The Altaids as seen by Eduard Suess, and present thinking on the Late Mesoproterozoic to Palaeozoic evolution of Central Asia

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Abstract

Eduard Suess recognized the unusual size and internal tectonic configuration of the mountainous terranes of Central Asia that he termed Altaids and which differ considerably from curvi-linear foldbelts such as the Alps and Urals. However, he did not realize that this orogenic domain or province evolved over a period of some 750 Ma from the late Mesoproterozoic (ca. 1000 Ma) to the late Permian (ca. 260 Ma), contains large volumes of pre-orogenic crust as well as many synorgenic metamorphic complexes, and exhibits many structures similar to modern thrust-and-fold belts. We therefore do not favour the name Altaids for this large orogenic domain because it is associated with the concept of an essentially Palaeozoic evolution and certain features that have since been shown to be incorrect. The non-genetic term Central Asian Orogenic Belt (CAOB) seems to be more appropriate and characterizes one of the largest accretionary terranes on Earth whose evolution has many similarities with the tectonics of the Indonesian Archipelago. In contrast to popular thinking, crustal growth in the CAOB during accretion was not anomalously high but was similar to that in the Palaeozoic Tasmanides of Australia and the Jurassic to Present evolution in southeastern Asia.

Eduard Suess erkannte die außergewöhnliche Größe und den internen tektonischen Aufbau der von ihm als Altaiden bezeichneten Gebirgsregionen Zentralasiens sowie deren wesentliche Unterschiede zu gebogenen Faltengebirgen wie Alpen und Ural. Allerdings erfasste er nicht dass sich dieses orogene Gebiet bzw. Provinz über einen Zeitraum von etwa 750 Ma entwickelte, vom späten Mesoproterozoikum (ca. 1000 Ma) bis ins späte Perm (ca. 260 Ma), dass es große Mengen an prä-orogener Kruste und viele synorogenen metamorphe Komplexe beinhaltet, und vergleichbare Strukturen zu modernen Falten- und Überschiebungsgürteln aufweist. Daher bevorzugen wir nicht den Namen Altaiden für diese große orogene Gebiet, einerseits da dieser Name mit dem Konzept eines im wesentlichen im Paläozoikum entstandenen Gebirges verbunden ist, andererseits da sich auch andere abweichende Charakteristika herausgestellt haben. Der nicht-genetische Begriff Zentralasiatischer Orogengürtel (Central Asian Orogenic Belt, CAOB) scheint daher besser passend, und charakterisiert eines der größtes Akkretionsterrane der Welt, dessen Entwicklung viele Ähnlichkeiten mit der tektonischen Geschichte des Indonesischen Archipels hat. Im Gegensatz zu gängigen Anschauungen ist das Krustenwachstum durch Akkretion im CAOB nicht außergewöhnlich hoch sondern war gleich jenem der paläozoischen Tasmaniden Australiens und der jurassisch bis heutigen Entwicklung im südöstlichen Asien.

1. Introduction

The term Altaids, named after the Altai Mountains in northwest China, western Mongolia, southern Siberia and northeastern Kazakhstan, was coined by Eduard Suess in 1901 to describe the mountain ranges south of the Siberian craton (platform) and east of the Ural Mountains (Fig. 1). Geological aspects of the Altai Mountains and much of Central Asia were earlier described by Alexander von Humboldt in his famous “Fragments of the geology and climatology of Asia“ (1843, in French) that resulted from a 16,000 km expedition from the Urals to the Chinese border. Von Humboldt recognized an Altai System, consisting of several mountain ranges in southern Siberia and Mongolia, but he separated these ranges from the Tianshan and other mountain chains in Central Asia and the intervening steppe basins. He observed that low-grade metasediments (“thonschiefer“) constitute the largest part of the Altai Mountains, but that gneisses occur in the south, and that eruptive rocks such as diorites, granites, and porphyries only played a secondary role and intruded into the „thonschiefer“ causing contact metamorphism.

As pointed out by Sengör and Natalin (2007), Suess (1901) noted that this wide mountain belt appeared different from the classical orogenic belts, explained in those days by the geosynclinal theory. It was non-linear and, in Suess’ view, predominantly contained relatively low-grade Palaeozoic rocks whereas “classical“ Alpine-type orogenic belts were relatively narrow and contained large proportions of high-grade gneisses. He also noted the ubiquitous steepness of bedding and schistosity in many rocks that was different to the structures in classical fold belts.

More than 100 years have passed since Suess noted this fundamental difference in the tectonic evolution between Central Asia and many other mountain belts and, in plate tectonic terms, these differences can now be explained as the result of two different orogenic processes, namely collisional orogeny and accretionary orogeny (Cawood et al., 2009). Suess (1901, 1908), followed by Sengör et al. (1993), considered that the Altaids primarily consisted of Palaeozoic rocks; however, we now know that the evolution of Central Asia begun in the latest Mesoproterozoic as documented by the oldest ophiolitic sequences in southern Siberia (Khain et al., 2002; Rytsk et al., 2011).

Also contrary to the observations of Suess (1901, 1908) there is a considerable volume of high-grade metamorphic rocks in Central Asia. Most of these assemblages were previously considered to constitute a Precambrian basement (e.g., Badarch et al., 2002; Dobretsov et al., 1995; Zonenshain et al., 1990), but many have since been shown to be of early Palaeozoic age, metamorphosed shortly after their formation (see below). Good examples are the amphibolite- to granulite-facies gneisses in the Lake Baikal region known as the Olkhon terrane (Gladkochub et al., 2008), metamorphic core complexes such as the Malkhan complex in the western Transbaikal region (Rytsk et al., 2011), and a high-grade gneiss belt extending from southwestern Mongolia to the Chinese Altai (Kozakov et al., 2002a; Sun et al., 2008; Jiang et al., 2012). Rocks metamorphosed up to granulite-facies and previously considered to be Archaean to Palaeoproterozoic in age also occur in several blocks in northeastern China and were shown to be derived from early Palaeozoic granitoids and pelitic metasediments (see Wilde et al., 2010, for discussion). Early Palaeozoic high-pressure metamorphic rocks associated with eclogites and subduction complexes have been recognized in southern Mongolia (Stipská et al., 2013), and in the Kyrgyz Tienshan (Kröner et al., 2012a; Rojas-Agramonte et al., 2013). Suess' impression that bedding, schistosity and foliation are generally steep can also not be generalized because there are numerous domains with flat structures, and structural analysis showed these to be parts of thrust-and-fold belts such as the Olkhon terrane around Lake Baikal (Gladkochub et al., 2008, 2010), parts of southern Mongolia (Lehmann et al., 2010), the Beishan orogen in northwestern China (Cleven et al., 2014; see Fig. 2), parts of central Kazakhstan (Degtyarev, 2011), and the spectacular thrusts in the Kyrgyz South Tianshan (Biske and Seltmann, 2010; see Fig. 3).

Safonova and Santosh (2014) listed numerous locations in the Palaeozoic domains of Central Asia containing thrust packages, including ocean island and ophiolitic components, that they interpreted as Japan-type accretionary complexes. Some of the original flat structures were later steepened towards the end of the Palaeozoic orogeny, as shown by Guy et al. (2014) in several areas of southwestern Mongolia (Fig. 4), when the last remnants of the Palaeo-Asian Ocean were closed and the North China and Tarim cratons collided with the large domain that had accreted south of the Siberian craton.

When Sengör et al. (1993) published their benchmark paper on the Palaeozoic evolution of Central Asia they adopted the name Altaids, as originally proposed by Suess (1901), and associated this name with two important features that have been a matter of considerable discussion for the last 20 years. The first is the proposal that the entire Palaeozoic domain of Central Asia evolved from one single giant island arc, the Kipchak-Tuva-Mongol arc, that formed outboard of a large continental mass, the combined cratons of Siberia and Baltica. When the paper by Sengör et al. (1993) was published, palaeomagnetic data available for Siberia and Baltica were inconclusive as to their precise Neoproterozoic to early Palaeozoic palaeogeographic positions. By 2007 the palaeomagnetic database had improved considerably (Windley et al., 2007) and showed that at 550–535 Ma the margins of Baltica and Siberia were separated by a major ocean that

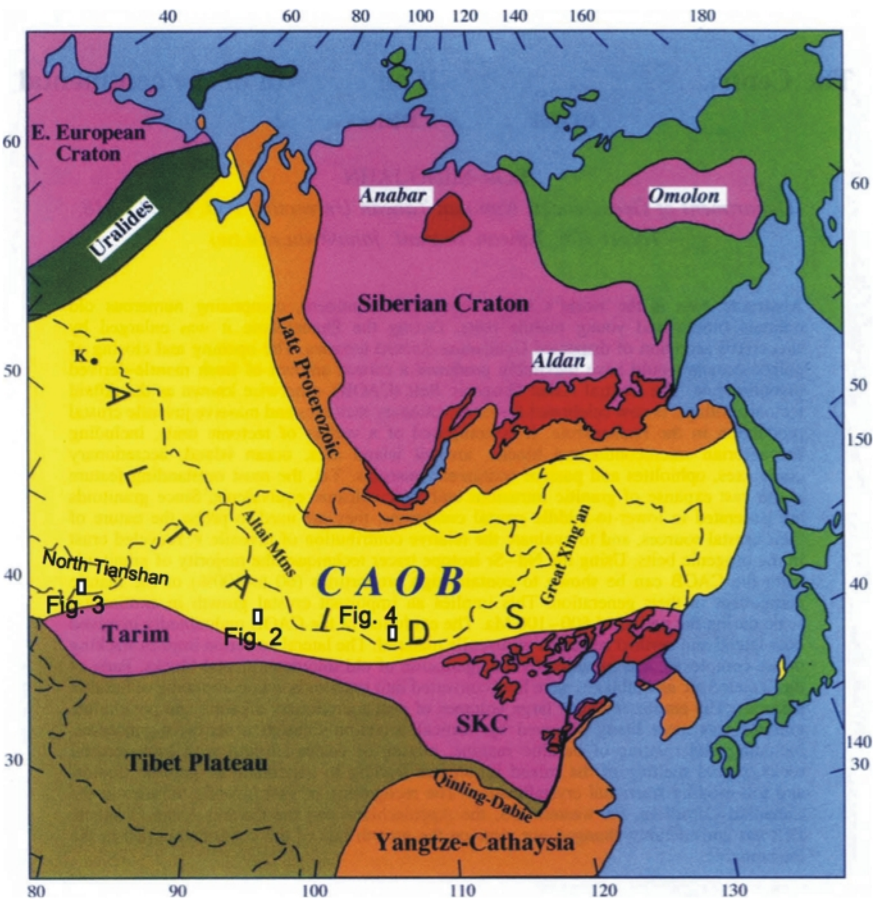

Figure 1: Schematic map of the Central Asian Orogenic belt showing the domains with predominantly Neoproterozoic rocks (light brown; Baikalides in much of the Russian literature) and Palaeozoic as well as younger assemblages (yellow; Caledonian and Hercynian in much of the Russian and Chinese literature). Reproduced from Jahn (2004). SKC = Sino-Korean Craton. The approximate locations of Figs. 2 to 4 are indicated.

occupied 20–30° of palaeolatitude or more (see Cocks and Torsvik, 2005). In discussing this palaeogeography, Windley et al. (2007) included palaeontological data from which McKerrow et al. (1992) had already concluded that Siberia and Baltica were separated in the early Cambrian by a ca. 1500 km wide ocean. Pisarevsky et al. (2008) confirmed this view, and in their reconstruction Baltica and Siberia were far apart at this time, as also shown in the compilations of Meert and Lieberman (2008) and Fedorova et al. (2013). Thus it appears very unlikely that an arc system could have evolved as envisioned by Sengör et al. (1993).

The second assumption of Sengör et al. (1993) was that most Palaeozoic magmatic rocks of Central Asia, having evolved from an intraoceanic arc system, are the result of subduction processes and are thus primitive in origin, leading to the conclusion that Central Asia was the location of anomalously high crust-production. This idea was taken up by Jahn et al. (2000a, b) and Jahn (2004), who concluded on the basis of Nd and Sr isotopic data of late Palaeozoic and Mesozoic granitoids that Central Asia reflected the highest crustal growth rate on Earth in the Phanerozoic. Thus, the name Altaids is closely associated with the concept of the Kipchak arc and unusually high crustal growth.

However, these two ideas of Sengör et al. (1993) have since been shown to be incorrect or have now be superseded on the basis of new data. First, it is now clear from field mapping and a large number of reliable geochronological data that there was no single arc system but that many Neoproterozoic to Palaeozoic terranes of Central Asia are individual arc terranes ranging in age from early Neoproterozoic to the late Carbonifereous (see Windley et al., 2007; Kröner et al., 2014 and references therein). Second, the idea of unusually high crustal growth is in conflict with increasing evidence for the existence of considerable volumes of pre-orogenic continental crust (basement blocks) and the generation of many arc rocks involved melting of this older basement (see Kovach et al., 2011; Kröner et al., 2014 and references therein). In view of the above we feel that the name Altaids is too strongly associated with the previous considerations that have now been shown to be incorrect, and we therefore favour the name Central Asian Orogenic Belt (CAOB). This term goes back to Yanshin (1965) and the Tectonic Map of Eurasia, including the explanatory notes (Yanshin, 1966). Since then the term CAOB has been widely used because it is not model-oriented or model-dependent and encompasses the entire evolution of this large accretionary orogenic system from the latest Mesoproterozoic to the late Palaeozoic. In the following we show that several of the original assumptions of Suess (1901) and Sengör et al. (1993) were incorrect and that the CAOB has ist best modern analogue in the evolution of the Indonesian archipelago.

2. Early evolution of the CAOB in the latest Mesoproterozoic and Neoproterozoic

Following Suess (1901, 1908) and many other authors in later years, the Altaids were interpreted as a Palaeozoic orogenic belt, subdivided into an early Palaeozoic part (Caledonian in the Russian literature; e.g., Degtyarev, 2011; Kozakov et al., 2011) and late Palaeozoic part (Hercynian in the Russian literature; e.g., Pavlovasky, 1948; Kovalenko et al., 1995). This subdivision is still in use today (e.g., Kozakov et al., 2013). The earlier, predominantly Neoproterozoic (Fig. 1), evolution was interpreted as a separate orogenic event, named Baikalian by Shatsky (1932). However, Obruchev (1949) had shown that there was not only one main orogenic event in the Neoproterozoic but several events that extended into the early Palaeozoic as revealed in the Saian-Baikal area. This observation led Zonenshain (1972) to consider the “Baikalides“ as part of what was then widely described in the Russian litera-

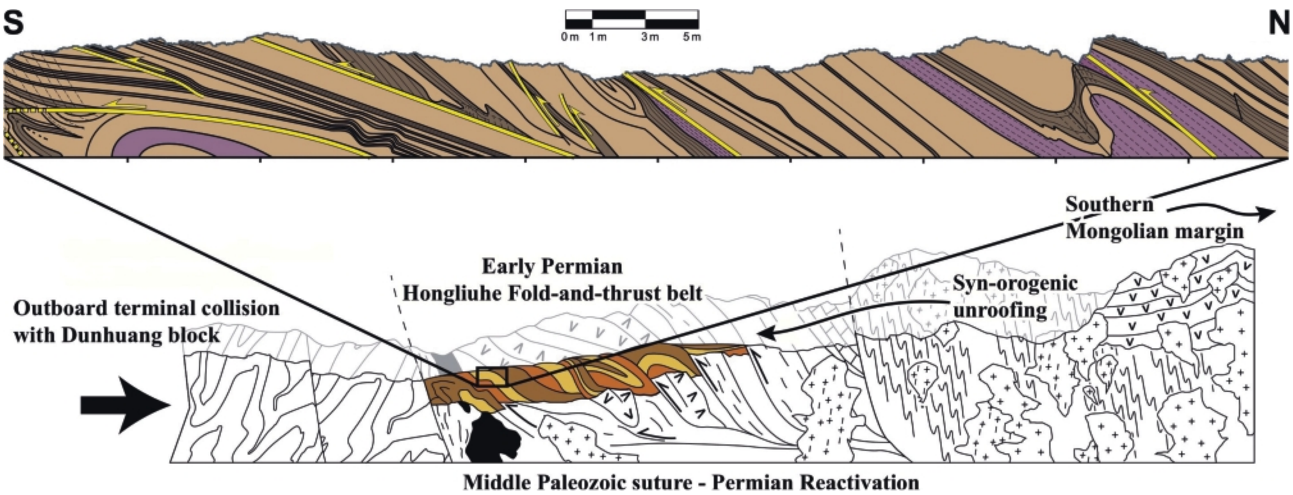

Figure 2: Schematic cross section of the early Permian Hongliuhe fold-and-thrust belt in the Beishan orogen of Gansu Province, NW China (Cleven et al., 2014), resulting from collision of the Tarim craton with the southern accretionary margin of the CAOB. Colour code: Brown = sandstone; olive = laminated sandy siltstone; purple = silty mudstone; yellow = thrust faults with movement direction, stippled parts inferred. Lower cartoon not to scale but several km long.

ture as the Ural-Mongolian fold belt. Berlichenko (1977) also considered the Baikalides as part of an orogenic system that continued into the Palaeozoic, and Khain (1979) followed this view, suggesting that geosynclines in Central Asia began to evolve in the middle and late Riphean. Dergunov (1989) also considered the Neoproterozoic rocks of Central Asia to be part of the Ural-Mongol belt and mainly used extensive carbonate sequences for this correlation. Kuzmichev (2004) and Rytsk et al. (2007a, 2011) provided detailed evidence for what they named early and late Baikalian events, including several island arc systems, and also interpreted these as part of the orogenic evolution in the evolving Palaeo-Asian Ocean (PAO). Finally, Yarmolyuk et al. (2013) again emphasized the continuous Vendian to Cambrian evolution in their summary of the geology of Central Asia It is surprising that Sengör et al. (1993) and Wilhem et al. (2012) did not discuss this issue but reverted back to Suess‘ definition of the Altaids.

Khain et al. (2002) were the first to provide geochronological evidence for latest Mesoproterozoic ocean opening of the PAO on the southern margin of the Siberian craton (present coordinates) in describing and dating the tectonically dismembered Dunzhugur ophiolite in East Sayan at 1020±0.7 Ma. This ophiolite is associated with an island arc of the same name whose antiquity was recently confirmed by zircon ages of 1048±12 and 1034±9 Ma (Kuzmichev and Larionov, 2013). Another ophiolitic complex, the Nurundukan suite in the Baikal-Muya fold belt at the northeastern end of Lake Baikal (Fig. 5), has an imprecise Sm-Nd isochron age of 1035±92 Ma (Rytsk et al., 1999). These two ophiolite sequences show that the southern margin of Siberia was already bordered by an open ocean in the latest Mesoproterozoic, and this was followed, in the early Neoproterozoic, by accretion of the first island arc assemblages onto the then active margin of the Siberian craton (Khain et al., 2002; Rytsk et al., 2011; Gordienko et al., 2010; Kuzmichev and Larionov, 2013). A well developed accretionary prism, compared with the Shimanto belt in Japan (Kuzmichev et al., 2007), is associated with the Shishkid island arc that is exposed in the border area between northern Mongolia and East Sayan in Russian Siberia (Fig. 5) and was dated at 775–819 Ma (Kuzmichev and Larionov, 2013). Further evidence for successive accretion onto the Siberian margin, from south to north, of island arc assemblages and ophiolitic complexes is provided by detailed mapping and geochronology (Rytsk et al., 2007b, 2013; Kozakov et al., 2013; Kovach et al., 2013; Gladkochub et al., 2013; Kuzmichev et al., 2001, 2005, 2007; Kröner et al., 2007). For example, Gladkochub et al. (2008, 2010, 2013) have shown that the Neoproterozoic island arcs and microcontinental fragments along the southern margin of the Siberian craton had already been amalgamated and collided with the Siberian craton during the

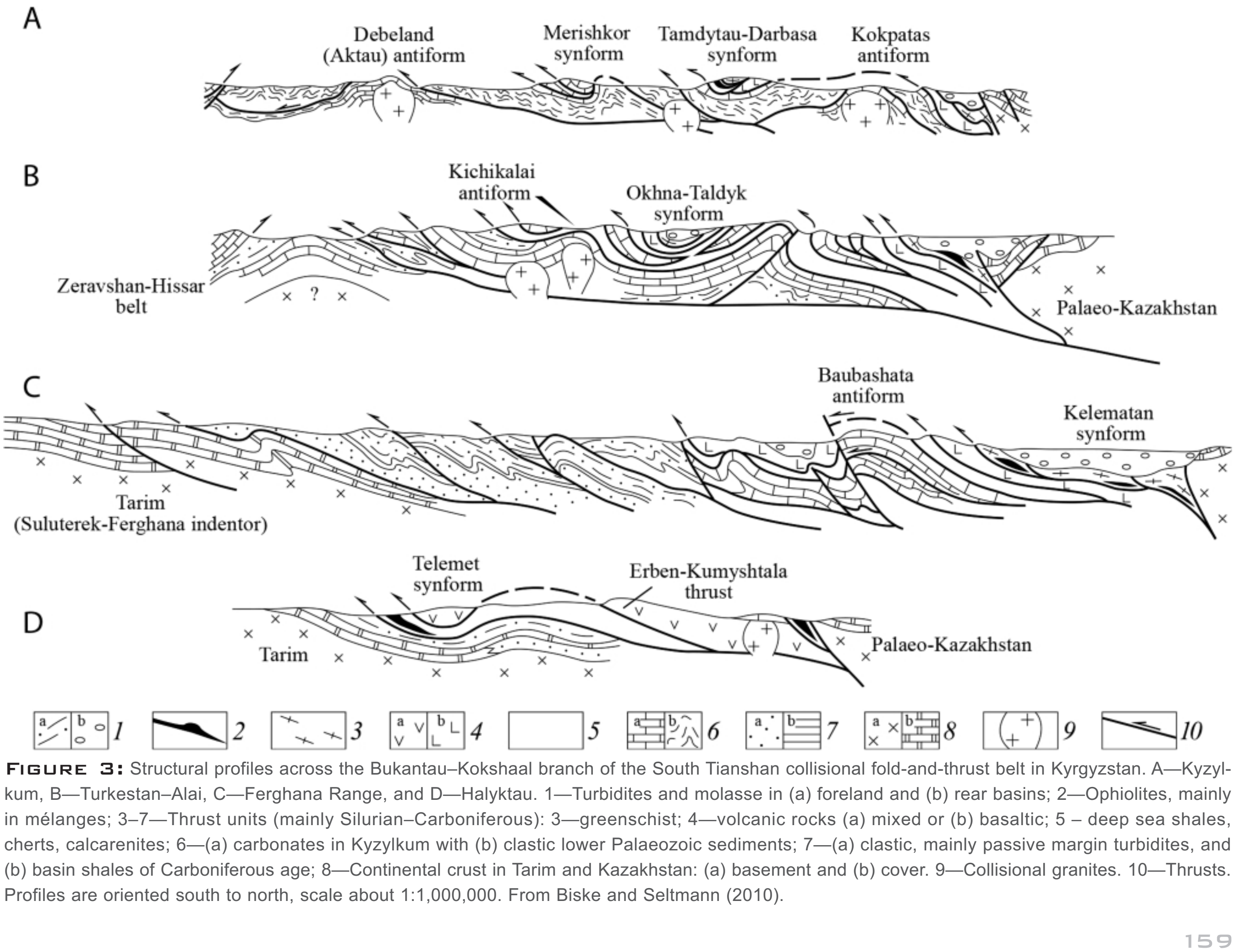

Figure 3: Structural profiles across the Bukantau–Kokshaal branch of the South Tianshan collisional fold-and-thrust belt in Kyrgyzstan. A—Kyzylkum, B—Turkestan–Alai, C—Ferghana Range, and D—Halyktau. 1—Turbidites and molasse in (a) foreland and (b) rear basins; 2—Ophiolites, mainly in mélanges; 3–7—Thrust units (mainly Silurian–Carboniferous): 3—greenschist; 4—volcanic rocks (a) mixed or (b) basaltic; 5 – deep sea shales, cherts, calcarenites; 6—(a) carbonates in Kyzylkum with (b) clastic lower Palaeozoic sediments; 7—(a) clastic, mainly passive margin turbidites, and (b) basin shales of Carboniferous age; 8—Continental crust in Tarim and Kazakhstan: (a) basement and (b) cover. 9—Collisional granites. 10—Thrusts. Profiles are oriented south to north, scale about 1:1,000,000. From Biske and Seltmann (2010).

early Palaeozoic, producing high-grade metamorphic assemblages in what these authors named the Baikal collisional belt. Such a scenario is supported by palaeomagnetic data that suggest that the active margin of southern Siberia in the Neoproterozoic to Cambrian was similar to the present SW Pacific (Metelkin, 2013).

3. Presence of pre-orogenic (pre-1000 Ma) continental crust

There is a considerable volume of mostly metamorphic, exposed pre-orogenic Precambrian basement in the CAOB much of which was not recognized in the early years of exploration in Central Asia. Large fragments are the Tuva-Mongolian, Dzabkhan, Tarbagatai, and Gargan Blocks in northwestern Mongolia and neighbouring Tuva (Kozakov et al., 2007; 2011), the Ishim-Middle Tianshan block extending from the Kokchetav area in northern Kazakhstan (Letnikov et al., 2007; Turkina et al., 2011; Glorie et al., 2014) to the Middle Tianshan in Kyrgyzstan (Windley et al., 2007), the Aktau-Dzhungar Massif in central Kazakhstan (Degtyarev et al., 2008), and the Aktau-Junggar block in eastern Kazakhstan and northwestern Xinjiang Province of China where it is considered as part of the Chinese North Tianshan (Wang et al., 2012). In addition, there are numerous smaller fragments that are sandwiched between the Palaeozoic arc terranes and often became refoliated and retrogressed during the accretionary history, making them difficult to identify in the field (e.g., Demoux et al., 2009a; Kröner et al., 2013).

Further evidence for the presence of pre-orogenic basement beneath many of the early Palaeozoic arc terranes in the CAOB is provided by isotopic data, in particular whole-rock Nd and Hf-in-zircon isotopic systematics, reflected by negative $\varepsilon_{Nd(t)}$ and $\varepsilon_{Hf(t)}$ values in arc volcanic rocks. This is particularly evident in the Tianshan of Kyrgyzstan and NW China. Most of the Kyrgyz North and Middle Tianshan are underlain by late Mesoproterozoic (Grenville-age) to Palaeoproterozoic basement from which early Palaeozoic granitoids were derived through custal melting (Kröner et al., 2012a, 2013). A similar conclusion was reached for the Chinese Central Tianshan (Ma et al., 2012a, b), and for granitoid rocks in the northeastern CAOB (Wu et al., 2000). Melting of Mesoproterozoic crust has also been inferred from Nd isotopes in the Chinese Altai (Wang et al., 2009). The presence of Archaean to Neproterozoic components in parts of the CAOB subcrustal mantle lithosphere as evidenced by Os isotopic data from mantle xenoliths in Quaternary basalts provides further evidence for old material in the region (Wang et al., 2013). Kröner et al. (2014) concluded from the growing evidence for the existence of pre-orogenic basement in the CAOB that crustal growth in the early Palaeozoic was not as high as previously estimated.

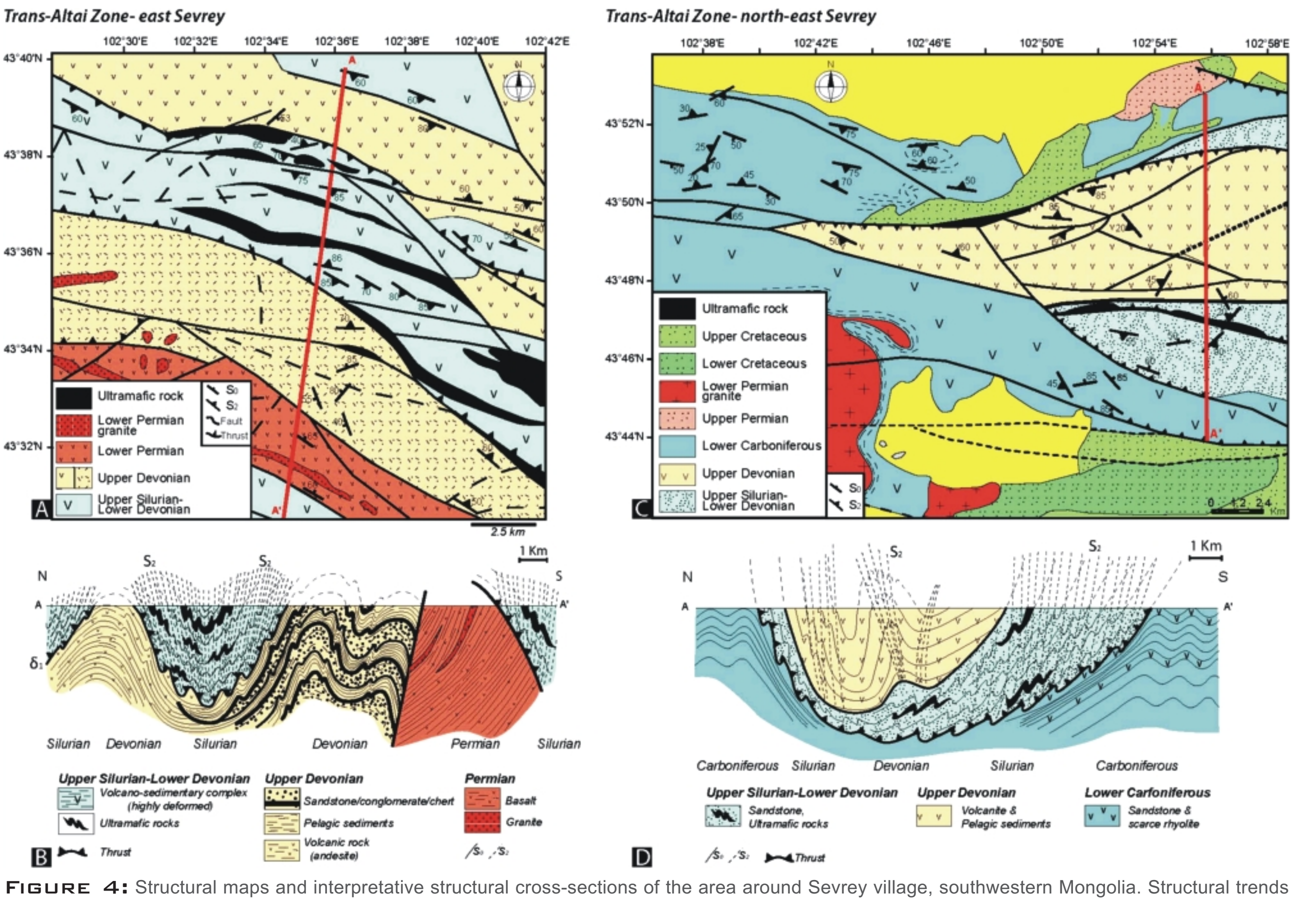

Figure 4: Structural maps and interpretative structural cross-sections of the area around Sevrey village, southwestern Mongolia. Structural trends indicate extrapolations of major orientations of structural foliations measured in the field. Red lines are the locations of the cross-sections. Reproduced from Guy et al. (2014).

4. Synorogenic metamorphic assemblages in the CAOB

Modern geochronology has shown that many metamorphic rocks of low to high metamorphic grade, previously interpreted as Archaean to Palaeoproterozoic, were generated during distinct Neoproterozoic to early Palaeozoic events related to accretion and collision. Well documented examples are the Lake Zone in Mongolia (see Fig. 5) (Kozakov et al., 2002a, b; Volkova and Sklyarov, 2007; Demoux et al., 2009b; Stipska et al., 2010; Jiang et al., 2012; Burenjargal et al., 2012), the Chinese Altai (Sun et al., 2008), southern and eastern Siberia (Gladkochub et al., 2010; Kovach et al., 2013; see "mobile belts" in Fig. 5), the Kyrgyz Tianshan (Kröner et al., 2012a; Rojas-Agramonte et al., 2013) and eastern Kazakhstan (Volkova and Sklyarov, 2007). Some authors have attributed this metamorphism to ocean-ridge subduction (e.g., Jian et al., 2008; Sun et al., 2009; Wilhem et al., 2012), but this cannot be verified through field relationships. There is little doubt that early Palaeozoic high-pressure metamorphic assemblages including eclogites, blueschists as well as diamond- and coesite-bearing gneisses are the result of tectonically emplaced components of subduction zones, possible marking sutures and terrane boundaries (Hacker et al., 2003; Volkova and Sklyarov, 2007; Stipská et al., 2010; Klemd et al., 2011; Rojas-Agramonte et al., 2013). The relatively large region (several hundred square kilometres) of high-grade early Palaeozoic gneisses in the Lake Baikal area was interpreted to have resulted from accretion and collision of arc assemblages with the margin of the Siberian craton (Gladkochub et al., 2010). Thus, the observation of Suess (1901, 1908) that the mountain ranges east of the West Siberian plains were mostly composed of low-grade sedimentary rocks and granites is not supported by modern investigations (Buslov et al., 2001; Kuzmichev and Larionov, 2013).

5. Interpretation of zircon ages and the Nd-Hf isotopic record

Analytical equipment such as high-resolution ion microprobes and laser-ablation inductively-coupled plasma mass spectrometers have made it possible to date grain domains in zircon and other U-bearing minerals, and this has led to an ever growing number of reliable ages for rocks of the CAOB. In particular there are now thousands of detrital zircon ages that add significantly to our understanding of geodynamic processes in Central Asia. In addition, the combination of zircon U-Pb dating with Sm-Nd and Lu-Hf isotopic characteristics makes it possible to reconstruct the petrogenetic history of many magmatic rocks, in particular granitoids, and this has provided new data on the nature of rocks that were involved in the melting (e.g., Sun et al., 2008; Kovach et al., 2011; Kröner et al., 2014).

In the intra-oceanic, single-arc model for the Palaeozoic evolution of Central Asia of Sengör et al. (1993), most magmatic rocks were inferred to be juvenile in nature, having been formed by partial melting of mantle sources during subduction

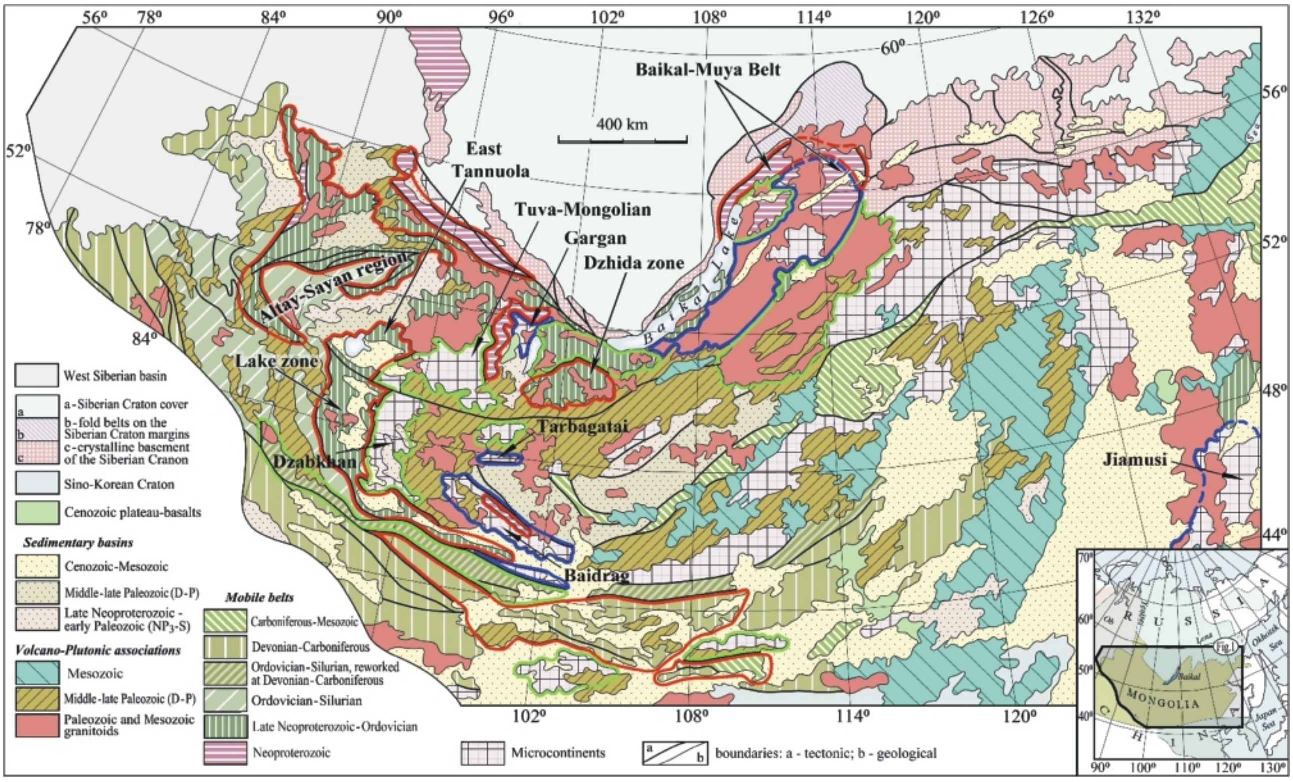

Figure 5: Simplified geological map of the northeastern part of the CAOB, reproduced from Kröner et al. (2014) and based on Kovach et al. (2013). Red heavy lines encircle fields of predominantly juvenile crust, blue lines denote predominant areas of crustal reworking, green lines denote areas of mixed crust. Precambrian microcontinental terranes are cross-hatched. For detailed explanation see Kröner et al. (2014). Areas showing strong early to late Palaeozoic deformation and metamorphism are designated as "mobile belts".

processes. This has resulted in the widespread and often cited belief that Central Asia represents the region with the highest global crust-production rate in the Phanerozoic (e.g., Jahn, 2004). However, zircon geochronology, in-situ Hf, and whole-rock Nd isotopic data for Neoproterozoic to early Palaeozoic granitoid rocks in the CAOB show that much of this growth did not occur during the accretionary history of this belt. As discussed in Kröner et al. (2014), many Mesoproterozoic to Archaean detrital zircons in metasediments and xenocrystic zircons in early Palaeozoic magmatic rocks of Mongolia and many other parts of the central and western CAOB indicate significant melting of older continental crust in the generation of these assemblages. Zhou et al. (2012, 2013) reported similar data for the northeastern CAOB. The age patterns shown by these data are unlike those for rocks of the Siberian craton, in particular a persistent age peak suggesting a Grenville-age source is evident. This led Rojas-Agramonte et al. (2011, 2014), Han et al. (2011) and Ma et al. (2012b) to suggest the Tarim craton as the most likely source for many of the Precambrian crustal fragments and detrital zircons. These authors suggested a tectonic scenario for the PAO where fragments of continental material were rifted off the northeastern margin of Gondwana (present coordinates, see Metcalfe, 2011; Burrett et al., 2014) and became incorporated in an evolving archipelago that may have looked similar to the islands in the present southwestern Pacific Ocean. The similarity of this model with the Mesozoic to present-day evolution of Indonesia is discussed below.

There is no doubt that several terranes in the CAOB seem to reflect an intra-oceanic evolution such as shown by isotopic data for rocks in central and eastern Kazakhstan, southern and western Mongolia, and the western Chinese Altai (see Kröner et al., 2014 for discussion). However, many Neoproterozoic and Palaeozoic arc complexes in the CAOB were built on older continental crust as shown by their Nd and Hf isotopic signatures, implying Andean- or Japan-type settings (e.g., Jahn, 2010). This is in line with the suggestion of Condie and Kröner (2013) that such arcs played a major role in continental evolution through geologic time. Subduction and ocean closure eventually led to arc and microcontinent amalgamation in Central Asia that ended when the oceanic domains vanished in the early Permian through collision of the accreted terranes with the North China and Tarim cratons to form a broad orogenic belt (Dobretsov and Buslov, 2007; Windley et al., 2007, Kröner et al., 2007, 2014). In summary, the isotopic record does not support an unusually high crust-production rate in the CAOB. Its evolution may have been similar to the southern Tasmanides of Australia where growth of this classical series of accretionary orogens, adding ~30 % of the area of Australia from 830 until 340 Ma, proceeded largely without the addition of new juvenile material (Glen, 2013).

6. Comparison with the Indonesian archipelago

There have been many comparisons of the CAOB evolution with the southwest Pacific, specifically the Indonesian Archipelago, and this was discussed extensively during a recent Penrose Conference (Schulmann and Paterson, 2011; Kröner et al., 2012b). The similarity is particularly striking in view of new findings that most of Indonesia is underlain by crustal fragments rifted off northern Gondwana, in particular northern Australia since the Jurassic, and there are only few areas that have no continental crust at depth (Hall and Sevastjanova, 2012).

As summarized above, much of Central Asia is also underlain by crust rifted off the northern margin of Gondwana, in particular the Tarim craton, and there are only few areas such as central and northeastern Kazakhstan and the Chinese Altai where the isotopic data suggest substantial volumes of early Palaeozoic juvenile crust (Kröner et al., 2014).

Some terranes in the CAOB seem to record significant changes in their tectonic setting during evolution of the CAOB, i.e. they contain magmatic assemblages recording both crustal reworking and juvenile additions, probably as a result of changing palaeogeography and plate geometry, similar to the evolution of the SW Pacific as shown in the computer-based reconstructions of Hall (2002). The field and isotopic data are therefore compatible with evolution of the CAOB in an archipelago-type Palaeo-Asian Ocean in which magmatic rocks were generated in intra-oceanic as well as continental margin tectonic settings, and where "soft" collisions occurred between arc and microcontinental terranes. Much of the original palaeogeography and structural configuration in Central Asia in the Neoproterozoic to early Palaeozoic cannot be reconstructed with confidence, in particular because of ubiquitous terrane rotations as documented by palaeomagnetic data (Alexjutin et al., 2005; Van der Voo et al., 2006) and the final collisional event in the Permian, ending orogeny and causing most structures to become overprinted and rotated in an E-W direction, accompanied by extensive strike-slip deformation. The same can be expected when Australia finally collides with SE Asia.

7. Conclusions

In a long essay to support the name "Altaids", Sengör and Natalin (2007) wrote: "In the name Altaids, an entire manner of looking at tectonic evolution is encapsulated. That has been our sole reason for insisting that the Altaids are called by their proper name, first given to them by Eduard Suess in 1901". However, we disagree with this conclusion since Suess did not recognize many of the distinctive features of the CAOB such as its unusually long evolution, the presence of significant volumes of pre-orogenic crust and synorogenic metamorphic assemblages, flat structures resulting from thrust stacking, and obvious younging of rocks from north to south, supporting successive accretion of terranes onto the Siberian craton margin throughout the Neoproterozoic and Palaeozoic. However, we agree with Sengör and Natalin (2007) that Suess was the first to recognize that only when viewed in its entirety does the structural evolution of the many mountain ranges making up the vast orogenic domain of Central Asia make sense. Thus, in recognizing that this was different from the generally long and linear fold belts such as the Alps and Urals, he was the first to describe an accretionary orogen but in terms of the prevailing geosynclinal concept of his time he could not fully understand ist evolution.

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