The Baikalide–Altaid, Transbaikal–Mongolian and North Pacific orogenic collages: similarity and diversity of structural patterns and metallogenic zoning

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Abstract: The Baikalide–Altaid, Transbaikal–Mongolian and North Pacific orogenic collages consist of several oroclinally bent magmatic arcs separated by accretionary complexes and ophiolitic sutures located between the major cratons. The tectonic and metallogenic patterns of these collages are principally similar as they were formed as a result of rotation of the surrounding cratons and strike-slip translation along the former convergent margins.

The Altaid and North Pacific collages have principally the same distribution of metallogenic belts. In particular, the mid–late Palaeozoic belts of porphyry and epithermal deposits in the Altaids occupy the same position as the Mesozoic–Cenozoic metallogenic belts of the North Pacific collage. The Ural platinum belt occupies a similar position to the belt of platinum-bearing intrusions in Alaska. Major mineralizing events producing world-class intrusion-related Au, Cu–(Mo)-porphyry and VMS deposits in the Altaid and North Pacific collages coincided with plate reorganization and oroclinal bending of magmatic arcs. Formation of major porphyry, epithermal and Alaska-type PGM deposits took place simultaneously with oroclinal bending.

The tectonic setting of the orogenic gold deposits in the Tien Shan and Verkhoyansk–Kolyma provinces, hosting world-class hard rock gold deposits, is also similar, especially the distribution of their gold endowments. Major orogenic gold deposits occur within the sutured backarc basins. The craton-facing passive margin rock sequences, initially formed within backarc basins and now entrapped within such oroclines, represent favourable locations for emplacement of orogenic gold deposits.

The land-locked Altaid orogenic collage occurs between cratons separated or bounded by the fragments of the Neoproterozoic fold belts, e.g. the Baikalides and their equivalents, and Phanerozoic fold belts of the Tethysides, whereas the North Pacific orogenic collage and its splay into the Transbaikal–Mongolian orogenic collage are fragments of the Circum-Pacific belt formed between the subducting oceanic plates of the Pacific Ocean and the continents of Eurasia and North America (Fig. 1). Both regions host numerous economically important copper, gold, lead, zinc, PGM, nickel and other deposits, many of world class (White *et al.* 2001). I had a unique opportunity to work across these regions of Eurasia since 1984, participating in the regional geological surveys, international academic projects and exploration works. This experience helped me to recognize some similarity and diversity between them, on the one hand, and the links between geodynamics and metallogeny, on the other. A comprehensive study of tectonics and metallogeny of the Russian Far East and Alaska was recently completed by Nokleberg *et al.* (1993, 1998) and Nokleberg & Diggles (2001), which represents an ideal combination for the purposes of this article. The key works by Sengör & Natal'in (1996 a, b) analysed the tectonic evolution of all Asia, including both the Russian Far East and Central Eurasia. These latter works revealed the complex tectonics of Asia that consists of multiple, oroclinally bent magmatic arcs and accretionary complexes (Sengör & Natal'in 1996*a, b*). However, metallogenic aspects of Central Eurasia were only recently analysed by Yakubchuk *et al.* (2001). All these studies employ plate tectonics to explain the evolution and metallogeny of these orogens, but they sometimes recognize different tectonic units, use different terminolgy and disagree with each other in details. This paper intends to compare and to revise the existing interpretations of the geodynamic evolution of the two regions in relation to the setting of selected types of mineral deposits in the orogenic collages of Central Asia and northern segments of the Circum-Pacific belt, aiming to reveal their metallo-tectonic features.

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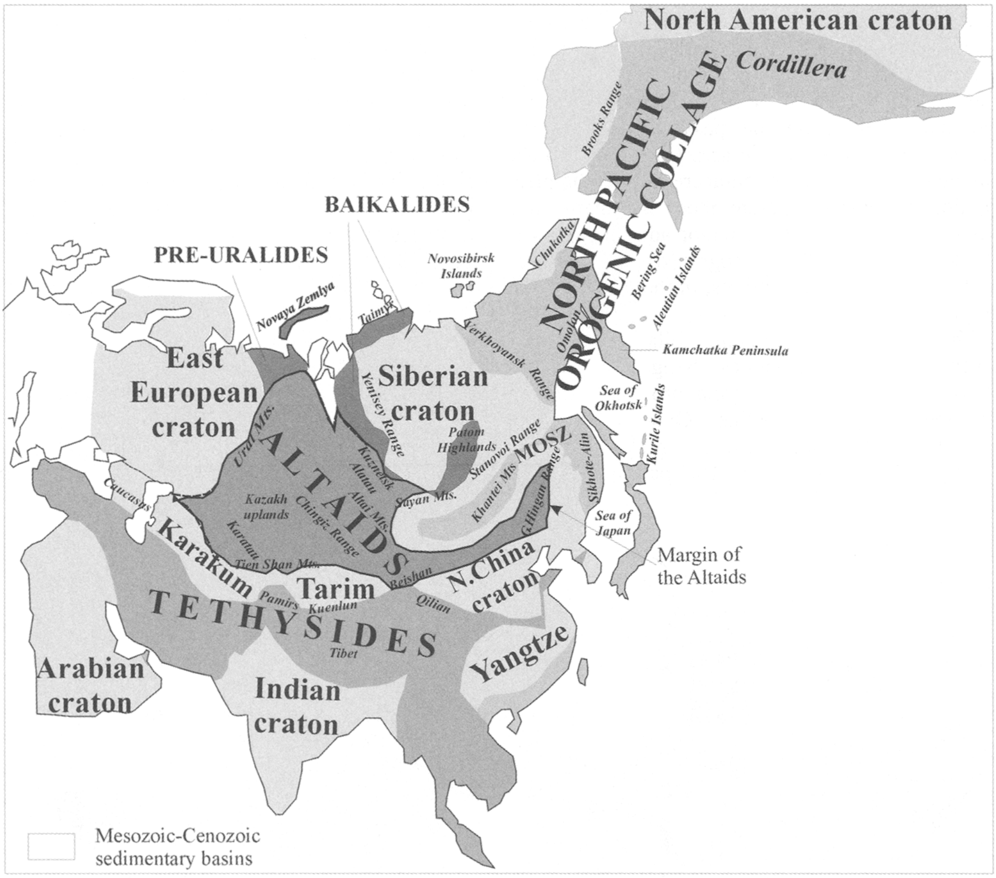

Fig. 1. First-order tectonic units of Eurasia and western North America (modified after Yakubchuk *et al.* 2001).

North Pacific and Transbaikal–Mongolian orogenic collages

Tectonics

This article considers the North Pacific orogenic collage as a system of orogenic belts extending from the Sikhote–Alin Mountains and Kurile Islands in the Russian Far East via mountainous ranges of northeast Russia and Alaska to the North American Cordillera in western Canada and USA. A detached fragment of the North Pacific orogenic collage constitutes the late Palaeozoic–early Mesozoic Transbaikal–Mongolian orogenic collage of central Mongolia (Yakubchuk & Edwards 1999; Yakubchuk *et al.* 2001). These orogenic collages were formed mostly in the Mesozoic–Cenozoic due to subduction of the oceanic plates of the Pacific Ocean (Scotese & McKerrow 1990; Nokleberg *et al.* 1993; Sengör & Natal'in 1996*a, b*). However, these collages also host fragments of now dismembered Palaeozoic orogenic belts, which formed in response to subduction of oceanic plates of the Palaeo-Pacific Ocean of Nokleberg *et al.* (1993) and Sengör & Natal'in (1996a, b) or Panthalassic Ocean of Scotese & McKerrow (1990).

The North Pacific orogenic collage is usually separately described as part of the North American and Eurasian continents. During the last few years, an international project, which synthesized the data on geology and mineral deposits on both sides of the northern Pacific Ocean, was completed (Nokleberg *et al.* 1993; Nokleberg & Diggles 2001). This was a significant breakthrough into understanding the tectonic evolution in this region and showed how tectonics links to mineralization.

The North Pacific orogenic collage occupies a unique position at the triple junction of the North American, Eurasian and Pacific plates, accompanied by several microplates. The active spreading axes of the Atlantic–Arctic and Pacific Oceans, as well as the extinct spreading axis of the Amerasian basin, also occur nearby. A simplified tectonic scheme of the North Pacific collage shows Siberian and North American cratons, including their deformed passive margins, and several adjacent magmatic arcs (Fig. 2). Each arc has generated a subduction-accretionary complex. Ophiolitic sutures separate these magmatic arcs from each other and from major adjacent cratons. Nokleberg *et al.* (1993) recognized major tectonic units, i.e. terranes and sutures, in the North Pacific orogenic collage.

The North Pacific orogenic collage consists of several discordant oroclines (Sengör & Natal'in 1996*a*, *b*). These are Kolyma orocline, Alaskan orocline, Sakhalin orocline, Okhotsk orocline, Koryak orocline and several oroclines in the Bering Sea area (Fig. 2). The pattern of these oroclines reflects a varying direction of strike-slip translation along the North Pacific margins during the accretionary growth of the North American and Eurasian continents. The principal structural markers within this collage are magmatic arcs. However, in several cases the tracing of their continuity is difficult, not only due to the obscuring Cenozoic sedimentary basins, especially in the central Kolyma area or in the Bering and Okhotsk Seas, but also due to tectonic 'shuffling' and repetition of the same accretionary complex along the giant strike-slip faults (Natal'in & Borukaev 1991; Khanchuk 2000).

Analysis of various tectonic schemes shows that in the present structure one can identify three fossil and still active late Palaeozoic to Cenozoic arc–backarc systems on the basis of synchroneity of magmatic arc, rifting and spreading events.

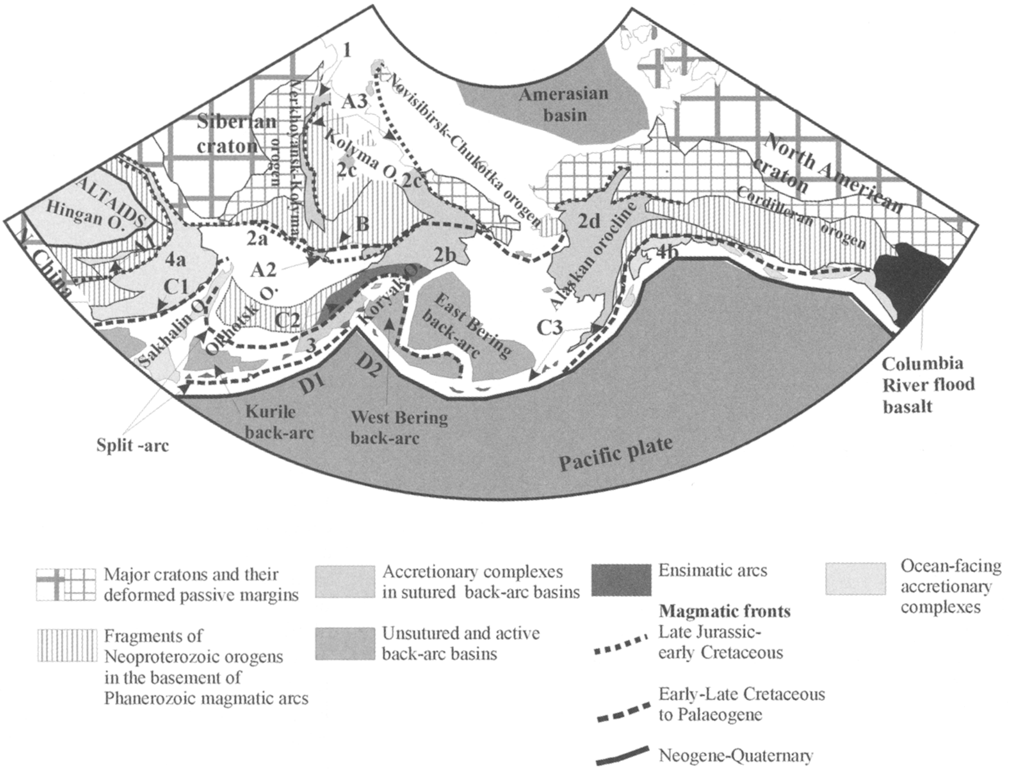

Fig. 2. Tectonics of the North Pacific orogenic collage (recompiled using data by Newberry *et al.* 1995;Nokleberg *et al.* 1997; Prokopiev 1998; Oksman *et al.* 2001). Magmatic arcs: A, Hingan and Omolon arcs (A1, Greater Hingan segment; A2, Uda–Murgal segment; A3, Alazeya–Oloy segment); B, Okhotsk–Chukotka arc; C, Sikhote–Alin–Aleutian arc (C1, Sikhote–Alin segment; C2, Kamchatka–Koryak segment; C3, Aleutian segment); D, Kurile–Komandor arc (D1, Kurile–East Kamchatka segment; D2, Komandor segment). Accretionary complexes in sutured backarc basins and ocean-facing subduction zones: 1, Chersky zone (former Oimyakon basin); 2, Okhotsk–Alaska backarc basin (2a, Okhotsk segment; 2b, Koryak segment; 2c, South Anyui segment; 2d, Yukon–Kuskokwim segment); 3, Kamchatka intra-arc basin; 4, ocean-facing accretionary complex (4a, Sikhote–Alin segment; 4b, Chugach segment).

These are the Verkhoyansk–Chukotka, Okhotsk–Alaska, and Kurile–Komandor systems (Fig. 3). In addition, there is an extinct Transbaikalian magmatic arc with an attached subduction-accretionary complex entrapped in the core of the Transbaikal–Mongolian orogenic collage. Although the former backarc basin of the Verkhoyansk–Chukotka system is totally sutured, backarc basins in the other systems were sutured only in part, and major inactive portions in the eastern Bering Sea remain unsutured. In addition, the backarc basins in the western Bering Sea, in the Kurile basin, and in the Sea of Japan are still actively spreading.

The Verkhoyansk–Chukotka arc–backarc system as described in this article, consists of the Verkhoyansk–Kolyma and Novosibirsk–Chukotka collisional orogens (Zonenshain *et al.* 1990; Bogdanov & Tilman 1992; Sengör & Natal'in 1996*a, b*). Nokleberg *et al.* (1993) and Sokolov *et al.* (1997) use the term super-terrane for these orogens. They formed as a result of several deformational events during the late Jurassic–Early Cretaceous collision of magmatic arcs with the adjacent Siberian and North American cratons against the background of their relative clockwise rotation with respect to each other and subduction of the Pacific plates (Parfenov 1991, 1995; Sengör

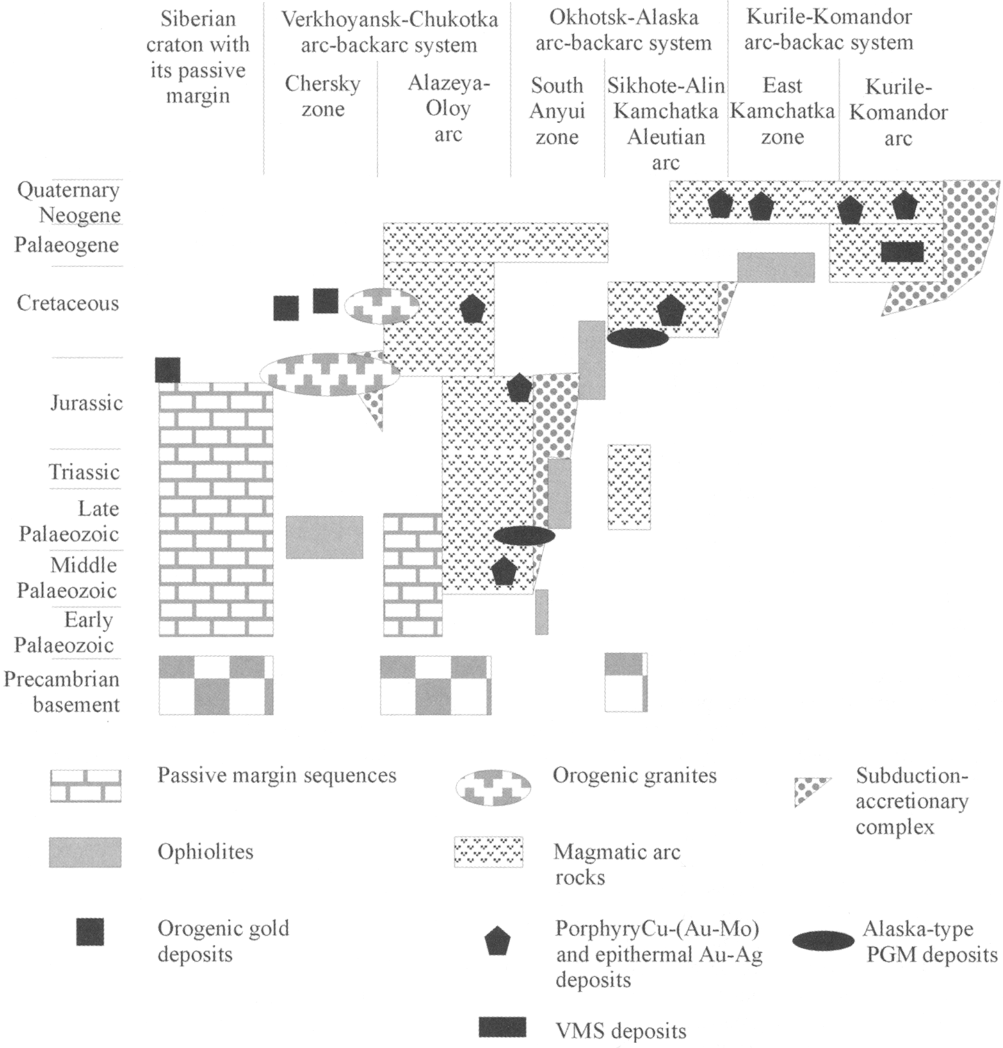

Fig. 3. Lithological sequences and metallogeny of the tectonic units of the North Pacific orogenic collage.

& Natal'in 1996*b*; Oksman *et al.* 2001). These multiple deformations were also responsible for oroclinal bending in the North Pacific orogenic collage.

In its external portion, the *Verkhoyansk–Kolyma* orogen, deformed into the Kolyma orocline, consists of craton-facing Palaeozoic to Mid-Jurassic passive margin shelf limestone and turbidite rocks (Fig. 3), which are now incorporated into imbricated allochthonous sheets thrust onto the rest of the Siberian craton (Prokopiev 1998). In the core of the Kolyma orocline there is an Alazeya–Oloy arc (Fig. 2, unit A3) consisting of Palaeozoic to Mesozoic rocks of magmatic and subduction-accretionary affinity. The arc remains attached to the Siberian craton via its Omolon segment (Fig. 2). The oldest magmatic rocks of the arc are Devonian to Carboniferous felsic and intermediate volcanics and intrusives found in the Alazeya and Omolon segments, and also in the Uda-Murgal segment (Fig. 2, unit A2) (Nokleberg *et al.* 1993; Sengör & Natal'in 1996b).

In their present structure, magmatic arc and passive margin units of the Siberian craton are separated by the Chersky zone (Fig. 2, unit 1), which bears the Palaeozoic ophiolites (Oksman *et al.* 2001). Late Jurassic collisional granites were emplaced within the suture zone, but formed a wider belt.

This orogen hosts several provinces of orogenic gold deposits constituting the Yana–Kolyma metallogenic belt (Fridovsky 2000), hosting medium to large and even world-class gold deposits (Nokleberg *et al.* 1993). The belt consists of several metallogenic provinces (Fig. 4), which form two sub-parallel strips in the external and internal portions of the orogen. Fridovsky (2000) classified the Verkhoyansk, Allakh–Yun and Ulakhan–Sis–Solur provinces as early collisional ore fields formed in the Late Jurassic to Neocomian, whereas the South Verkhoyansk, Kular and Adycha–Nera–Central Kolyma provinces are late collisional ore fields formed in the Early Cretaceous. The orientation of the provinces generally follows the strike of the orogen, but individual metallogenic clusters, especially those of orogenic gold deposits in the Verkhoyansk–Kolyma orogen, usually display an oblique orientation with respect to the general strike of the orogen.

The *Novosibirsk–Chukotka* orogen, forming the western part of the Chukotalaskides of Sengör & Natal'in (1996a, b), extends for approximately 2000 km from the Novosibirsk Islands in the Arctic Ocean towards northern Alaska. In the south, the Novosibirsk–Chukotka orogen is bound by the Alazeya–Oloy magmatic arc rocks (Fig. 2, unit A3), which were thrust northward onto Triassic passive margin rocks. In between there is a South Anyui suture (Fig. 2, unit 2c) hosting late Palaeozoic and Mid–Late Jurassic ophiolites (Sengör & Natal'in 1996*b*; Oksman *et al.* 2001).

The Verkhoyansk–Kolyma and Novosibirsk–Chukotka orogens were oroclinally bent and amalgamated in the early Late Cretaceous in response to the opening of the Amerasian basin (Nokleberg & Diggles 2001). This deformation also entrapped accretionary complexes of the Okhotsk–Alaska arc–backarc system in the core of the Kolyma orocline. Since the Mid-Cretaceous, the Okhotsk–Chukotka magmatic arc (Fig. 2, unit B) started to form above the amalgamated fragments of the two orogens. This magmatic arc system extended from Transbaikalia and the southern margin of the Siberian craton towards Alaska (Sengör & Natal'in 1996*a*, *b*).

The magmatic events related to the evolution of this latter arc are considered to be responsible for emplacement of some orogenic gold deposits, such as Nezhdaninskoe and Natalka, in its rear part in the Central Kolyma province of the Verkhoyansk–Kolyma orogen and a majority of orogenic gold deposits in the Novosibirsk–Chukotka orogen (Nokleberg *et al.* 1993). The arc developed on top of the older Devonian arc, which hosts epithermal gold deposits, e.g. Kubaka. The Cretaceous arc hosts small to medium epithermal Au deposits, e.g. Pokrovskoe, as well as medium to large Cu-porphyry deposits and occurrences such as Peschanka (Fig. 4). They host hypogene mineralization and lack supergene enrichment blankets (Nokleberg *et al.* 1993). In Alaska, the late Palaeozoic arc-related ultramafic rocks host platinoid mineralization (Nokleberg *et al.* 1993). Carlin-type gold mineralization was recognized in the southeastern portion of the Siberian craton in the rear of this arc (Yakubchuk 2000), where the Allakh–Yun province of the Sette–Daban orogen is considered to be prospective for this type of mineralization (Eirish 1998).

Transbaikal–Mongolian orogenic collage Here (Fig. 5), the accretionary complexes occur in the Khantei zone, and then they can be traced via the 500 km long Mongol–Okhotsk suture into the North Pacific orogenic collage (Yakubchuk & Edwards 1999). Sengör *et al.* (1993) and Sengör & Natal'in (1996a, b) recognized this link, but they considered the orogens of central Mongolia to be a part of the Altaid orogenic collage. The late Palaeozoic to early Mesozoic differentiated magmatic rocks form a Transbaikalian arc (Fig. 2, unit A1; Fig. 4, unit G), which is bent into the Central Mongolian and Hingan oroclines and extends from the Greater Hingan in NE China via southern and central Mongolia to Russian Transbaikalia and the Stanovoy Range on the southern

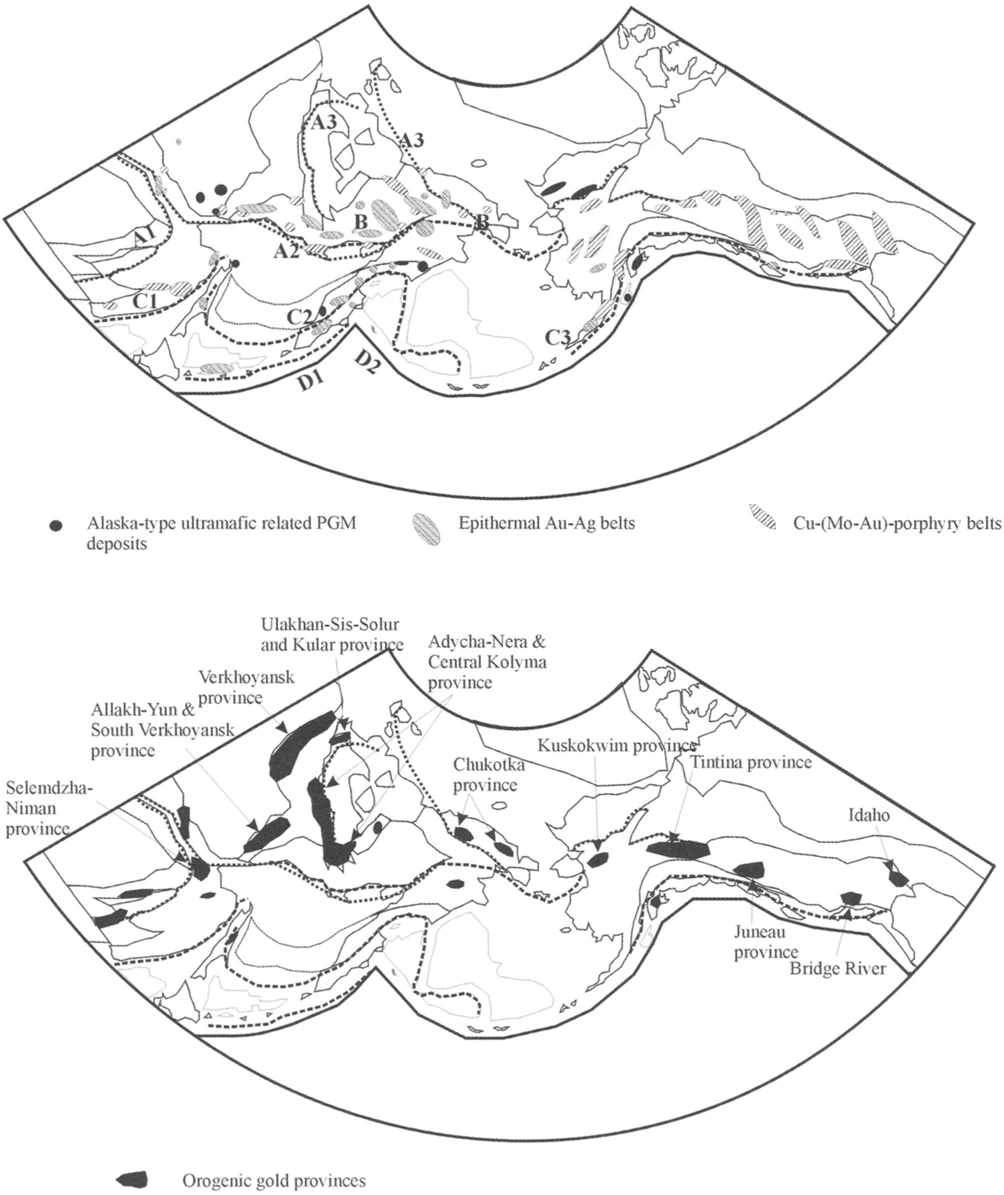

Fig. 4. Distribution of porphyry, epithermal, Alaska-type PGM, and orogenic gold deposits in the North Pacific orogenic collage. See Figure 2 for arc symbols.

rim of the Siberian craton. This magmatic arc represents a continuation of the synchronous magmatic arcs of the Verkhoyansk–Chukotka arc–backarc system. These structures are now almost completely tectonically isolated from the rest of the North Pacific orogenic collage.

In central Mongolia, the Transbaikalian arc rests on Neoproterozoic to early Palaeozoic rocks, consisting of turbidite sequences, ophiolites, and late Proterozoic to mid-Palaeozoic magmatic arcs. The tectonic affinity of the Neoproterozoic ophiolites and early to middle Palaeozoic terrigenous rocks in central Mongolia is not quite clear. In particular, previous studies (Sengör *et al.* 1993; Sengör & Natal'in 1996*a*, *b*) considered them as part of an accretionary complex of the Tuva–

Fig. 5. Tectonics of the Baikalide–Altaid orogenic collage and adjacent cratons. Semi-arrows show direction of strike-slip displacement of major blocks. Magmatic arcs: A, Kipchak arc (A1, Kokchetav–North Tien Shan segment; A2, Bozshakol–Chingiz segment; A3, Salair–Kuznetsk Alatau segment); B, Tuva–Mongol arc (B1, Tuva segment; B2, Bureya segment); C, Kazakh–Mongol arc (C1, mid-Palaeozoic segment; C2, late Palaeozoic segment); D, Mugodzhar–Rudny Altai arc (D1, Tagil segment; D2, Magnitogorsk segment; D3, Rudny Altai segment); E, Valerianov–Beltau–Kurama arc; F, Qilian arc; G, Transbaikalian arc; H, Hingan arc.Backarc rifts and backarc basin sutures: 1, Baikonur–Karatau backarc rift; 2, Khanty–Mansi backarc suture (2a, South Tien Shan segment; 2b, East Urals segment; 2c, Irtysh–Zaissan segment); 3, Sakmara backarc suture. MOSZ, Mongol–Okhotsk suture zone.

Mongol arc (Fig. 5, units B1–B2), which was framed by synchronous accretionary complexes on both sides.

All pre-Carboniferous differentiated magmatic rocks within the Transbaikal–Mongolian collage can be attributed more or less definitely to the Tuva–Mongol or Kazakh–Mongol arcs whose magmatic rocks were produced due to subduction in the Altaids.

The Transbaikalian magmatic arc consists of late Palaeozoic to early Mesozoic rocks, occurring on top of the older arc rocks and accretionary complexes to the west. It is rimmed by a late Palaeozoic to Triassic accretionary complex to the east, in the core portion of the Central Mongolian orocline. This allows subduction to be restored from the east, and if the link of this unit with the North Pacific collage is accepted, the accretionary complex might have been produced by subduction of the Palaeo-Pacific Ocean prior to the oroclinal bending of the arc in the Jurassic that caused collision of its present eastern part in the Hingan segment with the Stanovoy unit, producing the Mongol–Okhotsk suture zone and isolating the Transbaikal–Mongolian orogenic collage from the other Circum-Pacific orogens.

The Transbaikalian arc hosts large Triassic Cu-porphyry (Erdenet), Mo-porphyry (Zhireken), and large epithermal Au (Baley) deposits (Kirkham & Dunne 2000; Sotnikov & Berzina 2000; Yakubchuk *et al.* 2001). The Mesozoic (Cretaceous?) magmatism in the Stanovoy Range might be responsible for emplacement of large Carlin-type deposits of the Kuranakh group (Yakubchuk 2000).

The Okhotsk–Alaska arc–backarc system extends from the Korean Peninsula in the south to Alaska in the NE. Various units, such as the Tuva–Mongol arc of the Altaids, the Siberian craton, the Verkhoyansk–Chukotka arc–backarc system, and Transbaikalian arc and Khantei accretionary complex of central Mongolia, occur behind the magmatic arcs that form a discontinuous belt (Fig. 3) that starts in the Sikhote–Alin mountains in the south of the Russian Far East (Fig. 2, unit C1), then follows two oroclinal bends of Sakhalin and Okhotsk, and can be traced further using magnetic data on the Okhotsk shelf towards western Kamchatka (Fig. 2, unit C2). From Kamchatka, it continues northward to the Koryak segment. It constitutes several oroclines in the Bering Sea, finally extends into the Aleutian arc (Fig. 2, unit C3) and links the magmatic arcs of the North American Cordillera. This long magmatic arc rests in its various parts on Precambrian slivers and Palaeozoic accretionary complexes or consists of immature ensimatic magmatic arc fragments. The accretionary complexes of late Palaeozoic to Cretaceous age mark part of this arc. The oldest differentiated magmatic rocks of late Palaeozoic age are found in western Kamchatka above the Precambrian metamorphic rocks (Nokleberg *et al.* 1993), constituting the only fragment of the sialic-type basement in this arc. Sengör & Natal'in (1996a, b) suggest that it is an expelled fragment of the Palaeozoic orogens in northeast China, which was incorporated into this generally ensimatic arc, formed almost in the middle of the Pacific Ocean, and separated the floor of its northern part from the rest of its plates (Nokleberg & Diggles 2001). This northern part was then subducted under Eurasia and North America and the arc docked to these continents as suggested in the reconstructions by Nokleberg *et al.* (1998), Parfenov (1995) and Nokleberg & Diggles (2001).

In the Greater Hingan (Fig. 2, unit A1), there are Jurassic to Early Cretaceous magmatic arc rocks. The origin of this magmatism is debatable due to its location more than 500 km from the nearest palaeotrench. Sengör & Natal'in (1996*a*) suggested that strike-slip duplication of Precambrian slivers in front of this arc might significantly increase the width of its Pacific-facing accretionary complex in the late Mesozoic. The growth of a wide accretionary wedge could then have stopped subduction-related magmatism in the Greater Hingan and have been responsible for the eastward migration of the magmatic front in the Cretaceous to form the bulk of magmatic arc rocks in Cretaceous to Palaeogene times.

The rocks that can be identified with the backarc basin settings of the Okhotsk–Alaska system occur either in isolated sedimentary basins in the rear flank of the arc in eastern Mongolia and NE China or were incorporated into subduction-accretionary complexes accumulated in the front of the arcs of the Verkhoyansk–Chukotka system. Oceanic crustal rocks of this backarc basin are Late Cambrian to Cretaceous ophiolites within accretionary complexes in the Russian Far East and NE, which represent a mixture of oceanic crust generated in the backarc basin and the main ocean (Sokolov *et al.* 1997). The East Bering backarc basin with oceanic crust remains unsubducted. Its Mesozoic basaltic floor is now buried under deep sea and terrigenous sediments.

Metallogenically, this arc–backarc system hosts several minor Late Cretaceous to Palaeogene Cu-porphyry deposits and occurrences (Fig. 4) in the Kamchatka Peninsula and Sikhote–Alin (Nokleberg *et al.* 1993; Gusev *et al.* 2000). They host low-grade hypogene mineralization and lack supergene enrichment blankets. In Sikhote–Alin, there are medium-size economically viable Palaeogene–Neogene Au–Ag epithermal deposits such as Mnogovershinnoe (Khanchuk & Ivanov 1999). The latter province is also a host to important tin deposits (Khanchuk 2000). In central Alaska, the arc rocks host a Tintina gold province with major granitoid-related gold deposits (Goldfarb *et al.* 2001). Various workers emphasize difficulties in classifying these deposits as Au-porphyry or granitoid-related orogenic gold deposits (Lang *et al.* 2000). The Late Cretaceous immature arc rocks in northern Kamchatka host Alaska-type ultramafic intrusives, which are a bedrock source of significant platinum-producing placers in northern Kamchatka.

The Kurile–Komandor arc–backarc system extends from the Japanese Islands along the Kurile Islands to eastern Kamchatka and the Komandor Islands as a presently active system of magmatic arcs (Fig. 2, units D1–D2). Its Neogene–Quaternary volcanics rest on the Mesozoic arc or accretionary complex rocks accumulated due to subduction of the Pacific oceanic crust. In the rear of this arc, there is a system of still actively spreading backarc basins in the Kurile basin and in the western Bering Sea. However, in eastern Kamchatka, there is a suture with Cretaceous ophiolites (Fig. 2, unit 3), which separates the magmatic arcs of the Kurile–Komandor and Okhotsk–Alaska systems, thus representing an intra-arc suture.

The arc rocks host minor VMS deposits known in the Kurile and Komandor islands. Medium-size epithermal Au–Ag deposits of Neogene–Quaternary age are a potential source of these metals in Kamchatka. Some deposits of this type located in the Kurile Islands were gold producers in the past.

Distribution of mineralization in the North Pacific and Transbaikal–Mongolian collages

It was shown in numerous previous works that in the active Circum-Pacific orogens there is a regional-scale correlation between tectonic setting and principal types of mineral deposits (e.g. Nokleberg *et al.* 1993; Khanchuk 2000). In particular, the Cu–(Au) porphyry and epithermal Au deposits formed within the magmatic arcs with sedimentary hosted Cu and Pb–Zn deposits in backarc settings, whereas orogenic gold deposits form during or after collision in the orogens. A slab window theory was recently employed to explain clustering of giant Cu–(Mo–Au) porphyry, epithermal Au and Sn deposits in various orogens around the Circum-Pacific rim (Kirkham 1998; Khanchuk 2000). Similar factors may control the distribution of orogenic gold deposits.

Figure 4 shows the distribution of principal metallogenic belts of Cu–(Au) porphyry, epithermal Au, and Alaska-type ultramafic related PGM deposits, as well as orogenic Au deposits in the North Pacific collage. Analysis of the orogenic gold endowment using the data collected by Goldfarb *et al.* (2001) reveals that the most significant gold accumulations (>30 Moz Au) occur in the Yana–Kolyma, Verkhoyansk, Chukotka, Selemdzha–Niman, Kuskokwim, Tintina and Juneau provinces. Of these, the Yana–Kolyma province is the most anomalous region, which originally contained about 150 Moz of gold. Only placer operation in the Yana–Kolyma province produced in excess of 125 Moz of gold during the past 55 years (Goldfarb *et al.* 2001). In addition, the Verkhoyansk–Chukotka system hosts several world-class and large orogenic gold deposits (Fig. 4), e.g. Nezhdaninskoe (16 Moz) in the South Verkhoyansk province, Natalka (>6 Moz) in the Central Kolyma province, Kyuchus (>10 Moz) in the Ulakhan–Sis–Solur province, Maiskoe (>8 Moz) in the Chukotka province, numerous medium-size deposits and multiple prospective targets (Nokleberg *et al.* 1993; Goldfarb *et al.* 2001). The adjacent Okhotsk–Alaska and Kurile–Komandor systems host much smaller orogenic Au deposits (Goldfarb *et al.* 2001). However, they host medium to large epithermal Au deposits in western Canada and USA and in Kamchatka in Russia, large Au-porphyry deposits (Fort Knox, Tintina province in Alaska; Lang *et al.* 2000), and also large Carlin-type Au deposits in the Great Basin (Ludington *et al.* 1993) and in the Kuranakh area located in the Aldan shield of the Siberian craton in South Yakutia.

The search for what might be a reasonable explanation for such an irregular distribution of orogenic gold deposits in the North Pacific collage reveals two principal factors, which identify unique features in the Verkhoyansk–Chukotka system. These factors include the occurrence of black-shale-bearing passive margin sedimentary rocks, on the one hand, and a time affinity to major collisional/suturing events in the respective backarc basin, on the other. Several gold deposits, e.g. Fort Knox and Pogo in the Tintina belt in Alaska reveal an affinity to granitoid intrusives (Smith *et al.* 1999; Lang *et al.* 2000), a factor that may come to be recognized as very common with further progress of geological studies. These passive margin sediments accumulated on the craton-facing side of the Verkhoyansk–Chukotka backarc basin, and emplacement of orogenic deposits and granitoids also took place in the rear part of its frontal magmatic arc in the Late Jurassic. The orogenic gold deposits of the Verkhoyansk–Chukotka system form several clusters in the Yana–Kolyma belt. This region of the former backarc basin coincides with the area where its frontal magmatic arc was attached to the rear craton. The Early Cretaceous Okhotsk–Chukotka Andean-type magmatic belt amalgamated the oroclinally bent late Palaeozoic to Jurassic magmatic arcs of the Verkhoyansk–Chukotka system (Oksman *et al.* 2001). Orogenic gold deposits in other parts of the North Pacific collage, e.g. Mongol–Okhotsk, Chukotka, and Alaska, were also emplaced in the rear parts of the other arcs in the Early to Mid-Cretaceous, but they occur within former accretionary complexes and not in the deformed passive margin sediments. Their gold endowment is smaller by an order of magnitude. I speculate that this difference in tectonic setting might control the amount of gold emplaced or regenerated within the system. In addition, it seems to be important that the largest gold endowment is concentrated in the backarc basin area where a magmatic arc is attached to its craton.

Although orogenic gold deposits form metallogenic belts which are parallel to the strike of deformed arc–backarc systems, the distribution of the metallogenic provinces is often oblique with respect to the extent of such structures. They are clearly superimposed onto already amalgamated tectonic units forming several major provinces within the belt. The distribution of these provinces seems to be controlled by local structural factors.

This suggests searching for similar localities in other fossil backarc basins of the North Pacific orogenic collage. It appears that, with the exception of the Verkhoyansk-Chukotka arc–backarc system, the other structures host in general much smaller orogenic gold deposits within other arc–backarc systems of the North Pacific orogenic collage. Some areas, such as the East Bering basin, may represent one of the most favourable targets after its suturing.

Baikalides and Altaids

The Altaid orogenic collage of Palaeozoic age (Sengör *et al.* 1993), also known as the Ural–Mongolian, Ural–Okhotsk, or Central Asian fold belt (Coleman 1989; Zonenshain *et al.* 1990; Mossakovsky *et al.* 1993), is framed by the Neoproterozoic orogens of the Baikalides (Fig. 5). Many workers consider the Baikalides and their analogues as part of the Ural–Mongolian fold belt, whereas others identify them as an independent orogenic system (Milanovsky 1996).

The Baikalides and the Altaids consist of Neoproterozoic–Palaeozoic rocks forming an orogenic collage lying between the East European and Siberian cratons in the west and NE respectively. The Karakum, Alai–Tarim and North China blocks in the south (the intermediate units of Sengör & Natal'in 1996*a*, *b*) separate the Altaids from the Tethysides (Sengör & Natal'in 1996*a*, *b*). Traditional interpretations suggest that Palaeozoic structures of central Mongolia also constitute a part of the Altaids and join the Circum-Pacific belt via the Mongol–Okhotsk suture zone (Milanovsky 1996; Sengör & Natal'in 1996*a*, *b*). However, in western and southern Mongolia and in NE China, there are numerous Precambrian slivers that form the basement of the Neoproterozoic–Palaeozoic magmatic arc, known as the Tuva–Mongol arc (Fig. 5, units B1–B2) (Sengör *et al.* 1993; Yakubchuk *et al.* 2001). This arc everywhere separates the accretionary complexes of the Transbaikal–Mongolian and North Pacific orogenic collages, on the one hand, and the Altaid orogenic collage, on the other. In the east the Precambrian slivers in the basement of this arc have a T-shaped junction with the North China craton, thus providing a natural barrier between the Altaids and the Circum-Pacific belts. On this basis, I suggest using the Precambrian units in the basement of the Tuva–Mongol arc as a boundary between the Altaids and the Circum-Pacific belt and therefore to exclude the Palaeozoic structures of central Mongolia (Transbaikal–Mongolian orogenic collage) from the Altaids.

The absence of large Precambrian massifs in the east, if the narrow Precambrian slivers in Mongolia are excluded, allowed a reconstruction of the Neoproterozoic–Palaeozoic Palaeo-Asian Ocean as an embayment of the Palaeo-Pacific Ocean (Zonenshain *et al.* 1990; Mossakovsky *et al.* 1993; Sengör *et al.* 1993), in place of the Altaid orogenic collage. This assumption was based on the idea that the Alai–Tarim and North China cratons constitute a single block, whereas the significance of the Precambrian slivers in Mongolia was underestimated. However, as was shown above, these latter units can be considered as a boundary between the Altaid and Transbaikal–Mongolian orogenic collages, whereas the Alai–Tarim and North China cratons are clearly separated in their present structure by a Beishan orogen and, therefore, their identification as a single block is not correct. I suggest that this latter area and the Qinling orogen can be used as a link between the Altaids, to the north, and the Tethysides, to the south (Fig. 5).

Sengör *et al.* (1993) and Sengör & Natal'in (1996a, b) indicated that the stucture of the Altaids consists of several oroclines. They recognized that all early Palaeozoic magmatic arc and accretionary complex rocks in the Altaids are very similar across this vast region and suggested on this basis that they might be formed in front of a former single magmatic arc, which they named as the Kipchak arc (Fig. 5, units A1–A3). They interpreted almost all ophiolites as fragments of the main ocean-facing accretionary complex and largely ignored their possible position in the sutures of the backarc basins. They suggested that the Precambrian slivers found in the basement of this arc were rifted off the combined Eastern Europe–Siberia forming the Khanty–Mansi Ocean, which spread behind the Kipchak arc. According to Sengör *et al.* (1993) and Sengör & Natal'in (1996a, b), the Kipchak arc and its accretionary complex were later multiply repeated along giant strike-slips and oroclinally bent against the background by clockwise rotation of

Siberia relative to Eastern Europe. Palaeozoic magmatic arcs of the Urals were considered as an independent system formed during subduction of the oceanic crust of the Khanty–Mansi Ocean under Eastern Europe and Siberia, thus suggesting the presence of a second arc behind the Kipchak arc. In their work, these authors used magmatic arc fronts as structural markers, which helped them to identify the direction of the accretionary growth in the entire collage.

However, significant portions of the Neoproterozoic–early Palaeozoic basement of the Altaids are obscured under Mesozoic–Cenozoic sedimentary basins (Fig. 1) and middle to late Palaeozoic magmatic arcs (Fig. 5). This creates significant difficulties for correlation and understanding how different parts of the Altaids link to each other and how they strike under the sedimentary basins. The airborne magnetic data (National Geophysical Data Center 1996) employed in this study allow the orientation of the belts under the basins to be deciphered.

In addition, not all Neoproterozoic to early Palaeozoic volcanic and terrigenous rocks represent an accretionary complex, e.g. Baikonur–Karatau zone (Fig. 5, unit 1), which hosts alkaline basalts and chert to clastic sedimentary rocks, lacks ophiolites and might be better interpreted as a rift structure (Mossakovsky *et al.* 1993) behind the Kipchak arc. Its sedimentary rocks host vanadium–molybdenum deposits, which makes them metallogenically distinct from all other chert-terrigenous sequences in the area, where they might be interpreted as an accretionary complex. In addition, some ophiolites occur in sutures between the former magmatic arcs, reveal petrological signature of supra-subduction origin (Yakubchuk & Degtyarev 1991; Yakubchuk 1997; Degtyarev 1999) and are coeval with the differentiated magmatic rocks in the adjacent magmatic arcs, whereas others occur as slivers within long-lived, viz. longer than 200 Ma, and very wide accretionary wedges that might therefore face a former major ocean. The regional aeromagnetic data (National Geophysical Data Center 1996) allow magnetically distinct magmatic arcs and ophiolitic sutures to be traced, on the one hand, and non-magnetic accretionary complexes and passive margin sedimentary sequences, on the other. The orientation and relationships between various units recognized on this basis (Fig. 5) appears to differ from the maps suggested by Sengör & Natal'in (see Sengör & Natal'in 1996*b*, fig. 21.18) and therefore the details of the tectonic evolution of the Altaid orogenic collage can be also viewed differently.

However, this study recognizes the importance of Precambrian slivers and magmatic fronts in the same manner as suggested initially by Sengör *et al.* (1993). In the Baikalides and Altaids, there are several generations of arc magmatism from the Riphean (<1650>680 Ma) to the Mesozoic (Fig. 6). Recognition of the synchroneity of some ophiolites, largely neglected by Sengör *et al.* (1993) and Sengör & Natal'in (1996*a*, *b*), and magmatic arc rocks was the basis for a new tectonic interpretation of the Baikalides and the Altaids suggested recently by Yakubchuk *et al.* (2001).

Each fragment of the Baikalides consists of one magmatic arc separated by an ophiolitic suture from the craton-facing passive margin sequences, whereas the Altaid collage consists of two sub-parallel major island arcs of Vendian (<680 Ma) to early Palaeozoic age (Figs 5 and 6): Kipchak arc in Central Kazakhstan and Altai (Fig. 5, units A1–A3) and Mugodzhar–Rudny Altai in the Urals (Fig. 5, units D1–D2) and Altai (Fig. 5, unit D3), constituting the Kazakh orocline in the western half of the Altaids. The sutures, which trace former backarc basins, separate the Kipchak (Fig. 5, units 2a–2c) and Mugodzhar–Rudny Altai arcs (Fig. 5, unit 3) from the cratons and each other. The Tuva–Mongol arc in the east, an intermediate unit between the Altaids, on the one hand, and the Transbaikal–Mongolian and the North Pacific collages, on the other hand, is deformed into several en echelon oroclines. In the mid-Palaeozoic, the Kipchak and Tuva–Mongol arcs amalgamated into a single Kazakh–Mongol arc (Fig. 5, units C1–C2).

In their present structural configuration, there are difficulties and uncertainties in recognizing the affinity of accretionary complexes to the respective arcs. If the above-mentioned recognition that magmatic arc complexes of the Urals and Rudny Altai form a single structure is correct and that it is sub-parallel with the Kipchak arc, then it is difficult to interpret them as a result of strike-slip repetition of the same structure, because, on the one hand, they are not synchronous and, on the other hand, there would be a significant space problem if they constituted a single arc. One can constrain this problem using the migration of magmatic fronts with respect to magmatic arcs. Accretionary complexes might also develop within a system of several sub-parallel magmatic arcs, which may be considered as an alternative to a single, but complexly deformed arc. If there were several evolving arc–backarc systems in the western part of the Altaid collage, e.g. Ural–Altai, Kazakh–Khanty Mansi, each of them might generate its own accretionary complex, a magmatic arc and a backarc basin. This option does not require 'construction' of a single arc, whose length would exceed the length of the combined

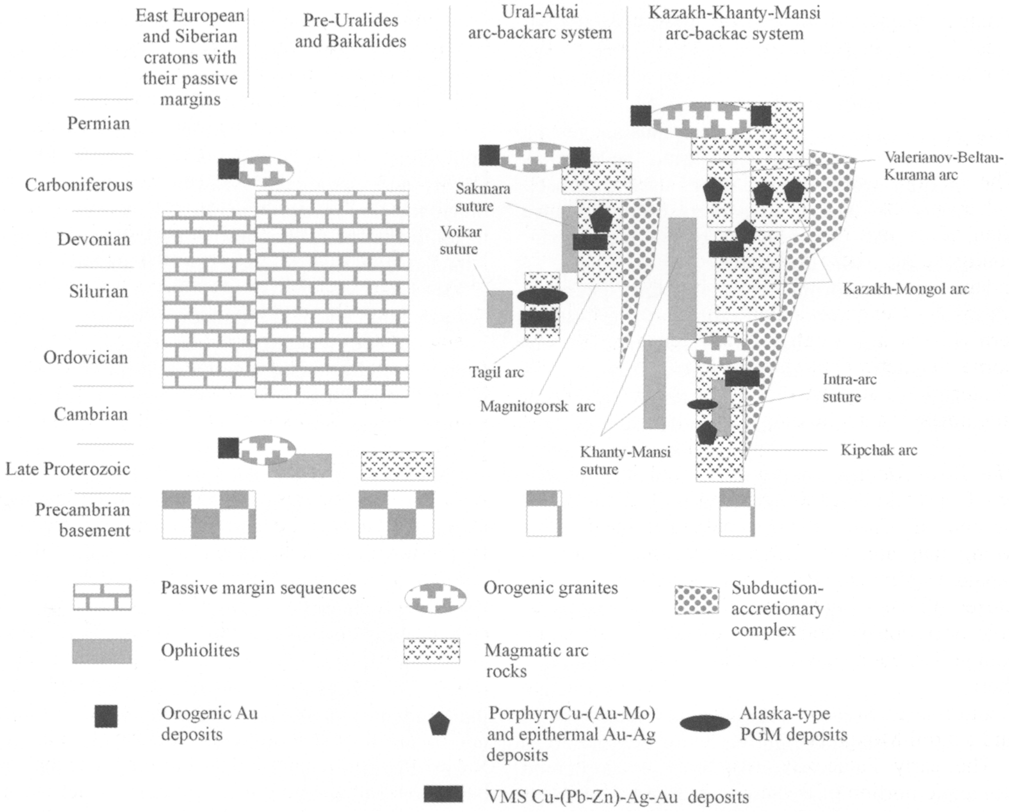

Fig. 6. Lithotectonic units and mineralization in the Baikalide–Altaid orogenic collage.

margin of united Eastern Europe–Siberia. In addition, each of these units reveals quite a distinct subduction-related metallogeny, which better fits into a system of more than one arc, and only late Palaeozoic orogenic gold deposits are superimposed onto various pre-orogenic tectonic units. The following describes an alternative tectonic interpretation of the Altaids employing the presence of several magmatic arcs in its western portion.

The Baikalides

The Baikalides and their analogues, such as the Pre-Uralides, were identified in the Patom Highlands, in the southwestern margin of the Siberian craton in the Eastern Sayan, in the Yenisey Range, in the Taimyr Peninsula, and in the Pechora Lowlands. In all these locations they bound either the Siberian or East European cratons. It is suggested that the Baikalides may constitute significant areas of the Arctic shelf (Shipilov & Tarasov 1998). Their analogues are also known as Neoproterozoic crustal slivers within the Altaid orogenic collage in the Urals, Altai, and in the Kazakh uplands.

The Baikalides and Pre-Uralides host sutures with late Proterozoic ophiolites (Vernikovskiy *et al.* 1996, 1999). The sutures represent traces of former backarc basins between late Proterozoic magmatic arcs and craton-facing passive margin sedimentary sequences. Around the Siberian craton, the late Proterozoic passive margin sedimentary rocks in the Baikalides host giant orogenic Au–(PGM) (Fig. 6) and large Pb–Zn deposits.

The Neoproterozoic ophiolitic sutures can be more or less clearly traced on the flanks of the East European and Siberian cratons. In orogenic belts in Transbaikalia and Mongolia, it is possible that ophiolitic sutures of the Patom orocline in northern Transbaikalia and the Tuva–Mongol arc might be dextrally offset by 1000 km (Yakubchuk *et al.* 2001). This indicates that a province of medium-size mesothermal gold deposits in south Transbaikalia may represent an offset continuation of the Lena orogenic gold province.

Other fragments of the Riphean magmatic arcs can also be found as slivers in the basement of younger magmatic arcs in the Kuznetsk Alatau, West Sayan, in the Kazakh uplands, and in the Northern Tien Shan.

The Altaid orogenic collage

The Altaid orogenic collage consists of the Palaeozoic orogens of the Urals, Kazakh uplands, Tien Shan and Altai. In their present structural configuration, these systems occur as apparently independent orogens separated by vast oil-bearing Mesozoic–Cenozoic sedimentary basins in western Siberia and Central Asia. However, the airborne magnetic data (National Geophysical Data Center 1996) suggest that they represent exposed fragments of a single orogenic collage.

The Tuva–Mongol arc can be traced from southern Transbaikalia to western and southern Mongolia and NE China. It now constitutes the Central Mongolian and the Hingan oroclines. The arc separates Vendian–Palaeozoic accretionary complexes of the Altaids from the mid–late Palaeozoic accretionary complexes of the Transbaikal–Mongolian collage. Within the Tuva–Mongol arc, there are intra-arc sutures with Vendian–Early Cambrian ophiolites in Transbaikalia, northern and central Mongolia.

The early Palaeozoic magmatic rocks of the ensimatic portion of this arc in Tuva and Transbaikalia host Cu–Pb–Zn–Ag–Au VMS deposits (Kovalev *et al.* 1998) and Cu-porphyry occurrences (Sotnikov & Berzina 2000) in its western portion in Tuva and western Mongolia (Figs 6 and 7). There are granite-related orogenic gold deposits emplaced after suturing of the intra-arc basins in the south Transbaikalia province (Yakubchuk *et al.* 2001).

The Kazakh–Khanty–Mansi arc–backarc system. consists of the Vendian–early Palaeozoic Kipchak arc and its Palaeozoic accretionary complex in the core of the Kazakh orocline, and a suture of the Khanty–Mansi backarc basin whose fragments are exposed in the southern Tien Shan, east Urals and Irtysh–Zaissan segments. The Kipchak differentiated magmatic rocks occur above the heterogenous basement in several ensialic fragments in the Gorny Altai, Salair, and Kuznetsk Alatau in Russia (Fig. 5, unit A3), the ensimatic Bozshakol–Chingiz segment in Kazakhstan (Fig. 5, unit A2), and the ensialic Stepnyak–Betpakdala segment in Kazakhstan and Kyrgyzstan (Fig. 5, unit A1). Even in their present structure the fragments of this arc remain attached to the Siberian craton in the east. Its opposite 'end' stops in the Kyrgyz and Chinese Tien Shan. The Palaeozoic magmatic arc rocks in the Altyn and Kunlun mountains on the southern rim of the Alai–Tarim, Karakum and perhaps including the Qaidam block may also represent equivalents of this arc. In this case, the Alai–Tarim and Karakum blocks could have been part 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 Palaeozoic (Scotese & McKerrow 1990; Zonenshain *et al.* 1990; Sengör & Natal'in 1996a). This means that the Altaids may have been formerly related to the Palaeo-Tethys Ocean and not to the Palaeo-Pacific Ocean.

The backarc structures of the Kipchak arc include a 1000 km long Vendian–early Palaeozoic Baikonur–Karatau backarc rift (Fig. 5, unit 1) in west Central Kazakhstan (Mossakovsky *et al.* 1993).

Within the Kipchak arc, there are several 500–1000 km long sutures with Cambrian–Ordovician ophiolites. However, even in their present structural configuration they appear as a system of en echelon sutures, which may represent a system of former intra-arc basins. Their ensimatic segments host early Palaeozoic VMS deposits in Central Kazakhstan (Maikain) and Altai (Salair group) and also Cu-porphyry deposits in Northern Kazakhstan (Bozshakol) (Heinhorst *et al.* 2000). Suturing and related strike-slip deformation at the end of the Ordovician led to the emplacement of Late Ordovician granitoid plutons which host orogenic granite-related gold deposits in the North Kazakhstan province (Shatov *et al.* 1996; Heinhorst *et al.* 2000) and in the Kuznetsk Alatau province in Russia (Distanov & Obolensky 1993; Yakubchuk *et al.* 2001). Their emplacement took place synchronously with the above-mentioned similar orogenic deposits in the South Transbaikal province.

In the rear part of the Kipchak arc, there is a very long suture marked by Ordovician–Devonian ophiolites, which strike from the South Tien Shan (Fig. 5, unit 2a) to the East Urals (Fig. 5, unit 2b) and then ends at the Irtysh–Zaissan segment (Fig. 5, unit 2c) (Yakubchuk *et al.* 2001). This suture marks the Khanty–Mansi backarc basin that started to open in the Latest Proterozoic to the early Palaeozoic.

The Kazakh–Mongol arc–backarc system formed as a result of reorganization at the Ordovician–Silurian transition. The mid-Palaeozoic ophiolites occur in the suture of the Khanty–Mansi backarc basin and the Kazakh–Mongol magmatic arc extending from Central Kazakhstan to Mongolia and NE China (Fig. 5, units C1 and C2). Its very wide accretionary complex occurs in the core of the Kazakh orocline and then extends to South Mongolia (Fig. 5). The synchronicity of ophiolites

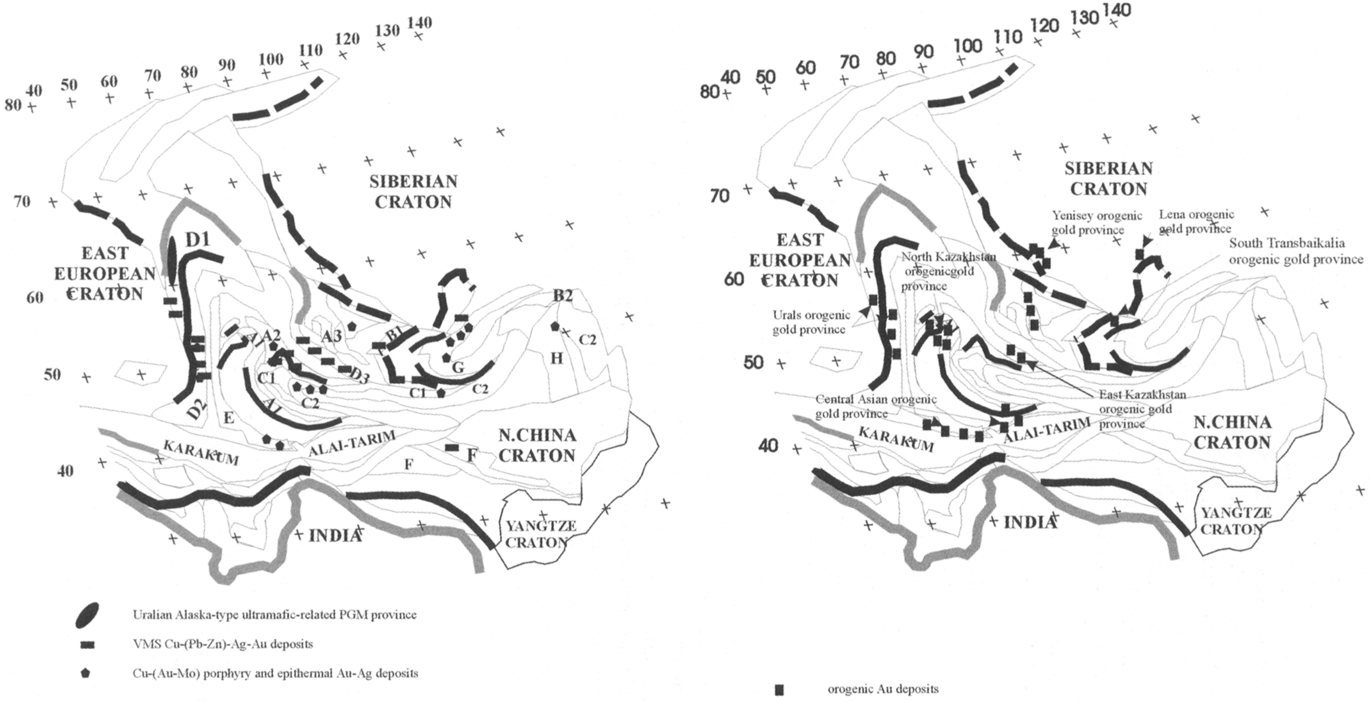

Fig. 7. Distribution of porphyry, epithermal, VMS, Alaska-type PGM, and orogenic gold deposits in the Baikalide–Altaid orogenic collage. See Figure 5 for symbols and unit numbers.

and magmatic arc rocks suggests an island arc setting for this arc.

The Silurian–Devonian Kazakh–Mongol magmatic arc (Fig. 5, unit C1) amalgamated fragments of the older Kipchak and Tuva–Mongol arcs. The mid-Palaeozoic arc rocks host several VMS and important porphyry Cu deposits in Central Kazakhstan (Nurkazghan), Mongolia (Oyu Tolgoi), and northeast China (Duobaoshan) (Fig. 7). The accretionary complex of this arc is not spectacular in terms of mineralization, but it is a good structural marker, which can be traced from the core of the Kazakh orocline via south Mongolia to the core of the Hingan orocline.

In the Early Carboniferous, there was a key transitional event in the tectonic and metallogenic evolution of Central Asia. In the Early–Mid-Carboniferous, the Kazakh orocline began to collide with the Mugodzhar–Rudny Altai arc to form a 3000 km long suture extending from the South Tien Shan to the East Urals and Irtysh–Zaissan zones (Puchkov 1993). Most porphyry deposits in Kazakhstan and Central Asia formed during this time (Heinhorst *et al.* 2000).

In the western part of the Kazakh–Mongol arc, a collision caused migration of the magmatic front and emplacement of numerous Cu–Mo-porphyry, skarn and epithermal deposits in Kazakhstan. In western Central Kazakhstan and Uzbekistan there is the Early–Mid-Carboniferous *Valerianov–Beltau–Kurama* arc. This arc magmatism produced large Fe-skarn deposits in northwest Kazakhstan and very large porphyry (Kalmakyr–Dalnee) and epithermal deposits in Uzbekistan (Kirkham & Dunne 2000). The giant sedimentary-Cu deposits of Dzhezkazghan formed between these two magmatic arcs. In the Late Carboniferous, Mo–W deposits controlled by pull-apart structures (Heinhorst *et al.* 2000) were emplaced in Central Kazakhstan.

In southern Mongolia and northeast China the Kazakh–Mongol arc produced large volumes of Early Carboniferous to Permian magmatic rocks (Fig. 5, unit C2) lacking significant mineralization. This magmatism buried the mineralized Silurian–Devonian arc, whose rocks are now found only in erosion windows. The frontal part of the arc is clearly marked by a late Palaeozoic accretionary complex striking from Central Kazakhstan to NE China.

If this is accepted, it implies a dextral (westward) displacement of the North China craton for 2000 km, its juxtaposition with the Tarim block, and oroclinal bending of central Mongolia, Hingan and the Yangtze craton with respect to North China. This event completely separated the Altaids from the Tethysides, and Mesozoic magmatic arcs and subduction-accretionary complexes began to grow on the northern periphery of the Palaeo-Tethys Ocean.

Collision of the Kazakh–Mongol arc with the Mugodzhar–Rudny Altai arc produced a 3000 km long suture in place of the Khanty–Mansi backarc basin. It hosts the Tien Shan and East Kazakhstan orogenic gold provinces with world-class deposits. The provinces broadly coincide with this suture, but their pattern indicates that they are clearly superimposed onto the suture and adjacent structures. The East Kazakhstan province hosts the Bakyrchik deposit; the Tien Shan province, extending from Muruntau to Kumtor and then to the Chinese Tien Shan, is the world's second largest gold province after the Witwatersrand (White *et al.* 2001). The host rocks of these deposits are early Palaeozoic black shale-bearing passive margin sedimentary sequences accumulated either on or near the adjacent crustal blocks. However, formation of economic gold deposits in these belts took place in the Permian (Drew *et al.* 1996) or even in the Triassic (Wilde *et al.* 2001).

Many orogenic-type gold deposits in the Tien Shan are located within late Palaeozoic granitoid intrusions or within their contact metamorphic aureoles (Shayakubov *et al.* 1999). Where radiometric dates have been obtained, mineralization is found to be broadly coincident with magmatism (Boorder 2000; Cole 2000). A number of recent studies, particularly in the Tien Shan, have developed geochemical, isotopic and fluid–structural models that implicate highly evolved syntectonic late Palaeozoic I-type granitoids as the source of fluids and metals for spatially associated orogenic-type gold deposits. In these examples, the gold–quartz vein systems represent only part of a larger magmatic–hydrothermal system that commonly includes earlier scheelite (±Au) skarn mineralization.

Ural–Altai arc–backarc system In this system, there are several generations of early to middle Palaeozoic island arcs extending from the South Urals to Rudny Altai (Fig. 5). It is obscured under Mesozoic–Cenozoic sediments of western Siberia, and it is now exposed in the two apparently separate locations in the Urals and Rudny Altai, whose affinity to a single system is based on magnetic data (Yakubchuk *et al.* 2001). In the Altai, it unites with the Kazakh–Mongol arc, thus making a system of two parallel, external and internal, arcs, which were oroclinally bent together. An accretionary complex is known on the eastern flank of the arc in the Urals and on the southwestern flank in Rudny Altai. It was interpreted as a subduction product of the Khanty–Mansi backarc basin (Yakubchuk *et al.* 2001).

The Urals portion of this arc–backarc system is better exposed. Its structure is traditionally simplified as a western slope hosting passive margin sediments of the East European craton and an eastern slope with magmatic arcs and intra-arc sutures (Puchkov 1993). It is commonly assumed that the Main Uralian fault represents a principal boundary between the western and eastern slope units. Some workers (Necheukhin 2001) recognized that the orientation of individual tectonic units of the eastern slope is oblique with respect to the Main Uralian fault. In particular, the Silurian Tagil arc is well known only in the Middle and North Urals and does not trace well to the South Urals. Its analogues constitute allochthonous fragments in the South Urals. The Devonian Magnitogorsk arc is exposed in the South Urals. Its southern continuation is obscured under Cenozoic sediments. Analysis of the present structural pattern suggests that the structure of the Urals is controlled by north–south-trending late Palaeozoic faults (Sazonov *et al.* 2001), which sinistrally offset some fragments of this arc.

In the South Urals, the Sakmara ophiolitic suture separates the Magnitogorsk arc segment and the East European craton. It can be traced to the south on the basis of magnetic data for 200–300 km. Its northern continuation is believed to coincide with the Main Uralian fault continuing towards the North Urals, representing a main trace of the sutured basin with the early–middle Palaeozoic oceanic crust (Puchkov 1993). Everywhere to the east this suture is bounded by the early to middle Palaeozoic magmatic arc rocks. This supports interpretation of these ophiolites as products of backarc spreading behind this arc. However, the Devonian–Early Carboniferous history of the closure of this basin is viewed as an east-dipping subduction of its oceanic crust under the Mugodzhar arc (Matte *et al.* 1993; Puchkov 1993) before collision with Eastern Europe and exhumation of the ultra-high pressure rocks in the Early Carboniferous (Matte *et al.* 1993).

Airborne magnetic patterns suggest that the Mugodzhar arc might have remained attached by its southwestern edge to the East European craton. This arc can be relatively well traced along the Urals orogen but, from the Polar Urals, this arc can be further traced southeastward under West Siberian Mesozoic–Cenozoic sediments towards Rudny Altai.

In the Urals, the main collision between the Mugodzhar–Rudny Altai arc and the East European craton took place in the Middle Carboniferous, with total suturing of the Sakmara backarc basin by the Early Permian (Puchkov 1993; Mossakovsky *et al.* 1993). This collision was associated with sinistral strike-slip translation, which provoked emplacement of a number of granite-related orogenic gold deposits in the Urals (Sazonov *et al.* 2001) and offset some tectonic units, possibly for up to 300 km.

The Urals and Rudny Altai host famous VMS deposits in the Middle Devonian differentiated volcanic rocks (Figs 6 and 7) in the Magnitogorsk arc of the Urals (Gusev *et al.* 2000) and in the same age rocks in Rudny Altai (Popov 1995, 1997; Yang 1994). There are also middle Palaeozoic Mo–(Cu)-porphyry sub-economic deposits in this arc in the Urals (Gusev *et al.* 2000; Kirkham & Dunne 2000) and in the Altai-Sayan region (Sotnikov & Berzina 2000). The Silurian Tagil arc segment hosts VMS deposits and numerous ultramafic massifs of the so-called Ural platinum belt associated with the Alaska-type intrusions. These intrusions contain minor to medium-size hard rock PGE deposits, which are a source of PGE placers (Dodin *et al.* 2000).

Paikhoi–Novaya Zemlya, North Barents and North Caspian basins The structures of Paikhoi and Novaya Zemlya orogens consist of Palaeozoic passive margin equivalents of the Urals' western slope. These orogens occur at the northern closure of the Kazakh orocline. Their setting is disputed. Some believe that it is a 'degenerated' northern continuation of the Urals whose further offset continuation is suggested to be found in the southern zones of the Taimyr Peninsula (Milanovsky 1996) or in the Arctic shelf (Zonenshain *et al.* 1990). These structures, however, may represent a part of another (en echelon?) system of backarc basins which developed due to stretching of the continental crust of the East European craton and Pre-Uralides further behind the Voikar backarc basin.

Similar basins remained undeformed in the North Barents and in the North Caspian areas. They host petroliferous sedimentary rocks that accumulated on oceanic crust from at least middle Palaeozoic time until the Mesozoic, in the North Caspian basin and, until the Quaternary, in the North Barents Sea. The thickness of these sequences now exceeds 15 km (Shipilov & Tarasov 1998). In the North Caspian basin, there are Permian evaporites that represent a fragment of the evaporite belt extending from Central Europe to the South Urals. The famous sedimentary rock-hosted base metal deposits of East Germany and Poland occur on the flanks of this basin, and their equivalents are found in the Ural fore-deep as far as Timan. Similar mid–late Palaeozoic sedimentary copper and lead–zinc deposits were discovered on the Novaya Zemlya archipelago on the periphery of the North Barents basin (Evdokimov *et al.* 2000).

Distribution of mineralization in the Baikalides and Altaids

The distribution of orogenic and pre-orogenic metallogenic belts in the Baikalides and Altaids is irregular. Porphyry and epithermal mineralization within magmatic arcs constituting the Baikalides and the Altaids occurs mostly within mature arcs (Fig. 6) and mostly within their oroclinally bent fragments (Fig. 7). The VMS and Alaska-type PGM deposits occur within immature magmatic arcs of the Urals and Rudny Altai.

Orogenic gold deposits formed at the final stages of suturing of the backarc basins between the magmatic arcs and cratons. As the Baikalide–Altaid collage is a product of several collided arc–backarc systems there are several metallogenic belts of orogenic gold deposits of various ages ranging from the Late Proterozoic to late Palaeozoic, which were superimposed onto sutured structures. Their calculated total gold resource exceeds 300 Moz (Goldfarb *et al.* 2001; White *et al.* 2001). However, analysis of the distribution of their gold endowment shows that the most significant deposits are clustered within the Yenisey and Lena provinces of Late Proterozoic to Late Palaeozoic age, containing in excess of 70 Moz of gold each, and in the Tien Shan gold province of late Palaeozoic age, containing in excess of 250 Moz of gold, whereas early to middle Palaeozoic orogenic gold provinces of the Urals, northern Central Kazakhstan and Altai host medium-size deposits. Analysis of the factors controlling distribution of such deposits reveals the same result as in the North Pacific orogenic collage. The deposits with the largest gold endowment are superimposed onto deformed black-shale-bearing craton-facing passive margin sedimentary sequences. In contrast to the North Pacific orogenic collage, they more clearly associate with the granitoid intrusions in the Tien Shan.

Tectonic evolution of the Altaid, Transbaikal–Mongolian and the North Pacific collages

The above description of the Altaid, Transbaikal–Mongolian and North Pacific orogenic collages reveals many similar features in their structural patterns and distribution of metallogenic belts. It is especially intriguing that both areas host world-class orogenic Au provinces in similar setting and timing of emplacement relative to the evolution of their respective orogens. The following discussion will compare their tectonic and metallogenic evolution.

Evolution of the Altaid and Transbaikal–Mongolian orogenic collages

In the 1990s, several plate-tectonic interpretations were proposed to explain the evolution of the Altaid orogenic collage (Zonenshain *et al.* 1990; Puchkov 1993; Mossakovsky *et al.* 1993; Sengör *et al.* 1993; Sengör & Natal'in 1996*a*; Yakubchuk 1997). Zonenshain *et al.* (1990) and Mossakovsky *et al.* (1993) suggested that Precambrian blocks occurring in the internal part of the Altaids and also Karakum and Alai–Tarim were rifted off the Gondwana super-continent in the Latest Proterozoic; then, they drifted across the Panthalassic (Palaeo-Pacific) Ocean and docked to Siberia and Eastern Europe to produce the orogenic collage.

An alternative interpretation by Sengör *et al.* (1993) suggested that the Precambrian slivers occurring in the internal portion of the Altaids were rifted off combined Eastern Europe–Siberia during the Neoproterozoic to produce the basement of the Kipchak magmatic arc. A similar mechanism was recently suggested to explain the Tuva–Mongol arc (Yakubchuk *et al.* 2001) as a structure, which might have rifted off combined Siberia–Laurentia together with the North China craton to form the Palaeo-Pacific ocean, which initially evolved as a backarc basin. The model by Sengör *et al.* (1993) suggested that clockwise rotation of the Siberian craton with respect to the East European craton caused oroclinal bending and strike-slip duplication of all arcs and their accretionary complexes, which then collided with the framing cratons.

All models suggested after 1993 employed the palaeomagnetic data of Torsvik *et al.* (1992) for the major cratons, which showed that the East European and Siberian cratons were attached to each other by their present northern margins during the early Palaeozoic. Since the Late Ordovician, Siberia began clockwise rotation with respect to Eastern Europe due to spreading events between Siberia and Laurentia (Fig. 8). This rotation continued until the late Palaeozoic when the Altaids had been finally amalgamated in the form of the present orogenic collage.

Yakubchuk *et al.* (2001) suggested a new interpretation for the tectonic evolution of the Altaids showing the setting and timing of emplacement of mineral deposits of VMS, porphyry, epithermal, Alaska-type PGM and orogenic Au types. This latter interpretation is in general agreement with the model by Sengör *et al.* (1993), but it recognizes a greater number of arc–backarc basins within the Altaid collage, puts more emphasis on collision, suggests lesser amplitude of displacement during strike-slip duplication of the structures and differs in the understanding how the

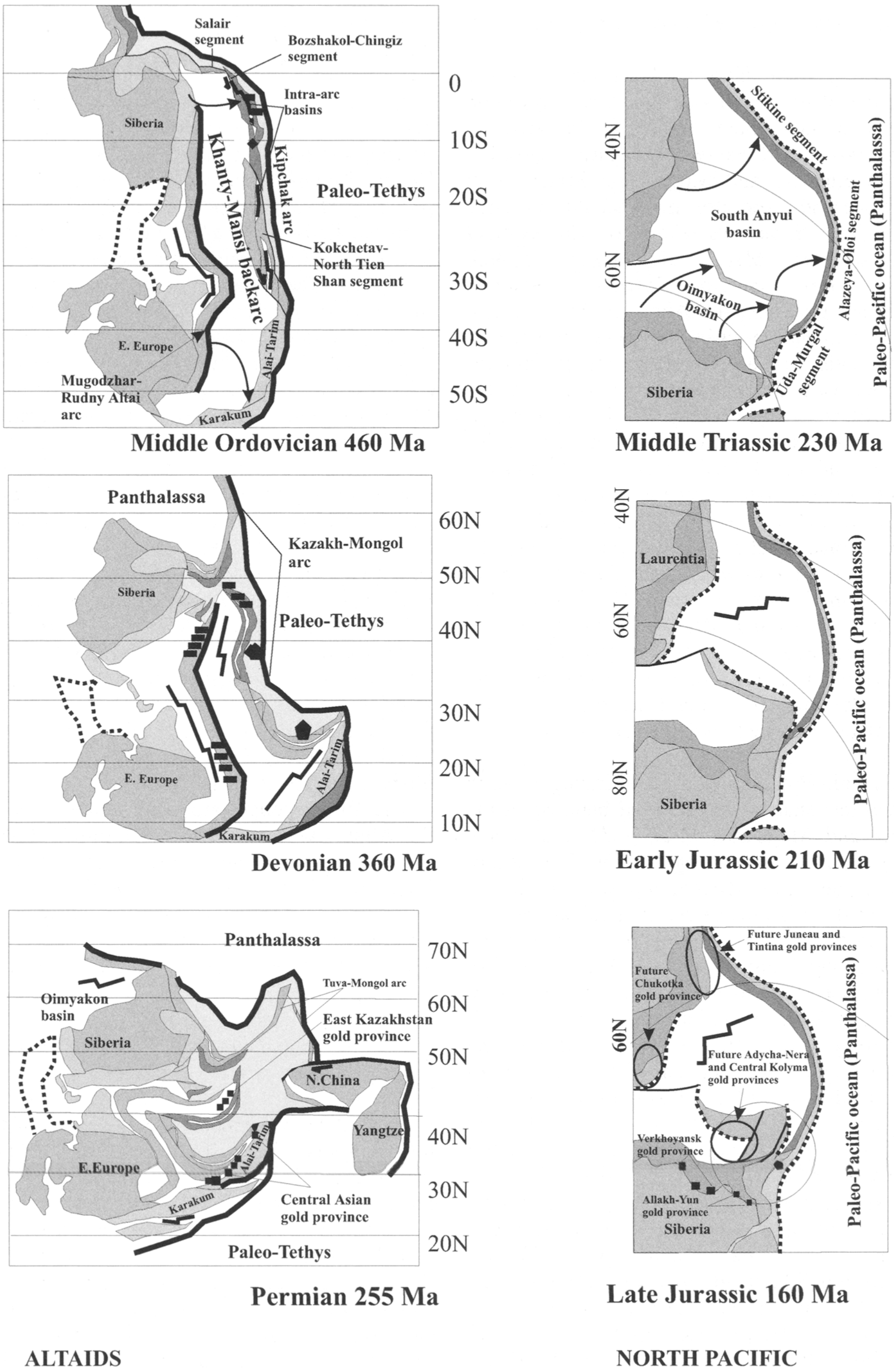

Fig. 8. Geodynamic evolution of the Altaid and North Pacific orogenic collages. Both orogenic systems evolved through backarc spreading in several basins and following collision of magmatic arcs with each other and adjacent cratons. Epithermal, porphyry, VMS, and Alaska-type PGM deposits formed within magmatic arcs. The amalgamation of orogenic collages took place due to clockwise rotation of adjacent cratons and subsequent arc–arc and arc–continent collisions with associated emplacement of orogenic gold deposits. See Figures 4 and 7 for deposit symbols and province names. Compiled using Parfenov (1995) and Yakubchuk *et al.* (2001).

oroclines were deformed into their present pattern.

According to this latter model, several episodes of rotation of the major cratons caused spreading in the two sub-parallel, external and internal, Khanty–Mansi and Sakmara backarc basins behind the Kipchak and Mugodzhar–Rudny Altai arcs, respectively, and also in the smaller intra-arc basins within these arcs (Fig. 8a). The external Kazakh–Khanty Mansi arc–backarc system started to form in the latest Proterozoic, whereas the internal Urals–Rudny Altai arc–backarc system began to evolve during the Late Ordovician–Silurian. This intra-arc rifting and spreading was associated with emplacement of the early Palaeozoic VMS and porphyry deposits in the Kipchak arc (Fig. 8a). The suturing of its intra-arc basins at the end of the Ordovician generated emplacement of granite-related orogenic gold deposits in northern Kazakhstan, North Tien Shan and also in southern Transbaikalia and Kuznetsk Alatau. The same rotation simultaneously stimulated the beginning of formation of the Mugodzhar–Rudny Altai arc with its VMS and Alaska-type PGM deposits in intra-arc basins in the Urals. Spreading in these basins resulted in oceanic crust containing Cr–(Os–Ir) deposits now found in the ophiolites, which were emplaced into the Ural orogen after suturing.

In the mid-Palaeozoic, the continuing rotation was then responsible for oroclinal bending of the Kipchak and Mugodzhar–Rudny Altai arcs and suturing of their intra-arc basins (Fig. 8b). Simultaneously the Tuva–Mongol arc was oroclinally bent as well. This process led to amalgamation of the Kipchak and Tuva–Mongol arcs into a single Kazakh–Mongol arc in the mid-Palaeozoic, but spreading continued in the Khanty–Mansi backarc basin and in the Sakmara backarc basin.

Spreading events and subduction against the continuing clockwise rotation of Siberia and oroclinal bending of the new Kazakh–Mongol magmatic arcs in the Devonian coincided with emplacement of the porphyry deposits of Central Kazakhstan and Mongolia and a new episode of VMS mineralization in the Mugodzhar–Rudny Altai arc. The oroclinal bending of the Kazakh–Mongol arc caused its intrusion between Tarim–Karakum and Siberia towards the East European craton. This created temporary subduction on the present western flank of the Kazakh–Mongol arc in the Early Devonian, but since the Mid-Devonian the evaporite-bearing and molasse-filled rift-related backarc basins started to cover the previously amalgamated fragments. In the early Carboniferous, continued clockwise rotation of major cratons caused southeastward migration of the western part of the Kazakh–Mongol arc and a new episode of bending in the Kazakh orocline, pushing it further towards the East European craton along its bounding strike-slip faults. This coincides with emplacement of main porphyry deposits in Central Kazakhstan and a new episode of temporary subduction to form the Valerianov–Beltau–Kurama arc, which produced its large porphyry, skarn and epithermal deposits.

In the Early to Mid-Carboniferous, the Kazakh orocline collided with the Mugodzhar–Rudny Altai arc to form a 3000 km long suture extending from the South 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) between the Mugodzhar arc and the East European craton. By the end of the late Palaeozoic, the continuing rotation of major cratons caused collision of the Kipchak and Mugodzhar–Rudny Altai arcs with each other and with the East European and Siberian cratons (Fig. 8c). These collisional events continued throughout the late Palaeozoic. At the final stage of amalgamation in the late Palaeozoic, this rotation formed an orogenic collage of the Altaids and produced transpressive strike-slip deformation in its external part in the Urals. This suturing was an important event in the structural preparation of the region, which later produced world-class orogenic gold provinces in the Tien Shan, eastern Kazakhstan and Urals.

The Tuva–Mongol arc in the eastern portion of the Altaids was bent into the Central Mongolian and Hingan oroclines mostly during the early Mesozoic, after generation of the Transbaikal arc. Since the Cretaceous, it was affected by Yanshanian arc magmatism of the Circum-Pacific belt, and then the Indian collision produced Eurasia.

Evolution of the North Pacific orogenic collage

Most publications about the early stages of evolution of the North Pacific orogenic collage suggest that the magmatic arcs were generated in the Pacific Ocean and then accreted to Laurentia and Eurasia (e.g. Sokolov *et al.* 1997). Similar to the Altaids, an alternative viewpoint (Sengör & Natal'in 1996*b*) suggests that first an arc was rifted off combined Siberia–Laurentia and then accreted back to the cratons.

In the Alaska–Kolyma portion, the shaping of the North Pacific orogenic collage started in the mid–late Palaeozoic with backarc rifting and spreading behind the Uda–Murgal, Alazeya–Oloy and Stikene magmatic arc segments in the Verkhoyansk–Chukotka arc–backarc system (Fig. 8d, e). This stimulated accumulation of the clinoforms on the craton-facing passive margins in the backarc basins. The arcs host Cu–Mo porphyry, epithermal Au and Alaska-type PGM occurrences. Spreading in the Amerasian basin caused rifting of the Chukotka–Brooks Precambrian crustal block off Laurentia and its migration towards Siberia to form the Verkhoyansk–Kolyma and Novosibirsk–Chukotka collisional orogens by the Late Jurassic to Early Cretaceous (Fig. 8f) (Nokleberg *et al.* 1993; Nokleberg & Diggles 2001). This collision was responsible for generation of the orogenic gold deposits in the Yana–Kolyma metallogenic belt.

In the Transbaikal–Mongolian collage, the late Palaeozoic–early Mesozoic Transbaikalian arc was the first arc, which can be explained via subduction from the Palaeo-Pacific Ocean. It continued to develop until the Early Cretaceous, but only Triassic arc magmatism is responsible for economic Cu–(Mo)-porphyry and epithermal Au mineralization in Mongolia and Transbaikalia. The magmatic products of the Tuva–Mongol and Kazakh–Mongol arcs of the Altaids occur now in its basement. Prior to oroclinal deformation, this arc might have formed a single structure with the North China craton.

The Sikhote–Alin–West Kamchatka–Aleutian arc and its backarc basin started to develop in the late Palaeozoic–early Mesozoic. Some workers (Nokleberg *et al.* 1998; Nokleberg & Diggles 2001) suggested that this arc formed in the centre of the Pacific Ocean and then docked to Siberia and Laurentia. In the Mid-Cretaceous–Palaeogene, there were two magmatic arcs, the internal Okhotsk–Chukotka and external Sikhote–Alin–West Kamchatka–Aleutian arc, which developed above the amalgamated portions of the Verkhoyansk–Chukotka and Transbaikal–Mongolian orogens. The front of the Okhotsk–Chukotka arc retreated towards the continent with respect to the Jurassic fronts in the same manner as in the Chilean segment of the Andean belt. This subduction-related magmatism produced medium-size epithermal Au–Ag and Cu-porphyry deposits in the Okhotsk–Chukotka arc. The Sikhote–Alin–West Kamchatka–Aleutian arc produced VMS, skarn, minor porphyry, and Alaska-type PGM deposits. Medium to large orogenic gold provinces were superimposed onto collisional and accretionary orogens in the rear parts of the two arcs.

Evolution of the North Pacific orogenic collage since the Cretaceous until the present can be considered as a gradual oceanward rollback of subduction zones with subsequent opening of a series of backarc basins and accretion of ensimatic arcs generated in the central parts of the Pacific Ocean. The beginning of spreading in each new backarc basin coincided with suturing of the previous backarc basin in the rear part of the former (Nokleberg & Diggles 2001). In the Palaeogene, the strike-slip translation along the active margins of the Pacific Ocean caused oroclinal bending of the Sikhote–Alin–West Kamchatka–Aleutian arc and its collision with the rest of Asia and Alaska. This collision stopped magmatism in the Okhotsk–Chukotka arc and sutured the Okhotsk–Alaska backarc basin, but its East Bering portion has remained unsutured. This subduction produced the Au-porphyry deposits of Alaska. At the same time, the intra-arc spreading split the Sikhote–Alin–West Kamchatka–Aleutian arc or intra-oceanic subduction produced a separate Kurile–Komandor arc, which collided by the end of the Palaeogene. In the Neogene–Quaternary, a still active magmatic arc developed on top of the previously collided structures in Kurile and Kamchatka. This subduction-related magmatism produced numerous medium size epithermal deposits in the Kamchatka Peninsula and some in the Kurile Islands.

Discussion

The interpretation of tectonic patterns and models of geodynamic evolution of the Baikalide–Altaid and North Pacific orogenic collages described above shows both similarities and differences between the two collages. The common features include similar tectonic patterns and similar distribution of Cu-porphyry, Au–Ag epithermal, Alaska-type PGM, and orogenic Au metallogenic belts. Besides the age, the differences relate mostly to the sequence in opening of backarc basins. For instance, in the Altaids the internal magmatic arcs (e.g. Mugodzhar–Rudny Altai) began to develop after and behind the external arcs (e.g. Kipchak), whereas in the North Pacific collage there is a subsequent oceanward younging of magmatic arcs. The consequence of this difference in evolution, along with many other individual differences, seems to be not critical for metallogeny, but it is important to emphasize that in both collages the largest gold deposits formed during major orogenic (collisional) events and occur predominantly within the deformed former passive margin black shale-bearing sedimentary sequences. This affinity of orogenic gold deposits to black shale host rocks has been a reason for intense discussions. At present, one can assume that initial enrichment of sediments in gold is as important as the later influence of collisional tectonism and granitoid magmatism.

Analysis of the global setting of the two orogenic collages shows that each of them evolved in a similar position relative to the two adjacent major oceans (Fig. 9). In particular, the North

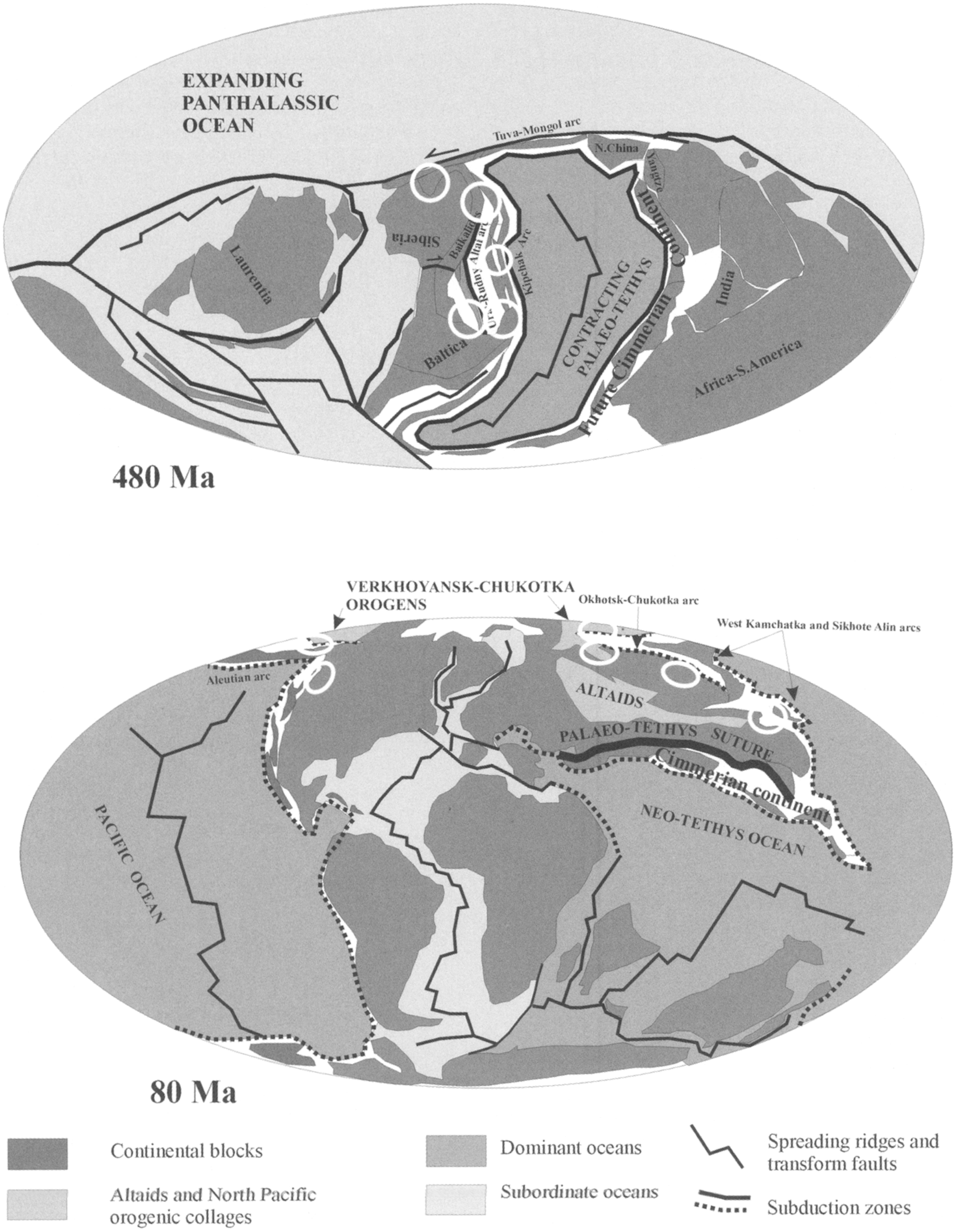

Fig. 9. Global tectonic patterns during backarc spreading in the Altaid (480 Ma ago) and North Pacific (80 Ma ago) orogenic collages (major cratons are shown after Scotese & McKerrow 1990). The arc–backarc systems in both collages initially evolved through rifting, which separated crustal fragments from adjacent cratons into arc basements to form several sub-parallel arc–backarc systems occurring on the flanks of the two dominant oceans surrounded by subduction zones on all margins, e.g. Palaeo-Tethys and Pacific Oceans respectively, whereas the margins of subordinate or expanding oceans remain largely inactive. White circles show the location of orogenic gold provinces with the most significant metal endowment. In the Altaid and North Pacific collages they are concentrated in a backarc setting, in areas where magmatic arcs remained attached to the cratons.

Pacific orogenic collage developed on the northern flank of the Pacific Ocean, which displays the most active spreading along its ridge, the most dominant spreading system on Earth today. This ridge extends from North America towards Australia and Antarctica and then continues in the Indian Ocean towards the Red Sea. Subduction zones bound oceanic plates of these two oceans. It is a global subduction zone, which can be subdivided into two major en-echelon segments. One of them extends from the Mediterranean region towards the Himalaya, Indonesia and SW Pacific region; the other starts near the Philippines and continues along the Asian island arcs towards the western coast of the Americas. The magmatic arcs developed near these zones are a host to all principal deposit types of Mesozoic–Cenozoic age. In contrast, the mostly passive margins of the Atlantic Ocean, except the Caribbean region, do not host Mesozoic–Cenozoic mineral deposit types considered in this review.

Analysis of the geodynamic setting of the Altaids against the global Palaeozoic plate tectonic pattern is difficult due to uncertainty with the existing global plate tectonic reconstructions for the Palaeozoic. These uncertainties mostly relate to the understanding of the relationships between the Palaeo-Tethys and Palaeo-Pacific Oceans (Scotese & McKerrow 1990). It is traditionally considered that the Altaids formed due to subduction of the oceanic crust of the Palaeo-Asian Ocean, which is believed to represent an embayment of the Palaeo-Pacific Ocean (Zonenshain *et al.* 1990; Mossakovsky *et al.* 1993; Sengör *et al.* 1993; Sengör & Natal'in 1996*a*). It is assumed that in Meosozoic–Cenozoic times, the latter developed into the present Pacific Ocean, and subduction of its oceanic plates produced the orogens of the Circum-Pacific rim. However, it was shown above that the structures of the Altaid orogenic collage cannot be directly traced into the orogens of the Circum-Pacific belt as the former and the latter are everywhere separated by Precambrian slivers in the basement of the Tuva–Mongol magmatic arc. The dominant polarity of this arc in Late Proterozoic–mid-Palaeozoic times was SW facing. This means that the Late Proterozoic–early Palaeozoic sequences occurring in the core of the Central Mongolian orocline must be considered as a portion of the Palaeo-Pacific Ocean, which automatically places the latter in a backarc position with respect to the Tuva–Mongol arc. Subduction-related magmatic arc complexes in the Eurasian portion of the North Pacific orogenic collage started to form in the Devonian and continued in the late Palaeozoic, whereas older rocks are mostly of passive margin or ocean-floor origin. This suggests that the Palaeo-Pacific Ocean evolved as a large backarc basin or Atlantic-type Ocean during its initial phases of opening and began to generate its own subduction zones when it expanded significantly.

On the other hand, the subduction-accretionary complexes of the Altaids might be considered as equivalents of similar complexes in the Tethysides, and the entire Altaid collage may simply represent a tectonically isolated fragment of the Tethysides.

Therefore, global Palaeozoic plate tectonics can be considered in the following way. Based on the distribution of the early–mid-Palaeozoic magmatic arcs one can suggest that by analogy with the present Pacific–Indian Ocean, dominant Palaeozoic spreading ridges were located in the Palaeo-Tethys Ocean, whereas the Palaeo-Pacific Ocean could be analogous to the present Atlantic Ocean. This means that the North Pacific and Altaid orogenic collages occupied almost exactly the same positions relative to the major cratons during their respective phases of development of the Pacific and Palaeo-Tethys Oceans, and therefore their global settings were principally the same at the respective times of their evolution.

Conclusion

The Baikalide–Altaid and North Pacific orogenic collages each consist of several oroclinally bent magmatic arcs separated by accretionary complexes and ophiolitic sutures located between the major cratons. The tectonic patterns of the two collages are principally similar as they were formed as a result of rotation of the framing cratons and strike-slip translation along the former convergent margins. Sometimes this includes such details as similarity of the oroclinal structural patterns of the Alaska orocline in the North Pacific collage and West Sayan orocline in the Altaid collage.

As a consequence, the two collages have principally the same distribution of metallogenic belts. In particular, the mid–late Palaeozoic belts of porphyry and epithermal deposits in the Altaids occupy the same position as the Mesozoic–Cenozoic belts of the North Pacific collage. The Ural platinum belt occupies the same position as the belt of platinum-bearing intrusions in Alaska. Major mineralizing events producing world-class intrusion-related Au, Cu–(Mo)-porphyry and VMS deposits in the Altaid and North Pacific collages coincided with plate re-organization and oroclinal bending of magmatic arcs. Formation of porphyry, epithermal and Alaska-type PGM deposits took place simultaneously with the episodes of oroclinal bending.

The tectonic setting of the orogenic gold belts in the Tien Shan and Verkhoyansk–Kolyma provinces, hosting large and giant hard rock gold deposits, is also similar, especially the distribution of their gold endowments. Major orogenic gold deposits occur within the sutured backarc basins. The craton-facing passive margin rock sequences initially formed within backarc basins. As they were entrapped within such oroclines, they represent favourable locations for emplacement of orogenic gold deposits.

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