The Geological Society of America
Memoir 200
2007

Accretionary growth and crust formation in the Central Asian Orogenic Belt and comparison with the Arabian-Nubian shield

A. Kröner*
Institut für Geowissenschaften, Universität Mainz, 55099 Mainz, Germany, and Tectonics Special Research Centre, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

B.F. Windley*
Department of Geology, University of Leicester, Leicester LE1 7RH, UK

G. Badarch[†]
O. Tomurtogoo*
Institute of Geology and Mineral Resources, Mongolian Academy of Sciences, Ulaanbaatar 210351, Mongolia

E. Hegner*
Department für Geowissenschaften, Universität München, Theresienstrasse 41, 80333 München, Germany

B.M. Jahn*
Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei 11529, Taiwan

S. Gruschka
Institut für Geowissenschaften, Universität Mainz, 55099 Mainz, Germany

E.V. Khain
Geological Institute, Russian Academy of Sciences, Pyzhevski per. 7, 109017 Moscow, Russia

A. Demoux*
Institut für Geowissenschaften, Universität Mainz, 55099 Mainz, Germany

M.T.D. Wingate*
Tectonics Special Research Centre, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

*Kröner: kroener@mail.uni-mainz.de; Windley: brian.windley@btinternet.com; Tomurtogoo: igmr@magicnet.mn; Hegner: hegner@lmu.de; Jahn: jahn@earth.sinica.edu.tw; Khain: khain@ginras.ru; Demoux: demoux@uni-mainz.de; Wingate: mwingate@tsrc.uwa.edu.au.

[†]Deceased.

Kröner, A., Windley, B.F., Badarch, G., Tomurtogoo, O., Hegner, E., Jahn, B.M., Gruschka, S., Khain, E.V., Demoux, A., and Wingate, M.T.D., 2007, Accretionary growth and crust formation in the Central Asian Orogenic Belt and comparison with the Arabian-Nubian shield, *in* Hatcher, R.D., Jr., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 181–209, doi: 10.1130/2007.1200(11). For permission to copy, contact editing@geosociety.org.

ABSTRACT

The Central Asian Orogenic Belt is one of the largest accretionary terrains on Earth and records a ca. 800 Ma history of arc and microcontinent accretion, from south to north, during evolution and closure of the southwest Pacific-type Paleo-Asian ocean in the period ca. 1020 to ca. 325 Ma. We contest the evolutionary model for the belt proposed by previous authors in terms of a single, long island arc.

Accretion of ophiolites, arcs, and Precambrian microcontinents took place in southern Siberia in late Neoproterozoic to Cambrian times. Ultrahigh-pressure subduction and metamorphism occurred in the Cambrian at Kokchetav, Kazakhstan, and high-pressure metamorphism took place in the Gorny Altai, together with arcward accretion of a seamount. In the Chinese Altai, Precambrian microcontinents and island arcs collided into the accreting margin.

Overall the Central Asian Orogenic Belt records the formation of small forearc and backarc ocean basins that probably evolved between island arcs and microcontinents and were closed during continuous accretion between the Neoproterozoic and Paleozoic. During this time the southward-growing southern margin of the Siberian craton always faced an open ocean. Final closure of the Paleo-Asian ocean probably occurred in the late Permian when the North China craton was attached to the orogenic belt.

Large volumes of felsic volcanic rocks and the presence of Precambrian zircon xenocrysts as well as ancient detrital zircons in arc-derived sediments suggest substantial reworking of old crust despite seemingly primitive Nd isotopic characteristics. Similar characteristics in arc terranes of the Arabian-Nubian shield in Saudi Arabia suggest that previously proposed anomalously high crust-formation rates in both the Central Asian Orogenic Belt and Arabian-Nubian shield require revision.

Keywords: accretion, Arabian-Nubian shield, central Asia, Kazakhstan, Mongolia, zircon geochronology.

INTRODUCTION

The Central Asian Orogenic Belt (or Altaids) extends from northeastern Asia to the Ural Mountains and is one of the largest accretionary terrains on Earth (Zonenshain et al., 1990; Şengör et al., 1993; Mossakovsky et al., 1993; Yakubchuk et al., 2001; Yakubchuk, 2002) (Fig. 1). There have been many studies on the origin and evolution of this belt since Şengör et al. (1993) proposed an innovative but highly speculative model, deriving the entire orogen from one single, giant intra-oceanic island arc, the Kipchak arc, from the early Cambrian (ca. 540 Ma) to the Permian (ca. 260 Ma). The alternative, and more widely accepted, interpretation explains the Central Asian Orogenic Belt in terms of southwest Pacific-style accretion of arcs and microcontinents and final collision between the Siberian and North China cratons (e.g., Mossakovsky and Dergunov, 1985; Coleman, 1989; Mossakovsky et al., 1993; Abdulin et al., 1995; Fedorovsky et al., 1995; Ruzhentsev and Mossakovskiy, 1996; Filippova et al., 2001; Buslov et al, 2001; Badarch et al., 2002; Dobretsov et al., 2003; Kheraskova et al., 2003; Xiao et al., 2003, 2004a, 2004b). Whichever model is correct, the Central Asian Orogenic Belt represents a site of major crustal growth in the Phanerozoic (Şengör et al., 1993; Jahn et al., 2000, 2004; Jahn, 2004), comparable, in many respects, to the Neoproterozoic Arabian-Nubian shield (Reymer and Schubert, 1987; Johnson and Woldehaimanot, 2003).

Much new information has become available since the Şengör et al. (1993) synthesis was published, particularly as a result of IGCP (International Geological Correlation Programme) Project 473 (for summary see Jahn et al., 2004) and the international project "Atlas of lithological, paleogeographic, structural, palinspastic, and geoecologic maps of central Eurasia" of the Geological Surveys of central Asian countries, Russia, and China (Fedorenko and Militenko, 2002; Filippova et al., 2001). However, there is still a paucity of geochemical data, precise zircon ages, and detailed structural work for many of the terranes proposed in Kazakhstan, Mongolia, northwestern China, and southern Siberia. Nevertheless, a crude age zonation, from north to south, is now apparent in the Central Asian Orogenic Belt (Kröner et al., 2004) that we interpret to have resulted from successive ocean basin closure and accretion of arcs and microcontinents in the long-lived Paleo-Asian ocean (Zonenshain et al., 1990; Khain et al., 2002, 2003). The oldest ophiolitic rocks were generated ca. 1020–1035 Ma near the present margin of the Siberian craton (Khain et al., 2002), followed by the ca. 800 Ma

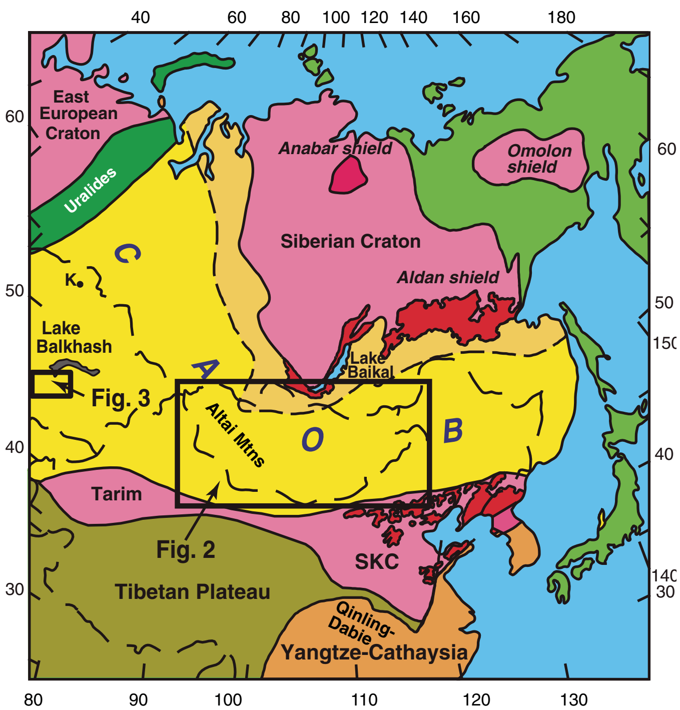

Figure 1. Simplified tectonic divisions of central Asia. The Central Asian Orogenic Belt (CAOB), also known as the "Altaid tectonic collage" (Şengör et al., 1993), is situated between the Siberian craton in the north and the Sino-Korean and Tarim cratons in the south. Red areas are exposed Archean to Paleoproterozoic rocks. Yellow-brown area surrounding Siberian craton is late Meso- to Neoproterozoic part of the Central Asian Orogenic Belt. Brown area is Paleo- to Neoproterozoic Yangtze-Cathaysia craton. Green pattern, including the Japanese islands, represents Pacific fold belts. K—Kokchetav (in northern Kazakhstan); SKC—Sino-Korean craton. Long broken lines are political boundaries; short broken line is approximate border between "Baikalian" and Phanerozoic domains of the Central Asian Orogenic Belt. The approximate locations of Figures 2 and 3 are indicated. Modified from Jahn (2004).

Shishkhid arc and ophiolite complex in northernmost Mongolia (Konnikov et al., 1994; Kuzmichev et al., 2005) and the large ca. 665 Ma Bayankhongor ophiolite in western Mongolia. Farther south, a broad belt of 570 Ma ophiolites extends from southern Tuva (Agardagh Tes-Chem; Pfänder and Kröner, 2004) into Mongolia via Dariv and Khantaishir (Khain et al., 2003; Matsumoto and Tomurtogoo, 2003).

Early Paleozoic arc formation dominates much of Kazakhstan (Heinhorst et al., 2000; Degtyarev and Ryazantsev, 2007; Kröner et al., 2007) and Mongolia (Ruzhentsev and Burashnikov, 1996; Badarch et al., 2002) and, as documented below, was followed by Carboniferous ophiolite formation south of Ulaanbaatar (Tomurtogoo et al., 2005), Silurian to Permian arc formation in southern Mongolia (Lamb and Badarch, 1997; Badarch et al., 2002), and finally, late Permian suturing and accretion of the southern Central Asian Orogenic Belt to the North China craton (Xiao et al., 2003). This indicates that this belt is a long-lived accretionary orogen, details of which still have to be unraveled.

Şengör et al. (1993) proposed that an area of more than five million square kilometers of juvenile crust was generated in central Asia in the Paleozoic, making this the largest Phanerozoic area of crustal growth, comparable, in crust-production rates, to the Neoproterozoic Arabian-Nubian shield (Reymer and Schubert, 1987). However, one striking aspect of the Central Asian Orogenic Belt in comparison to the Arabian-Nubian shield is the large volume of felsic volcanic rocks, particularly in Mongolia, and the relative paucity of true andesites. Furthermore, there is increasing evidence from precise zircon geochronology that Precambrian basement is more widespread in the belt than previously assumed (e.g., Yarmolyuk et al., 2005; Kozakov et al., 2007). In this contribution we particularly examine this aspect and summarize our field relationships and precise zircon ages from Kazakhstan and Mongolia in order to test which of the tectonic models proposed so far is most compatible with the available age and isotopic data. Bykadorov et al. (2003) and Windley et al. (2007) have already advanced important arguments why the Central Asian Orogenic Belt is unlikely to have evolved from a single, long-lived arc, and we discuss some of this evidence and further arguments against the single-arc hypothesis after presentation of our field and age data.

SOUTHERN SIBERIA, NORTHERN AND WESTERN MONGOLIA

The earliest history of ocean opening, probably linked to initiation of the Paleo-Asian ocean, is recorded by the 1020 Ma forearc Dunzhugur ophiolite in East Sayan, southern Siberia, that, together with a volcanic arc and blueschist accretionary wedge, was thrust onto the margin of the Siberian craton (Khain et al., 2002), probably during an accretion-obduction event prior to 790 Ma (Kuzmichev et al., 2001). Farther northeast at Lake Baikal, the ca. 1035 Ma Nurudukan arc and ophiolite suite records a similar tectonic setting (Khain et al., 2002; Dobretsov et al., 2003).

The next younger event, farther south, is exemplified by the evolution of the large but tectonically complex ca. 920–630 Ma Baikal-Muva-Dzhida-Yenisei arc and ophiolite terrane (Khain et al., 1997; Sklyarov et al., 2003), including the 800 Ma Shishkhid ophiolite complex of northern Mongolia that formed in an extensional island-arc environment (Kuzmichev et al., 2005). Kuzmichev et al. (2005) have recently identified a 600 km-long ~750 Ma accretionary prism, known as Oka belt, in southern Siberia and adjacent northern Mongolia and considered this to be an ancient analog of the Tertiary Shimanto belt in Japan.

The largest ophiolite complex of the Central Asian Orogenic Belt at Bayankhongor, western Mongolia (Buchan et al., 2001), has now been dated at 665 ± 15 Ma (sensitive high-resolution ion microprobe [SHRIMP] zircon age of anorthosite from a layered gabbro sequence; Kovach et al., 2005) and lies in the same tectonic position as Shishkhid on the margin of the Tuva-Mongolia block. Kovach et al. (2005) also pointed out that the

Bayankhongor ophiolite has a geochemical signature comparable to that of the Ontong Java Plateau; this may be the first oceanic plateau to be defined in the Central Asian Orogenic Belt, and the comparison is consistent with the fact that this 300 km long ophiolite is far larger than any other ophiolite in the orogenic belt.

This was followed, still farther south, by a broad belt of late Neoproterozoic ophiolites and arc terranes extending from Tuva in southern Siberia (Tes-Chem ophiolite, 570 Ma; Pfänder and Kröner, 2004) to western Mongolia and including the well-exposed and complete ophiolite sections of Dariv and Khantaishir (both ca. 570 Ma; Khain et al., 2003; Matsumoto and Tomurtogoo, 2003).

The northernmost part of the Central Asian Orogenic Belt adjacent to the Siberian craton was strongly deformed and metamorphosed after having been accreted to the Siberian margin, and significant crustal thickening leading to extensive granulite formation occurred at ca. 475 Ma (Donskaya et al., 2000) during a transpressive collisional event. This is particularly well exemplified by the Olkhon terrane fringing the craton along the northern shore of Lake Baikal (Fedorovsky, 1997, 2004), where a Neoproterozoic passive margin sequence and an early Paleozoic island-arc assemblage (previously interpreted as Paleoproterozoic basement) were thrust over Paleoproterozoic rocks of the craton in the early Paleozoic (Fedorovsky, 1997; Fedorovsky et al., 2005). The marginal region of the Siberian craton also shows that orogenic episodes, previously separated into a Neoproterozoic "Baikalian orogeny" (yellow-brown area on Fig. 1) and an early Paleozoic "Caledonian orogeny" are, in fact, part of a continuous sequence of accretion and collision events in the northern Central Asian Orogenic Belt (Fedorovsky et al., 2005).

Similarly, the Tuva-Mongolian Massif, previously interpreted as a Precambrian microcontinent because of the occurrence of high-grade rocks (Mossakovsky et al., 1993; Berzin and Dobretsov, 1994), has now been shown to consist of discrete Neoproterozoic tectonic domains, juxtaposed by thrusting prior to 497 Ma and subjected to high-grade metamorphism between 497 and 489 Ma (Kozakov et al., 2003, 2005; Yarmolyuk et al., 1999; Salnikova et al., 2001).

South of Lake Baikal and extending into northernmost Mongolia is the Dzhida terrane where late Neoproterozoic to early Paleozoic ophiolite, island arc, and backarc basin complexes are interpreted to have accreted in the Paleo-Asian ocean and onto the southward-growing Central Asian Orogenic Belt (Gordienko and Mikhaltsov, 2001; Gordienko and Filimonov, 2005). This terrane also contains a boninite suite (Almukhamedov et al., 2002) and a large allochthonous seamount (Gordienko and Filimonov, 2005).

These results imply that a large part of the northern Central Asian Orogenic Belt, including southern Siberia and northern Mongolia, had accreted to the Siberian craton through the Neoproterozoic until the end of the Ordovician during what were previously considered discrete and different orogenic events, named "Baikalian" (Neoproterozoic) and "Caledonian" (early Paleozoic) in the Russian literature (Zonenshain et al., 1990; Gordienko, 2006). Windley et al. (2004, 2007) suggested that this accreted and stabilized terrane extended as far south as the Main Mongolian Lineament (Yarmolyuk, 1983; Windley et al., 2004), a major tectonic line to the south of which lay an open ocean, the subduction of which gave rise to Silurian, Devonian, and Carboniferous island arcs and accretionary complexes (Fig. 2).

SOUTHERN KAZAKHSTAN

In Kazakhstan, several microcontinental fragments with Precambrian granitic gneisses have been identified (Abdulin et al., 1995) (Table 1), variously considered to be derived by Neoproterozoic rifting from the Siberian margin (Berzin and Dobretsov, 1994) or the East Gondwana margin (Mossakovsky et al., 1993; Kheraskova et al., 2003). The latter view is based on (1) similarities in the late Neoproterozoic and early Paleozoic stable margin sequences between Kazakhstan, Australia, China, and Tarim (Eganov and Sovetov, 1979) and (2) the fact that Kazakhstan has consistently drifted northwards from at least the Early Ordovician through the Permian as indicated by paleomagnetic data (Bazhenov et al., 2003; Collins et al., 2003; Alexyutin et al., 2005). Some investigators consider this rifting event to be related to breakup of the Rodinia supercontinent (e.g., Kheraskova et al., 2003), but the origin of continental fragments in the Central Asian Orogenic Belt remains uncertain. We have dated zircons from one of these crystalline complexes exposed in the Chu-Yili microcontinent (Nikitin and Nikitina, 2000), in the Russian literature also known as the "Zheltau Massif" or "Anrakhai-Altynemel microcontinent" (Avdeyev et al., 1990; Abdulin et al., 1995), and also from the accretionary terranes in traverses southwest of Lake Balkhash (Figs. 3 and 4). For this we used SHRIMP and the Pb-Pb evaporation technique, complemented by Sm-Nd whole-rock data. We have specifically investigated the field relationships in the Koyandisai-Uzunbulak area, the Kendyktas Mountains, the Sulu River area, and at the southwest end of Lake Balkhash near the village of Chiganak (Fig. 3).

The basement complex in the Anrakhai Mountains consists of strongly deformed and partly migmatized granitoid gneisses, granites, strongly foliated amphibolites and rare crystalline schists of likely sedimentary origin. The zircons from a well-foliated granite-gneiss exposed in the Koyandisai River in the Uzunbulak area (Fig. 3) were dated on the Perth SHRIMP II and are long-prismatic with rounded terminations and show oscillatory zoning under cathodoluminescence and in backscattered images (Fig. 5A), typical of magmatic growth. Four grains were analyzed (sample KZ 19, Table 2), and the discordant data yielded an upper concordia intercept at 2791 ± 24 Ma and a lower intercept at 1661 ± 43 Ma (Fig. 6A). The older age is interpreted to reflect the time of gneiss protolith emplacement, whereas the lower intercept age probably reflects Pb loss. However, there is no recorded event at this time in the basement of Kazakhstan, and the zircons do not reveal younger overgrowths (Fig. 5A), so we are hesitant to consider this "age" to signify a major thermal

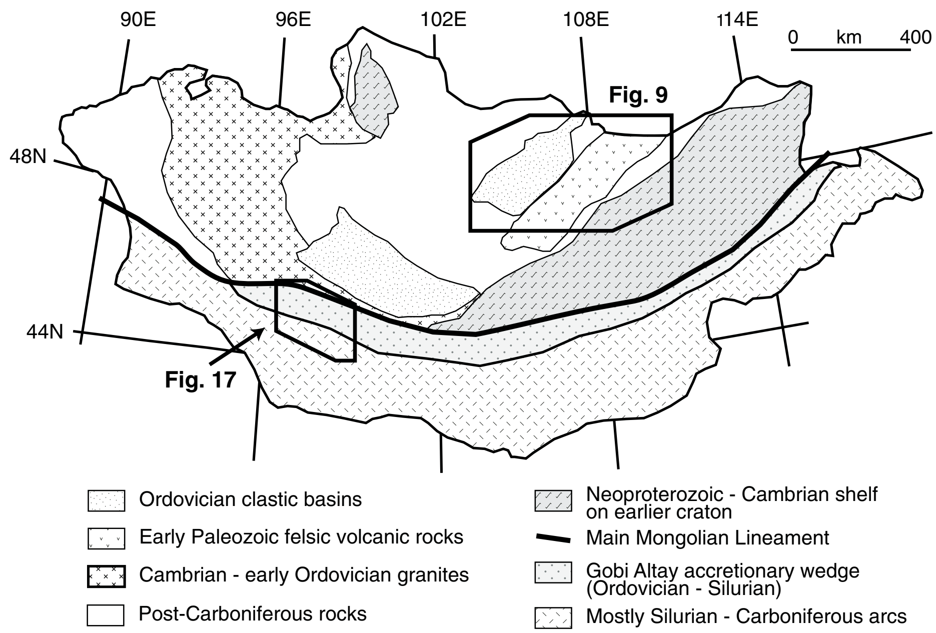

Figure 2. Generalized map of Mongolia showing main tectonic units (from Windley and Xiao, 2004). Locations of Figures 9 and 17 are indicated.

event. In any case, the above age documents Archean basement in the Anrakhai gneiss terrain.

A sample of well-foliated granite-gneiss in the Serektas River (KZ 12) that is intrusive into a sequence of fine-grained felsic gneisses of probably sedimentary origin contains long-prismatic, euhedral zircons, and evaporation of four grains produced a mean $^{207}Pb/^{206}Pb$ age of 1789.1 ± 0.6 Ma (Table 3; Fig. 7A). Another sample of fine-grained felsic gneiss (KZ 18) from the Uzunbulak River northwest of Kopa (Fig. 3) contains long-prismatic zircons with rounded terminations (Fig. 5B) of which four grains yielded a mean $^{207}Pb/^{206}Pb$ age of 2187.1 ± 0.5 Ma, whereas one xenocrystic grain is as old as 2431.0 ± 1.0 Ma (Table 3; Figs. 7B and 7C). The mean Nd crustal residence age of this sample is 2.3 Ga (Table 4).

Extensive rifting in the Anrakhai basement is documented by Neoproterozoic bimodal volcanic sequences dominated by dacitic to rhyolitic lavas and tuffs and locally known as the Kopa Formation. We dated single zircons from a coarse-grained, porphyritic and sheared rhyolitic rock (KZ 1) collected in the Kendyktas Mountains (Fig. 3), using the evaporation technique. The grains are long-prismatic with slight rounding at their terminations and well-developed oscillatory zoning defined by low- and high-U domains (Fig. 5C). The mean $^{207}Pb/^{206}Pb$ age is 775.9 ± 0.8 Ma (Table 3; Fig. 7D), and we interpret this to reflect the time of basement rifting and felsic volcanism. This corresponds to the widespread end-Riphean rifting event documented in central Kazakhstan and the Russian Platform (Kheraskova et al., 2003). The mean Nd crustal residence age of this sample is 1.87 Ga (Table 4) and shows that the source of felsic volcanism is of crustal origin and reflects melting of Paleoproterozoic basement.

Red gneissic granite in the hills northwest of Aschisu (Fig. 3) may be related to the above rifting event since six single zircons of one sample (KZ 22) yielded a mean $^{207}Pb/^{206}Pb$ age of 741.5 ± 0.7 Ma (Table 3; Fig. 7E). Since the gneiss is overlain by Paleozoic supracrustal rocks, its deformation records a late Neoproterozoic event in southern Kazakhstan. The overlying strata consist of coarse clastic sediments, including conglomerates and interlayered felsic volcanic rocks. Zircons of a strongly deformed metadacite (KZ 20) collected in the northwestern part of the Aschisu River (Fig. 3) vary from perfectly euhedral with only slight rounding at their terminations and well-developed oscillatory zoning (Fig. 5D) to well-rounded with older cores (Fig. 5E). Five grains were analyzed on SHRIMP and are highly variable in their isotopic composition (Table 2). The youngest, euhedral grain is concordant (Figs. 5D and 6B) and has a $^{206}Pb/^{238}U$ age of 534 ± 7 Ma. Three additional grains define a discordia line whose upper concordia intercept age of 1365 ± 24 Ma is determined by one concordant analysis (Fig. 6B), and the lower intercept is at 503 ± 178 Ma, compatible with the youngest concordant grain. The core of one additional well-rounded grain (Fig. 5E) has a minimum $^{207}Pb/^{206}Pb$ age of 2441 ± 9 Ma (Table 2; Fig. 6B, inset). We interpret the 1365 and 2441 Ma ages to reflect zircon inheritance from the basement complex, whereas the early Cambrian age of 534 Ma probably represents the time of dacite formation. The interlayered volcanic and sedimentary rocks here

TABLE 1. ISOTOPIC AGE DATA USED IN STRATIGRAPHIC CHART OF THE EARLY PRECAMBRIAN OF KAZAKHSTAN AND KYRGYZSTAN

No.	Composition (rock, mineral)	Sampling area	Formation	Method	Age (Ma)	Laboratory
1	Biotite-amphibole crystalline schist, metamorphogenic zircon first generation	Middle Tian Shan, Sarydzhaz area, Kuilyu River	Kuilyu suite	Pb-Pb isochron	2600 ± 50	Institute of Geology, Bishkek, Kyrgyzstan
2	as above	as above	as above	U-Pb discordia	2600	as above
3	as above	as above	as above	$^{207}Pb/^{206}Pb$	2570 ± 50	Kaz IMS, Alma-Ata, Kazakhstan
4	Biotite gneiss, metamorphogenic zircon first generation	as above	as above	as above	2570 ± 30	Institute of Geology, Bishkek, Kyrgyzstan
5	Biotite-amphibole crystalline schist	as above	as above	as above	1840	as above
6	as above	as above	as above	as above	1900	as above
7	Quartz-garnet-muscovite schist; metamorphic zircons	Kokchetav area, eastern shore of Lake Chelkar	Berlykskaya suite, Zerendinskaya series	U-Pb discordia	>2000	KazIMS, Alma-Ata, Kazakhstan
8	as above	as above	as above	$^{207}Pb/^{206}Pb$	1950	as above
9	Granitized gneiss	Kokchetav massif	Zerendinskaya series, altered due to granitization	as above	1200 ± 75	GEOKHI, Moscow, Russia
10	as above	as above	as above	as above	1050 ± 65	as above
11	as above	as above	as above	as above	1185 ± 80	as above
12	as above	as above	as above	U-Pb discordia	1200	MGU, Moscow, Russia
13	Garnet-micaceous schists and muscovite schists	Aktyuz-Boordy area, Malyi Kemin River	Aktyuz complex, granitization, mylonitization	Pb-Pb isochron	1140 ± 60	KazIMS, Alma-Ata, Kazakhstan
14	as above	as above	as above	U-Pb discordia	1140 ± 60	as above
15	as above	as above	as above	Pb-Pb isochron	1230 ± 50	as above
16	as above	as above	as above	U-Pb discordia	1230 ± 50	as above
17	Garnet-micaceous schists, syntectonic gneiss-granites, metamorphic zircon	Makbal area, western part of the Kyrghyz Ridge, Makbal River	Kirgiz series	as above	2165 ± 100	Institute of Geology, Bishkek,, Kyrgyzstan
18	as above	as above	as above	as above	2010 ± 100	Kaz IMS, Alma-Ata, Kazakhstan
19	Quartzites and schists, detrital and metamorphic zircons (?)	Makbal area, western part of Kyrghyz Ridge, Makbal River	Kirgiz series	U-Pb discordia	2028 ± 11	as above
20	Quartz-garnet-muscovite schist, detrital and metamorphic zircons	Makbal area, northern slope of Kyrghyz Ridge, Mamai-Kaindy River	as above	$^{207}Pb/^{206}Pb$	1870	as above
21	as above	as above	as above	Pb-Pb isochron	1920 ± 50	as above
22	Quartz- eclogite rock, garnet	Makbal area, west of the Kyrghyz Ridge, Tyuekarn Pass	Tyuekaryn suite, Kirgiz series	K-Ar	1688 ± 75	as above
23	as above	as above	as above	as above	1678 ± 75	as above
24	Crystalline schists, metamorphic zircons, later (?) metamorphic stages	as above	Sarychabyn suite	U-Pb discordia	1388 ± 11	as above
25	Granites, magmatic zircons	Karsakpai area, South Ulutau, west of Kar-sakpai village, north of Maityube hill	Zhaunkarskiy Complex, North-Sarysu Massif	Pb-Pb isochron	2230	IGG, UNC

(*continued*)

TABLE 1. ISOTOPIC AGE DATA USED IN STRATIGRAPHIC CHART OF THE EARLY PRECAMBRIAN OF KAZAKHSTAN AND KYRGYZSTAN (*continued*)

No.	Composition (rock, mineral)	Sampling area	Formation	Method	Age (Ma)	Laboratory
26	Granite-gneiss; magmatic zircons	Junggar region	Pioner Massif	U-Pb-Th	1715 ± 120	MGU, Moscow, Russia
27	as above	as above	Granite-gneiss complex	U-Pb discordia	1800	as above
28	as above	as above	Pioner Massif	Pb-Pb isochron (microprobe)	1950	IGG, UNC
29	Nepheline-syenite, magmatic zircons	as above	Karsakpai Massif, intrusive into the surrounding gneisses	U-Pb discordia	1675 ± 110	MGU, Moscow, Russia
30	as above	as above	as above	Pb-Pb isochron (microprobe)	1380	IGG, UNC
31	Sericite-feldspar schist, detrital zircons	West Sarysai-Teniz region, upper reaches of Kirei River	Opar suite	$^{207}Pb/^{206}Pb$ U-Pb-Th	3240 ± 480	MGU, Moscow, Russia
32	as above	as above	as above	Pb-Pb microprobe	3270	IGG, UNC
33	Quartz-biotite schist, detrital and metamorphic zircon	Chu area	Ogiztau suite	$^{207}Pb/^{206}Pb$ U-Pb-Th	1750 ± 50	Kaz IMS, Alma-Ata, Kazakhstan
34	Quartz-garnet-micaceous schist, metamorphic zircon, later metamorphic phases	Kokchetav area, Lake Chelkar	Berlykskaya suite	U-Pb discordia	>2000	as above
35	Pegmatite, muscovite	Ishkeolmes area	Granite-gneiss in Stepnogorsk series	K-Ar	1880 ± 60	IGEM, Moscow, Russia
36	Porphyroids, magmatic zircon	Atasu-Mointy area, upper reaches of Atasu River	Urkendeuskaya suite	Pb-Pb isochron	1850 ± 30	MGU, Moscow, Russia
37	as above	as above	as above	U-Pb discordia	1850 ± 60	as above
38	Granite-gneiss and granites, magmatic zircon	Karakamys area	Localized in Karakamys suite	as above	1900	Kaz IMS, Alma-Ata, Kazakhstan
39	Quartz-biotite crystalline schist, metamorpic zircon (late generation)	as above	Karakamys suite	Pb-Pb isochron	1750	as above
40	Quartz-biotite crystalline schist, metamorphogenic zircon (late generation)	as above	as above	$^{207}Pb/^{206}Pb$ U-Pb-Th	1755	as above
41	Biotite gneiss, metamorphic zircon (late generation)	Karakamys area, out-skirts of Anrakhai Mountains, middle reaches of Koyandsai River	Uzunbulak suite, Anrakhai series	U-Pb discordia	1797 ± 8	as above
42	Gneiss-granites and granitized crystalline schists, metamorphogenic zircon	Karakamys area outskirts of Anrakhai Mountains	Product of granitization of the Anrakhai series	as above	1800 ± 50	as above
43	as above	as above	as above	Pb-Pb isochron	1620 ± 70	as above
44	Granite-gneiss	Kendyktas, Sarybulak and Kerbulak blocks	Sarybulak suite	U-Pb discordia	1977 ± 14	as above
45	as above	as above	as above	$^{207}Pb/^{206}Pb$	1817	as above

Note: From Resolution of 3rd Kazakhstan stratigraphic conference on the Precambrian and Phanerozoic (1991, p. 18–21).

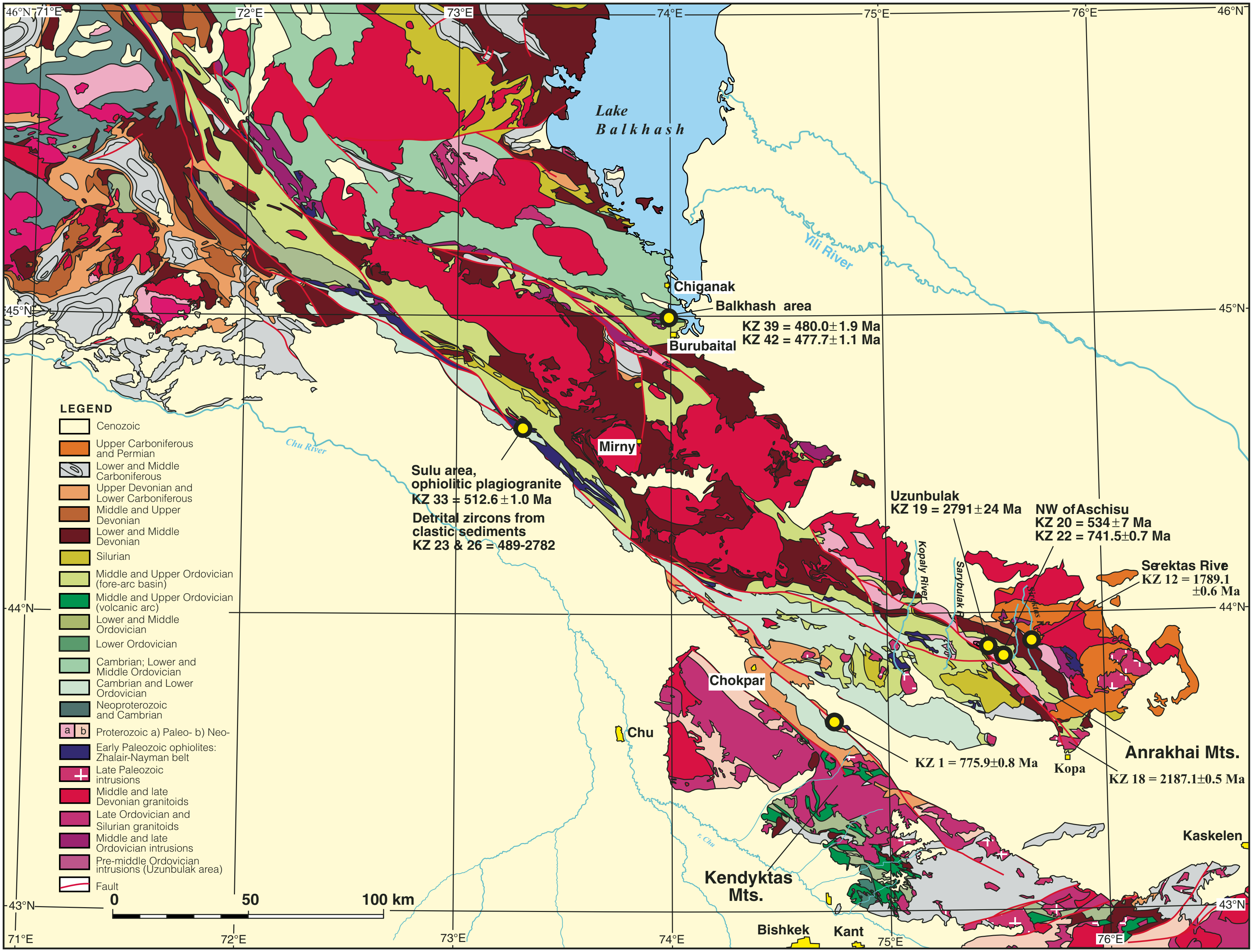

Figure 3. Sample location map and zircon ages of southern Kazakhstan. Base map is from Chakabaev et al. (1979).

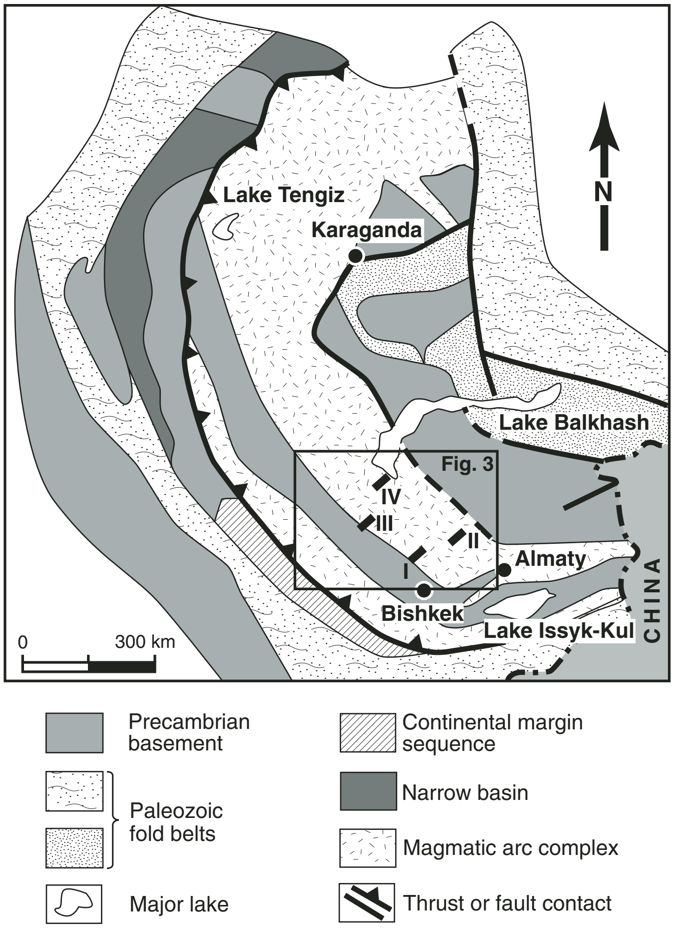

Figure 4. Geological map of southern Kazakhstan (simplified from Chakabaev et al., 1979) showing major tectonic units and working traverses (I–IV). Location of Figure 3 is indicated.

may represent an overlap sequence of a continental margin arc on the edge of the Anrakhai microcontinent.

There are many ophiolites in southern and central Kazakhstan that range in age from Vendian to Ordovician (Yakubchuk, 1994; Avdeev et al., 1995). The Sulu River area near the town of Mirny exposes a sequence of strongly deformed clastic sediments consisting of medium-grained gray to reddish sandstone (Djambul sequence) and laminated sandstone-siltstone (Solushai sequence). These rocks rest directly, with a well-preserved sedimentary contact, on fragmented basaltic pillow lava and red jaspilite. The basalts, in turn, are underlain by isotropic gabbro cut by diabase dikes and containing small pods and lenses of plagiogranite. There is no doubt that this succession constitutes part of an ophiolite sequence, and Avdeev (1984) interpreted the association of ophiolitic rocks with clastic sediments, which is typical of several ophiolite occurrences in southern Kazakhstan, as reflecting formation in a relatively narrow ocean basin. We envision a situation such as in the Red Sea or the Gulf of California since ocean floor sediments in larger oceans usually consist of fine-grained pelagic, cherty, and jaspilitic material (Anonymous, 1972).

We dated zircons from one of the above plagiogranite pods (KZ 33, Figs. 3 and 4), and four short-prismatic, euhedral grains yielded a mean $^{207}Pb/^{206}Pb$ age of 512.6 ± 1.0 Ma (Table 3; Fig. 7F), which we interpret to reflect ocean crust formation in the middle Cambrian. Detrital zircons from the clastic sediments resting on ocean floor basalts are highly variable in age. The youngest, long-prismatic, and euhedral grains (Fig. 5F) from a sample of Djambul sandstone directly resting on basalt (KZ 23; Fig. 3) have a mean early Ordovician $^{207}Pb/^{206}Pb$ evaporation age of 489.6 ± 1.0 Ma (Table 3; Fig. 7G), whereas two rounded detrital grains (Fig. 5G) have Precambrian ages of 2037.6 ± 4.3 and 2782.1 ± 2.1 Ma (Figs. 7H and 7I), probably reflecting input from the nearby Anrakhai microcontinent. Three rounded, detrital zircons from a sample of the Solusai siltstone (KZ 26, Fig. 3) higher up in the sedimentary sequence yielded virtually identical isotopic ratios with a mean $^{207}Pb/^{206}Pb$ age of 2230.6 ± 0.4 Ma (Table 3; Fig. 8A) and also document sedimentary input from the nearby basement.

The antiquity of most detrital zircons proves derivation of the above sediments from an ancient crustal source and supports the view of Avdeev (1984) that the oceanic domains between the microcontinents and early Paleozoic arc complexes in southern Kazakhstan were relatively narrow, probably marginal basins.

Finally, we dated zircons from a well-exposed, early Paleozoic arc complex from the western end of Lake Balkhash, exposed in roadcuts and a railway cut near the village of Chiganak (Fig. 3). A metadacite (KZ 42) with oscillatory-zoned zircons (Fig. 5H) and a granodiorite (KZ 39) with similar zircons (Fig. 5I) from this terrane provided almost identical mean $^{207}Pb/^{206}Pb$ zircon evaporation ages of 477.7 ± 1.1 and 480.0 ± 1.0 Ma respectively and, surprisingly, contain zircon xenocrysts as old as 2288 Ma (Table 3; Figs. 8B–8F). The Nd mean crustal residence age of the metadacite is 1.11 Ga (Table 4), and we consider it unlikely for these rocks to have formed in an intra-oceanic environment, but favor an Andean- or Japan-type setting. This view is compatible with the model of Heinhorst et al. (2000) who, on the basis of geochemistry and Nd isotopic systematics, suggested the central and northern Kazakhstan crust to have formed behind oceanward-drifting continental slivers.

In summary, our data do not support a purely juvenile origin for the early Paleozoic rocks in the accretionary belt of southern Kazakhstan. Furthermore, evidence for early Ordovician to late Carboniferous island-arc magmatism in central and northern Kazakhstan (Zonenshain et al., 1990; Heinhorst et al., 2000; Filippova et al., 2001; Kröner et al., 2007) argue against a stable Kazakhstan block as early as late Ordovician, as inferred by Bykadorov et al. (2003), but support continuous accretion until at least the Carboniferous.

Avdeev et al. (1995) reported ophiolite ages of 680 and 570 Ma from the Altai Mountains and elsewhere in Kazakhstan, and this is complemented by our Middle Cambrian plagiogranite

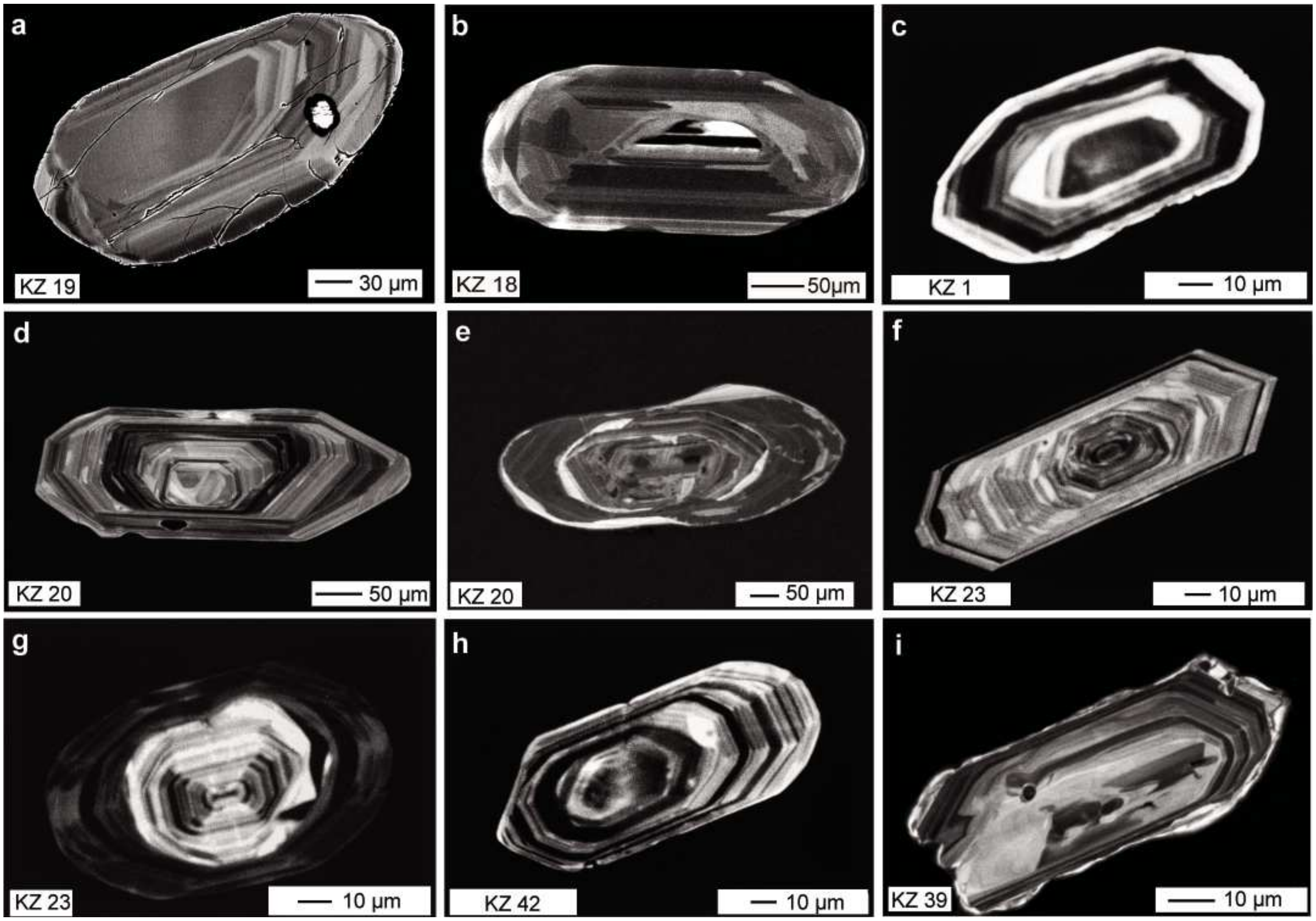

Figure 5. Cathodoluminescence (CL) and backscattered (BS) images of zircons from southern Kazakhstan dated in this study. (A) BS image of zircon from sample KZ 19. White spot is burn-mark of SHRIMP ion beam. (B) CL zircon image of sample KZ 18. (C) CL zircon image of sample KZ 1; note dark (high-U) and light (low-U) zoning. (D) CL image of zircon with well-developed oscillatory zoning. (E) CL image of zircon from sample KZ 20 with older core and overgrowth. (F) CL zircon image of sample KZ 23 showing euhedral shape and oscillatory zoning. (G) CL image of well-rounded, detrital zircon from sample KZ 23. (H) CL image of oscillatory-zoned zircon from sample KZ 42. (I) CL image of oscillatory-zoned zircon from sample KZ 39.

TABLE 2. SENSITIVE HIGH-RESOLUTION ION MICROPROBE (SHRIMP) ANALYTICAL DATA FOR SPOT ANALYSES OF MAGMATIC ZIRCONS FROM GRANITOID GNEISSES OF SOUTHERN KAZAKHSTAN*

Sample no.	U (ppm)	Th (ppm)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$ age (Ma)	$^{207}Pb/^{235}U$ age (Ma)	$^{207}Pb/^{206}Pb$ age (Ma)
KZ 19-1†	197	95	26,643	0.1333 ± 13	0.1615 ± 9	0.4148 ± 48	9.24 ± 13	2237 ± 22	2363 ± 12	2471 ± 10
KZ 19-2	233	93	11,797	0.1078 ± 13	0.1851 ± 9	0.4926 ± 58	12.58 ± 17	2582 ± 25	2648 ± 13	2699 ± 9
KZ 19-3	538	155	11,122	0.0832 ± 8	0.1408 ± 6	0.3621 ± 40	7.03 ± 9	1992 ± 19	2115 ± 11	2237 ± 7
KZ 19-4	135	55	9180	0.1154 ± 18	0.1786 ± 13	0.4708 ± 58	11.59 ± 18	2487 ± 25	2572 ± 14	2640 ± 12
KZ 20-1	228	82	4967	0.1145 ± 13	0.0843 ± 11	0.2009 ± 23	2.34 ± 4	1180 ± 12	1223 ± 13	1301 ± 26
KZ 20-2	164	101	4688	0.1792 ± 31	0.0871 ± 14	0.2371 ± 27	2.85 ± 6	1372 ± 15	1369 ± 16	1364 ± 31
KZ 20-3	249	132	19,303	0.1455 ± 12	0.1586 ± 8	0.4376 ± 50	9.57 ± 13	2340 ± 23	2394 ± 12	2441 ± 9
KZ 20-4	187	106	3824	0.1617 ± 27	0.0861 ± 12	0.2171 ± 25	2.58 ± 5	1267 ± 13	1294 ± 14	1340 ± 28
KZ 20-5	103	64	299	0.2354 ± 186	0.0598 ± 79	0.0863 ± 11	0.71 ± 10	534 ± 7	546 ± 57	596 ± 294

*All analyses were performed on the Perth Consortium SHRIMP II. For analytical details such as instrumental conditions, data reduction procedure, and error assessment see Kröner et al. (2003) and references cited therein. All errors are 1σ.
†1 is spot 1 on grain 1, 2 is spot 1 on grain 2, etc.

TABLE 3. SINGLE-ZIRCON EVAPORATION DATA FOR SAMPLES FROM SOUTHERN KAZAKHSTAN

Sample no.	Zircon color and morphology	Grain no.	Mass scan[1]	Evaporation temperature (°C)	Mean $^{207}Pb/^{206}Pb$ ratio[2] and 2σ error	$^{207}Pb/^{206}Pb$ age and 2σ error (Ma)
KZ 1	pink to clear, long-prismatic, ends rounded	1	97	1594	0.065048 ± 46	775.9 ± 1.5
		2	174	1601	0.065047 ± 32	775.8 ± 1.0
		3	131	1599	0.065047 ± 39	775.9 ± 1.2
		4	66	1598	0.065051 ± 68	776.0 ± 2.2
mean of four grains		1–4	468		0.065048 ± 21	***775.9 ± 0.8**
KZ 12	clear to light brown, long-prismatic, idiomorphic	1	105	1595	0.109337 ± 72	1788.4 ± 1.2
		2	131	1597	0.109406 ± 49	1789.5 ± 0.8
		3	131	1599	0.109433 ± 66	1790.0 ± 1.1
		4	86	1598	0.109299 ± 82	1787.8 ± 1.4
mean of four grains		1–4	453		0.109378 ± 33	**1789.1 ± 0.6**
		5	122	1598	0.110887 ± 69	1814.0 ± 1.1
KZ 18	clear to light gray-brown, long-prismatic, ends slightly rounded	1	129	1596	0.136825 ± 63	2187.2 ± 0.8
		2	129	1598	0.136805 ± 60	2187.1 ± 0.8
		3	108	1597	0.136816 ± 37	2187.3 ± 0.5
		4	74	1598	0.136772 ± 106	2186.7 ± 1.3
mean of four grains		1–4	440		0.136802 ± 37	**2187.1 ± 0.5**
		5	128	1598	0.157690 ± 90	2431.0 ± 1.0
KZ 22	yellowish, transparent, long-prismatic, idiomorphic	1	85	1598	0.039883 ± 41	741.2 ± 1.4
		2	144	1597	0.063967 ± 43	740.8 ± 1.4
		3	122	1598	0.064003 ± 60	741.7 ± 2.0
		4	206	1599	0.060049 ± 19	741.8 ± 0.6
		5	132	1597	0.063997 ± 28	741.5 ± 0.9
		6	60	1597	0.063994 ± 99	741.4 ± 3.3
mean of six grains		1–6	749		0.063995 ± 17	***741.5 ± 0.7**
KZ 23	yellowish to clear, long-prismatic, idiomorphic	1	109	1596	0.056950 ± 36	489.6 ± 1.4
		2	84	1597	0.056947 ± 42	489.5 ± 1.6
		3	84	1597	0.056954 ± 27	489.7 ± 1.1
mean of three grains		1–3	277		0.056950 ± 20	***489.6 ± 1.0**
	red, well rounded	4	43	1595	0.125623 ± 307	2037.6 ± 4.3
		5	86	1598	0.194678 ± 244	2782.1 ± 2.1
KZ 26	brownish, long-prismatic, idiomorphic	1	88	1598	0.140263 ± 29	2230.5 ± 0.4
		2	61	1599	0.140597 ± 33	2234.6 ± 0.4
		3		1597	0.140131 ± 27	2228.8 ± 0.3
mean of three grains		1–3	277		0.140275 ± 33	**2230.6 ± 0.4**
		62	1596		0.157142 ± 51	2425.1 ± 0.6
KZ 33	yellowish to dark red, short-prismatic, idiomorphic	1	102	1595	0.057555 ± 42	512.9 ± 1.6
		2	88	1598	0.057551 ± 24	512.7 ± 0.9
		3	165	1592	0.057552 ± 18	512.8 ± 0.7
		4	132	1596	0.057536 ± 27	512.1 ± 1.0
mean of four grains		1–4	487		0.057548 ± 13	***512.6 ± 1.0**
KZ 39	clear, long-prismatic, idiomorphic	1	129	1597	0.056691 ± 25	479.5 ± 1.0
		2	109	1598	0.056709 ± 46	480.2 ± 1.8
		3	215	1598	0.056706 ± 22	480.2 ± 0.9
mean of three grains		1–3	453		0.056702 ± 17	***480.0 ± 1.0**
		4	198	1596	0.058483 ± 27	547.9 ± 1.0
		5	44	1597	0.145035 ± 434	2288.2 ± 5.2
KZ 42	clear to yellowish, transparent, idiomorphic	1	84	1600	0.056627 ± 58	477.0 ± 2.3
		2	91	1596	0.056655 ± 29	478.1 ± 1.1
		3	116	1598	0.056652 ± 41	478.0 ± 1.6
		4	108	1596	0.056648 ± 29	477.9 ± 1.1
		5	146	1597	0.056638 ± 13	477.5 ± 0.5
mean of five grains		1–5	545		0.056644 ± 15	***477.7 ± 1.1**
		6	99	1598	0.067173 ± 63	843.1 ± 2.0

[1]Number of $^{207}Pb/^{206}Pb$ ratios evaluated for age assessment.

[2]Observed mean ratio corrected for nonradiogenic Pb where necessary. Errors based on uncertainties in counting statistics.

*Error based on reproducibility of internal standard. For analytical procedures and error assessment see Kröner and Hegner (1998) and references cited therein.

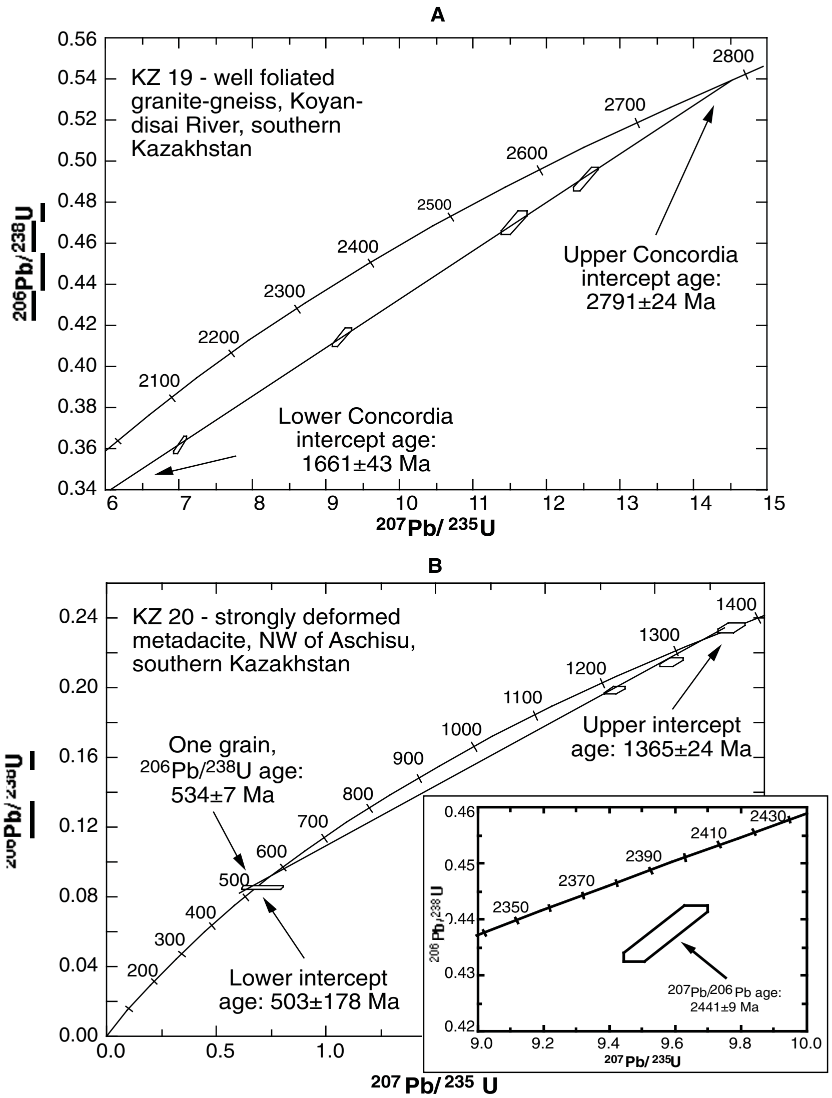

Figure 6. Concordia diagrams for SHRIMP zircon analyses of rocks from southern Kazakhstan. Data boxes for each analysis are defined by standard errors in $^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{206}Pb$. A: Well-foliated granite-gneiss sample KZ 19, Koyandisai River. B: Strongly deformed metadacite sample KZ 20, NW of Aschisu.

age of 512 Ma presented above. These and further ages reported from Mongolia by Khain et al. (2003) demonstrate that Siberia and the East European craton could not have had a common margin during the late Neoproterozoic and early Paleozoic, because oceanic crust of the Paleo-Asian ocean separated the various cratonic blocks and microcontinental fragments. This is further supported by paleomagnetic results (compare data for Siberia by Smethurst et al. [1998a] and Pisarevsky and Natapov [2003] with data for Baltica by Smethurst et al. [1998b], Popov et al. [2002], and Nawrocki et al. [2004]). The best available paleomagnetic and paleofaunal data (e.g., Hartz and Torsvik, 2002; Murphy et al., 2004; Meert and Lieberman, 2004) indicate that in the early Cambrian, when the Kipchak arc was supposed to have formed (Şengör et al., 1993), Baltica and Siberia were separated by ~30° of paleolatitude by a wide ocean commonly called the Aegir Sea.

NORTHERN AND CENTRAL MONGOLIA

Late Neoproterozoic to early Paleozoic stable continental margin (carbonates) and arc formations dominate much of northern and central Mongolia (Badarch et al., 2002), overlain

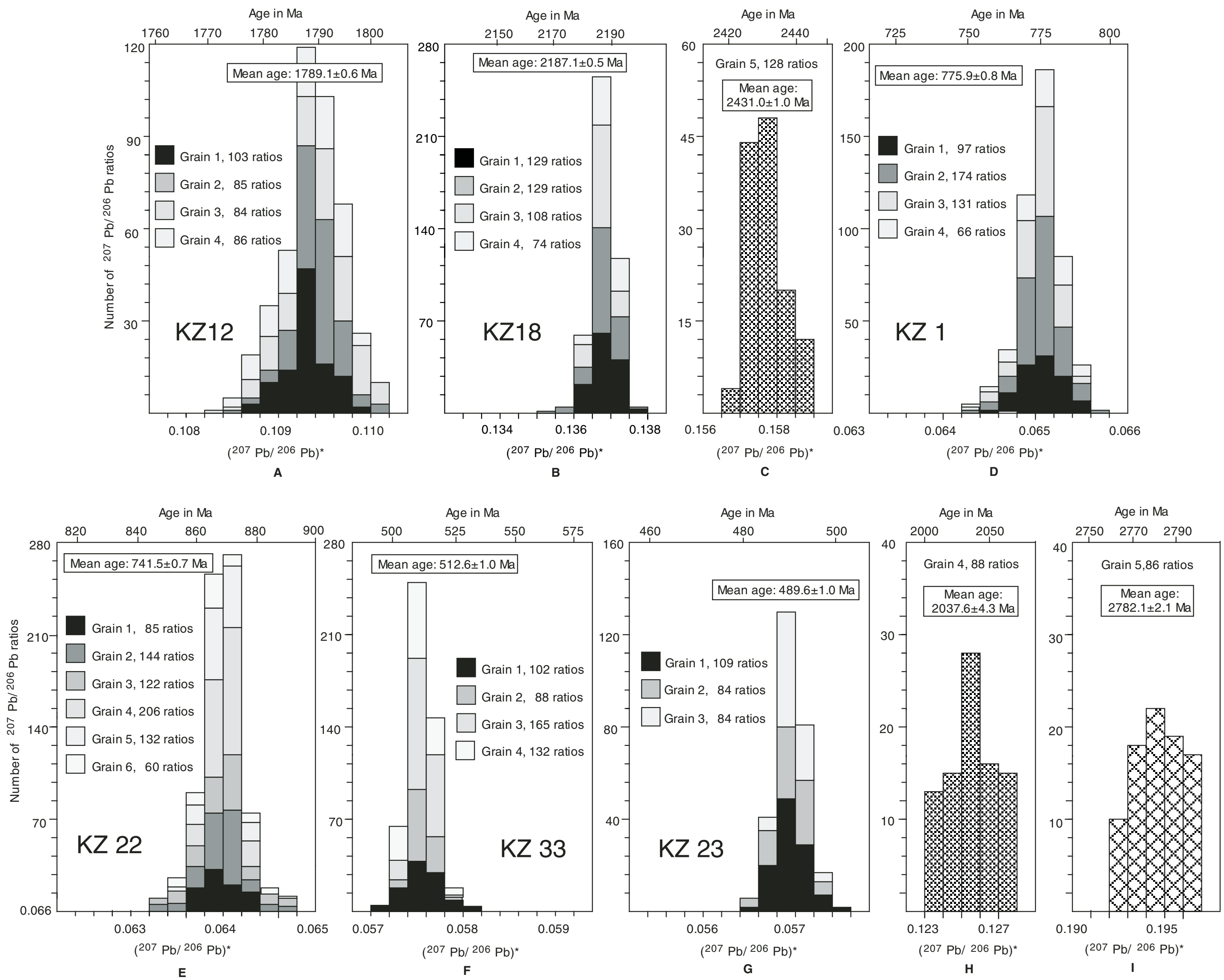

Figure 7. Histograms showing distribution of radiogenic Pb isotope ratios derived from evaporation of single zircons from Precambrian and Paleozoic rocks in southern Kazakhstan. (A) Spectrum for four grains from red granite-gneiss sample KZ 12, Serektas River, NW of Kopa, integrated from 453 ratios. (B) Spectrum for four grains from felsic gneiss sample KZ 18, Uzunbulak River, integrated from 440 ratios. (C) Spectrum for xenocrystic grain from same sample. (D) Spectrum for four grains from porphyritic metarhyolite sample KZ 1, collected near Yeshlilikurda and integrated from 468 ratios. (E) Spectrum for six grains from gneissic granite sample KZ 22, hills NW of Aschisu, integrated from 749 ratios. (F) Spectrum for four grains from ophiolitic plagiogranite sample KZ 33, east of Kompakty River, Mirny area, integrated from 487 ratios. (G) Spectrum for three detrital grains from Djambul sandstone sample KZ 23, Kompakty River near Mirny, integrated from 277 ratios. (H–I) Spectra for Precambrian detrital grains reflecting input from ancient basement.

TABLE 4. Sm-Nd ISOTOPIC COMPOSITION OF IGNEOUS ROCKS FROM SOUTHERN KAZAKHSTAN

Sample no.	Rock type	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	±2σ	eNd(t)	T_{DM} (Ma)
KZ1	Metarhyolite	776	6.01	33.65	0.1079	0.511862	10	–6.4	1.87
KZ18	Felsic gneiss	2190	4.57	25.03	0.1104	0.511594	12	2.1	2.30
KZ33	Plagiogranite	513	5.61	24.33	0.1394	0.512771	14	6.2	0.81
KZ42	Metadacite	478	3.60	24.24	0.0898	0.512263	14	–0.9	1.11

Note: For analytical procedures see Lackschewitz et al. (2003). Isotopic analyses were performed in the Max-Planck-Institut für Chemie, Mainz. T_{DM}—Nd model age assuming a depleted mantle reservoir (DePaolo, 1981).

and intruded by voluminous Permian felsic volcanic rocks and granites. We have investigated a north-south traverse from the Tarvagatay terrane in the north to the Haraa terrane around and west of Ulaanbaatar as well as volcanic sequences in the area around Mörön, in the Idermeg terrane southeast of Ulaanbaatar (Fig. 9). Most of the arc-related rocks of northern and central Mongolia consist of Ordovician to Silurian volcanic and volcaniclastic sequences, intruded by a variety of granitoids, and these rocks were generated in the relatively short time period from 460 to 417 Ma (A. Kröner, B.F. Windley, G. Badarch, unpubl. data) (Table 5). However, there are also Carboniferous arc sequences, particularly around Ulaanbaatar (Popeko, 2002). One striking aspect of these rocks is a predominance of felsic compositions, mainly dacites and rhyolites and their sedimentary derivatives (Fig. 10), and we found these rocks in great abundance north of and around Ulaanbaatar as well as south of Ulaanbaatar and in the Mörön area (Fig. 9). Although these rocks are chemically arc-related, andesites and basalts are relatively rare (Figs. 10 and 11). Murphy and MacDonald (1993) have shown that discrimination diagrams developed for volcanic rocks, in particular HFS (high field strength) elements, are useful to reconstruct the provenance of chemically immature sediments such as those exposed in northern and central Mongolia. We have plotted some of our trace element data for arc-related sedimentary rocks in the Nb-Zr-Y discrimination diagram of Meschede (1986), and there is a well-developed grouping in the volcanic arc field (Fig. 12).

We consider it unlikely that these large volumes of predominantly felsic rocks were generated entirely from juvenile sources since some samples contain Precambrian xenocrystic zircons, and Nd mean crustal residence ages for some of these felsic rocks are between 600 and 1300 Ma, suggesting that at least some older material was involved in their generation. In fact, there is a relatively large crustal block with Archaean to Paleoproterozoic rocks in south-central Mongolia, known as the Baidrag terrane (Kozakov et al., 1997; Badarch et al., 2002). A comparison of Nd isotope data for Central Asian Orogenic Belt rocks from Tuva, Transbaikalia, and Mongolia shows that Transbaikalia and northern Mongolia (Fig. 13) reflect the input of older crust, perhaps derived from the Siberian craton, whereas southern Mongolia appears to be largely, but not exclusively, juvenile, supporting the data of Jahn et al. (2004) and Helo et al. (2006).

By the end of the Ordovician, the northern part of the orogenic belt had probably amalgamated to create a new continental margin (the Main Mongolian Lineament of Windley et al., 2004) (Fig. 2). Evidence of stabilization by this time of the northern region is provided by Eocambrian to Cambrian shelf carbonates, Ordovician clastic basins, and relatively little-deformed, extensive Ordovician ash-fall tuffs, dacites, and rhyolites (Figs. 2 and 10). The Main Mongolian Lineament appears to be a major tectonic boundary separating crustal provinces with different isotopic characteristics. This is in agreement with the conclusion of Kovalenko et al. (2004) that the Neoproterozoic to early Paleozoic area to the north of the lineament (mean age of 570–475 Ma) has a Nd mean crustal residence age of 1.1–0.55 Ga, whereas the late Paleozoic area to the south (mean age of 420–320 Ma) has a T_{DM} of 0.8–0.5 Ga.

The above scenario of a stabilized accreted margin in Ordovician times in northern and central Mongolia is a perfect setting to generate large volumes of felsic volcanic rocks, and we quote from Bryan et al. (2002): "The largest volume silicic igneous provinces occur along accreted continental margins… and ultimately reflect large-scale crustal melting processes in response to lithospheric extension and high thermal input from underlying hot mantle. Partial melting of hydrous, mafic-intermediate composition (amphibolite) crust is critical in generating the large volumes of predominantly I-type silicic igneous melt. In these cases, subduction as much as hundreds of millions of years prior to the emplacement of the silicic igneous province seems crucial in producing a hydrous lower crustal source receptive to melting."

We have reconnaissance-dated zircons from several felsic volcanic samples and clastic sediments, complemented by Sm-Nd whole-rock isotopic systematics, and these data are summarized in Table 5. Specific examples to illustrate our conclusion that older material was involved in the generation of many of these rocks are given below.

Stable depositional conditions in northern Mongolia are documented by a carbonate-quartzite sequence (Darhan Formation) of presumed late Neoproterozoic to earliest Paleozoic age that is exposed in the hills south of the city of Darhan (Byamba, 1996). We have dated detrital zircons from a quartzite exposed in a small abandoned quarry, using SHRIMP and the evaporation method.

Three quartzite samples were taken, NM 16, M 02/115, and M 04/146, and the zircon populations are very heterogeneous, containing transparent, perfectly euhedral grains with no trace

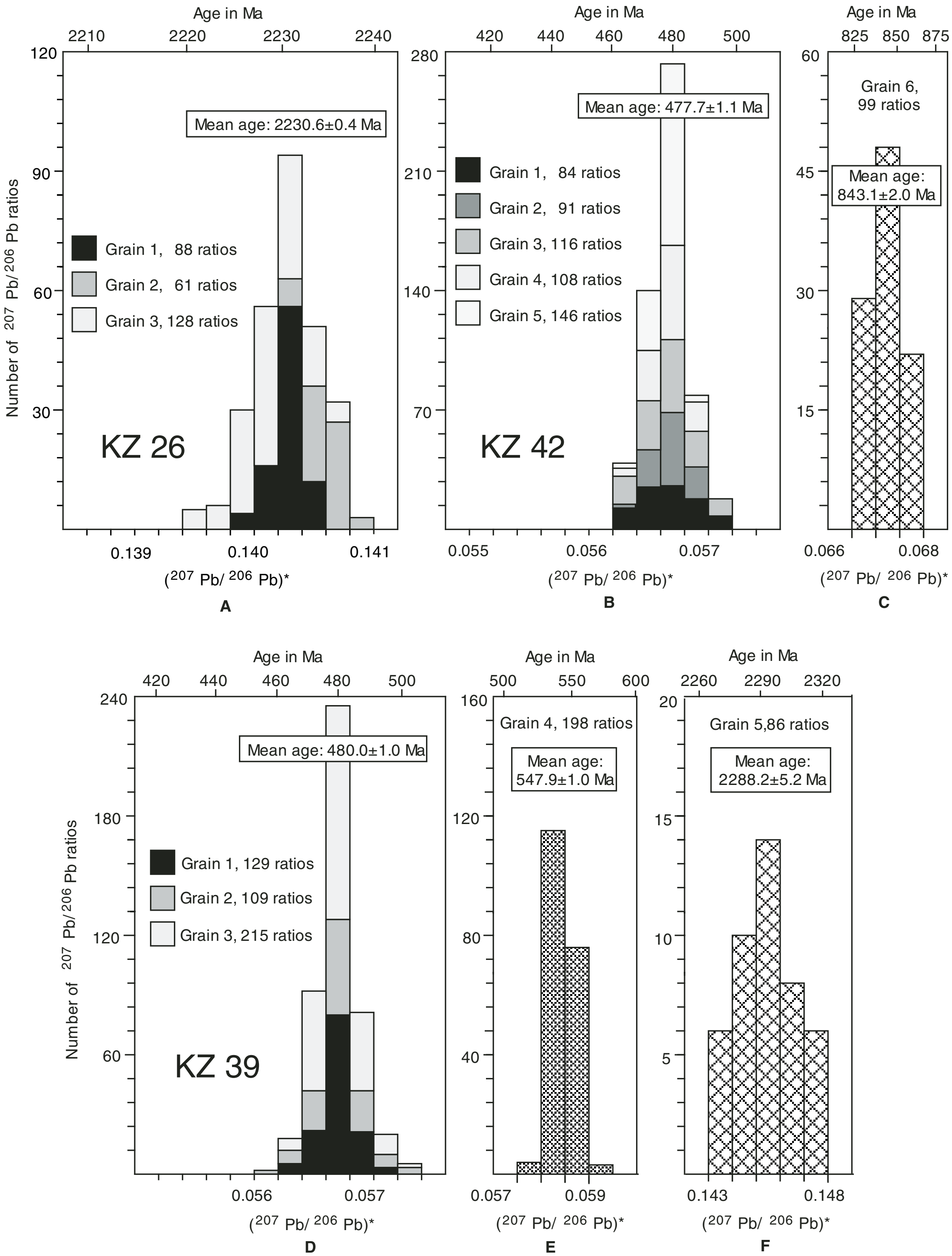

Figure 8. Histograms showing distribution of radiogenic Pb isotope ratios derived from evaporation of single zircons from Paleozoic rocks in southern Kazakhstan. (A) Spectrum for three detrital grains from laminated siltstone sample KZ 26, Kompakty River, Mirny area, integrated from 277 ratios. (B) Spectrum for five grains from metadacite sample KZ 42, north of Chiganak near Lake Balkhash, integrated from 545 ratios. (C) Spectrum for xenocrystic grain from same sample. (D) Spectrum for three grains from arc-related granodiorite sample KZ 39, Chiganak near Lake Balkhash, integrated from 453 ratios. (E–F) Spectra for xenocrystic grains.

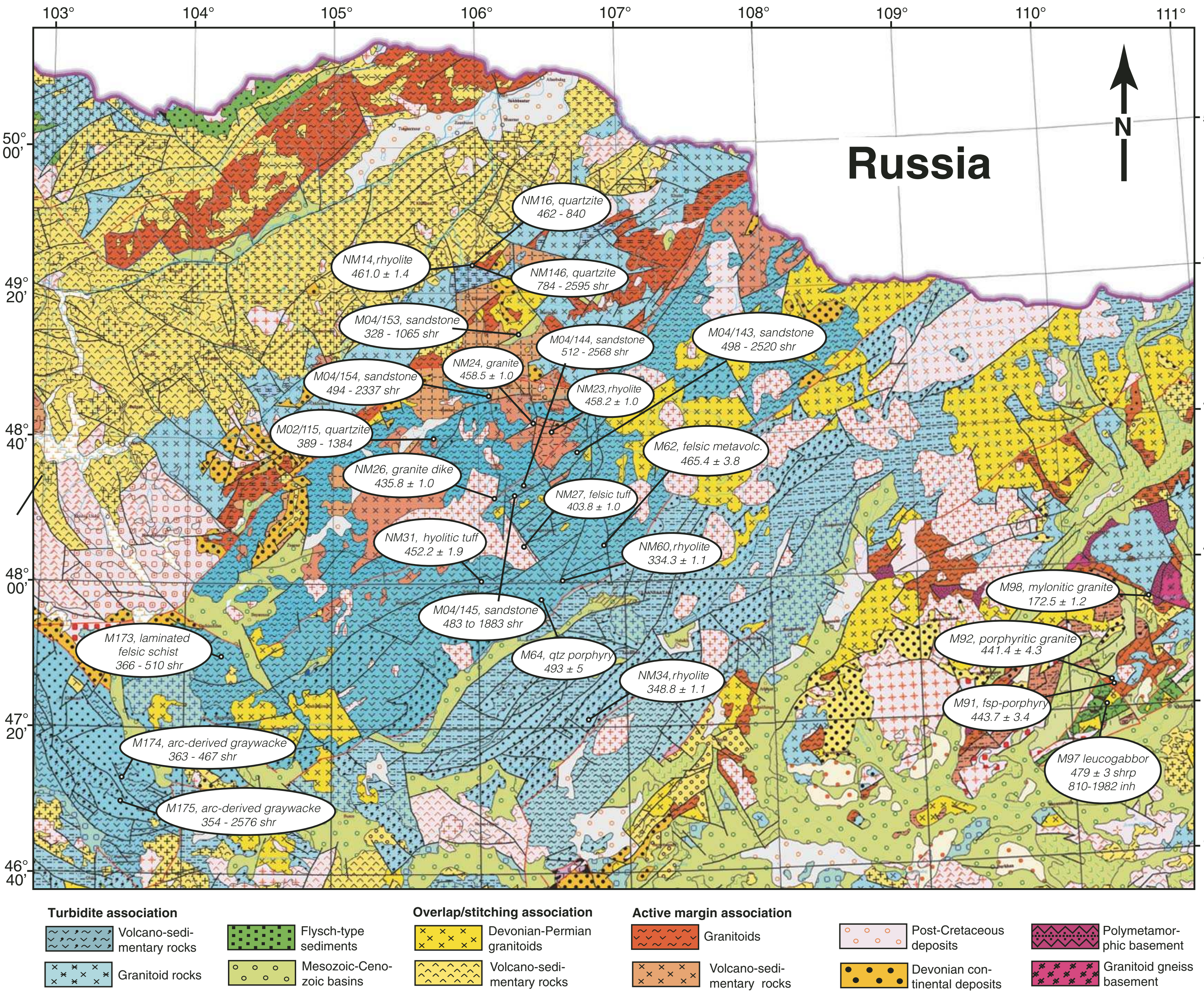

Figure 9. Geological map of part of northern and central Mongolia showing location of dated samples. Ages in Ma. shr—SHRIMP results (other data by zircon evaporation); inh.—ages for inherited zircons. Simplified from Tomurtogoo (1998).

TABLE 5. SUMMARY OF ZIRCON AGES FOR VOLCANIC, GRANITOID, AND SEDIMENTARY ROCKS FROM NORTHERN AND CENTRAL MONGOLIA†

Sample no.	Rock type and location	Zircon age (Ma)	Dating method§
NM 14	Rhyolite, S of Darhan, northern Mongolia	461.0 ± 1.4	Evap.
NM 16	Detrital zircons from quartzite N or Darham, northern Mongolia	462–840	Evap.
NM 23	Rhyolite, NE of Ulaanbaatar	458.2 ± 1.0	Evap.
NM 24	Granite intrusive into arc sequence, NE of Ulaanbaatar	458.5 ± 1.0	Evap.
NM 26	Granite dyke, intrusive into arc sequence, NE of Ulaanbaatar	435.8 ± 1.0	Evap.
NM 27	Felsic tuff, N of Ulaanbaatar	403.8 ± 1.0	Evap.
NM 31	Rhyolitic tuff, N of Ulaanbaatar	452.2 ± 1.9	Evap.
NM 34	Rhyolite from Carboniferous volcanic sequence, S of Ulaanbaatar	348.8 ± 1.1	Evap.
NM 60	Rhyolite, northeastern outscirts of Ulaanbaatar	334.3 ± 1.1	Evap.
M 01/64	Quartz porphyry, Haraa arc sequence W of Ulaanbaatar	493 ± 5	SHRIMP
M 01/91	Feldspar porphyry, arc sequence of Mörön area, east-central Mongolia	443.7 ± 3.4	SHRIMP
M 01/92	Granodiorite, Buteel Range, northern Mongolia	441.4 ± 4.3	SHRIMP
M 01/97	Leucogabbro from Haraa arc sequence, Mörön River, Herlen terrane	479 ± 3	SHRIMP
M 02/115	Detrital zircons from quartzite S of Darhan, northern Mongolia	389–1384	Evap
M 02/134	Migmatitic orthogneiss, Tseel terrane, southern Mongolia	360.5 ± 1.1	Evap.
M 04/143	Detrital zircons from sandstone along Haraa River NE of Darhan	498–2520	SHRIMP
M 04/144	Detrital zircons from Ordovician volcanic sandstone, Haraa terrane	512–2568	SHRIMP
M 04/145	Detrital zircons from Ordovician volcanic sandsatone, Haraa terrane	483–1883	SHRIMP
M 04/146	Detrital zircons from Eocambrian quartzite S of Darhan, northern Mongolia	784–2595	SHRIMP
M 04/153	Detrital zircons from early Carboniferous sandstone, northern Mongolia	328–1065	SHRIMP
M 04/154	Detrital zircons from Ordovician sandstone N of Baruun	494–2337	SHRIMP

†Data of A Kröner, B.F. Windley and G. Badarch, personal communication.

§SHRIMP (sensitive high-resolution ion microprobe)—U/Pb single grain age with 2σ error; Evap.—single grain evaporation $^{207}Pb/^{206}Pb$ age with 2σ (mean) error.

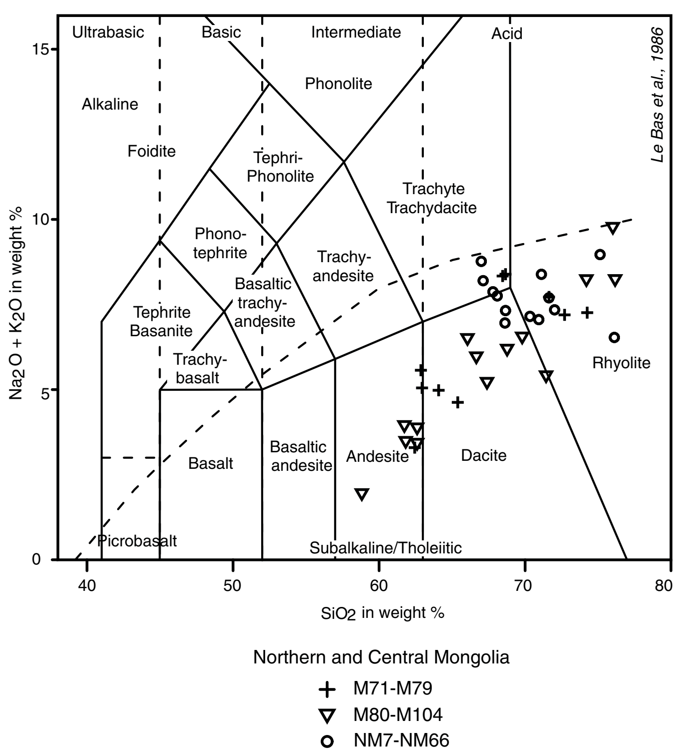

Figure 10. Le Bas et al. (1986) plot of volcanic rocks from northern and central Mongolia. Unpubl. data of A. Kröner, B.F. Windley, and G. Badarch.

of sedimentary transport as well as mostly red to red-brown, strongly abraded, well-rounded to spherical grains. As expected, the euhedral zircons were the youngest, and evaporation of two grains from sample M 02/115 provided a mean $^{207}Pb/^{206}Pb$ age of 389.3 ± 1.4 Ma (Table 5; Fig. 14F), whereas the youngest grain in sample NM 16 has a $^{207}Pb/^{206}Pb$ age of 462.2 ± 1.2 Ma (Table 5; Fig. 14A). It follows from these data that the depositional age of the quartzite must be younger than 389 Ma, presumably middle Devonian. The remaining detrital grains display various degrees of rounding, and the $^{207}Pb/^{206}Pb$ ages range from 812 to 1384 Ma (Table 5; Fig. 14), suggesting detrital input into the Darhan sediments from ancient continental sources. SHRIMP dating of further detrital grains from sample M 04/146 produced ages varying between 784 and 2595 Ma (Table 5; Fig. 15D).

The area along the Haraa River northeast of Darhan is composed of basaltic, andesitic, and dacitic metavolcanic rocks of presumed early Paleozoic age, interlayered with volcanic-derived sandstone, siltstone, and shale. Our sample M 04/143 (location in Fig. 9) is a greenish sandstone, and the detrital zircons are almost exclusively well rounded. SHRIMP (non-representative) reconnaissance dating revealed a large variation in ages with the youngest, idiomorphic grain at 498 ± 4 Ma and the remaining grains varying between 1693 and 2520 Ma (Table 5; Fig. 15A). An Ordovician depositional age is therefore likely for this sandstone, compatible with the volcanic rocks of this region (Table 5). Sample M 04/144 is a green sandstone of presumed Cambro-Ordovician age from a volcano-sedimentary sequence similar to M 04/143 but farther to the southwest

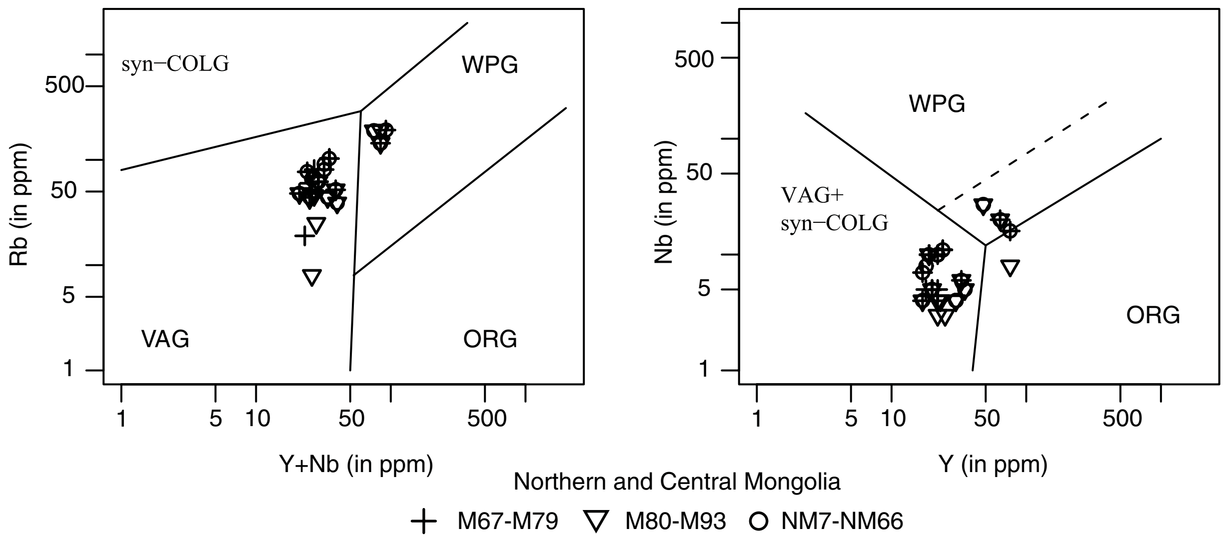

Figure 11. Pearce et al. (1984) plots for northern and central Mongolian rocks. Data as in Figure 10. VAG—volcanic arc granite; ORG—organic granite; WPG—within-plate granite; syn-COLG—syncollisional granite.

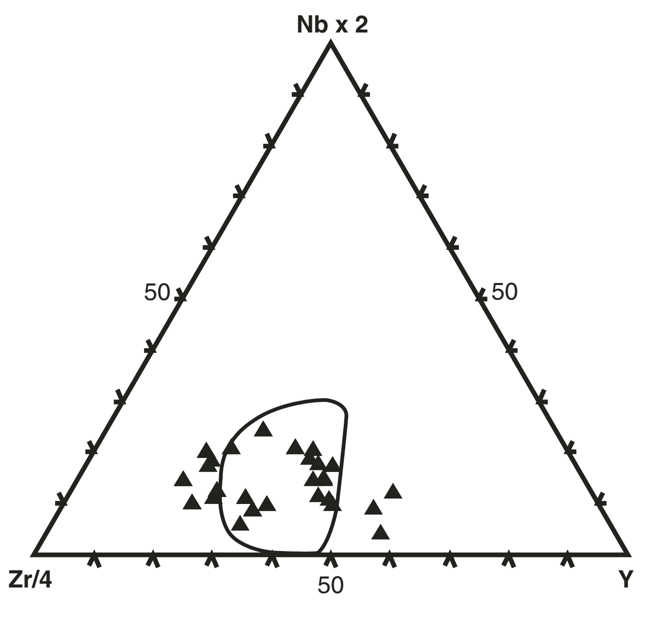

Figure 12. Nb-Zr-Y discrimination plot of Meschede (1986) showing position of northern and central Mongolian arc volcanics and arc-derived sediments (unpublished data of A. Kröner, B.F. Windley and G. Badarch). Black line is field of arc-derived rocks from Murphy and MacDonald (1993).

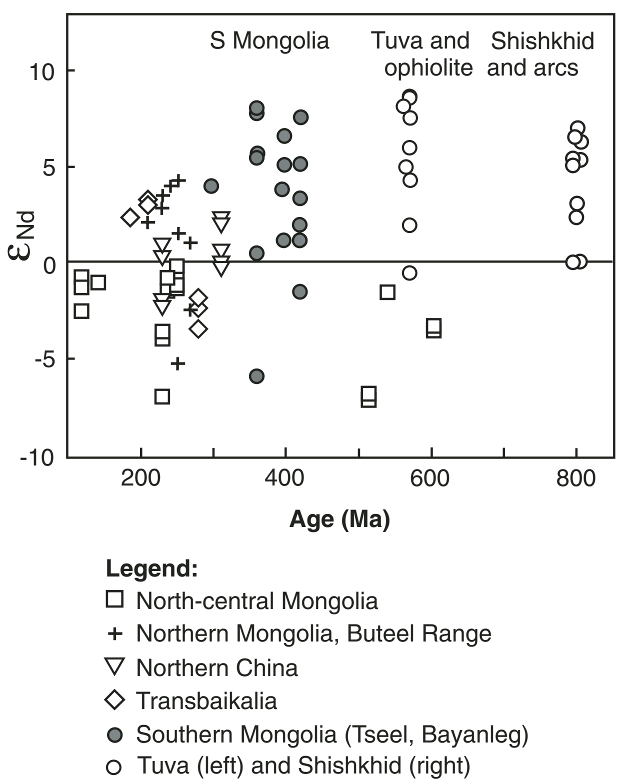

Figure 13. Nd evolution diagram for metaigneous and metasedimentary rocks of the Central Asian Orogenic Belt. Data sources: Shishkhid ophiolite and island arc, northern Mongolia—Kuzmichev et al. (2005); Agardagh Tes-Chem ophiolite and arc, Tuva, Siberia—Pfänder and Kröner (2004); northern and central Mongolia—unpublished data of A. Kröner, Jahn et al. (2004); northernmost China—Chen et al. (2000); Transbaikalia—Litvinovsky et al. (2002); southern Mongolia—Helo et al. (2006).

(Fig. 9). The detrital zircon population is also similar, and two euhedral grains yielded concordant ages of 512 ± 48 and 556 ± 4 Ma, whereas the well-rounded remaining grains range in age from 790 to 2568 Ma (Table 5; Fig. 15B). This sample is therefore also compatible with an early Paleozoic depositional age and contains a record of substantial Precambrian continental input. Lastly, volcanic sandstone sample M 04/145 from the same general sequence was collected from a roadcut still farther west near the village of Bornuur (Fig. 8). As before, idiomorphic zircons are rare, and most grains are little to well rounded. SHRIMP dating produced one young, concordant, age of 483 ± 4 Ma, whereas the remaining analyses range in age between 597 and 1883 Ma (Table 5; Fig. 15C). Again these data are compatible with a maximum Ordovician depositional age and substantial Precambrian detrital input.

We also analyzed detrital zircons from a volcanic-derived and fossiliferous early Carboniferous sandstone northeast of Ulaanbaatar (sample M 04/153, Fig. 9). This sample contains numerous clear, euhedral zircons showing virtually no sedimentary transport, and the youngest concordant age of 328 ± 3 Ma (Table 5; Fig. 16A) suggests deposition in the Carboniferous, compatible with the fossil evidence. The remaining grains vary in age between 367 and 1065 Ma (Table 5; Fig. 16A), and here the input of ancient continental material is less pronounced than in the previous samples.

Our last sandstone sample from the early Paleozoic volcano-sedimentary arc assemblage of northern Mongolia comes from an alternating sandstone-shale sequence exposed in a roadcut along the asphalt road just north of Bayangol, 153 km north of Ulaanbaatar (M 04/154, Fig. 9). SHRIMP dating produced concordant ages ranging between 494 and 2337 Ma (Table 5; Fig. 16B), again revealing input of substantial Precambrian material and compatible with an Ordovician depositional age.

Input of ancient material is recorded not only in volcanic-derived arc sediments but also in igneous rocks of the arc sequences. A massive quartz porphyry from a sequence of strongly deformed felsic volcanic rocks west of Ulaanbaatar (sample M 01/64) yielded a mean SHRIMP $^{206}Pb/^{238}U$ age of 493 ± 5 Ma, based on the analysis of five idiomorphic grains, whereas one euhedral zircon has a concordant age of 888 ± 6 Ma (Table 5; Fig. 16C) thus documenting at least some inheritance from the source terrain of the porphyry. A similar example of crustal contamination is provided by a fresh leucogabbro sample (M 01/97) from a sequence of calc-alkaline volcanic rocks exposed on the Mörön River in the Herlen terrane (Fig. 9). The zircons are clear and idiomorphic, and eight concordant SHRIMP analyses provided a mean $^{206}Pb/^{238}U$ age of 479 ± 3 Ma, whereas four additional analyses are discordant but compatible with the above age (Table 5; Fig. 16D). However, three zircons in this sample are xenocrystic and provided ages of 810, 814, and 1982 Ma (Fig. 16D) thus again documenting involvement of older crust in the generation of the gabbro.

The above examples provide strong evidence for the conclusion that early Paleozoic arc magmatism in northern and central Mongolia was not entirely intra-oceanic as previously assumed. This is also supported by whole-rock Sm-Nd isotopic systematics shown in Figure 13.

SOUTHERN MONGOLIA

Ocean crust formation still occurred south of the Main Mongolian Lineament in the early Carboniferous as indicated by a zircon age of 325 Ma for the Adaatsag ophiolite in south-central Mongolia (Tomurtogoo et al., 2005) that we ascribe to opening of the Mongol-Okhotsk ocean. Early to late Carboniferous magmatic activity in the Zam Bilgikh and Transaltai Ranges in the Gobi Desert of southern Mongolia is documented by zircon ages for a variety of granitoid rocks (K. Schulmann and A. Kröner, unpubl. data).

Several terranes of Mongolia containing metamorphic rocks and previously interpreted as Precambrian microcontinents have since been shown to be much younger, and a good example is the Tuva-Mongolian Massif of southern Siberia and northwestern Mongolia (Salnikova et al., 2001; Kozakov et al., 2005). The Tseel terrane in southern Mongolia (Fig. 17) is another example and consists of low-grade Early Devonian arc volcanics in the north dated at ca. 397 Ma (Kröner, Badarch and Windley, unpubl. data) (Fig. 17), which grade into successively higher-grade assemblages to the south with amphibolite-facies migmatitic gneisses (deformed arc granitoids), one of which (M 02/134, Fig. 17) was dated at 360.5 ± 1.1 Ma (Table 3; Fig. 18). Rare granulite-facies rocks may correlate with a similar high-grade assemblage in the Tsogt block farther west for which Kozakov et al. (2002) obtained a metamorphic age of 365 Ma. We interpret these high-grade rocks as representing the root zone of an arc system.

From southern Mongolia, Lamb and Badarch (1997) described a variety of Devonian and Carboniferous volcanic arcs ranging from submerged island arcs, mature oceanic arcs, and continental margin arcs. Helo et al. (2006) presented geochemical and Nd isotopic data for metaigneous and metavolcaniclastic rocks from a variety of ca. 470–290 Ma island-arc assemblages in the Gurvan Sayan and Zoolen Ranges, in order to define their tectonic environments and their mode of crustal generation. These arc terranes formed during the last phases of the evolution of the Central Asian Orogenic Belt. The whole-rock geochemical data are consistent with an origin in juvenile intra-oceanic arc/forearc and backarc settings. However, the remarkably wide range of initial ε_{Nd} values of ~+8 to –6 indicates the presence of juvenile crust as well as much older material with mean crustal residence ages up to 1.5 Ga, and some Nd isotopic data indicate derivation of the host volcanic rocks from a variably rejuvenated Paleoproterozoic crustal domain (Helo et al., 2006). Our unpublished detrital zircon ages from arc-derived sediments in southern Mongolia (A. Kröner, M.T.D. Wingate, A. Demoux, G. Badarch) support this view (Fig. 17), and all these data convincingly demonstrate that the crust of the Central Asian Orogenic Belt in southern

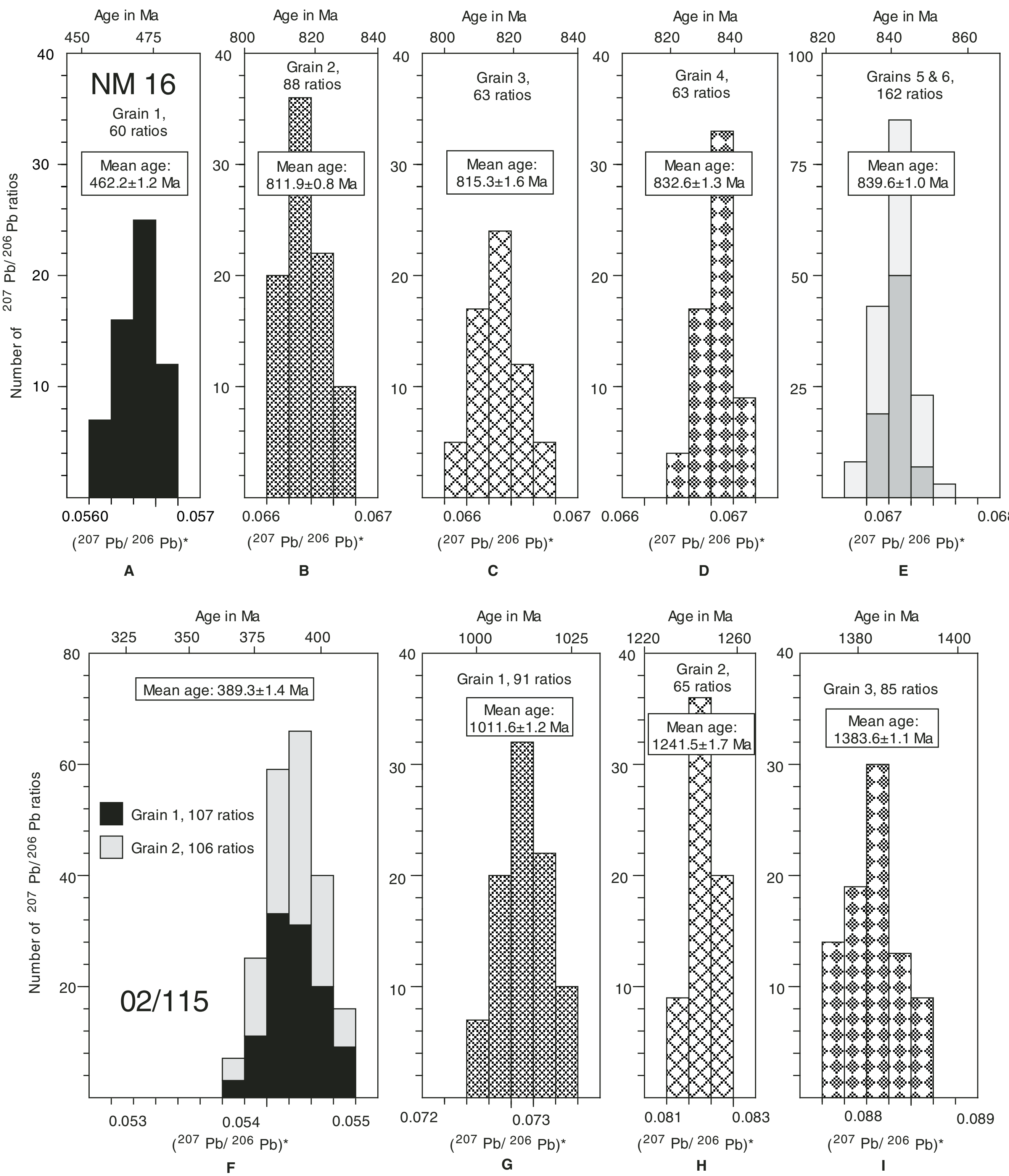

Figure 14. Histograms showing distribution of radiogenic Pb isotope ratios derived from evaporation of detrital zircons from two quartzite samples, quarry south of Darhan, northern Mongolia. (A–E) Zircons from sample NM 16. (F–I) Zircons from sample M 02/115. The spectra have been integrated from ratios as shown for each diagram. Mean ages are given with 2σ (mean) errors.

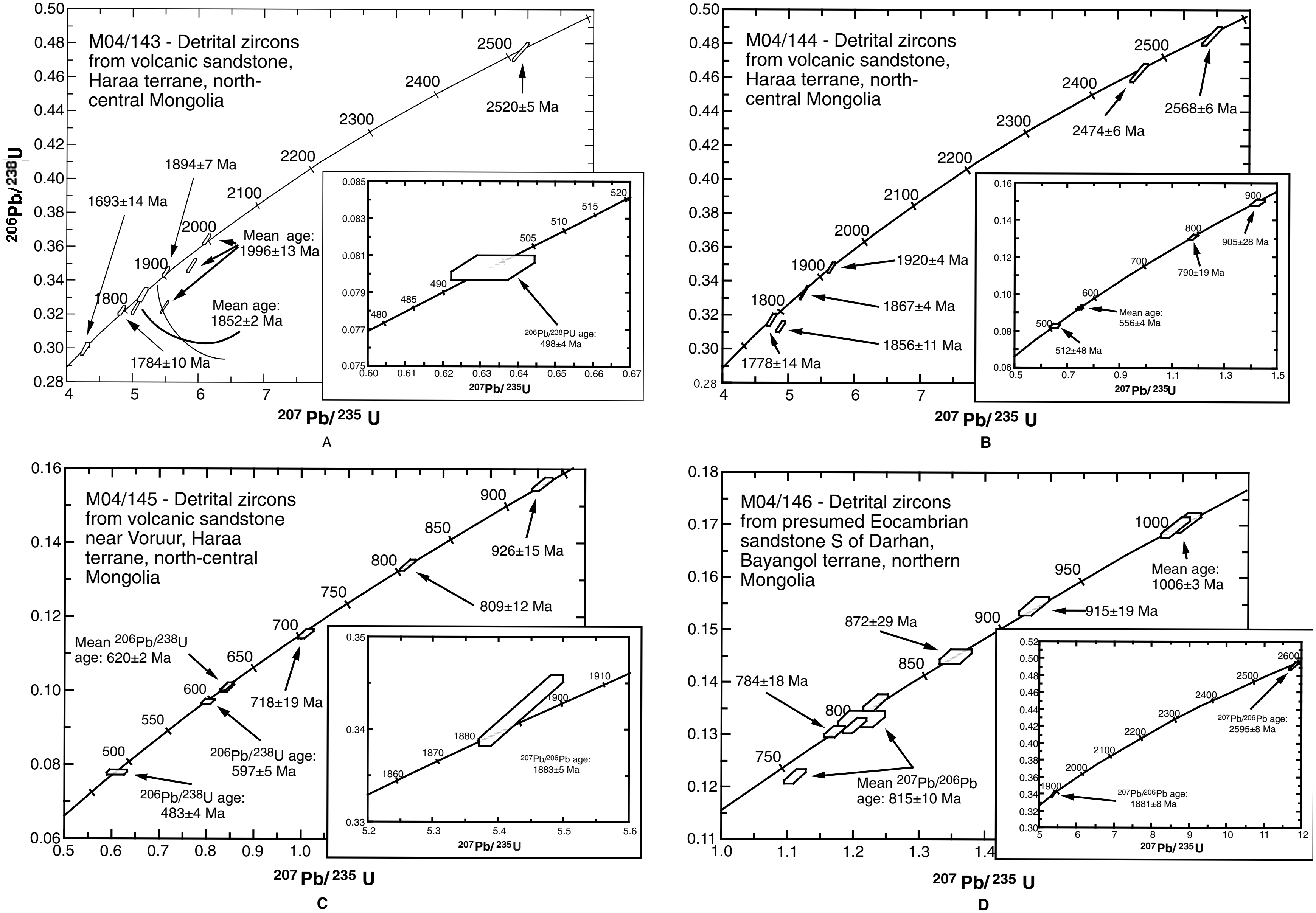

Figure 15. Concordia diagrams showing SHRIMP analyses of detrital zircons from Paleozoic sediments in northern and central Mongolia. Data boxes for each analysis are defined by standard errors in ^{207}Pb/^{235}U, ^{206}Pb/^{238}U, and ^{207}Pb/^{206}Pb. (A) Volcanic sandstone sample M 04/143, Haraa terrane. (B) Volcanic sandstone sample M 04/144, Haraa terrane. (C) Volcanic sandstone sample M 04/145, Haraa terrane. (D) Quartzite sample M 04/146, Bayangol terrane.

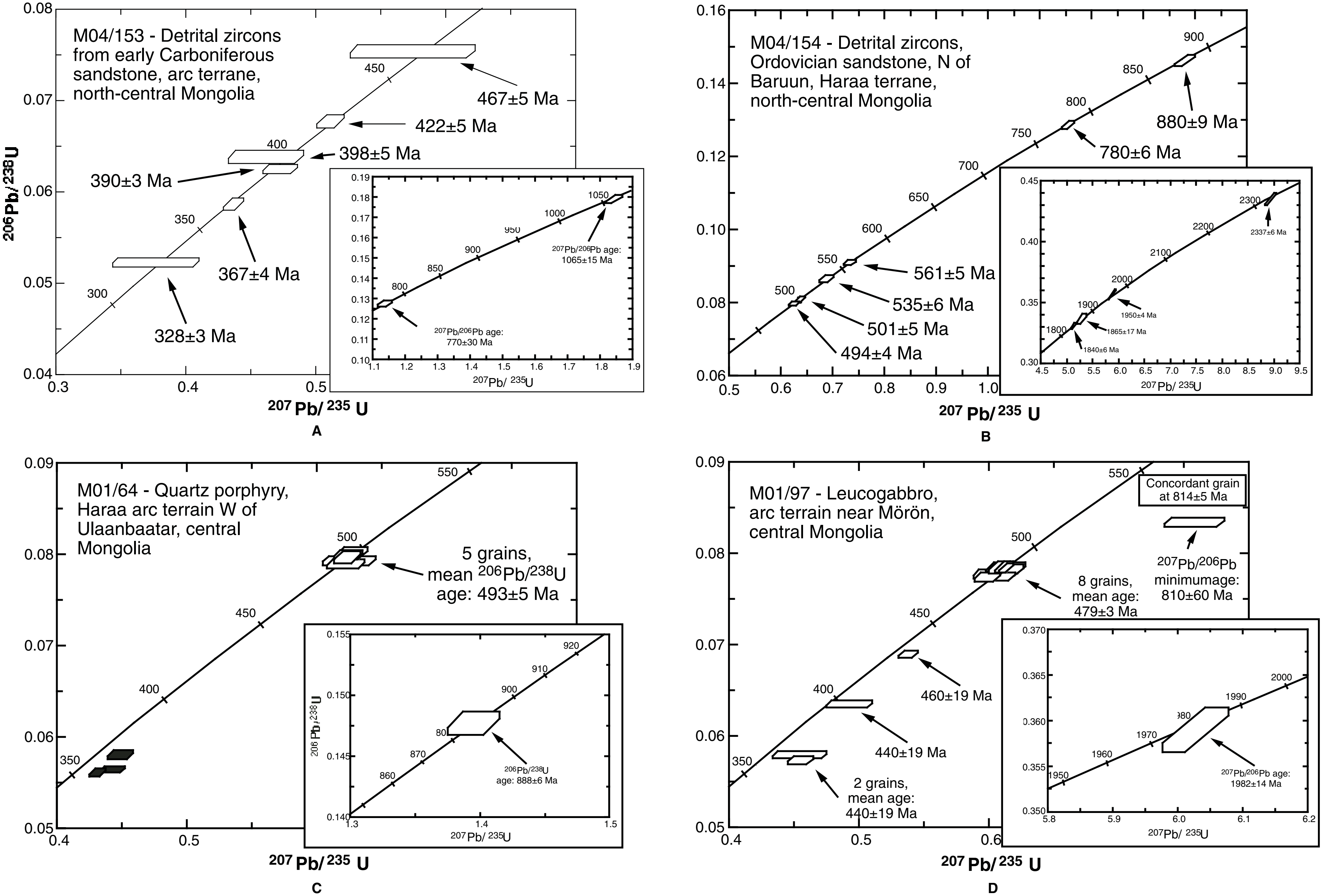

Figure 16. Concordia diagrams showing SHRIMP analyses of detrital zircons from Paleozoic arc-related sediments and magmatic rocks in northern and central Mongolia. Data boxes as in Figure 15. A: Sandstone sample M 04/153, Haraa terrane. B: Sandstone sample M 04/154, Haraa terrane. C: Quartz porphyry sample M 01/64, Haraa terrane. D: Leucogabbro sample M 01/97, Herlen terrane.

Mongolia has an isotopically highly heterogeneous composition. Helo et al. (2006) speculated that a juvenile arc and backarc system was tectonically juxtaposed with a rejuvenated Paleoproterozoic microcontinent, a situation similar to that envisaged for Kazakhstan by Bykadorov et al. (2003). There appear to be only few areas in the orogenic belt where $\varepsilon_{Nd}(t)$ values are consistently positive and as high as +8, and the Junggar terrane in the Xinjiang province of northwestern China is one of them (Chen and Jahn, 2004).

ARABIAN-NUBIAN SHIELD

The Arabian-Nubian shield is a wide Neoproterozoic accretionary orogen at the northern end of the East African orogen (Kröner and Stern, 2005). It consists of continental-margin as well as intra-oceanic arc terranes and a few continental fragments containing Archean and Paleoproterozoic rocks. Magmatic terranes began to form at ca. 870 Ma, and terrane amalgamation was completed by ca. 600 Ma (for recent summary see Johnson and Woldehaimanot, 2003, and references therein). Reymer and Schubert (1987) calculated extraordinarily high crust-production rates for the shield, assuming that most of the arc-related rocks were juvenile, as suggested by low $^{87}Sr/^{86}Sr$ initial isotopic ratios and positive $\varepsilon_{Nd}(t)$ values. These rates are comparable, or even higher, than those proposed for the Central Asian Orogenic Belt by Şengör et al. (1993).

Recent SHRIMP dating of felsic metavolcanic and granitoid rocks from the northern Arabian arc sequences (Fig. 19) (Kennedy et al., 2004, 2005; Hargrove et al., 2006) reveals zircon age patterns similar to the Mongolian felsic rocks. The majority of zircons in these samples are idiomorphic and constitute concordant clusters, interpreted to reflect the age of magmatism (Kennedy et al., 2004, 2005) (Fig. 20). In addition, a variable number of grains, in some cases characterized by variously rounded morphologies, exhibit substantially older ages (Fig. 20), in one case up to 2750 Ma, and these are interpreted as xenocrysts derived from an older basement (Kennedy et al., 2004, 2005; Hargrove et al., 2006). All these rocks reflect various proportions of crustal input and are therefore unlikely to be entirely juvenile. Hargrove et al. (2006) were puzzled by the fact that their trace element and Nd isotopic signatures are primitive and speculated that large volumes of juvenile arc magmas could perhaps melt enough older crust to inherit xenocrystic zircons, yet retain their original arc and isotopic characteristics. Whatever the cause of zircon inheritance in the Arabian-Nubian shield rocks, it would appear that there was more old crust around than previously thought, and previous estimates for crust-production rates are almost certainly too high.

DISCUSSION AND CONCLUSIONS

The above zircon ages show that there appear to be remarkable similarities between the Central Asian Orogenic Belt and the Arabian-Nubian shield, but the origin of ancient xenocrysts in seemingly juvenile arc-derived rocks remains enigmatic. We point out that the term "juvenile crust" cannot be defined precisely on the basis of Nd isotopic systematics alone. Even rocks with positive $\varepsilon_{Nd}(t)$ values may contain ancient crustal material, as shown for some of our samples from Kazakhstan and Mongolia and as demonstrated for the shield by Kennedy et al. (2004, 2005) and Hargrove et al. (2006). It is the proportion of mantle-derived material versus material resulting from crustal recycling that counts, and such estimates contain a large degree of uncertainty (e.g., Jahn et al., 2004). The high crust-production rates suggested for the orogenic belt and the shield were based on the simplistic assumption that most arc-derived rocks were juvenile, whereas more realistic estimates imply significantly lower growth rates.

The Central Asian Orogenic Belt and the Arabian-Nubian shield have frequently been compared to the present southwest Pacific where ancient crustal fragments derived from Australia occur together with juvenile crust produced by subduction-related magmatism, seafloor spreading, and ocean plateau formation (Hall, 2002). This region, once accreted to Asia and caught up in the collision between Asia and Australia in ~50 m.y. from now, will probably look rather similar to the orogenic belt.

There have been some misconceptions about the role of granitic rocks (sensu lato) in the Central Asian Orogenic Belt. Şengör et al. (1993) considered that the subduction-accretion complexes of the Altaids were intruded by vast (granitic) plutons of mainly magmatic arc origin, and that half of these complexes, including the granitic rocks, were of juvenile origin. However, they failed to distinguish the relatively few granitic rocks in mature island arcs from the vast majority that can be broadly termed "crustal-melt granites." For example, granitic rocks occupy more than 40% of the present surface area of the Chinese Altai, and most of these are posttectonic and garnet-bearing (Windley et al., 2002). From their Sm-Nd isotopic study of granitic rocks in several parts of the orogenic belt, Jahn et al. (2000) concluded that the majority are of juvenile origin, "implying a massive addition of new continental crust." However, these crustal-melt granitic rocks are only a proxy for the juvenile arcs that are the main component of the Central Asian Orogenic Belt. The granites are surrounded by, and presumably underlain by, juvenile arc-dominated rocks from which granitic material was derived by partial melting.

There are two different scenarios to explain the generation of silicic magmas. The first is where felsic magmas are derived from a basaltic reservoir by fractional crystallization, or assimilation combined with fractional crystallization (AFC). This generally produces relatively small magma batches, such as those described from seafloor eruptions (Fiske et al., 2001), because to generate large volumes of felsic magmas, unreasonably large amounts of basalt must first be crystallized (Riley et al., 2001). The second scenario is a continental margin where basaltic underplating provides heat for partial melting of crustal rocks, and this is considered more appropriate for large-volume felsic magma bodies such as the Sierra Madre Occidental in Mexico, the Choiyoi province of the Chilean Andes, and the large rhyolite

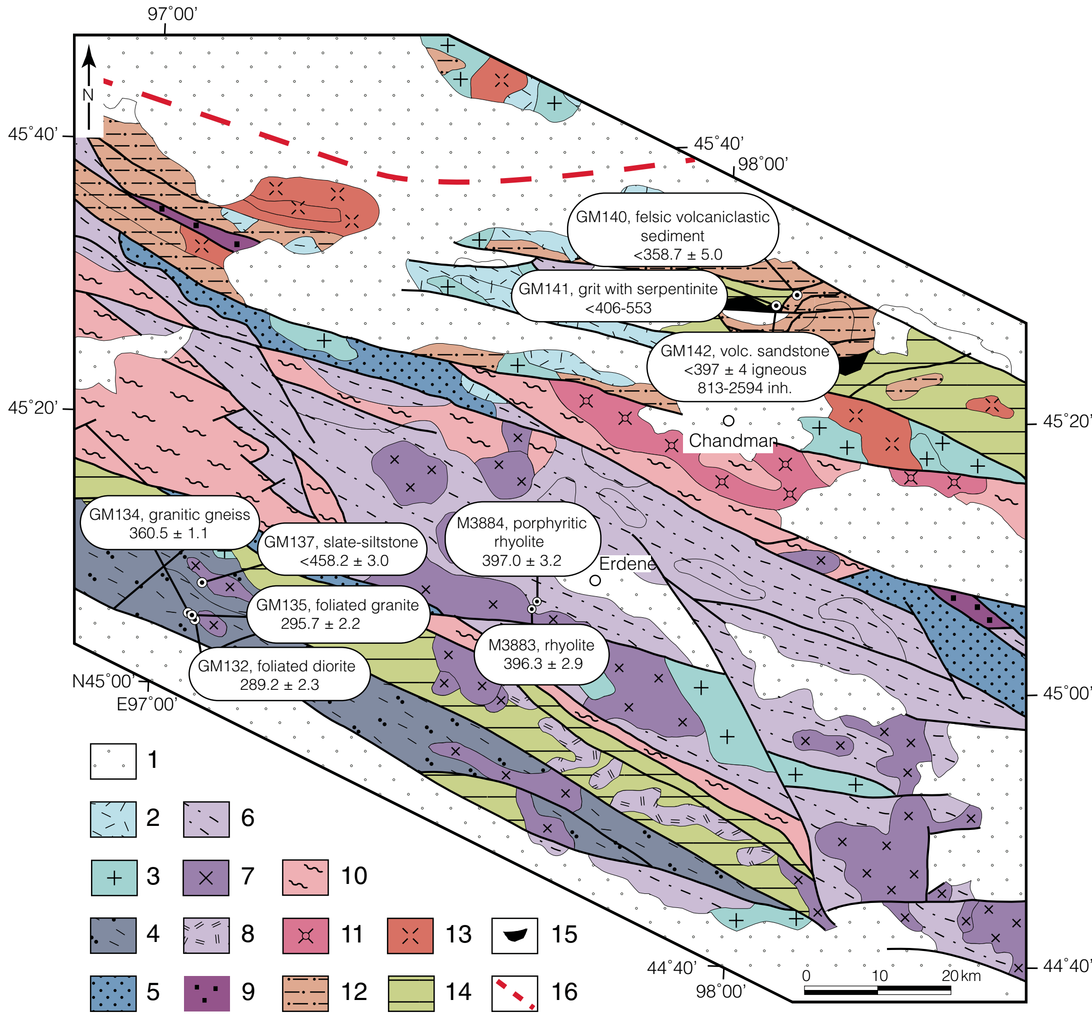

Figure 17. Geological map of the Tseel terrane of southern Mongolia, showing location of dated samples. Ages in Ma. shr—SHRIMP results (other data by zircon evaporation); inh.—ages for inherited zircons. Simplified from Tomurtogoo (1998), sheet L-47. 1—Mesozoic-Quaternary cover; 2—Permian volcanic rocks; 3—Permian granite; 4—Late Carboniferous–Early Permian metavolcano-sedimentary rocks; 5—Early Carboniferous metasediments; 6—Devonian volcano-sedimentary sequence; 7—Middle Devonian granite; 8—Early Devonian volcanic rocks; 9—Silurian volcanogenic rocks; 10—Ordovician metavolcanic rocks; 11—Ordovician granodiorite; 12—early Cambrian volcanogenic schist; 13—Cambrian quartz diorite; 14—Neoproterozoic metasediments; 15—ultramafic mélange; 16—Main Mongolian Lineament.

province in the Antarctic Peninsula and Patagonia (Riley et al., 2001, and references therein).

The latter setting also seems applicable to the Central Asian Orogenic Belt of central and northern Mongolia that was stabilized into a continental margin by early Ordovician time. We suggest that the large volume of predominantly felsic magmatic rocks generated in Ordovician and Silurian times resulted from mixing between a fractionated mafic underplate and partial melts of the previously stabilized lower continental margin crust that consisted predominantly of Neoproterozoic to Cambrian rocks. Therefore, many silicic rocks show apparent juvenile Nd isotopic signatures and model ages up to ca. 1100 Ma (Jahn et al., 2004; Kovalenko et al., 2004; our data for northern Mongolia; see Table 4). The Mongolian felsic rocks have trace element characteristics of subduction-related magmas that are probably inherited from their source. Riley et al. (2001) observed that “water-assisted” generation of partial melts will occur across a broad region adjacent to an evolving arc, and the crust overlying the subduction zone will, over a period of time, become extensively intruded by hydrous, mantle-derived magmas. A large proportion of such magmas will

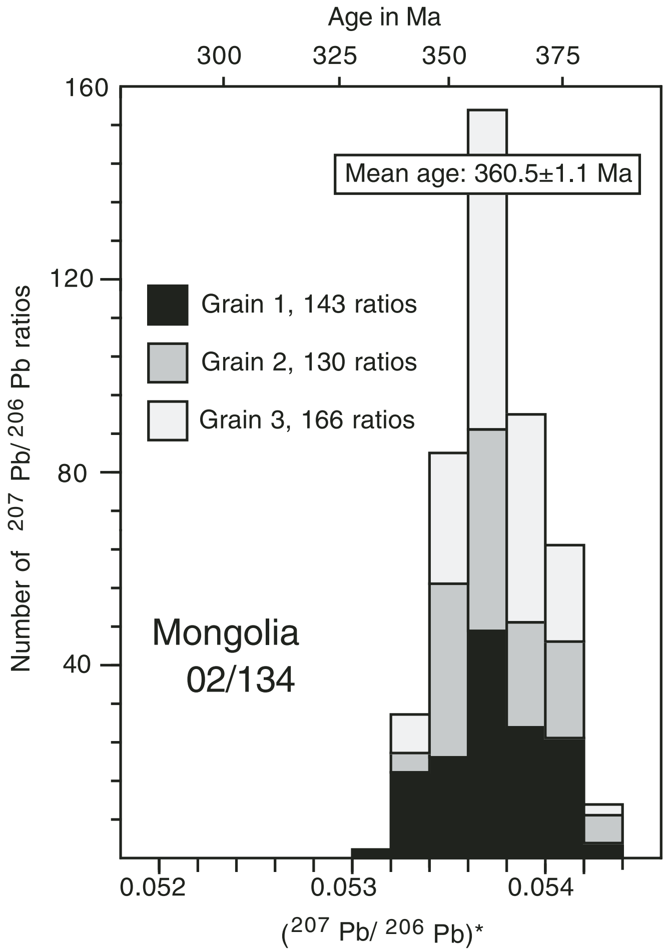

Figure 18. Histogram showing distribution of radiogenic Pb isotope ratios derived from evaporation of three zircon grains from granitic gneiss sample M 02/134, Tseel terrane, southern Mongolia. The spectrum plotted has been integrated from 439 ratios.

Figure 19. Terrane map of the Arabian part of the Arabian-Nubian shield showing major tectonic units (from Johnson, 1998). Magmatic rocks displaying variable degrees of crustal contamination as reported by Kennedy et al. (2004, 2005) occur in the Hijaz, Afif, Ad Dawadimi, and Asir terranes. Considerable inheritance is also described from the Jiddah and Hijaz terranes by Hargrove et al. (2006). f.z.—fracture zone.

collect in the lower crust, generating a hydrous, amphibole-rich mafic layer. We follow this model and suggest that such conditions were initiated in the Early Ordovician, or possibly earlier, through north-dipping subduction of oceanic lithosphere of the evolving Paleo-Asian ocean underneath the relatively young continental margin growing southwards away from the Siberian craton.

We thus agree with Şengör and Natal'in (1996) and Jahn et al. (2004) that juvenile crust formation in the Central Asian Orogenic Belt was considerable, but there was also a significant amount of remelting of older, Archean to earliest Paleozoic crust, to produce the large Ordovician to Permian felsic volcanic province observed in Mongolia and Kazakhstan. Therefore, crust production was spread over a longer time-span than previously estimated, and crust-production rates were not as high as assumed by Şengör and Natal'in (1996). As a corollary, the available ages and geochemical data for the orogenic belt make it unlikely that this vast accretionary belt was derived from one single, giant arc, and we favor a southwest Pacific-type scenario for its origin.

ACKNOWLEDGMENTS

Most of this paper was written while the senior author held a Gledden Visiting Fellowship at the University of Western Australia, and discussions with members of the Tectonics Special Research Centre (TSRC) are appreciated. This is part of a collaborative study with the Mongolian Academy of Sciences, funded by the Volkswagen Foundation of Germany Grant I/76399. Our work in Kazakhstan was funded by the German Science Foundation (DFG). We thank Dmitry Alexeiev (Moscow) for providing Figure 3, Table 1, and information on Kazakhstan geology. Peter Johnson (Jeddah) made available an Open-File Report of the Saudi Arabian Geological Survey and Figure 19, and Ulysses Hargrove (Dallas) provided Figure 20B. Kent Condie and Bob Hatcher helped with constructive reviews. Many of the zircon analyses were carried out on the sensitive high-resolution ion microprobe mass spectrometer in Perth (SHRIMP II), operated by a consortium consisting of Curtin University of Technology,

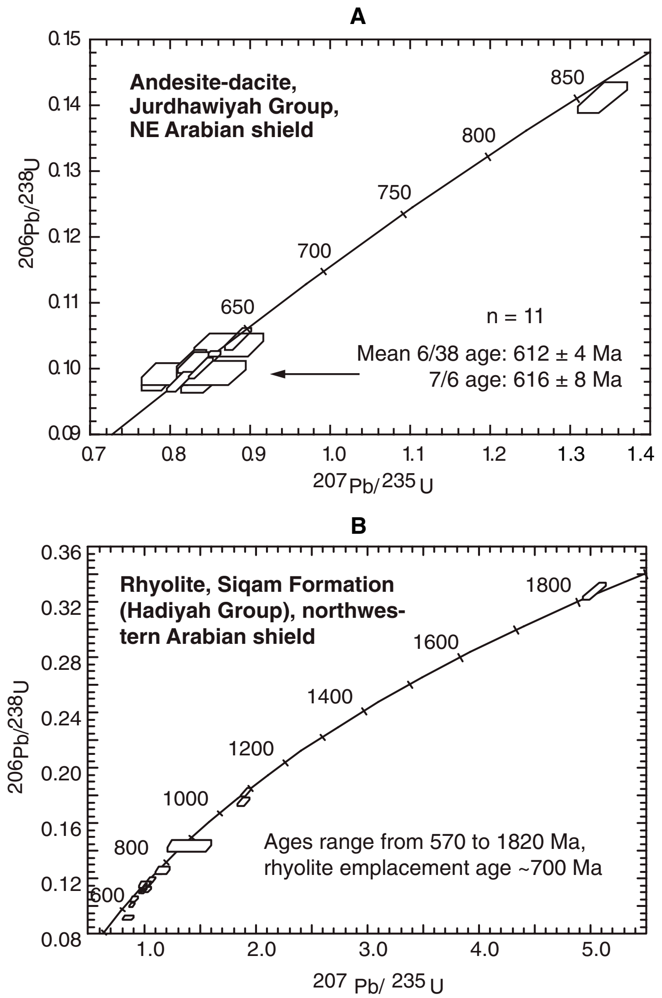

Figure 20. Concordia diagrams showing SHRIMP zircon analyses from Neoproterozoic felsic volcanic rocks of the northern Arabian shield. (A) Age pattern for an andesite-dacite sample, reproduced from Figure 2 of Kennedy et al. (2004). (B) Age pattern for a rhyolite sample, reproduced from Figure 27 of Kennedy et al. (2004).

the Geological Survey of Western Australia, and the University of Western Australia with the support of the Australian Research Council. This is TSRC publication number 364, publication number 50 of the Geocycles Cluster of Mainz University, and a contribution to the ERAS-Project of the International Lithosphere Program and to IGCP Project 480.

REFERENCES CITED

Abdulin, A.A., Avdeev, A.V., and Seitov, N.S., 1995, On the study of microcontinents and ophiolite zones in Kazakhstan: ESRI Occasional Publications, New Series No. 12B, University of South Carolina, USA, p. 97–112.

Alexyutin, M.V., Bachtadse, V., Alexeiev, D.V., and Nikitina, O.I., 2005, Paleomagnetism of Ordovician and Silurian rocks from the Chu-Yili and Kendyktas Mountains, South Kazakhstan: Geophysical Journal International, v. 161, p. 1–12.

Almukhamedov, A.I., Gordienko, I.V., Kuzmin, M.I., Tomurtogoo, O., and Tomurkhuu, D., 2002, Boninites of the Dzidha Caledonide zone, northern Mongolia: Transactions of the Russian Academy of Sciences, v. 377, p. 526–529.

Anonymous, 1972, Penrose field conference on ophiolites: Geotimes, v. 17, p. 24–25.

Avdeev, A.V., 1984, Ophiolite zones and the geologic history of Kazakhstan from the mobilist standpoint: International Geological Review, v. 26, p. 995–1005.

Avdeev, A.V., Khalilov, V.A., Seliverstov, V.A., Ilin, L.I., and Tsygankov, A.I., 1995, New data on geochronology of metamorphic and magmatic formations of South Kazakhstan: Geology and Exploration in Kazakhstan, v. 4, p. 2–6.

Badarch, G., Cunningham, W.D., and Windley, B.F., 2002, A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia: Journal of Asian Earth Sciences, v. 21, p. 87–104.

Bazhenov, M.L., Collins, A.Q., Degtyarev, K.E., Levashova, N.M., Mikolaichuk, A.V., Pavlov, V.E., and Van der Voo, R., 2003, Paleozoic northward drift of the North Tien Shan (Central Asia) as revealed by Ordovician and Carboniferous paleomagnetism: Tectonophysics, v. 366, p. 113–141, doi: 10.1016/S0040-1951(03)00075-1.

Berzin, N.A., and Dobretsov, N.L., 1994, Geodynamic evolution of southern Siberia in late Precambrian–early Paleozoic time, *in* Coleman, R.G., ed., Reconstruction of the Paleo-Asian Ocean: Proceedings of the 29th International Geological Congress, part B: Utrecht, VSP Publishers, p. 53–70.

Bryan, S.E., Riley, T.R., Jerram, D.A., Stephens, C.J., and Leat, P.T., 2002, Silicic volcanism: An undervalued component of large igneous provinces and volcanic rifted margins, *in* Menzies, M.A., et al., eds., Volcanic rifted margins: Geological Society of America Special Paper 362, p. 99–120.

Buchan, C., Cunningham, D., Windley, B.F., and Tomurhuu, D., 2001, Structural and lithological characteristics of the Bayankhongor ophiolite zone, central Mongolia: Geological Society [London] Journal, v. 158, p. 445–460.

Buslov, M.M., Saphonova, I.Yu., Watanabe, T., Obut, O., Fujiwara, Y., Iwata, K., Semakov, N.N., Sugai, Y., Smirnova, L.V., and Kazansky, A.Yu., 2001, Evolution of the Paleo-Asian ocean (Altay-Sayan region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent: Geosciences Journal, v. 5, p. 203–224.

Byamba, J., 1996, Tectonics of old structures and phosphates of Mongolia: Joint Soviet-Mongolian Scientific Research Geological Expedition, Transactions, v. 57, 179 p.

Bykadorov, V.A., Bush, V.A., Fedorenko, O.A., Filippova, I.B., Miletenko, N.V., Puchkov, V.N., Smirnov, A.V., Uzhkenov, B.S., and Velozh, Y.A., 2003, Ordovician-Permian Palaeogeography of central Eurasia: Development of Paleozoic petroleum-bearing basins: Journal of Petroleum Geology, v. 26, p. 325–350, doi: 10.1111/j.1747-5457.2003.tb00033.x.

Chakabaev, S.E., chief editor, 1979, Geological map of Kazakh SSR, Southern Kazakhstan series: Leningrad, USSR, Aerogeologiya Map Enterprise, scale 1:500,000.

Chen, B., and Jahn, B.-M., 2004, Genesis of post-collisional granitoids and basement nature of the Junggar terrane, NW China: Nd-Sr isotope and trace element evidence: Journal of Asian Earth Sciences, v. 23, p. 691–703, doi: 10.1016/S1367-9120(03)00118-4.

Chen, B., Jahn, B.-M., Wilde, S., and Xu, B., 2000, Two contrasting Paleozoic magmatic belts in northern Inner Mongolia, China: Petrogenesis and tectonic implications: Tectonophysics, v. 328, p. 157–182, doi: 10.1016/S0040-1951(00)00182-7.

Coleman, R.G., 1989, Continental growth of northwest China: Tectonics, v. 8, p. 621–635.

Collins, A.Q., Degtyarev, K.E., Levashova, N.M., Bazhenov, M.L., and Van der Voo, R., 2003, Early Paleozoic paleomagnetism of east Kazakhstan: Implications for paleolatitudinal drift of tectonic elements within the Ural-Mongol belt: Tectonophysics, v. 377, p. 229–247, doi: 10.1016/j.tecto.2003.09.003.

Degtyarev, K.E., and Ryazantsev, A.V., 2007, Cambrian arc-continent collision in the Paleozoides of Kazakhstan: Geotectonics, v. 41, p. 63–86 (translated from Russian).

DePaolo, D.J., 1981, A Nd and Sr isotopic study of Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California: Journal of Geophysical Research, v. 86, p. 10370–10488.

Dobretsov, N.L., Buslov, M.M., and Vernikovsky, V.A., 2003, Neoproterozoic to Early Ordovician evolution of the Paleo-Asian ocean: Implications to the break-up of Rodinia: Gondwana Research, v. 6, p. 143–159, doi: 10.1016/S1342-937X(05)70966-7.

Donskaya, T.V., Sklyarov, E.V., Gladkochub, D.P., Mazukabzov, A.M., Sal'nikova, E.B., Kovach, V.P., Yakovleva, S.Z., and Berezhnaya, N.G., 2000, The Baikal collisional metamorphic belt: Transactions (Doklady) of the Russian Academy of Sciences, Earth Science Section, v. 372, p. 1075–1079.

Eganov, E.A., and Sovetov, Yu.K., 1979, Karatau—A model for phosphorite deposition: Novosibirsk, Nauka Publishing House, Transactions of the Institute of Geology and Geophysics, Siberian Branch, USSR Academy of Sciences, v. 427, 190 p. (in Russian with English abstract).

Fedorenko, O.A., and Militenko, K., editors, 2002, Atlas of lithological, paleogeographic, structural, palinspastic, and geoecologic maps of central Eurasia: Almaty, Yuggeo.

Fedorovsky, V.S., 1997, Domic tectogenesis in the Caledonides collisional system in the western Near Baikal area: Geotectonics, v. 6, p. 56–71.

Fedorovsky, V.S., 2004, Geological map of the southwestern part of Olkhon region: Vernadsky State Geological Museum, Russian Academy of Sciences, Moscow.

Fedorovsky, V.S., Khain, E.V., Vladimirov, A.G., Kargopolov, S.A., Gibsher, A.S., and Izokh, A.E., 1995, Tectonics, metamorphism, and magmatism of collisional zones of the Central Asian Caledonides: Geotectonics, v. 29, p. 193–212.

Fedorovsky, V.S., Donskaya, T.V., Gladkochub, D.P., Khromykh, V.P., Mazukabzov, A.M., Mekhonoshin, A.S., Sklyarov, E.V., Sukhorukov, V.P., Vladimirov, A.G., Volkova, N.I., and Yudin, D.S., 2005, The Ol'khon collision system (Baikal region), *in* Sklyarov, E.V., ed., Structural and tectonic correlation across the central Asia orogenic collage, northeastern segment: Guidebook and abstract volume of the Siberian workshop (International Geological Correlation Programme 480), Irkutsk-Ulan Ude, Russia: Institute of the Earth's Crust, Russian Academy of Sciences, Siberian Branch, Irkutsk, p. 6–97.

Filippova, I.B., Bush, V.A., and Didenko, A.N., 2001, Middle Paleozoic subduction belts: The leading factor in the formation of the Central Asian fold-and-thrust belt: Russian Journal of Earth Sciences, v. 3, p. 405–426.

Fiske, R.S., Naka, J., Iisasa, K., Yuiasa, M., and Klaus, A., 2001, Submarine silicic caldera at the front of the Izu-Bonin arc, Japan: Voluminous seafloor eruptions of rhyolite pumice: Geological Society of America Bulletin, v. 113, p. 813–824, doi: 10.1130/0016-7606(2001)113<0813:SSCATF>2.0.CO;2.

Gordienko, I.V., 2006, Geodynamic evolution of late Baikalides and Paleozoids in the folded periphery of the Siberian craton: Russian Geology and Geophysics, v. 47, p. 53–70.

Gordienko, I.V., and Filimonov, A.V., 2005, The Dzidha zone of the Paleo-Asian Ocean: Main stages of geodynamic evolution (Vendian–early Paleozoic oceanic, island-arc and back-arc basin complexes), *in* Sklyarov, E.V., ed., Structural and tectonic correlation across the central Asia orogenic collage, northeastern segment: Guidebook and abstract volume of the Siberian workshop (International Geological Correlation Programme 480), Irkutsk-Ulan Ude, Russia: Institute of the Earth's Crust, Russian Academy of Sciences, Siberian Branch, Irkutsk, p. 98–164.

Gordienko, I.V., and Mikhaltsov, N.E., 2001, Location of the Vendian–early Cambrian ophiolitic and island-arc complexes in the Dzhida Caledonite zone in the Paleo-Asian ocean structures according to paleomagnetic data: Doklady Earth Sciences, v. 379, p. 508–513.

Hall, R., 2002, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations: Journal of Asian Earth Sciences, v. 20, p. 353–431, doi: 10.1016/S1367-9120(01)00069-4.

Hargrove, U.S., Stern, R.J., Kimura, J.I., Manton, W.I., and Johnson, P., 2006, How juvenile is the Arabian-Nubian Shield? Evidence from Nd isotopes and pre-Neoproterozoic inherited zircon: Earth and Planetary Science Letters, v. 252, p. 308–326.

Hartz, E.H., and Torsvik, T.H., 2002, Baltica upside down: A new plate tectonic model for Rodinia and the Iapetus Ocean: Geology, v. 30, p. 255–258, doi: 10.1130/0091-7613(2002)030<0255:BUDANP>2.0.CO;2.

Heinhorst, J., Lehmann, B., Ermolov, P., Serykh, V., and Zhuratin, S., 2000, Paleozoic crustal growth and metallogeny of central Asia: Evidence from magmatic-hydrothermal ore systems of central Kazakhstan: Tectonophysics, v. 328, p. 69–87, doi: 10.1016/S0040-1951(00)00178-5.

Helo, C., Hegner, E., Kröner, A., Badarch, G., Tomurtogoo, O., Windley, B.F., and Dulski, P., 2006, Geochemical signature of Paleozoic accretionary complexes of the Central Asian Orogenic Belt in South Mongolia: Constraints on arc environments and crustal growth: Chemical Geology, v. 227, p. 236–257.

Jahn, B.M., 2004, The Central Asian Orogenic Belt and growth of the continental crust in the Phanerozoic, *in* Malpas, J., et al., eds., Aspects of the tectonic evolution of China: Geological Society [London] Special Publication 226, p. 73–100.

Jahn, B.M., Wu, F., and Chen, B., 2000, Granitoids of the Central Asian Orogenic Belt and continental growth in the Phanerozoic: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 91, p. 181–193.

Jahn, B.M., Capdevila, R., Liu, D.Y., Vernon, A., and Badarch, G., 2004, Sources of Phanerozoic granitoids in the transect Bayanhongor–Ulaan Baatar, Mongolia: Geochemical and Nd isotopic evidence, and implications for Phanerozoic crustal growth: Journal of Asian Earth Sciences, v. 23, p. 629–653, doi: 10.1016/S1367-9120(03)00125-1.

Johnson, P.R., 1998, Tectonic map of Saudi Arabia and adjacent areas: Saudi Arabian Deputy Ministry for Mineral Resources, Technical Report USGS-TR-98-3, scale 1:4,000,000.

Johnson, P.R., and Woldehaimanot, B., 2003, Development of the Arabian-Nubian Shield: Perspectives on accretion and deformation in the northern East African orogen and the assembly of Gondwana, *in* Yoshida, M., et al., eds., Proterozoic East Gondwana: supercontinent assembly and breakup: Geological Society [London] Special Publication 206, p. 289–325.

Kennedy, A., Johnson, P.R., and Kattan, F.H., 2004, SHRIMP geochronology in the northern Arabian Shield, part I: Data acquisition: Saudi Arabian Geological Survey Open-File Report SGS-OF-2004-11, 28 p.

Kennedy, A., Johnson, P.R., and Kattan, F.H., 2005, SHRIMP geochronology in the northern Arabian Shield, part II: Data acquisition, 2004: Saudi Arabian Geological Survey Open-File Report SGS-OF-2005-10, 44 p.

Khain, E.V., Bibikova, E.V., Kröner, A., Zhuralev, D.Z., Sklyarov, E.V., Fedotova, A.A., and Kravbchenko-Berezhnoy, I.R., 2002, The most ancient ophiolite of the Central Asian fold belt: U-Pb and Pb-Pb zircon ages for the Dunzhugur complex, Eastern Sayan, Siberia, and geodynamic implications: Earth and Planetary Science Letters, v. 199, p. 311–325, doi: 10.1016/S0012-821X(02)00587-3.

Khain, E.V., Bibikova, E.V., Salnikova, E.B., Kröner, A., Gibsher, A.S., Didenko, A.N., Degtyarev, K.E., and Fedotova, A.A., 2003, The Palaeo-Asian ocean in the Neoproterozoic and early Paleozoic: New geochronologic data and palaeotectonic reconstructions: Precambrian Research, v. 122, p. 329–358, doi: 10.1016/S0301-9268(02)00218-8.

Kheraskova, T.N., Didenko, A.N., Bush, V.A., and Volozh, Yu.A., 2003, The Vendian–early Paleozoic history of the continental margin of eastern Paleogondwana, Paleoasian ocean, and Central Asian foldbelt: Russian Journal of Earth Sciences, v. 5, p. 165–184.

Konnikov, E.G., Gibsher, A.S., Izokh, A.E., Sklyarov, E.V., and Khain, E.V., 1994, Late Proterozoic evolution of the northern segment of the Paleoasian ocean: New radiological, geological, and geochemical data: Russian Geology and Geophysics, v. 35, p. 131–145.

Kovach, V.P., Jian, P., Yarmolyuk, V.V., Kozakov, I.K., Kovalenko, V.I., Liu, D.Y., and Terent'eva, L.B., 2005, Magmatism and geodynamics of early stages of the Paleoasian ocean formation: Geochronological and geochemical data on ophiolites of the Bayan-Khongor zone: Doklady Earth Sciences, v. 404, p. 1072–1077.

Kovalenko, V.I., Yarmolyuk, V.V., Kovach, V.P., Kotov, A.B., Kozakov, I.K., Salnikova, E.B., and Larin, A.M., 2004, Isotope provinces, mechanism of generation and sources of the continental crust in the Central Asian mobile belt: Geological and isotopic evidence: Journal of Asian Earth Sciences, v. 23, p. 605–627, doi: 10.1016/S1367-9120(03)00130-5.

Kozakov, I.K., Kotov, A.B., Kovach, V.P., and Salnikova, E.B., 1997, Crustal growth in the geologic evolution of the Baidarik Block, central Mongolia: Evidence from Sm-Nd isotopic systematics: Petrology, v. 5, p. 201–207 (translated from Russian).

Kozakov, I.K., Glebovistsky, V.A., Bibikova, E.V., Azimov, P.Y., and Kirnozova, T.I., 2002, Hercynian granulites of Mongolian and Gobian Altai: Geodynamic setting and formation conditions: Doklady Earth Sciences, v. 386, p. 781–785 (translated from Russian).

Kozakov, I.K., Kovach, V.P., Yarmolyuk, V.V., Kotov, A.B., Salnikova, E.B., and Zagornaya, N.Yu., 2003, Crust-forming processes in the geologic development of the Tuva-Mongolian Massif: Sm-Nd isotopic and geochemical data for granitoids: Petrology, v. 11, p. 444–463 (translated from Russian).

Kozakov, I.K., Sal'nikova, E.B., Natman, A., Kovach, V.P., Kotov, A.B., Podkovyrov, V.N., and Plotkina, Yu.V., 2005, Metasedimentary complexes of the Tuva-Mongolian Massif: Age, provenances, and tectonic position: Stratigraphy and Geological Correlation, v. 13, p. 1–20 (translated from Russian).

Kozakov, I.K., Sal'nikova, E.B., Wang, T., Didenko, A.N., Plotkina, Yu.V., and Podkovyrov, V.N., 2007, Early Precambrian crystalline complexes of the Central Asian microcontinent: Age, sources, tectonic position: Stratigraphy and Geological Correlation, v. 15, p. 121–140 (translated from Russian).

Kröner, A., and Hegner, E., 1998, Geochemistry, single-zircon ages and Sm-Nd systematics of granitoid rocks from the Góry Sowie (Owl) Mts., Polish West Sudetes: Evidence for early Palaeozoic arc-related plutonism: Geological Society [London] Journal, v. 155, p. 711–724.

Kröner, A., and Stern, R.J., 2005, Pan-African orogeny: Encyclopedia of geology, v. 1: Amsterdam, Elsevier, p. 1–12.

Kröner, A., Muhongo, S., Hegner, E., and Wingate, M., 2003, Single-zircon geochronology and Nd isotopic systematics of Proterozoic high-grade rocks from the Mozambique belt of southern Tanzania (Masasi area): Implications for Gondwana assembly: Geological Society [London] Journal, v. 160, p. 745–757.

Kröner, A., Windley, B.F., Khain, E.V., Jahn, B.M., Hegner, E., Badarch, G., Tomurtogoo, O., Kuzmichev, A., and Liu, D.Y., 2004, Accretionary growth and crust formation in the Central Asian Orogenic Belt during the Neoproterozoic and Paleozoic and comparison with the present southwest Pacific: Abstract volume, 17th International Basement Tectonics Association Conference "4-D framework of the continental crust—Integrating crustal processes through time," Oak Ridge, Tennessee, p. 77–78.

Kröner, A., Hegner, E., Lehmann, B., Heinhorst, J., Wingate, M., Liu, D.Y., and Ermelov, P., 2007, Palaeozoic arc magmatism in the Central Asian Orogenic Belt of Kazakhstan: SHRIMP zircon ages and whole-rock isotopic systematics: Journal of Asian Earth Sciences (in press).

Kuzmichev, A.B., Bibikova, E.V., and Zhuralev, D.Z., 2001, Neoproterozoic (~800 Ma) orogeny in the Tuva-Mongolia Massif (Siberia): Island arc–continent collision at the northeast Rodinia margin: Precambrian Research, v. 110, p. 109–126, doi: 10.1016/S0301-9268(01)00183-8.

Kuzmichev, A., Sklyarov, E., Postnikov, A., and Bibikova, E., 2007, The Oka belt (southern Siberia and northern Mongolia): A Neoproterozoic analog of the Japanese Shimanto belt? Island Arc, doi:10.1111/j.1440-1738.2007.00568.x.

Kuzmichev, A., Kröner, A., Liu, D.Y., and Wan, Y.S., 2005, The Shishkhid ophiolite, northern Mongolia: A key to the reconstruction of a late Neoproterozoic island-arc system in central Asia: Precambrian Research, v. 138, p. 125–150, doi: 10.1016/j.precamres.2005.04.002.

Lackschewitz, K.S., Mertz, D.F., Devey, C.W., and Garbe-Schönberg, C.-D., 2003, Late Cenozoic volcanism in the western Woodlark Basin area, SW Pacific: The sources of marine volcanic ash layers based on their elemental and Sr-Nd isotopic compositions: Bulletin of Volcanology, v. 65, p. 182–200.

Lamb, M.A., and Badarch, G., 1997, Paleozoic sedimentary basins and volcanic-arc systems of southern Mongolia: New stratigraphic and sedimentologic constraints: International Geological Review, v. 39, p. 542–576.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Litvinovsky, B.A., Jahn, B.-M., Zanvilevich, A.N., Saunders, A., Poulain, S., Kuzmin, D.V., Reichow, M.K., and Titov, A.V., 2002, Petrogenesis of syenite-granite suites from Bryansky Complex (Transbaikalia, Russia): Implications for the origin of A-type granitoid magmas: Chemical Geology, v. 189, p. 105–133, doi: 10.1016/S0009-2541(02)00142-0.

Matsumoto, I., and Tomurtogoo, O., 2003, Petrological characteristics of the Hantaishir ophiolite complex, Altai region, Mongolia: Coexistence of podiform chromitite and boninite: Gondwana Research, v. 6, p. 161–169, doi: 10.1016/S1342-937X(05)70967-9.

Meert, J.G., and Lieberman, B.S., 2004, A palaeomagnetic and palaeobiogeographical perspective on latest Neoproterozoic and early Cambrian tectonic events: Geological Society [London] Journal, v. 161, p. 477–487.

Meschede, M., 1986, A model of discrimination between different types of mid-ocean ridge basalts and continental tholeiites with the Nd-Zr-Y diagram: Chemical Geology, v. 56, p. 207–218, doi: 10.1016/0009-2541(86)90004-5.

Mossakovsky, A.A., and Dergunov, A.B., 1985, The Caledonides of Kazakhstan, Siberia, and Mongolia: A review of structure, development history, and palaeotectonic environments, *in* Gee, D.G., and Sturt, B.A., eds., The Caledonide orogen—Scandinavia and related areas: Chichester, Wiley and Sons, p. 1201–1215.

Mossakovsky, A.A., Ruzhentsev, S.V., Samygin, S.G., and Kheraskova, T.N., 1993, Central Asian fold belt: Geodynamic evolution and formation history: Geotectonics, v. 27, p. 445–473.

Murphy, J.B., and MacDonald, D.L., 1993, Geochemistry and tectonic discrimination of Late Proterozoic arc-related volcaniclastic turbidite sequences, Antigonish Highlands, Nova Scotia: Canadian Journal of Earth Sciences, v. 30, p. 2273–2282.

Murphy, J.B., Pisarevsky, S.A., Nance, R.D., and Keppie, J.D., 2004, Neoproterozoic–early Paleozoic evolution of peri-Gondwanan terranes: Implications for Laurentia-Gondwana connections: International Journal of Earth Sciences, v. 93, p. 659–682, doi: 10.1007/s00531-004-0412-9.

Nawrocki, J., Zylinska, A., Bula, Z., Brabowski, J., Krzywiec, P., and Poprawa, P., 2004, Early Cambrian location and affinities of the Brunovistulian terrane (central Europe) in the light of palaeomagnetic data: Geological Society [London] Journal, v. 161, p. 513–522.

Nikitin, I.F., and Nikitina, O.I., 2000, To the geodynamics of Kazakhstan in early Paleozoic (hypothetical reconstructions), *in* Bespaev, K.A., ed., Geodynamics and mineragency of Kazakhstan: VAC Publishing House, Almaty, p. 64–72.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956–983.

Pfänder, J.A., and Kröner, A., 2004, Tectono-magmatic evolution, age and emplacement of the Agardagh Tes-Chem ophiolite in Tuva, Central Asia: Crustal growth by island arc accretion, *in* Kusky T., ed., Precambrian ophiolites and related rocks: Elsevier Science, Amsterdam, p. 207–221.

Pisarevsky, S.A., and Natapov, L.M., 2003, Siberia and Rodinia: Tectonophysics, v. 375, p. 221–245, doi: 10.1016/j.tecto.2003.06.001.

Popeko, L.I., 2002, Carboniferous of the Mongol-Okhotsk orogenic belt: Vladivostok, Russia, Dalnauka Publishing House, 124 p. (in Russian).

Popov, V., Iosifidi, A., and Khramov, A., 2002, Paleomagnetism of Upper Vendian sediments from the Winter Coast, White Sea region, Russia: Implications for the paleogeography of Baltica during Neoproterozoic times: Journal of Geophysical Research, v. 107, no. B11, 2315, doi: 10.1029/2001JB001607.

Resolution of 3rd Kazakhstan stratigraphic conference on the Precambrian and Phanerozoic, 1991, Part 1: Precambrian and Paleozoic, Alma-Ata, 148 p.

Reymer, A.P.S., and Schubert, G., 1987, Phanerozoic and Precambrian crustal growth, *in* Kröner, A., ed., Proterozoic lithospheric evolution: American Geophysical Union Geodynamics Series, v. 17, p. 1–9.

Riley, T.R., Leat, P.T., Pankhurst, R.J., and Harris, C., 2001, Origins of large-volume rhyolitic volcanism in the Antarctic Peninsula and Patagonia by crustal melting: Journal of Petrology, v. 42, p. 1043–1065, doi: 10.1093/petrology/42.6.1043.

Ruzhentsev, S.V., and Burashnikov, V.V., 1996, Tectonics of the western Mongolian Salairides: Geotectonics, v. 29, p. 379–394.

Ruzhentsev, S.V., and Mossakovskiy, A.A., 1996, Geodynamics and tectonic evolution of the Central Asian Paleozoic structures as the result of the interaction between the Pacific and Indo-Atlantic segments of the Earth: Geotectonics, v. 29, p. 294–311.

Salnikova, E.B., Kozakov, I.K., Kotov, A.B., Kröner, A., Todt, W., Bibikova, E.V., Nutman, A., Yakopvleva, S.Z., and Kovach, V.P., 2001, Age of Paleozoic granites and metamorphism in the Tuvino-Mongolian Massif of the Central Asian mobile belt: Loss of a Precambrian microcontinent: Precambrian Research, v. 110, p. 143–164, doi: 10.1016/S0301-9268(01)00185-1.

Şengör, A.M.C., and Natal'in, B.A., 1996, Paleotectonics of Asia: Fragments of a synthesis, *in* Yin, A., and Harrison, T.M., eds., The tectonic evolution of Asia: Cambridge, UK, Cambridge University Press, p. 486–640.

Şengör, A.M.C., Natal'in, B.A., and Burtman, V.S., 1993, Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia: Nature, v. 364, p. 299–307, doi: 10.1038/364299a0.

Sklyarov E.V., Gladkochub D.P., Mazukabzov A.M., Donskaya T.V., and Stanevich A.M., 2003, Geological complexes in the margin of the Siberian Craton as indicators of the evolution of a Neoproterozoic Supercontinent: Russian Journal of Earth Sciences, v. 5, p. 347–359.

Smethurst, M.A., Khramov, A.N., and Torsvik, T.H., 1998a, The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: From Rodinia to Pangea: Earth-Science Reviews, v. 43, p. 1–24, doi: 10.1016/S0012-8252(97)00019-6.

Smethurst, M.A., Khramov, A.N., and Pisarevsky, S., 1998b, Palaeomagnetism of the Lower Ordovician Orthoceras Limestone, St. Petersburg, and a revised drift history for Baltica in the early Palaeozoic: Geophysical Journal International, v. 133, p. 44–56, doi: 10.1046/j.1365-246X.1998.1331463.x.

Stern, R.A., 1997, The GSC sensitive high-resolution ion microprobe (SHRIMP): Analytical techniques of zircon U-Th-Pb age determinations and performance evaluation, *in* Radiogenic age and isotopic studies: Geological Survey of Canada Report 10-1997-F, p. 1–31.

Tomurtogoo, O., editor, 1998, Geological map of Mongolia: Mineral Resources Authority of Mongolia, Mongolian Academy of Sciences, Ulaanbaatar, scale 1:100,000, CD-ROM (with English summary).

Tomurtogoo, O., Windley, B.F., Kröner, A., and Liu, D.Y., 2005, Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: Constraints on the evolution of the Mongol-Okhotsk ocean, suture and orogen: Geological Society [London] Journal, v. 162, p. 125–134, doi: 10.1144/0016-764903-146.

Windley, B.F., Kröner, A., Guo, J., Qu, G., Li, Y., and Zhang, C., 2002, Neoproterozoic to Paleozoic geology of the Altai orogen, Chinese Central Asia: New zircon age data and tectonic evolution: Journal of Geology, v. 110, p. 719–739, doi: 10.1086/342866.

Windley, B.F., Kröner, A., and Xiao, W., 2004, The tectonic evolution of central Asia, *in* Jahn, B.M., ed., International workshop on accretionary orogens and continental growth [abs.]: Taipei, Taiwan, National Taiwan University, p. 91–93.

Windley, B.F., Alexeiev, D., Xiao, W.J., Kröner, A., and Badarch, G., 2007, Tectonic models for accretion of the Central Asian Orogenic Belt. Journal of the Geological Society of London, v. 164, p. 31–47.

Xiao, W.J., Windley, B.F., Hao, J., and Zhai, M.G., 2003, Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt: Tectonics, v. 22, p. 1069, doi: 10.1029/2002TC001484.

Xiao, W., Windley, B.F., Badarch, G., Sun, S., Li, J., Qin, K., and Wang, Z., 2004a, Palaeozoic accretionary and convergent tectonics of the southern Altaids: Implications for the growth of Central Asia: Geological Society [London] Journal, v. 161, p. 339–342.

Xiao, W.J., Zhang, L.C., Qin, K.Z., Sun, S., and Li, J.L., 2004b, Paleozoic accretionary and collisional tectonics of the eastern Tianshan (China): Implications for the continental growth of central Asia: American Journal of Science, v. 305, p.

Yakubchuk, A., 1994, Polychronous ophiolite belts of central Kazakhstan and their evolution, *in* Ishiwatari, A., et al., eds., Circum-Pacific ophiolites: Proceedings of the 29th International Geological Congress, part D: Utrecht, VSP Publishers, p. 235–254.

Yakubchuk, A., 2002, The Baikalide-Altaid, Transbaikal-Mongolian and North Pacific orogenic collages: Similarity and diversity of structural patterns ands metallogenic zoning, *in* Blundell, D.J., et al., eds., The timing and location of major ore deposits in an evolving orogen: Geological Society [London] Special Publication 204, p. 273–297.

Yakubchuk, A., Seltmann, R., Shatov, V., and Cole, A., 2001, The Altaids: Tectonic evolution and metallogeny: Society of Economic Geologists (SEG) Newsletter, v. 46, p. 7–15.

Yarmolyuk, V.V., 1983, Carboniferous volcanism of Mongolia, *in* Luchitsky, I.V., ed., Continental volcanism of Mongolia: Moscow, Nauka, Joint Soviet-Mongolian Scientific Research Geological Expedition, Transactions, v. 36, p. 67–85.

Yarmolyuk, V.V., Kovalenko, V.I., Kovach, V.P., Budnikov, S.V., Kozakov, I.K., Kotov, A.B., and Salnikova, E.B., 1999, Nd-isotopic systematics of western Transbaikalian crustal protoliths: Implications for Riphean crust formation in central Asia: Geotectonics, v. 33, p. 271–286.

Yarmolyuk, V.V., Kovalenko, V.I., Sal'nikova, E.B., Kozakov, I.K., Kotov, A.B., Kovach, V.P., Vladykin, N.V., and Yakovleva, S.Z., 2005, U-Pb age of syn- and postmetamorphic granitoids of South Mongolia: Evidence fort he presence of Grenvillides in the Central Asian foldbelt. Doklady Earth Sciences, v. 404, p. 986–990 (translated from Russian).

Zonenshain, L.P., Kuzmin, M.I., and Natapov, L.M., 1990, Plate tectonics of the USSR: A plate-tectonic synthesis: American Geophysical Union Geodynamics Series, v. 21, 242 p.

Manuscript Accepted by the Society 1 February 2007