Contrasting styles of mineralization in the Chinese Altai and East Junggar, NW China: implications for the accretionary history of the southern Altaids

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Abstract: The Chinese Altai–East Junggar collage in the southern Altaids hosts three metallogenic belts, which are, from north to south: (1) a volcanogenic massive sulphide (VMS) Cu–Pb–Zn belt; (2) a belt of shear zone-related gold deposits; (3) a porphyry Cu–Au–Mo belt. The VMS deposits formed in two pulses (c. 405 Ma and c. 375 Ma) in the Chinese Altai arc. The porphyry deposits developed in three pulses in the East Junggar arc, the first two synchronous with the VMS mineralization, and the third at c. 330 Ma. The shear zone-related gold deposits developed in the late Carboniferous to Permian at the contact between the Chinese Altai and East Junggar arcs. Time–space distributions of diverse ore deposits across the Altai–East Junggar collage indicate that the collage developed from two independent arcs, the Chinese Altai and the East Junggar. The VMS and porphyry deposits developed in the Chinese Altai and East Junggar arcs, respectively. The Chinese Altai arc is interpreted to be a Japanese-type arc, and the East Junggar arc a Mariana-type arc. During the latest Palaeozoic, the two arcs were juxtaposed by the Ergis Fault, when many shear zone-related lode gold deposits were emplaced. These metallogenic distributions were a likely response to spatially localized mechanisms of crust growth and to the tectonic evolution of the Altai–East Junggar collage, and they are consistent with interpretation of the Altaids as a multiple subduction–accretion collage.

Accretionary orogens are a dominant site of juvenile and continental growth and of fertile mineralization (e.g. Sawkins 1984). Subduction-related magmatic rocks are episodically injected into an active plate margin, and give rise to a wide variety of ore deposits. Mineral-deposit types can help to unravel specific tectonic settings, hence their distribution can constrain the associated geodynamic history (Goldfarb et al. 1999; Groves & Bierlein 2007).

The Altaids range is a long-lived accretionary orogen squeezed between the cratons of Baltica, Siberia, Tarim and North China (Fig. 1 inset). Two contrasting models have been proposed to explain the development of this extraordinary accretionary phenomenon: (1) a single, long-lived arc (Sengör et al. 1993); (2) collision of multiple island arcs, oceanic plateaux and microcontinents with different subduction polarities (Windley et al. 2007; Xiao et al. 2009a). Despite many investigations into the geochronology, geochemistry and tectonics of key regions and problems, much controversy remains. We note that metallogeny stands out as a subject that has been insufficiently applied to constrain major tectonic problems (Goldfarb et al. 2003), and we wish to redress this imbalance with focus on the metal-rich Altai mountain range, which extends for more than 2500 km from Kazakhstan through Russia and China to SW Mongolia. The Altai range is noted for the remarkable number and types of its ore reserves and metallogenic zones, including many world-class mineral deposits (Alt means gold in the Mongolian language). In China, the mountain range is juxtaposed against the Junggar block by the dominantly strike-slip Ergis (Erxis or Irtysh) Fault, the displacement across which was so considerable that rocks on either side have different geological, metamorphic and metallogenic affinities. In contrast to most earlier studies, which concentrated on the regional geology, petrochemistry and geochronology, we use the time–space distribution of ore deposit types, in conjunction with conventional tectonic and petrogenetic evidence, to test the hypothesis that the East Junggar and Altai mountains contain a record of multiple subduction–accretion events, which could or could not be explained by a single or multiple subduction zones. Accordingly, the aim of this paper is to review the metallogenic framework and development of the Chinese Altai and East Junggar so as to decipher and better understand the tectonic processes that have contributed to the evolutionary growth of this accretionary orogen.

Geological background

The Altaids preserve a geological history from the Mesoproterozoic (c. 1.0 Ga; Khain et al. 2002) to the Permian or even the mid-Triassic (Xiao et al. 2009a,b, 2010a; Jian et al. 2010). The southern boundary of the Altaids is the Tianshan–Solonker
suture, which extends along the northern margins of the Tarim and North China cratons (Fig. 1 inset; Zonenshain et al. 1990; Allen et al. 1993; Cunningham et al. 1996; Sengo¨r & Natal’in 1996). Current data suggest that most of the Altaiids accreted northwards (present coordinates) towards the Siberian craton (Windley et al. 2007), although Charvet et al. (2007) argued for some accretion to the south in the Tianshan region. The northern boundary of the Chinese Altai–East Junggar collage is located in Mongolia and Russia (Badarch et al. 2002; Buslov et al. 2004), and the southern boundary is the Kelameili ophiolitic belt (Xiao et al. 2009a).

The Erqis Fault separates the Chinese Altai to the north from the East Junggar to the south (Fig. 1). Other major NW–SE-trending faults are the Abagong, Tesibahan, Armantai and Kelameili faults, and the general strike in both the Chinese Altai and East Junggar is NW–SE (He et al. 1990).

Fig. 1. Geological and metallogenic map of the Chinese Altai showing the main units and ore deposit belts. R, Russia; K, Kazakhstan; M, Mongolia; C, China. Modified after He et al. (1990), Wan & Zhang (2006b) and Xiao et al. (2009a). Detailed information on the ore deposits is listed in Table 1. Faults: K, Kelameili; Ar, Armantai; E, Erqis; T, Tesibahan; F, Fuyun.

The Chinese Altai

The Chinese Altai mountain range is separated by the Abagong fault into two parts: the northern high Altai Mountains and the southern margin of the Altai Mountains. The former consists predominantly of Ordovician to Silurian metamorphosed sandstone, siltstone, shale, marble, and chert lenses, and Devonian to Carboniferous volcanic rocks. The metamorphic grade increases from greenschist facies in the west to high-T-low-P granulites (SE) and Barrovian amphibolites (NE) in the east. A few 920–614 Ma zircon xenocrysts have been reported (Windley et al. 2002), but most detrital zircon age populations concentrate at c. 540 Ma and 460 Ma; these typically show very depleted HF values (Long et al. 2007, 2008, 2010; Sun et al. 2008). The southern margin of the Altai Mountains contains several volcanic–sedimentary basins that are mainly filled by Devonian volcanic and sedimentary rocks and minor Silurian sedimentary and Carboniferous volcanic rocks. Apart from some mid-Devonian high-Mg andesites (Niu et al. 1999), most early and mid-Devonian volcanic rocks show bimodal characteristics.

Intrusions in the Chinese Altai occurred in two main pulses at 450–375 Ma, and 340–280 Ma (Fig. 2; Zou et al. 1988; Jahn et al. 2000; Briggs et al. 2007, 2009); the former is distinguished by calc-alkaline chemistry and the latter by alkaline chemistry (Chen & Jahn 2004; Wang et al. 2006; Yuan et al. 2007). Wei et al. (2007) demonstrated that the Chinese Altai experienced two stages of metamorphism: an early kyanite-type related to burial history (Zheng et al. 2007), and a late andalusite-type resulting from magmatism and limited fluid activity during exhumation (Wang, W. et al. 2009).

The Erqis Fault

A large-scale strike-slip fault zone (Erqis Fault) separates the Chinese Altai in the north from the East Junggar in the south. The fault zone mainly consists of schist, gneiss and minor andesite and sandstone (Yu et al. 1993); most rocks have been strongly deformed by the Erqis Fault, thus mylonites are well developed (Windley et al. 2002). The highly deformed rocks have Ordovician to Carboniferous zircon U–Pb ages, and an unfoliated granitic dyke, intruded into the deformed rocks and cut by the Erqis Fault, has an emplacement age of 286 ± 12 Ma (Briggs et al. 2007). Based on these relationships, we suggest that the Erqis Fault developed from at least c. 450 Ma at depth, and was strongly reactivated at a much shallower depth after intrusion of the granitic dyke.
East Junggar

The East Junggar mountains consist largely of mafic–intermediate lavas and tuffs, and minor sandstones, limestone lenses, cherts, and conglomerates. In contrast to the Chinese Altai, the rocks in the East Junggar record only low-grade metamorphism and contain fewer sedimentary rocks. There is a sharp break in metamorphic grade, lithology, topography, and the number of sedimentary basins across the Erqis Fault, indicating that it is an important crustal–tectonic boundary (Windley et al. 2002). The oldest U–Pb zircon ages from an East Junggar andesite have a concordant age of 441 ± 2 Ma (Zhang, H. et al. 2008), but most andesites are Devonian (Fig. 2). Most Devonian volcanic rocks are characterized by adakitic, boninitic and Nb-enriched chemistry (Niu et al. 2006). In the East Junggar numerous ophiolitic blocks occur along two thrust faults, the Armantai and Kelameili faults. A plagiogranite in the Armantai ophiolite has a sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon age of 503 ± 7 Ma (Xiao et al. 2009a), and plagiogranite and gabbro from the Kelameili ophiolite have SHRIMP U–Pb zircon ages that range from 497 ± 12 Ma to 342 ± 3 Ma (Jian et al. 2005). However, these isotopic dates are mostly older than the early Carboniferous age of radiolaria in cherts described by Shu & Wang (2003). All the ophiolite blocks become younger southwards, and show suprasubduction-zone chemical signatures (Wang, Z. et al. 2003); therefore Xiao et al. (2009a) suggested that they indicate southwards retreat of a subduction zone.

Besides the differences in lithology and other characteristics listed above, there are also geochemical distinctions between the Chinese Altai and East Junggar. From detailed t Nd mapping of intrusive rocks Wang, T. et al. (2009) showed that all the granitoids in the Chinese Altai have the same t Nd value ranges (t Nd = −4 to c. 8), but those in the East Junggar are more depleted (t Nd > 6). O’Hara et al. (1997) used oxygen isotopes to trace the origin of the fluids and found that the average δ 18O shows an abrupt decrease from 17‰ to 10.86‰ across the Erqis Fault toward the NE.

Metallogeny in the Altai–East Junggar collage

The Altai–East Junggar collage contains the following three distinctive metallogenic belts from north to south: (1) a volcanicogenic massive sulphide (VMS) Cu–Pb–Zn belt; (2) a belt containing shear zone-related gold deposits; (3) a porphyry Cu–Au–Mo belt. Shear zone-related gold deposits are mainly located in the contact between the VMS and porphyry belts.

VMS Cu–Pb–Zn deposits

VMS deposits (>10) occur only in the southern margin of the Altai Mountains. The Ashele Cu–Zn deposit (Wan et al. 2010b) and the Kekekale Pb–Zn deposit (Wan et al. 2010a) are representative and formed in the mid- and early Devonian, respectively. The host rhyolite that directly underlies the Ashele ore deposit has a U–Pb laser ablation inductively coupled plasma...
mass spectrometry (LA-ICPMS) zircon age of 375 ± 3 Ma (Fig. 3). The host rhyolitic tuff of the Keketale deposit has a secondary ionization mass spectrometry (SIMS) U–Pb zircon age of 401 ± 3 Ma (Liu et al. 2010). Many other Cu–Pb–Zn deposits (e.g. Keyinbulake, Abagong and Tiemuerte; Table 1) have similar geological and geochemical characteristics to the Keketale Pb–Zn deposit, and likewise are recognized as syngenetic VMS deposits (Wan & Zhang 2006b). The underlying rhyolitic tuff of the Keyinbulake deposit has a U–Pb zircon concordant age of 401 ± 4 Ma (Table 2; Fig. 3). The host rocks of the Abagong and Tiemuerte deposits have SHRIMP U–Pb zircon ages of 409 ± 5 Ma and 407 ± 4 Ma, respectively (Chai et al. 2009). All the above ages are interpreted as the time of mineralization of the VMS deposits because the base metal mineralization was coeval with the volcanism (Chai et al. 2009; Liu et al. 2010). In this study, we report new high-precision dates of the time of ore formation of the Ashele and Keyinbulake deposits. Clearly, the formation age of the Keyinbulake deposit is similar to that of other VMS deposits of Early Devonian age, which is the earliest VMS epoch (Fig. 2), and the Ashele deposit is representative of the youngest VMS-forming epoch (this study). In addition to these VMS Cu–Pb–Zn deposits, there are many iron deposits in this belt, such as that at Mengku, which is the largest iron deposit in Xinjiang. It is hosted by the same strata that host the VMS deposits, and was arguably interpreted as the distal iron-rich portion of a VMS deposit (Wang, Y.W. et al. 2003). The time of formation of the ore was assumed to be early Devonian, because the deposit occurs in the same strata that host other VMS ore deposits (Wang, Y.W. et al. 2003). The Chinese Altai extends westwards to the Rudny Altai in Kazakhstan, where VMS deposits have the same age as those in China (Shatov et al. 1996; Popov 1998). In the Chinese Altai, extensive geochemical studies have concentrated on the host rocks of the VMS ore deposits. Early and mid-Devonian volcanic rocks show highly fractionated trace element patterns between high field strength elements (HFSE) and large ion lithophile elements (LILE), and notably Nb and Ta are depleted (Wan et al. 2010a). Sr–Nd–Pb isotopic compositions of the volcanic rocks and ores show that their sources are mainly juvenile (Chiaradia et al. 2006; Wan & Zhang 2006b). The combined geochemical results are consistent and indicate that the volcanic rocks and ores formed by subduction-generated processes.

Porphyry Cu–Au–Mo deposits

All porphyry deposits are situated in the East Junggar (Fig. 1). The Hersai porphyry Cu–Mo deposit formed at c. 408 ± 3 Ma (Re–Os isochron; Du et al. 2010), which represents the earliest porphyry mineralization event. The ore deposits have the typical characteristics of worldwide porphyry deposits, and their ore geology was described in detail by Du et al. (2010). The Halasu Cu–Au–Mo deposit (Wan & Zhang 2006a), resulting from the second porphyry intrusion event, occurs in a diorite porphyry that has a SHRIMP U–Pb zircon age of 379 ± 2 Ma (Zhang et al. 2006), which is within error of a Re–Os isochron age of 377 ± 2 Ma on syn-intrusive molybdenite (Xue et al. 2010). These ages are consistent within error and indicate that the Cu–Au–Mo mineralization was at c. 380 Ma. Near the Halasu porphyry deposit, there are more porphyry deposits, including those at Yuleken and Kalaxianger, which have mineralization ages of c. 380–390 Ma (Xiang et al. 2009). A third porphyry intrusion event is indicated by the Xilekuduke Cu–Mo deposit, which has an SIMS U–Pb zircon mineralization age of 330 ± 4 Ma (Long et al. 2009) (Fig. 2). The porphyries in each of the three events have depleted Sr–Nd isotopes (Du et al. 2010; Xue et al. 2010) and adakitic chemistry (Wan & Zhang 2006a; Zhang H. et al. 2008; Long et al. 2009). Notably, many Nb-enriched, adakitic volcanic rocks, and high-Mg andesites form the wallrocks of the Xilekuduke and Suoerkuduke porphyry Cu–Mo deposits (Niu et al. 2006). All the porphyries and volcanic wall rocks are characterized by enriched LILE, depleted HFSE, and depleted Sr–Nd isotopes, indicating generation from a source in subduction-fertilized lithospheric mantle (Wan & Zhang 2006a; Long et al. 2009; Du et al. 2010).

Shear zone-related gold deposits

The Erqis Fault transects the Altai–East Junggar collage, extends east–west for more than 1000 km with a width of 10–15 km, and was particularly active from the early Permian (Briggs et al. 2007, 2009). Many gold deposits are within or close to the fault zone, and are directly or indirectly related to the fault movements. Thus the Altai–East Junggar collage hosts significant gold reserves (Table 1). There are placer, intrusion-related, and
Table 1. Representative ore deposits in the various tectonostratigraphic units of the Chinese Altai–East Junggar collage

<table>
<thead>
<tr>
<th>No. and deposit</th>
<th>Style</th>
<th>Metals</th>
<th>Size</th>
<th>Orebody age (Ma)</th>
<th>Analytical method</th>
<th>Host rock</th>
<th>Probable tectonic setting</th>
<th>Reference</th>
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<tbody>
<tr>
<td><strong>Chinese Altai</strong></td>
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</tr>
<tr>
<td>1 Nuoerte</td>
<td>Placer</td>
<td>Au</td>
<td>Medium</td>
<td>Unknown</td>
<td>Ar–Ar rapid neutron activation</td>
<td>Sediments</td>
<td></td>
<td>Wang et al. (1998)</td>
</tr>
<tr>
<td>2 Aketishikan</td>
<td>Orogenic</td>
<td>Au</td>
<td>Large</td>
<td>139 ± 2 Ma</td>
<td></td>
<td>Vokanic rock</td>
<td></td>
<td>Yuan et al. (2004)</td>
</tr>
<tr>
<td>3 Xichahe</td>
<td>Placer</td>
<td>Au</td>
<td>Medium</td>
<td>Unknown</td>
<td></td>
<td>Sediments</td>
<td></td>
<td>Wang et al. (1998)</td>
</tr>
<tr>
<td>4 Kulukagai</td>
<td>Pegmatite</td>
<td>Li–B–Nb–Ta</td>
<td>Large</td>
<td>Unknown</td>
<td></td>
<td>Granite</td>
<td></td>
<td>Wang et al. (1998)</td>
</tr>
<tr>
<td>5 Keketuohai</td>
<td>Pegmatite</td>
<td>Li–B–Nb–Ta</td>
<td>Large</td>
<td>220 Ma</td>
<td>SHRIMP U–Pb</td>
<td>Granite</td>
<td></td>
<td>Wang et al. (2007)</td>
</tr>
<tr>
<td>6 Axediate</td>
<td>Pegmatite</td>
<td>Li–B–Nb–Ta</td>
<td>Large</td>
<td>Unknown</td>
<td></td>
<td>Granite</td>
<td></td>
<td>Zou et al. (1988)</td>
</tr>
<tr>
<td>7 Ashele</td>
<td>VMS</td>
<td>Cu–Zn–Au</td>
<td>Large</td>
<td>375 ± 3 Ma</td>
<td>LA-ICPMS U–Pb</td>
<td>Bimodal volcanics</td>
<td>Intra-arc rift</td>
<td>This study</td>
</tr>
<tr>
<td>8 Keyinbulake</td>
<td>VMS</td>
<td>Cu–Zn</td>
<td>Medium</td>
<td>401 ± 4 Ma</td>
<td>LA-ICPMS U–Pb</td>
<td>Bimodal volcanics</td>
<td>Intra-arc rift</td>
<td>This study</td>
</tr>
<tr>
<td>9 Tiemuerde</td>
<td>VMS</td>
<td>Cu–Pb–Zn</td>
<td>Medium</td>
<td>407 ± 4 Ma</td>
<td>SHRIMP U–Pb</td>
<td>Bimodal volcanics</td>
<td>Intra-arc rift</td>
<td>Chai et al. (2009)</td>
</tr>
<tr>
<td>10 Surekuobo</td>
<td>Orogenic</td>
<td>Au</td>
<td>Large</td>
<td>321 ± 4 Ma</td>
<td>Ar–Ar rapid neutron activation</td>
<td>Bimodal volcanics</td>
<td>Intra-arc rift</td>
<td>Ding et al. (2004)</td>
</tr>
<tr>
<td>11 Abagong</td>
<td>VMS</td>
<td>Cu–Pb–Zn</td>
<td>Medium</td>
<td>409 ± 5 Ma</td>
<td>SHRIMP U–Pb</td>
<td>Bimodal volcanics</td>
<td>Intra-arc rift</td>
<td>Chai et al. (2009)</td>
</tr>
<tr>
<td>13 Kekeiwa</td>
<td>VMS</td>
<td>Pb–Zn</td>
<td>Large</td>
<td>401 ± 3 Ma</td>
<td>SHRIMP U–Pb</td>
<td>Bimodal volcanics</td>
<td>Intra-arc rift</td>
<td>Liu et al. (2010)</td>
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<tr>
<td><strong>East Junggar</strong></td>
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<tr>
<td>15 Duonalasayi</td>
<td>Orogenic</td>
<td>Au</td>
<td>Large</td>
<td>289 ± 5 Ma</td>
<td>Zircon evaporation U–Pb</td>
<td>Granite and volcanic rocks</td>
<td>Arc juxtaposition</td>
<td>Li &amp; Chen (2004)</td>
</tr>
<tr>
<td>16 Saidu</td>
<td>Orogenic</td>
<td>Au</td>
<td>Large</td>
<td>278 ± 21 Ma</td>
<td>Rb–Sr isochron</td>
<td>Vokanic rocks</td>
<td></td>
<td>Li &amp; Chen (2004)</td>
</tr>
<tr>
<td>17 Akekei</td>
<td>Orogenic</td>
<td>Au</td>
<td>Medium</td>
<td>Unknown</td>
<td></td>
<td>Vokanic rocks</td>
<td></td>
<td>Wu et al. (1993)</td>
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<tr>
<td>18 Serbulake</td>
<td>Orogenic</td>
<td>Au</td>
<td>Medium</td>
<td>Unknown</td>
<td></td>
<td>Porphyry</td>
<td>Island arc</td>
<td>Wang et al. (1998)</td>
</tr>
<tr>
<td><strong>Erqis Fault zone</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>19 Xilekudaka</td>
<td>Porphyry</td>
<td>Cu–Au–Mo</td>
<td>Medium</td>
<td>330 ± 4 Ma</td>
<td>LA-ICPMS U–Pb</td>
<td>Mafic volcanic rocks</td>
<td>Island arc</td>
<td>Long et al. (2009)</td>
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<tr>
<td>20 Qiaoxiahala</td>
<td>Skarn?</td>
<td>Fe–Cu–Au</td>
<td>Medium</td>
<td>378 ± 4 Ma</td>
<td>Ar–Ar</td>
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<td>Island arc</td>
<td>Ying et al. (2008)</td>
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<tr>
<td>21 Halasu</td>
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<td>Medium</td>
<td>377 ± 2 Ma</td>
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<td>Vokanic rocks</td>
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<td>Xue et al. (2010)</td>
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<td>22 Kalatongke</td>
<td>Magmatic sulphide</td>
<td>Cu–Ni</td>
<td>Large</td>
<td>287 ± 3 Ma</td>
<td>SHRIMP U–Pb</td>
<td>Vokanic rocks</td>
<td>Island arc</td>
<td>Han et al. (2004)</td>
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<td>23 Suroerkuduke</td>
<td>Porphyry</td>
<td>Cu–Au–Mo</td>
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<td></td>
<td>Porphyry</td>
<td>Arc juxtaposition</td>
<td>Li &amp; Chen (2004)</td>
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<tr>
<td>24 Kekesiya</td>
<td>Orogenic</td>
<td>Au</td>
<td>Medium</td>
<td>227 ± 24 Ma</td>
<td>Rb–Sr isochron</td>
<td>Vokanic rocks</td>
<td>Arc juxtaposition</td>
<td>Li &amp; Chen (2004)</td>
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<td>25 Kubasu</td>
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<td>Au</td>
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<td>269 ± 11 Ma</td>
<td>Rb–Sr isochron</td>
<td>Vokanic rocks</td>
<td>Arc juxtaposition</td>
<td>Li &amp; Chen (2004)</td>
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<td>26 Hersai</td>
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<td>Cu–Mo</td>
<td>Medium</td>
<td>408 ± 3 Ma</td>
<td>Re–Os isochron</td>
<td>Porphyry</td>
<td>Island arc</td>
<td>Du et al. (2010)</td>
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Table 2. U–Pb isotopic data for zircons from the ore-host rocks

<table>
<thead>
<tr>
<th>No.</th>
<th>Isotopic ratio</th>
<th>Age (Ma)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
<th>Th/U</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>207Pb/206Pb</td>
<td>1σ</td>
<td>206Pb/235U</td>
<td>1σ</td>
<td>206Pb/238U</td>
</tr>
<tr>
<td>Ashelé</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0552</td>
<td>0.0016</td>
<td>0.4538</td>
<td>0.0123</td>
<td>0.0596</td>
</tr>
<tr>
<td>2</td>
<td>0.0554</td>
<td>0.0016</td>
<td>0.4546</td>
<td>0.0122</td>
<td>0.0594</td>
</tr>
<tr>
<td>3</td>
<td>0.0543</td>
<td>0.0020</td>
<td>0.4495</td>
<td>0.0147</td>
<td>0.0600</td>
</tr>
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<td>4</td>
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<td>5</td>
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<td>0.0130</td>
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For Ashelé, zircons are from rhyolitic tuff directly underlying the orebody; for Keyinbulake, zircons are from rhyolite beneath the orebody.

### Tectonic implications of the metallogenesis

Discrete metallogenic belts in the Altai–East Junggar collage include a shear zone-related gold belt separating a VMS belt in the north from a porphyry belt in the south. The Erqis Fault zone is located at the contact between the Chinese Altai and East Junggar. The VMS belt and the porphyry belt are located in the Chinese Altai and East Junggar belt respectively, and the shear zone-related belt is located between them. The different metallogenic belts are consistent with the tectonic subdivisions of the Altai–East Junggar collage, hence they can be used to help constrain the associated geodynamic history.

Generally, VMS deposits of all ages worldwide occur in tectonic settings associated with rifted arcs, intra-arc rifted volcanic basins and back-arc basins, with only a few known at mid-ocean ridges or in continental rifts (e.g. Franklin et al. 2005; Hambartsumyan et al. 2005). In all cases, the mineralization forms synvolcanic sea-floor deposits above hydrothermal vents or syngenic, sub-sea-floor replacement deposits (e.g. Lydon 1988). An extensional regime decreases the pressure of the synvolcanic sea-floor deposits above hydrothermal vents or syngenic, sub-sea-floor replacement deposits (e.g. Lydon 1988).
magma chamber, and so increases the igneous activities. An extensional environment increases the number of fissures of the crust, and more igneous activity supplies more heat. Taken together, these processes accelerate the hydrothermal circulation and so increase the possible formation of ore deposits (e.g. Lydon 1988; Franklin et al. 2005). Hence the presence of a VMS deposit can be diagnostic of an extensional regime on the sea floor (Sillitoe 1982). In the Altai–East Junggar collage all VMS deposits are hosted by late Palaeozoic bimodal volcanic rocks. Precise geochronology of the wall rocks of the ore deposits indicates that the ores developed during two discrete periods: c. 405 Ma and c. 375 Ma (Chai et al. 2009; Liu et al. 2010; this study). Combined with evidence from the associated Devonian bimodal volcanic rocks and mafic dykes in the southern Chinese Altai (Cai et al. 2010; Wan et al. 2010a), the Chinese Altai was very possibly in an extensional environment during the periods of VMS ore formation.

The origin of the Chinese Altai is currently hotly debated, because a few old zircon xenocrysts have been reported (920–614 Ma; Windley et al. 2002), and some workers have argued that the Altai represents a Precambrian recrystallized basement (Li et al. 1996; Li et al. 2006). However, the detrital zircons from old sediments yield predominant age populations of 540 Ma and 460 Ma, and all the zircons have very depleted 

Hf (Long et al. 2007, 2008, 2010; Sun et al. 2008). These zircons demonstrate that the Chinese Altai could not have been a Precambrian microcontinent. Moreover, extensive geochemical and isotopic studies on the syn-mineralization volcanic rocks indicate that they were generated from juvenile material in a suprasubduction-zone setting (Chiaradia et al. 2006; Wan & Zhang 2006b; Chai et al. 2009; Liu et al. 2010). Therefore, subduction-related extensional settings, such as an intra-arc rift or an infant back-arc basin, are most likely (Wan et al. 2010a,b).

Xiao et al. (2009a) proposed that the Chinese Altai is a Japan-type arc based on age distributions, origins, and structural characteristics of the exposed rocks. In this study, we show that the metallogeny is consistent with that interpretation. The inboard part of the Japanese arc is dominated by Kuroko-type VMS deposits that were coeval with the opening of the Japan Sea (e.g. Ohmoto & Skinner 1983). The Chinese Altai arc is dominated by VMS deposits that formed simultaneously with the c. 405–375 Ma rifting of the arc. This illustrates the fact that metallogenic deposits provide a viable constraint on the construction of a tectonic model.

The East Junggar arc is different from the Chinese Altai arc in that it is dominated by porphyry deposits. Most porphyry Cu–Au–Mo belts worldwide are closely related to subduction-generated lithosphere that formed either during active subduction processes (Garwin et al. 2005; Seedorff et al. 2005; Sillitoe 2010), or in a post-subduction stage as in the collisional Himalayan orogen (Hou et al. 2006). All the porphyry deposits in the East Junggar formed in three epochs: c. 405 Ma, c. 375 Ma and c. 330 Ma (Long et al. 2009; Du et al. 2010; Xue et al. 2010). All the porphyry deposits show adakite chemistry (Wan & Zhang 2006a; Long et al. 2009; Du et al. 2010), and the volcanic wall-rocks are characterized by Nb-enriched basalts, adakites and high-Mg andesites (Niu et al. 2006; Zhang, H. et al. 2008). All the early to late Palaeozoic volcanic rocks have primitive intra-oceanic geochemical characteristics, having formed in a high-temperature environment (Defant & Drummond 1990; Zhao et al. 2008). Also, and most importantly, many contemporaneous ophiolites at Kelameili formed at 403 ± 9 Ma or 336 ± 4 Ma (Jian et al. 2005). Therefore, the consistency between the geological and geochronological evidence in the East Junggar clearly indicates that all the porphyry Cu–Au–Mo deposits formed during active subduction processes from the early to late Palaeozoic. Because most volcanic rocks in the East Junggar and the Chinese Altai arc formed in successively accreting primitive arcs, Xiao et al. (2009a) proposed that the East Junggar arcs share similarities with the Mariana arc. The metallogenic relationships support this proposal.

Across the Erquis Fault zone, two contrasting ore deposit types formed almost simultaneously at c. 405 Ma and c. 375 Ma, and formation of the youngest porphyry deposit lasted until c. 330 Ma. Sengör et al. (1993) tried to explain the Altai as a single long-lived arc that grew progressively younger southwards. The East Junggar arc might be younger than the Chinese Altai arc based on the ages of dominant rock associations, but the distribution of metallogenic belts across the Altai–East Junggar collage does not support a single subduction zone model. If Briggs et al. (2007) are correct that Erquis is not a strike-slip but a SW-directed crustal-scale thrust in the late Palaeozoic, then the model of Sengör et al. (1993) is invalidated, and the accreted–thrust amalgamation of the two arcs is consistent with our metallogenic data. The classic Alaskan orogen was built by accretion of terranes (e.g. Engebretson et al. 1984), not one of which contains VMS and porphyry deposits (e.g. Goldfarb et al. 1999). Sillitoe (1980) pointed out that the VMS and porphyry deposits are mutually incompatible. The Andean mountain belt is dominated by porphyry deposits of different age, but they are not associated with any contemporary VMS deposits (see Sillitoe & Perelló 2005, and references therein). Therefore, it is reasonable to conclude that the formation of these two kinds of deposit was a response to two different subduction processes, in which case the metallogenic data from the Chinese Altai and East Junggar are consistent with the regional, tectonic framework and evolutionary development (Xiao et al. 2009a).

Except for the VMS and porphyry ore deposits, it is worth noting that all the pegmatite-related rare metal deposits in the Altai–East Junggar collage occur in the Chinese Altai. Although the mineralization ages of c. 220 Ma to c. 197 Ma of the rare metal deposits (Wang et al. 2007) are much younger than the time of termination of the orogeny (Permian; Jian et al. 2010), they still support the idea that the Erquis Fault was a major tectonic boundary between the Chinese Altai and East Junggar arcs (Xiao et al. 2009a). The metallogenic differences on either side of the fault support the geological, petrological and metamorphic differences. Many orogenic gold deposits along the Erquis Fault formed from the Permian to the Triassic (Chen et al. 2000; Rui et al. 2002), and the youngest main movement of the Erquis Fault was in the early Permian (Laurent-Charvet et al. 2002; Briggs et al. 2007). All these orogenic gold deposits are structurally controlled by faults, and have close spatial relations with the master Erquis Fault, hence their formation may be a response to the accretion of the East Junggar arc to the Chinese Altai arc.

Tectonic and metallogenic evolution of the Altai–East Junggar collage

The Altai–East Junggar collage contains two Palaeozoic arc systems (Xiao et al. 2004, 2009a). The Chinese Altai arc developed on partly juvenile and minor continental Cambro-Ordovician crust, whereas the East Junggar arc evolved on oceanic crust. There are two alternative explanations for the Altai–East Junggar: (1) two independent subduction systems created arcs that were amalgamated by collision, like the Kyushu and Bonin arcs in Japan, or (2) one subduction zone was present,
which varied in style along strike from active continental margin to oceanic island arc, as in the present-day Alaskan–Aleutian arc system. Because they are separated by the Erqis Fault, the Chinese Altai and East Junggar collages probably developed in laterally distinct and remote areas. A similar tectonic scenario apparently developed in southern Mongolia (Lamb & Badarch 2001; Helo et al. 2006), which Lehmann et al. (2010) convincingly explained by juxtaposition of several arcs by major strike-slip faults before the final docking of the Tarim and North China cratons.

When the amalgamation of the Chinese Altai and East Junggar arcs was initially presented (Xiao et al. 2004), the above two alternative explanations were both taken into account. We now consider that the most likely model is (1) because, first, the Chinese Altai was a Japanese-type arc during most of Palaeozoic time (Sun et al. 2008; Jiang et al. 2010; Xiao et al. 2010b) rather than a continental margin arc as in the Aleutian Islands of the Alaskan Peninsula, and, second, the Erqis Fault was a SW-directed crustal-scale thrust in the Permian with no obvious strike-slip movement (Briggs et al. 2007, 2009). Therefore, we are not convinced that there was huge strike-slip duplication in the Permian.

In summary, the tectonic and metallogenic characteristics and relationships discussed above allow us to favour model (1). The VMS and porphyry metallogenic events, which were results of Palaeozoic magmatic–hydrothermal activities, were the response of separate subduction processes during arc generation (Fig. 4a). As mentioned above, VMS ore deposits worldwide are always related to extensional regimes, hence in the Chinese Altai they probably indicate an extensional environment during their formation. Besides the VMS deposits, the southern Chinese Altai includes Devonian bimodal volcanic rocks (Wan et al. 2010a), and many intrusive Devonian mafic dykes (Cai et al. 2010), which indicate that the Chinese Altai was in an extensional environment in the Devonian. In general, slab roll-back may be responsible for the development of arc rifts and back-arc basins, and may induce magma upwelling, which increases the possibility of igneous and hydrothermal activity that promotes the VMS mineralization (e.g. Franklin et al. 2005). Xiao et al. (2009a) recognized south-vergent structures in several Palaeozoic accretionary mélanges between the Chinese Altai arc and the Erqis Fault, and hence proposed that the Chinese Altai was built by northward subduction. The VMS deposits in the Chinese Altai may have formed during the roll-back stage of a north-dipping slab beneath the Chinese Altai arc, which was coeval with the opening of intra-arc or infant back-arc basins in the early to mid-Devonian. Before the early Devonian, the Chinese Altai arc was probably in a compressional regime, when porphyry deposits and related epithermal deposits formed in the Ordovician to Silurian. Although no lode or porphyry gold deposits have been found in the high Altai Mountains, the presence of many placer gold deposits on their northern and southern sides (e.g. Nuoerte, Xichahe) indicates the existence of primary gold. The arc-related magmatism of the Chinese Altai arc ended by the late Carboniferous, Early Permian and younger igneous rocks show very evolved, alkaline affinities (Wang et al. 2006), and there are no Permian volcanic rocks in the Chinese Altai (Fig. 4b).

Porphyry Cu–Au–Mo deposits in the East Junggar arc formed episodically from the Early Devonian to the Carboniferous. Their host rocks show adakitic, Nb-enriched and boninitic characteristics that resulted from northward subduction of a young, hot slab beneath the East Junggar arc (Niu et al. 2006; Wan & Zhang 2006a; Zhang, H. et al. 2008). The youngest porphyry Cu–Au–Mo deposits at Xilekuduke formed at 330 ± 4 Ma (Long et al. 2009), which indicates that subduction–accretion lasted at least

Fig. 4. Schematic time-diagrams illustrating the tectonic and metallogenic evolution of the Altai–East Junggar collage. The cross-sectional directions are in present-day coordinates. (a) Pre-Middle Devonian: development of the island arcs and the related subduction-generated VMS and porphyry deposits; (b) Middle Devonian–Late Carboniferous: the formation of the Altai arc was completed, but the East Junggar arc with its porphyry deposits continued to develop; (c) Late Carboniferous to Late Permian: the two arcs were juxtaposed along the Erqis Fault, which controlled the formation of lode gold deposits.
to the late Carboniferous (Fig. 4b). Notably, a c. 285 Ma magmatic Cu–Ni deposit in the East Junggar arc is reasonably interpreted as an Alaskan-type intrusion (Han et al. 2007); this may indicate that the subduction process even lasted to the early Permian (Fig. 4c).

There are many other types of ore deposits in the Altai–East Junggar collage like the lode gold deposits that did not form during subduction, but are related to the interaction between the two arcs. Lode gold deposits are well studied in the circum-Pacific rim (e.g. Goldfarb et al. 2001). This kind of deposit forms in or against deep crustal fault zones that serve as fluid conduits, are spatially associated with greenschist-facies rocks, and have a spatial–temporal association with widespread calc-alkaline magmatic rocks (e.g. Groves & Bierlein 2007). In the Altai–East Junggar collage the two arcs are in fault contact across the Erqis Fault, which acted as a conduit for circulating fluids. Detailed kinematic and geochronological studies of the Erqis Fault show that it is either a sinistral strike-slip fault (Laurent-Charvet et al. 2002) or a SW-directed thrust fault, the youngest main movement of which was in the early Permian at 290 Ma (Briggs et al. 2007). Many lode gold deposits on both sides of and within the Erqis Fault zone have been dated as 227 ± 24 Ma and 269 ± 11 Ma (Rb–Sr; Li & Chen 2004), and this was the active time of movement of the Erqis Fault (Fig. 4c).

**Conclusions**

The time and space distributions of diverse and diagnostic ore deposits across the Altai–East Junggar collage strongly indicate that two independent Palaeozoic island arcs developed from different subduction zones. The Chinese Altai arc, a Japanese-type arc, hosts many VMS deposits, whereas the East Junggar arc, a Mariana-type arc, contains porphyry Cu–Au–Mo deposits. These relationships support the concept that the Altaiads are a multiple subduction–accretion collage. VMS deposits and porphyry deposits formed during the building of the Chinese Altai and East Junggar arcs, respectively. Subsequently, the two arcs were juxtaposed and the Chinese Altai arc was thrust southwards over the East Junggar arc along Erqis Fault. During the transition stage from contraction to extension between these two arcs, decreasing pressure and increasing temperature triggered large-scale hydrothermal fluid activities that have leached gold from wallrocks. The Erqis Fault acted as a fluid channel and location for lode gold deposits.

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**Appendix: brief sample descriptions and analytical methods**

Two samples were collected for zircon separation from the underlying rhylolites of the orebodies of each deposit. Zircons were separated by a combination of heavy liquid and magnetic separation techniques, then mounted in epoxy resin and polished to remove the upper one-third of the grains. Cathodoluminescence (CL) images were obtained to identify internal structures and choose potential target sites for U–Pb analyses. Isotopic measurements were carried out at the MC–ICPMS laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing. An Agilent 7500a quadrupole (Q)-ICPMS system was used for simultaneous collection of U–Pb isotope and trace element data. Detailed analytical procedures and experimental parameters were described by Xie et al. (2008). Standards were zircon 91500, GJ-1 and NIST SRM 610. 206Pb/238U ratios were calculated using GLITTER 4.0 (Griffin et al. 2008). The relative standard deviations of reference values for 91500 were set at 2%. Common Pb was corrected according to the method proposed by Andersen (2002). The weighted mean U–Pb ages and concordia plots were processed using ISOPLOT 2.3 (Ludwig 2001).

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The SE Asian Gateway: History and Tectonics of the Australia-Asia collision

Edited by R. Hall, M. Cottam and M. E. J. Wilson

Collision between Australia and SE Asia began in the Early Miocene and reduced the former wide ocean between them to a complex passage which connects the Pacific and Indian Oceans. Today, the Indonesian Throughflow passes through this gateway and plays an important role in global thermohaline flow, and the region around it contains the maximum global diversity for many marine and terrestrial organisms. Reconstruction of this geologically complex region is essential for understanding its role in oceanic and atmospheric circulation, climate impacts, and the origin of its biodiversity.

The papers in this volume discuss the Palaeozoic to Cenozoic geological background to Australia and SE Asia collision, and provide the background for accounts of the modern Indonesian Throughflow, oceanographic changes since the Neogene, and aspects of the region’s climate history.

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Edited by G. P. Goffey, J. Craig, T. Needham and R. Scott

Onshore fold-thrust belts are commonly perceived as ‘difficult’ places to explore for hydrocarbons and are therefore often avoided. However, these belts host large oil and gas fields and so these barriers to effective exploration mean that substantial unexploited resources may remain. Over time, evaluation techniques have improved. It is possible in certain circumstances to achieve good 3D seismic data. Structural restoration techniques have moved into the 3D domain and increasingly sophisticated palaeo-thermal indicators allow better modelling of burial and uplift evolution of source and reservoirs. Awareness of the influence of pre-thrust structure and stratigraphy and of hybrid thick and thin-skinned deformation styles is augmenting the simplistic geometric models employed in earlier exploration. But progress is a slow, expensive and iterative process. Industry and academia need to collaborate in order to develop and continually improve the necessary understanding of subsurface geometries, reservoir and charge evolution and timing; this publication offers papers on specific techniques, outcrop and field case studies.

- **Special Publication 347**

Reservoir Compartmentalization

Edited by S. J. Jolley, Q. J. Fisher, R. B. Ainsworth, P. J. Vrolijk and S. Delisle

Reservoir compartmentalization, the segregation of a petroleum accumulation into a number of individual fluid/pressure compartments, controls the volume of moveable oil or gas that might be connected to any given well drilled in a field, and consequently impacts on reserves ‘booking’ and operational profitability. This is a general feature of modern exploration and production portfolios, and has driven major developments in geoscience, engineering and related technology. Given that compartmentalization is a consequence of many factors, an integrated subsurface approach is required to better understand and predict compartmentalization behaviour, and to minimize the risk of it occurring unexpectedly. This volume reviews our current understanding and ability to model compartmentalization. It highlights the necessity for effective specialist discipline integration, and the value of learning from operational experience in: detection and monitoring of compartmentalization; stratigraphic and mixed-mode compartmentalization; and fault-dominated compartmentalization.

- **Special Publication 340**

Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform

Edited by M. Sosson, N. Kaymakci, R. A. Stephenson, F. Bergerat and V. Starostenk

This wide area of the Alpine-Himalayan belt evolved through a series of tectonic events related to the opening and closure of the Tethys Ocean. In doing so it produced the largest mountain belt of the world, which extends from the Atlantic to the Pacific oceans. The basins associated with this belt contain invaluable information related to mountain building processes and are the locus of rich hydrocarbon accumulations. However, knowledge about the geological evolution of the region is limited compared to what they offer. This has been mainly due to the difficulty and inaccessibility of cross-country studies. This Special Publication is dedicated to the part of the Alpine-Himalayan belt running from Bulgaria to Armenia, and from Ukraine to the Arabian Platform. It includes twenty multidisciplinary studies covering topics in structural geology/tectonics; geophysics; geochemistry; palaeontology; petrology; sedimentology; stratigraphy; and subsidence and lithospheric modelling. This volume reports results obtained during the MEBE (Middle East Basin Evolution) Programme and related projects in the circum Black Sea and peri-Arabian regions.