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Tectonic models for accretion of the Central Asian Orogenic Belt

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Abstract: The Central Asian Orogenic Belt (c. 1000–250 Ma) formed by accretion of island arcs, ophiolites, oceanic islands, seamounts, accretionary wedges, oceanic plateaux and microcontinents in a manner comparable with that of circum-Pacific Mesozoic–Cenozoic accretionary orogens. Palaeomagnetic and palaeofloral data indicate that early accretion (Vendian–Ordovician) took place when Baltica and Siberia were separated by a wide ocean. Island arcs and Precambrian microcontinents accreted to the active margins of the two continents or amalgamated in an oceanic setting (as in Kazakhstan) by roll-back and collision, forming a huge accretionary collage. The Palaeo-Asian Ocean closed in the Permian with formation of the Solonker suture. We evaluate contrasting tectonic models for the evolution of the orogenic belt. Current information provides little support for the main tenets of the one- or three-arc Kipchak model; current data suggest that an archipelago-type (Indonesian) model is more viable. Some diagnostic features of ridge–trench interaction are present in the Central Asian orogen (e.g. granites, adakites, boninites, near-trench magmatism, Alaskan-type mafic–ultramafic complexes, high-temperature metamorphic belts that prograde rapidly from low-grade belts, rhyolitic ash-fall tuffs). They offer a promising perspective for future investigations.

Accretionary orogens have been forming throughout the geological record, when they were the main sites of crustal growth (Windley 1992; Sengör & Natal'in 1996a, b). The best-known modern accretionary orogens are in Japan, Alaska, Indonesia and the Caribbean. Like most accretionary orogens that are as wide as they are long, the Central Asian Orogenic Belt (Mossakovsky *et al.* 1993; Khain *et al.* 2002, 2003), or Altaids (Sengör *et al.* 1993; Sengör & Natal'in 1996a, b, 2004; Yakubchuk *et al.* 2001, 2005; Yakubchuk 2002, 2004), extends from the Urals to the Pacific and from the Siberian and East European (Baltica) cratons to the North China (Sino-Korean) and Tarim cratons. It began its growth at c. 1.0 Ga (Khain *et al.* 2002) and continued to c. 250 Ma, when the Palaeo-Asian ocean closed and the Solonker suture formed (Fig. 1a; Xiao *et al.* 2003).

Contrasting models to explain the evolution of the Central Asian Orogenic Belt include the following.

(1) Several syntheses interpret the geology from c. 1.0 Ga to 250 Ma in the light of the geology and tectonics of the modern western Pacific; that is, in terms of growth and accretion of island arcs, oceanic islands, seamounts, accretionary wedges and microcontinents (Zonenshain *et al.* 1990; Mossakovsky *et al.* 1993; Fedorovskii *et al.* 1995; Buslov *et al.* 2001, 2004; Filippova *et al.* 2001; Badarch *et al.* 2002; Khain *et al.* 2003; Kheraskova *et al.* 2003). The key aspects are: (a) many island arcs formed in the Palaeo-Asian ocean and accreted to the margins of Siberia and Baltica; (b) several Precambrian blocks were rifted off the margins of Gondwana and/or Siberia and drifted to dock with the growing accretionary margins.

(2) Sengör *et al.* (1993) and Sengör & Natal'in (1996a, b,

2004) synthesized the later part of the Central Asian Orogenic Belt that formed from c. 542 Ma to 250 Ma and they called this orogen the Altaids; the earlier part they included in the Baikaliide–Pre-Uralide orogen (Fig. 1). The key aspects of this model are as follows. (a) Only one main island arc (the c. 7000 km long Kipchak–Tuva–Mongol arc) formed in this orogen, along the outboard margin of the Baikaliides and Pre-Uralides orogen (Fig. 1). Successive roll-back of the arc in the Cambrian to mid-Silurian gave rise to the Khanty–Mansi back-arc ocean. Differential rotation of Siberia and Baltica led to duplication of the arc by strike-slip shuffling and to oroclinal bending and caused closure of the ocean by the late Carboniferous. (b) Several Precambrian blocks were rifted off the margins of Siberia and Baltica, but none from Gondwana.

(3) Yakubchuk *et al.* (2001, 2005) and Yakubchuk (2002, 2004) modified the Kipchak model by increasing the number of arcs and back-arcs and placing more emphasis on collision and metallogenesis and less on strike-slip duplication.

Petrochemical and isotopic data have been applied to the problem of crustal growth of the Central Asian Orogenic Belt. Using Sm–Nd isotopic data for granitic rocks, Jahn *et al.* (2000) and Jahn (2004) emphasized their juvenile character and short life since separation of source rocks or magmas from the mantle. Kovalenko *et al.* (2004) used similar data to define isotopic provinces in this orogenic belt that were produced from juvenile sources in island arcs and active continental margin arcs. They also suggested that initial formation of the Central Asian Orogenic Belt was connected with break-up of the Rodinia supercontinent by action of the South Pacific superplume.

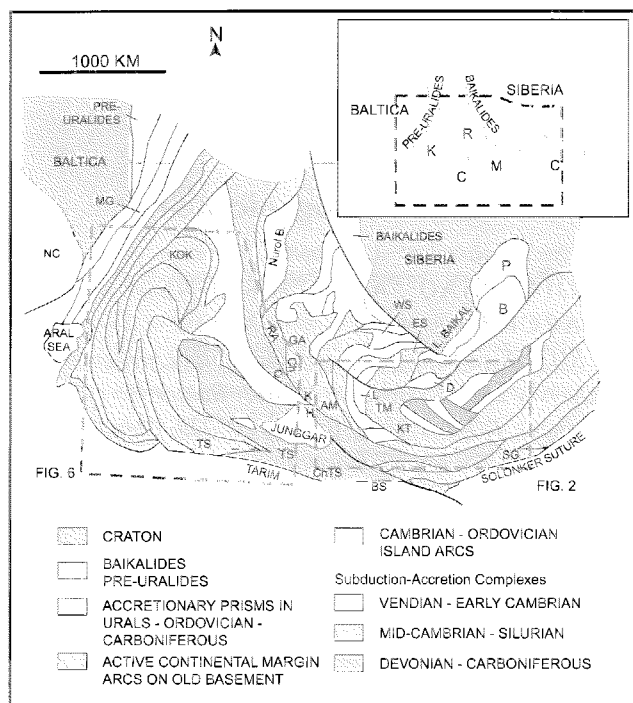


Fig. 1. Simplified tectonic map of the Central Asian Orogenic Belt. Inset shows the location of the map. R, Russia; K, Kazakhstan; M, Mongolia; C, China. Main map: AM, Altai-Mongolia block; B, Barguzin; BS, Beishan; C, Charysh suture; Ch, Charysh suture; ChTS, Chinese Tien Shan; D, Dzhida; ES, East Sayan; GA, Gorny Altai; H, Halatongke; K, Keketuohai; KOK, Kokchetav; KT, Khantaishir; L, Lake (Ozernaya); MG, Magnitogorsk; NC, North Caspian basin; P, Patom; RA, Rudny Altai; SG, South Gobi microcontinent; TM, Tuva-Mongol massif; TS, Tien Shan; WS, West Sayan. Modified after Sengör & Natal'in (2004).

The aim of this paper is to present a review of the geology of the Central Asian Orogenic Belt, to evaluate published tectonic models and to suggest new ideas for the accretionary development. This will not include the Mongol-Okhotsk Ocean, which closed in the Jurassic-Cretaceous (Tomurtogoo *et al.* 2005).

Outline and tectonic setting

Central Asia has had a long, complex geological history. As a result of their mapping of Siberia, Kazakhstan, Kyrgyzstan and Mongolia, Russian geologists realized that the older rocks were in the north (present coordinates) and the younger in the south (Zonenshain *et al.* 1990). Figure 1 shows the general geological framework of the Central Asian Orogenic Belt. Because there is a general coincidence of geographical position and age of the belts, the following discussion will start with the oldest rocks on the margins of Siberia and Baltica and move outwards from there.

Tectonic evolution in the Neoproterozoic (c. 1000–542 Ma)

According to the palaeomagnetic constraints of Pisarevsky *et al.* (2003), the supercontinent of Rodinia was assembled at c. 1000 Ma and began to break up soon after that. Siberia and Baltica were externally situated, but not adjacent to each other, against an open ocean on their southern (present coordinates) margins, and thus were in a position to receive shelf sequences on their passive margins.

Rifting of the Siberian margin

Sklyarov *et al.* (2003) reported that volcanic (high-alkali basalts) and clastic sedimentary rocks, up to 2.7 km thick, occur in rifts in the West Baikal region on the margin of the Siberian craton. Although they lack isotopic ages, their geological relations with

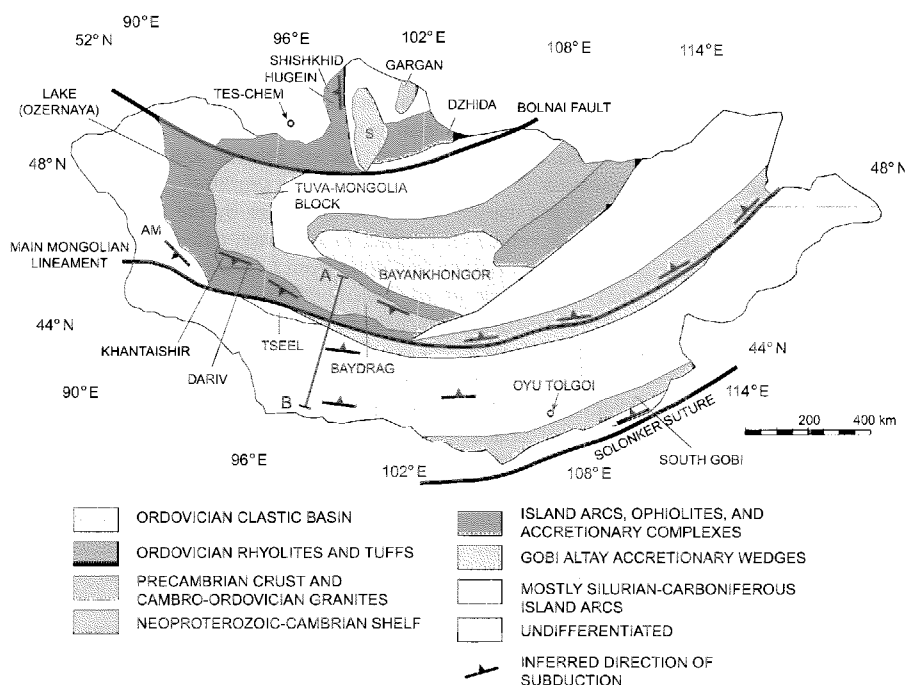


Fig. 2. Simplified tectonostratigraphic map of Mongolia showing the main units to the north and south of the Main Mongolian Lineament, demonstrating that a stable block was created on the northern side by the end of the Ordovician. Modified after Badarch *et al.* (2002). Position of section in Figure 3 is shown.

dated rocks suggest formation in the intervals 1300–1100 and 850–750 Ma. Rifts near Lake Baikal contain within-plate alkali basalts and 300 m thick low-K flood basalts (Khain *et al.* 2003). From about 1100 Ma carbonate–clastic sediments developed in a shelf–continental slope–continental rise setting in the region east of Lake Baikal (Fig. 1) on the margin of the Siberian craton (Sklyarov *et al.* 2003; Khain *et al.* 2003; Pisarevsky & Natapov 2003). Major swarms of basic (subalkali basalt and tholeiite) dykes that have isotopic ages in the range 974–900 Ma were intruded near the margins of the craton (Dobretsov *et al.* 2003); some dyke swarms underlie carbonate–clastic sediments (Sklyarov *et al.* 2003). All these rocks and structures mark the onset of rift-induced extension and break-up of the margin of Siberia.

Tuva–Mongolian microcontinent

The Tuva–Mongolian block (Fig. 2) microcontinent (e.g. Sengör *et al.* 1996b; Buslov *et al.* 2001; Dobretsov *et al.* 2004) consists of an early Precambrian Gargan continental block in the north in which gneisses have a Rb–Sr whole-rock isochron age of 3153 ± 57 Ma and a U–Pb zircon age of 2 Ga (Badarch *et al.* 2002, and references therein), the central part of the Tuva–Mongolian block, the gneisses of which have a protolith Pb–Pb zircon age of 1868 ± 3 Ma (Badarch *et al.* 2002), and the Baydrag block in central Mongolia (Figs 2 & 3), which contains an Archaean complex with gneisses and granulites that have U–Pb zircon protolith ages of 2650 ± 30 Ma and 2364 ± 6 Ma and a Palaeoproterozoic complex comprising granulites, gneisses, schists, marbles, quartzites and granitic dykes that have granulite-facies peak metamorphic U–Pb zircon ages of 1854 ± 5 Ma and 1839.8 ± 0.6 Ma (Badarch *et al.* 2002, and references therein). From palaeomagnetic data, Kravchinsky *et al.* (2001) concluded that in the Vendian and early Cambrian the Tuva–Mongolia block (Fig. 2) was still adjacent to Siberia, from which it had earlier rifted. In the Tuva area there are alternating high- and low-grade metamorphic belts, both long thought to be Precambrian in age. However, Salnikova *et al.* (2001) showed that both yield predominantly early Palaeozoic, protolith U–Pb zircon ages, and thus questioned the existence of much of this so-called Precambrian microcontinent.

Early subduction–accretion

An early Neoproterozoic belt of ophiolites surrounds the Siberian craton (Khain *et al.* 1997); the oldest seem to be situated closest to it (Sklyarov *et al.* 2003). The Nyurundukan ophiolite at the northern end of Lake Baikal has a Sm–Nd whole-rock isochron age of 1035 ± 92 Ma on metabasalts (Ritsk *et al.* 1999). A plagiogranite in the Dunzhugur ophiolite in eastern Sayan (Fig. 1) has a mean U/Pb and Pb/Pb zircon age of 1019 ± 0.7 Ma; petrochemical data support a suprasubduction-zone setting in a forearc rift (Khain *et al.* 2002). A subduction-related tonalite on the SW margin of the Siberian craton has a U–Pb zircon age of 1017 ± 47 Ma (Turkina 2002). All these data indicate that the Siberian craton was surrounded by oceanic crust by c. 1000 Ma.

Between c. 900 and 544 Ma, the formation of many island arcs, seamounts, oceanic crust and accretionary wedges occurred, and the creation of subduction–accretion complexes that include ophiolites and some exhumed high-pressure and ultrahigh-pressure rocks. An ophiolite in the embayment of the Siberian craton (marked P in Fig. 1) contains ultramafic rocks, gabbros, a dyke complex and pillow lavas with normal mid-ocean ridge basalt (N-MORB) affinities, and contains a plagiogranite with a Rb–Sr whole-rock age of 880 Ma (Dobretsov *et al.* 2003). Subduction-

related rocks near northern Baikal have Sm–Nd isochron ages of 850–830 Ma, and in eastern Sayan and northern Mongolia felsic arc-type volcanic rocks have Rb–Sr ages of 720 Ma (see Khain *et al.* 2002). The 800 Ma Shishkhid ophiolite (Fig. 2) in northern Mongolia contains sheeted basic dykes overlain successively by arc-derived bimodal basalts and rhyolites and andesitic pyroclastic rocks (Kuzmichev *et al.* 2005); a rhyolite contains zircons with a sensitive high-resolution ion microprobe (SHRIMP) U–Pb age of 800 ± 3 Ma. The Shishkhid ophiolite collided with the Tuva–Mongolian microcontinent at the end of the Neoproterozoic (Kuzmichev *et al.* 2005). In the Baikal–Muya belt a plagiogranite in island arc volcanic rocks has a U–Pb zircon age of 812 ± 19 Ma (Ritsk *et al.* 2001). The Gorny Altai of southern Siberia (Figs 1, 8 and 9) contains a subduction–accretion complex that consists of fragments of an oceanic plateau capped by limestones with a Pb–Pb isochron age of 598 ± 25 Ma (Uchio *et al.* 2004), an Ediacaran–Early Cambrian intra-oceanic island arc, and high-pressure metamorphic rocks that contain basalts with oceanic plateau basalt chemical affinities (Ota *et al.* 2006). This recent detailed study of the Gorny Altai shows that the island arc and ocean plateau formed in the mid-ocean and were accreted in the Cambrian to the front of the Siberian craton.

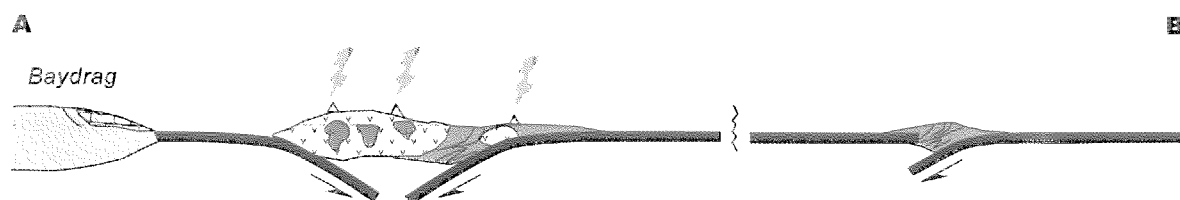
The >300 km long Bayankhongor ophiolite in central Mongolia (Fig. 2) (Buchan *et al.* 2001) has a Sm–Nd cpx–whole-rock tie-line age on gabbro of 569 ± 21 Ma (Kepezhinskis *et al.* 1991) that has long been interpreted to be the crystallization age of the host rock. However, Kovach *et al.* (2005) published a new SHRIMP U/Pb zircon crystallization age of 665 ± 15 Ma for an anorthosite, and their geochemical data indicate that the ophiolite is a fragment of a plume-derived (presciently predicted by Sengör & Natal'in 2004) oceanic plateau generated in a large ocean; this means that it could not have developed in an intra-arc suture (Yakubchuk 2004). Granitic plutons and dykes that intrude the ophiolite and its boundary fault have a mean $^{207}\text{Pb}/^{206}\text{Pb}$ zircon evaporation age of 539 ± 5 Ma, providing a minimum age for the accretion event (Buchan *et al.* 2002).

Along the southern side of the Bayankhongor ophiolite is the best-preserved accretionary prism in Mongolia, termed the Burd Gol mélange (c. 25 km wide, subvertical) that is situated on the northern margin of the Baydrag block (Figs 2 and 3). It consists of graphite-rich chlorite–biotite schists and phyllites that contain lenses of basaltic greenschists and is intruded by arc-type andesite dykes (an excellent example of near-trench magmatism created by ridge subduction). Higher-grade parts of the prism contain biotite from a gneiss that has an $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 533 ± 3 Ma (Buchan *et al.* 2002, and references therein), and sillimanite–kyanite schist that has a metamorphic U–Pb zircon age of 562 ± 2 Ma (Kovach *et al.* 2005).

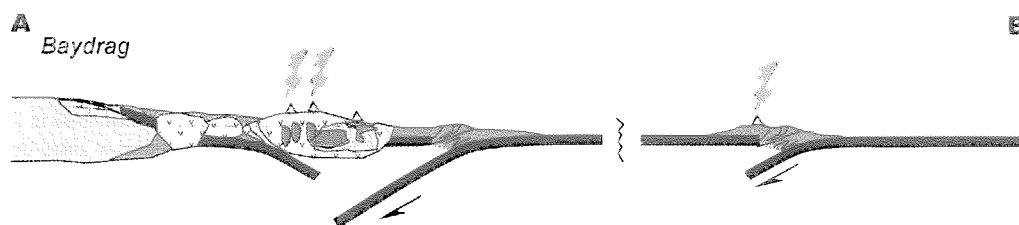
There are several high-pressure rocks in the northern Central Asian Orogenic Belt (Dobretsov *et al.* 2003). Eclogites (16–17 kbar, 700–800 °C) and garnet peridotites, occurring as lenses in gneisses in the Muya region (near P in Fig. 1), have a mineral and whole-rock Sm–Nd age of 650 Ma (Shatsky *et al.* 1996). Blueschists at Hugein (Fig. 2) in northern Mongolia (7–9 kbar, 400–540 °C) have a Rb–Sr whole-rock isochron age of 624 ± 52 Ma (Sklyarov *et al.* 1996), are associated with basalts, tuffs, greywackes and cherts, and are close to the Shishkhid ophiolite. The geology and chemistry of these high-pressure rocks suggest that they formed in low- to high-grade accretionary prisms that developed on, or close to, the margins of microcontinents in accretionary complexes.

In Tuva, southern Siberia, the (Agardagh) Tes-Chem ophiolite (Fig. 2) has an island arc geochemical signature and yielded a mean $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age of 569.6 ± 1.7 Ma (Pfänder &

a. Cambrian to mid-Ordovician



b. Late-Ordovician to Silurian



c. Early-Devonian to mid-Carboniferous

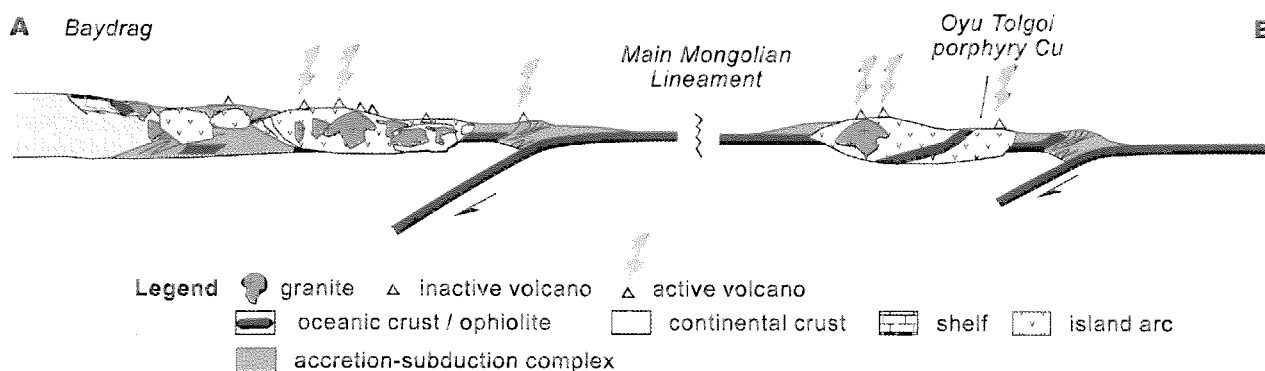


Fig. 3. Schematic sections through southern Mongolia (location indicated in Fig. 2), illustrating the tectonic evolution from the Cambrian to the Carboniferous. The cross-sectional directions are present-day coordinates. Modified after Xiao *et al.* (2004a).

Kröner 2004). Along strike in the Lake or Ozeraya (Fig. 2) zone (accretionary prism) in the Mongolian Altai, other ophiolites have similar ages and were thrust onto gneissic blocks. The Bayannor ophiolite in the Dariv (Daribi) Range (Fig. 2) has a mean $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age of 571 ± 4 Ma, and the Khantaishir ophiolite near Altay (Fig. 2) has a $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age of 568 ± 4 Ma. Geochemical data from both ophiolites suggest that they formed in forearc suprasubduction settings (Khain *et al.* 2003); Khantaishir has sheeted dykes and lavas of boninitic high-Mg andesite composition (Matsumoto & Tomurtogoo 2003), and Dariv formed, at least in part, from a boninitic magma (Dijkstra *et al.* 2006). These ophiolites were accreted to the southern margin of the Tuva–Mongolian microcontinent. In northern Mongolia the poorly dated, but presumably Cambrian, Dzhiba ophiolite (Fig. 2) contains boninites and boninitic melt inclusions in clinopyroxenes and likewise may have formed in a forearc setting (Simonov *et al.* 2004; Dobretsov *et al.* 2005). The above ophiolites were thrust in different directions onto the margins of their respective old gneissic blocks, demonstrating that there was not a single direction of subduction polarity (see Sengör *et al.* 1993). Figure 3 illustrates the tectonic development from the Cambrian to the Carboniferous of a NNE–SSW section (shown in Fig. 2) that extends across the Main Mongolian Lineament.

Palaeo-positions of Siberia and Baltica in the late Vendian and Cambrian

'The most important initial constraint in this proposed reconstruction of the Altai evolution is the assumption that the Angaran (Siberia) and Russian (East European or Baltica) cratons had been united as a single cratonic mass along their present northern margins at 610–530 Ma, thus enabling the Kipchak arc to form as a single arc along their unified margins in the early Cambrian' (Sengör & Natal'in 1996b). Is this assumption correct? Figure 4 presents a compilation of six main plate configurations. Figure 4a shows the position, at 630–530 Ma, of Baltica, Siberia and the Kipchak arc in the model of Sengör *et al.* (1993, 1994) and Sengör & Natal'in (1996a, b, 2004). Figure 4c (Murphy *et al.* 2004), Figure 4d (Hartz & Torsvik 2002), Figure 4e (Cocks & Torsvik 2005) and Figure 4f (Meert & Lieberman 2004) show more recent palaeomagnetically constrained positions of the two continental blocks for this critical early Cambrian period. Figure 4b provides confirmatory palaeontological evidence (McKerrow *et al.* 1992), and Figure 5 shows a reconstruction of the positions of Baltica and Siberia from 650 Ma to 500 Ma, based on palaeomagnetic data as indicated for Baltica (Popov *et al.* 2005) and Siberia (Smethurst

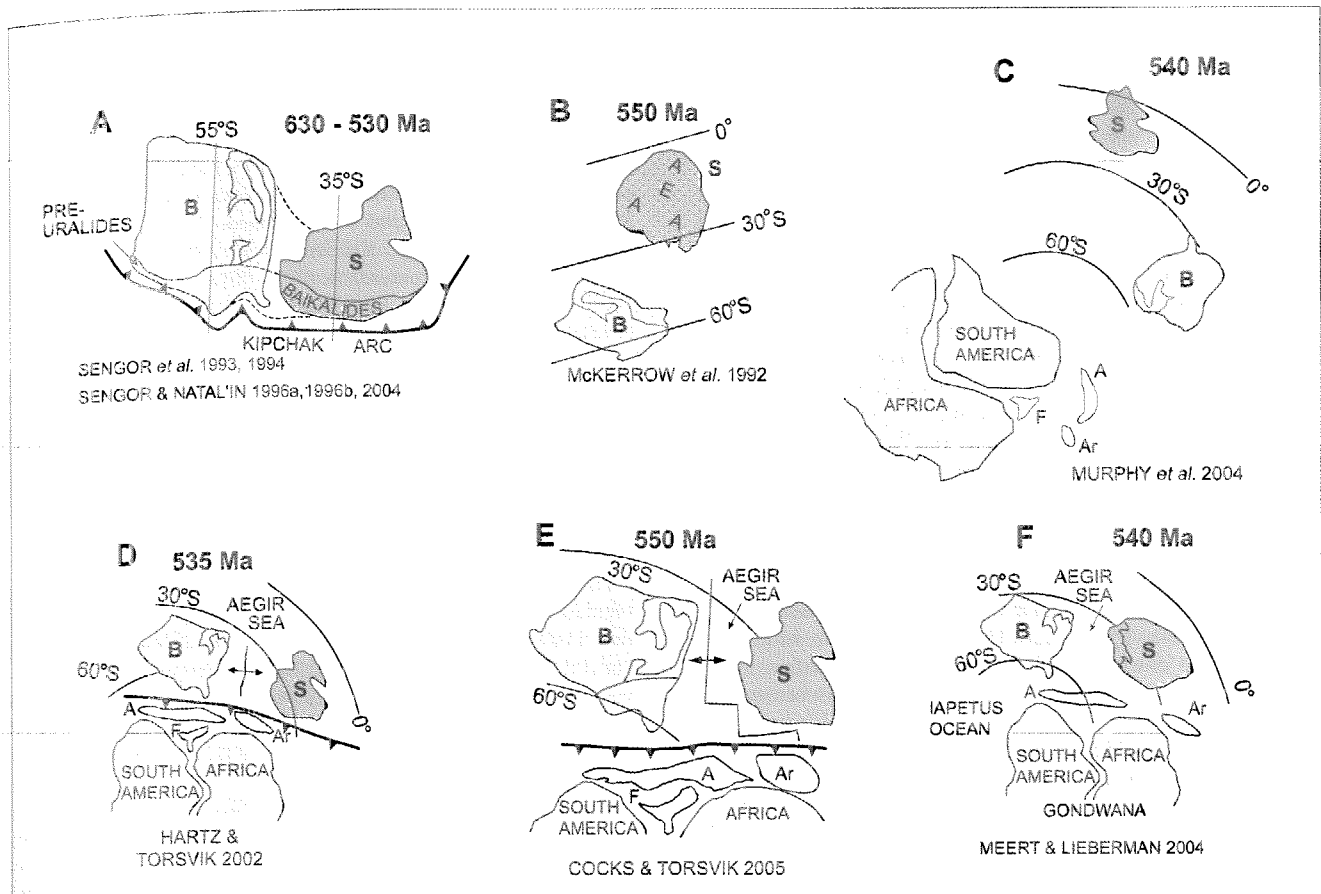


Fig. 4. Six palaeomagnetically determined continental reconstructions showing the relative positions of Baltica (B) and Siberia (S) for the period 550–530 Ma when the Kipchak arc was largely built. (a) shows the continents joined together (Sengör *et al.* 1993, 1994; Sengör & Natal'in 1996a, b, 2004); (b)–(f) show Baltica and Siberia separated by a wide ocean. Faunal data added in (b): A, Archaeocyathans; E, evaporites; stipple in Siberia indicates bigotinid trilobite realm; stipple in Baltica indicates olenellid trilobite realm (McKerrow *et al.* 1992). (c) after Murphy *et al.* (2004); (d) after Hartz & Torsvik (2002); (e) after Cocks & Torsvik (2005); (f) after Meert & Lieberman (2004). In (c)–(f): A, Avalonia; Ar, Armorica. In (c)–(e), F, Florida.

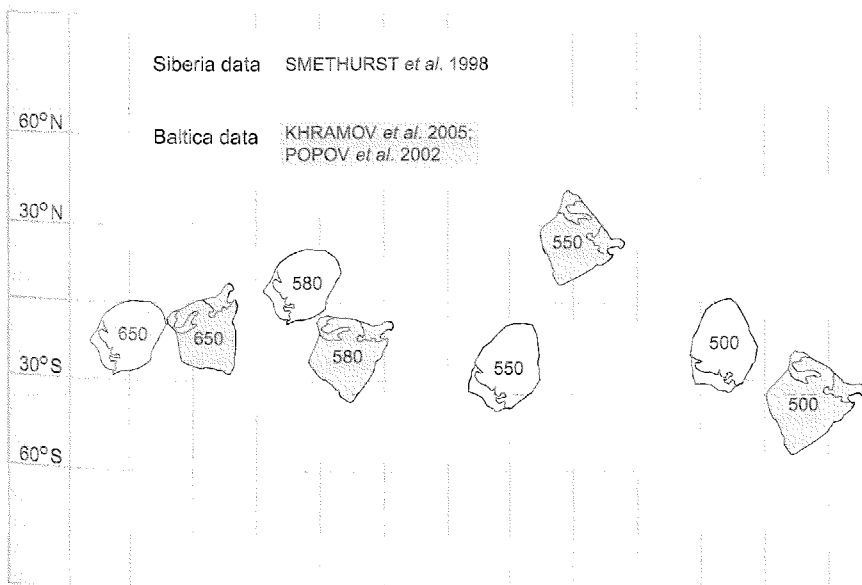


Fig. 5. A palaeomagnetically determined reconstruction showing the positions of Siberia and Baltica from 650 Ma to 500 Ma, using data from Smethurst *et al.* (1998), Popov *et al.* (2005) and Khranov *et al.* (pers. comm. 2006).

et al. 1998). At 550 Ma the closest margins of the continents were separated by about 20° of palaeolatitude.

Important points that arise from these reconstructions are as follows.

(1) 'The most important constraint for the initial conditions of the Altiid evolution is that Baltica and Siberia were attached to one another in the Vendian' (Sengör *et al.* 1993) (see also Sengör & Natal'in 1996a, b, 2004; Yakubchuk *et al.* 2005, and references therein). The placing of Baltica and Siberia together in a unified continent by Sengör *et al.* (1993) was based on 1990–1992 published palaeomagnetic data that allowed just 2° of palaeolatitudinal separation of their closest margins (Fig. 4a). However, in the most recent and best-constrained palaeomagnetically determined reconstructions, shown in Figure 4c–f at 550–535 Ma and in Figure 5 at 550 Ma, the margins of Baltica and Siberia were separated by about 20–30° of palaeolatitude by a major ocean that Torsvik & Rehnström (2001) termed the Aegir Sea from the God of Oceans in Nordic mythology. Further confirmation of this wide separation has been provided by Li & Powell (2001), Kheraskova *et al.* (2003), Meert & Torsvik (2003) and Metelkin *et al.* (2005).

(2) McKerrow *et al.* (1992) pointed out that archaeocyathans in Siberia (Fig. 4b) formed reef-like assemblages in warm seas similar to those in which modern coral reefs grow within 30° of the equator, and evaporites had similar latitudinal constraints. However, the benthic olenellid trilobite fauna of Baltica required a cooler climate and higher latitude. McKerrow *et al.* concluded that Siberia and Baltica were separated by an ocean *c.* 1500 km wide in the early Cambrian.

(3) The existence of an ocean between Siberia and Baltica in the latest Neoproterozoic is confirmed by the presence of ophiolites in Kazakhstan and the Altai, as pointed out by Bykadorov *et al.* (2003).

Whereas in the model of Figure 4a the subduction zone of the Kipchak island arc dips towards Siberia and Baltica, in Figure 4d and e the subduction zone dips away from Siberia and Baltica towards and below the island arcs of Avalonia and Armorica.

The traditional orientation of Baltica is shown in Figure 4c. Hartz & Torsvik (2002) proposed the revolutionary 'Baltica upside-down' model, but Murphy *et al.* (2004) argued that the geological relations are not consistent with the upside-down orientation. If Murphy *et al.* (2004) are correct, then the relevant margins of Baltica and Siberia in Figure 4c and f were not aligned to allow the formation of a continuous arc on them.

The palaeogeographical configurations in Figures 4c–f and 5 are based on the best available palaeomagnetic data. Taken together, the configurations and the points raised above completely negate the existence of a single Kipchak arc along a continuous continental margin in the earliest Cambrian.

Tectonic evolution 542–250 Ma

We present a new tectonic map of Kazakhstan and contiguous China in Figure 6 with a cross-section in Figure 7, and a palinspastic map in Figure 8. In Figures 8 and 9 we show tectonic scenarios for the same time-slice at *c.* 390 Ma to illustrate the differences between the contrasting models of Filippova *et al.* (2001) and Sengör *et al.* (1993), updated to Sengör & Natal'in (2004). In Figure 9 it should be noted that the Tuva–Mongol arc is that part of the Kipchak arc NW of the Kazakhstan orocline.

Kazakhstan microcontinent

Kazakhstan comprises a collage of Precambrian microcontinental fragments and Early Palaeozoic island arcs (Fig. 8). Microcontinents are characterized by Palaeoproterozoic basement and Neoproterozoic to Early Palaeozoic cover. Many basement schists and gneisses in different parts of Kazakhstan and the Tien Shan have Proterozoic and Late Archaean (2.6–1.2 Ga) isotopic ages (Kasymov 1994). Kröner *et al.* (2006) obtained late Archaean and Palaeoproterozoic ²⁰⁷Pb/²⁰⁶Pb zircon protolith ages for gneisses in southern Kazakhstan. Microcontinents are largely bounded by ophiolite-strewn sutures (Fig. 6) that are mutually very different and thus indicate distinctly different depositional settings and geological histories during the Vendian and Early Palaeozoic. Such features imply that originally they were mutually isolated, allochthonous blocks.

The Precambrian fragments have been considered to be derived from the margin of East Gondwana (Mossakovsky *et al.* 1993; Kheraskova *et al.* 2003), or from the Siberian Baikaliid margin by Neoproterozoic (Berzin & Dobretsov 1994) or Cambrian (Sengör & Natal'in 1996b) rifting. An East Gondwana provenance is favoured by palaeomagnetic data that indicate that individual microcontinents (Stepnyak–North Tien Shan, Fig. 6) and later the amalgamated Kazakhstan continent drifted northwards from at least the early Ordovician to the Permian (Bazhenov *et al.* 2003; Collins *et al.* 2003; Alexyutin *et al.* 2005). This is also supported by similarities between late Neoproterozoic to early Palaeozoic passive margin sediments in south Kazakhstan (Ishim–Middle Tien Shan microcontinent, Fig. 6), China, Tarim and Australia (Eganov & Sovetov 1979). Kazakhstan was not included as a microcontinent in the model of Sengör *et al.* (1993) and Sengör & Natal'in (1996a, b, 2004), who instead incorporated the rifted Baikaliid fragments with the Cambrian Kipchak island arc (Fig. 4a). A bend in the latter gave rise to the Kazakhstan orocline, which was driven into the growing gap between Siberia and Baltica.

A number of island arcs ranging in age from Cambrian to Early Silurian occur within the Early Palaeozoic accretionary collage of the Kazakhstan continent (Fig. 6). Synthesized geological and geochemical data suggest that some arcs developed on oceanic crust (Baidautlet–Akbastau arc, Fig. 6), others on heterogeneous basement that included oceanic and continental fragments (Boshchekul–Chingiz and Selety arcs, Fig. 6), and some on continental crust (Stepnyak–North Tien Shan arc, Fig. 6) (Degtyarev 1999; Filippova *et al.* 2001). The presence of continental basement is indicated by the widespread occurrence of Precambrian felsic metamorphic rocks within some arcs, and by zircon xenocrysts in arc volcanic rocks. For instance, Early Ordovician andesites with zircon evaporation ages of 477–480 Ma in the Chu–Yili mountains in southern Kazakhstan contain xenocrysts as old as 2288 Ma, which indicates a Palaeoproterozoic substratum (Kröner *et al.* 2006). From palaeogeographical data (green, fine-grained marine deposits and lack of continental clastic molasse) we envisage that Ordovician epi-continental arcs had a low relief, similar to present-day west Indonesia or Alaska, rather than the high-relief Andes.

Early Palaeozoic arcs in Kazakhstan, with the sole exception of the Boshchekul Chingiz arc (Fig. 6), are generally characterized by relatively short periods of volcanic activity, which, according to faunal data, were not synchronous (see Fig. 6 for ages). This feature argues against models that suggest the existence of permanently active arcs from the Vendian to the Early Palaeozoic, and instead suggests several independent and

short-lived arc systems that were welded together by a process of consecutive collisions.

Microcontinents and island arcs are separated by suture zones that represent narrow belts of deep, marine, volcanic and sedimentary formations and ophiolites. These rocks, ranging in age in different zones from Neoproterozoic to early Silurian (Avdeev 1984; Yakubchuk 1990; Kröner *et al.* 2006) originally formed in basins with oceanic crust and were then incorporated into accretionary wedges and collisional sutures. Several sutures contain HP to UHP metamorphic rocks, such as diamond-bearing rocks in the Cambrian Kumdykol suture at Kokchetav (Parkinson *et al.* 2002), and eclogites in the Makbal area (Tagiri *et al.* 1995) in the west of the Early Ordovician Kirgiz–Terskey suture (Fig. 6). The Kumdykol suture comprises a subhorizontal pile of nappes, predominantly composed of pelitic–psammitic schists, gneisses, amphibolites and orthogneisses, with discontinuous lenses of eclogite, marble, whiteschist and garnet pyroxenite. The presence of diamond and coesite inclusions in zircons indicates that highest *P–T* conditions reached 37–60 kbar and 780–1000 °C, and zircons from diamond-bearing gneisses have SHRIMP U–Pb ages of 530 ± 7 Ma, which documents the peak metamorphism (Parkinson *et al.* 2002). The suture includes continental margin rocks that were subducted to the south (present coordinates); material in the core of the nappe reached 200 km depth and in the margins 30–40 km, and exhumation is interpreted to be by wedge extrusion towards the foreland (Parkinson *et al.* 2002).

Ophiolites in some suture zones, as in the Dzhair Naiman belt (Fig. 6), are associated with abundant clastic sediments, from which Avdeev (1984) concluded that the derivative oceans were relatively narrow. In other belts (e.g. Erementau–Yili, Fig. 6) sediments comprise cherts with very condensed sections, which indicate open oceanic settings. Based on the fact that many accretionary wedges developed over tens of million years, the width of the oceanic basins that were consumed during subduction can be estimated to within hundreds or a few thousand kilometres.

Ages of accretion, estimated according to stratigraphic and structural data, are summarized in Figure 6. The directions of subduction of the principal belts shown on the map are deduced from a variety of criteria that include Na–K petrochemical zoning of arc magmatic rocks, relative position of arcs with respect to coeval accretionary wedges, predominant thrust vergence in accretionary wedges (for cases where thrusts are proven to form synchronously with arc magmatism), and the relative position of continental and deeper marine areas with respect to a magmatic arc (Fig. 6).

Amalgamation of major island arcs and microcontinents to form the Kazakhstan continent was generally completed by the Late Silurian. In the Early Devonian subduction under the Kazakhstan continental margin gave rise to a major Andean-type magmatic arc (the ‘Devonian’ belt, Fig. 6). This is consistent with the conclusion of Heinhorst *et al.* (2000) from a study of hydrothermal ore deposits in Central Kazakhstan that ‘growth of the continental crust since the Ordovician was not accomplished by the accretion of island arcs, but by active continental arc magmatism’.

Continuing accretion in front of the arc led to oceanward roll-back of the subduction zone in the late Devonian, which displaced the active margin arc eastwards to the Balkhash–Yili belt (Fig. 6). In this younger arc volcanism continued in a subduction setting from the Famennian to the Late Carboniferous or earliest Permian (Kröner *et al.* 2006), and in a collisional setting during the Permian. The curved shape of the Balkhash–

Yili and Devonian volcanic belts reflects oroclinal bending, probably in the Permian. This bending, which is indicated by structural (Zonenshain *et al.* 1990) and palaeomagnetic data (Levashova *et al.* 2003), was apparently a result of the opposing motion of the Siberia and Tarim continents, which squeezed Kazakhstan during the latest stage of collision.

The western and southern margins of Kazakhstan lack evidence of volcanic activity from the Givetian to the Serpukhovian and Bashkirian, and instead became passive margin carbonate platforms at that time (Alexeiev *et al.* 2000; Cook *et al.* 2002). Subduction under the Kazakhstan continent that began in the mid-Carboniferous led to convergence and collision of Kazakhstan with the Turan (Karakum) and Tarim continents in the south.

Palaeo-Asian oceans

In the following sections we follow the archipelago model of Filippova *et al.* (2001); this is not to say that we believe this model is perfect, but that it offers the most likely conceptual direction. Kazakhstan divides the Palaeo-Asian ocean into four interconnected oceans (Fig. 8), namely: Ob–Zaisan (between Siberia and Kazakhstan), Uralia (between Baltica and Kazakhstan), Turkestan (between Kazakhstan and Tarim), and Junggar–Balkash (between the limbs of the Kazakhstan orocline). Much documentation of this western part of the Central Asian Orogenic Belt was synthesized by the international project between Azerbaijan, Kazakhstan, Kyrgyzstan, China, Russia, Tajikistan, Turkmenistan and Uzbekistan that led to a major lithological–palaeogeographical atlas (Daukeev *et al.* 2002). Filippova *et al.* (2001), Bykadorov *et al.* (2003) and Kheraskova *et al.* (2003) utilized palinspastic maps from this atlas. According to Filippova *et al.* (2001) and Kheraskova *et al.* (2003), Tarim was rifted off the eastern margin of Gondwana. Subduction within the Uralian ocean began first in the Tagil arc in the Mid-Urals in the Late Ordovician to Early Devonian, and continued in the Magnitogorsk arc in the southern Urals in the Early–Late Devonian (Puchkov 2000; Figs 1 and 6). In the Devonian, island arcs developed around the margins of the Siberian craton, whereas passive margins surrounded the Tarim and Baltica (East European) continents. The margin of the East European craton occupied by the pre-Caspian Basin faced the open Palaeo-Asian ocean and was passive throughout the entire Palaeozoic. Abundant nutrient supply against an open ocean in the late Devonian–early Permian led to major carbonate platforms with organic-rich shales that host giant oil- and gas-fields. As Bykadorov *et al.* (2003) pointed out, this geology is not compatible with active subduction on the southeastern margin of the East European craton as envisaged by Sengör *et al.* (1993), or indeed the closed back-arc Khanty–Mansi ocean of Yakubchuk (2002).

Siberia–Kazakhstan collision

Closure of the Ob–Zaisan ocean (Fig. 8) led to collision of the Siberian and Kazakhstan continental terranes or blocks. We follow Buslov *et al.* (2001), who first recognized that the overall collision zone is composed ‘from NE to SE’ of blocks or terranes separated by reactivated suture zones (Figs 1 and 6): the accretionary Gorny Altai block and the Charysh suture, the Altai–Mongolian block and the Chara suture.

The Gorny Altai block

This accretionary block (Figs 1, 6 and 8) contains tectonic fragments of a Vendian–Cambrian juvenile island arc and an

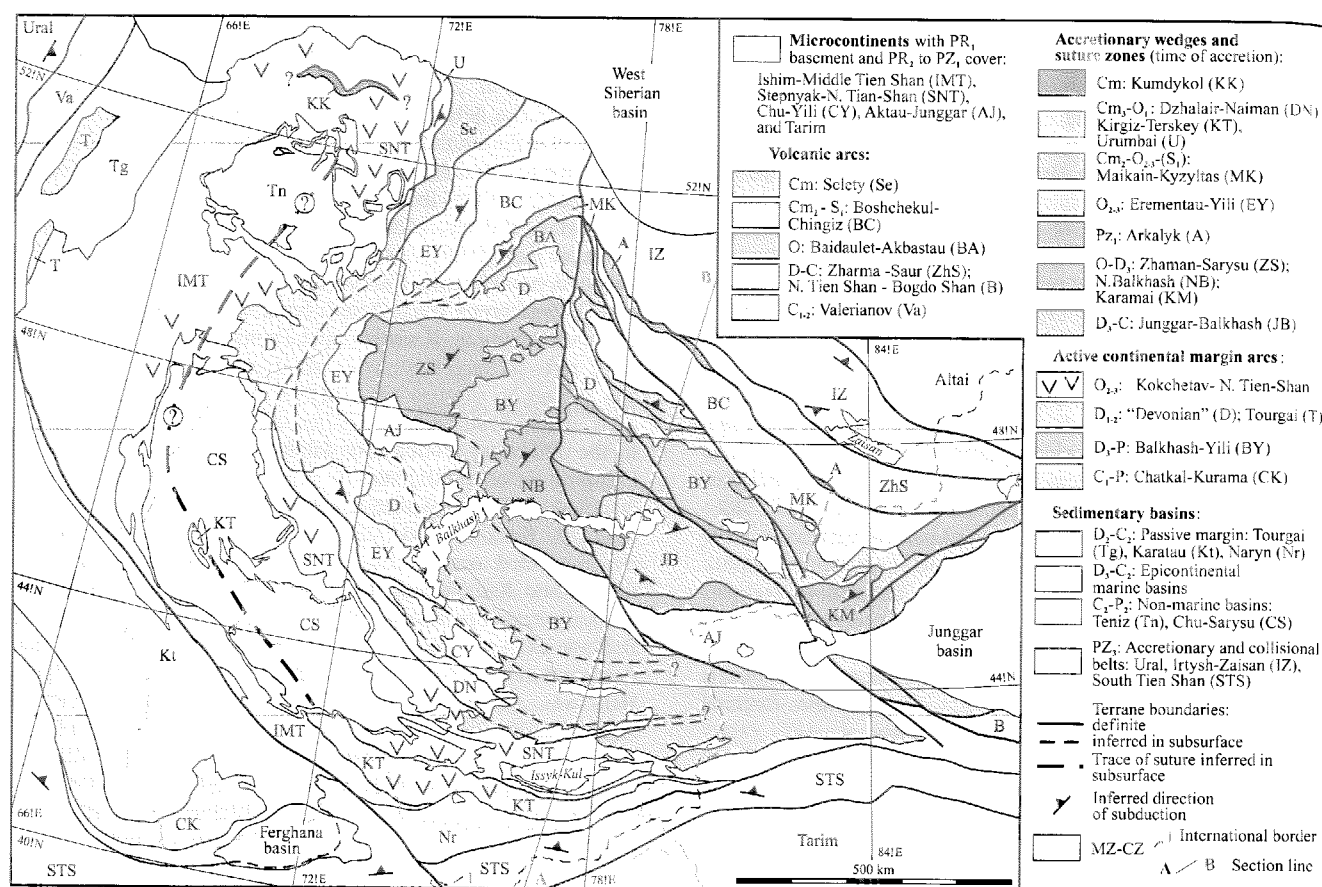


Fig. 6. Geotectonic map of the Palaeozoic of Kazakhstan and contiguous China. Position of the section of Figure 7 is shown. Compiled from many published sources. Compiled from Abdulin & Zaitsev (1976), Avdeev (1984), Yakubchuk (1990), Degtyarev (1999) and other sources. PR, Proterozoic; Cm, Cambrian; O, Ordovician; S, Silurian; D, Devonian; C, Carboniferous; P, Permian; PZ, Palaeozoic; MZ, Mesozoic; CZ, Cenozoic. Subscripts 1, 2, 3 refer to Early, Middle, Late.

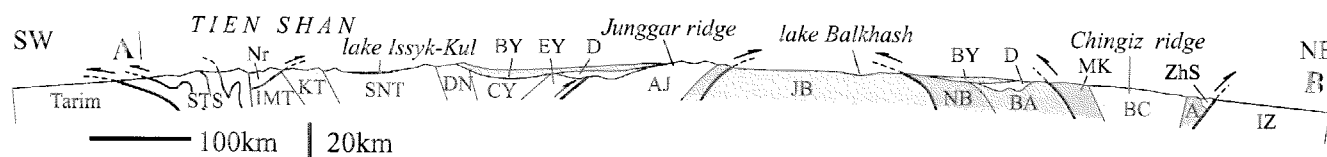


Fig. 7. Schematic cross-section across Kazakhstan from the Tarim basin to the Altai along line indicated in Figure 6. Abbreviations are as in Figure 6. Vertical exaggeration is 1:2.

oceanic plateau or seamount, a Cambrian accretionary prism with fragments of basalts with ocean island basalt (OIB) chemistry and MORB-type basalts, an early to mid-Cambrian island arc with calc-alkaline rocks and shoshonites, a forearc basin containing mid-late Cambrian turbidites, and a back-arc basin; U-Pb zircon ages on granites and metamorphic rocks in this block are *c.* 490 Ma (Dobretsov *et al.* 2004). Basalts that have a geochemical signature identical to that of modern oceanic plateau basalts are capped by shallow-marine, stromatolite-bearing limestones that have a Pb-Pb isochron age of 598 ± 25 Ma (Uchio *et al.* 2004). Watanabe *et al.* (1994) pointed out that the Gorny Altai arc is compositionally similar to the incipient Izu-Bonin arc of Japan, and Ota *et al.* (2006) compared it with the

Pacific Mariana arc on account of its boninites, deep-sea pelagic sediments and absence of continental sedimentary material.

There are many high-pressure rocks in the Gorny Altai that formed in subduction-accretion complexes. Eclogites (2 GPa at 660 °C) and garnet amphibolites associated with an island arc and accretionary prism at Chagan-Uzun in the Gorny Altai have an $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of *c.* 630 Ma (Buslov *et al.* 2001; Ota *et al.* 2002). In the south the Vendian-Cambrian Kurai accretionary prism (Dobretsov *et al.* 2004) contains lenses of oceanic island basalts, retrogressed eclogites, garnet amphibolites, barroisite-actinolite schists in a serpentinite matrix, and a seamount capped with black limestone that has a Pb-Pb whole-rock age of 577 ± 100 Ma (Uchio *et al.* 2001). Other blueschists have

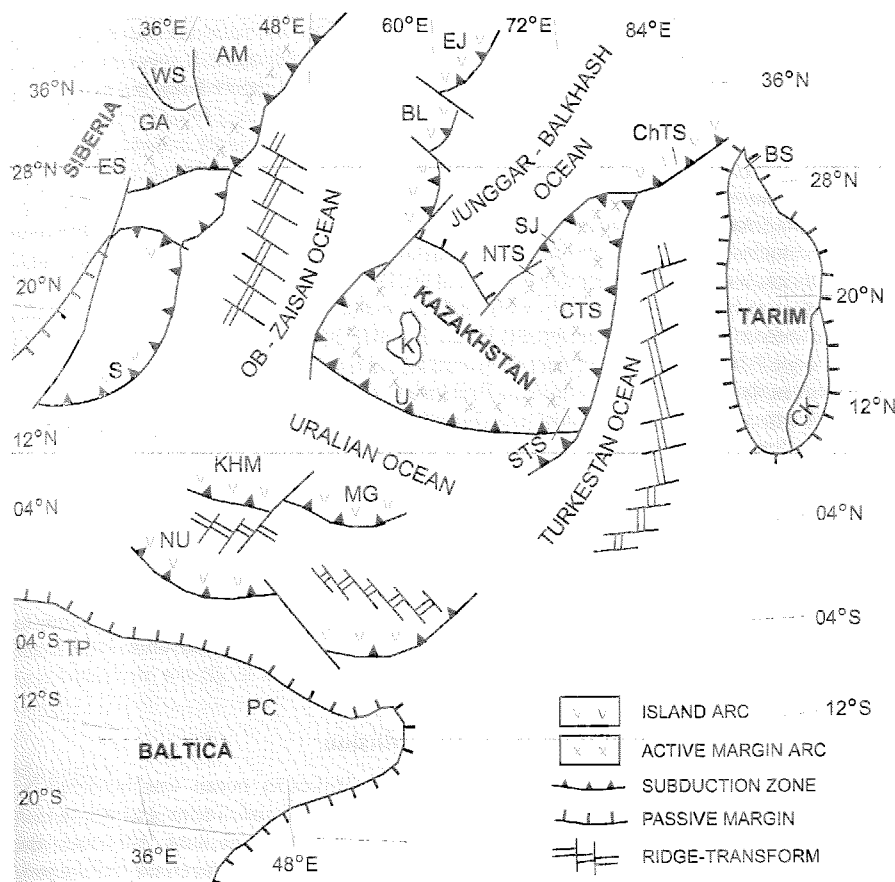
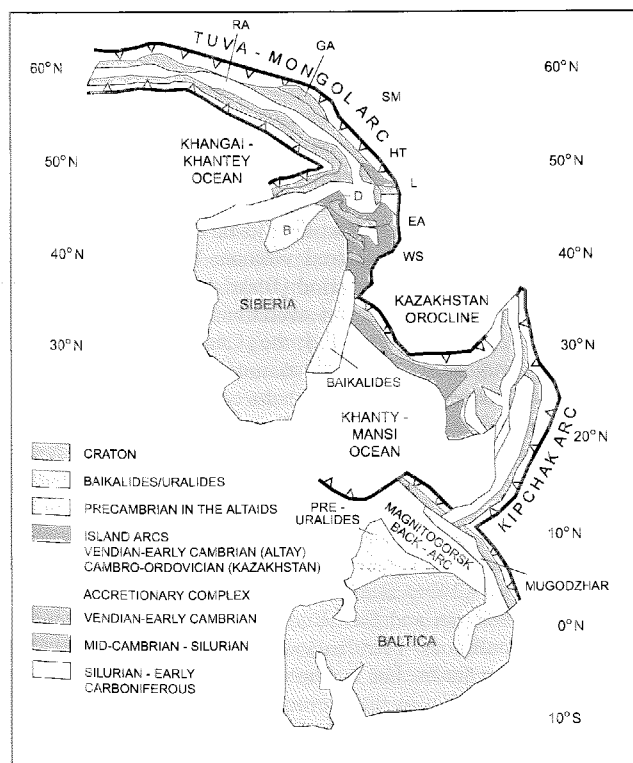


Fig. 8. Palinspastic map of the Central Asian Orogenic Belt for the early Devonian (390 Ma). AM, Altai-Mongol; BL, Barlyk arc; BS, Beishan; ChTS, Chinese Tien Shan; CK, Central Kunlun; CTS, Central Tien Shan; EJ, East Junggar; ES, East Sayan; GA, Gorny Altai; K, Kokchetav; KHM, Khanty-Mansi; MG, Magnitogorsk; NTS, North Tien Shan; NU, North Urals; PC, Pre-Caspian basin; S, Salym; SJ, Southern Junggar; STS, South Tien Shan; TP, Timan-Pechora; WS, West Sayan; U, Ubagan. Modified after Filippova *et al.* (2001).



Ordovician $^{40}\text{Ar}/^{39}\text{Ar}$ ages on phengite and glaucophane of 491–484 Ma, and their trace element chemistry is comparable with that of alkaline basalts of oceanic islands (Volkova *et al.* 2005). The Gorny Altai block contains evidence of arc and oceanic plateau growth in an intra-oceanic environment in the Vendian-Cambrian and later accretion and subduction to high pressures.

The Charysh suture

This is a subduction-accretion-collision zone (Fig. 1) that was reactivated by strike-slip faulting in the late Carboniferous-early Permian. It contains tectonic lenses of Vendian-Eifelian rocks derived from the Siberian continent (lithological similarities), a mélange with lenses of ocean plate stratigraphy rocks (gabbros, basaltic pillow lavas, cherts containing late Cambrian-early Ordovician conodonts and radiolaria, and sandstones; Iwata *et al.* 1997). The volcanic rocks have N-MORB and OIB geochemical signatures; the latter are similar to Hawaiian basalts and suggest the presence of a plume in an open ocean between the Altai-Mongolian block and Siberia in the late Cambrian-early Ordovician (Buslov *et al.* 2001).

Fig. 9. Palaeotectonic reconstruction of the Altaids for the period 420–390 Ma modified after Sengör & Natal'in (2004). B, Barguzin; D, Dzhida; EA, Eastern Altai; GA, Gorny Altai; HT, Khantaishir; L, Lake (Ozernaya); RA, Rudny Altai; SM, South Mongolia; WS, Western Sayan.

The Altai–Mongolian block

This 1000 km long microcontinent extends southwards from the Rudny Altai in Siberia, via the Altai of western Mongolia, to the Chinese Altai (Figs 1 and 8). It is dominated by Vendian–Cambrian quartz–feldspar polymictic sandstones and siliceous shales. According to Buslov *et al.* (2001), these are passive margin, shelf and continental slope terrigenous sediments. However, in western Mongolia they also contain volcanoclastic sediments, intermediate–mafic volcanic rocks, mélanges with basalt, andesite and tuff lenses, and thrust-imbricated metabasites, suggesting deposition or formation in an arc-proximal setting (Badarch *et al.* 2002). Farther SW, in the Chinese Altai, this terrane contains a central block of high-grade gneisses thrust southward over a late Silurian–early Devonian island arc with formation of inverted, Barrovian-type metamorphic isograds (Windley *et al.* 2002). The collisional and exhumation processes led to formation and emplacement in this central block of abundant juvenile Devonian–Carboniferous granites derived by mixed arc–crust melting (Chen & Jahn 2002). On the southern margin of this block, felsic arc-type lavas have a $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age of 505 ± 2 Ma, reflecting the time of arc volcanism, and contain zircon xenocrysts with ages between 614 and 921 Ma, suggesting that this is an Andean-type arc built (by northward subduction) on the margin of this block of continental crust (Windley *et al.* 2002). Another Andean-type Ordovician magmatic arc is situated on the northern side of the central block. Xiao *et al.* (2004a) demonstrated that in a NE–SW transect across this terrane from Mongolia to China accreted rocks young progressively from Neoproterozoic in the north to Carboniferous in the south; this is consistent with a northward-subducting, roll-back forearc accretion model (Sengör *et al.* 1993). However, the presence of an ‘out-of-time-sequence’ of an Ordovician–Devonian arc, and of Ordovician and Devonian ophiolites demonstrates that the evolutionary process was more complicated, and involved docking and collision of arcs and ophiolites from the ocean northwards to the accreting margin.

The Rudny Altai block

This block (Figs 1 and 9) is situated along strike to the NW of the Altai Mongolian block. It consists largely of basal Silurian oceanic basalts and greenschist-facies early Devonian sandstones and mudstones regarded as forearc trough sediments. Late Devonian–Carboniferous reef limestones associated with tuffs accumulated near an island arc (Buslov *et al.* 2001).

The Chara suture

This c. 1000 km long collisional suture zone (Fig. 1) is located on the northeastern margin of the Kazakhstan continent. It contains ophiolites, high-pressure rocks and three types of tectonic mélanges (Buslov *et al.* 2001).

Type I mélange is an accretionary prism containing lenses of high-pressure gabbro, basalt, volcanoclastic rocks, greywacke, chert, eclogite, garnet amphibolite and glaucophane schist (Dobretsov *et al.* 1992). Muscovites from eclogites and blueschists have K–Ar ages of 429–444 Ma.

Type II mélange is a 250 km long Ordovician ophiolitic mélange. It contains blocks of peridotite, gabbro, oceanic basalt, siliceous mudstone and chert with radiolaria of mid-Devonian–early Carboniferous age. The lavas are high-Al and high-Ti alkali plagiobasalts, interpreted to have formed at a mid-ocean ridge (Buslov *et al.* 2001).

Type III is a late Carboniferous–early Permian mélange containing blocks of types I and II mélanges. It separates tectonic sheets that were brought to the Chara suture from the margins of the Siberian and Kazakhstan continents.

Baltica–Kazakhstan collision

Closure of the Uralian ocean (Fig. 8) led to collision between Baltica and the Kazakhstan continent starting from the mid-Carboniferous (Puchkov 1997). Early collision of the Magnitogorsk arc with Baltica occurred in the late Devonian–early Carboniferous, when Kazakhstan was still far away. The main convergence between Kazakhstan and Baltica was in the mid-Viséan to mid-Bashkirian, as documented by volcanism in the Valerianov arc (Figs 1 and 6; Filippova *et al.* 2001). Thrust-nappe stacking led to crustal thickening and generation of crustal melt granites in the central Urals, and subduction of material derived from the leading edge of Baltica gave rise to ultrahigh-pressure metamorphism (coesite and graphite after diamond) in the Maksyutov Complex (Fig. 1), which was exhumed at 300 ± 25 Ma (Leech & Stockli 2000). A major foreland basin developed on the Baltica side from the mid-Carboniferous to Permian when a foredeep migrated westwards onto the former shelf of the continental margin.

Kazakhstan–Tarim collision

In the early Palaeozoic the Turkestan ocean was bordered by passive margins of the Kazakhstan and Tarim cratons, which evolved into active margins with island arcs. However, the tectonic environments of the margins are uncertain and controversial. According to Filippova *et al.* (2001), subduction beneath the Kazakhstan continent in the early and mid-Devonian gave rise to an active continental margin in which low-K calc-alkaline rocks on the ocean side passed to high-K shoshonites–latite lavas on the continental side; this now belongs to the North Tien Shan volcanic belt (Figs 6 and 8). However, although such volcanic centres, mainly with felsic lavas of early and mid-Devonian age, are widespread in the northern Tien Shan of Kazakhstan, we emphasize that very little is known about their tectonic environment; they may have formed in a continental magmatic arc or as a result of rifting or hotspot activity.

There was a passive continental margin in western Kazakhstan from the Givetian to mid-Viséan (Cook *et al.* 2002) and on its southern side from the Givetian to mid-Bashkirian (Alexeev *et al.* 2000). No subduction-derived volcanic belts formed within the Turkestan ocean in this period (Biske 1996). In the western South Tien Shan of Kyrgyzstan accretionary wedges started to form in the latest Viséan, and the Chatkal–Kurama active continental margin arc (Fig. 6) was initiated in the SW of the Kazakhstan continent (Biske 1996). In eastern Kyrgyzstan subduction began in the mid-Bashkirian, as indicated by synchronous cessation of passive margin sedimentation in the Naryn area (Fig. 6; Alexeev *et al.* 2000) and by initiation of thrusting in the eastern South Tien Shan (Biske 1996). In contrast, in the western segment of this convergent margin, subduction volcanism was suppressed.

Buslov *et al.* (2004) demonstrated that the collision of the Kazakhstan, Siberian and East European (Baltica) continents in the late Carboniferous–Permian led to the formation of several major strike-slip faults. For example, the Charysh suture underwent sinistral faulting in the Devonian–late Carboniferous. The 10 km wide Irtysh (Erqis) fault (Fig. 6) and the Chara suture zone underwent several hundred kilometres of sinistral displace-

ment in the late Carboniferous (Buslov *et al.* 2001). In the early Permian, dextral faulting took place in the Urals and sinistral faulting in the South Tien Shan and along the Siberian margins (Filippova *et al.* 2001), and in the late Permian there was sinistral strike-slip between Baltica and Siberia. These strike-slip displacements were caused by differential movements and rotation of the main continental blocks during collisional and post-collisional times (Buslov *et al.* 2003).

Junggar–Balkash closure

In the early Devonian the Junggar–Balkash ocean (Fig. 8) closed by convergence of opposite-dipping subduction zones on the two limbs of the wing-shaped Kazakhstan structure (see Fig. 6); the evidence for this is in island arcs in present-day eastern Junggar and the Chinese Tien Shan. Partly by oceanward retreat of the two subduction zones, the ocean closed progressively with development of numerous island arcs in the mid-Devonian (Ili, central Junggar), by the end-Devonian (eastern Junggar) and to the late Carboniferous (Bogdoshan in the eastern Chinese Tien Shan). The ocean disappeared by the early Permian and gave rise to the Junggar orogenic belt (Filippova *et al.* 2001). Ophiolites that are preserved as relicts between many of these arcs in Kazakhstan are mostly of suprasubduction-zone type (Yakubchuk 1990).

Mongolia

We now consider the area of Mongolia (Fig. 2). We have already considered the Archaean Baydrag massif as part of the Tuva–Mongolian microcontinent with Neoproterozoic ophiolites on its northern and southern sides.

The predominantly early Palaeozoic domain of northern Mongolia is separated from the dominant late Palaeozoic domain of southern Mongolia by a prominent structural boundary, the Main Mongolian Lineament (see Figs 2 and 3; Badarch *et al.* 2002). Following Zonenshain *et al.* (1990), Sengör *et al.* (1993) demonstrated that the arcs young progressively southwards from the Vendian–early Cambrian to the Carboniferous–Permian. In the northern domain the island arcs, accretionary wedges, passive and active margins, and Precambrian microcontinents had mostly amalgamated by the end of the Ordovician to create a stabilized block bordered on its southern side by the Main Mongolian Lineament. Evidence for such stabilization is provided (see Fig. 2) by Neoproterozoic shelf sediments on older cratons, Ordovician clastic basins unconformable on older rocks, belts of Cambrian–early Ordovician granites, and an extensive belt (Fig. 2) of little-deformed, Ordovician–Silurian rhyolites, ash-fall tuffs, and sub-volcanic granites (Kröner *et al.* 2006). These silicic rocks were not derived solely from juvenile sources such as island arcs, because some contain Precambrian xenocrystic zircons, and provide Nd mean crustal residence ages ranging from 1300 to 600 Ma, suggesting that older continental material was involved in their generation. They are similar to the rhyolite–ash fall tuff fields of the late Permian–Triassic Choiyoi province of the Chilean Andes (Kay *et al.* 1989) and the Jurassic Tobifera of Patagonia and Antarctica (Pankhurst & Rapela 1995). It is widely agreed that such silicic magmas were generated by ponding, at the base of or within preheated lower crust, of basaltic magmas that provided heat for substantial partial melting of hydrous crustal rocks that formed only a few hundred million years earlier. A common factor they share is their presence on a stabilized active margin, which, as Bryan *et al.* (2002) pointed out, is ideal for their generation. We suggest that

the Main Mongolian Lineament marks a major late Ordovician plate boundary at which north-dipping subduction of oceanic lithosphere occurred in the early Palaeozoic (Fig. 3) and led to emplacement of a hydrous mafic magma that triggered partial melting and production of the voluminous silicic melts.

The southern domain of Mongolia is dominated by Silurian, Devonian and Carboniferous accretionary complexes and arc-related volcanic–volcaniclastic rocks (Lamb & Badarch 1997). The Gobi Altai terrane (Badarch *et al.* 2002) on the immediate southern side of the Main Mongolian Lineament contains a 15 km wide belt of Devonian fossiliferous marbles that formed on a passive margin. The massive porphyry Cu–Au deposit at Oyu Tolgoi (Figs 2 and 3) occurs in a Silurian–Devonian island arc (Perello *et al.* 2001). Sm–Nd isotopic data indicate that most arc rocks (Helo *et al.* 2006), and intrusive post-tectonic granitic rocks (Jahn *et al.* 2000) have positive $\epsilon_{\text{Nd}(t)}$ values, indicating that they are largely juvenile, although some rocks contain Precambrian zircon xenocrysts (Kröner *et al.* 2006).

The Tseel terrane (Fig. 2) in SW Mongolia contains greenschist-grade early Devonian volcanic arc rocks with a mid-Devonian zircon age of c. 397 Ma that are metamorphosed progressively across strike southwards to amphibolite-facies migmatitic amphibolites and gneisses from which zircons were dated at 360.5 ± 1.1 Ma by Kröner *et al.* (2006); those workers suggested that the high-grade rocks represent the root of an arc system. Kozakov *et al.* (2002) reported similar U–Pb ages of 371 ± 2 Ma to 365 ± 4 Ma for low-grade rocks and 385 ± 5 Ma for granites in migmatized amphibolite-facies rocks 80 km to the east along strike from Tseel. An alternative interpretation is that ridge subduction within the overall accreting system was responsible for the high-grade metamorphism and granites of the Devonian arc, because such rapid increases of metamorphism and associated granites are typical of ridge subduction in modern accretionary orogens such as Alaska (Sisson *et al.* 2003).

Yarmolyuk *et al.* (2005) reported Grenville-age rocks (U–Pb zircon crystallization age of 952 ± 8 Ma on a gneissic granite) in the South Gobi microcontinent in SSE Mongolia, the Hutag Uul cratonic block of Badarch *et al.* 2002 (Fig. 2). This is the first indication that this continental block may have been derived from the northern margin of the North China craton, where Grenville-age rocks have been reported in continental rifts (Zhai *et al.* 2003).

Northernmost China

Finally, we come to the strip along northernmost China that contains the Solonker suture (Fig. 2) and information on the termination of the Central Asian Orogenic Belt.

The early accretionary history of the Chinese Altai was summarized above in the section on the Altai–Mongolian block. After the accretion of the island arcs, many garnet-bearing A-type crustal melt granites were emplaced, the early ones deformed into gneisses, and these amount to 40–60% of the surface area. Sm–Nd and Sr isotope data on granitic gneisses and post-orogenic granites indicate that both arc material and old continental crust contributed to their generation (Hu *et al.* 2000; Chen & Jahn 2002). Just west of the Keketuohai granite, Barrovian-type kyanite-grade metamorphic rocks are juxtaposed with Buchan-type andalusite-bearing rocks, and during arc-continent collision high-grade gneisses on the southern margin of the central Precambrian block were thrust southward over a late Silurian–early Devonian island arc with formation of inverted Barrovian-type isograds (Windley *et al.* 2002).

South of the Chinese Altai are island arc terranes in East and

West Junggar (Fig. 8) that contain many ophiolites, the geochemistry of which indicates derivation from mid-ocean ridges, island arcs and oceanic islands; Wang *et al.* (2003a) found that none had a typical back-arc signature. They used the Sengör *et al.* (1993) Kipchak arc model to explain the development of the arcs, but Xiao *et al.* (2004a) found that some arcs had grown in the ocean and docked northwards into already accreted arcs in a manner that is compatible with the accretion tectonics of Japan, but not with the Kipchak arc model (Sengör *et al.* 1993). Post-subduction crustal melt granites that intruded the arcs have positive $\epsilon_{\text{Nd}(t)}$ values (Hu *et al.* 2000), indicating that their sources were deep sections of recently accreted juvenile arcs (Wang *et al.* 2003a). In the northernmost eastern Junggar (Fig. 1) at Halatongke (Kalatongke) Carboniferous gabbro–norite bodies containing major nickel–copper deposits (Windley *et al.* 2002) are situated close to peralkaline A-type granites with Rb–Sr whole-rock isochron ages of 300 and 270 Ma that were emplaced in a post-collisional extensional environment (Han *et al.* 1997). Farther south the northern Tien Shan is dominated by Ordovician–Carboniferous island arc lavas and volcanoclastic rocks generated by variable subduction polarities to the north and south. The following rocks are distinctive (Xiao *et al.* 2004b).

(1) Early Permian zoned mafic–ultramafic complexes with copper and nickel deposits that Xiao *et al.* (2004b) regarded as analogous to the zoned mafic–ultramafic complexes in Alaska (Taylor 1967). The complexes in the Tien Shan are associated with coeval A-type granitic plutons.

(2) Considerable porphyry gold–copper, orogenic-type gold and epithermal gold deposits (Yakubchuk *et al.* 2001, 2005), many of which are similar to those in Alaska (Goldfarb *et al.* 2001; Xiao *et al.* 2004b).

(3) The Devonian Yushugou ophiolite has been strongly metamorphosed and now consists of lherzolitic garnet granulites and hypersthene–garnet amphibolites (Windley *et al.* 1990). This high-pressure granulite-facies ophiolite has SHRIMP zircon ages of 596 Ma (probably an inheritance age) and 430 Ma, and a later metamorphic zircon age of 398 ± 4 Ma (D. W. Zhou, cited by Xiao *et al.* 2004b).

The above three distinctive rock groups probably have the same thermal mechanism of formation, ridge subduction, as in the Cenozoic orogen of Alaska (Sisson *et al.* 2003). This idea is supported by a seismic refraction profile across the eastern Tien Shan by Wang *et al.* (2003b), who reported a homogeneity of the crust, which they interpreted as a result of 'a late Palaeozoic thermal event that caused the crust to undergo partial melting and differentiation' and gave rise to post-collisional granites that are independently indicated by 'a surprisingly low Poisson's ratio of 0.25–0.26 within the entire upper and middle crust, consistent with the intrusion of quartz-rich granites'. Zhou *et al.* (2004) suggested that the zoned mafic–ultramafic complexes and the A-type granites were generated by a mantle plume that provided the necessary heat and that arose under a zone of crust thickened by collision tectonics. However, the seismic data of Wang *et al.* (2003b) do not support the idea of massive crustal thickening, and such major thickening with consequent uplift is also inconsistent with the fact that the neighbouring arc rocks have not been strongly exhumed as they still have a greenschist-facies mineralogy. Ridge subduction is a better mechanism to provide the necessary heat.

The northern boundary of the Central Tien Shan block marks the Permian suture zone that represents the termination of the Central Asian Orogenic Belt (Xiao *et al.* 2004b). This suture can be traced eastwards to the Solonker suture (Figs 1 and 2) of

Inner Mongolia (Sengör *et al.* 1993; Xiao *et al.* 2003). The Solonker suture separates a northern accretionary belt that had consolidated by the Permian, when it developed into an Andean-type continental margin above a north-dipping subduction zone, from a southern accretionary belt that had consolidated by the Carboniferous–Permian when it evolved into an Andean-type continental margin above a south-dipping subduction zone. With final subduction of the intervening ocean, these two opposing continental margins collided to give rise to the Solonker suture (Xiao *et al.* 2003). Confirmation of the middle or late Permian age of the collision is provided by a widespread change in climate, from a Carboniferous–early Permian humid-climate, coal-bearing sedimentary facies to a late Permian–early Triassic arid climate with red beds (Cope *et al.* 2005). The Angaran–Cathaysian floral boundary of Central Asia coincides with the Solonker suture, and major post-collisional deformation in the Triassic–Jurassic led to formation of a vast south-directed fold-and-thrust belt of Himalayan proportions (Xiao *et al.* 2003b).

Thus the Central Asian Orogenic Belt underwent three final stages of tectonic development: early Japanese- or Alaskan-style accretion, Andean-style active continental margin formation and magmatism, and Himalayan-style collisional and post-collisional tectonics.

Discussion

From this review of the Central Asian Orogenic Belt several considerations emerge.

First, the dominant contrasting hypotheses to account for the Central Asian Orogenic Belt are the Indonesian multi-arc archipelago model, the Kipchak one-arc model, and the Kipchak three-arc model. Much current debate concerns the viability of these models, especially the last two.

The starting point of Altaid evolution was the assumption that Siberia and Baltica were attached to one another along their present boundaries in the Neoproterozoic (Sengör *et al.* 1993), thus allowing the Kipchak arc to form, all along the conjoined margin in the early Cambrian. However, all recent, best constrained, palaeomagnetic reconstructions are in agreement in placing a wide ocean between them. The presence of such an ocean, the Aegir Sea, is supported by ophiolite and faunal data.

The Kipchak arc model does not include the possibility of the accretion and docking of exotic fragments from the ocean into the arc. However, from geochemical data we can infer that the giant 665 Ma Bayankhongor ophiolite (Kovach *et al.* 2005) and the 598 Ma Baratal basalts in the Gorny Altai (Uchio *et al.* 2004) are fragments of oceanic plateaux that must have docked into the accretion front of the evolving orogen.

In Kazakhstan there are many distinct pre-Devonian subduction–accretion complexes and island arcs (Fig. 6) that have completely different lithologies and different geological histories (Nikitin 1972, 1973; Degtyarev 1999), and that are bounded by ophiolite-strewn sutures (Avdeev 1984; Yakubchuk 1990; Degtyarev 1999). It is not possible that these very different arcs were part of, or could be combined into a single island arc. Many stratigraphic and tectonic data indicate that the mutually different, early Palaeozoic complexes or terranes were amalgamated by subduction and accretion into a Kazakhstan microcontinent by the early Devonian. In other words, the Kazakhstan block could not have been created by the imbrication of a single arc, as depicted by Sengör *et al.* (1993, 1994) and Sengör & Natal'in (2004). Many Early Palaeozoic terranes in Kazakhstan lack a volcanic arc and consist only of shelf-type sediments, as in the Ishim–Middle Tien Shan unit (Fig. 6; Nikitin 1972; Eganov &

Sovetov 1979). Although their formation on the margins of older blocks plays an important role in an archipelago model for Kazakhstan, they are inconsistent with the concept of a single, dominant arc that was active from the late Vendian to the end-Silurian.

Second, interpretation of the overall structure and tectonic setting of the Altaid component of the Central Asian Orogenic Belt by Sengör *et al.* (1993), Sengör & Natal'in (2004), Yakubchuk (2004) and Yakubchuk *et al.* (2005) was based mainly on a definition of polarity of magmatic arcs, which in turn was based on position of magmatic fronts, as implied by Spiegelman & McKenzie (1987) for offshore intra-oceanic arcs such as the Aleutians. However, when such arcs move via a trench and an accretionary wedge into an accretionary orogen, their volcanic rocks and their forearc sediments become intensely thrust and folded, with the result that the arcs, which we see today in the Central Asian Orogenic Belt, have been highly shortened often to a fraction of their original width. All arcs have been deformed by folding, thrusting and/or strike-slip shaving. Alternatively, if arcs form by oceanward, roll-back accretion, they become highly deformed by thrusting and folding during subsequent arc accretion and by strike-slip shaving.

From our fieldwork in many arcs throughout the Central Asian Orogenic Belt we conclude that what we see today are largely tectonic relationships within and between arcs, and that existing data from many arcs are insufficient to draw definite conclusions on arc polarity. Use of thrust vergence to define subduction polarity is often possible, if one avoids complications caused, first, by the presence of back-thrusts inherited from the oceanic domain (e.g. where there has been double subduction as in the Moluccas), or of syn- to post-accretionary back-thrusts, and, second, by overprinting of synsubduction, accretionary thrusts by later imposed structures. For instance, in Early Palaeozoic rocks in central Kazakhstan thrust vergence is commonly the result of strong reworking in the mid-Devonian and early Carboniferous, and thus does not reflect original subduction polarity. Likewise, we consider that use of 'accretionary vergence beneath unconformable forearc deposits' as a means of defining subduction polarity (Sengör *et al.* 1993) is largely unreliable. The main uncertainties with such an approach are connected, first, with the usual deformation of unconformities in accreted arcs (resolvable in the field but not from published geological maps), and, second, with the ambiguous identification on maps and in the field of forearc versus back-arc sediments that can also overlie thrust-faulted complexes in both forearc and back-arc settings. Finally, we question the identification of some magmatic fronts in Kazakhstan where there is no magmatic arc of corresponding age; for example, in the early Palaeozoic of the Middle Tien Shan (Fig. 6).

Duplication of arcs by strike-parallel, strike-slip faulting is an essential part of the Kipchak model. However, we find little evidence for such structural repetition of arcs. ENE-trending sinistral strike-parallel faults are documented in the Tien Shan, and north-south-trending, sinistral faults in the Urals, but elsewhere there is almost no evidence that would support duplication.

Third, all proponents of the tectonic models of the Central Asian Orogenic Belt agree that the best modern analogues are to be found in the circum-Pacific. However, one of the most important tectonic controls in the formation of the accretionary orogens in Japan (Maruyama 1997) and Alaska (Sisson *et al.* 2003) was ridge-trench interaction, because virtually all subduction systems eventually interact with a spreading ridge. However, ridge subduction has not yet been considered in the published

literature of the Central Asian Orogenic Belt as a means of generating key features that are very similar to those in Japan and Alaska, although this may not be surprising, in so far as 'the impact of ridge-trench interactions on the development of orogenic belts is largely unappreciated' (Brown 1998). The first evidence of ridge-trench interaction in the Central Asian Orogenic Belt has been provided by Liu *et al.* (in press). We therefore summarize below some of the key features of the Central Asian Orogenic Belt that are explicable by ridge-trench interaction.

(1) The Central Asian Orogenic Belt is characterized by voluminous post-tectonic, post-accretionary granites *sensu lato*, especially of A-type composition. Although many of these in central-eastern Mongolia and Trans-Baikal are Mesozoic in age and a result of formation of the Mongol-Okhotsk orogen, elsewhere the majority are late Palaeozoic. Most granites have low initial Sr isotopic ratios, positive $\epsilon_{Nd(t)}$ values and Nd model ages (T_{DM}) of 300–1200 Ma (Jahn *et al.* 2000). The isotopic data indicate their largely juvenile character and imply juvenile sources. To account for the generation of the granitic liquids Jahn *et al.* (2000) suggested massive underplating of basaltic magma and partial melting of lower crustal rocks. Finding similar isotopic data for similar, post-tectonic, intraplate granites throughout the Central Asian Orogenic Belt, Kovalenko *et al.* (2004) concluded that each belt of granites was formed from recently accreted, juvenile, arc-dominated crust and inherited its isotopic signature. To account for the increased heat necessary to cause partial melting of the crust, they suggested the influence of mantle plumes and hotspots. However, there is no evidence for such plumes and hotspots in the Central Asian Orogenic Belt, nor indeed for basaltic underplating. There is no need for either process when the mechanism of ridge subduction is readily available and to be expected in an accretionary orogen. Let us consider the modern analogue of Japan, where 'the formation and intrusion of granitoids are the keys to continental growth which is the most important process in Pacific-type orogeny, the most important cause of which is the subduction of a mid-oceanic ridge' (Maruyama 1997). In Japan, ridge subduction has occurred every 100 Ma in the last 450 Ma. At a similar rate, there could have been at least seven ridge subductions in the evolution of the Central Asian Orogenic Belt. Ridge subduction tends to give rise to belts of new rocks such as granitoids at distinct time-intervals. For example, in the Chinese Altai the emplacement of crustal-melt granites took place in two broad intervals centred on 393 Ma and 317 Ma (Chen & Jahn 2002).

(2) In several places in this orogenic belt upper amphibolite- to granulite-facies belts are juxtaposed against greenschist-grade accretionary prisms, arcs and ophiolites; for example, the Burd Gol south of Bayankhongor, the Tseel-Tsogt belt, alternating belts in the Tuva-Mongolian microcontinent, and the granulite-facies Yushugou ophiolite in the Tien Shan. Such a juxtaposition of high- and low-grade metamorphic belts is characteristic of modern accretionary orogens and is a result of ridge subduction (Brown 1998; Iwamori 2000).

(3) Adakites occur in the Chinese Altai, eastern Junggar, and the Ili area of the Tien Shan, and comparable adakites and high-Mg andesites occur in Japan, Ecuador, Aleutians, Baja and California (Sisson *et al.* 2003). The production of these chemically distinctive rocks is widely regarded as a result of the subduction of hot young crust at a ridge that creates a slab window through which upwelling mantle rises to trigger crustal anatexis and high-grade metamorphism in the forearc: the 'blowtorch effect'.

(4) Other rocks in the Central Asian Orogenic Belt reviewed

in this paper that could be well explained by ridge subduction in a forearc environment are: (a) boninites in the Gorny Altai, Erqis unit in the Chinese Altai, Khantaishir ophiolite in Mongolia, and Dzhida zone of southern Siberia; (b) Ordovician–Silurian silicic lavas and granites in northern Mongolia; (c) Alaska-type zoned mafic–ultramafic complexes in the eastern Tien Shan; (d) mafic bodies with Ni–Cu deposits and associated peralkaline granites at Halatonke in the Chinese Altai; (e) near-trench intrusions of andesite dykes in the Burd Gol accretionary prism; (f) suprasubduction-type ophiolites that are commonly interpreted to have formed in a back-arc, but that ideally occur in a ridge-affected forearc (Sisson *et al.* 2003).

(5) Orogenic gold deposits are common throughout this orogenic belt and especially in the Tien Shan (Yakubchuk *et al.* 2005). The major orogenic gold deposits were interpreted to have formed in sutured back-arc basins (Yakubchuk 2004). However, in the eastern Tien Shan shear zone-type deposits are associated with Alaska-type Ni–Cu-bearing, zoned mafic–ultramafic bodies, and epithermal gold deposits were emplaced in post-accretionary times, followed by hydrothermal gold deposits (Zhang *et al.* 2004). These gold deposits more probably formed above a slab window created by a subducting ridge, as in Alaska (Haeussler *et al.*, in Sisson *et al.* 2003).

Conclusions

Field-based evidence, complemented by geochemical and isotopic data, strongly suggests that the main components of the Central Asian Orogenic Belt are similar to equivalents in Mesozoic–Cenozoic accretionary orogens of the circum-Pacific. Therefore, it is reasonable to use ‘modern’ accretionary models to explain the tectonic evolution of the Central Asian Orogenic Belt. The question arises: which model is the most viable? Recent palaeomagnetic data supported by faunal data are inconsistent with the Kipchak arc-based models, according to which Baltica and Siberia were joined together in the early Cambrian when this arc was supposed to have developed on the conjoined margin. Therefore, this negates the fundamental starting point and building-block of the model. Furthermore, current data provide little support for the main tenets of the one- or three-arc Kipchak model; they point towards an archipelago-type (Indonesian) model for the growth of the Central Asian Orogenic Belt.

Ridge–trench interaction provides a promising perspective for understanding many aspects of the evolution of this orogenic belt because many of its diagnostic features appear to be present.

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