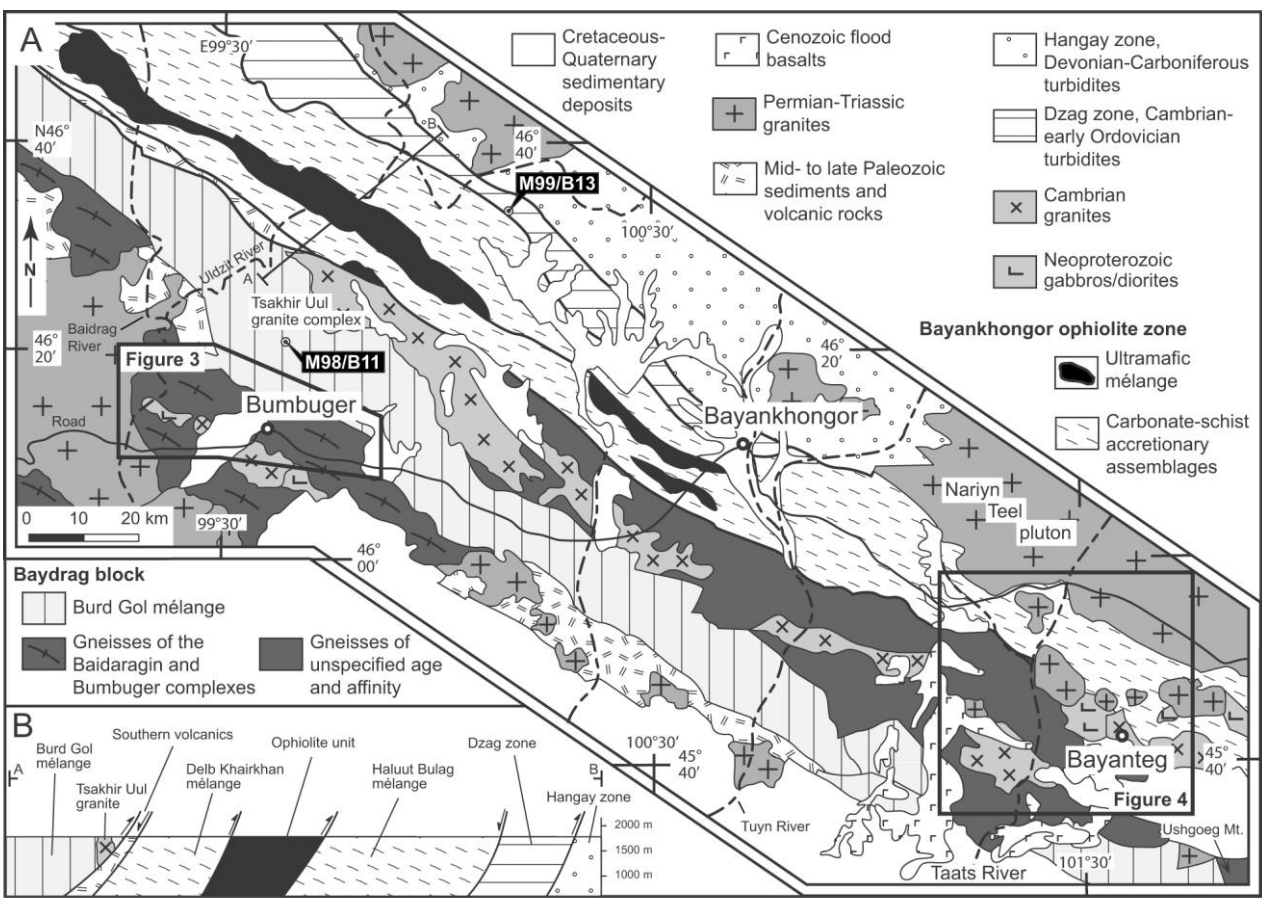

Figure 2. *A*, Simplified geological map of the Bayankhongor area and Baydrag block (modified after 1 : 500,000 geological map of western Mongolia); also indicated are areas investigated in this study (figs. 3, 4) and the location of samples M98/B11 and M99/B13 from the Burd Gol mélange and Dzag zone, respectively. *B*, Simplified cross section showing tectonic contacts between the Burd Gol mélange, the Bayankhongor ophiolite zone, and the Dzag zone (modified after Buchan et al. 2002; Osozawa et al. 2008).

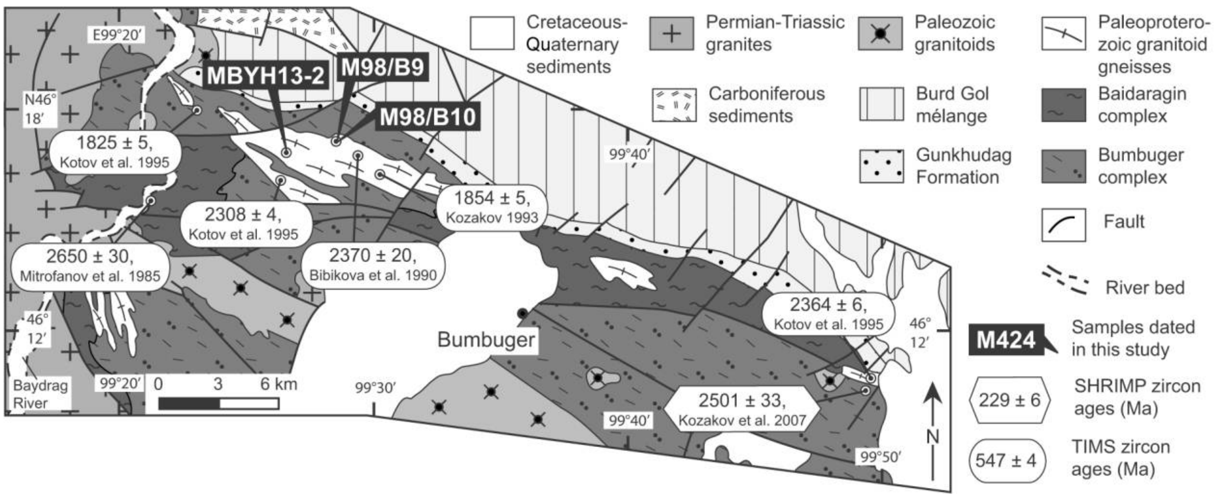

Figure 3. Geological sketch map of the Baydrag block (modified after Tomurtogoo et al. 1998). Previous geochronological results and location of dated samples are also indicated.

phism and record a polyphase tectonometamorphic evolution. The structural relationship between both complexes is uncertain due to strong reworking of lithological contacts during a ca. 1.8-Ga tectonothermal event (Kozakov et al. 2007). However, Kozakov et al. (1997) speculated on the basis of Nd model ages that the Bumbuger metasediments were most likely derived from the Neoarchean Baidaragin complex.

Previous geochronological studies within the Baydrag block led to recognition of three major tectonothermal events summarized as follows: (1) a Neoarchean event between 2890 and 2650 Ma related to protolith emplacement of metaigneous rocks of the Baidaragin complex (Mitrofanov et al. 1985; Kozakov et al. 2007); (2) an early Paleoproterozoic event between 2370 and 2308 Ma related to the emplacement of two-pyroxene granodiorite, quartz diorite, and biotite granite veins (Bibikova et al. 1990; Kotov et al. 1995); and (3) a late Paleoproterozoic event between 1854 and 1825 Ma related to the emplacement of enstatite-bearing garnet granodiorite and amphibole granosyenite veins (Kozakov 1993; Kotov et al. 1995). The third tectonothermal event produced the dominant present-day structural grain recognized within both the Baidaragin and Bumbuger complexes and was previously interpreted as the final phase of stabilization of the Baydrag block (Kotov et al. 1995). However, Kozakov et al. (2007) reported SHRIMP ages of ca. 2.0–1.7 Ga for homogeneous rims and recrystallized domains of zircons from rocks of both the Baidaragin and Bumbuger complexes, suggesting that at least part of the Baydrag block underwent post-Paleoproterozoic reworking.

Northwest of Bumbuger village (fig. 2*A*), gneisses of the Baydrag block are overlain unconformably by the unmetamorphosed Gunkhudag Formation (Tomurtogoo and Gerel 1999), a shelflike sedimentary sequence about 250 m thick. The lower part contains northeast-dipping coarse-grained quartzite and conglomerate beds, overlain upsection by pebbly sandstone and stromatolite-bearing dolomite of early Mesoproterozoic age (Dergunov et al. 1997).

Burd Gol Mélange. To the northeast of the Gunkhudag Formation, the Burd Gol mélange forms a northwest-southeast elongated trough (fig. 2*A*). The mélange is composed of phyllites and graphite-rich chlorite-biotite schists that contain lenses of metaigneous and -sedimentary rocks cross cut by abundant quartz veins (Buchan et al. 2001). Microfossils from black shales suggest Mesoproterozoic to Neoproterozoic ages (Mitrofanov et al. 1981). Mineral assemblages within the mélange indicate Barrovian metamorphic conditions and point to a general northward increase of the metamorphic grade toward the thrust contact with the BOZ (Buchan et al. 2001). The lithological characteristics and structural patterns of the Burd Gol mélange suggest that it constitutes an accretionary complex built up against the Baydrag block (Buchan et al. 2001; Windley et al. 2007). Metamorphic white micas from pelitic schists yielded a K-Ar age of 699 ± 35 Ma (Teraoka et al. 1996), whereas a biotite-garnet gneiss from the southeastern termination of the mélange (Ushgoeg Mountain; fig. 2*A*) yielded a $^{40}Ar/^{39}Ar$ biotite plateau age of 533 ± 3 Ma (Höck et al. 2000). Carbonaceous phyllites and pelitic schists yielded initial ε_{Nd} values of −16.1 to −11.5 and Nd mean crustal residence ages of 2.7–2.5 Ga (Kovalenko et al. 2005; Kozakov et al. 2007), suggesting that gneisses of the Baydrag block constitute a potential source area. The mélange is intruded along its northern margin by the Tsakhir Uul granite complex (fig. 2*A*), from which a leucogranite and a monzogranite body yielded zircon crystallization ages of 539 ± 5 and 514 ± 10 Ma, respectively (Buchan et al. 2002; Jahn et al. 2004).

Southern Volcanics. To the north of the Burd Gol mélange, this lithotectonic unit consists of a narrow belt of Carboniferous marine sediments (Dergunov et al. 1997), which unconformably overlies a sequence of island arc-related volcanic rocks (Buchan et al. 2002). The time of island arc magmatism is uncertain, but a minimum age is provided by a zircon crystallization age of 474 ± 8 Ma for a rhyolite dike cross cutting the volcanic sequence (Buchan et al. 2002).

BOZ. The BOZ (fig. 2*A*) consists of a central ophiolite unit tectonically bounded by the Delb Khairkhan and Haluut Bulag mélanges (fig. 2*B*; Buchan et al. 2001; Osozawa et al. 2008). The Delb Khairkhan mélange contains lenses of igneous and sedimentary rocks distributed in a matrix of pelitic schists. Carbonate rocks contain Neoproterozoic stromatolites and early to middle Cambrian fossils (Dergunov et al. 1997). Along its northern side, the lithological characteristics of mafic igneous lenses (gabbro, dolerite, pillow basalt) are similar to those in the ophiolite unit to the north (Buchan et al. 2001). The ophiolite unit contains virtually all typical ophiolite lithologies, but the original sequence is tectonically dismembered into blocks enclosed within a matrix of serpentinite. Based on a Sm-Nd mineral/whole rock isochron age for a gabbro, the ophiolite has long been considered to have formed at ca. 569 Ma (Kepezhinskas et al. 1991). However, Kovach et al. (2005) obtained a SHRIMP zircon age of 665 ± 15 Ma for an anorthosite from a layered gabbro sequence and challenged the significance of the former Sm-Nd age. Pillow basalts locally exhibit a mineral lineation defined by metamorphic amphiboles with a $^{40}Ar/^{39}Ar$ plateau age of 485 ± 6 Ma (Delor et al. 2000). The fault-bounded contact between the Delb Khairkhan mélange and the ophiolite unit is stitched by the undeformed Ulaan Uul red granite, which yielded zircon crystallization ages of 545 ± 2 and 539 ± 1 Ma (Buchan et al. 2002). The Haluut Bulag mélange shows a block-in-matrix structure and is predominantly composed of sedimentary lenses embedded in a matrix of low-grade phyllite (Buchan et al. 2001). Slate-carbonate rocks of the matrix yielded initial ε_{Nd} values of −4.2 to −3.2 with Nd mean crustal residence ages of 1.64–1.57 Ga (Kovalenko et al. 2005).

Based on the dominant northeast vergence of thrusts faults (fig. 2*B*), Buchan et al. (2001) proposed that the Bayankhongor ophiolite crust was subducted to the southwest with the Burd Gol mélange representing an accretionary prism build up against the northeastern margin of the Baydrag block. In addition to the phase of accretion and northeastward thrust stacking, Osozawa et al. (2008) recognized a superimposed phase of brittle deformation associated with two detachment faults bounding the BOZ (fig. 2*B*). These authors related this event to terminal Devonian collision between the Baydrag block and the Dzag zone to the northeast.

Dzag Zone. This lithotectonic unit consists of asymmetrically folded chlorite-rich psammitic and pelitic schists of grenschist-facies and less deformed fine-grained siltstone and sandstone beds. Relicts of sedimentary structures suggest a deep-sea turbiditic origin and deposition on a passive margin (Buchan et al. 2001). Metamorphic white micas from pelitic schists yielded K-Ar ages of 454 ± 9 to 395 ± 20 Ma (Teraoka et al. 1996; Kurimoto et al. 1998) that were interpreted to reflect regional low-grade metamorphism. Pelitic schists yielded initial ε_{Nd} values of −3.3 and −3.1, with Nd mean crustal residence ages of 1.58–1.47 Ga (Jahn et al. 2004). Rocks of the Haluut Bulag mélange and Dzag zone display much younger Nd model ages than sediments of the Burd Gol mélange, suggesting an origin from distinct sources.

Hangay Zone. This unit is predominantly composed of unmetamorphosed and gently folded middle to late Paleozoic turbidite-dominated sediments intruded by undeformed early Permian to late Triassic granitoids (Takahashi et al. 2000; Jahn et al. 2004; Orolmaa et al. 2008; Yarmolyuk et al. 2008*b*). Kovalenko et al. (2004) speculated that sediments of this zone cover an unexposed Precambrian microcontinental block because of Mesoproterozoic Nd model ages of ca. 1.4–1.1 Ga for late Paleozoic and Mesozoic granitoids. This hypothesis is supported by late Archean to early Neoproterozoic detrital zircons in arc-derived sediments of the Hangay-Hentey basins (Kelty et al. 2008) and by Re-Os data from mantle xenoliths, which together suggest the presence of Mesoproterozoic subcontinental lithospheric mantle (Wang et al. 2006).

Field Relationships along the Taats River

The rocks exposed along the north-south-trending Taats River are primarily composed of high- and low-grade metamorphic lithologies, intruded by undeformed granitoids of Cambrian to Permian age (fig. 4). These rocks are presumed to constitute the eastern extension of the Baydrag block (fig. 2*A*), and most "stratigraphic" ages used in the following description are taken from a 1 : 200,000-scale geological map (fig. 4; Zabotkin 1988), unless stated otherwise.

The section is described from south to north and is based on our own field observations. The southern termination is composed of presumed Paleoproterozoic gneisses (fig. 4; Zabotkin 1988). Among these are strongly foliated and layered, fine-grained granite-gneisses with a penetrative subvertical foliation striking east-west and steeply dipping north or south. This foliation is locally folded into tight isoclinal folds with steeply dipping fold axes and stretching lineation. These gneisses contain several meter-wide tectonic lenses of foliated garnet-bearing metagabbro and amphibolite wrapped around by the surrounding foliation and probably representing a phase of mafic magmatism that occurred before the deformation of the entire package. Toward, the north, the gneisses predominantly consist of interlayered quartzite, metagraywacke, biotite-rich gneisses, calc-silicate schists, and minor garnet-bearing amphibolite bands. These lithologies are intruded by a large granite pluton of Cambrian age. Close to the southern margin of this pluton is a gently folded S-verging sequence of metagraywacke with conformable granitic pegmatite sills and cross cut by undeformed aplite dikes (fig. 5*A*). A garnet-bearing metagranite interlayered with the surrounding metasediments yielded a TIMS zircon age of 532 ± 9 Ma (Kozakov et al. 2008). Foliation in the metasediments generally strikes northwest-southeast and dips between 30° and 60° southwest.

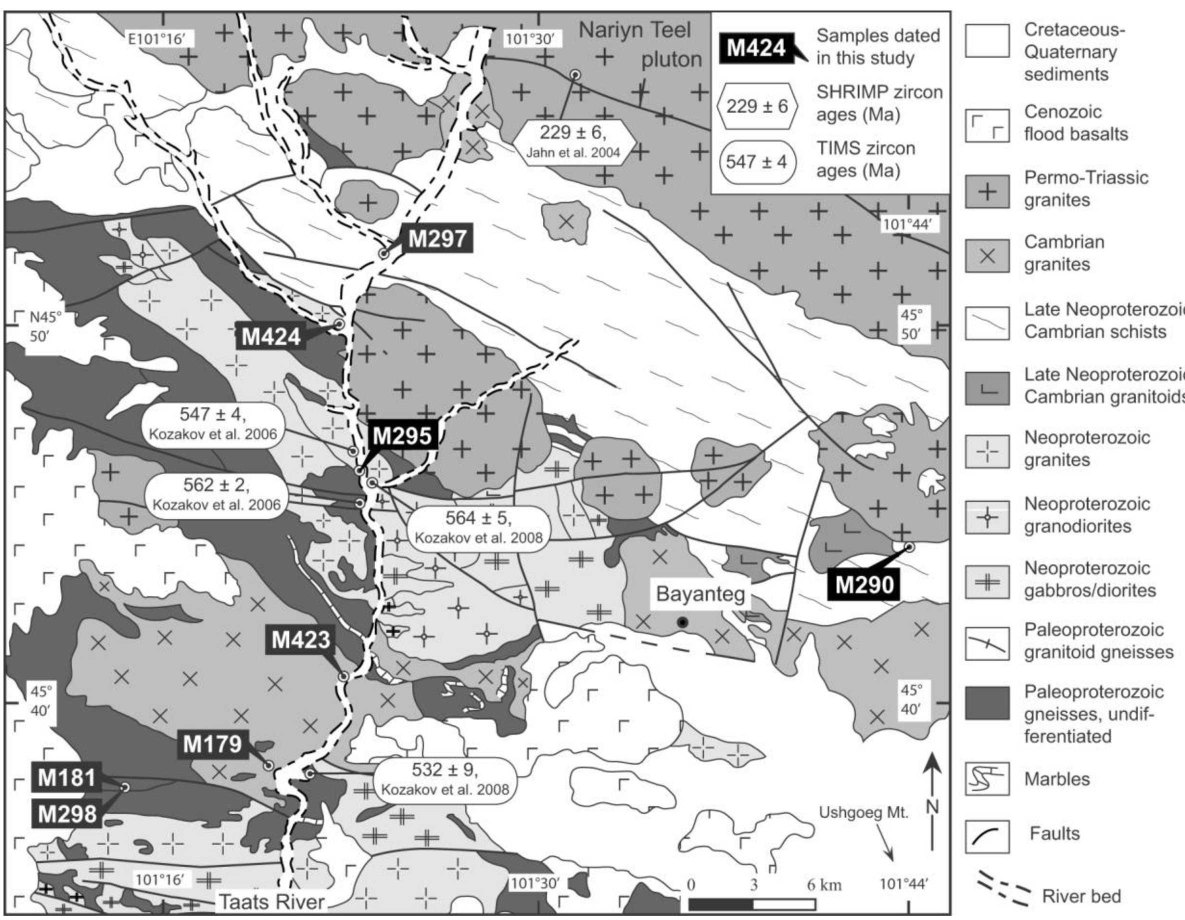

Figure 4. Geological sketch map of the region surrounding the Taats River (modified after Zabotkin 1988). Previous geochronological results and location of dated samples are also indicated.

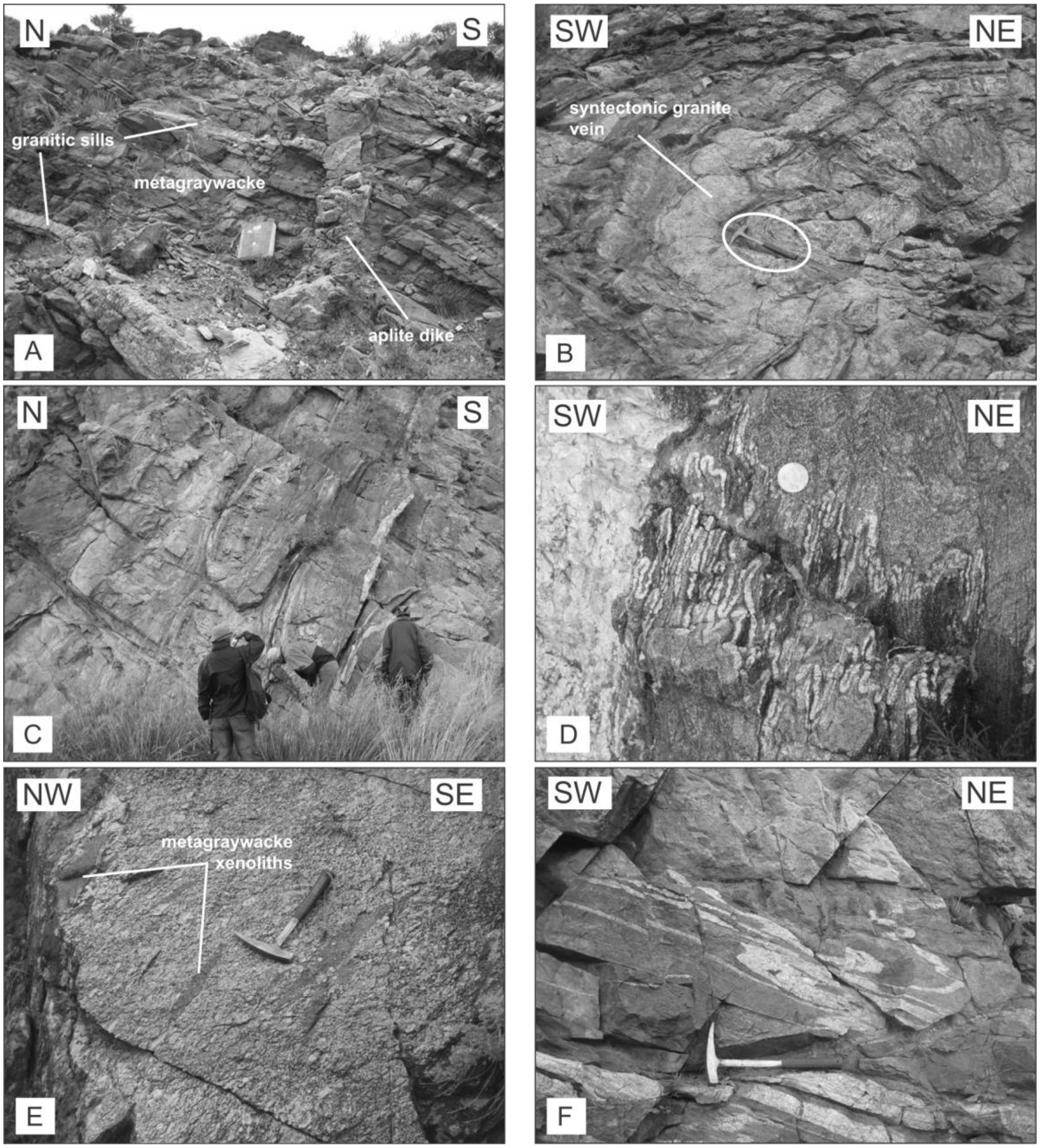

Figure 5. Field photographs of rocks exposed along the Taats River. *A*, Gently folded metagraywacke and pegmatite sills cut by aplite dike. *B*, South-verging recumbent fold and syntectonic granite vein (sample M423) showing boudinage. *C*, Steeply north-dipping sequence of partly migmatitic metasediments. *D*, Ptygmatic fold with subvertical fold axes. *E*, Porphyritic granite with flattened and aligned metagraywacke xenoliths (sample M295). *F*, Isoclinally folded and partly disrupted leucosomes in migmatitic metasediment. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

Elongate biotite aggregates in biotite-rich gneisses define a mineral lineation plunging between 20° and 30° west-southwest. Close to the northern margin of this pluton, the metasediments are deformed into several meter-scale south-verging recumbent folds. Syntectonic granite veins emplaced conformably to the foliation in the metasediments occur locally and are folded together with the entire pile and boudinaged in some places (fig. 5*B*).

Rocks north of the granite pluton predominantly consist of strongly deformed clastic metasediments, including mostly felsic schists and metagraywacke with interlayered meter-thick beds of garnetiferous metapelite, marble, calc-silicate rocks, and quartzite. The structural grain is defined by a penetrative foliation striking northwest-southeast and dipping steeply north-northeast (fig. 5*C*). This sequence is locally migmatitic with leucocratic veinlets or melt patches of gabbroic to granodioritic composition. Rare ptygmatic folds with subvertical axes indicate local coaxial deformation (fig. 5*D*). The entire sequence is cut by randomly distributed pegmatite veins. The relationship between the steeply north-dipping metasediments and the aforementioned flat-lying and folded metasediments to the south is obscured by the Cambrian pluton and was not observed along this transect.

About 1.5 km north of the Cambrian pluton, there is a 15-m-wide zone of sheared marble with a northwest-southeast-striking foliation steeply dipping northeast. The S-C fabrics, the asymmetric shape of marble boudins and slickensides, and an associated shallow-dipping striation suggest a top-to-the-southeast dextral sense of movement. Farther north, there is a coarse-grained and foliated porphyritic granite of presumed Neoproterozoic age (fig. 4) with K-feldspar porphyroblasts that reach several centimeters long and show a preferred orientation. This granite contains flattened xenoliths of metagraywacke (fig. 5*E*) with a consistent orientation. The intrusive relationship between the pluton and surrounding metasediments is poorly preserved because contacts are generally sheared and lie parallel to the foliation observed in the granite and the surrounding metasediments. Kozakov et al. (2006, 2008) reported TIMS zircon ages of 547 ± 4 and 564 ± 5 Ma for foliated granodiorite and granosyenite bodies, respectively. About 1 km south of the porphyritic granite, a syntectonic kyanite-bearing pegmatite vein yielded a TIMS zircon age of 562 ± 2 Ma (Kozakov et al. 2006). Toward the north, the sedimentary lithologies are still partly migmatitic and show an east-west-striking foliation gently dipping north-northeast and axial planar to isoclinally folded and rootless leucosomes (fig. 5*F*).

The northern termination of the transect is composed of a thick sequence of greenschist-facies quartz-chlorite-epidote schists of presumed late Neoproterozoic-Cambrian age (fig. 4). The schistosity generally strikes northwest-southeast and dips between 45° and 65° northeast. This sequence is intruded in the north by the Nariyn Teel pluton, assumed to be Permian in age (fig. 4). However, Jahn et al. (2004) obtained a SHRIMP zircon age of 229 ± 6 Ma for a syenogranite from this pluton. The entire schist sequence is assumed to constitute the southeastern extension of the BOZ as shown on a 1 : 500,000 geological map (fig. 2*A*). In contrast to the metasediments in the south, these low-grade schists do not show evidence of migmatization.

Geochronological Results

Zircons were separated using conventional procedures including magnetic separation and heavy liquids. Representative zircons were handpicked under a binocular microscope according to their morphological habits and crystallographic quality. Internal zircon structures were documented with cathodoluminescence (CL) images obtained using a JEOL JXA-8900 RL Superprobe. Isotopic measurements were carried out by the single-zircon evaporation technique using a Finnigan-MAT 261 mass spectrometer at the Max-Planck-Institut für Chemie in Mainz and with SHRIMP II instruments in the Beijing SHRIMP Centre of the Chinese Academy of Geological Sciences and the Perth Consortium, Australia. Details of the analytical methods are available in the appendix in online edition or from the *Journal of Geology* office, and analytical results are listed in tables A2 and A3.

Baydrag Block, Burd Gol Mélange and Dzag Zone. Sample M98/B9 (46°16′59″N, 99°28′40″E; fig. 3) is a massive and foliated enderbitic gneiss of dioritic composition intruding a sequence of banded metapelite in the Bumbuger complex. Zircons are dark red in color and predominantly long-prismatic with rounded terminations. Evaporation of three grains yielded a mean $^{207}Pb/^{206}Pb$ age of 2409.1 ± 0.4 Ma (fig. 6*A*), which we consider to reflect the time of dioritic protolith emplacement.

Sample M98/B10 is a granulite-facies banded garnetiferous metapelite collected about 100 m southwest of sample M98/B9 (fig. 3). This rock shows many anatectic features and diffuse contacts, grading into more homogeneous charnockites and enderbites. Our sample contains metamorphic zircons of dark red brown color with spherical and multifaceted habits. Evaporation of four grains yielded a mean $^{207}Pb/^{206}Pb$ age of 1839.8 ± 0.6 Ma (fig. 6*B*) that we interpret to reflect the time of high-grade metamorphism in the Baydrag block.

Sample MBYH 13-2 is a garnet-two-pyroxene granulite collected within the Bumbuger complex (46°16′51″N, 99°26′35″E; fig. 3). Zircons are spherical or long-prismatic and subhedral with smooth terminations related to metamorphic growth. The CL images show sector-zoned domains and wide and structureless metamorphic rims that mantle older igneous cores in some grains. Metamorphic rims of six grains were analyzed on the SHRIMP II in Beijing and yielded a cluster of near-concordant

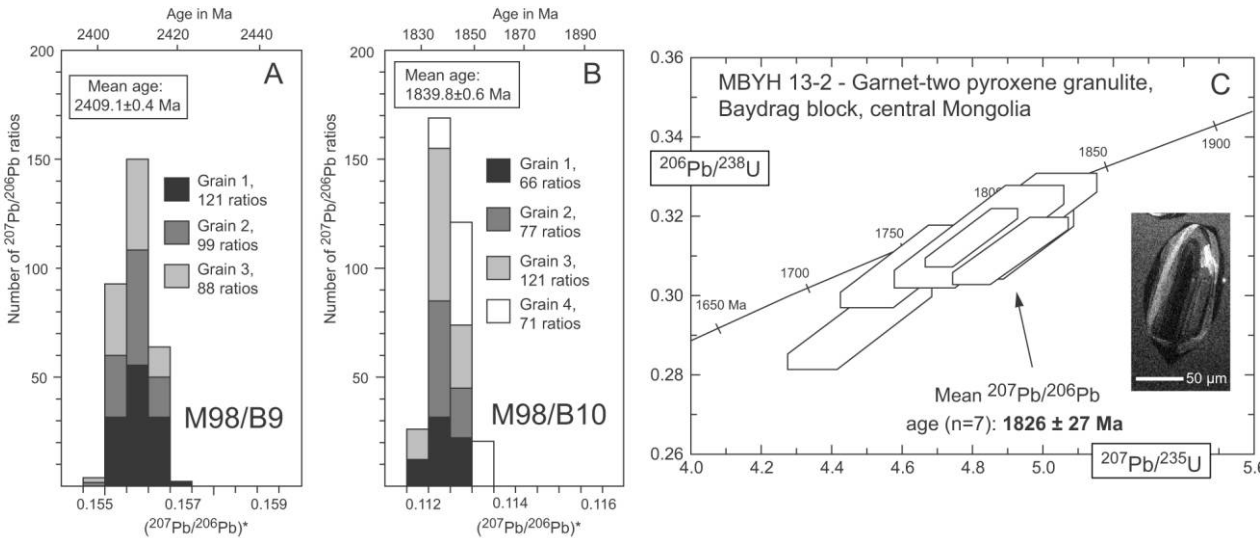

Figure 6. *A*, *B*, Histograms showing distribution of radiogenic lead isotope ratios derived from evaporation of single zircons from high-grade rocks of the Baydrag block. Mean ages are given with 2σ (mean) error. *A*, Spectrum for three zircons from enderbitic gneiss sample M98/B9, integrated from 308 ratios (table A2, available in the online edition or from the *Journal of Geology* office). *B*, Spectrum for four zircons from metapelite sample M98/B10, integrated from 335 ratios (table A2, available in the online edition or from the *Journal of Geology* office). *C*, Concordia diagram showing SHRIMP analyses of single zircons for garnet–two pyroxene granulite sample MBYH 12-3. Data boxes for each analysis are defined by standard errors in $^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{206}Pb$. Error for pooled age is at 95% confidence level. Inset shows cathodoluminescence image of an analyzed zircon.

data points (fig. 6*C*) with a weighted mean $^{207}Pb/^{206}Pb$ age of 1826 ± 26 Ma (MSWD = 0.69). This age is identical, within error, to the evaporation age obtained for sample M98/B9 and reflects a major late Paleoproterozoic metamorphic event in the Baydrag block.

Sample M98/B11 is a fine-grained, whitish-blue quartzite lens, several meters thick and embedded within cleaved phyllites of the Burd Gol mélange (46°20′57″N, 99°38′31″E; fig. 2). It contains a heterogeneous population of zircons with clear to yellow-brown colors and short- to long-prismatic habits with well-rounded terminations and pitted surfaces. Thirteen zircons were evaporated and produced highly variable isotopic ratios, with $^{207}Pb/^{206}Pb$ ages ranging between 2032 and 1017 Ma (fig. 7). This age pattern suggests a maximum earliest Neoproterozoic depositional age and a heterogeneous sedimentary source dating to the Paleoproterozoic.

Sample M99/B13 is a volcanic sandstone from the Dzag zone (46°33′38″N, 100°09′21″E; fig. 2*A*). Zircons are mostly composed of dark red-brown, oval to ball-rounded grains that indicate long-distance sedimentary transport and a few stubby, near-idiomorphic grains that indicate detrital input from proximal sources. Eight zircons were evaporated and produced variable $^{207}Pb/^{206}Pb$ ages ranging from 2143 to 1771 Ma (fig. 8). This suggests detrital input into the Dzag sediments from a source terrane that contains Paleoproterozoic rocks. The range of detrital ages is most likely not representative of the entire population in this sample, and nothing definite can be said about the time of deposition of the Dzag sediments. However, the pattern of detrital zircon ages supports the previous assumption of the existence of a Paleoproterozoic basement (Kovalenko et al. 2004), now present at depth and covered by the Paleozoic Hangay sediments.

Taats River and Bayanteg Areas. Sample M181 is a strongly foliated and layered fine-grained biotite gneiss collected at the southern end of the transect (45°37′47″N, 101°14′52″E; fig. 4). It is composed of quartz with undulose extinction, fresh biotite flakes, K-feldspar mostly altered into fine-grained sericite, plagioclase, and minor secondary white mica. Zircons are subhedral with smooth edges, subrounded terminations and pitted surfaces. In CL images, most grains have dark (high-U) cores and brightly luminescent (low-U), narrow, and structureless rims, presumably reflecting metamorphic overgrowth. Cores of 15 grains were analyzed on the SHRIMP II in Perth and yielded a complex array

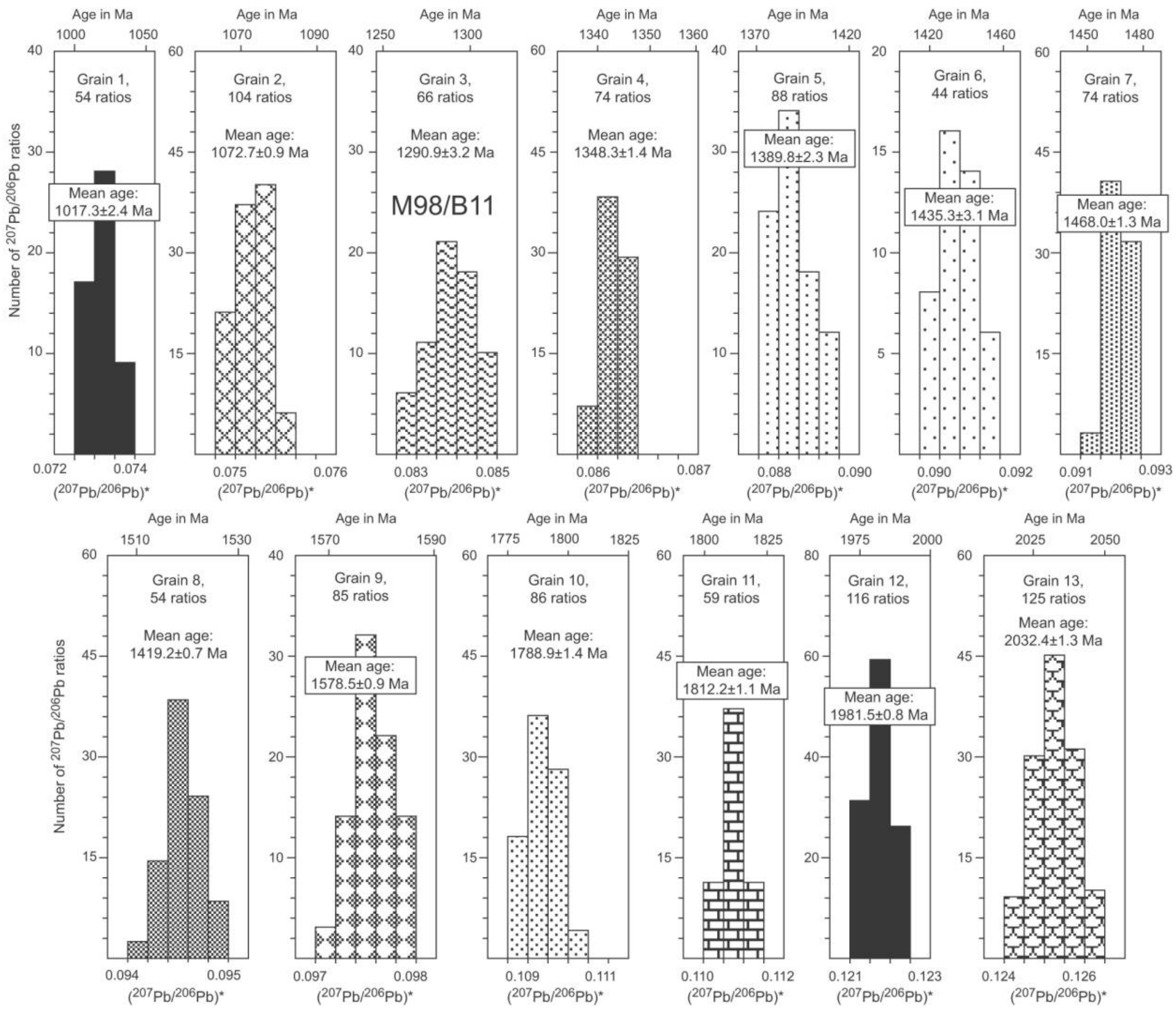

Figure 7. Histograms as in figure 6*A* for detrital zircons from quartzite sample M98/B11 from the Burd Gol mélange. The spectra have been integrated from ratios as shown. For analytical data see table A2, available in the online edition or from the *Journal of Geology* office.

of predominantly discordant results. Seven analyses are aligned along a chord (MSWD = 0.004) yielding an upper Concordia intercept age of 1839 ± 11 Ma and a lower intercept at −3 ± 120 Ma (fig. 9*A*). These analyses have a weighted mean $^{207}Pb/^{206}Pb$ age of 1839 ± 8 Ma (MSWD = 0.003), identical to the upper intercept age, which we consider to best approximate the time of emplacement of the granitic protolith. Three additional grains display a crude alignment and have a weighted mean $^{207}Pb/^{206}Pb$ age of 1992 ± 14 Ma. The remaining analyses yielded much older and discordant results with minimum $^{207}Pb/^{206}Pb$ ages of 3119, 2936, and 2664 Ma (fig. 9*A*). These grains reflect inheritance from Archean to Paleoproterozoic sources.

Sample M298 is a strongly foliated granite-gneiss collected some 150 m southwest of sample M181 (45°37′45″N, 101°14′48″E; fig. 4). Both samples display a similar foliation indicating that they underwent a common phase of deformation. Zircons are light to dark brown in color and are mostly long-prismatic with slightly rounded terminations that we ascribe to partial dissolution and recrystallization during a metamorphic overprint. The CL images show oscillatory zoning related to igneous growth. Some grains have a few micrometer-thick rims overgrowing the primary igneous texture. Five zircon cores were analyzed on the Beijing SHRIMP II; one result is concordant, and the four remaining data are discordant (fig. 9*B*). The five analyses are aligned along a chord (MSWD = 0.002) with an up-

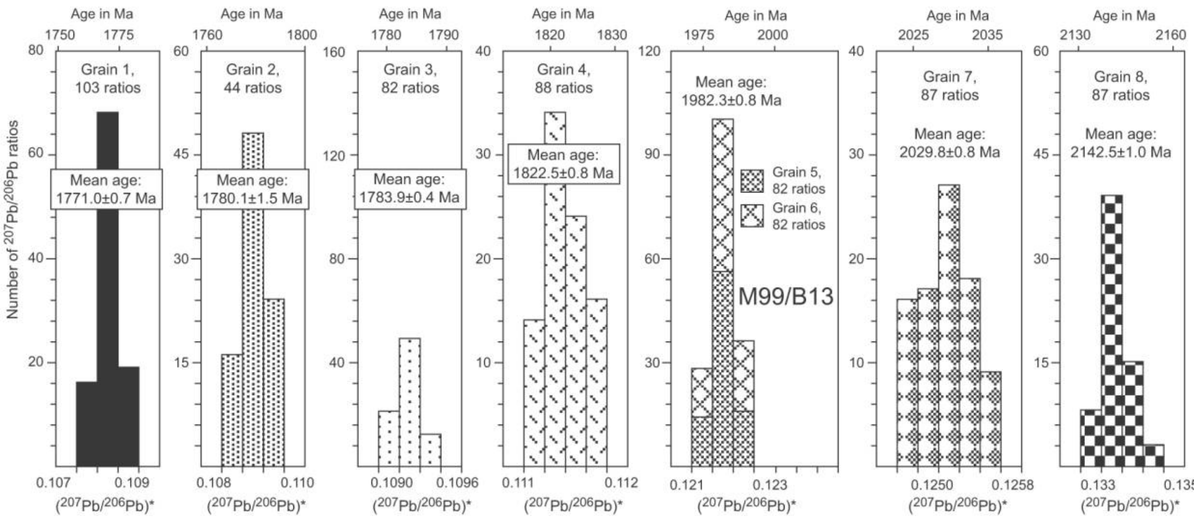

Figure 8. Histograms as in figure 6*A* for detrital zircons from volcanic sandstone sample M99/B13 from the Dzag zone. The spectra have been integrated from ratios as shown. For analytical data see table A2, available in the online edition or from the *Journal of Geology* office.

per Concordia intercept age of 1053 ± 28 Ma and a lower intercept age at 21 ± 330 Ma, suggesting recent Pb loss. The concordant grain has a $^{207}Pb/^{206}Pb$ age of 1053 ± 20 Ma, and all analyses define a weighted mean $^{207}Pb/^{206}Pb$ age of 1051 ± 10 Ma (MSWD = 0.01), which is identical, within error, to the upper intercept age. We therefore consider the latter age to approximate the time of crystallization of the granite protolith.

Sample M179 (45°38′19″N, 101°20′04″E; fig. 4) is a peraluminous leucocratic granite vein about 1 m wide and interlayered with the surrounding metagraywacke. It consists of quartz, K-feldspar, biotite, muscovite, minor plagioclase, euhedral small garnet, and secondary sericite. Quartz often shows undulose extinction, K-feldspar is altered into fine-grained sericite, and biotite is partly replaced by chlorite. Myrmekite is locally developed along K-feldspar grain boundaries. Only a few zircons of poor crystallographic quality were recovered, and they show igneous-related internal structures as well as inherited rounded cores in CL images. Only two grains could be analyzed on the Perth instrument, and three analyses yielded concordant and similar results (fig. 10*A*) with a weighted mean $^{206}Pb/^{238}U$ age of 537 ± 6 Ma (MSWD = 0.15) that we interpret to reflect the time of crystallization of the granite vein. A further analysis from the core of a grain yielded a much older and concordant $^{206}Pb/^{238}Pb$ age of 793 ± 12 Ma that we interpret as a xenocryst assimilated from the surrounding host rocks.

Sample M423 (45°40′45″N, 101°22′53″E; fig. 4) is a medium-grained syntectonic granite vein about 40 cm wide and deformed together with the surrounding metasediment (fig. 5*C*). This sample is composed of quartz, plagioclase, and K-feldspar variably altered into fine-grained sericite and biotite mostly replaced by chlorite. Zircons are predominantly clear, pale yellow, short-prismatic, and idiomorphic, but some are subrounded and dark colored. The idiomorphic grains have typical magmatic internal zoning, whereas the subrounded grains tend to have higher luminescence and structureless cores. Three idiomorphic zircons were analyzed on the Beijing SHRIMP II and produced similar and concordant results (fig. 10*B*) with a weighted mean $^{206}Pb/^{238}U$ age of 519 ± 9 Ma (MSWD = 0.11). This is interpreted to reflect the time of emplacement of the syntectonic granite and the last tectonometamorphic event undergone by the enclosing metasediments.

Sample M295 (45°46′05″N, 101°23′31″E; fig. 4) is a coarse-grained porphyritic granite that intrudes a sequence of metasediments and contains numerous enclaves of metagraywacke. The rock is composed of orthoclase phenocrysts set in a fine-grained matrix of recrystallized quartz and plagioclase. Zircons are translucent, faintly yellow, short-prismatic, and subhedral with slightly rounded terminations. The CL images reveal oscillatory zoning that is typical of igneous growth. All grains display a narrow and strongly luminescent overgrowth that truncates and corrodes the primary internal zoning.

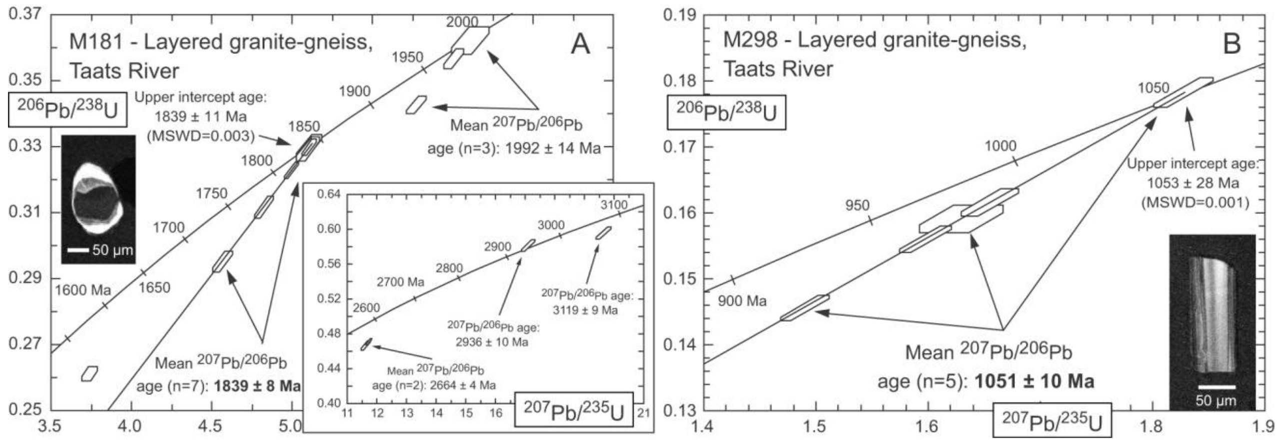

Figure 9. Concordia diagrams showing SHRIMP analyses of single zircons for granite-gneisses from the Taats River. Data boxes for each analysis are defined by standard errors in $^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{206}Pb$. Pooled and intercept errors are at 95% confidence level. Insets show cathodoluminescence images of analyzed zircons.

Five zircon cores were analyzed on the Beijing instrument and produced a tight cluster of results (fig. 10*C*) with a weighted mean $^{206}Pb/^{238}U$ age of 579 ± 7 Ma (MSWD = 0.15), which we interpret as the time of granite emplacement.

Sample M424 (45°50′07″N, 101°23′04″E; fig. 4) is a fine-grained layered granite-gneiss consisting of K-feldspar, biotite, quartz, and plagioclase. Secondary minerals include chlorite, white mica, and minor calcite. Zircons are translucent, short-prismatic, and mostly subhedral with smooth edges and have oscillatory-zoned internal structure. All grains display a narrow (a few were μm-wide), high-luminescent rim, and some have dark and rounded inherited cores. Igneous domains of four zircons were analyzed on the Beijing instrument, of which one grain yielded a concordant result with a $^{206}Pb/^{238}U$ age of 560 ± 12 Ma, whereas the three other results are discordant (fig. 10*D*). When forced through the origin, the four analyses are aligned along a chord (MSWD = 0.0003) with an upper Concordia intercept age of 569 ± 54 Ma. All analyses have a mean $^{207}Pb/^{206}Pb$ age of 569 ± 62 Ma, identical to the upper intercept and the concordant age. We consider the latter as the best estimate for the time of emplacement of the granite-gneiss protolith.

Sample M297 (45°51′54″N, 101°24′17″E) is a strongly sheared felsic schist most likely derived from a volcaniclastic protolith and collected within the presumed late Neoproterozoic-Cambrian sequence bordering the northern part of the study area (fig. 4). The rock is composed of quartz, K-feldspar, and biotite and secondary white mica, clinozoisite, and calcite. Quartz is often found as ribbons and shows undulose extinction. The zircon population is heterogeneous and consists of rare short-prismatic and idiomorphic grains and abundant subhedral and long- to short-prismatic grains, usually dark colored. Most grains have well-developed oscillatory zoning. Ten zircons were analyzed on the Beijing SHRIMP II, and six results are aligned along a chord (MSWD = 0.06) with an upper Concordia intercept age of 606 ± 39 Ma and a lower intercept at 21 ± 330 Ma. All six analyses have a weighted mean $^{207}Pb/^{206}Pb$ age of 601 ± 7 Ma (MSWD = 0.06), which is identical, within error, to the upper intercept age (fig. 11*A*). We therefore consider the latter age to best approximate the time of emplacement of the felsic volcanic protolith. Three other grains yielded much older and concordant $^{207}Pb/^{206}Pb$ ages of 950, 912, and 823 Ma. The remaining grain yielded a concordant and much younger $^{206}Pb/^{238}U$ age of 196 ± 5 Ma (fig. 11*A*), for which we do not have a satisfactory explanation. The zircon morphology and internal structure is identical to the 601-m.yr.-old grains, and the analysis represents the center of the grain and is unlikely to reflect a metamorphic overprint. No Jurassic thermal event has previously been reported from this area.

Finally, sample M290 (45°44′15″N, 101°43′32″E) is a strongly sheared felsic metavolcanic rock collected about 12 km northeast of Bayanteg village (fig. 4). This sample also belongs to the presumed late Neoproterozoic-Cambrian sequence and is composed of K-feldspar, quartz, and rare relicts of amphibole and secondary sericite. Zircons are clear,

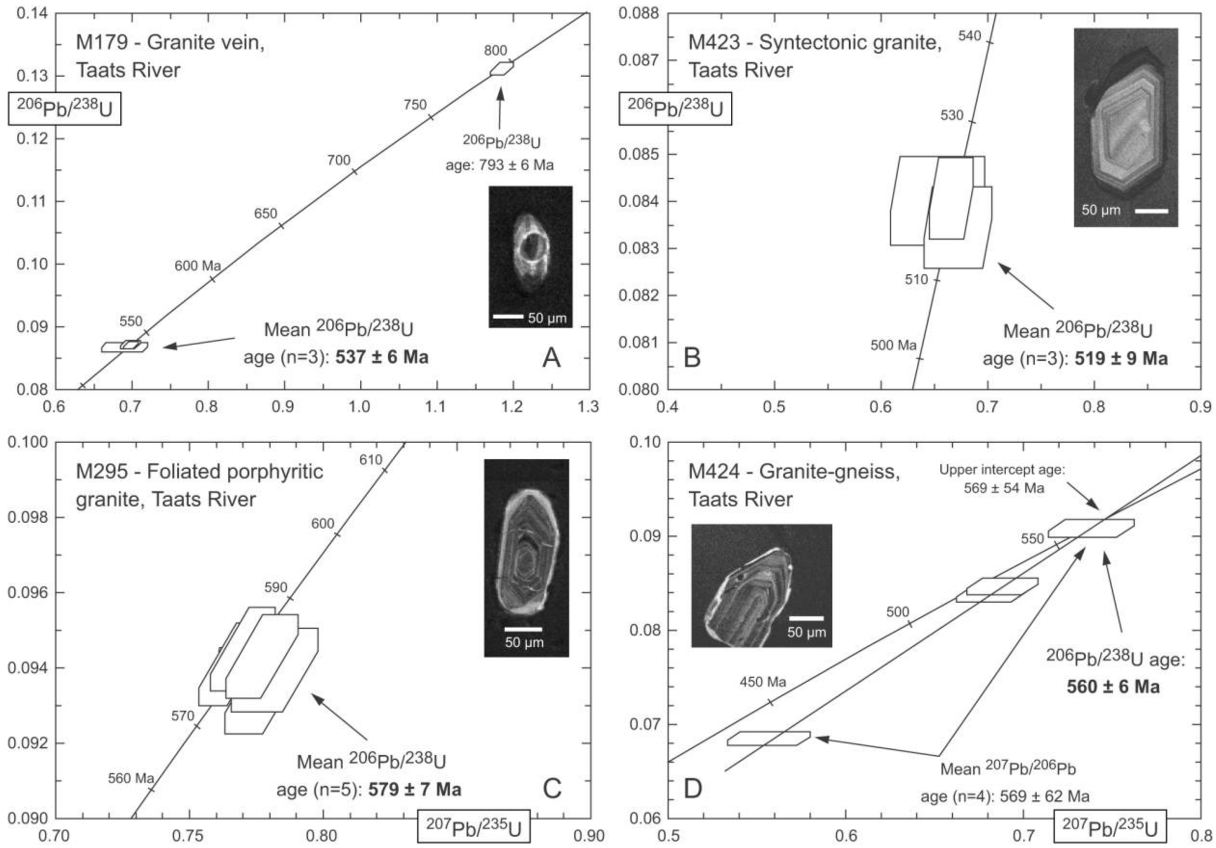

Figure 10. Concordia diagrams showing SHRIMP analyses of single zircons from granites and granite-gneisses of the Taats River. Data boxes and errors on pooled ages and intercepts as in figure 9. Insets show cathodoluminescence images of analyzed zircons.

colorless, short-prismatic, and euhedral to subhedral. The CL images reveal typical igneous oscillatory zoning and rare and small subrounded inherited cores. Igneous domains of five zircons were analyzed on the Beijing instrument, and the results define a cluster of concordant results (fig. 11*B*) with a weighted mean $^{206}Pb/^{238}U$ age of 472 ± 6 Ma (MSWD = 0.08) that we interpret as the time of emplacement of the felsic volcanic protolith. This age is much younger than the age obtained for sample M297, presumed to be part of the same lithological unit, and therefore raises the question whether these rocks really belong to the same lithostratigraphic sequence.

Discussion

Tectonothermal Evolution of the Baydrag Block Before 1.8 Ga. The tectonothermal evolution of the Baydrag block is characterized by three distinct events, namely Neoarchean magmatic activity between ca. 2.80 and 2.65 Ga and two Paleoproterozoic tectonothermal episodes at 2.37–2.31 Ga and 1.85–1.82 Ga. Our zircon ages provide a more accurate timing for the upper age limit of the second event and for the peak of metamorphism related to third thermal event.

A metadiorite intrusive into a high-grade metapelitic sequence of the Bumbuger complex has a crystallization age of 2409 ± 1 Ma. This date is slightly older than the timing of magmatism previously reported at 2370 and 2364 Ma (Bibikova et al. 1990; Kotov et al. 1995) and is ascribed to the beginning of the second tectonothermal event. We suggest that the upper age limit of this event should be extended to 2.41 Ga. In addition, deposition of the metapelite protolith must have occurred before 2.41 Ga, and the sequence underwent high-grade metamorphism dated by metamorphic zircons at 1840 ± 1 Ma. Another sample that underwent granulite-facies metamorphism contains metamorphic zircons with a SHRIMP age of 1826 ± 26 Ma. We interpret these ages to reflect a major high-grade metamorphic event at 1.84–1.83 Ga related to the

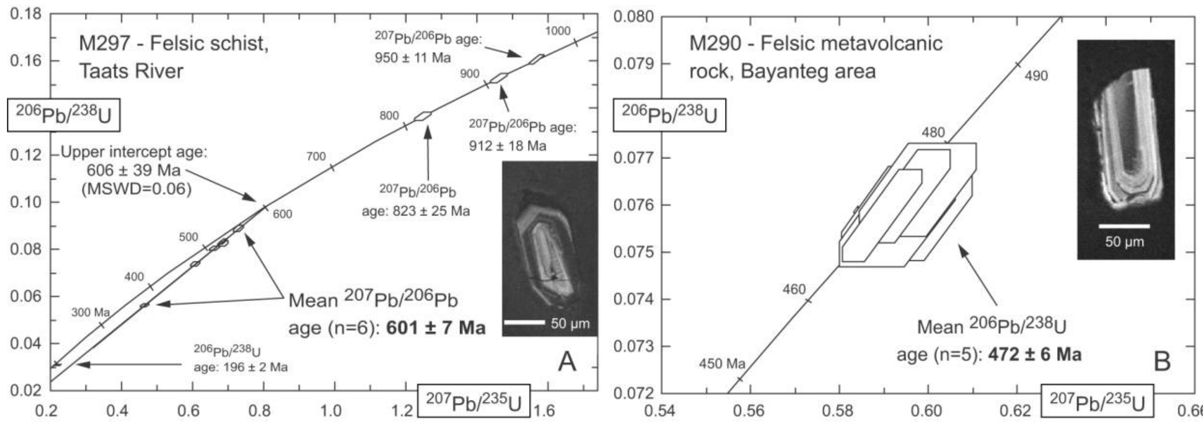

Figure 11. Concordia diagrams showing SHRIMP analyses of single zircons for felsic schists from the Taats River and Bayanteg area. Data boxes and errors on pooled ages and intercepts as in figure 9. Insets show cathodoluminescence images of analyzed zircons.

third tectonothermal episode that resulted in regional metamorphism and deformation of the Baydrag block.

The granite-gneiss M181 from the southern part of the Taats River transect has a SHRIMP zircon age of 1839 ± 8 Ma. This sample also contains inherited zircon cores with ages between ca. 3.12 and 1.99 Ga, suggesting that the granitic protolith was formed by melting of Archean to Paleoproterozoic sources. These results suggest that the Paleoproterozoic gneisses exposed at the southern termination of the Taats River transect should be considered as a part of the Baydrag block. The 3.12-billion-yr.-old zircon core is the oldest record of crust-formation in this crystalline complex. We note that the crystallization age for the granite-gneiss protolith is identical, within error, to the age of high-grade metamorphism at 1.84–1.83 Ga recorded in the Bumbuger complex. This may be explained by the emplacement of the gneiss protolith at middle-crustal level, whereas rocks of the northwestern domain of the Baydrag block represent a deeper crustal section.

Evidence for Meso- and Neoproterozoic Episodes of Zircon Growth and Heterogeneity of the Baydrag Block. One interesting aspect of our study is the occurrence of granite-gneiss M298, interlayered with the ca. 1.84-billion-yr.-old granite-gneiss M181 but derived from a much younger granitic protolith with a crystallization age of 1051 ± 10 Ma. This is the first Grenvillian magmatic crystallization age reported from the Baydrag block. Since both granite-gneisses record the same ductile deformation, they most likely experienced a common phase of deformation and metamorphism after 1.05 Ga. Moreover, this age provides further evidence for late Grenvillian-age igneous activity in south-central Mongolia as recently recognized within the Gurvan Bogd Mountains, located about 80 km southeast of the Baydrag block (fig. 12; Demoux et al. 2009).

The pattern of inherited zircons in late Neoproterozoic to Cambrian granitic rocks intrusive into the rock assemblages of the BOZ, the Burd Gol mélange, and the Taats River transect indicates substantial inheritance from Neoproterozoic sources (fig. 13). These results are moreover supported by geochronological data for the quartzite lens from the Burd Gol mélange, which most likely formed through erosion of the Baydrag gneisses. This sample contains an array of detrital zircons ranging in ages from 2032 to 1017 Ma (fig. 13), which suggests that Paleoproterozoic and late Mesoproterozoic rocks were exposed at the surface at the time of sediment deposition. The geological evolution of the Baydrag block has been restricted to the Neoarchean and late Paleoproterozoic, but the data presented here attest to considerable lithological heterogeneity and a long Precambrian history of this crustal domain, the details of which still need to be unraveled.

Finally, felsic schist sample M297 of volcaniclastic origin, collected on the southeastern side of the BOZ, yielded a SHRIMP zircon age of 601 ± 7 Ma. Regarding its composition and position within the BOZ, we suggest that this sample belongs to the Delb Khairkhan mélange. The late Neoproterozoic age agrees with previous paleontological ages reported for carbonate rocks from this unit (Dergunov et al. 1997). This sample suggests

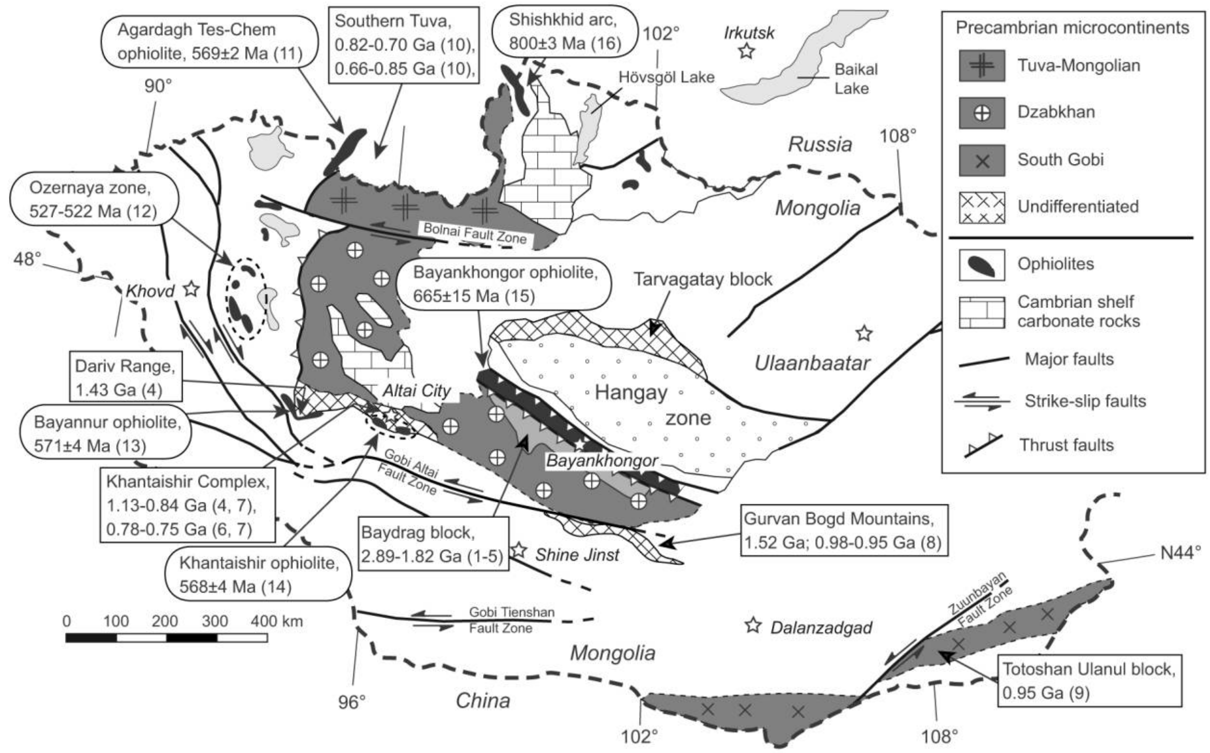

Figure 12. Simplified lithotectonic map of western and central Mongolia showing location of Precambrian basement and mid-Neoproterozoic to Cambrian ophiolite complexes discussed in the text (modified after Badarch et al. 2002; Buchan et al. 2002). Ages for igneous events shown by Precambrian rocks and time of ocean crust formation for ophiolite complexes are indicated. Data sources: *1*, Bibikova et al. 1990; *2*, Kotov et al. 1995; *3*, Kozakov et al. 2007; *4*, Kröner et al. 2001; *5*, Mitrofanov et al. 1985; *6*, Yarmolyuk et al. 2008*a*; *7*, Zhao et al. 2006; *8*, Demoux et al. 2009; *9*, Yarmolyuk et al. 2005; *10*, Kozakov et al. 2005; *11*, Pfänder and Kröner 2004; *12*, Kovalenko et al. 1996; *13*, Kozakov et al. 2002; *14*, Khain et al. 2003; *15*, Kovach et al. 2005; *16*, Kuzmichev et al. 2005.

that the northern margin of the Baydrag block was the site of sporadic volcanic activity during the late Neoproterozoic, likely developed in response to southward subduction of the Bayankhongor oceanic crust. We therefore speculate that the Delb Khairhan mélange represents an accretionary complex, developed in front of the Burd Gol mélange, that received volcanic products shed from the Baydrag margin as well as igneous and sedimentary material scraped off the subducting Bayankhongor oceanic crust. The felsic schist contains zircon xenocrysts with early Neoproterozoic ages (fig. 13), which again supports the heterogeneous composition of the Baydrag block.

Late Neoproterozoic-Cambrian Magmatism and Regional Implications. Along strike, to the northwest of the Taats River, the Tsakhir Uul granite intrudes the Burd Gol mélange and yielded zircon crystallization ages of 539 and 514 Ma (Buchan et al. 2002; Jahn et al. 2004). This granite is deformed only on its northern margin where a weak foliation is developed along a thrust fault (Buchan et al. 2002). Our protolith crystallization ages of 579 and 560 Ma for two granite-gneiss samples suggest that plutonic activity began at least in late Neoproterozoic times. These dates are, moreover, comparable to the crystallization ages of 562 and 564 Ma obtained for a syntectonic kyanite-bearing granitic vein and a granosyenite from the Taats River area (Kozakov et al. 2006, 2008). The occurrence of kyanite, which we could not substantiate, suggests that magmatism occurred contemporaneously with a phase of medium-pressure metamorphism.

The fault-bounded contact between the Delb Khairkhan mélange and the ophiolite unit is stitched by the undeformed 545–539-m.yr.-old Ulan Uul granite (Buchan et al. 2002), which suggests that both units were juxtaposed before 545 Ma. This pluton shows a pattern of inherited zircons (fig. 13) and Nd isotopic data similar to those reported for the Tsakhir Uul granite (Buchan et al. 2002). This may suggest that both granite com-

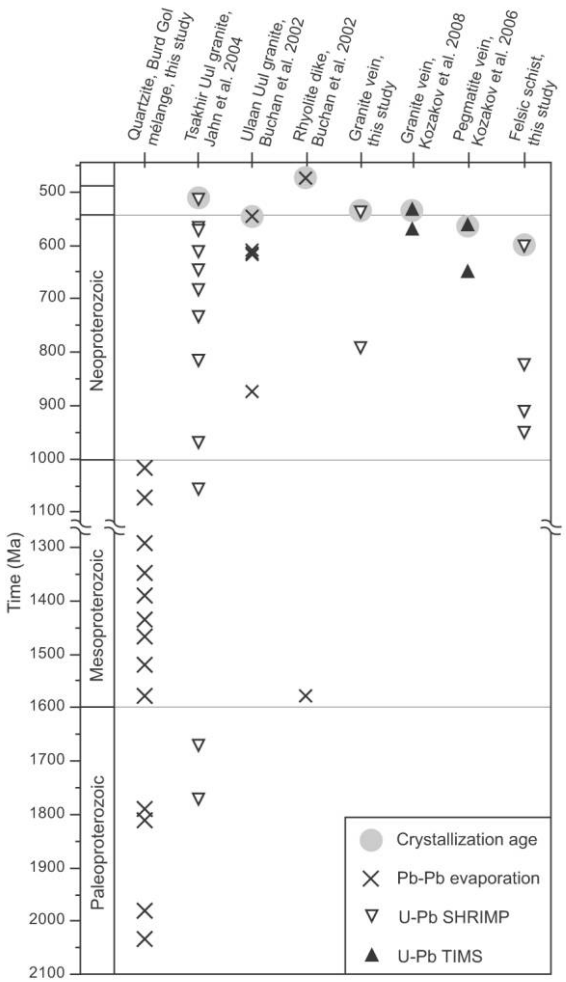

Figure 13. Synoptic diagram showing pattern of inherited zircon ages for rocks of the Bayankhongor ophiolite zone, the Burd Gol mélange, and the Taats River transect. The data indicate inheritance from predominantly Neoproterozoic sources for igneous rocks, whereas the quartzite from the Burd Gol mélange displays considerable detrital input from Mesoproterozoic sources.

plexes were produced during the same magmatic event, possibly related to the early stage of accretion of the BOZ onto the Burd Gol accretionary complex (Buchan et al. 2002). Our zircon age of 537 ± 6 Ma obtained for granite vein M179 is comparable to the emplacement ages of the Ulaan Uul and Tsakhir Uul granites (fig. 14) and may have been produced during the same magmatic event.

In summary, our data together with previous ages from the BOZ and the Taats River area indicate protracted granitoid activity from late Neoproterozoic to early Cambrian times between 579 and 537 Ma (fig. 14). We speculate that this phase of magmatism was developed at the northeastern (present-day coordinates) active margin of the Baydrag block in response to southward subduction of the Bayankhongor oceanic crust (Buchan et al. 2001).

A zircon age of 519 ± 9 Ma obtained for syntectonic granitic vein M423 reflects a mid-Cambrian tectonomagmatic event that produced S-verging recumbent folds and asymmetric drag folds. We suggest that this event corresponds to the "peak" of accretion of the BOZ onto the Baydrag block, which began at about 540 Ma (Buchan et al. 2002). The ductile fabrics were then overprinted by brittle deformation as exemplified by a dextral strike-slip shear zone developed within a marble horizon. We propose that dextral shearing postdates the north-south ductile deformation and is related to a transpressive tectonic regime during terminal collision. However, we do not have a reliable time constraint for this contractional event.

The mid-Cambrian tectonomagmatic event identified in the Taats River area is significantly younger than the biotite Ar-Ar age of 533 ± 6 Ma (fig. 14; Höck et al. 2000) obtained for a garnet-biotite gneiss from the Ushgoeg Mountain (fig. 2*A*). This may be attributed to different levels of exposure of crustal blocks with different exhumation histories. The Taats River crustal domain was probably still at depth when rocks of the Ushgoeg Mountain area already occupied a higher crustal level.

Post-Accretion Ordovician Volcanic Activity. On a 1 : 200,000-scale geological map, the sheared felsic metavolcanic rock M290 is located within the late Neoproterozoic-Cambrian schist sequence of the BOZ (fig. 4). The zircon age of 472 ± 6 Ma obtained for this sample does not support this correlation, and we suggest that this sample belongs to a separate Ordovician volcanic sequence. However, our zircon age is comparable to the zircon age of 474 ± 8 Ma reported for a rhyolite dike in the southern volcanics unit (Buchan et al. 2002). Within the ophiolite unit, metamorphic amphiboles from a pillow basalt yielded an Ar-Ar plateau age of 485 ± 6 Ma (fig. 14; Delor et al. 2000), indicating that parts of the BOZ still underwent deformation at that time. We therefore speculate that early Ordovician punctuated volcanic centers developed on the southern margin of the BOZ in response to prolonged southward subduction. Final amalgamation and stabilization of the region may not have occurred before the late Ordovician as indicated by K-Ar ages of about 450 Ma for white micas from pelitic schists of the Dzag zone (fig. 14; Teraoka et al. 1996; Kurimoto et al. 1998), suggesting a persistent strain field and crustal deformation at that time.

Regional Correlation with Cambro-Ordovician Meta-

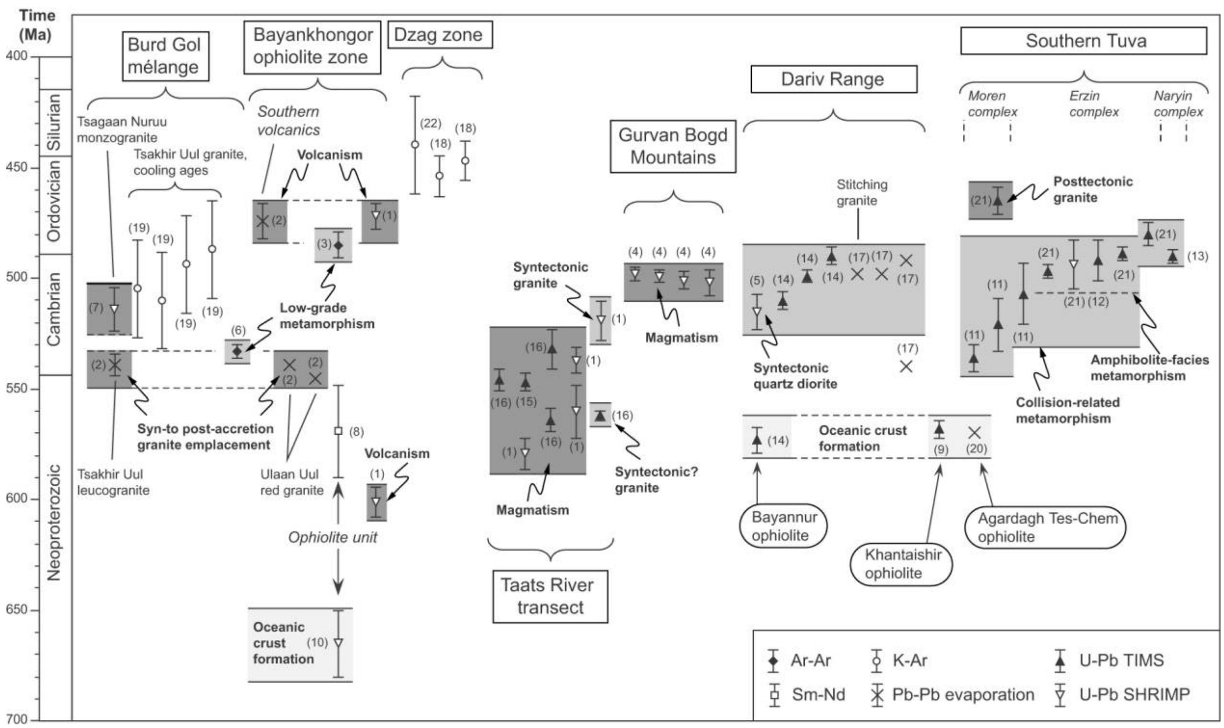

Figure 14. Synoptic diagram showing isotopic ages obtained in central and western Mongolia and southern Tuva. Data sources: *1*, this study; *2*, Buchan et al. 2002; *3*, Delor et al. 2000; *4*, Demoux et al. 2009; *5*, Dijkstra et al. 2006; *6*, Höck et al. 2000; *7*, Jahn et al. 2004; *8*, Kepezhinskas et al. 1991; *9*, Khain et al. 2003; *10*, Kovach et al. 2005; *11*, Kozakov et al. 1999*a*; *12*, Kozakov et al. 1999*b*; *13*, Kozakov et al. 2001; *14*, Kozakov et al. 2002; *15*, Kozakov et al. 2006; *16*, Kozakov et al. 2008; *17*, Kröner et al. 2001; *18*, Kurimoto et al. 1998; *19*, Osozawa et al. 2008; *20*, Pfänder and Kröner 2004; *21*, Sal'nikova et al. 2001; *22*, Teraoka et al. 1996. See figure 12 for location of areas mentioned.

morphic and Magmatic Events in Western Mongolia and Southern Tuva. Remnants of mid-Neoproterozoic to Cambrian oceanic crust are sporadically distributed, from western Mongolia to southern Tuva along a discontinuous and gently curved belt (fig. 12). The Khantaishir, Bayannur, and Agardagh Tes-Chem ophiolites show a good age correlation for their time of formation at about 570 Ma (fig. 14; Kozakov et al. 2002; Khain et al. 2003; Pfänder and Kröner 2004). These ophiolites also display comparable geochemical signatures related to suprasubduction zone environments (Pfänder et al. 2002; Matsumoto and Tomurtogoo 2003; Dijkstra et al. 2006). The BOZ has long been interpreted as part of the same ca. 570-m.yr.-old ophiolite belt based on its former Sm-Nd age. However, as mentioned earlier, this ophiolite formed at about 665 Ma (Kovach et al. 2005) and represents a fragment of older oceanic crust. In addition, the BOZ shows distinct chemical features pointing to enriched mantle and intraplate signatures and does not show any subduction-related components (Kovach et al. 2005; Kovalenko et al. 2005). The BOZ also differs from the other ophiolites by its tectonic position. It is sandwiched between two Precambrian complexes and may represent part of an ocean-floored basin, whereas the ca. 570-Ma ophiolite complexes show strong relationships with island arc environments.

The ophiolite complexes are broadly distributed along the margin of the presumed Tuva-Mongolian and Dzabkhan microcontinents (fig. 12). However, recent geochronological data for high-grade gneisses of the Tuva-Mongolian microcontinent do not record Precambrian metamorphic events but show these gneisses to represent deep-seated crustal sections of Cambrian to late Ordovician collisional zones (fig. 14; Sal'nikova et al. 2001; Kozakov et al. 2002). In southern Tuva, the Moren, Erzin, and Naryn metamorphic complexes are adjacent to the Agardagh Tes-Chem ophiolite (fig. 12) and underwent high-grade metamorphism between ca. 536 and 480 Ma (Kozakov et al. 1999*a*, 1999*b*, 2001; Sal'nikova et al. 2001). A post-tectonic granite with a zircon age of ca. 465 Ma (Sal'nikova et al. 2001) suggests that these metamorphic complexes were stabilized by the middle Ordovician. In western Mongolia, the Bayannur ophiolite is in tectonic contact with the gneissic basement of the Dariv Range (fig. 12) and was accreted onto its margin between ca. 515 and 498 Ma (Kröner et al. 2001; Dijkstra et al. 2006). During this time interval, metamorphic rocks of the Dariv Range underwent high-grade metamorphism between ca. 510 and 490 Ma (fig. 14; Kozakov et al. 2002).

The Bayankhongor/Baydrag orogenic zone shows a comparable tectonomagmatic history with a phase of accretion between ca. 540 and 519 Ma and continuous convergence until about 472 Ma. All data presented above suggest that a large part of the CAOB in western Mongolia and southern Tuva underwent accretion/collision processes at a similar time, thus contributing to formation of a stable continental margin by the late Ordovician as proposed by Windley et al. (2007) and Kröner et al. (2007).

Our data are difficult to reconcile with the geodynamic model of Şengör et al. (1993) for the eastern CAOB, which considers the evolution, beginning in the latest Neoproterozoic, of a single and long-lived magmatic arc. The Bayankhongor/Baydrag orogenic zone demonstrates that final amalgamation of three contrasting lithotectonic units did not occur before the late Ordovician. Therefore, it is unlikely that the aforementioned regions underwent subduction-accretion processes along a single and continuous along strike arc front before the late Ordovician.

Conclusions

Our geochronological results provide new time constraints on the tectonothermal evolution of the Baydrag block before 1.8 Ga and on the late Neoproterozoic to Cambrian tectonomagmatic evolution of the Bayankhongor/Baydrag orogenic zone in central Mongolia. The principal results are summarized as follows.

1. The Baydrag block underwent a major tectonothermal event in the late Paleoproterozic that was characterized by high-grade metamorphism between 1840 and 1826 Ma and coeval with the intrusion of granitic magma at middle-crustal level at 1839 Ma.

2. A crystallization age of 1051 Ma for a granite-gneiss, together with predominantly Mesoproterozoic detrital zircons for a quartzite lens within the Burd Gol mélange and Neoproterozoic inherited zircons for granitic intrusions, testify to the heterogeneity and long Precambrian history of the Baydrag block.

3. The northeastern margin of the Baydrag block was an active margin in the late Neoproterozoic to early Cambrian as indicated by prolonged granitoid activity from 579 to 537 Ma.

4. Accretion of the BOZ to the northern active margin of the Baydrag block occurred in the mid-Cambrian as signified by a zircon age of 519 Ma for a syntectonic granite vein from the Taats River transect. This reflects a major phase of deformation at deep crustal levels.

5. The region was still converging in the early Ordovician as suggested by punctuated volcanic activity at about 474–472 Ma, developed at the junction between the BOZ and the Baydrag block.

ACKNOWLEDGMENTS

This is a collaborative study with the Institute of Geology and Mineral Resources, Mongolian Academy of Sciences, and it was funded by Volkswagen Foundation grant I/76399 to A.K. A.D. and laboratory work in Mainz were supported by the German Research Foundation (DFG) through grant GK392 ("Composition and Evolution of Crust and Mantle"). We are grateful to Dunyi Lui for access to the SHRIMP in Beijing. We thank B. F. Windley and an anonymous reviewer for helpful and constructive comments. This is publication 582 of the Earth System Science Research Center of Mainz University and a contribution to International Geological Correlation Programme Project 480.

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