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The boundary between the Central Asian Orogenic belt and Tethyan tectonic domain deduced from Pb isotopic data

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ABSTRACT

A detailed comparison of the tectonic features of Central Asian Orogenic belt (CAOB) and Tethyan Tectonic domain (TTD) is of great significance to our understanding of the origin of global orogenic systems. Currently, there are many uncertainties in the general framework to fully define the tectonic properties of the CAOB and TTD. The Pb isotope data from Paleo-Asian Ocean (PAO) ophiolites in the CAOB and Tethyan ophiolites in the TTD allow us to conduct a detailed comparative study between these two global orogenic systems. Results of the study show the presence of an isotopic boundary between the different mantle domains and tectonic properties of the CAOB and TTD, with the Xinjiang region in the former representing the transition between the two systems. The distinctive $^{208}Pb/^{204}Pb$ isotope compositions of the PAO and Tethyan mantles suggest the existence of a long time-integrated lower Th/U reservoir beneath the CAOB compared to that beneath the TTD throughout the Paleozoic. Results thus suggest the distinct Pb isotope compositions of the PAO and Tethyan mantles are intimately related to the different magma–tectonic processes that formed the CAOB and TTD. Based on plate tectonic reconstruction, the Neoproterozoic to Paleozoic evolution of the accretionary margins of the CAOB mimics the modern circum-Pacific Ocean rim. In this scenario, the PAO had a low Th/U mantle isotopic signature and the subduction of PAO crust gave rise to the circum-Pacific type accretionary orogen. On the other hand, the Tethys oceans produced the high Th/U mantle isotopic signatures in an evolving collisional orogen. Significantly, the generally radiogenic and juvenile Hf isotopic signature of the CAOB is consistent with an accretionary orogenic setting for PAO whereas the relatively more unradiogenic Hf isotopic signature of TTD is consistent with a collisional orogenic setting for Tethys oceans. Thus, our study sheds some light on the PAO evolution as well as the plate tectonic reconstruction of Central Asian and Tethyan orogens.

1. Introduction

Investigations of supercontinent cycles (Cawood and Buchan, 2007; Condie, 1998, 2000; Li et al., 2008) have shown that the formations and dispersals of super-continents caused openings and closings of world oceans and these were accompanied by plate tectonic convergence, collision and accretion processes that produced the global orogenic systems. This general knowledge about orogenesis has been known for quite some time, but is based mainly on surface tectonic features such as suture zones, tectonic domains and mountain belts. However, very few studies have focused on the underlying mantle mechanism(s) and/or process(es) that may have formed these tectonic features. Collins and co-workers (Collins, 2003; Collins et al., 2011) have quite recently suggested that the two long-lived global-scale mantle convection systems are related to the different styles of orogenic processes in the Phanerozoic: accretionary and collisional. The composition, history and evolution of the underlying mantle and their relationships to surface tectonic features will lead to a better understanding of the coupling between crust and mantle processes. Specifically, surface tectonic processes coupled with mantle

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convection systems could be the reason for the globally different Hf isotope evolution between accretionary and collisional orogens (Collins et al., 2011). Ophiolites, pieces of ocean floor that are occasionally preserved in on-land (e.g., Dilek, 2003; Hawkins, 2003; Moores, 1970, 2003; Wakabayashi et al., 2010), are interesting to study in this context since their modes of emplacement provide important keys to understand the major tectonic features of an orogenic belt as well as their chemical and isotopic characteristics generally reflect those of the composition and evolution of underlying mantle (e.g., Dewey and Bird, 1971; Dilek, 2003; Mahoney, 1998; Moores and Jackson, 1974; Moores and Vine, 1971; Shervais, 2001; Shervais et al., 2005; Pfänder et al., 2002; Wakabayashi et al., 2010; Wakabayashi and Dilek, 2000; Xu and Castillo, 2004; Xu et al., 2002; Zhang et al., 2005).

The Paleo-Asia and Tethys oceans are two extinct ancient oceans. The Paleo-Asia Ocean (PAO) was formed during the break up of the Rodinia Supercontinent between 900 and 700 Ma (Dobretsov et al., 1995, 2003; Li et al., 2008). The Tethys can be further subdivided into Paleo-Tethys Ocean (PTO) and Neo-Tethys Ocean (NTO). The Tethys most probably was formed from Cambrian to Cretaceous, roughly between ~550 and ~90 Ma based on ophiolite ages, corresponding to the separation and northward migration of the various continental terranes from Gondwana (Metcalfe, 2013; Stampfii et al., 2002; Stampfli, 2000). The Central Asian Orogenic Belt (CAOB; Jahn, 2004) and Tethyan Tectonic domain (TTD) are the two largest global complex tectonic domains associated with the evolution and closure of PAO and Tethys oceans, respectively. Many studies have also recognized that CAOB and TTD represent typical global accretionary and collisional orogens, respectively (Collins, 2003; Collins et al., 2011; Cawood and Buchan, 2007; Cawood et al., 2009; Sengör and Natal'in, 1996; Sengör et al., 1993; Windley et al., 2007; Xiao et al., 2008, 2010, 2009a, 2003, 2009b). Relict fragments of PAO and Tethys crusts are preserved as 'ophiolites' along the CAOB and TTD suture zones. Although the term ophiolite has different meanings as applied by different authors (Dilek, 2003; Wakabayashi et al., 2010), we use it in this paper simply to define a sequence of rocks comprising a generic oceanic crust. Moreover, we primarily focus on the mafic and ultramafic igneous members of the PAO and Tethys crusts as their geochemistry offers a natural window to constrain the properties of PAO and Tethyan mantles that, in turn, can be related to the surface tectonic features of CAOB and TTD.

In this paper, we compare the Pb isotopic compositions of mafic rocks (basalts and gabbros) collected from typical PAO (Liu et al., 2014, 2015; Wang, 2009) and Tethyan ophiolites (Hou et al., 2006a, 2006b; Mahoney, 1998; Xu and Castillo, 2004; Xu et al., 2002; Zhang et al., 2005) representing the sub-PAO and Tethyan mantle, respectively. Based on the comparison of Pb isotopic data, we found a distinct isotopic difference between the sub-PAO and Tethyan mantles. Finally, we present the geodynamic significance of these mantle domains by comparing the orogenic histories and characteristics with the modern boundary between the CAOB and TTD domains.

2. Geologic background

The history and evolution of the now extinct PAO (Dobretsov et al., 1995, 2003) and Tethys (Metcalfe, 2013; Stampfii et al., 2002; Stampfli, 2000) resulted into the formation of two major tectonic zones, the CAOB and TTD, respectively. The TTD lies at the boundary between the Indian and Tarim–North China cratons (Fig. 1) and represents the subduction of the Paleo- and Neo-Tethys oceans during the Paleozoic and Mesozoic, respectively, although they partly overlapped in time (Metcalfe, 2013; Sengör, 1987; Sengör and Yilmaz, 1981; Stampfii et al., 2002; Stampfli, 2000). Neo-Tethyan ophiolites occur mainly along the Yar-lung-Zangbo and Bangong Lake–Nujiang suture zones in Tibet whereas Paleo–Tethyan ophiolites mainly occur in northern Tibet, Sanjiang area of southwest China and central China (Xu and Castillo, 2004; Xu et al., 2002; Zhang et al., 2008a) (Fig. 1).

The PAO probably opened in Mid- to Neo-Proterozoic (ca. 900 Ma, Dobretsov et al., 1995, 2003) and closed in ~Permian (ca. 280–250 Ma, Xiao et al., 2008, 2009a; Zhang et al., 2008b). The CAOB, also known as the Altaid tectonic collage (Sengör and Natal'in, 1996; Sengör et al., 1993), was a collage of multiple former subduction–accretionary complexes associated with the evolution and closure of the PAO (Windley et al., 2007; Xiao et al., 2009a). It is currently located at the boundary between the Siberian and Tarim–North China cratons (Fig. 1). The PAO ophiolites occurring in the suture zones in northern Xinjiang and Inner Mongolia are in the southern portion of CAOB.

2.1. Paleo-Asian ophiolite

The eight PAO ophiolite exposures investigated in this study include three from North Xinjiang (Bindaban and Bayan Gol ophiolites of Tianshan, Dalabute and Karamaili ophiolites of Junggar) and four from Inner Mongolia (Hegenshan, Chaokeshan, Ondor Sum and Ulan Valley ophiolites). The Bindaban and Bayan Gol ophiolite are exposed in the North Tianshan suture zone section of the North Tianshan fault (Fig. 1). The slices of Bindaban ophiolite mainly consist of gabbro, diabase and basalt (Dong et al., 2007) and were formed in Ordovician based on the chert interlayered with the ophiolite mélange that conformably underlies the lower Silurian Mishigou Formation containing late Cambrian – Ordovician Radiolaria fossils and Conodont fossils (Che et al., 1994). The Bayan Gol ophiolite consists of fault-bounded slices of pillowed and massive lavas, diabase, gabbro, and ultramafic rocks (Xia et al., 2005). A plagiogranite from this ophiolite has a SHRIMP zircon age of 324.8 ± 7.1 Ma (Xu et al., 2005) whereas a gabbro has a LA–ICP–MS zircon age of 344.0 ± 3.4 Ma (Xu et al., 2006b).

The Karamaili and Dalabute ophiolite belts are the two largest exposures of Devonian ophiolites in the Junggar Basin in northern Xinjiang. They have almost all the igneous components of a classic ophiolite, e.g. mantle peridotites, cumulate ultramafics, gabbros, and volcanics (Liu et al., 2014, 2009a, 2007). The age of Karamaili ophiolite has been determined by U–Pb zircon dating that includes 336 Ma and 342 Ma for the gabbros (Jian et al., 2005), 403 Ma (Jian et al., 2005) and 373 Ma (Tang et al., 2007) for the plagiogranites and 371 Ma for the tonalities (Liu et al., 2009a). These dates are consistent with the Devonian and Early Carboniferous age of the radiolarian chert (Cai, 1986; He et al., 2000; Shu and Wang, 2003). The age of Dalabute ophiolite has been constrained by a Sm–Nd isochron age of 395 Ma (Zhang and Huang, 1992) and U–Pb zircon ages of 391 Ma (Gu et al., 2009), 332 Ma (Xu et al., 2006a), and 302 Ma for its gabbro units (Liu et al., 2009b). Although quite variable, these igneous ages of the ophiolite combined with the Devonian age of the radiolarian chert (Xiao et al., 1992) give a conclusive Devonian to early Carboniferous age (391–332 Ma) for the Dalabute ophiolite.

The other four ophiolites exposures investigated occur in two of the four major ophiolite belts in Inner Mongolia that include, from north to south, Eren Hot–Hegenshan, Jiaoqier–Xilin Hot, Solon Obo–Linxi, and Ondor Sum–Xar Moron (Fig. 1; Miao et al., 2008; Xiao et al., 2003; Zhang et al., 2008b). Hegenshan and Chaokeshan ophiolites are located within the early Paleozoic Eren Hot–Hegenshan ophiolite belt. The ophiolite pieces consist chiefly of mantle peridotites and cumulate gabbros as well as sparse basaltic lavas and dikes (Miao et al., 2008; Zhang et al., 2008b). SHRIMP

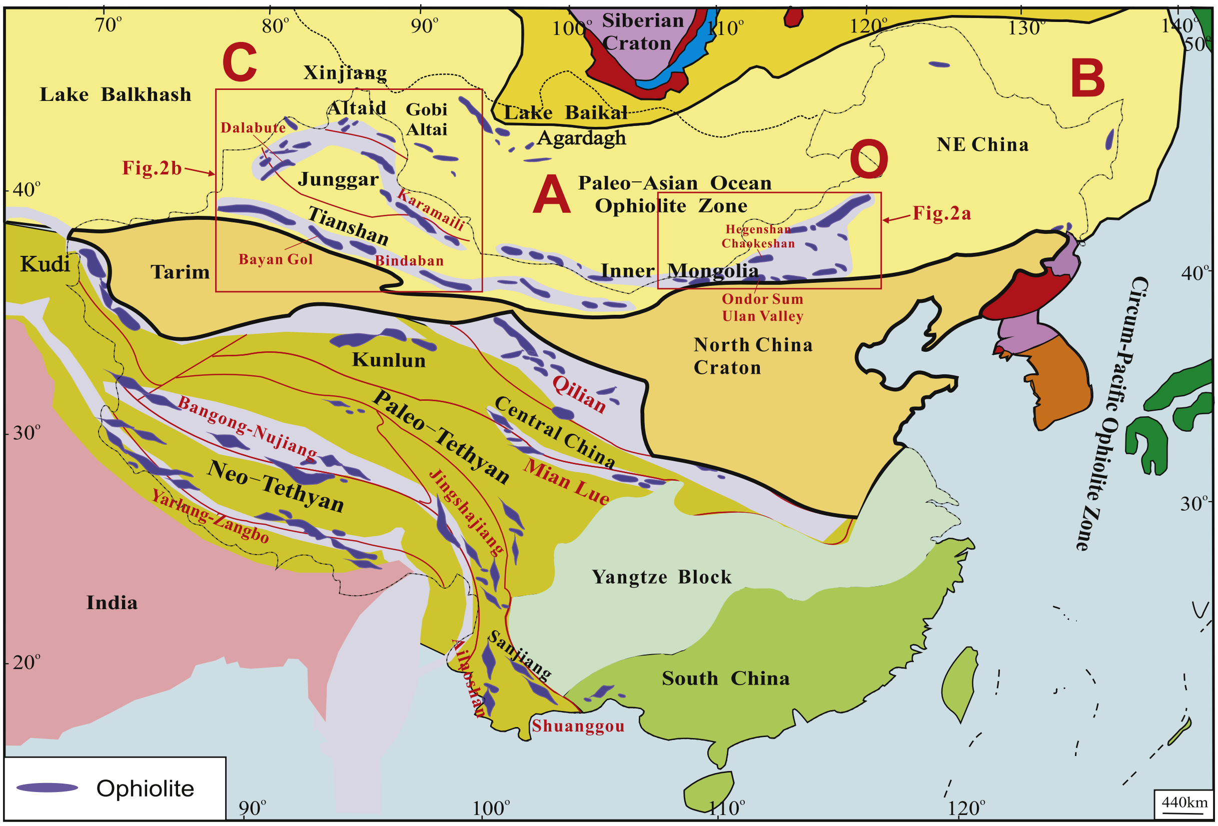

Fig. 1. Simplified tectonic map of central Asia and Tibetan plateau showing distributions of ophiolite belts (modified after Jahn, 2004; Zhang et al., 2008a). The Central Asian Orogenic Belt (CAOB) is located between Siberian craton to the north and Tarim–North China craton to the south. The Tethyan tectonic zone is located between the Indian and Tarim–North China cratons.

U–Pb zircon ages acquired for the Hegengshan ophiolite include 354 ± 7 Ma for a microgabbro (Jian et al., 2012), 333 ± 4 Ma for a plagiogranite (Jian et al., 2012), 298 ± 9 Ma for a basaltic dike (Miao et al., 2008), 295 ± 15 Ma for a gabbro (Miao et al., 2008), and a whole-rock $^{40}Ar/^{30}Ar$ age of 293 ± 1 Ma that was interpreted as the time of eruption of the basaltic lavas.

The Ondor Sum and Ulan Valley ophiolites are located in the early Paleozoic Ondor Sum–Xar Moron ophiolite belt (Fig. 1). The Ondor Sum ophiolite consists chiefly of basalt and gabbro with minor diorite locally intruded by diabase dikes (Zhang et al., 2008a). Pillow basalts in Ondor Sum ophiolite give a Rb–Sr isochron age of 624 Ma (Zhang and Wu, 1998) whereas adakitic diorites give a SHRIMP U–Pb zircon age of 467 Ma (Liu et al., 2003). The best section of Ondor Sum ophiolite is in the Ulan Valley and consists mainly of pillow lavas, massive basalts, gabbros and ultramafic slices; some of the basalts experienced high-pressure metamorphism and had been transformed to blueschists (de Jong et al., 2006; Miao et al., 2008). The Sm–Nd and Rb–Sr isochron ages of basalts from Ulan Valley ophiolite are 961 Ma and 624 Ma, respectively (Zhang and Wu, 1998). Although the previously reported ages of Ondor Sum ophiolite are variable, from 425 to 961 Ma, the ocean basin represented by Ondor Sum ophiolite most likely formed in early Paleozoic (Miao et al., 2008; Zhang and Wu, 1998).

2.2. Tethyan ophiolites

For comparison with those from the PAO ophiolites, lead isotopic data were compiled from the PTO and NTO ophiolites that include Shuanggou, Jingshajian and Ailaoshan ophiolites from southwest China, Mian Lue and Qilian ophiolites from central China and Yar-lung-Zangbo and Bangong Lake–Nujiang ophiolites from Tibet (Fig. 1). They are the best preserved ophiolites in the region and contain all the igneous components of a classic ophiolite, e.g. mantle peridotites, cumulate ultramafics, gabbros, diabases, and basalts; the age of these ophiolites range from 550 to 90 Ma (Hou et al., 2006a, b; Xu and Castillo, 2004; Zhang et al., 2008a, 2005).

3. Results and discussion

3.1. Distinctive Pb isotope compositions between sub-PAO and Tethyan mantles

The Pb isotope compositions of mafic samples from different PAO and Tethyan ophiolites are shown graphically in Fig. 2. One should note that all samples were corrected to their respective crystallization ages using measured and published Th, U and Pb concentrations. There is a clear difference in the Pb isotopic compositions between PAO and Tethyan ophiolites in $^{208}Pb/^{204}Pb_{(t)}$ versus $^{206}Pb/^{204}Pb_{(t)}$ plots. Although the Pb isotopic ratios of the three late Paleozoic ophiolites (Bayan Gol, Dalabute and Karamail ophiolites) from Xinjiang plot within the Tethyan field (Fig. 2b), all other ophiolites from Inner Mongolia and the early Paleozoic Bindaban ophiolite (also in Xinjiang) are distinct compared to those of the Tethyan ophiolites. In detail, the PAO ophiolites plot below or on the NHRL (Hart, 1984), or have lower $^{208}Pb/^{204}Pb_{(t)}$ for given $^{206}Pb/^{204}Pb$ ratios than the Tethyan ophiolites (Hou et al., 2006a, b; Mahoney, 1998; Xu and Castillo, 2004; Xu et al., 2002; Zhang et al., 2005). This suggests lower $^{208}Pb/^{206}Pb$ that, in turn, suggests a systematically long time-integrated lower (parent) Th/U ratio of

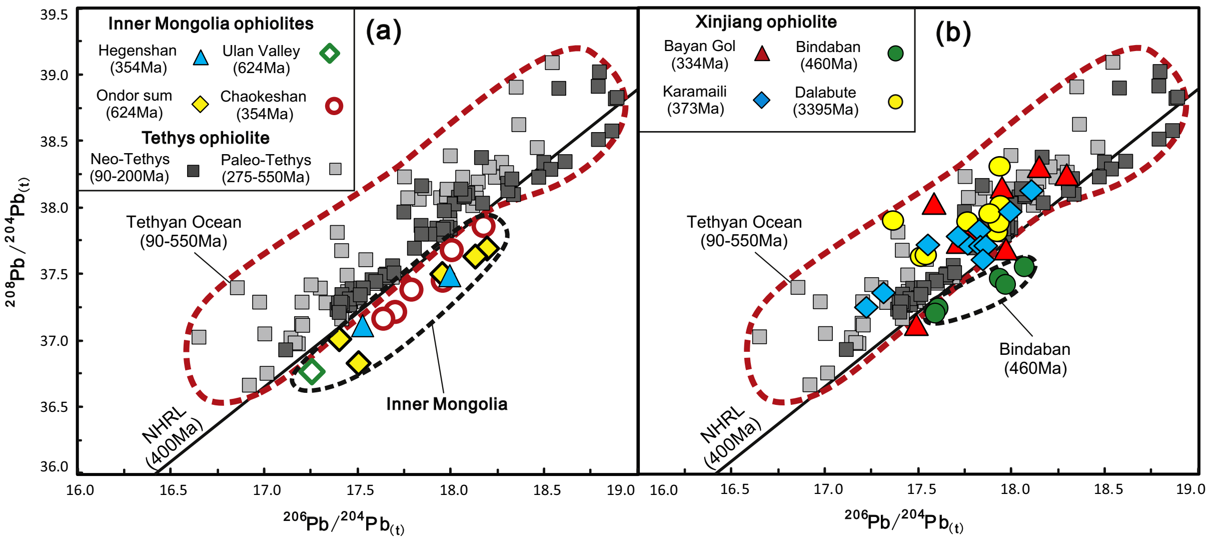

Fig. 2. Age-corrected initial $^{208}Pb/^{204}Pb_{(t)}$ versus $^{206}Pb/^{204}Pb_{(t)}$ for PAO ophiolites from (a) Inner Mongolia (Wang, 2009; Liu et al., 2015) and (b) Xinjiang (Liu et al., 2014; Xia et al., 2005) compared to age-corrected PTO mafic rocks (Hou et al., 2006a, b; Mahoney, 1998; Xu et al., 2006b, 2005; Zhang et al., 2005), NHRL (Northern Hemisphere Reference Line) is from Hart (1984).

the sub-PAO mantle relative to that of the sub-Tethyan mantle throughout the Phanerozoic.

In detail, the Inner Mongolia ophiolites have a different Pb isotopic trend from that of the Tethyan ophiolites (Fig. 2a), but the isotopic ratios of the Xinjiang ophiolites exhibit two trends: the early Paleozoic Bindaban ophiolite (~460 Ma) is isotopically different from that of Tethyan ophiolites, whereas the late Paleozoic Bayan Gol (334 Ma), Dalabute (~395 Ma) and Karamaili (~373 Ma) ophiolites are isotopically similar to Tethyan ophiolites (Fig. 2b). This observation raises the possibility that Pb isotope differences exist between early and late Paleozoic PAO ophiolites in Xinjiang. In other words, the PAO most likely occupied portions of the Tethyan mantle as well during late Paleozoic (Liu et al., 2014). Unfortunately, Pb isotope data are currently not available for other early Paleozoic ophiolite(s). Therefore, further sampling and analysis are needed to trace the mantle property of the PAO ophiolites in the Xinjiang Province.

3.2. Geodynamic implications

The global orogenic systems were basically developed through accretionary and collisional orogenic processes (Collins et al., 2011; Cawood and Buchan, 2007; Cawood et al., 2009). The CAOB is one of the typical accretionary orogens (Jahn, 2004; Windley et al., 2007; Xiao et al., 2008, 2010, 2009a, b) and is associated with PAO evolution whereas the TTD is a collisional orogen associated with Tethys evolution (Xu and Castillo, 2004; Xu et al., 2002). Based on our results, we propose that the distinct Pb isotopic compositions of the PAO and Tethyan mantles are intimately related to the different magma–tectonic processes that formed the CAOB and TTD that, in turn, were associated with long-lived mantle convection (Bahlburg, 2011). In this scheme, the markedly different Pb isotopic signatures of the PAO and Tethyan mantles are reminiscent of the Hf isotope evolution of global accretionary and collisional orogenic systems (Fig. 3), which shows fundamentally different Hf isotopic signatures. Note that the mixed radiogenic and unradiogenic Hf isotopic ratios of TTD are part the original data set used by Collins et al. (2011) to define the collisional orogen array. On the other hand, the radiogenic Hf isotopic ratios of CAOB, which are not part of the said data set, plot with the accretionary orogen array.

It is also important to note that the production of two distinctive isotopic mantle domains beneath the PAO and Tethys raises a major question: what mechanism(s) elevated the Th/U ratio in the mantle beneath the Tethyan relative to that beneath the PAO realm. Our data suggest that the different Pb isotope compositions of the PAO and Tethyan mantles most likely were affected by different tectonic events that produced two different isotope signatures. Specifically, contamination of high Th/U continental material occurred during the opening of the Tethys oceans (Chung et al., 2001; Hanan et al., 2004; Mahoney, 1998), subsequent subduction around Tethys (Kempton et al., 2002; Rehkämper and Hofmann, 1997), or during tectonic processes that produced the Tethyan domain.

Significantly, based on recent plate reconstructions (Fig. 4; Scotese, 2001), the PAO and Tethys had dramatic different evolutionary and tectonic histories. The PAO was formed by Neoproterozoic rifting of Rodinia (Cawood, 2005; Dobretsov et al., 1995, 2003; Li et al., 2008) and most likely was a branch of the Paleo-Pacific Ocean that had a remarkable permanency, at least throughout the Phanerozoic (Fig. 4; Coney, 1992; Dobretsov et al., 1995, 2003). The subduction system around and of PAO was on average relatively stable and the subducting plate mainly consisted of oceanic lithosphere, similar to the present-day circum Pacific margin subduction system (Xiao et al., 2010, 2009b). Thus, no extensive continental crust and sub-continental lithospheric mantle (SCLM) were involved during subduction-related magmatism within this accretionary orogenic system. As a typical subdution-accretionary orogenic system, the CAOB had evolved around PAO margins although the Gondwanaland microcontinents (e.g. Tarim or Kazakhstan, He et al., 2014; Liu et al., 2011) crossed the PAO and finally collided the Siberian and East European continents in late Paleozoic (Dobretsov et al., 2003). Thus, a large part of CAOB growth may have been produced dominatedly by the addition of juvenile materials (e.g., oceanic fragments and island arcs) that were extracted from the underlying mantle wedge relatively free of continental material contamination (Sengör et al., 1993; Xiao et al., 2008, 2010, 2009b). Such an evolution is apparently explained by the more radiogenic Hf isotope compositions of zircon minerals from the CAOB (Fig. 3; Ao et al., 2010; Cai et al., 2014, 2011; Geng et al., 2009; Kröner et al., 2014; Li et al., 2013; Sun et al., 2008; Yang et al., 2011).

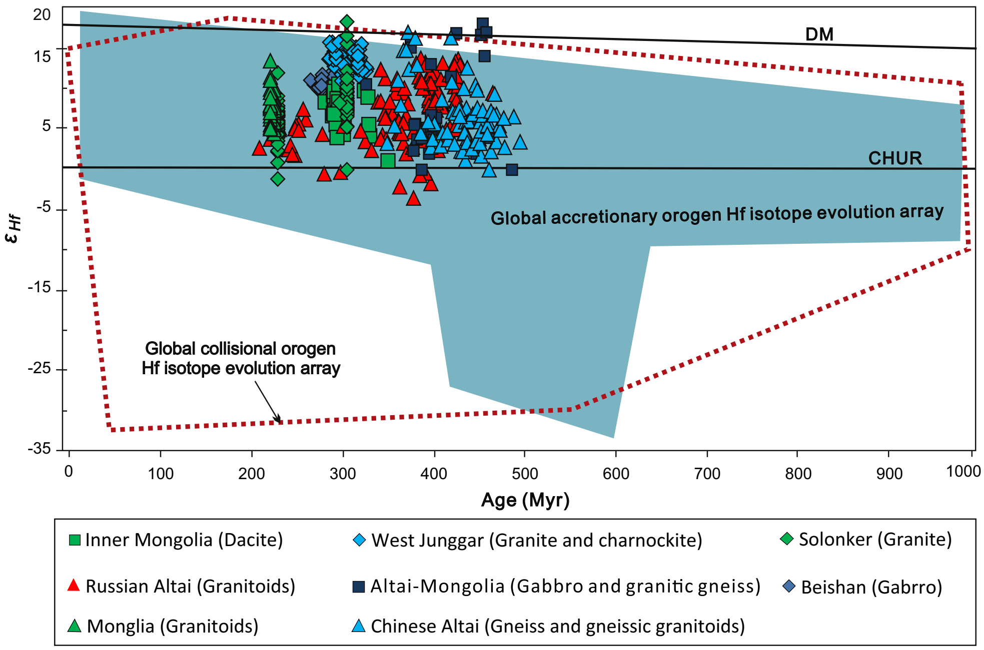

Fig. 3. Zircon hafnium isotopic compositions of CAOB and the global orogenic systems from ~550 Ma to present. The zircon hafnium isotopic data for CAOB are from Inner Mongolia (Yu et al., 2014), Mongolia (Li et al., 2013), Solonker (Chen et al., 2009), Altai-Mongolia (Yang et al., 2011), Chinese Altai (Sun et al., 2008), Russian Altai (Cai et al., 2014), West Junggar (Geng et al., 2009), and Beishan (Ao et al., 2010); the fields of global orogenic systems are from Collins et al. (2011). See text for more detailed discussion.

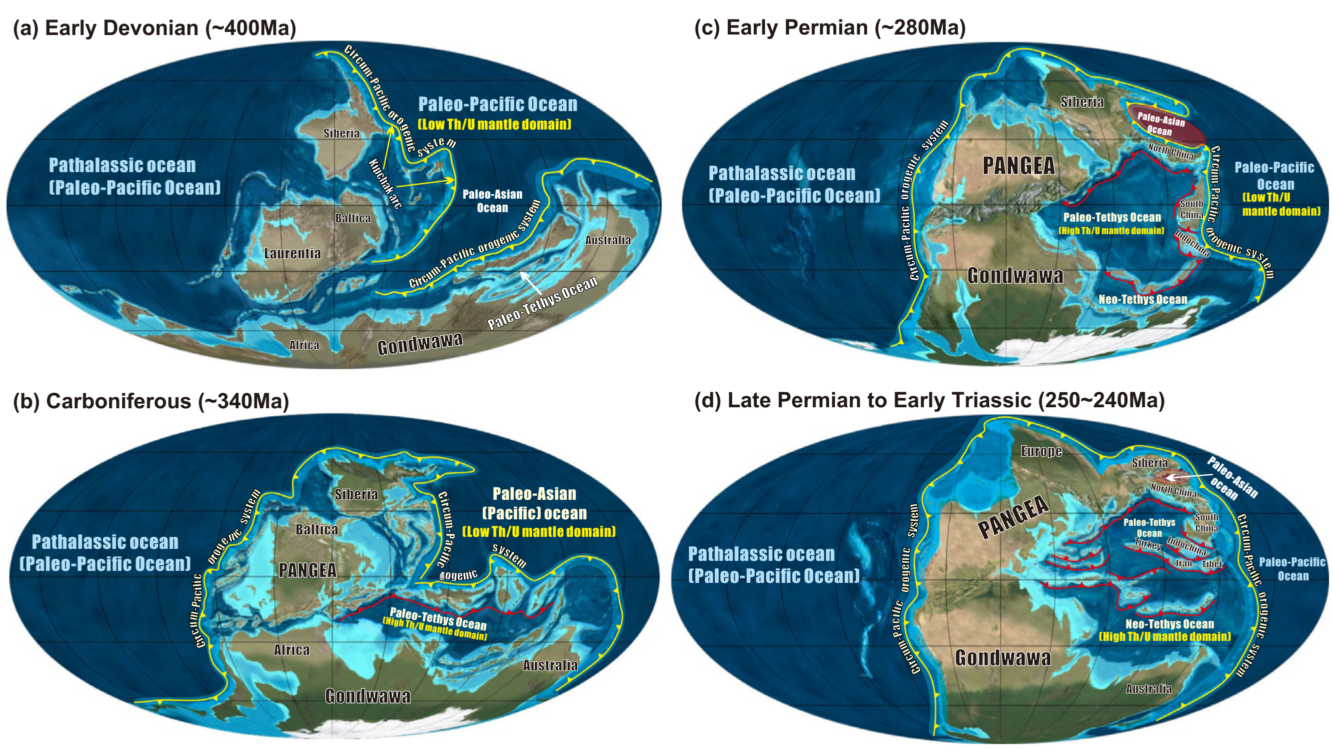

Fig. 4. Devonian to Permian geodynamic plate reconstructions (modified from Scotese, 2001, PALEOMAP Project, http://www.scotese.com and http://cpgeosystems.com, Stampfli, 2000, de Jong et al., 2006) showing possible paleo-positions of Paleo-Asian Ocean (PAO) and Tethys oceans. Subduction zones and circum-Pacific orogenic systems are also shown. (a) Early Devonian. The PAO between Gondwanaland and Laurentialand was a branch of the Paleo-Pacific Ocean, extending northward from the circum-Pacific margin of Gondwanaland and Siberia across and beyond the North Polar regions. In general, the Paleo-Pacific Ocean had a permanent and stable subduction system where only oceanic crust comprises the subducting plate; an intra-oceanic arc (Kipchak arc of Sengör et al., 1993) extended from Siberia to the south of Baltica. During this period, the separation and northward migration of the various continental terranes from Gondwanaland initially opened the Paleo-Tethys Ocean (PTO). (b) Carboniferous. The PAO gradually closed from west to east, corresponding to the collision of Africa (west Gondwanaland) with Pangea. The PTO continued extending northward, successively transferring Gondwanaland microcontinents across the ocean; subduction zones evolved around the Paleo–Tethyan margin. (c) Early Permian. The PAO shrinked into limited ocean basin(s) between North China and Siberia. During this period the PTO opening was at a maximum and continental break-up of mid-Gondwanaland formed the Neo-Tethys Ocean (NTO). (d) Late Permian to Early Triassic. The PAO completely closed and Gondwanaland derived micro-continents crossed the PTO and NTO and subducted along a long-term, N-dipping subduction; finally, North China collided with Eastern Europe.

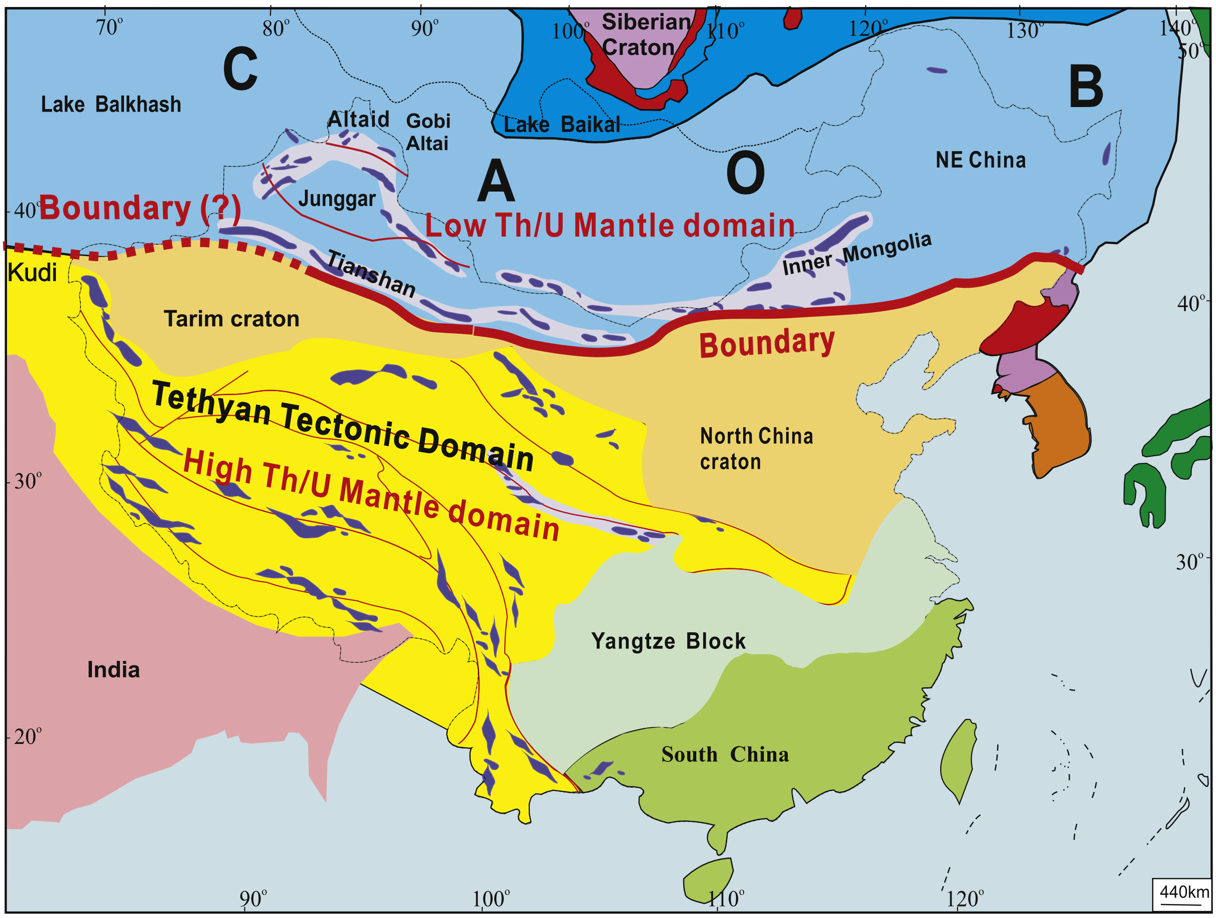

Fig. 5. Schematic map of the boundary between the CAOB and Tethyan Tectonic domains (modified after Jahn, 2004; Xiao et al., 2009a; Zhang et al., 2008a). The solid and dashed sections of the red bold line denote the exact and approximate locations of the boundary, respectively, along the Tianshan–Solonker suture zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In contrast, the Tethys realms, including the PTO, NTO and Indian Ocean, experienced repeated openings and closures, successive transfers of continental fragments across ocean areas and, finally, evolution through collisional orogeny around the Tethys margins (Fig. 4; Collins et al., 2011; Coney, 1992). In detail, continental break-up of the Gondwana landmasses formed the Paleo–Tethyan, then Neo_Tethyan, and Indian mid-ocean systems (Stampfii et al., 2002; Stampfli, 2000). Detachment and dispersal of continental lower crust and SCLM into the shallow mantle during rifting and breakup of Gondwana may adequately account for high the Th/U Tethyan mantle (Chung et al., 2001; Hanan et al., 2004; Mahoney, 1998). These processes may also explain the mixed radiogenic and unradiogenic Hf isotope signal (Fig. 3) through episodic mixing between young oceanic and old continental lithosphere in the upper mantle during repeated cycles of ocean basin evolution (Collins et al., 2011).

3.3. The boundary between CAOB and TTD

Lead isotope data coupled with Hf isotope evolution of global accretionary and collisional orogens suggest that surface tectonic and underlying mantle processes influence each other. The distinctive isotope compositions of the sub-PAO and Tethyan mantles is also consistent with plate reconstructions (Fig. 4; Scotese, 2001). The ancient Panthalassan Ocean, most likely the precursor of PAO or Paleo-Pacific Ocean (Coney, 1992; de Jong et al., 2006; Dobretsov et al., 1995, 2003), had permanent stable subduction systems but lacked major continental collisions and, thus, extensive contamination of the shallow mantle did not occur. Meanwhile, the circum-Pacific orogenic system evolved along the subduction zone of outer PAO or Paleo-Pacific Ocean rim, a part of which was located in front of Kipchak arc system (Sengör et al., 1993). Thus, the PAO eventually evolved into the accretionary CAOB after its closure in the Permian (Xiao et al., 2008, 2009a). As a result, the PAO ophiolites that formed in Inner Mongolia have a low $^{208}Pb/^{206}Pb$ (or Th/U) mantle isotopic signature that is different from that of the Tethyan mantle. In contrast, the separation and northward migration of the various continental terranes from Gondwanaland wherein the Tethyan and then Indian oceans were formed through repeated openings and closures (Stampfii et al., 2002; Stampfli, 2000). The closure of the Tethyan realm formed a long-term, N-dipping subduction system (Fig. 4d; Collins, 2003; Collins et al., 2011) that represents the collisional TTD, wherein detached fragments of Gondwana lower crust and SCLM continuously entered the shallow mantle producing a high Th/U mantle reservoir of Tethys (Chung et al., 2001; Hanan et al., 2004; Mahoney, 1998).

In summary, our results show that the Pb isotopic composition of PAO opholites is distinct from that of Tethyan ophiolites and this, in turn, reflects a long time-integrated lower Th/U mantle beneath the PAO, or at least, beneath the southern part of PAO (e.g., in Inner Mongolia and Tianshan) throughout the Paleozoic. The different orogenic histories of the CAOB and TTD are consistent with the different Pb isotopic compositions of these mantle domains. Based on tectonic features and mantle properties, we delineate the present-day boundary between the CAOB and TTD along the Tianshan–Solonker suture (Fig. 5). The eastern boundary in Inner Mongolia and western boundary in Tianshan of Xinjiang is solid (red solid line in Fig. 5), but the western boundary further from Kudi in Xinjiang cannot be constrained with certainty (represented by red dashed line in Fig. 5) because the Pb isotope characteristics of late Paleozoic ophiolites from Xinjiang are equivocal as they also show Tethyan characteristics. This boundary reflects not only the surface tectonic features but also the mantle compositional distinction between the CAOB and TTD. Therefore, our results provide testable models for the connection between orogenic and mantle processes and the boundary between mantle geochemical and tectonic features of two orogenic systems.

4. Conclusions

The following are the main conclusions of this study:

(1) The comparison between the isotopic compositions of PAO and Tethyan ophiolites suggests the existence of a boundary between the mantle domains and tectonic features of CAOB and TTD.
(2) The distinctive $^{208}Pb/^{206}Pb$ isotopic ratios of the PAO and Tethyan mantle domains are due to differences in their long-time integrated Th/U ratios.
(3) The Pb isotopic distinction between these two mantle domains suggests that an intimate relationship exists between mantle and tectonic evolutions in individual global orogens. The different magma–tectonic processes that formed the CAOB and TTD resulted into distinct Pb isotope compositions of the PAO and Tethyan mantles.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2015.04.039.

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