Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Asian Earth Sciences 23 (2004) 761–779
Journal of Asian Earth Sciences
www.elsevier.com/locate/jseaes

Architecture and mineral deposit settings of the Altaid orogenic collage: a revised model

Alexander Yakubchuk

Department of Mineralogy, Centre for Russian and Central Asian Mineral Studies, Natural History Museum, Cromwell Road, London SW7 5BD, UK

Abstract

The Altaids are an orogenic collage of Neoproterozoic–Paleozoic rocks located in the center of Eurasia. This collage consists of only three oroclinally bent Neoproterozoic–Early Paleozoic magmatic arcs (Kipchak, Tuva–Mongol, and Mugodzhar–Rudny Altai), separated by sutures of their former backarc basins, which were stitched by new generations of overlapping magmatic arcs. In addition, the Altaids host accreted fragments of the Neoproterozoic to Early Paleozoic oceanic island chains and Neoproterozoic to Cenozoic plume-related magmatic rocks superimposed on the accreted fragments. All these assemblages host important, many world-class, Late Proterozoic to Early Mesozoic gold, copper–molybdenum, lead–zinc, nickel and other deposits of various types.

In the Late Proterozoic, during breakup of the supercontinent Rodinia, the Kipchak and Tuva–Mongol magmatic arcs were rifted off Eastern Europe–Siberia and Laurentia to produce oceanic backarc basins. In the Late Ordovician, the Siberian craton began its clockwise rotation with respect to Eastern Europe and this coincides with the beginning of formation of the Mugodzhar–Rudny Altai arc behind the Kipchak arc. These earlier arcs produced mostly Cu–Pb–Zn VMS deposits, although some important intrusion-related orogenic Au deposits formed during arc–arc collision events in the Middle Cambrian and Late Ordovician.

The clockwise rotation of Siberia continued through the Paleozoic until the Early Permian producing several episodes of oroclinal bending, strike–slip duplication and reorganization of the magmatic arcs to produce the overlapping Kazakh–Mongol and Zharma-Saur–Valerianov–Beltau-Kurama arcs that welded the extinct Kipchak and Tuva–Mongol arcs. This resulted in amalgamation of the western portion of the Altaid orogenic collage in the Late Paleozoic. Its eastern portion amalgamated only in the early Mesozoic and was overlapped by the Transbaikal magmatic arc, which developed in response to subduction of the oceanic crust of the Paleo-Pacific Ocean. Several world-class Cu–(Mo)-porphyry, Cu–Pb–Zn VMS and intrusion-related Au mineral camps, which formed in the Altaids at this stage, coincided with the episodes of plate reorganization and oroclinal bending of magmatic arcs. Major Pb–Zn and Cu sedimentary rock-hosted deposits of Kazakhstan and Central Asia formed in backarc rifts, which developed on the earlier amalgamated fragments. Major orogenic gold deposits are intrusion-related deposits, often occurring within black shale-bearing sutured backarc basins with oceanic crust.

After amalgamation of the western Altaids, this part of the collage and adjacent cratons were affected by the Siberian superplume, which ascended at the Permian–Triassic transition. This plume-related magmatism produced various deposits, such as famous Ni–Cu–PGE deposits of Norilsk in the northwest of the Siberian craton.

In the early Mesozoic, the eastern Altaids were oroclinally bent together with the overlapping Transbaikal magmatic arc in response to the northward migration and anti-clockwise rotation of the North China craton. The following collision of the eastern portion of the Altaid collage with the Siberian craton formed the Mongol–Okhotsk suture zone, which still links the accretionary wedges of central Mongolia and Circum-Pacific belts. In the late Mesozoic, a system of continent-scale conjugate northwest-trending and northeast-trending strike–slip faults developed in response to the southward propagation of the Siberian craton with subsequent post-mineral offset of some metallogenic belts for as much as 70–400 km, possibly in response to spreading in the Canadian basin. India–Asia collision rejuvenated some of these faults and generated a system of impact rifts.

Keywords: Altaid orogenic collage; Kipchak arc; Tuva–Mongol arc; Mugodzhar–Rudny Altai arc

1. Introduction

Suess (1908) suggested the term ‘Altaids’ for the orogenic system in the center of Asia, but during the 20th century it was mostly known as the Ural–Mongolian, Ural–Okhotsk, or Central Asian fold belt (Coleman, 1989; Zonenshain et al., 1990; Mossakovskiy et al., 1993). In the 1990s, Sengör et al. (1993) revived the term Altaids, which became very popular in the West. However, the other terms also remain in use, especially in Russian literature.

E-mail address: slaurum@aol.com (A. Yakubchuk).

1367-9120/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jseaes.2004.01.006

The Altaid orogenic collage hosts numerous gold, silver, copper–molybdenum, lead–zinc, and nickel deposits of Late Proterozoic to Early Mesozoic age. Therefore, the correct understanding of tectonics is important for the explanation of its rich metal endowment, which is a result of a prolonged and complex history of crustal growth and deformation in diverse tectonic settings.

The Altaids are framed by the pre-0.6 Ga orogens of the Baikalides and the Pre-Uralides and older cratonal blocks of Eastern Europe, Siberia, North China and Tarim. The Karakum, Tarim and North China blocks in the south separate the Altaids from the Tethysides. Various geoscientists have suggested different boundaries for the Altaids. Some of them considered the pre-0.6 Ga-old orogens and their fragments inside the collage as parts of a single orogenic system with the Altaids (see discussion in Milanovskiy, 1996). However, because the Baikalides represent a separate tectonic cycle of the opening and subsequent suturing of the oceanic (backarc) basin, it seems natural to consider them separately from the Altaids.

There is no common understanding about western, southwestern, northern, and eastern limits of the Altaids. The Urals, in particular, is often considered as an independent orogen due to its isolated position (Mossakovskiy et al., 1993; Sengör et al., 1993; Sengör and Natal'in, 1996), but other workers treat it as part of the Altaids (Zonenshain et al., 1990; Puchkov, 1993). The northern continuation of the Urals, in particular, and the entire Altaid orogenic collage, in general, is a subject for long-lasting debate (Hamilton, 1970). Many geologists (Puchkov, 1993, 1997; Milanovskiy, 1996) consider the orogens of Pai-Khoi and Novaya Zemlya archipelago as a 'degraded' continuation of the Urals, where oceanic/backarc spreading did not take place. The links between the fragments of orogens exposed on the Arctic islands are also far from clear. The Mesozoic–Cenozoic sedimentary basin of Western Siberia obscures significant parts of the orogenic collage in the north that also stimulated invention of various tectonic models for its basement.

The southwestern portion of the Altaid collage is also obscured under the Mesozoic–Cenozoic sedimentary basins and this uncertainty was a basis for various interpretations, such as a direct link between the Greater Caucasus and the Urals (Samygin and Khain, 1985), complete termination of the Urals under the sedimentary basin at the Ust-Yurt plateau or continuation of the Urals, or some of its zones, into the southern Tien Shan (Zonenshain et al., 1990; Puchkov, 1993; Milanovskiy, 1996).

Many geoscientists acknowledged that the central Mongolian structures could be traced into the Circum-Pacific orogenic belts via the Mongol–Okhotsk suture (Sengör et al., 1993; Sengör and Natal'in, 1996; Milanovskiy, 1996; Yakubchuk and Edwards, 1999). These Paleozoic lithologic units of central Mongolia form an oroclinal structure and cannot be traced to the central parts of the Altaid collage in Kazakhstan, being separated by the Precambrian slivers of western and southern Mongolia. On this basis, Parfenov et al. (2001) and Yakubchuk et al. (2001) suggested that central Mongolian structures could not be considered as part of the Altaid orogenic collage. It was suggested that these orogenic structures constitute a Mongol–Okhotsk orogenic belt (Parfenov et al., 2001) or Transbaikal–Mongolian orogenic collage (Yakubchuk, 2002), which should be viewed as a fragment of the Circum-Pacific orogenic belts and, therefore, the boundaries of the Altaid collage must be reconsidered.

Several mutually contradictory plate-tectonic interpretations of the Altaid collage or its parts have arisen in the 1990s (Zonenshain et al., 1990; Mossakovskiy et al., 1993; Sengör et al., 1993; Berzin et al., 1994; Didenko et al., 1994; Sengör and Natal'in, 1996; Puchkov, 2000). These works employ two principally different approaches to explain the origin of Precambrian slivers and Neoproterozoic–Paleozoic ophiolites in the Altaid collage.

Zonenshain et al. (1990) compiled schematic plate-tectonic reconstructions. They suggested that ophiolites of Central Asia represent the subducted crust of the Paleo-Asian Ocean that separated Eastern Europe, Siberia and Gondwana in the end of the Neoproterozoic. Using the same principle as in the Tethys orogenic belt, they suggested that numerous Precambrian slivers were rifted off Gondwana, drifted across the Paleo-Asian Ocean and docked to the East European and Siberian cratons to form the Central Asian fold belt. This model was based on the global reconstructions of Scotese and McKerrow (1990), which reflected the then widely accepted idea that large cratons of Laurentia, Eastern Europe and Siberia were rifted off the northern margin of Gondwana and therefore it was logical to suggest the same scenario for the smaller Precambrian units. In addition, the interpretation of Zonenshain et al. (1990) was developed in the early 1980s and was based on the assumption that most ophiolites in the Altaids are of Late Precambrian or Early Cambrian age and, therefore, older than magmatic arcs.

In the 1980s, Early Paleozoic conodonts were found in most ophiolites of Kazakhstan. This indicated synchronicity of magmatic arcs and ophiolites suggesting that the Altaid collage hosts relics of former oceanic backarc rather than true oceanic basins (Yakubchuk, 1997). On this basis, Mossakovskiy et al. (1993), Berzin et al. (1994), and Didenko et al. (1994) modified the model by Zonenshain et al. (1990) and compiled detailed reconstructions of the collage. These workers suggested that numerous ophiolitic sutures record the presence of intra-arc and backarc basins, which spread and then collided between the drifting Precambrian crustal blocks. It is worth mentioning that this very complicated model lacks modern analogues.

These problems stimulated Sengör et al. (1993) and Sengör and Natal'in (1996) to suggest that Precambrian crustal blocks and Early–Middle Paleozoic turbiditic units of the Altaids could originally constitute the basement and accretionary wedges of only two magmatic arcs of Kipchak (future Kazakhstan) and Tuva–Mongol. These workers suggested that Precambrian blocks were rifted off united Eastern Europe–Siberia to form the Kipchak magmatic arc and Khanty–Mansi backarc ocean in the beginning of Paleozoic time. The Kipchak arc remained attached to Siberia and Eastern Europe, then the Mugodzhar arc developed in the rear part of the latter, and the Tuva–Mongol arc was attached to Siberia only by its one end. This model considered that in the middle to late Paleozoic these arcs and their accretionary complexes were oroclinally bent and duplicated many times along the giant strike–slip faults against the background of the clockwise rotation of Siberia relative to Eastern Europe.

Despite different approaches, these interpretations considered oceanic units of the Altaids as a fragment of the Panthalassic (Paleo-Pacific) Ocean. However, Yakubchuk et al. (2002) showed that the Altaid orogenic collage may have formed due to subduction of the Paleo-Tethys Ocean and, therefore, the reality of the Paleo-Asian Ocean is questionable or it should be considered a branch of the Paleo-Tethys Ocean.

This paper will consider the tectonics, metallogeny and plate-tectonic evolution of the Altaid orogenic collage as a fragment of the Paleo-Tethys Ocean. Its tectonic evolution and metallogeny was strongly influenced by plume events (Kovalenko et al., 1999; Dobretsov and Vernikovsky, 2001), forming such giant deposits as Norilsk. However, the detailed analysis of plume-related tectonics and metallogeny is not a subject of this paper, but it will be used for plate-tectonic reconstructions.

2. Tectonics of the Altaid orogenic collage

2.1. General

The Altaid orogenic collage consists of several eroded Paleozoic orogens preserved in the Urals and Kazakh uplands and separated by vast oil-bearing Mesozoic–Cenozoic sedimentary basins in western Siberia and Central Asia (Fig. 1), whereas in the south and east there are young mountainous ranges produced in response to the collision of the Indian craton. These young orogens were superimposed on older Paleozoic orogens in the Altai–Sayan, Transbaikalia, and Mongolia, and to a lesser degree in Inner Mongolia and Heilongjiang of China.

Fig. 1 shows the suggested outline of the Altaid orogenic collage on the basis of the distribution of the Neoproterozoic–late Paleozoic oceanic, accretionary, and island arc complexes with respect to the framing Precambrian crustal blocks. East of the collage, the western margin of the Precambrian slivers of Mongolia and northeast China is a suggested border of the Altaids (Yakubchuk et al., 2001). To the south, in agreement with previous studies (Mossakovskiy et al., 1993; Sengör et al., 1993; Sengör and Natal'in, 1996), the boundary follows the northern margin of the Karakum, Alai–Tarim, and North China cratonic blocks. In the west, the boundary starts near the Caspian Sea and then follows the Main Urals fault as a principal boundary between the non-oceanic and oceanic complexes. In the northeast, this boundary is exposed in Kuznetsk Alatau and can be inferred further northward under the West

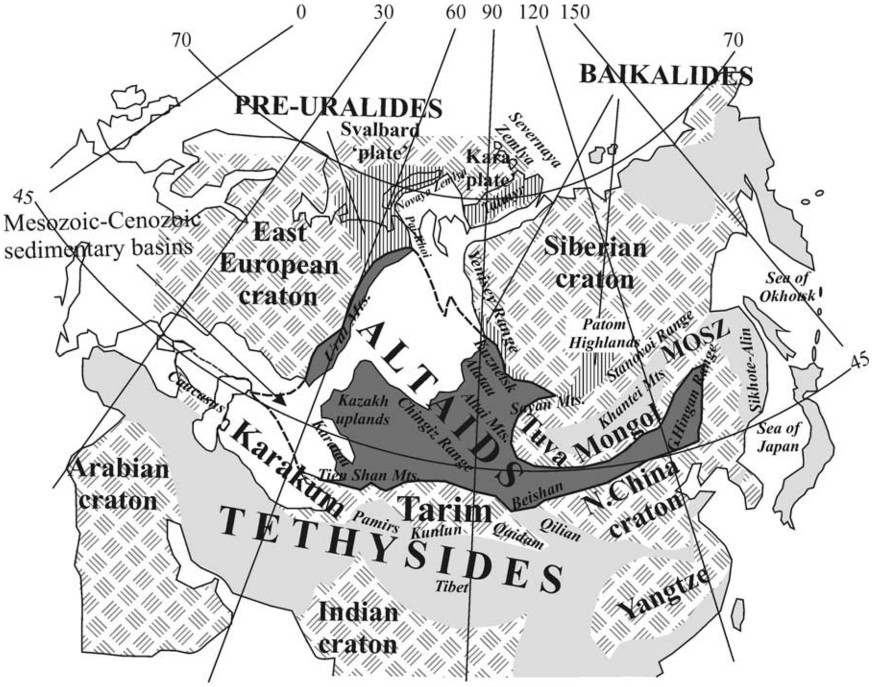


Fig. 1. Altaid orogenic collage and adjacent structures.

Siberian sedimentary basin following the western boundary of the Baikalides.

The Baikalides and Pre-Uralides are not within the scope of this paper, but a brief mention of the relationships between their various fragments is important for understanding of suggested boundaries of the Altaid orogenic collage. Fragments of the Baikalides occur in the Patom highlands in Transbaikalia and in the Yenisey range, tracing the southern flank of the Siberian craton (Vernikovskiy et al., 1999). On the basis of magnetic data (National Geophysical Data Center, 1996), their continuation is suggested under the eastern part of the West Siberian sedimentary basin, extending as far north as the Kara Sea and also under the eastern half of the West Siberian basin (Yakubchuk et al., 2001). The Neoproterozoic orgen of Taimyr (Vernikovskiy et al., 1996) is usually suggested as the northern frame of the Siberian craton, thus surrounding this craton along its three margins. However, Taimyr structures can also be considered as the continuation of the Pre-Uralides via Neoproterozoic orogenic fragments of the Novaya Zemlya archipelago (Bogatskiy et al., 1996; Bogdanov et al., 1998). The Svalbard and Kara 'plates' of Bogdanov et al. (1998) can be considered as smaller offshore equivalents of the East European craton, framing the Pre-Uralides in the west and northwest. The continental crust of this offshore area was significantly stretched in the Paleozoic to produce the sedimentary basins with still undeformed oceanic crust and overlying sedimentary sequences in the East Barents 'trough'. This allows tracing the Pre-Uralides to Taimyr as a 2000-km-long belt, which is truncated in the east by the oceanic floor of the Arctic Ocean (Bogdanov et al., 1998). Torsvik et al. (1992) suggested that present northern margins of the Siberian and East European cratons were facing each other in the Neoproterozoic, but the above-mentioned offshore Svalbard and Kara plates must be placed between these two cratons. This reconstruction would allow restoration of the Pre-Uralides and Baikalides as a single belt that might strike for approximately 6000 km before dismemberment into several fragments during clockwise rotation of Siberia relative to Eastern Europe in the Paleozoic (Torsvik et al., 1992). The fragments of this Neoproterozoic orogen and older slivers can also be found inside the Altaid orogenic collage (Fig. 2).

In brief summary to this section, the suggested outlines of the Altaids mean that they do not continue to the Arctic shelf and Circum-Pacific orogens and, therefore, they could not be linked with the Caledonian or Circum-Pacific orogens. Apparently, the Altaids form an entirely intracratonic collage, which should preserve links with adjacent orogens. Yakubchuk et al. (2001) suggested that the Altaids could constitute a detached fragment of the Tethysides, and such a link can be proposed between Alai–Tarim and North China (Fig. 1).

For a better understanding of the internal architecture of the Altaid orogenic collage, this paper will analyze its

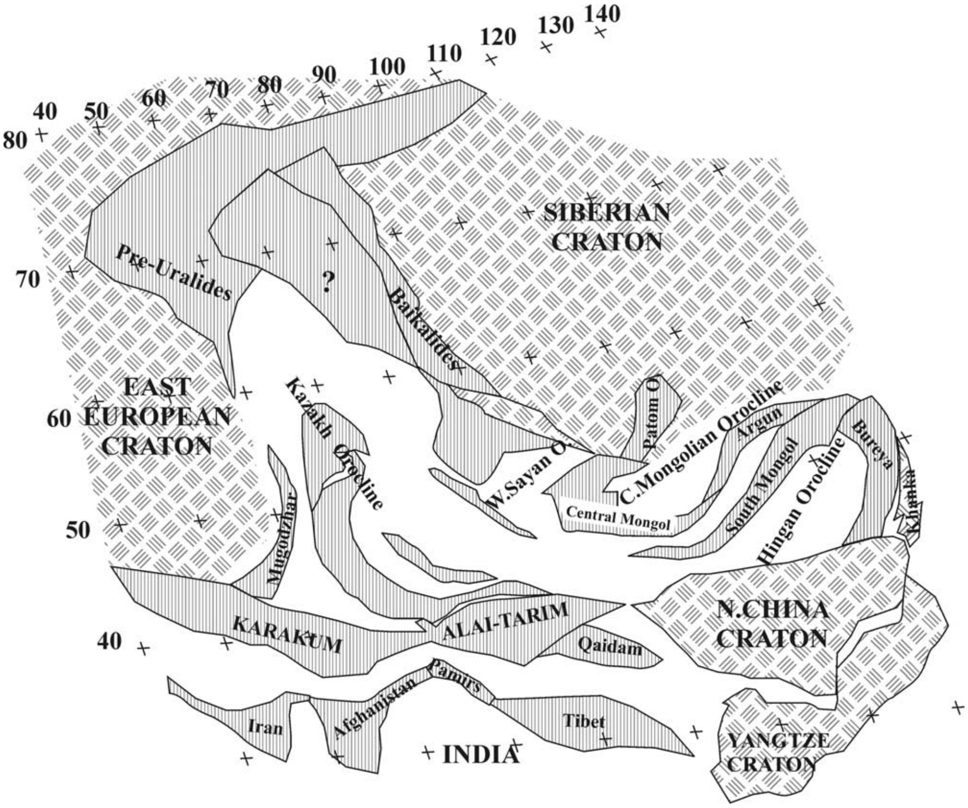


Fig. 2. Pre-1.0 Ga cratons, 0.6 Ga orogens and their fragments in the Altaid orogenic collage.

tectonics from younger to older assemblages, starting from the most evident Mesozoic intra-plate structures toward older Neoproterozoic–Early Paleozoic tectonic elements.

2.2. Late mesozoic tectonics

The Mesozoic–Cenozoic intra-plate deformations represent one of the most outstanding features of the Central Asian tectonics in the form of strike-skip faults that can be traced for several thousand kilometers (Fig. 3). They offset older structures and metallogenic belts by as much as 100–400 km. However, in many cases these features did not attract the attention of previous investigators. Some of them were considered to be Cenozoic in age and to be the result of India–Asia collision and impact rifting, e.g. Baikal rift, whereas these structures in Kazakhstan were considered to be older than Mesozoic (Zaitsev, 1984).

In Central Asia and Kazakhstan, these faults form a 2000-km-wide system of northwest-striking dextral strike–slip faults of Talas–Fergana, Jalair–Naiman, Central Kazakhstan, Chingiz, Irtysh and Yenisei–Sayan. Most of these faults are traditionally considered to be Late Paleozoic–Early Mesozoic in age (Zaitsev, 1984). However, many of them offset Middle Jurassic rocks, being 'sealed' by the Paleogene sediments, that indicates their *Late Jurassic to Cretaceous* age. The Talas–Fergana fault remains active until present time (Burtman, 1997) due to the continuing India–Asia collision.

In Mongolia and northeast China, these faults predominantly strike to the northeast or north. Their documented amplitudes of displacement vary from 100 to 700 km. These are the Mongol–Okhotsk, Hingan, Tang Lu, and several other faults (Fig. 3). Some of these faults have not been recognized yet as single faults, because they are 'shared' between several countries. For instance, the northeast-trending Hingan fault sinistrally offsets the northern continuation of the Jurassic–Early Cretaceous Greater Hingan magmatic arc for as much as 400 km. At its northeastern continuation, this fault strikes toward the eastern edge of the Mongol–Okhotsk suture zone, where it splits into several branches and sinistrally offsets Late Paleozoic auriferous metamorphic units of Selemdzha, Niman, and Kerbi for as much as 100–200 km (Yakubchuk and Edwards, 1999). In the southwest, this fault can be

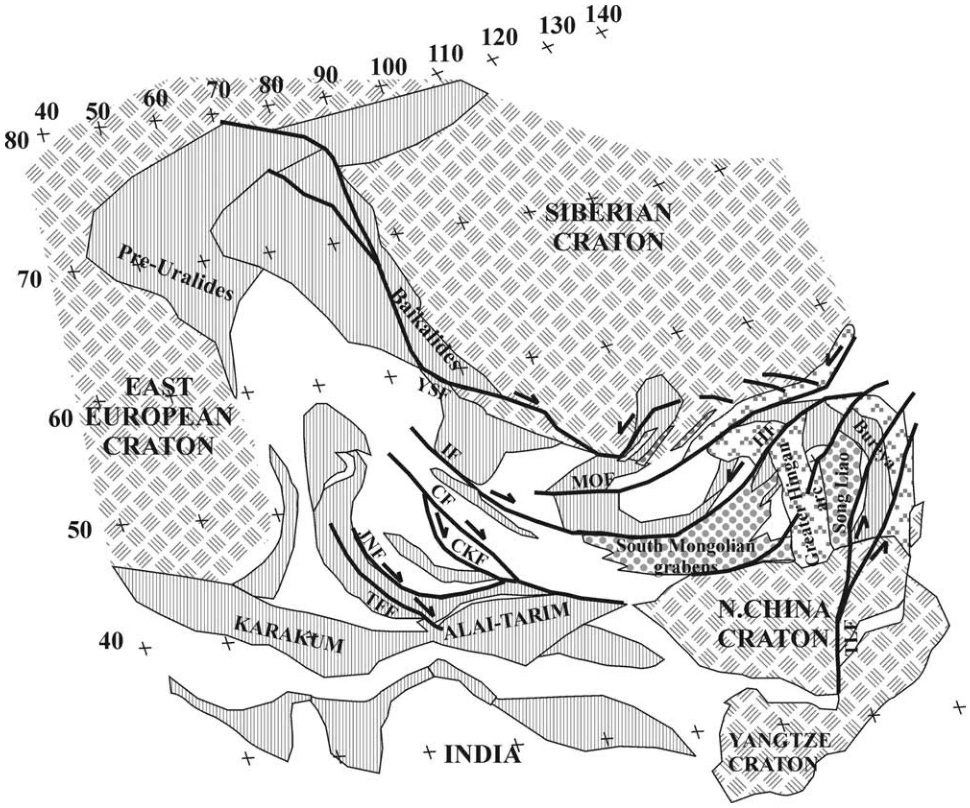


Fig. 3. Mesozoic strike–slip faults have been superimposed onto the Altaid orogenic collage. They form a conjugate fault system that was produced in response to the southward propagation of the Siberian craton in the Late Jurassic–Cretaceous when the Amerasian basin in the Arctic began to open. Northwest-trending dextral strike–slip faults in Central Asia and Kazakhstan reveal a total displacement of approximately 500 km. Northeast-trending sinistral strike–slip faults in Mongolia, Transbaikalia and Far East display similar amplitude of displacement. In addition Tang Lu fault, which relates to the Circum-Pacific orogens, reveals 700 km sinistral offset in its southern segment. TFF, Talas–Ferghana fault (200 km offset); JNF, Jalair–Naiman fault (100 km offset); CKF, Central Kazakhstan fault (70 km offset); CF, Chingiz fault (100 km offset); IF, Irtysh fault (?); YSF, Yenisei–Sayan fault (?); MOF, Mongol–Okhotsk fault (100 km offset); HF, Hinggan fault (400 km offset); TLF, Tang Lu fault (700 km offset).

traced along the northern boundary of the Mesozoic grabens in southern Mongolia, which are superimposed both on the Paleozoic orogenic structures of the Altaids and North China craton. To the west of the Greater Hingan arc, these faults control the southern flanks of the Cretaceous grabens of southern Mongolia. These graben structures have been superimposed onto Paleozoic magmatic arc units that host Cu-porphyry mineralization (Perelló et al., 2001). One of them, the recently discovered Cu–Au-porphyry deposit of Oyu Tolgoi (Turquoise Hill), hosts a supergene enrichment blanket that developed in the Mesozoic (117–93 Ma) (Perelló et al., 2001) and its development was favored by the differential movements of blocks in these strike–slip controlled graben structures.

Sengör and Natal'in (1996) suggested another northeast-trending fault system along the eastern margin of the Greater Hingan arc, mostly hidden under the Song Liao sedimentary basin, but exposed in the north, where it separates the Argun and Bureya Precambrian slivers. They suggested that this strike–slip faulting sinistrally duplicated the Greater Hingan arc and was responsible for northward translation of the Bureya and Khanka slivers, which ultimately caused cessation of the westward-directed subduction in this arc whose magmatic front migrated eastward in the *Late Cretaceous*. However, the presence of similar late Paleozoic granitoids to the west and east of the Greater Hingan arc shows that Argun and Bureya slivers occur in the basement of a single late Paleozoic magmatic belt, now offset along sinistral strike–slip faults for 200–300 km. In plan view, these slivers and magmatic belt form a Hingan orocline with well-preserved Greater Hingan magmatic arc rocks in its core and several smaller volcanic clusters along the northern and eastern flanks of the Bureya sliver. Therefore, these Precambrian metamorphic blocks could not be independent prior to the Late Cretaceous as suggested by Sengör and Natal'in (1996) and must be considered as a single magmatic belt.

The north–south striking Tang Lu fault, located further to the east, controls the petroliferous Mesozoic–Cenozoic sedimentary basins of eastern China (Tian and Zhang, 1997). Its amplitude of sinistral displacement is 700 km, if to measure offset of the southern margin of the North China craton. In the north, it splits into several faults, which can be traced to the southern Russian Far East. Their amplitude of displacement varies from 100 to 200 km. The Tang Lu fault could be related to the sinistral transtensional deformations between the Pacific and Eurasian plates.

In southern Siberia and northern Mongolia, the recognition of Mesozoic faults is difficult due to significant rejuvenation during Cenozoic tectonism. However, there are east–west-trending reverse faults that are marked by the Jurassic–Early Cretaceous coal-bearing sedimentary basins. In particular, these are thrust and reverse faults between the Stanovoy and Aldan shields of the Siberian craton, but the most spectacular west–east-trending reverse fault structure can be traced for approximately 3000 km from the Altai mountains through northern Mongolia toward the Mongol–Okhotsk suture.

As a result, one can recognize Mesozoic faults of three dominant orientations, northeast, northwest, and west–east, which can be considered as a conjugate system that formed as a result of north–south compression in the Cretaceous. This age does not allow the India–Asia collision to explain its pattern. One apparent possibility is a generation of these intra-plate deformations in response to the southward propagation of the Siberian craton due to the opening of the Amerasian basin in the Arctic Ocean in Jurassic–Cretaceous time (Yakubchuk et al., 2002). If this is correct, than there is an attractive solution to explain many features of the Mesozoic intra-plate tectonics that have not been explained before, but they are important for the post-mineralizing history of the Altaids and especially some aspects of its supergene enrichment. Some aspects of this tectonic pattern have been outlined in previous works on southern Mongolia and northwestern China (Cunningham et al., 1996), but this paper shows their much wider extent, systematic pattern, and significance.

2.3. Early Mesozoic tectonics

In early Mesozoic time, subduction-related activity was concentrated in the presently oroclinally bent Transbaikal arc and other arcs of the Circum-Pacific orogens. Jurassic–Cretaceous magmatism in northeast China and south of the Russian Far East is considered to be prospective for porphyry Cu and epithermal Au mineralization. These magmatic arc rocks unconformably overlie or intrude the Paleozoic accretionary complexes and Precambrian metamorphic crustal blocks of Mongolia and northeast China. These units have been tectonically separated into several fragments, but prior to the Mesozoic, they might have formed a single linear(?) structure with the North China craton. If we accept this, it implies a significant dextral (westward) offset of the North China craton for 2000 km, its juxtaposition with the Tarim block, and oroclinal bending of the Central Mongolian and Hingan oroclines due to relative dextral motion between North China and Siberia. This culminated in collision between the eastern Altaids and Siberian craton in the Early–Middle Jurassic to form the Mongol–Okhotsk suture zone (Yakubchuk and Edwards, 1999).

2.4. Paleozoic tectonics

To decipher the internal tectonic architecture of the Altaid orogenic collage it is necessary to select the most important and recognizable tectonic features. These include the Precambrian slivers, accretionary complexes, and magmatic arcs. The magmatic fronts of the latter structures, as suggested by Sengör et al. (1993), are perhaps the best markers that can help to trace the structures inside the collage. In addition, ophiolite-bearing sutures, largely neglected by Sengör et al. (1993) and Sengör and Natal'in (1996), can also be used as good structural markers. Some ophiolites occur in sutures of former backarc (intra-arc) basins, whereas others occur as slivers within accretionary wedges that faced a former major ocean. The synchronicity of ophiolites and adjacent magmatic arcs coupled with their petrological features are the main criteria behind identification of ophiolites as backarc and main ocean fragments. Metallogenic belts can be used to constrain tectonic correlations.

A regional aeromagnetic map (National Geophysical Data Center, 1996) was used to trace the continuity of these tectonic elements under Mesozoic–Cenozoic sedimentary basins of magnetically distinct magmatic arcs and ophiolitic sutures. In contrast, accretionary complexes and passive margin sedimentary sequences reveal a chiefly non-magnetic pattern.

This approach, coupled with major unconformities, reveals that there are three groups of structural-lithologic units, Late Paleozoic, Middle Paleozoic, and Late Proterozoic–Early Paleozoic, that correspond to three different structural patterns. They reflect major tectonic reorganizations, which took place at the end of the Paleozoic, in the Early Carboniferous and at the Ordovician–Silurian transition (Zaitsev, 1984; Zonenshain et al., 1990). The above-mentioned Mesozoic magmatic events superimposed in the east of the collage relate to the Circum-Pacific evolution that took place after its final amalgamation in the Late Paleozoic.

One of the most striking features of Altaid tectonics is the presence of oroclinal structures that were analyzed in detail by Sengör et al. (1993) and Sengör and Natal'in (1996). In the western half of the Altaid orogenic collage, there is just one Kazakh orocline, whereas in its eastern half, there are several oroclines of West Sayan, Patom, Central Mongolia and Hingan, recognizable mostly by the orientation of Paleozoic magmatic arcs and Precambrian slivers (Fig. 2). Although compression was very significant, in the framing structures outside the Altaid collage there are several still undeformed sedimentary basins with oceanic crust and 10–15 km thick sedimentary sequences, such as the North Caspian and East Barents basins that opened in the Middle or even Early Paleozoic.

2.5. Late Paleozoic units

The Late Paleozoic units are the easiest to trace in the Altaid orogenic collage (Fig. 4). However, significant uncertainties exist in correlation of the fragments of these units across the collage as they are obscured under extensive Mesozoic–Cenozoic sedimentary basins.

This stage of tectonic evolution started in the Early Carboniferous and continued until the end of the Paleozoic. It was a time of intensive arc magmatism and major collisional events that culminated in assemblage of the Altaid orogenic collage. The Early Carboniferous was the time of a key transitional event in the tectonic and metallogenic evolution of Kazakhstan and Central Asia. Most porphyry deposits of Kazakhstan formed during this time (Heinhorst et al., 2000). Magmatic arc rocks in many cases unconformably overlie the previously amalgamated tectonic units, and Late Carboniferous to Permian granites of various types are responsible for generation of the bulk of the continental crust of the area (Zaitsev, 1984; Mossakovskiy et al., 1993; Heinhorst et al., 2000).

Arc magmatism took place in the *Kazakh–Mongol magmatic arc* that starts from the Turfan region of Xinjang in China, continues westward to southern Kazakhstan, makes a bend near Lake Balkhash, forming the Kazakh orocline, and then extends to southern Mongolia and northeast China where it is obscured under the Greater Hingan magmatic arc. Its continuation to the east near the Chinese–Russian border can be inferred by the presence of Late Paleozoic granite intrusions in the Bureya Precambrian sliver. Kovalenko et al. (1999) showed definite presence of the Late Precambrian crust in the basement of these arcs using Sm–Nd data.

The structure, however, is quite complicated. Sengör and Natal'in (1996) analyzed this area in detail and suggested that a fragment of this arc could be repeated along strike–slip faults to explain the presence of narrow Precambrian slivers within the accretionary complex in southern Mongolia. In many places, the Kazakh–Mongol arc formed on top of the extinct Early to Middle Paleozoic arcs and accretionary complexes, which formed quite wide crustal units by that time, especially in central Kazakhstan, where they mark the active eastern margin of the wide crustal block, which are sometimes classified as the Kazakhstan continent (Zonenshain et al., 1990).

The western part of the Kazakh–Mongol arc hosts numerous Cu–Mo-porphyry (Kounrad, Aktogai, Borly, etc.), skarn (Sayak), and epithermal deposits in Kazakhstan, both exposed and buried under younger sediments. The giant sedimentary-Cu deposits of Dzhezkazghan in Kazakhstan formed behind this arc to the west. In the Late Carboniferous, Mo–W deposits (Akchatau, Batystau, Verkhnee Kairakty) were emplaced in Central Kazakhstan under control of pull-apart-like structures (Heinhorst et al., 2000). Mineral deposits of this stage relate to a continental arc and associate with backarc rifts.

In southern Mongolia and northeast China, the Kazakh–Mongol arc produced a large amount of the Early Carboniferous–Permian magmatic rocks, and its potential for significant mineralization is still to be explored. This magmatism buried the mineralized Silurian–Devonian portion of the same arc, whose rocks are now found only in the erosion windows. The frontal part of the arc is clearly marked by a Late Paleozoic accretionary complex, striking from Central Kazakhstan to northeast China.

To the west of the Kazakh–Mongol arc, in eastern and western Central Kazakhstan and in Uzbekistan, is the Early–Middle Carboniferous *Zharma-Saur–Valerianov–*

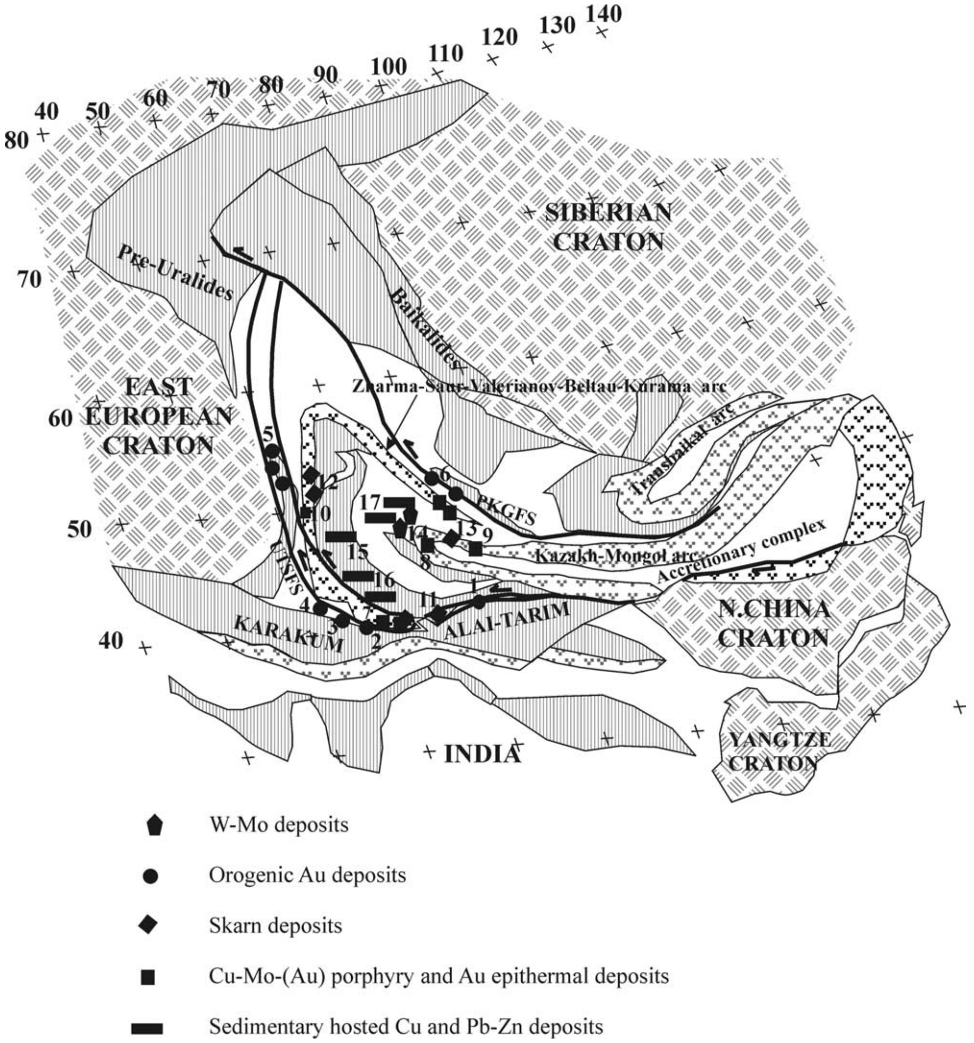


Fig. 4. Late Paleozoic structures and mineral deposits of the Altaid orogenic collage. Magmatic arcs of the Kazakh uplands were pushed westward and collided with Mugodzhar–Rudny Altai arc and East European craton. The transform-like Urals–Tien Shan (UTSFS) and Pai Khoi–Gobi (PKGFS) fault systems bound the Kazakh orocline. Each of them reveals at least 500 km combined measurable sinistral displacement. They control and offset orogenic gold deposits in Central Asia, Urals, and eastern Kazakhstan. Presence of magmatic arc rocks on the northern rim of the North China craton suggests that it could be dextrally offset with respect to the eastern end of the Kazakh–Mongol arc for as much as 2000 km if they formed a single arc in the past. Orogenic Au deposits: (1) Kumtor, (2) Jilau–Taror, (3) Zarmitan, (4) Muruntau, Daugyztau, Amantaitau, (5) Berezovskoe, (6) Bakyrchik and Suzdal; Cu-porphyry and epithermal Au deposits: (7) Kalmakyr-Dalnee and Kochbulak, (8) Kounrad, (9) Aktogai, (10) Varvarinskoe; Skarn deposits: (11) Makmal, (12) Sokolovsko–Sarbaiskoe, (13) Sayak; W–Mo deposits: (14) Verkhnee Kairakty, Akchatau; Sedimentary rock-hosted Cu and Pb–Zn deposits: (15) Dzhezkazghan, (16) Shalkiya and Mirgalimsai, (17) Akzhal–Uspenskaya group.

Beltau-Kurama arc that developed on top and at the western flank of the amalgamated pre-Late Paleozoic tectonic units of Central Kazakhstan and Kyrgyzstan, forming a 5000-km-long structure. This arc was short-lived and terminated its activity after collision with the magmatic arcs of the Urals and Rudny Altai and with Precambrian crustal blocks of Karakum and Alai–Tarim in the Middle Carboniferous. However, this arc magmatism managed to produce large copper-rich Fe-skarn deposits (Sokolovsko–Sarbaiskoe, northwest Kazakhstan) (Herrington et al., 2002) and very large porphyry (Almalyk) and epithermal (Kochbulak) deposits in Uzbekistan (Shayakubov et al., 1999; Yakubchuk et al., 2002), far larger than similar style deposits that were discovered to date in the synchronous Kazakh–Mongol arc. The exploration within this arc is difficult due to significant thickness of the overlying Mesozoic–Cenozoic sediments so that arc rocks are exposed in only three areas, e.g. Zharma-Saur in eastern central Kazakhstan, Valerianov zone in the East Urals, and Chatkal–Kurama in Uzbekistan, where this arc terminates and its rocks are not known to the east of the Talas–Fergana fault in Kyrgyzstan with the possible exception of the Makmal area.

To the south, west and northeast, this arc is framed by a 5000-km-long *South Tien Shan–East Urals–Irtysh–Zaissan suture zone*, which can be recognized as a single unit using magnetic data (Yakubchuk et al., 2001). This suture zone is a complex structure that incorporates the tectonic elements of passive margins, accretionary and fore-arc complexes, and ophiolites. The age of ophiolites ranges from Vendian(?) to Middle Paleozoic, the longest time span in the Altaids. Yakubchuk et al. (2001) suggested identifying it with the Khanty–Mansi backarc basin of Sengör et al. (1993). It separates the magmatic arcs of Central Kazakhstan, on the one hand, and Rudny Altai–Urals, on the other. It also separates the Kyrgyz–Kazakh arcs and Karakum–Alai–Tarim cratons.

In the Irtysh–Zaissan area, it is a wide collisional zone separating Devonian Rudny Altai and Carboniferous Zharma-Saur arcs. An accretionary complex, hosting long slivers of the Early–Middle Paleozoic ophiolites thrust southwestward, dominates in this zone. It probably does not continue to China, as is traditionally suggested (Zonenshain et al., 1990; Mossakovskiy et al., 1993; Sengör et al., 1993; Sengör and Natal'in, 1996). This consideration here is primarily based on the absence of orogenic gold deposits in northwest China and their presence in eastern Kazakhstan and Central Asia. Magnetic data suggest that the suture starts in the Irtysh–Zaissan zone near the Kazakh–Chinese border to be traced northwest under the Mesozoic–Cenozoic sediments of West Siberia and then continues southward to the eastern zones of the Urals, where it separates the Valerianov arc, on the one hand, and the Mugodzhar Precambrian sliver and Middle Paleozoic arc of Magnitogorsk and Tagil, on the other. The relationships between these tectonic fragments are quite complicated and are believed to be of thrust nature (Puchkov, 1997) or strike–slip fault nature (Yakubchuk, 2001). Many of the Urals arcs reveal a lens-shaped pattern, suggesting their significant fragmentation, possibly due to sinistral strike–slip offset in the Middle–Late Carboniferous or Permian along the strike of the orogen for as much as 200–300 km (Yakubchuk, 2001).

The southward continuation of the eastern Urals zones has been a subject of continuous discussion since the 1930s. At present, it is almost universally agreed (Puchkov, 1993, 1997, 2000) that some eastern Urals zones continue to the southern Tien Shan via the Kyzylkum area.

In the CIS part of the Tien Shan, there are three traditional divisions: Northern, Middle, and Southern (see, for instance, Zonenshain et al., 1990 or Milanovskiy, 1996). The Nikolaev line is a fault structure that separates the Northern and Middle Tien Shan to the east of the Talas–Fergana strike–slip fault. However, no clear western continuation was suggested for the Nikolaev line. Taking into account the 200 km dextral offset along the Talas–Fergana fault suggests that possible continuation of the Nikolaev line can be proposed in the exposed southern part of the Karatau range, but it is mostly hidden under the Mesozoic–Cenozoic sediments of the Chu basin and can be traced using a magnetic map towards the north–south-trending strike–slip faults in the Urals. Detailed maps of eastern Kyrgyzstan show that there are en echelon folds near the Nikolaev line indicating sinistral strike–slip displacement along this fault. In the open pit of the Kumtor gold mine at the eastern termination of the Nikolaev line in Kyrgyzstan there are slicken-sides indicating sinistral strike–slip kinematics.

The Atbashi–Inylchek suture divides the Middle and Southern Tien Shan in eastern Kyrgyzstan. The detailed maps and field observations also identify a sinistral strike–slip component. To the west of the Talas–Fergana fault, the equivalent of this suture is the Turkestan suture, which also displays a sinistral sense of displacement. These faults can be then traced to the Urals suggesting that a continent-scale 4000-km-long sinistral strike–slip fault system can be recognized, a feature that was largely missed during previous studies. These strike–slip faults are clearly superimposed onto Early Carboniferous imbricated thrusts and Middle Carboniferous molasse of the southern Tien Shan, but they only slightly offset the Late Permian syenite and granite bodies, suggesting Late Carboniferous to Early Permian age of deformation. This fault system might have developed during westward 'intrusion' of the Kazakh–Mongol magmatic arc and its collision with the Urals and Karakum–Alai–Tarim.

The Southern Tien Shan–East Urals–Irtysh–Zaissan suture zone is a very important metallogenic element in the western Altaids. It hosts giant orogenic Late Paleozoic Au deposits in the Tien Shan and eastern Kazakhstan. It offsets the auriferous metallogenic clusters in the Urals, which formed both before and after the Late Carboniferous (Sazonov et al., 2001). One group of deposits is exposed near the Bakyrchik deposit and another extends from Muruntau to Kumtor and then to the Chinese Tien Shan. The latter belt is known as the Kyzylkum, Central Asian, or Tien Shan belt, and is the world's second largest gold province after the Witwatersrand (White et al., 2001; Yakubchuk et al., 2002). The Tien Shan belt also hosts important mercury deposits in Kyrgyzstan, constituting the third largest province in the world (White et al., 2001).

It is commonly believed that formation of economic deposits in these belts, e.g. Muruntau and a number of analogous, but smaller deposits, took place during emplacement of the granitoid intrusions in the Permian (Drew et al., 1996), but the new Ar–Ar data suggest a Triassic age for some of the latest alteration events at Muruntau (Wilde et al., 2001). Recent research in the Tien Shan (Cole, 2000) has shown that Late Paleozoic granitoids are temporally, mineralogically, compositionally and isotopically similar, whether related to orogenic-style Au–W vein and associated skarn systems in the accretionary complex of the South Tien Shan or related to porphyry Cu–Au systems in the Valerianov–Beltau-Kurama magmatic arc.

Many orogenic-type gold deposits in the Tien Shan are located within Late Paleozoic granitoid intrusions or within their contact metamorphic aureoles. Where radiometric dates have been obtained, mineralization is found to be broadly coincident with magmatism (Cole, 2000; Sazonov et al., 2001). Furthermore, a number of recent studies, particularly in the Tien Shan, have developed geochemical, isotopic and fluid-structural models that implicate highly evolved syntectonic Late Paleozoic I-type granitoids as the source of fluids and metals for spatially associated orogenic-type gold deposits. Principal examples in the Tien Shan include Zarmitan (Bortnikov et al., 1996) in Uzbekistan and Jilau (Cole et al., 2000) in Tajikistan.

The magnetic data also suggest that magmatic arcs of the Urals and Rudny Altai may represent fragments of the same arc. Yakubchuk et al. (2001) suggested calling it the *Mugodzhar–Rudny Altai arc*. It was almost inactive in the Late Paleozoic as the Mugodzhar–Rudny Altai arc collided with Eastern Europe in the Middle Carboniferous and totally sutured the *Sakmara backarc basin*, whose fragments are now found in the Main Urals fault zone, by the Early Permian (Puchkov, 1993, 2000; Mossakovskiy et al., 1993). To the south, this suture can be traced as far as Ust-Yurt, while to the north, it extends to the Polar Urals. Its further continuation is disputable, but magnetic data suggest a possibility of its turn to the southeast and continuation to the *Tom–Kolyvan zone*(?), to the north of the Kuznetsk basin. This collision was responsible for emplacement of the Late Paleozoic granitoids that relate to some large orogenic gold deposits in the Urals, such as Berezovskoe (Sazonov et al., 2001; Shatov et al., 2001), which formed earlier than similar mineralization in the Tien Shan.

However, the *East Barents basin* in Russia and the *North Caspian basin* in western Kazakhstan, which formed due to stretching of the continental crust of the East European craton and Pre-Uralides in the Middle Paleozoic or earlier, survived as largely undeformed petroliferous sedimentary basins (Bogatskiy et al., 1996). The recorded and inferred thickness of sedimentary rocks that accumulated on oceanic-type crust in these basins from at least the Middle Paleozoic now exceeds 15 km (Shipilov and Tarasov, 1998). In the North Caspian basin, there are Permian evaporites that represent a fragment of the evaporite belt that extends from Central Europe to the South Urals. The famous sedimentary rock-hosted metalliferous deposits of East Germany and Poland occur on the flanks of this basin, and smaller(?) equivalents are found in the Urals fore-deep. Similar Middle–Late Paleozoic deposits exist on the periphery of the East Barents basin in the Novaya Zemlya archipelago (Evdokimov et al., 2000).

2.6. Middle Paleozoic units

The Middle Paleozoic, e.g. Silurian to Early Carboniferous, units reveal a more or less continuous and consistent tectonic pattern. They can be easily traced and correlated across the entire Altaid orogenic collage (Fig. 5).

Three Middle–Late Paleozoic active magmatic arcs, Mugodzhar–Rudny Altai, Kazakh–Mongol, and Valerianov–Beltau-Kurama, can be recognized within the Altaid orogenic collage at this stage. They are separated from each other and older crustal blocks by the accretionary complexes with ophiolites, e.g. Southern Tien Shan–East Urals–Irtysh–Zaissan and Sakmara sutures. In the core of the Kazakh orocline one can identify an accretionary complex that can be traced further to southern Mongolia and northeast China.

The *Kazakh–Mongol arc* formed during several magmatic episodes in the Silurian–Middle Devonian and Middle–Late Devonian mostly on top of the older welded fragments of the Kipchak arc. It can be well traced for approximately 5000 km from the Turfan area of northwest China to the Junggar–Balkhash region of central Kazakhstan, where it forms even a separate magmatic belt and even tighter oroclinal structure than its late Paleozoic segment, and then turns eastward toward Mongolia and northeast China where its continuation is hidden under the Mesozoic volcanic rocks of Greater Hingan, but it again appears in the Bureya block in the south of the Russian Far East and NE China.

In Mongolia and China, it forms a more or less single structure, but in Kazakhstan two generations of arc magmatism produced two distinct belts of this arc that progressively young eastward. In northeast China, Sengör and Natal'in (1996) suggested that some of its fragments could be repeated along the strike–slip faults. However, in general this arc developed on top of welded different fragments of the Neoproterozoic–Early Paleozoic Tuva–Mongol and Kipchak arcs. The Silurian–Devonian arc rocks host several VMS deposits (Progress, Abyz, etc. in central Kazakhstan) and important medium-size porphyry Cu deposits (Samarka or Nurkazgan) in central Kazakhstan, and possibly Oyu Tolgoi in Mongolia, if to accept the Late Silurian age of the latter), demonstrating that this tectonic unit is very prospective for medium-size porphyries (Yakubchuk et al., 2001). The Devonian volcanic rocks in Kazakhstan also host uneconomic volcanic redbed Cu mineralization and economic Pb–Zn–(Ag) deposits in Late Devonian carbonate rocks (Shatov et al., 1996) in the backarc setting.

The *Valerianov–Beltau-Kurama arc* was briefly active only during the Early–Middle Devonian and did not produce notable mineralization at that time.

Middle Paleozoic ophiolites in the suture identified with the Khanty–Mansi backarc basin and the Kazakh–Mongol magmatic arc in Central Kazakhstan constitute an internal portion of the Kazakh orocline (Fig. 5). The synchronicity of ophiolites and magmatic arc rocks suggests an island arc setting for the latter and backarc setting for the former.

In the external portion of the Kazakh orocline in the Urals is the *Mugodzhar–Rudny Altai island arc*. The suture of the Sakmara backarc basin separates the arc and the East European craton. Using magnetic data, the Mugodzhar–Rudny Altai arc can be traced from Ust-Yurt in the South Urals to the Middle and North Urals, from where it turns southeastward under the Mesozoic–Cenozoic sediments towards Rudny Altai in eastern Kazakhstan and northwest China, where it unites with the Kazakh–Mongol arc, thus

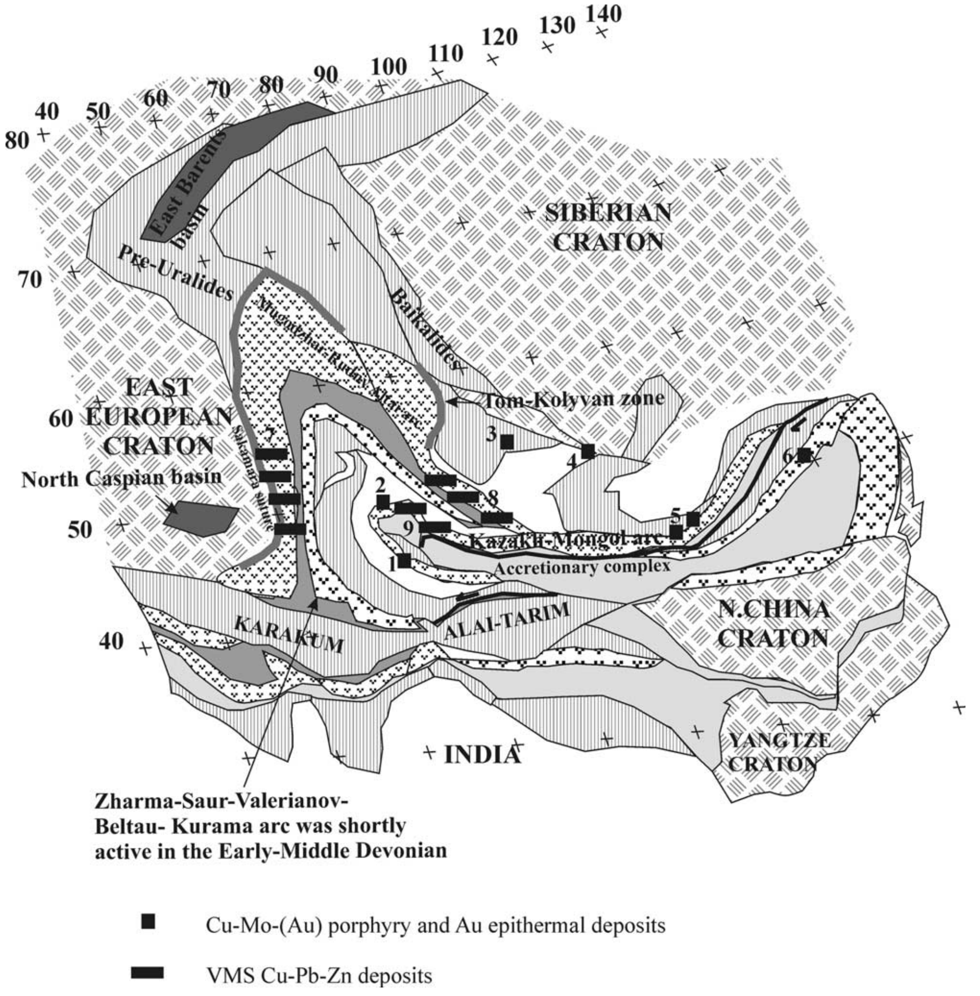


Fig. 5. Middle Paleozoic structures and mineral deposits of the Altaid orogenic collage. Duplication of the eastern part of the Kazakh–Mongol arc could possibly take place in the eastern Altaids, whereas in the western part this arc was only oroclinally bent that could cause migration of this segment of the arc in the Late Paleozoic. Porphyry and epithermal deposits: (1) Akbakai, (2) Samarskoe (Nurkazgan), (3) Sora, (4) Aksug, (5) Oyu Tolgoi and Tsagan Suvarga, (6) Duobaoshan; VMS deposits: (7) Urals group, (8) Rudny Altai group, (9) Central Kazakhstan VMS.

making a system of two parallel arcs, which were together oroclinally bent. The basement of this arc seems to be heterogeneous. In Rudny Altai, magmatic arc rocks occur on top of the Early Paleozoic accretionary complex, whereas in the Magnitogorsk and Tagil zones in the Urals this arc is considered to be mostly ensimatic. Presence of the Mugodzhar and Berezovo Precambrian slivers in the Urals orogen could be explained through the strike–slip model. The Mugodzhar block could be detached from the Karakum block, whereas the Berezovo sliver might be a strike–slipped fragment of the East European craton.

The Mugodzhar–Rudny Altai arc hosts large VMS deposits in Middle Devonian rocks in the Urals (Sibai, Uchaly, Gai, etc.) of Russia, Rudny Altai (Ridder–Sokolnoe, Maleyevskoe, etc.) in Kazakhstan and Russia (Popov, 1995, 1997; Herrington et al., 2000). Middle Paleozoic Mo–(Cu)-porphyry subeconomic deposits in this arc are known in the Urals (Kirkham and Dunne, 2000) and in the Altai–Sayan region (Sora, Aksug; Sotnikov and Berzina, 2000).

The suture of the *Sakmara backarc* basin hosts Middle Paleozoic ophiolites with large Cr–(Os–Ir) deposits (Kempirsai in Kazakhstan and Rai–Iz in Russia). Paleozoic ophiolites are also a source of Ni–Co production from lateritic deposits. The North Urals segment of the Mugodzhar arc hosts a so-called Urals platinum belt associated with Alaska-type intrusives. These intrusions contain minor to medium-size hardrock PGE deposits, which are a source of PGE placers whose total estimated historic production was up to 400 tonnes of PGE (Dodin et al., 2000). A number of granite-related gold deposits in the Urals include Berezovskoe, Kumak, Kochkar, Yubileinoe (Seltmann et al., 2000).

2.7. Late Proterozoic–Early Paleozoic Units

Only three Neoproterozoic–Early Paleozoic island arc assemblages can be recognized in the internal structure of the Altaid orogenic collage (Fig. 6). These are: Kipchak arc, consisting of three segments in the Tien Shan, Kazakh

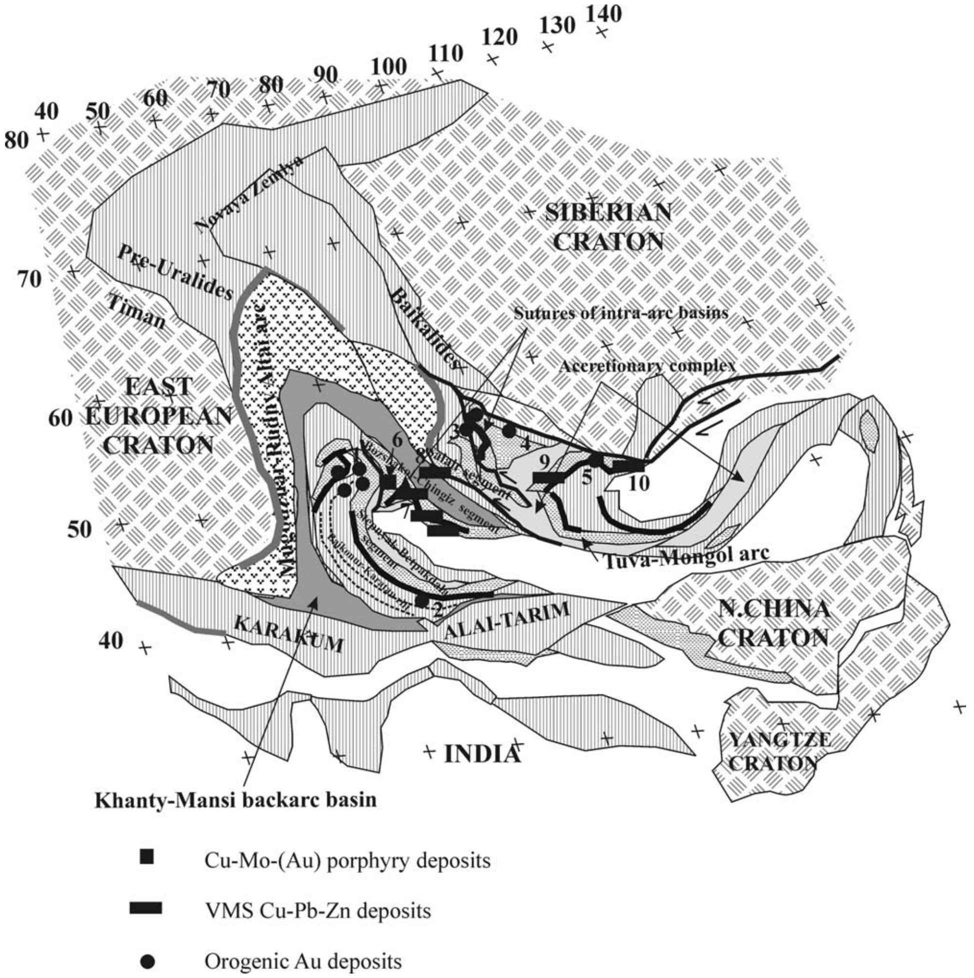


Fig. 6. Neoproterozoic–Early Paleozoic structures and mineral deposits of the Altaid orogenic collage. The arcs and accretionary complexes of this stage reveal significant segmentation by dextral and sinistral strike–slip faults for as much as 400–1000 km. Orogenic gold deposits: (1) Vasilkovskoe, Bestobe, Zholymbet, Stepnyak, (2) Jerooy, (3) Berikul, Saralinskoe, (4) Kommunarskoe, (5) Zun–Kholba; Cu-porphyry: (6) Bozshakol; VMS deposits: (7) Maikain, Akbastau–Kusmurun, Mizek, (8) Salair group, (9) Kyzyltashtyg, (10) Ozernoe.

uplands, and Altai; Mugodzhar–Rudny Altai arc that can be traced from the Urals to Rudny Altai; and Tuva–Mongol arc that separates the Altaid and Transbaikal–Mongolian orogenic collages (Yakubchuk et al., 2001). These arcs constitute tighter oroclinally deformed and more fragmented structures than younger arcs. Their plan view distribution justifies recognition of the western and eastern Altaids. In the western Altaids, there are Kipchak and Mugodzhar–Rudny Altai arcs separated by the sutures of former backarc basins from the cratons and each other. In the eastern Altaids, only relatively small fragments of the Kipchak arc occur in Kuznetsk Alatau, Salair and Altai, whereas the Tuva–Mongol arc dominates in the east of the Altaids. Crustal fragments older than 0.6–1.0 Ga are found in the basement of these magmatic arcs in the Kazakh uplands, Altai–Sayan, Mongolia, and northeast China.

The *Tuva–Mongol arc* hosts Vendian–Early Paleozoic intermediate magmatic rocks. The arc can be traced from Transbaikalia to western Mongolia, where it turns southward and then eastward. Some of its segments do not reveal older basement and can be considered as ensimatic arcs, but such basement is available in most parts of this arc (Kovalenko et al., 1999). The Early Paleozoic rocks of this arc host Cu–Pb–Zn–Ag–Au VMS deposits in its western portion (e.g. Kyzyltashtyg) (Yakubchuk et al., 2001) and probably Ozernoe in Transbaikalia (Kovalev et al., 1998). Within this arc, there are intra-arc sutures with Vendian–Early Cambrian ophiolites, e.g. Dzhida in Transbaikalia and Bayan–Khongor in Mongolia (Zonenshain et al., 1990). After suturing, granitoid intrusions have been emplaced to produce some medium-size orogenic gold deposits such as Zun–Kholba in Russia. On the western flank of the Tuva–Mongol arc in West Sayan, south Mongolia and northeast China, there is a Late Proterozoic–Early Paleozoic accretionary complex.

Fragments of >0.6 Ga crustal slivers can be found in Kuznetsk Alatau and West Sayan, in the Kazakh uplands, and in the North Tien Shan (Figs. 2 and 6) where they form either basement of the Vendian–Early Paleozoic *Kipchak magmatic arc* or its 'backstops', in the terminology of Sengör et al. (1993). In the two latter regions, they occur in the basement of the Vendian–Early Paleozoic differentiated magmatic rocks forming a Stepnyak–Betpakdala ensialic segment of the Kipchak arc. The sialic basement is not known in the Bozshakol–Chingiz segment in Kazakhstan and Salair segment in Russia, where it remains attached to the fragments of the Baikalides that frame the Siberian craton in the west. In the Tien Shan, the Stepnyak–Betpakdala segment reveals a 'free end' and it is not clear where other fragments of this arc might be found outside the Northern Tien Shan. Yakubchuk et al. (2001) suggested that it could be previously linked with Paleozoic magmatic arc rocks in the Altyntag and Kunlun mountains at the southern rim of the Tarim and Karakum blocks, then extending to the Caucasus. In this case, the Tarim and Karakum blocks could have been part or backstops of the Kipchak arc since the Late Proterozoic, in contrast to their traditional interpretation as fragments of Gondwana docked to Laurasia only in the Late Paleozoic (Scotese and McKerrow, 1990; Zonenshain et al., 1990; Sengör and Natal'in, 1996). In other words, the Tarim and North China cratons could always have been independent, and, therefore, their recognition as a single craton may be incorrect. This also means that the Altaids may have been formerly linked to the Tethysides and not to the Circum-Pacific belt.

The striking difference of this interpretation with the model by Sengör et al. (1993) and Sengör and Natal'in (1996) is the much smaller number of fragments in the Kipchak arc than they suggested. In the present structure, these segments are separated from each other by fault zones that can be interpreted as sinistral and dextral strike–slip faults with displacement for as much as 400–1000 km, making a so-called 'stacked structure' of Sengör et al. (1993) and Sengör and Natal'in (1996), which was suggested for a greater number of tectonic units. In a simpler model here, there are only three units with the Salair segment sinistrally offset with respect to the Bozshakol–Chingiz segment for 1000 km and the latter dextrally offset for approximately 400 km with respect to the Stepnyak–Betpakdala segment. The simatic segments of the Kipchak arc host VMS deposits (e.g. Maikain, Kusmurun, Mizek in Central Kazakhstan and the Salair group in Russia) and Cu-porphyry deposits (Bozshakol in Kazakhstan) (Heinhorst et al., 2000; Yakubchuk et al., 2001).

The segments of the Kipchak arc reveal a complex structure. At its rear in the Stepnyak–Betpakdala segment is a more than 1000-km-long Vendian–Early Paleozoic Baikonur–Karatau backarc rift (Mossakovskiy et al., 1993; Yakubchuk, 1997) with V–Mo sedimentary rock-hosted deposits. Alternative interpretations (Sengör and Natal'in, 1996) suggest it is an accretionary complex that grew up in front of the Kipchak arc and then was repeated along a strike–slip fault, but this is not supported by its distinct metallogeny in comparison with the other synchronous accretionary complexes in the region whose fragments are now found in the core of the Kazakh and West Sayan oroclines. Berzin et al. (1994) demonstrated that fragments of the Vendian–Early Cambrian oceanic island chains were accreted in the West Sayan.

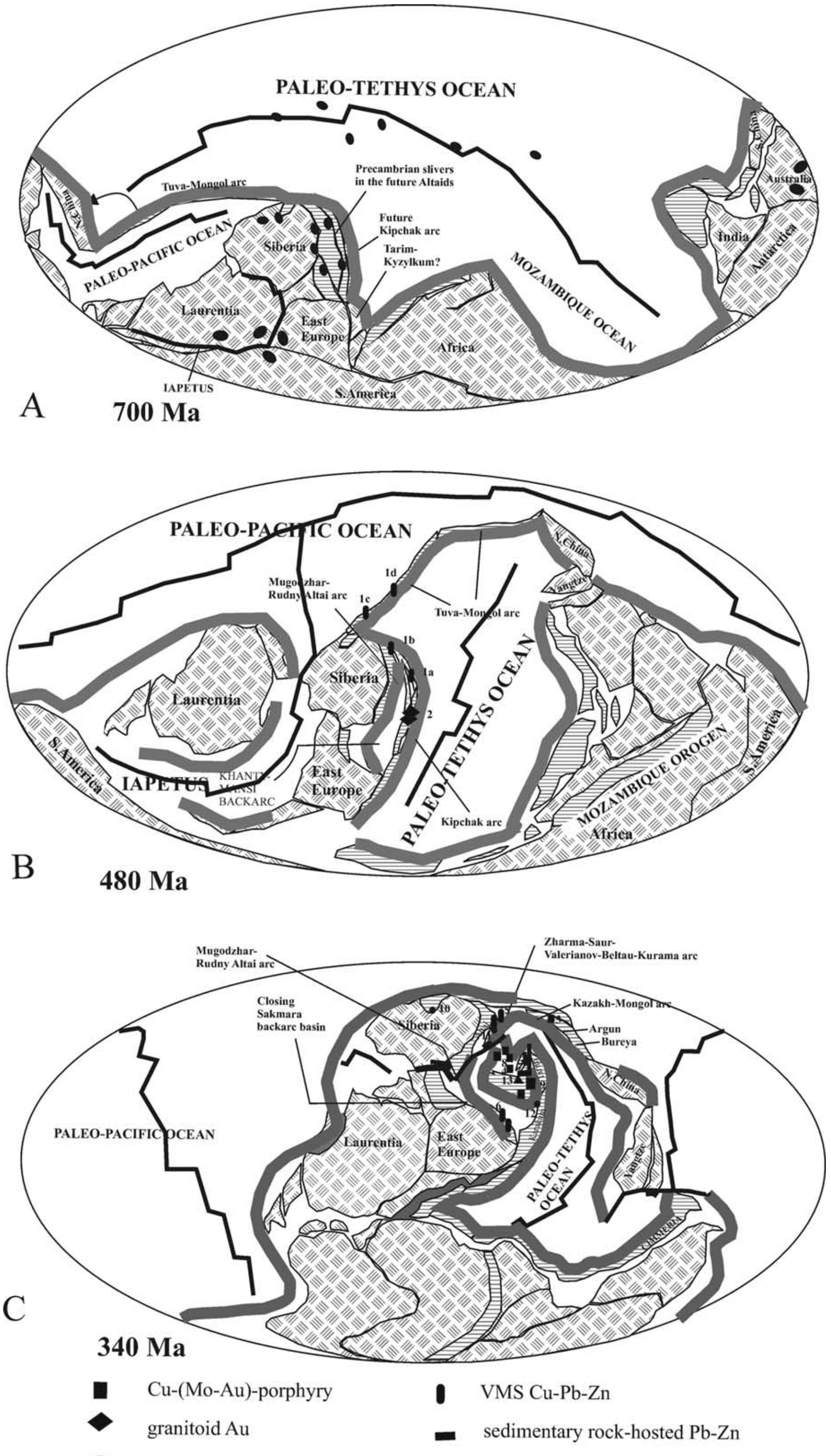
Within the Kipchak arc in the Kazakh uplands and Northern Tien Shan, the ophiolitic sutures mark a system of Cambrian–Ordovician intra-arc basins, for which one can reconstruct their former en echelon position. Their suturing and related strike–slip deformation at the end of the Ordovician led to the emplacement of Late Ordovician granitoid plutons, which host orogenic gold deposits in Kazakhstan (Vasilkovskoe, Zholymbet, Bestobe, Aksu–Kvartsytovye Gorki deposits) (Shatov et al., 1996; Heinhorst et al., 2000) and in the Kuznetsk Alatau in Russia (Berikul, Kommunar) (Distanov and Obolenskiy, 1993). Almost all Early Paleozoic ophiolite sutures of Central Kazakhstan produced lateritic weathering crusts with Ni–Co deposits during the Mesozoic. None of these ophiolites contains significant chromite deposits.

Outside the Kipchak arc, in the suture of the *Khanty–Mansi backarc basin*, there are Early Paleozoic ophiolites suggesting that the Kipchak arc was separated from the Mugodzhar–Rudny Altai arc in the Early Paleozoic.

The *Mugodzhar–Rudny Altai arc* was recently suggested by Yakubchuk et al. (2001) on the basis of the similar style of magmatism, metallogeny, and structural continuity of magnetic anomalies. Similar ideas were expressed in the 1980s by Zaitsev (1984). The arc mostly consists of the above-mentioned Middle Paleozoic ensimatic island arc rocks, which started to develop in the Ordovician (Puchkov, 1993) and was separated from the East European craton by the Sakmara backarc basin, whose suture hosts the Ordovician ophiolites (Ryazantsev et al., 2001).

3. Tectonic evolution of the Altaids and mineral deposit setting

The tectonic evolution of the Altaid orogenic collage can be understood in the context of the breakup of Rodinia (Moores, 1991) and rotational history of the East European and Siberian cratons and adjacent Late Proterozoic orogens. Hoffman (1991) proposed that Laurentia was in the core of the Late Proterozoic supercontinent, which had an absolutely different configuration of the constituent cratons than future Gondwana. This supercontinent was later called Rodinia (Powell et al., 1993). It was surrounded by the ocean, part of which was recognized as the Mozambique Ocean (Fig. 7A). This global scenario suggested that in the Late Proterozoic, Australia–Antarctica–India were rifted off present western Laurentia with opening of the Panthalassic (Paleo-Pacific) Ocean, drifted into the opposite hemisphere ('turned inside out' according to Hoffman, 1991) and collided with African cratons to suture the Mozambique Ocean and to form Gondwana only by



■ Cu-(Mo-Au)-porphyry

◆ granitoid Au

● sedimentary rock-hosted Au

▮ VMS Cu-Pb-Zn

▬ sedimentary rock-hosted Pb-Zn

▲ sedimentary rock-hosted Cu

Fig. 7. Tectonic evolution of the Altaid orogenic collage against the global background. Major cratons are after Scotese and McKerrow (1990). (A) Beginning of breakup of Rodinia (700 Ma), (B) expansion of Paleo-Pacific Ocean (480 Ma), (C) contraction of Paleo-Tethys Ocean, beginning of final amalgamation of the Altaid collage (340 Ma). Black spots show continental flood basalts and oceanic islands. Major deposits are shown on time slices corresponding to mineralization (except Muruntau, which was formed in the Late Permian): (1a) Maikain, (1b) Salair, (1c) Ozernoe, (1d) Kyzyltashtyg, (2) future Vasilkovskoe, Zholymbet, Bestobe, (3) Oyu Tolgoi, (4) Samarskoe (Nurkazgan), (5) Rudny Altai group, (6) South Urals group, (7) Mirgalimsai, Shalkiya, (8) Kounrad, Aktogai, (9) Kalmakyr—Dalnee, (10) Sukhoi Log, (11) Bakyrchik, (12) Muruntau.

the beginning of the Cambrian. This new continent assembled in the southern hemisphere. On the other hand, Eastern Europe and Siberia drifted from the southern into northern hemisphere.

Kovalenko et al. (1999) suggested that breakup of Rodinia and apparent northward drift of Eastern Europe, Siberia and small Precambrian slivers of the Altaids could be driven by ascending convention that generated the plume province, which is still active in the South Pacific region. These workers suggest that this plume and convection were a primary source that forced Rodinia to turn inside out. This plume can be reconstructed from Neoproterozoic flood basalts in the Siberian craton and accreted oceanic chains in the adjacent orogens (Kovalenko et al., 1999). Its ascending preceded the breakup of the supercontinent Rodinia, and in the end of Proterozoic it was followed by spreading of new oceanic crust so that Laurentia became surrounded by the Paleo-Pacific and Iapetus Oceans in the same way as present Africa, whereas Eastern Europe, Siberia, Australia–Antarctica–India, and African–South American cratons drifted apart towards the pre-Rodinian ocean. It cannot be identified with the Paleo-Pacific Ocean. Yakubchuk et al. (2001) and Yakubchuk (2002) suggested that it could be the Paleo-Tethys Ocean, an unsutured continuation of the Mozambique Ocean.

In this scenario, the present Pre-Uralides and Baikalides occur at the active margin of Eastern Europe–Siberia, facing the Paleo-Tethys Ocean. Therefore, it does not contradict the interpretation by Sengör et al. (1993) that the Precambrian slivers of the Kipchak arc that are now found inside the Altaids were rifted off the combined Eastern Europe–Siberia continent during the Neoproterozoic (Vendian). A similar mechanism can be suggested for the origin of the Tuva–Mongol arc, but it might have rifted off the combined Siberia–Laurentia continent, together with the North China and Australia–Antarctic cratons, so that the Paleo-Pacific Ocean remained behind this arc. Paleomagnetic data (Torsvik et al., 1992) indicate that the East European and Siberian cratons were very close during the Paleozoic, but they faced each other by their present northern margins in the Early Paleozoic. Since the Late Ordovician, Siberia began its clockwise rotation with respect to Eastern Europe due to spreading events between Siberia and Laurentia. Several episodes of such rotation caused the opening of the Khanty–Mansi, Sakmara backarc and small intra-arc basins (Fig. 7B). The progressing rotation also caused the oroclinal bending of the Kipchak and Tuva–Mongol arcs, their amalgamation into a single Kazakh–Mongol arc in the mid-Paleozoic, then further oroclinal bending and collision with the cratons during the late Paleozoic to form the orogenic collage of the Altaids.

The Khanty–Mansi backarc basin started to spread in the Late Proterozic between the Kipchak arc and combined Eastern Europe–Siberia, possibly in response to the beginning of clockwise rotation of Siberia. This process continued in the Early Paleozoic, but in the Late Cambrian–Early Paleozoic, the Kipchak arc was additionally split by intra-arc basins and at the same time produced Early Paleozoic VMS and porphyry deposits.

The continuing clockwise rotation of Siberia with respect to Eastern Europe in the Late Ordovician caused intra-arc collision in the Kipchak arc and closure of its intra-arc basins. This event generated emplacement of granite-related gold deposits in north Central Kazakhstan. This also coincides with the beginning of formation of the Mugodzhar–Rudny Altai arc, with first VMS deposits in the Urals, and then with spreading in the Sakmara basin whose oceanic-type crust produced Cr–(Os–Ir) deposits emplaced into the Ural orogen after suturing.

Spreading events and subduction against the continuing clockwise rotation of Siberia and oroclinal bending of the new Kazakh–Mongol magmatic arcs in the Silurian–Devonian coincided with emplacement of the porphyry and small VMS deposits of Central Kazakhstan and Mongolia and major VMS mineralization in the Mugodzhar–Rudny Altai arc. The ongoing oroclinal bending of the Kazakh–Mongol arc caused its intrusion between Alai–Tarim–Karakum and Siberia towards the East European craton. This created temporary subduction on the present western flank of the arc in the Early–Middle Devonian, but in the Mid-Devonian the evaporite-bearing and molasse-filled rift-related backarc basins started to cover the previously amalgamated fragments.

In the Early Carboniferous (Fig. 7C), Siberia continued its clockwise rotation towards Eastern Europe and caused further southeastward migration of the western part of the Kazakh–Mongol arc and bending of the Kazakh orocline, pushing it further towards the East European craton along its bounding strike–slip faults. This coincided with further emplacement of porphyry deposits in Central Kazakhstan. The westward motion of the Kazakh orocline was responsible for subduction of the Khanty–Mansi basin under its present western flank to form the Zharma-Saur–Valerianov–Beltau-Kurama arc, which also produced porphyry, skarn, and epithermal deposits.

In the Early–Middle Carboniferous, the western part of the Zharma-Saur–Valerianov–Beltau-Kurama arc collided with the Mugodzhar–Rudny Altai arc to form a 5000 km-long suture extending from the Southern Tien Shan to the East Urals and Irtysh–Zaissan zones (in place of the Khanty–Mansi backarc basin) and the Main Ural suture (in place of the Sakmara backarc basin) in between the Mugodzhar arc and the East European craton; the process ended in the Early Permian to produce the western portion of the Altaid orogenic collage almost in its present shape. This suturing was an important event in the structural preparation of the region, which produced such gold deposits as Muruntau, Kumtor, Bakyrchik, and Berezovskoe. The final amalgamation culminated in emplacement of the Late Permian A-type granites, forming a giant province extending from western Central Kazakhstan to

Table 1
Tectonic belts and related ore deposits of the Altaid orogenic collage (modified after Yakubchuk et al., 2001)

Belt name	Age	Ore types	Examples
Tuva–Mongol arc	Vendian–Early Paleozoic	VMS Cu–Pb–Zn–Ag–Au	Kyzyltashtyg, Ozernoe
		Orogenic Au	Zun–Kholba
		Porphyry Cu–Mo	Aksug
Kipchak arc	Vendian–Early Paleozoic	VMS	Maikain, Kusmurun, Mizek, Salair Group
		Porphyry Cu	Bozshakol
		Orogenic Au	Vasilkovskoe, Bestobe, Zholymbet, Aksu, Kvartsytovye Gorki, Berikul, Kommunar
		Sediment-hosted Pb–Zn	Tekeli
Kazakh–Mongol arc and its backarc rifts	Middle–Late Paleozoic	Porphyry and epithermal	Oyu Tolgoi, Nurkazgan, Akbakai, Duobaoshan, Kounrad, Aktogai
		Skarn	Sayak
		Pb–Zn–(Ag) (VMS, sediment-hosted)	Progress, Abyz, Zhairem, Shalkiya, Mirgalimsai
		Redbed volcanics	Kodzhanchad
		W–Mo	Akchatau, Batystau, Verkhnee Kairakty
Zharma-Saur–Valerianovka –Beltau-Kurama arc	Early–Middle Carboniferous	Porphyry Cu–Mo	Kalmakyr
		Fe oxide, skarn	Sokolovsko–Sarbaiskoe
		Epithermal	Kochbulak
South Tien Shan–East Urals –Irtysh–Zaissan suture	Early–Middle Carboniferous –Permian	Orogenic Au	Kumtor, Muruntau, Zarmitan, Bakyrchik, Suzdal
Mugodzhar–Rudny Altai arc	Late Ordovician–Middle Paleozoic	VMS	Ridder–Sokolnoe, Maleyevskoe, Sibai, Gai, Uchaly
		Porphyry Mo–(Cu)	Sora in Kuznetsk Alatau, Yubileinoe in the Urals
		Orogenic Au	Berezovskoe, Kochkar
Sakmara suture	Paleozoic	Cr-deposits in ophiolites	Kempirsai, Rai–Iz

Mongolia, and producing the modern continental crust of the region.

In the eastern Altaids, the Transbaikal arc, facing the Paleo-Pacific Ocean, overlapped the Altaid units. Its oroclinal bending into Central Mongolian and Hingan oroclines together with the Kazakh–Mongol arc occurred from Triassic to mid-Jurassic time, when Bureya block collided with the Siberian craton to form the Mongol–Okhotsk suture. The emplacement of most important mineral deposits of the Altaid orogenic collage (Table 1) occurred during several pulses of oroclinal bending and related events.

The Yanshanian arc magmatism then welded these units during the Late Jurassic to Early Cretaceous. Prior to this, the North China craton may have formed a continuation of the Precambrian slivers in the basement of the Tuva–Mongol arc of northeast China. However, during this event, it may have been pushed westward, i.e. dextrally with respect to the axis of the Hingan orocline towards its present position with respect to Tarim. After this collision, the entire Altaid collage was formed in its present form, but in the Middle to Late Cretaceous it was significantly corrugated by a system of conjugate strike–slip faults in response to the southward propagation of the Siberian craton that offset all earlier formed structures and metallogenic belts.

4. Conclusions

The Altaids constitute an orogenic collage of Neoproterozoic–Paleozoic rocks that lie between the East European, Siberian, North China and Tarim cratons, smaller Precambrian slivers of Mongolia and Late Proterozoic orogens. The basement structures of this collage consist of only three oroclinally bent Neoproterozoic–Early Paleozoic magmatic arcs (Kipchak, Tuva–Mongol, and Mugodzhar–Rudny Altai), separated by sutures of their former backarc basins. There are also Middle to Late Paleozoic overlapping magmatic arcs that stitched the fragments of the earlier arcs. These structures host important Early Paleozoic to Early Mesozoic gold, copper–molybdenum, lead–zinc, and other deposits of various types.

In the Late Proterozoic, these arcs were rifted off the Eastern Europe, Siberia and Laurentia to produce oceanic backarc basins. In the Late Ordovician, the Siberian craton began its clockwise rotation with respect to Eastern Europe. This process continued in the Middle Paleozoic until the Early Permian producing several episodes of oroclinal bending and reorganization of the magmatic arcs to produce the Kazakh–Mongol and Zharma-Saur–Valerianov–Beltau-Kurama arcs that welded the extinct Kipchak and Tuva–Mongol arcs and whose fronts migrated oceanward in time. Amalgamation of these tectonic elements resulted in the formation of the Altaid orogenic collage in the Late Paleozoic.

Major mineralizing events producing world-class intrusion-related Au, Cu–(Mo)-porphyry and VMS deposits in the Altaids coincided with plate reorganization and oroclinal bending of magmatic arcs. Pb–Zn and Cu sedimentary rock-hosted deposits occur in backarc rifts developed on the amalgamated fragments of earlier arcs. Major orogenic gold deposits are intrusion-related deposits occurring within black shale-bearing sutured backarc basins with oceanic crust. The major mineralizing episodes in the Altaids coincide with generation of new magmatic arcs and tectonic episodes of oroclinal bending.

After amalgamation of the western Altaids, this part of the collage and adjacent cratons were affected by the Siberian superplume, which ascended at the Permian–Triassic transition. This plume-related magmatism produced various deposits, such as the famous Ni–Cu–PGE deposits of Norilsk in the northwest of the Siberian craton.

In the early Mesozoic, the eastern Altaids were oroclinally bent together with the overlapping Transbaikal magmatic arc in response to the northward migration and anti-clockwise rotation of the North China craton. The following collision of the eastern portion of the Altaid collage with the Siberian craton formed the Mongol–Okhotsk suture zone, which still links the accretionary wedges of central Mongolia and Circum-Pacific belts. In the late Mesozoic, a system of continent-scale conjugate northwest-trending and northeast-trending strike–slip faults developed in response to the southward propagation of the Siberian craton with subsequent post-mineral offset of some metallogenic belts for as much as 70–400 km, possibly in response to spreading in the Canadian basin. India–Asia collision rejuvenated some of these faults and generated a system of impact rifts.

Acknowledgements

I thank Jeffrey Hedenquist, Noel White, Rich Goldfarb, Celal Sengör, Boris Natal'in, Reimar Seltmann, Richard Herrington, Sergei Diakov, Brian Windley, Chris Stanley, Pepe Perello, Koh Naito, Rod Kirkham, Evgeniy Milanovskiy, Anatoly Nikishin, Aleksei Ryazantsev, Kirill Degtyarev, Valery Borisenok, Victor Puchkov, and Tatiana Kheraskova for the interest to my work during many recent and previous years and for inspiring discussions. I also thank E. Distanov and A. Vladimirov for useful comments that helped to improve the manuscript.

References

Berzin, N.A., Coleman, R.G., Dobretsov, N.L., Zonenshain, L.P., Xiao, X., Chang, E.Z., 1994. Geodynamic map of the western part of the Paleo-Asian Ocean. Geologiya i Geofizika 35 (7–8), 8–29.In Russian.

Bogatskiy, V.I., Bogdanov, N.A., Kostyuchenko, S.L., Senin, B.V., Sobolev, S.F., Shipilov, E.V., Khain, V.E., 1996. Explanatory Note and Tectonic Map of the Barents Sea and Northern Part of European Russia at a Scale of 1:2,500,000, Institute of Lithosphere, Russian Academy of Sciences, Moscow.

Bogdanov, N.A., Khain, V.E., Rozen, O.M., Shipilov, E.V., Vernikovskiy, V.A., Drachev, S.S., Kostyuchenko, S.L., Kuzmichev, A.B., Sekretov, S.B., 1998. Explanatory Note and Tectonic Map of the Kara and Laptevs Sea at a Scale of 1:2,500,000, Institute of Lithosphere, Russian Academy of Sciences, Moscow.

Bortnikov, N.S., Prokof'ev, V.Yu., Razdolina, N.V., 1996. Origin of the Charmitan gold–quartz deposit (Uzbekistan). Geology of Ore Deposits 38, 208–226.

Burtman, V.S., 1997. Kyrgyz republic. In: Moores, E.M., Fairbridge, R.W. (Eds.), Encylopedia of European and Asian Regional Geology, Chapman & Hall, London, pp. 483–492.

Cole, A., 2000. Genesis of granitoid-hosted gold–tungsten mineralization, Jilau, Tajikistan. Doctoral Thesis, University of London, UK, 240 pp.

Cole, A., Wilkinson, J.J., Halls, C., Serenko, T.J., 2000. Geological characteristics, tectonic setting and preliminary interpretations of the Jilau gold–quartz vein deposit, Tajikistan. Mineralium Deposita 35, 600–618.

Coleman, R.G., 1989. Continental growth of Northwest China. Tectonics 8, 621–635.

Cunningham, W.D., Windley, B.F., Dorjnamjaa, G., Badamganov, J., Saandar, M., 1996. A structural transect across the Mongolian Altai: active transpressional mountain building in central Asia. Tectonics 15 (1), 142–156.

Didenko, A.N., Mossakovskiy, A.A., Pecherskiy, D.M., Ruzhentsev, S.G., Samygin, S.G., Kheraskova, T.N., 1994. Geodynamics of Paleozoic oceans of Central Asia. Geologiya i Geofizika 35 (7–8), 59–76.In Russian.

Distanov, E.G., Obolenskiy, A.A., 1993. Some problems of metallogeny of the Central Asian mobile belt according to their geodynamic evolution. In: Dobretsov, N.L., Berzin, N.A. (Eds.), Report No 4 of the IGCP Project 283: Fourth International Symposium on Geodynamic Evolution of the Paleoasian Ocean, Novosibirsk, Abstracts, pp. 189–191.

Dobretsov, N.L., Vernikovsky, V.A., 2001. Mantle plumes and their geologic manifestations. International Geology Review 43, 771–787.

Dodin, D.A., Chernyshov, N.M., Yatskevich, B.A., 2000. Platinum-Metal Deposits of Russia, Nauka, St Petersburg, In Russian.

Drew, L.J., Berger, B.R., Kurbanov, N.K., 1996. Geology and structural evolution of the Muruntau gold deposit, Kyzylkum desert, Uzbekistan. Ore Geology Reviews 11, 175–196.

Evdokimov, A.N., Kalenich, A.P., Kryukov, V.D., Lastochkin, A.V., Semenov, Yu.P., 2000. Novaya Zemlya as a new prospective resource target on the Barents–Kara shelf. Razvedka i Okhrana Nedr 12, 40–43.In Russian.

Hamilton, W.B., 1970. The Uralides and the motion of the Russian and Siberian platforms. Bulletin of the Geological Society of America 81, 2553–2576.

Heinhorst, J., Lehmann, B., Ermolov, P., Serykh, V., Zhurutin, S., 2000. Paleozoic crustal growth of Central Asia: evidence from magmatic-hydrothermal ore systems of Central Kazakhstan. Tectonophysics 328, 69–87.

Herrington, R.M., Armstrong, R.N., Zaykov, V.V., Maslennikov, V.V., 2000. Massive sulfide deposits in the south Urals, their ore facies and geological settings. In: Gemmel, J.B., Pongratz, J. (Eds.), Program with abstracts: volcanic environments and massive sulfide deposits, CODES Special Publication 4, pp. 81–82.

Herrington, R.M., Smith, M., Maslennikov, V., Belogub, E., Armstrong, R., 2002. A short review of Palaeozoic hydrothermal magnetite iron-oxide deposits of the south and central Urals and their geological setting. In: Porter, T.M., (Ed.), Hydrothermal Iron Oxide Copper–Gold and Related Deposits: A Global Perspective, vol. 2. PGC Publishing, Adelaide, pp. 343–353.

Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside out? Science 252, 1409–1412.

Kirkham, R.V., Dunne, K.P.E., 2000. World distribution of porphyry, porphyry-associated skarn, and bulk-tonnage epithermal deposits and occurrences. Geological Survey of Canada, Open File 3792, Scale 1:35, 000,000, accompanied by one diskette; www.nrcan.gc.ca/gsc/gicd/pubs/circular/2000_02/ofiles_e.htm

Kovalenko, V.I., Yarmolyuk, V.V., Kovach, V.P., Budnikov, S.V., Zhuravlev, D.Z., Kozakov, I.K., Kotov, A.B., Rytsk, E.Yu., Salnikova, E.B., 1999. Crust-forming magmatic processes during formation of the Central Asian fold belt: Sm–Nd isotopic data. Geotektonika 3, 21–41.In Russian.

Kovalev, K.R., Distanov, E.G., Pertseva, A.P., 1998. Variations in isotopic composition of sulphur during volcanic-sedimentary ore formation and metamorphism of the Ozernoe ore district, western Transbaikalia. Geology of Ore Deposits 40 (4), 336–353.In Russian.

Milanovskiy, E.E., 1996. Geology of Russia and Adjacent Countries, Moscow State University Press, Moscow, In Russian.

Moores, E.M., 1991. SW US-East Antarctic (SWEAT) connection: a hypothesis. Geology 19, 425–428.

Mossakovskiy, A.A., Ruzhentsev, S.V., Samygin, S.G., Kheraskova, T.N., 1993. Central Asian fold belt: geodynamic evolution and history of formation. Geotektonika 6, 3–33.In Russian.

National Geophysical Data Center, 1996. Magnetic anomaly data of the former Soviet Union, Boulder, CO, CD-ROM.

Parfenov, L.M., Popeko, L.I., Tomurtogoo, T., 2001. Problems of tectonics of the Mongol–Okhotsk orogenic belt. Geology of Pacific Ocean 16, 797–830.

Perelló, J., Cox, D., Garamjav, D., Sanjdorj, S., Diakov, S., Schissel, D., Mukhbat, T.-O., Oyun, G., 2001. Oyu Tolgoi, Mongolia: Siluro-Devonian porphyry Cu–Au–(Mo) and epithermal Cu mineralization with a Cretaceous chalcocite blanket. Economic Geology 96, 1407–1428.

Popov, V.V., 1995. Geological localization of large polymetallic deposits in Rudny Altai. Geology of Ore Deposits 37 (5), 371–389.In Russian.

Popov, V.V., 1997. Regional factors in origin of large concentrations of polymetallic ore in the Urals. Geology of Ore Deposits 39 (5), 465–476. In Russian.

Powell, C.McA., Li, Z.-X., McElhinny, M.W., Park, J.K., 1993. Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana. Geology 21, 889–892.

Puchkov, V.N., 1993. Paleo-oceanic structures of the Urals. Geotektonika 3, 18–33.In Russian.

Puchkov, V.N., 1997. Structure and geodynamics of the Uralian orogen. Geological Society Special Publication 121, 201–236.

Puchkov, V.N., 2000. Paleogeodynamics of the South and Middle Urals, Dauriya, Ufa. In Russian.

Ryazantsev, A.V., Dubinina, S.V., Borisenok, V.I., 2001. Upper Ordovician in the structure of Silurian and Devonian accretionary complexes in the South Urals, in: Karyakin, Y. (Ed.), Tectonics of the Neogean: General and Regional Aspects, GEOS vol. 2, Moscow, pp. 166–169. In Russian.

Samygin, S.G., Khain, E.V., 1985. South Urals and northern Caucasus in the Paleozoic: a comparison. Geotektonika 2, 40–56.In Russian.

Sazonov, V.N., van Herk, A.H., de Boorder, H., 2001. Spatial and temporal distribution of gold deposits in the Urals. Economic Geology 96, 685–703.

Scotese, C.R., McKerrow, W.S., 1990. Revised world maps and introduction. Geological Society of London Memoirs 12, 1–21.

Seltmann, R., Koroteev, V., Fershtater, G., Smirnov, V. (Eds.), 2000. The eroded Uralian Paleozoic ocean to continent transition zone: granitoids and related ore deposits. Excursion Guidebook of the IGCP-373 International Field Conference in the Urals, Russia, 18–30 July 2000. IAGOD Guidebook Series 8. Natural History Museum, London.

Sengör, A.M.C., Natal'in, B.A., 1996. Turkic-type orogeny and its role in the making of the continental crust. Annual Review in Earth and Planetary Sciences 24, 263–337.

Sengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature 364 (6435), 299–307.

Shatov, V., Seltmann, R., Kremenetsky, A., Lehmann, B., Popov, V., Ermolov, P. (Eds.), 1996. Granite-related ore deposits of Central Kazakhstan and adjacent areas, Glagol Publishing House, St Petersburg.

Shatov, V.V., Cole, A., Seltmann, R., Yakubchuk, A., 2001. Metallogeny of gold in the Tien Shan and Urals Paleozoic fold belts: a GIS-based approach. In: Piestrzynski, A., et al. (Eds.), Mineral Deposits at the Beginning of the 21st century, Swets and Zeitlinger, Lisse, pp. 489–492.

Shayakubov, T., Islamov, F., Krementsky, A., Seltmann, R. (Eds.), 1999. Au, Ag, and Cu deposits of Uzbekistan. IGCP 373 International Field Conference, Excursion B6 of the Joint SGA-IAGOD Symposium, 27/28 August–4 September 1999, Natural History Museum, London-Tashkent.

Shipilov, E.V., Tarasov, G.A., 1998. Regional geology of the oil-bearing sedimentary basins of the Russian West-Arctic shelf. Apatity 1998. In Russian.

Sotnikov, V.I., Berzina, A.P., 2000. Porphyry Cu–(Mo) ore-magmatic systems of Siberia and Mongolia. In: Kremenetsky, A.A., Lehmann, B., Seltmann, R. (Eds.), Ore-bearing Granites of Russia and Adjacent Countries, Moscow, pp. 263–279.

Suess, E., 1908. The Face of the Earth, vol. 3. Clarendon Press, Oxford.

Tian, Z., Zhang, Q., 1997. Petroliferous Sedimentary Basins in China and Basin Analysis, Petroleum Industry Press, Beijing.

Torsvik, T.H., Smethurst, M.A., Van der Voo, R., Trench, A., Abrahamsen, N., Halvorsen, E., 1992. Baltica. A synopsis of Vendian–Permian paleomagnetic implications. Earth Science Reviews 33, 133–152.

Vernikovskiy, V.A., Vernikovskaia, A.E., Chernykh, A.I., Melgunov, M.S., 1996. Petrology and geochemistry of the Riphean ophiolites in northern Taimyr. Geologiya i Geofizika 37 (1), 113–129. In Russian.

Vernikovskiy, V.A., Vernikovskaia, A.E., Salnikova, E.B., Kotov, A.B., 1999. New U–Pb data on age of the paleo-island arc complex of the Predivinsky Terrane, Yenisey Range. Geologiya i Geofizika 40 (2), 255–259. In Russian.

White, N.C., Hedenquist, J.W., Kirkham, R.V., 2001. Asia: the waking giant. Mining Journal Supplement.

Wilde, A.R., Layer, P., Mernagh, T., Foster, J., 2001. The giant Muruntau gold deposit: geologic, geochronologic, and fluid inclusion constraints of ore genesis. Economic Geology 96, 633–644.

Yakubchuk, A.S., 1997. Kazakhstan. In: Moores, E.M., Fairbridge, R.W. (Eds.), Encyclopedia of European and Asian Regional Geology, Chapman & Hall, London, pp. 450–465.

Yakubchuk, A.S., 2001, New opportunities in deciphering the tectonic zonation of the Urals: a metallogenic implication. GEODE, VMS Deposits of the Urals and Their Tectonic Setting Field Workshop, London, October 14–17.

Yakubchuk, A., 2002. The Baikalide-Altaid, Transbaikal–Mongolian and North Pacific orogenic collages: similarity and diversity of structural patterns and metallogenic zoning. In: Blundell, D., Neubauer, F., von Quadt, A. (Eds.), The Timing and Location of Major Ore Deposits in an Evolving Orogen, Geological Society London Special Publication 206, pp. 273–297.

Yakubchuk, A.S., Edwards, A., 1999. Auriferous Paleozoic accretionary terranes within the Mongol–Okhotsk suture zone, Russian Far East. In: Proceedings of Pacrim'99, 10–13 October 1999, Bali, Indonesia, The Australasian Institute of Mining and Metallurgy Publication Series No. 4/99, pp. 347–358.

Yakubchuk, A.S., Seltmann, R., Shatov, V.V., Cole, A., 2001. The Altaids: tectonic evolution and metallogeny. Society of Economic Geologists Newsletter 46 (1), 7–14.

Yakubchuk, A.S., Cole, A., Seltmann, R., Shatov, V., 2002. Tectonic setting, characteristics and regional exploration criteria for gold mineralization in Central Eurasia: the southern Tien Shan province as a key example. In: Goldfarb, R., Nielsen, R.L. (Eds.), Integrated methods for discovery: global exploration in the twenty first century, SEG Special Publication N9, pp. 177–202.

Zaitsev, Y.A., 1984. Evolution of Geosynclines, Nedra, Moscow, in Russian.

Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1990. Geology of the USSR: A Plate Tectonic Synthesis, American Geophysical Union, Washington, DC.