# A Tale of Amalgamation of Three Permo-Triassic Collage Systems in Central Asia: Oroclines, Sutures, and Terminal Accretion

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paleogeographic separation, palinspastic reconstructions, subduction complex

## Abstract

The Central Asian Orogenic Belt records the accretion and convergence of three collage systems that were finally rotated into two major oroclines. The Mongolia collage system was a long, N–S-oriented composite ribbon that was rotated to its current orientation when the Mongol-Okhotsk orocline was formed. The components of the Kazakhstan collage system were welded together into a long, single composite arc that was bent to form the Kazakhstan orocline. The cratons of Tarim and North China were united and sutured by the Beishan orogen, which terminated with formation of the Solonker suture in northern China. All components of the three collage systems were generated by the Neoproterozoic and were amalgamated in the Permo-Triassic. The Central Asian Orogenic Belt evolved by multiple convergence and accretion of many orogenic components during multiple phases of amalgamation, followed by two phases of orocline rotation.

## INTRODUCTION

According to the current plate tectonic paradigm, orogenesis takes place either during accretion at a subducting continental margin (Maruyama et al. 2009, Wakita & Metcalfe 2005, Wakita et al. 2013)—variably termed Pacific-type (Maruyama 1997), Turkic-type (Şengör & Natal'in 1996b), Altaid-type (Şengör & Natal'in 1996a), or, more widely, accretionary-type (Cawood & Buchan 2007, Jian et al. 2014, Kröner et al. 2007, Li et al. 2013, Safonova & Santosh 2014, Windley et al. 2007, Xiao & Santosh 2014, Xu et al. 2013b)—or as a result of continent-continent collision, which is largely a destructive process (Yin & Harrison 2000). However, the process of accretionary orogenesis includes several unresolved questions, such as the duration and architecture of the orogenesis. Some orogens, such as the Caledonian-Appalachian, have a short duration (Dewey 2005, van Staal et al. 1998), whereas others, such as the Central Asian Orogenic Belt and those in South America, are long-lived (Dalziel et al. 2000, Windley et al. 2007). The architectural framework of accretionary orogens may vary from multiple blocks (Levashova et al. 2011; van Staal et al. 1998; Xiao et al. 2004a,b, 2008, 2010a,b,c) to long, linear belts duplicated by slicing and bending (Şengör et al. 1993, Yakubchuk 2004).

The Altaids of Central and East Asia (**Figure 1**) were defined by Şengör et al. (1993) as an accretionary orogen that extends from the southern side (present coordinates) of the Uralide and Baykalide orogens southward to the Solonker suture in northern China (**Figure 1**). Much subsequent work by the international community has established that the Uralide and Baykalide orogens also formed by comparable accretionary processes and in fact constitute the northernmost part of the entire orogen (Khain et al. 2002; Kheraskova et al. 2003, 2010; Sklyarov et al. 2003). Thus, the term Altaids does not adequately describe the extent and duration of the orogen, and for this reason the now widely used term Central Asian Orogenic Belt was coined to encompass the extended orogen in time and space (He et al. 2013, Kheraskova et al. 2011, Seltmann & Porter 2005, Wakita et al. 2013, Windley et al. 2007, Xiao & Santosh 2014).

The Central Asian Orogenic Belt is one of the largest and longest-lived accretionary orogenic collages in the world, with considerable Neoproterozoic and Phanerozoic crustal growth (Jahn et al. 2004, Zheng et al. 2013, Zhou et al. 2011). The formation of the two oroclines therefore had a profound effect on the duration and final architecture of the Central Asian Orogenic Belt. Although Şengör et al. (1993) and Şengör & Natal'in (1996a) outlined the two oroclines, neither they or any subsequent studies have documented and reviewed the processes and timing of their mutual amalgamation and their interactions with the evolving accretionary orogen. To redress this imbalance, we summarize in this article the relevant main tectonics of the Central Asian Orogenic Belt (**Figure 1**), its continuous accretion from the southern active margins of the Siberia and Baltica cratons, and the eventual formation of and interaction between the two oroclines, culminating in the terminal South Tianshan–Solonker suture in northern China.

## GEOLOGICAL BACKGROUND AND PREVIOUS REVIEWS

The Central Asian Orogenic Belt (also known as the modified Altaids) is situated between the Siberia and Baltica cratons to the north and the Tarim and North China cratons to the south (**Figure 1**). This immense area extends from the Urals in the west through Kazakhstan, northwest China, Mongolia, and northeast China to the Okhotsk Sea in the Russian Far East (Glorie et al. 2011, Han et al. 2011, Kröner et al. 2007, Windley et al. 2007, Xu et al. 2013a, Yakubchuk 2004, Zonenshain et al. 1990). Two contrasting models have dominated the discussion of the tectonic evolution of the orogen: (*a*) oroclinal bending and slicing of a single Kipchak-Tuva-Mongol arc (e.g., Şengör et al. 1993) and (*b*) accretion and collision of multiple small island arcs,

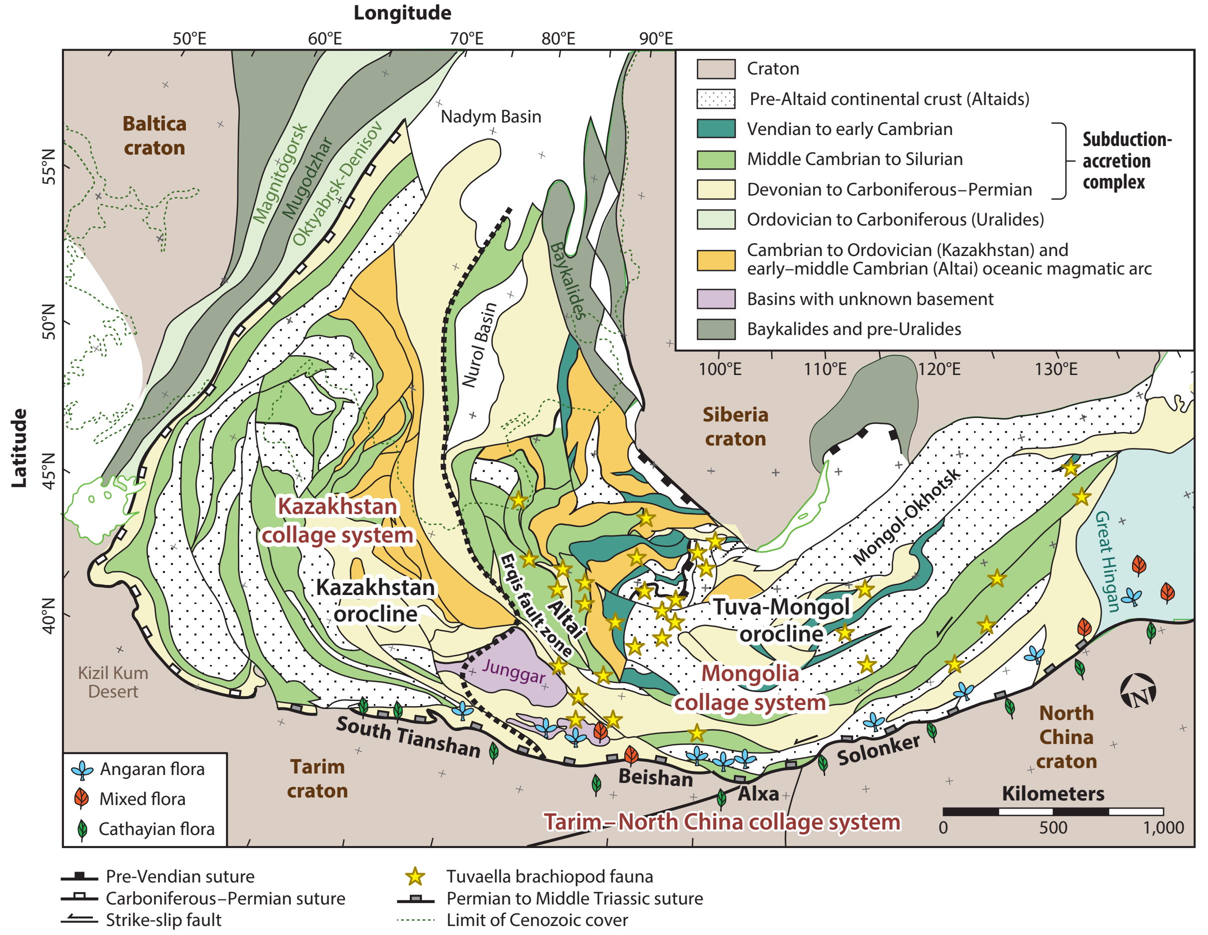
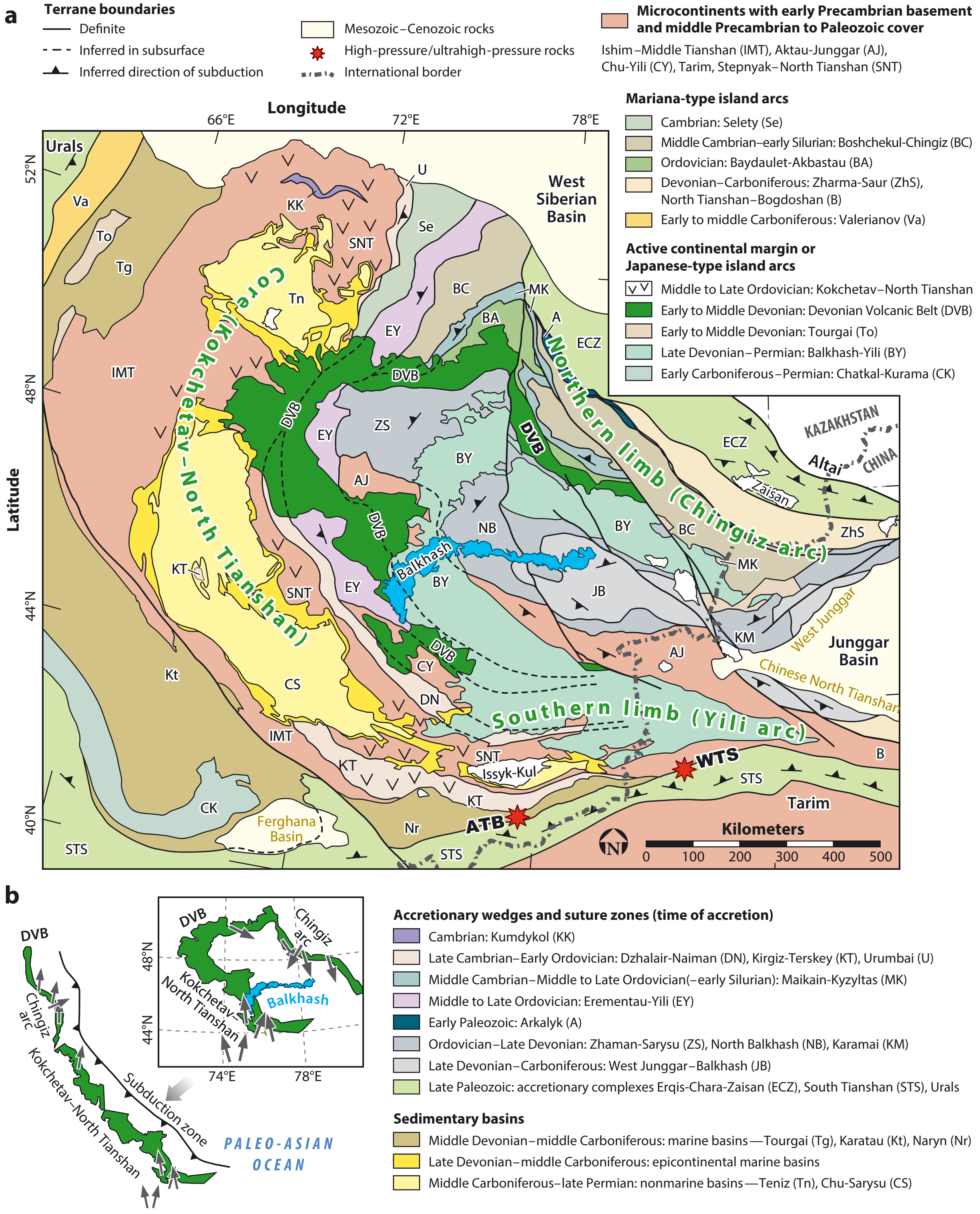


**Figure 1**

Tectonic map of the main components of the Central Asian Orogenic Belt, showing the Kazakhstan, Mongolia, and Tarim–North China collage systems, separated by a thick black dotted line, and the South Tianshan–Solonker suture. Tectonic elements are modified and simplified from Şengör & Natal'in (1996b). Yellow stars show the distribution of the Silurian Tuvaella brachiopod fauna (data points from Cocks & Torsvik 2007, Rong & Zhang 1982, Rong et al. 1995). The distribution of Permian flora is modified after Dewey et al. (1988) and Zhang et al. (2014).

microcontinents, and terranes (Kröner et al. 2007, Wakita et al. 2013, Wilhem et al. 2012, Windley et al. 2007, Yakubchuk 2004, Zonenshain et al. 1990).

Neither of these two models has been satisfactorily applied to the tectonics of the Central Asian Orogenic Belt. Recent paleomagnetic data (Bazhenov et al. 2012) show that the paleomagnetic declinations in different segments of a strongly curved, single Devonian Volcanic Belt (**Figure 2*a***), part of the Kipchak arc in Kazakhstan, would have unanimously pointed to a similar north direction if the curved belt was restored to a straight chain (**Figure 2*b***), which supports the single arc orocline hypothesis (Şengör et al. 1993). The fact that some microcontinents form the cores of some arcs, such as Kokchetav (Dobretsov et al. 2006, Masago et al. 2010), and that some terranes in Kazakhstan show a Gondwana affinity (Bazhenov et al. 2012) seems inconsistent with


a
Terrane boundaries
Definite
Inferred in subsurface
Inferred direction of subduction
Mesozoic–Cenozoic rocks
High-pressure/ultrahigh-pressure rocks
International border
Microcontinents with early Precambrian basement and middle Precambrian to Paleozoic cover
Ishim–Middle Tianshan (IMT), Aktau-Junggar (AJ), Chu-Yili (CY), Tarim, Stepnyak–North Tianshan (SNT)
Mariana-type island arcs
Cambrian: Selety (Se)
Middle Cambrian–early Silurian: Boshchekul-Chingiz (BC)
Ordovician: Baydaulet-Akbastau (BA)
Devonian–Carboniferous: Zharma-Saur (ZhS), North Tianshan–Bogdoshan (B)
Early to middle Carboniferous: Valerianov (Va)
Active continental margin or Japanese-type island arcs
Middle to Late Ordovician: Kokchetav–North Tianshan
Early to Middle Devonian: Devonian Volcanic Belt (DVB)
Early to Middle Devonian: Tourgai (To)
Late Devonian–Permian: Balkhash-Yili (BY)
Early Carboniferous–Permian: Chatkal-Kurama (CK)
Longitude
66°E
72°E
78°E
Latitude
52°N
48°N
44°N
40°N
Urals
Va
To
Tg
KK
U
Se
SNT
West Siberian Basin
Core (Kokchetav–North Tianshan)
Tn
BC
MK
BA
A
ECZ
EY
DVB
IMT
DVB
ZS
EY
Northern limb (Chingiz arc)
DVB
ECZ
KAZAKHSTAN
Altai
CHINA
Zaisan
AJ
BY
DVB
NB
BY
BC
ZhS
MK
Balkhash
BY
JB
KT
SNT
EY
West Junggar
Junggar Basin
KM
AJ
DVB
CY
Chinese North Tianshan
Kt
CS
DN
Southern limb (Yili arc)
IMT
KT
SNT
Issyk-Kul
WTS
STS
B
CK
KT
Tarim
Ferghana Basin
Nr
ATB
STS
STS
N
Kilometers
0 100 200 300 400 500
b
DVB
Chingiz arc
Kokchetav–North Tianshan
Subduction zone
PALEO-ASIAN OCEAN
DVB
Chingiz arc
Kokchetav North Tianshan
Balkhash
48°N
44°N
74°E
78°E
Accretionary wedges and suture zones (time of accretion)
Cambrian: Kumdykol (KK)
Late Cambrian–Early Ordovician: Dzhalair-Naiman (DN), Kirgiz-Terskey (KT), Urumbai (U)
Middle Cambrian–Middle to Late Ordovician(–early Silurian): Maikain-Kyzyltas (MK)
Middle to Late Ordovician: Erementau-Yili (EY)
Early Paleozoic: Arkalyk (A)
Ordovician–Late Devonian: Zhaman-Sarysu (ZS), North Balkhash (NB), Karamai (KM)
Late Devonian–Carboniferous: West Junggar–Balkhash (JB)
Late Paleozoic: accretionary complexes Erqis-Chara-Zaisan (ECZ), South Tianshan (STS), Urals
Sedimentary basins
Middle Devonian–middle Carboniferous: marine basins—Tourgai (Tg), Karatau (Kt), Naryn (Nr)
Late Devonian–middle Carboniferous: epicontinental marine basins
Middle Carboniferous–late Permian: nonmarine basins—Teniz (Tn), Chu-Sarysu (CS)

the single arc model in which the single Kipchak-Tuva-Mongol arc was rifted away from the joint Baltica-Siberia continent (Şengör et al. 1993).

Furthermore, several aspects of the geology of the accretionary orogen in China have been only partially considered. For example, the Tarim and North China cratons have been either regarded together as an integral block (Wilhem et al. 2012, Yin & Nie 1996) or treated as separate blocks with uncertain positions (Şengör et al. 1993). Also, in reconstruction by Cocks & Torsvik (2007), the Junggar terrane was integrated and combined with the Tarim craton; this is inconsistent with recent paleomagnetic, geological, and geochemical data, which indicate that they were independent terranes with oceans separating them (Choulet et al. 2012, Xiao et al. 2008, Yang et al. 2012a).

The many recent developments in fields such as structural relations, petrochemistry, and geochronology along with paleogeographic and palinspastic reconstructions based on paleomagnetic data on the Central Asian Orogenic Belt (de Jong et al. 2006, Domeier & Torsvik 2014, Guy et al. 2014, Li et al. 2014, Torsvik & Cocks 2013, Torsvik & Cocks 2004) have created a need to redefine the tectonic settings of the orogenic components. Accordingly, we can now better constrain the tectonic framework of the southern Central Asian Orogenic Belt, particularly in northern China and its adjacent areas.

## PALEOGEOGRAPHIC FRAMEWORK OF THREE COLLAGE SYSTEMS

It is widely accepted that the southern Central Asian Orogenic Belt is made up of widespread multiple archipelagos with arcs, microcontinents, ophiolites, subduction-accretion complexes, seamounts, blueschists, eclogites, and gneiss-schist complexes (Volkava & Budanov 1999, Yakubchuk 2004, Yang et al. 2012b). To facilitate description, we describe the Kazakhstan and Mongolian collage systems (**Figure 1**), which are founded on the Kazakhstan and Tuva-Mongol oroclines (**Figure 1**), and the Tarim–North China collage system, which incorporates the Tarim and North China cratons and the South Tianshan–Solonker suture (**Figure 1**). Before coming to the collage systems, we first present an evaluation of current paleomagnetic and flora-fauna data in terms of the paleogeography of the Central Asian Orogenic Belt.

### Neoproterozoic to Early Paleozoic Paleogeographic Framework

The outboard cratons of the Altaids are Siberia and Baltica in the north and Tarim and North China in the south, together with the minor, southern Dunhuang and Alxa blocks (**Figure 1**). The distribution of these cratons and the geological history of their margins provide key constraints on the early and late tectonic stages of the Central Asian Orogenic Belt.

Paleomagnetic data suggest that, in the late Precambrian, Siberia faced northward on its Baikal margin (Kheraskova et al. 2003), a paleogeography that differs from its present-day geography and may have endured into the early Paleozoic (**Figure 3**). Based on the best available paleomagnetic

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**Figure 2**

(*a*) Geological map of the Kazakhstan part of the Western Altaids, showing the Kazakhstan orocline. Panel modified after Windley et al. (2007). (*b*) Diagrams illustrating the declinations (*gray arrows*) of the primary Silurian and Devonian magnetizations for the inferred Middle Devonian configuration of the Devonian Volcanic Belt before oroclinal bending began. The inset shows a configuration prior to the distributed rotations that occurred later—i.e., in Permo-Triassic time. The distribution of the Devonian Volcanic Belt is outlined from panel *a*. Panel modified after Bazhenov et al. (2012), with permission from Elsevier. Additional abbreviations: ATB, Atbashi; WTS, Western Tianshan.

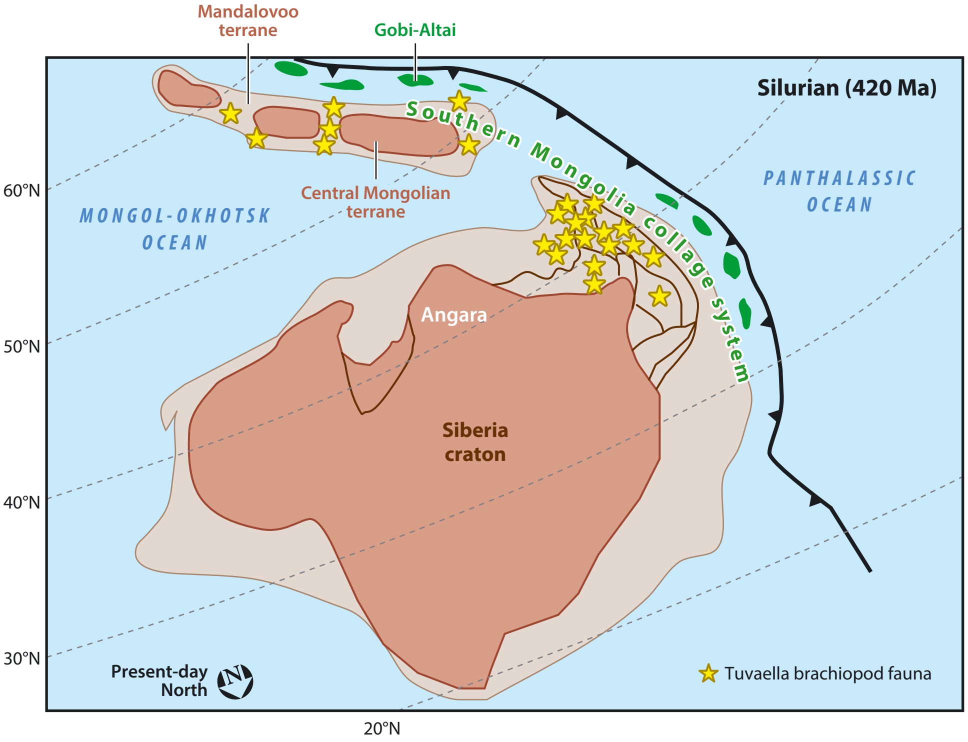


**Figure 3**

Paleogeographic map of the Siberia craton and adjacent area during the late Silurian, at about 420 Ma. Figure modified after Cocks & Torsvik (2007), with permission from Elsevier.

data, this configuration suggests that Siberia and Baltica were externally situated with a major ocean of the Aegir Sea between them, which negates the possibility of a joint single Kipchak arc rifted from these two separated continents in the earliest Cambrian (Windley et al. 2007).

The Silurian Tuvaella brachiopod fauna is widespread in the southwest Siberia craton and adjacent terranes in southern Siberia, Mongolia, eastern Kazakhstan, and northwest China (Domeier & Torsvik 2014, Rong et al. 1995, Rong & Zhang 1982, Torsvik & Cocks 2013). This distribution hints at the paleogeographic affinity of the terranes that host these fossils. In a recent paleogeographic reconstruction of the Silurian period, the Tuvaella fauna is distributed around both margins of the center of the Siberia craton as well as in the Mongolia collage system, which was at that time north of the main Siberia craton (**Figure 1**). There is a boundary roughly between the Chinese Altai and East Junggar that separates the Mongol-Okhotsk province fauna (with Tuvaella) to the north and the Sino-Australia province fauna (without Tuvaella) to the south (present coordinates) (Guo 2000, Rong et al. 1995, Rong & Zhang 1982). This should be considered as an important early Paleozoic paleogeographic boundary separating geological terranes with the Mongol-Okhotsk province fauna from those with the Sino-Australia province fauna. The distribution of the brachiopod fauna, and the fact that the Siberia craton was originally oriented with its present-day south to the north, may suggest that the Mongolia collage system was located far from the Kazakhstan collage system at least in the Silurian.

## Late Paleozoic Paleogeographic Framework

Sutures separate different archipelagos, each of which has a unique paleogeographic signature. The floral, faunal, and paleomagnetic data are unique signatures for defining the paleogeography of the Central Asian Orogenic Belt. Paleomagnetic data and other paleogeographic constraints indicate that, since the Early Devonian, the Siberia craton and its northern arc chain formed a huge circum-Siberia subduction system at 5–35°N (Cocks & Torsvik 2007, Smethurst et al. 1998, Torsvik & Cocks 2013). The Kazakhstan terranes were amalgamated along a single ribbon continental arc, located east of the Siberia craton (Domeier & Torsvik 2014). The Tarim craton would have been close to and partially connected with the North China craton in the Northern Hemisphere.

Much like the distributions of early Paleozoic fauna provinces, the distributions of various fauna and flora in the middle to late Paleozoic also mark important paleogeographic affinities of the geological terranes that host them, suggesting significant separations of these terranes. Since the Devonian, the fauna in the Siberia craton were similar to that in western North America, whereas the fauna in the Tarim and North China cratons belonged to the Proto-Tethys bioprovince (Guo 2000). In the Carboniferous–Permian, the Baltica craton was characterized by the Euramerian flora. The Siberia craton and Kazakhstan terranes shared the Angaran flora (Guo 2000), which may suggest that they were contiguous in the Carboniferous–Permian. At that time, the Tarim craton had the Cathaysian and Euramerian floras (e), which means that the Baltica craton might have been joined with the southern part of the Tianshan collage and the Tarim craton. The North China craton was characterized only by the Cathaysian flora (Guo 2000). The presence of the Cathaysian flora in the Tarim and North China cratons may indicate that there was a long distance between the conjoined Siberia-Kazakhstan collage systems.

Detailed investigations of the flora demonstrate separation and mixture of the Permian Angaran and Cathaysian floras in the southern Central Asian Orogenic Belt (Dewey et al. 1988, Zhang et al. 2014). Although not a perfect match, the separation and mixture zone between the Angaran and Cathaysian floras is distributed approximately along the South Tianshan–Solonker suture (e) (Xiao et al. 2008). In the Beishan and Alxa areas the distributions of the Angaran and Cathaysian floras match the main tectonic sutures in southern Mongolia and northern China (Yue et al. 2001). The separation and mixture zone between the floras may suggest that the Mongolian and Kazakhstan collage systems were not close to the collage system to their south until the Permian. Therefore, the Tarim–North China collage system south of this Permian boundary should have been separated from the Mongolia and Kazakhstan collage systems to the north.

Accordingly, we subdivide the Central Asian Orogenic Belt into three main collage systems: Mongolia in the north, Tarim–North China in the south, and Kazakhstan in the west (**Figure 1**). Paleomagnetic data show that the Mongolia(-Okhotsk) collage system was situated as an archipelago north of the Siberia craton with a reverse, upside-down orientation, compared with its present-day position, inherited from its early Paleozoic paleogeography (**Figure 3**). The paleomagnetic data also show that the Siberia and Mongolia collage systems underwent large-scale clockwise rotations of ~50° from the Cambrian to the end-Permian–Early Triassic (Cocks & Torsvik 2007, Domeier & Torsvik 2014, Xiao et al. 2009). The Angaran flora and its constituent rocks are situated only to the north of the South Tianshan–Solonker suture. Therefore, the Siberia craton and the Mongolia collage system probably did not join the Central Asian Orogenic Belt until the end-Permian to Early Triassic, as indicated by independent (Lehmann et al. 2010, Tian et al. 2013), sedimentary (Heumann et al. 2012), geochemical (Tian et al. 2015), and geochronological (Eizenhöfer et al. 2014) data.

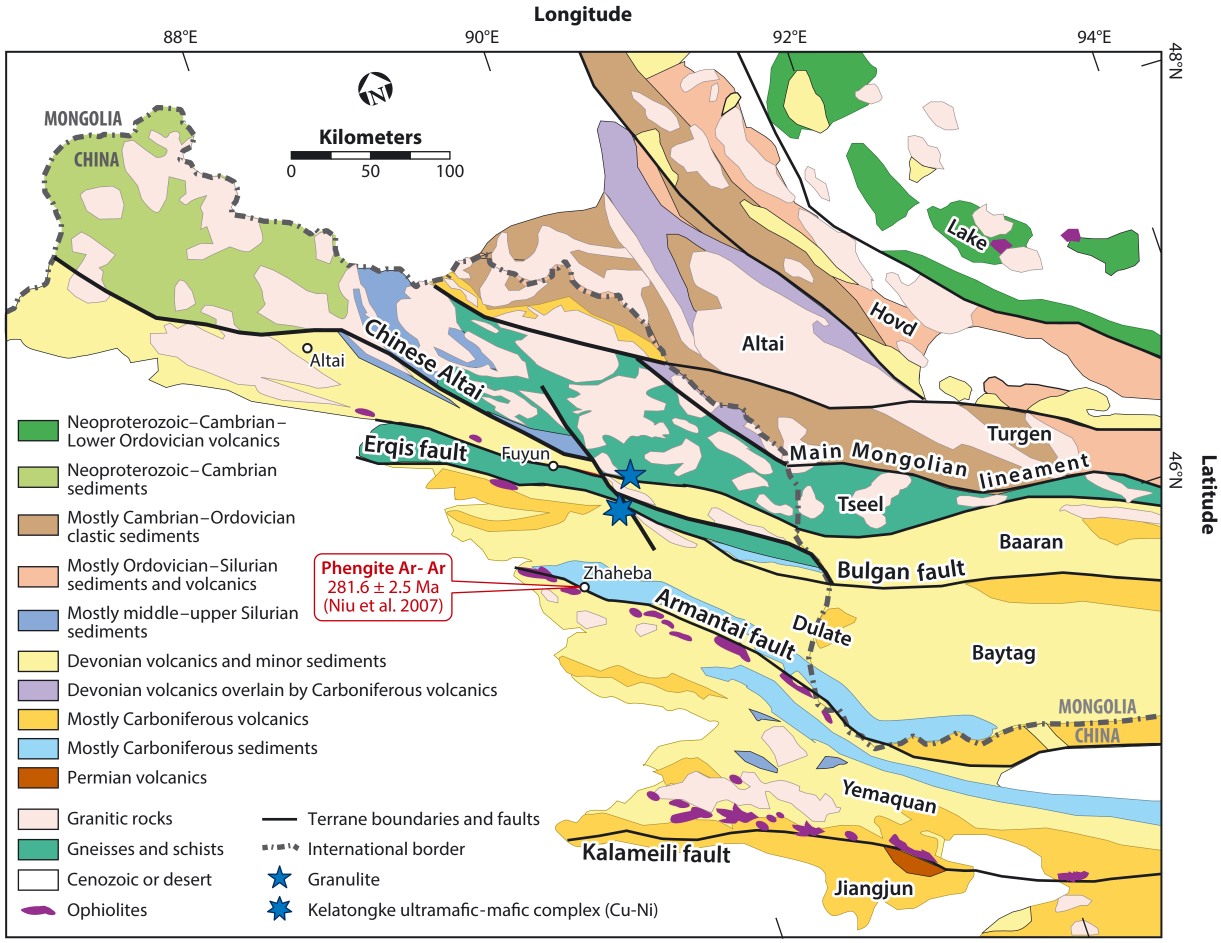


**Figure 4**

Simplified tectonic map of the southern Central Asian Orogenic Belt that crosses the Chinese-Mongolian border area (*thick dashed gray line*), showing the main tectonostratigraphic units. Figure modified with permission after Xiao et al. (2004a).

## SOUTHERN MONGOLIAN COLLAGE SYSTEM

The Mongolia collage system developed along the southern Siberia active margin as a long, ribbon-like archipelago composed of many island arcs. The present-day Mongolia collage system is mostly an amalgamation of several zones. From north to south, these are the Lake, Gobi-Altai, Trans-Altai, and South Gobi zones, which can be connected with some similar terranes in the China-Mongolia border area to the west (**Figures 4** and **5**). The composition and deformation of the Mongolia collage system were studied in a major transect (Lehmann et al. 2010); these findings are briefly described below (**Figure 5**).

Along strike to the west in northern Xinjiang in northwest China, the local tectonic units can be correlated with a fourfold subdivision in central Mongolia (**Figure 4**) (Xiao et al. 2004a). The Chinese Altai is predominantly composed of variably deformed and metamorphosed sedimentary and volcanic rocks and granitic intrusions. Systematic correlations further suggest that the Chinese

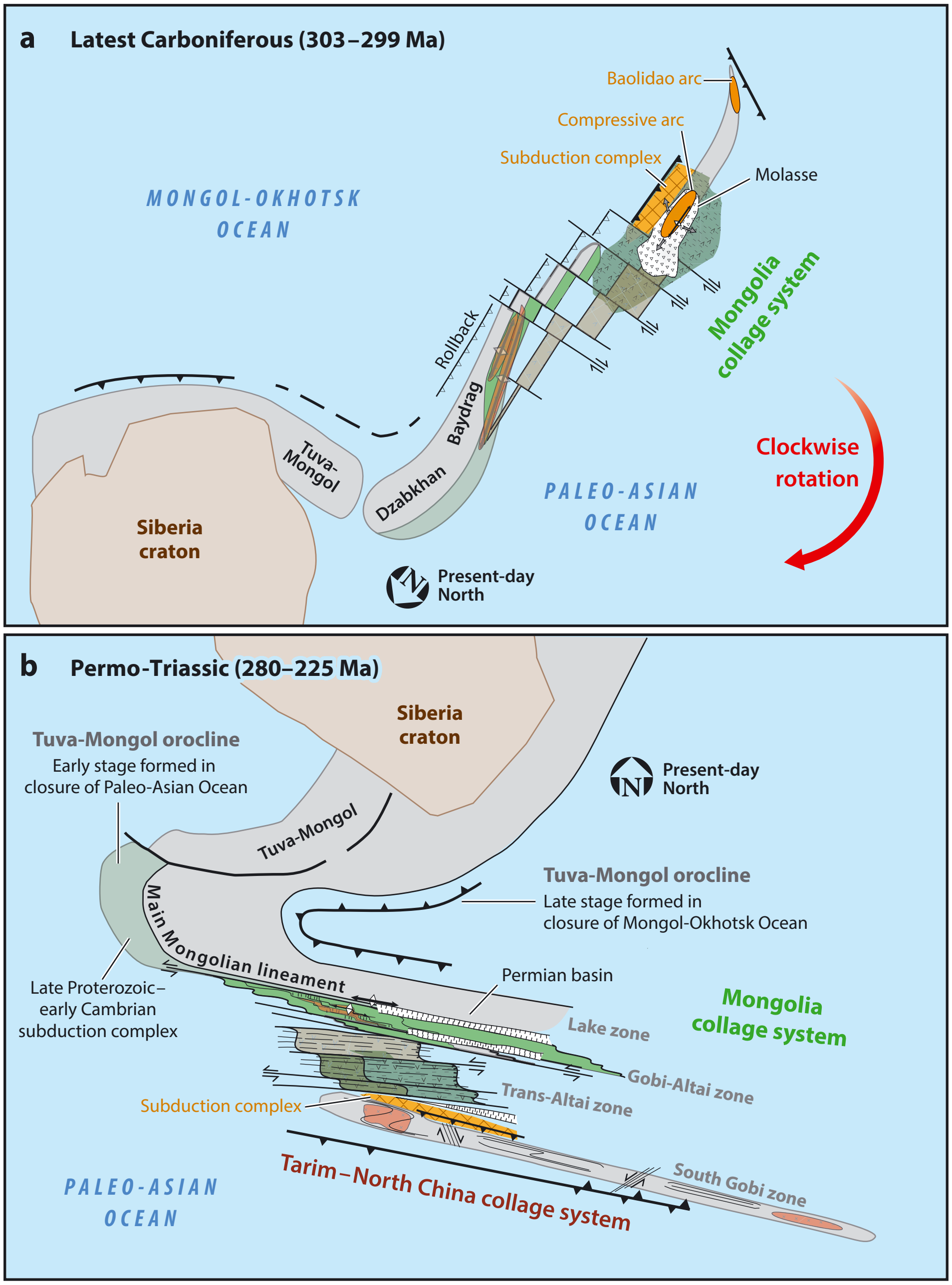


**Figure 5**

Conceptual model for the Paleozoic evolution of the Central Asian Orogenic Belt in southwest Mongolia. (*a*) The locus of arc activity was in the South Gobi zone in the latest Carboniferous (303–299 Ma). (*b*) An orthogonal tectonic switch and onset of the Permo-Triassic NNE–SSW-directed shortening enabled the southern limb of the Tuva-Mongol orocline to eventually amalgamate with the Tarim–Dunhuang–Alxa–North China collage system to the south. Figure modified after Lehmann et al. (2010), with permission from *American Journal of Science*.

Altai was mainly a Japan-type arc in the early Paleozoic to Devonian (Cai et al. 2011, Xiao et al. 2008).

The Siberian margin remained active after the early Paleozoic, and its accretionary wedge was rifted from Gondwana to form the Chinese Altai arc (Long et al. 2007, Sun et al. 2007). Along strike to the east in Inner Mongolia in northern China, the tectonic units were defined as local units that can be correlated with the fourfold subdivision in central southern Mongolia, which is described in a later section.

Structural analysis of tectonic components, including deformation partitioning of the strain zones of lithoboundaries tested against published paleomagnetic data and paleogeographic reconstructions, enabled Lehmann et al. (2010) to demonstrate that the Paleozoic evolution of the southern Central Asian Orogenic Belt in southwest Mongolia was characterized by a long tail of Tuva-Mongol ribbons of Devonian–Carboniferous age. Analysis of overthrust ophiolites, passive margins sediments, and arc subduction polarity has demonstrated that in the Early Devonian, island arc/backarc systems formed in the rear of the N–S-oriented Tuva-Mongol and Dzabkhan-Baydrag amalgamated continental ribbons. The arcs migrated eastward in the Late Devonian–early Carboniferous toward the Gobi-Altai zone. Later, the Tuva-Mongol ribbons became a locus of arc activity in the South Gobi zone in the latest Carboniferous (303–299 Ma) (**Figure 5*a***).

In the period from 280 to 225 Ma, orthogonal indentation of the undeformed Gobi-Tianshan pluton associated with the colliding of the Tarim–North China collage system into the Tuva-Mongol ribbons caused a 90° change in orientation and up to 70% NNE–SSW-directed shortening in the Gobi-Altai (**Figure 5*b***). The convergence between the southern limb of the Tuva-Mongol orocline and the Tarim–North China collage system to the south eventually terminated the Paleo-Asian Ocean in what is now northern China.

## KAZAKHSTAN COLLAGE SYSTEM

The Kazakhstan collage system is mainly composed of several orogenic components, including the Chingiz arc, the Kokchetav microcontinent, and the North Tianshan–Yili arc (**Figures 2** and **6**) that were amalgamated and/or welded together to generate a long, single composite arc by the Devonian, the evidence for which is largely derived from structural relations constrained by zircon dating of key components (Kröner et al. 2007; Safonova et al. 2004, 2009; Safonova & Santosh 2014; Windley et al. 2007; Zonenshain et al. 1990). There are more than 30 occurrences of high-pressure (HP) blueschists in this collage system (Simonov et al. 2008, Volkova & Budanov 1999, Volkova & Sklyarov 2007), and some ultrahigh-pressure (UHP) rocks occur at Kokchetav (Maruyama et al. 2009; Masago et al. 2009, 2010) and in the South Tianshan (Ai et al. 2006, Zhang et al. 2007a). Masago et al. (2009, 2010) demonstrated that in Kokchetav continental crust was subducted to diamond-coesite depths (Dobrzhinetskaya 2012, Faryad et al. 2013).

Several independent and short-lived arc systems in the western Paleo-Asian Ocean were welded together through consecutive collisions, forming the Kokchetav–North Tianshan arc in the early Paleozoic (Windley et al. 2007): Several sutures contain HP to UHP metamorphic rocks, such as diamond-bearing rocks in the Cambrian Kumdykol suture at Kokchetav (Masago et al. 2009, 2010) and eclogites in the Makbal area west of the Early Ordovician Kirgiz-Terskey suture (Tagiri et al. 1995).

From paleolatitudes integrated with regional geological data, Bazhenov et al. (2012) demonstrated that an ∼E–W-trending active margin of the Kazakhstan landmass was situated at a low (∼10°S) latitude in the Middle to Late Ordovician (∼460 Ma) (**Figure 6*a***) and collided with the Baydaulet-Akbastau intraoceanic island arc and with the Aktau-Junggar microcontinent at

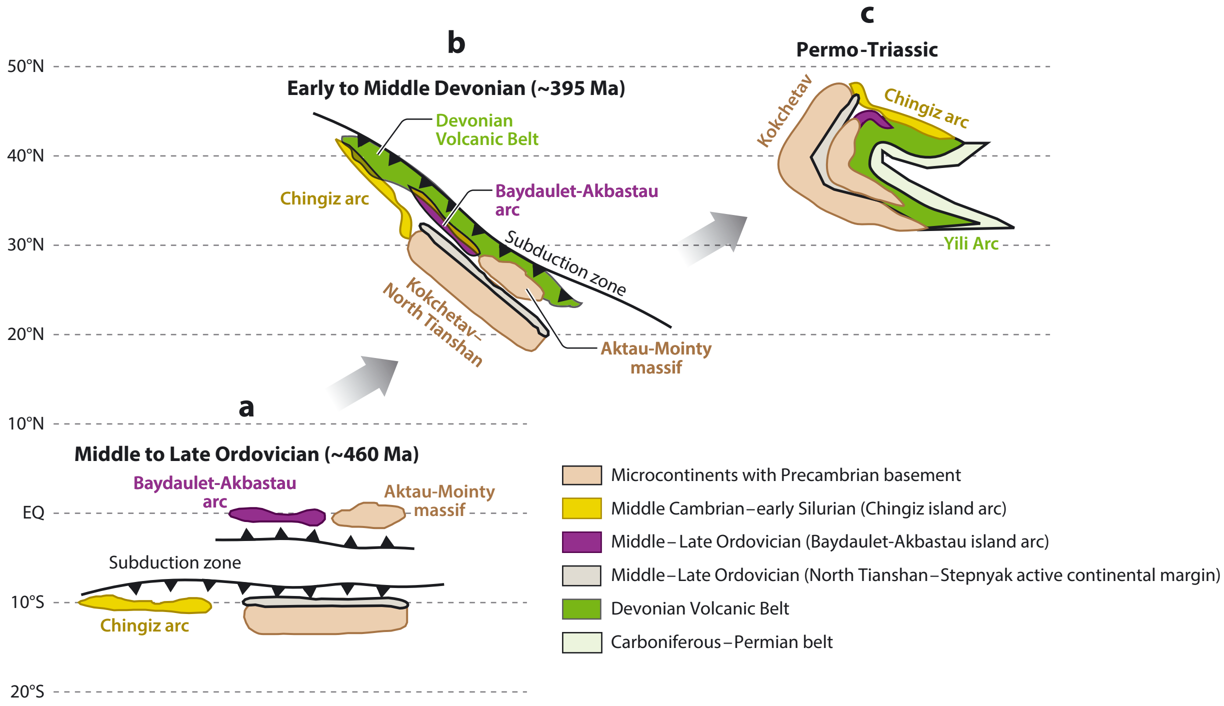


**Figure 6**

Orocline formation in the Kazakhstan part of the western Central Asian Orogenic Belt in the Paleozoic. (*a*) Middle to Late Ordovician (~460 Ma). (*b*) Early to Middle Devonian (~395 Ma). (*c*) Permo-Triassic. Figure modified after Bazhenov et al. (2012), with permission from Elsevier.

approximately 440 Ma. It seems that the Kokchetav–North Tianshan region, which incorporates a significant volume of continental crust, acted as a core around which smaller arcs amalgamated. In the Silurian, the Kokchetav–North Tianshan arc moved northward, crossed the equator and rotated clockwise by ~45° to a NW–SE orientation, and thereafter acted as the (rectilinear) predecessor of a Silurian volcanic arc that evolved into a composite Devonian (~395 Ma) Alaskan-Aleutian-type volcanic arc (**Figure 6*b***) (Bazhenov et al. 2012). In the late Paleozoic, the Chingiz–Kokchetav–North Tianshan composite arc probably attained its U-shaped structure through oroclinal bending with the Kokchetav region located in the core (**Figure 2**), because the present-day strongly curved outline of the Devonian Volcanic Belt resulted from oroclinal bending of an originally rectilinear active margin that was deformed together with surrounding older structures during the late Paleozoic. The northern limb of the Kazakhstan orocline is composed of the Chingiz arc, which extends almost to the Erqis fault in the north, and the southern limb is defined by the Yili arc (**Figures 2** and **6*c***).

Paleomagnetic studies reveal the important role of block rotations around vertical axes during oroclinal bending (Abrajevitch et al. 2007, 2008; Bazhenov et al. 2012), such as the 180° rotation of the northern limb of the Kazakhstan orocline with respect to the southern limb (**Figures 2** and **6**) (Levashova et al. 2003, 2007). From their paleomagnetic data, Van der Voo et al. (2006) concluded that Ordovician and Silurian rocks in the Chingiz and North Tianshan underwent relative rotations of ~180°, and that about 50% of the total post-Ordovician rotations were pre–late Permian and the other half were late Permian–earliest Mesozoic in age. Xiao et al. (2010b) suggested that the first half of orocline formation took place in the Carboniferous to early Permian; this idea is in good agreement with paleomagnetic and tectonic investigations that show that there was probably a ridge-subduction system in the late Carboniferous–early Permian in West Junggar (Geng et al. 2011, Ma et al. 2012, Yin et al. 2010), which consumed an oceanic basin, thereby accommodating rotation and bending of the Kazakhstan orocline (Choulet et al. 2012, Yi et al. 2014). Formation of the second half of the Kazakhstan orocline probably took place when the southernmost tip of the Kokchetav–North Tianshan arc system underwent large-scale, post-Permian eastward displacements of the Yili and Junggar arcs with respect to the Siberia craton and the Altaids to the south of the Chinese Altai (Wang et al. 2007). In summary, the originally linear Kazakhstan composite arc was bent to form the early Kazakhstan orocline in the Carboniferous to early Permian, which was then tightened to form the present orocline in the late Permian to Early Triassic (Choulet et al. 2012, Yi et al. 2014).

## TARIM–NORTH CHINA COLLAGE SYSTEM

To the south of the Central Asian Orogenic Belt are the Tarim and North China cratons, between which lie the Dunhuang and Alxa blocks (**Figure 1**). All these cratons and blocks are included in the Tarim–North China collage system, because their mutual collisions and their interactions with the southernmost belts of the Central Asian Orogenic Belt gave rise to the Beishan orogen and the South Tianshan and Solonker sutures (**Figures 1** and **7**).

The Dunhuang block, originally considered to be part of the Tarim craton, is composed of metamorphosed supracrustal rocks (Dunhuang Group) and subordinate tonalite-trondhjemite-granodiorite (TTG)-like intrusions (Mei et al. 1998). The Alxa block, originally regarded as part of the North China craton, contains a late Archean and Paleoproterozoic metamorphic basement along with Neoproterozoic meta-supracrustal rocks (Geng et al. 2007).

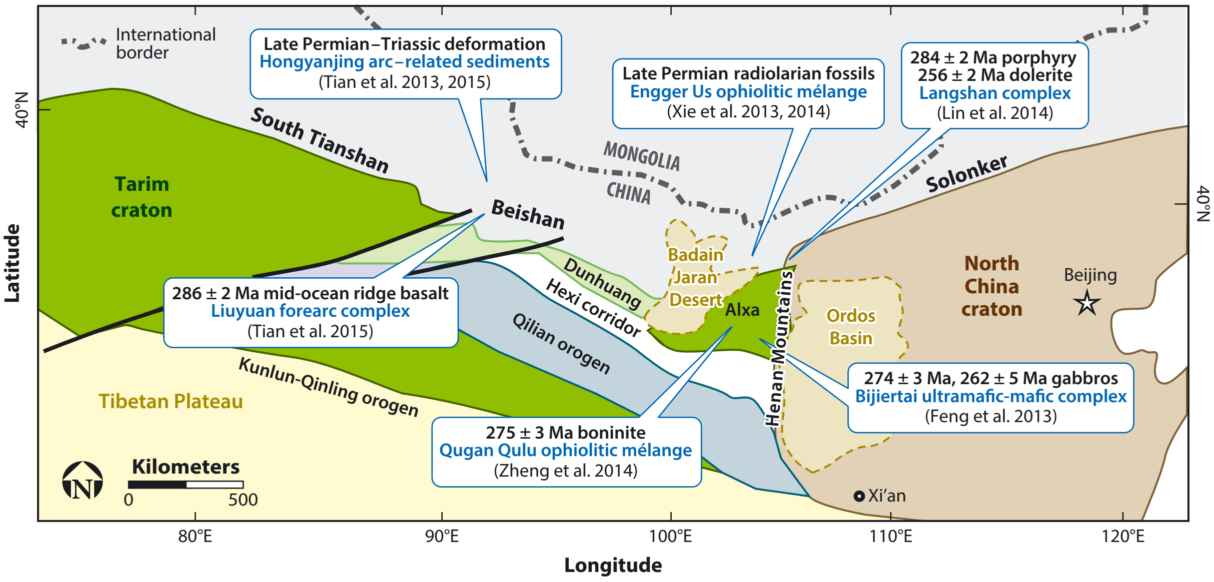


Figure 7

Simplified tectonic map of the Tarim–North China collage system and its adjacent areas, showing tectonic subdivisions.

The NE-trending Beishan orogen contains several ophiolitic mélanges that are situated in sutures and record the convergence between the Tarim craton–Dunhuang block in the west and the North China craton in the east (**Figure 1**). Between the East Tianshan and the Beishan, near Liuyuan town, a gabbro in a Permian forearc sliver has a zircon age of 286 ± 2 Ma (Mao et al. 2012). Besides gabbros, this forearc sliver contains abundant basaltic lavas, which have high $TiO_2$ contents, flat rare earth element patterns, and high field strength elements, similar to those of mid-ocean ridge basalts (MORB) (Mao et al. 2012). These basalts are imbricated with Permian tuffaceous sediments and limestones. The Liuyuan forearc complex formed part of an ophiolite in Carboniferous–Permian time (**Figure 7**).

Kilometer-sized fold interference patterns in the Beishan orogen were formed by fold superimposition in fossiliferous Permian sedimentary rocks, which have arc-related basin geochemistry (Tian et al. 2013). The two phases of folding are interpreted to result from a major change in plate configuration that caused the inversion of an interarc basin during the final amalgamation of the Beishan in the latest Permian to Early–Middle Triassic (Tian et al. 2013) (**Figure 7**).

Eastward in the Alxa area, several NE-trending ophiolitic mélanges include Engger Us in the north, Quagan Qulu in the middle, and Bijiertai in the south (**Figure 7**) (Feng et al. 2013). Zircons from a pillow lava in the Engger Us ophiolitic mélange have a sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb age of 302 ± 14 Ma (e). The Engger Us ophiolitic mélange contains late Permian radiolarian fossils (Xie et al. 2014). Massive and pillow basalts in the Engger Us ophiolite exhibit normal MORB (N-MORB) geochemical affinities, displaying high $TiO_2$ and low $K_2O$ contents and tholeiitic signatures (Zheng et al. 2014); the magma of this ophiolite was interpreted to be derived from a depleted mantle source in a mid-ocean ridge setting.

The Quagan Qulu ophiolite has gabbros with a SHRIMP zircon U-Pb age of 275 ± 3 Ma (Zheng et al. 2014). The gabbros have high MgO and compatible element (Ni, Co, Sc, and V) contents and high $Al_2O_3/TiO_2$ ratios but low $TiO_2$ and $SiO_2$ contents. They are enriched in large ion lithophile elements and depleted in light rare earth elements and high field strength elements, indicating that they were derived from an extremely depleted mantle source that was infiltrated by a subduction-derived fluid or melt (Zheng et al. 2014).

In the Bijiertai mélange shown in **Figure 7**, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb zircon geochronology on gabbros yielded ages of 274 ± 3 Ma (mean square weighted deviation = 0.35) and 262 ± 5 Ma (mean square weighted deviation = 1.2) (Feng et al. 2013), representing the formation ages of the mafic-ultramafic rocks that formed by south-dipping subduction—most likely with a slab window caused by ridge subduction—of the Paleo-Asian Ocean plate beneath the Alxa block in the late Permian before the ocean completely closed (Feng et al. 2013). These new geochemical and geochronological data suggest that subduction in the Alxa block continued in the late Permian, indicating that the final closure of the Paleo-Asian Ocean most likely took place after the late Permian.

Recent geological and paleomagnetic studies indicate that the Alxa block was not part of the North China craton until the late Permian (Yuan & Yang 2015a). Zircons with U-Pb age spectra of 2.4–2.7 and >3.0 Ga, and their corresponding $\varepsilon_{Hf(t)}$ values, are significantly different from those in the North China craton, demonstrating that these detrital zircons are not from the North China craton (Yuan & Yang 2015b). Paleomagnetic data indicate that, if the apparent polar wander path of the Alxa block rotated counterclockwise by 32° around an Euler pole at 44°N, 84°E, then the coeval apparent polar wander path of the Alxa block overlaps with that of the North China craton (Yuan & Yang 2015a). This suggests that the Alxa block migrated to the North China craton after the Early–Middle Triassic along a N–S-trending tectonic boundary located approximately along the Helan Mountains (**Figure 7**).

In summary, the formation of the Tarim–North China collage system was mostly completed in the end-Permian to Middle Triassic.

## COMPLICATED AMALGAMATION OF SEVERAL COLLAGE SYSTEMS

We need to understand the time of final formation of the three collage systems, and when they were welded together. Judging by the triangular shape of the Kazakhstan collage system and by the lithologies in the three systems, the northern limb (Chingiz and West Junggar arcs) of the Kazakhstan orocline collided with the Mongolia collage system (Altai arc), and the southern limb (Yili arc) collided with the Tarim craton. Therefore, the time of suturing between the Kazakhstan and Mongolia collage systems is recorded in the ophiolitic mélanges and/or accretionary complexes along the Altai and West Junggar, and the time of suturing between the Kazakhstan and Tarim–North China collage systems is documented in the ophiolitic mélanges and/or accretionary complexes along the southern Tianshan. In the eastern Central Asian Orogenic Belt, the suturing time between the Mongolia and Tarim–North China collage systems is recorded in the East Tianshan–Beishan–Alxa orogens and farther eastward to the Solonker suture (**Figure 8**).

### Suturing Processes Between the Southern Altai and Chingiz Arcs

The southernmost unit of the Mongolian collage system is the Altai orogen, which is composed of various terranes including the southern Altai that trends NWW–SEE across the borders of Kazakhstan, China, Russia, and Mongolia (**Figure 1**). Throughout the Paleozoic, the Altai was continuously accreting on a long-lived active margin.

The Erqis fault (and subduction complex), located along the Altai range (**Figure 1**) and long regarded as a strike-slip fault, is littered with ophiolitic fragments, volcanic rocks, and abundant mylonites. The extreme thickness of metamorphic-mylonitic Erqis shear zone indicates a 1,000-m strike-slip offset (Şengör et al. 1993). In Kazakhstan, several terranes, including the Chingiz, Kokchetav, Baydaulet-Akbastau, and Aktau-Mointy, amalgamated to form a long continent ribbon with arc magmatism along its margin (**Figure 9*a***). The Erqis fault separates the Kalba-Narym terrane to the south from the Rudny Altai terrane to the north (**Figure 9*b***) (Buslov et al. 2004). The fault zone reaches 50 km in width and consists of many tectonic sheets of differing composition separated by serpentinite mélange, mylonites, blastomylonites, and greenschists.

The Kalba-Narym terrane, located between the Chara and Erqis strike-slip faults, is composed of Late Devonian–early Carboniferous sedimentary rocks intruded by early Permian granitoids (Buslov et al. 2004). The sedimentary rocks consist of black shales and siltstones with thin interbeds of polymictic sandstones, which increase in thickness up section giving a total thickness of over 1,500 m; the sediments were thought by Buslov et al. (2004) to be deposited on a passive margin. However, when compared with the along-strike sediments in China, there is no such passive margin along the Chinese Altai. Moreover, the lithologies do not have the character of typical passive margin sediments; we suggest they are more likely coherent units of an accretionary complex. Accordingly, we tentatively reinterpret the Kalba-Narym terrane as part of a subduction complex located either along the southern margin of the Mongolia collage system or along the northern margin of the Chingiz arc.

The Erqis fault in China contains an ophiolitic mélange belt that includes mélange fragments at Keksantao, Qiaoxiahala, and Qinghe as well as volcanic rocks and high-grade gneisses (Xiao et al. 2009). Late Carboniferous to Permian mafic-felsic volcanic and volcaniclastic rocks are mutually imbricated with high-grade gneisses and schists. And most rocks in the Erqis fault are strongly deformed into early Permian mylonites and/or ultramylonites.

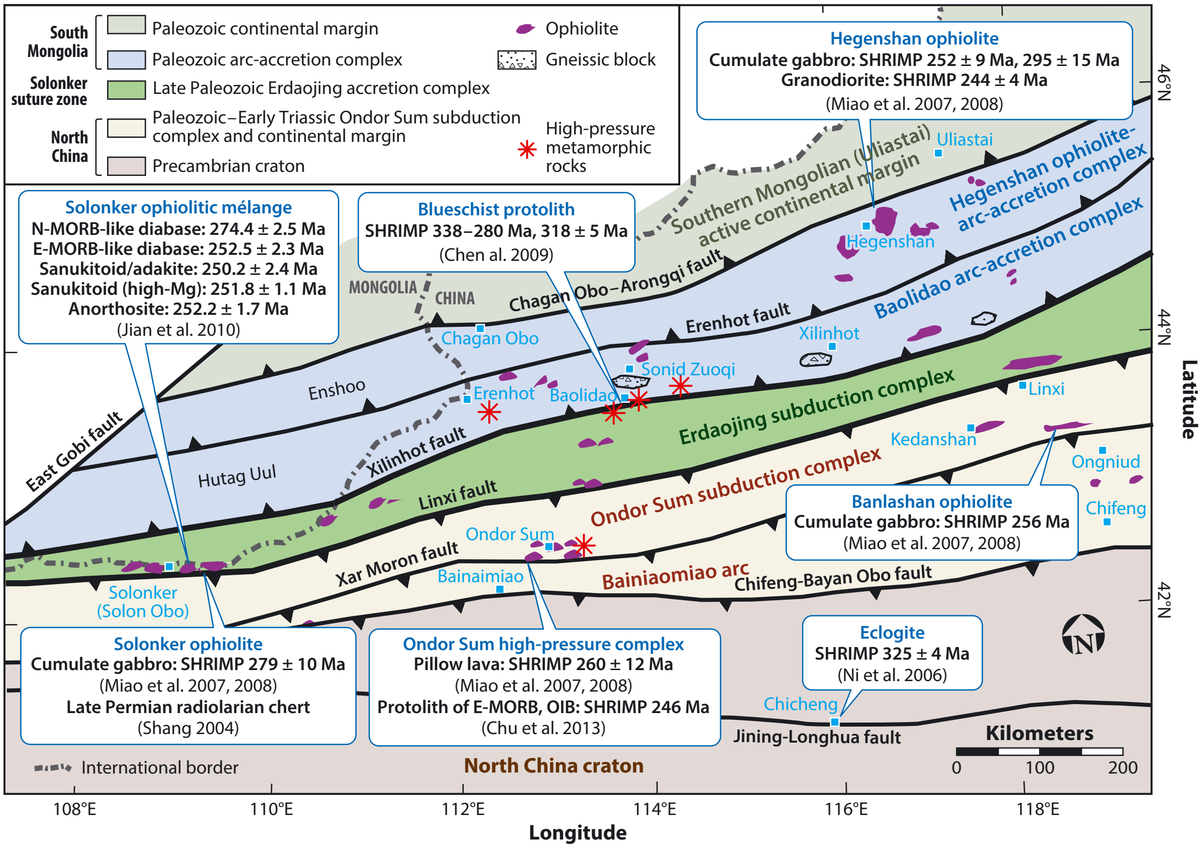


**Figure 8**

Simplified tectonic map of the Chinese-Mongolian border area, showing its structures and tectonic belts. Tectonic elements modified after Xiao et al. (2003). Abbreviations: E-MORB, enriched mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt; OIB, ocean island basalt; SHRIMP, sensitive high-resolution ion microprobe.

In addition, there is an ophiolite mélange at Tuerkubantao that includes ultramafic rocks, gabbro, and basalt; its flat rare earth element and trace element patterns point to formation in a mid-oceanic ridge setting. Zircons in a gabbro yielded U-Pb ages of 363 Ma, suggesting Late Devonian mid-ocean ridge spreading, and 355 Ma zircons in a gneissic granite indicate suprasubduction magmatism (Wang et al. 2012).

Therefore, on the northeastern margin of the Kazakhstan collage system, there is an approximately 1,000-km-long ophiolitic mélange zone (**Figure 9**) that contains ophiolites, HP rocks, and three types of tectonic mélanges (Buslov et al. 2004). The northernmost part of the Kazakhstan collage system contains the Chingiz arc and the Chara-Zaisan subduction complex (**Figure 9*c***). The major Chara sinistral strike-slip fault that hosts the Chara ophiolitic belt is a suture that separates the Altai arc to the north from the Chingiz arc to the south (**Figure 9**). Southwest of the Chara fault are the Chingiz, Tarbagatai, Zharma, and Saur terranes that formed along the Kazakhstan continental margin (**Figure 9**). They are composed of fragments of a Cambrian–early Carboniferous island arc. Northeast of the Chara fault are terranes that were rotated along strike-slip faults and associated thrusts to the south from their initial position in the marginal zones of the Siberian continent (Buslov et al. 2004).

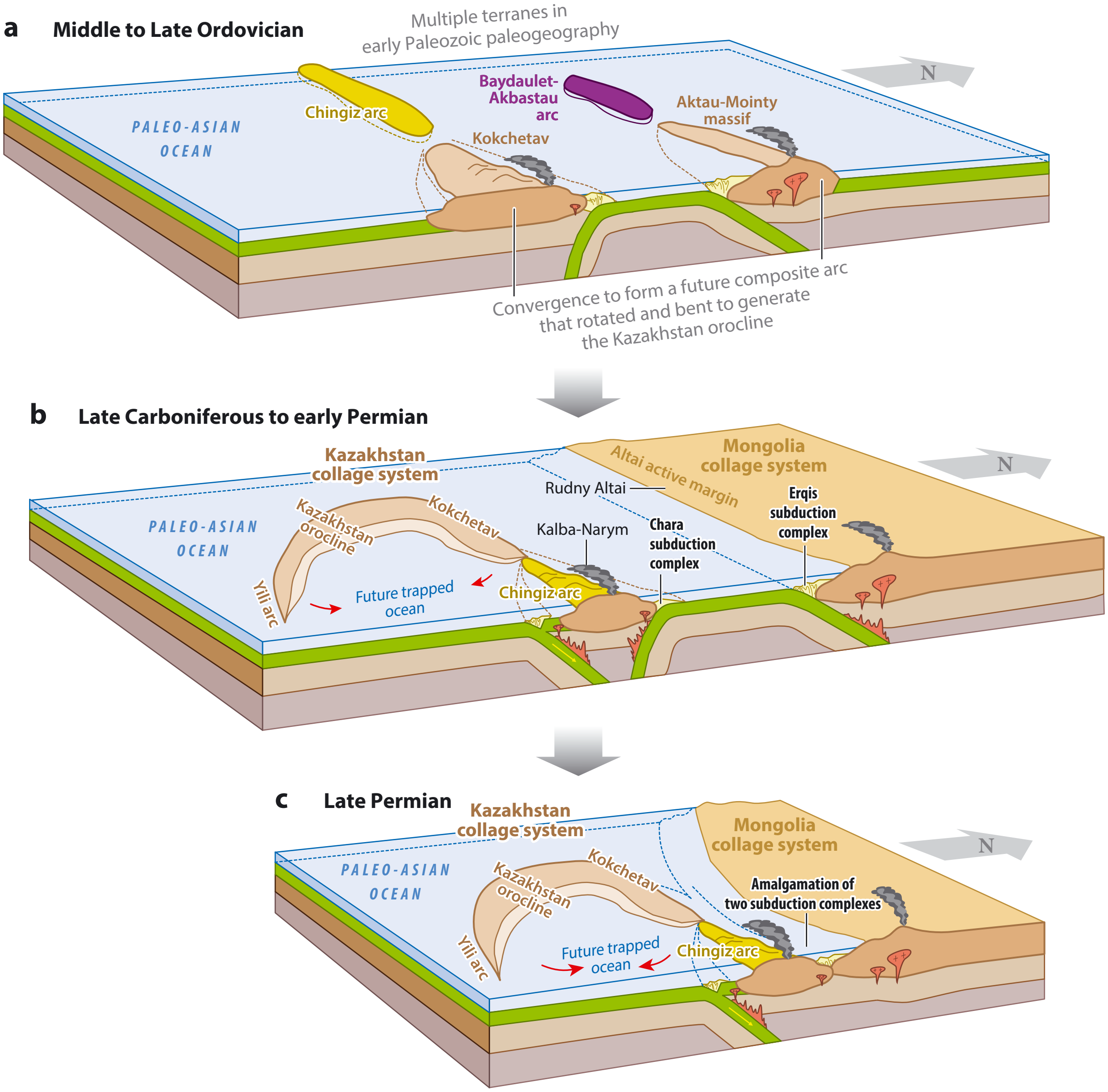


**Figure 9**

Diagrams illustrating the convergence between the Altai and Chingiz arcs in the western Central Asian Orogenic Belt. (*a*) Middle to Late Ordovician. (*b*) Late Carboniferous to early Permian. (*c*) Late Permian.

According to Buslov et al. (2004), there are three types of mélanges in the Chara suture. Type I mélange contains lenses of HP gabbro, basalt, volcaniclastic rocks, greywacke, chert, eclogite, garnet amphibolite, and glaucophane schist. Muscovites from eclogites and blueschists have K-Ar ages of 429–444 Ma. Type II describes a 250-km-long Ordovician ophiolitic mélange that contains blocks of peridotite, gabbro, oceanic basalt, siliceous mudstone, and chert with radiolaria of mid-Devonian to early Carboniferous age. The lavas are high-Al and high-Ti alkali plagiobasalts, interpreted to have formed at a mid-ocean ridge (Buslov et al. 2004). Type III is a late Carboniferous–early Permian mélange containing blocks of types I and II mélanges.

The Chara ophiolitic belt is surrounded by Devonian–early Carboniferous sedimentary-volcanic rocks, which were regarded as fragments of early Carboniferous subduction complexes and forearc troughs. The tectonic units between the Altai and Chingiz arcs are composed of two large subduction complexes (**Figure 9**). The distribution of the arcs and subduction complexes suggests that during convergence the subduction polarities were opposite (**Figure 9**). As mentioned above, the youngest units in the Chara subduction complex are early Permian, and those in the Erqis subduction complex are Permian, both of which predate the final amalgamation event. From the above data we conclude that the two subduction complexes amalgamated and formed a suture zone in the late Permian, called the Erqis-Chara-Zaisan suture (**Figure 9**), which separates the arcs of the Kazakhstan collage system to the south from the southern margins of the Siberian continent that was part of the contemporaneous Mongolian collage system to the north.

In contrast, in the Chinese Altai–East Junggar area, the East Junggar arc docked to the Mongolia collage system in the early Carboniferous, thus forming an enlarged active margin on the Altai belt. Shu & Wang (2003) suggested that the collision between the East Junggar and Tianshan arcs took place in the early Carboniferous, because of the presence of early Carboniferous radiolarian cherts in ophiolitic mélanges in the suture between the East Junggar and Tianshan arcs. However, these ages could equally have been related to docking of the East Junggar arc against the Altai active margin (Xiao et al. 2004a). More recently, Niu et al. (2007) reported that phengites from a quartz-magnesite rock in the Zhaheba ophiolite of East Junggar have an $^{40}$Ar/$^{39}$Ar UHP metamorphic age of 281.6 ± 5 Ma (**Figure 4**), suggesting that subduction in East Junggar lasted until the early Permian. Therefore, we can reasonably conclude that the amalgamation between the East Junggar arc (Mongolia collage system) and southerly collage systems occurred in the Permian.

## Suturing Processes Between the Yili Arc and Tarim Craton

The Yili arc is on the southern limb of the Kazakhstan orocline in the southernmost part of the Kazakhstan collage system. The convergence between the Yili arc and Tarim craton is best recorded in the South Tianshan subduction complex (**Figure 1**). The Yili magmatic arc, located to the west of Urumqi city, has a triangular shape that becomes narrower eastwards into the Chinese Tianshan (**Figure 2*a***). Its main components include Paleoproterozoic to Neoproterozoic high-grade metamorphic rocks, late Neoproterozoic to early Paleozoic passive margin sediments, Late Ordovician–Silurian granites, and Devonian to Carboniferous–early Permian volcanic and clastic sedimentary rocks (Xiao et al. 2013). In summary, the Yili arc is an Andean-type arc built on the margin of a Precambrian microcontinent that was mostly active in the Devonian, Carboniferous, and early Permian.

The so-called South Tianshan unit (mainly represented by the South Tianshan ophiolitic mélange) separates the Tarim craton from the Central or Middle Tianshan arc (Burtman 2010). In the South Tianshan unit, high-temperature/low-pressure (HT/LP) metamorphic rocks have an earliest Permian protolith age (298.5 ± 4.9 Ma), which predates the HT/LP metamorphism that likely occurred later in the Permian (Li & Zhang 2004, Zhang et al. 2007a).

In the Tianshan of Kyrgyzstan, the South Tianshan unit contains the Turkestan suture with the southern Ferghana ophiolitic mélange that has blocks of glaucophane-bearing blueschists and HP eclogites at Atbashi (**Figure 2**) (Tagiri et al. 1995). Glaucophane-bearing blueschists and HP eclogitic/mafic granulite relics occur in South Tianshan in Xinjiang, China (**Figures 1** and **2**). Coesite-bearing UHP eclogites contain zircons, the rims of which have a mean age of ~319 Ma (Gao et al. 1995, Gao & Klemd 2003, Hegner et al. 2010, Klemd et al. 2005). The HP/UHP rocks have N-MORB and ocean island basalt (OIB) trace element signatures suggesting that their protoliths formed in an ocean, and were accreted in a trench, subducted to high pressures, and now occur in the southernmost mélange of the South Tianshan subduction complex. Some Permo-Triassic Ar-Ar ages of large-scale ductile high-strain zones can be interpreted to indicate formation of these associated HP/UHP rocks on a backstop of the South Tianshan subduction complex (Cai et al. 1995). A mylonite immediately north of the HP/UHP rocks yielded an $^{40}Ar/^{39}Ar$ plateau age of 230 ± 8 Ma (Li & Cui 1994), which might record a phase of uplift on the backstop of the subduction complex.

The Tarim craton has a variably deformed and metamorphosed basement of Archean–Proterozoic to early Paleozoic rocks (Lu et al. 2008), which are characterized by Archean high-grade bimodal TTG gneisses and amphibolites and Proterozoic granitic gneisses with Nd model ages ranging from 3.2 to 2.2 Ga (Hu et al. 2000). Sinian through Permian sedimentary rocks crop out in the Keping and Bachu areas along the Chinese Tianshan in the west (Carroll et al. 2001). The western part of the Tarim craton was mainly covered by passive margin sediments during most of Paleozoic time (Biske & Seltmann 2010). However, the eastern part may have been an active margin in the Paleozoic (Ge et al. 2014; Xiao et al. 2004b, 2010c).

The Paleozoic tectonic framework of the Chinese South Tianshan is characterized by the South Tianshan (Kokshaal-Kumishi) subduction complex that separates the Tarim and Karakum cratons from the Yili arc (Xiao et al. 2013). The presence of subduction-related late Carboniferous and late Permian magmatism, late Permian radiolarian cherts, and precollisional late Carboniferous to Triassic HP/UHP rocks in the South Tianshan subduction complex suggests that subduction was active in the late Carboniferous to Permian or even Middle Triassic. This may be supported by an explosion seismic reflection profile (Gao et al. 2013) across the junction between the southwest Tianshan orogen and Tarim craton, which shows interwedging of lower crustal layers caused by late Paleozoic compression.

Therefore, final collision between the Tarim craton and the northern accretionary systems likely occurred in the late Carboniferous to Permian in the east and in the end-Permian to Middle Triassic in the west, which suggests that the Paleo-Asian Ocean closed progressively westward along the South Tianshan suture.

## Suturing Processes Between the Mongolia Collage System and North China Craton

As mentioned above, the southern margin of the Mongolian collage system and the northern margin of the North China craton remained active during most of the Paleozoic. In Chinese Inner Mongolia (**Figure 8**), convergence between the two active margins of South Mongolia and the North China craton continued during most of the Paleozoic to give rise to the terminal Solonker suture (Chen et al. 2009, Li et al. 2011, Xiao et al. 2003). In the north, the Uliastai (Southern Mongolia) active continental margin extends along the northern border of Inner Mongolia from Chagan Obo to Uliastai (**Figure 8**), and to the south of the margin are the Hegenshan ophiolite-arc-accretion complex and the Baolidao arc-accretion complex. To the south of the Solonker suture are the Ondor Sum subduction-accretion complex (de Jong et al. 2006), the Bainiaomiao arc, and the North China craton (**Figures 8** and **10*a***).

The Solonker suture zone contains the Erdaojing subduction complex (Xiao et al. 2003), which comprises tectonic mélanges typical of a modern accretionary wedge and coherent turbidites that are imbricated with ophiolitic rocks, chert, marble, and arc volcanic rocks. The mélanges are characterized by lenses of mafic-ultramafic rocks, dolomite, quartzite, marble, and blueschist within an argillite matrix. In the Linxi area (**Figure 8**) ophiolitic lenses of pyroxenite, layered

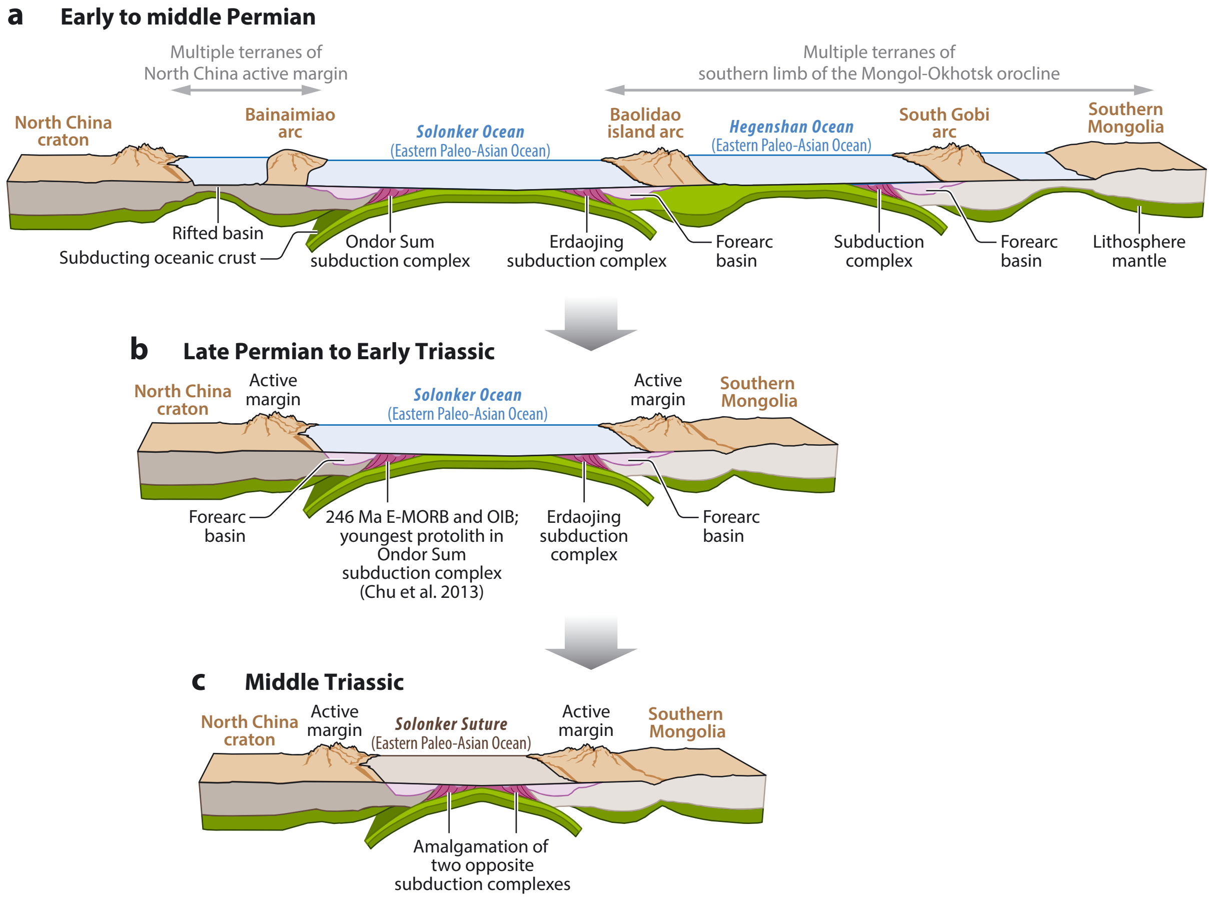


**Figure 10**

Diagrams illustrating the amalgamation of two opposite-dipping subduction complexes in Inner Mongolia in the eastern Central Asian Orogenic Belt. (*a*) Early to middle Permian. (*b*) Late Permian to Early Triassic. (*c*) Middle Triassic. Multiple terranes of southern limb of the Mongol-Okhotsk orocline correspond to those in **Figure 5**. Abbreviations: E-MORB: enriched mid-ocean ridge basalt; OIB, ocean island basalt.

gabbro, sheeted mafic dikes, basalt, and chert occur in lower Permian clastic sediments (Wang & Liu 1986). Within the Erdaojing complex a cumulate gabbro from the Solon Obo ophiolite (**Figure 8**), which straddles the China-Mongolia border, has a SHRIMP U-Pb age of 279 ± 10 Ma (Miao et al. 2007, 2008). Some sedimentary blocks in mélanges near Solonker contain middle Permian radiolaria (Shang 2004). These data suggest that the ophiolites were derived from the Permian Paleo-Asian oceanic crust/mantle and were most likely incorporated into the Erdaojing accretion complex after the late Permian.

The poorly exposed Ondor Sum subduction complex (**Figure 8**) contains ophiolites, HP rocks, and granitic gneisses. In the well-exposed Ulan Valley near Ondor Sum, ophiolitic pillow lavas and ocean plate stratigraphy occur in the south, folded phyllites in the center, and thrusted mylonitic HP rocks containing glaucophane and phengite ($^{40}$Ar/$^{39}$Ar ages of 453.2 ± 1.8 Ma and 449.4 ± 1.8 Ma) in the north (de Jong et al. 2006, e); all these rocks were juxtaposed in a south-directed thrust stack. Some late Permian–Early Triassic components have recently been found in the Ondor Sum subduction complex; an undeformed pillow lava from the southern ophiolite, however, has a zircon SHRIMP age of ∼260 Ma (Miao et al. 2007). Zircons from a plagiogranite in the Kedanshan ophiolite have a SHIRMP age of 277 ± 4 Ma (Jian et al. 2007, 2008). A cumulate gabbro from an ophiolitic fragment southwest of Kedanshan has a zircon SHRIMP U-Pb age of 256 ± 3 Ma (Miao et al. 2007). Some cherts in mélanges contain late Permian radiolaria (Wang & Fan 1997). A youngest zircon age of 246 Ma in protoliths of metabasic volcanics in the Ondor Sum complex with an E-MORB to OIB signature (Chu et al. 2013) provides an Early Triassic upper age limit for this previously defined late Permian subduction complex. These dates confirm that the Ondor Sum accretionary wedge was still active in the end-Permian to Early Triassic (**Figure 10*b***).

An important constraint on the style and timing of final closure of the Paleo-Asian Ocean in Inner Mongolia is the presence of an Andean-type active magmatic arc on the northern continental margin of the North China craton. Calc-alkaline hornblende-bearing I-type granitic plutons have U-Pb zircon ages ranging from 324 ± 6 Ma to 274 ± 6 Ma, demonstrating that the ocean was closing with southward subduction from the late Carboniferous to the mid-Permian (**Figure 10*a***) (Zhang et al. 2009).

Farther westward in the Langshan area (Lin et al. 2014), deformed granitic-granodioritic porphyries (**Figure 7**) are characterized by geochemical features that can be ascribed to a heterogeneous source in a subduction-related environment. Two granitic porphyries yielded U-Pb weighted mean ages of 284.7 ± 2.1 Ma. The geochemistry of some gabbros and dolerites also shows a subduction-related setting signature; one dolerite has concordia ages of 256.2 ± 2.6 Ma and 256 ± 2.5 Ma. The ages and geochemistry of the deformed porphyries indicate that in the early Permian there was important deformation and recrystallization in a subduction-related setting. The isotopic and geochemical signatures of all the rocks indicate that they formed under subduction-related conditions (Lin et al. 2014). The Langshan area was part of a Permian active continental margin arc built on the edge of the North China craton by southward subduction, which led to closure of the ocean, concomitant formation of the Solonker suture in the late Permian–Early Triassic, and termination of the accretion-subduction orogen of the southern Central Asian Orogenic Belt (Lin et al. 2014).

Therefore, the final amalgamation of the Mongolian collage system and the North China craton probably occurred in the late Permian to Middle Triassic (**Figures 10*c*** and **11**) (Zhang et al. 2007b, 2009). The suture was imaged on a deep seismic reflection profile across the Solonker suture (Zhang et al. 2014).

In summary, the Kazakhstan collage system (Chingiz and West Junggar arcs) amalgamated with the Mongolia collage system (Altai arc) in the Permian or even later. The southern part of the Kazakhstan collage system collided with the Tarim craton in the late Carboniferous–end-Permian to Middle Triassic. The suturing between the Mongolia collage system and the Tarim–North China collage system was in the Permian to Early Triassic (**Figure 11*a***). The termination of these amalgamation events was likely in the Permo-Triassic (**Figure 11*b***).

# DISCUSSION AND IMPLICATIONS

## Duration of the Orogenesis

It is widely accepted that the subduction-related developments of the Central Asian Orogenic Belt started at ∼1.0 Ga (Khain et al. 2002, Kröner et al. 2007) and gradually migrated southward (present coordinates), as recorded in the vast areas of Russia, Mongolia, and Kazakhstan and other Central Asian countries. Northern China mainly records the youngest and terminal accretionary events, which were in the Permo-Triassic.

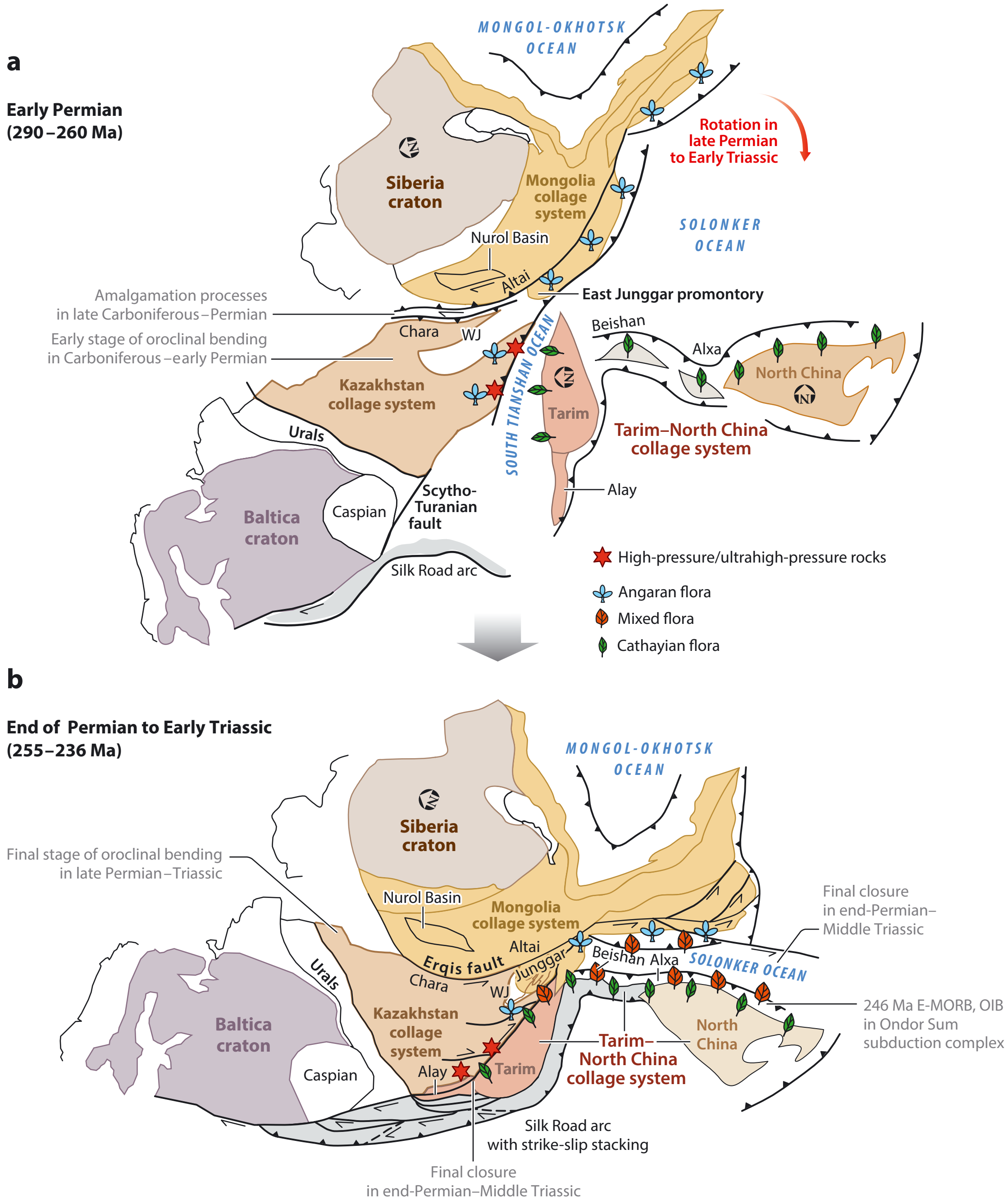
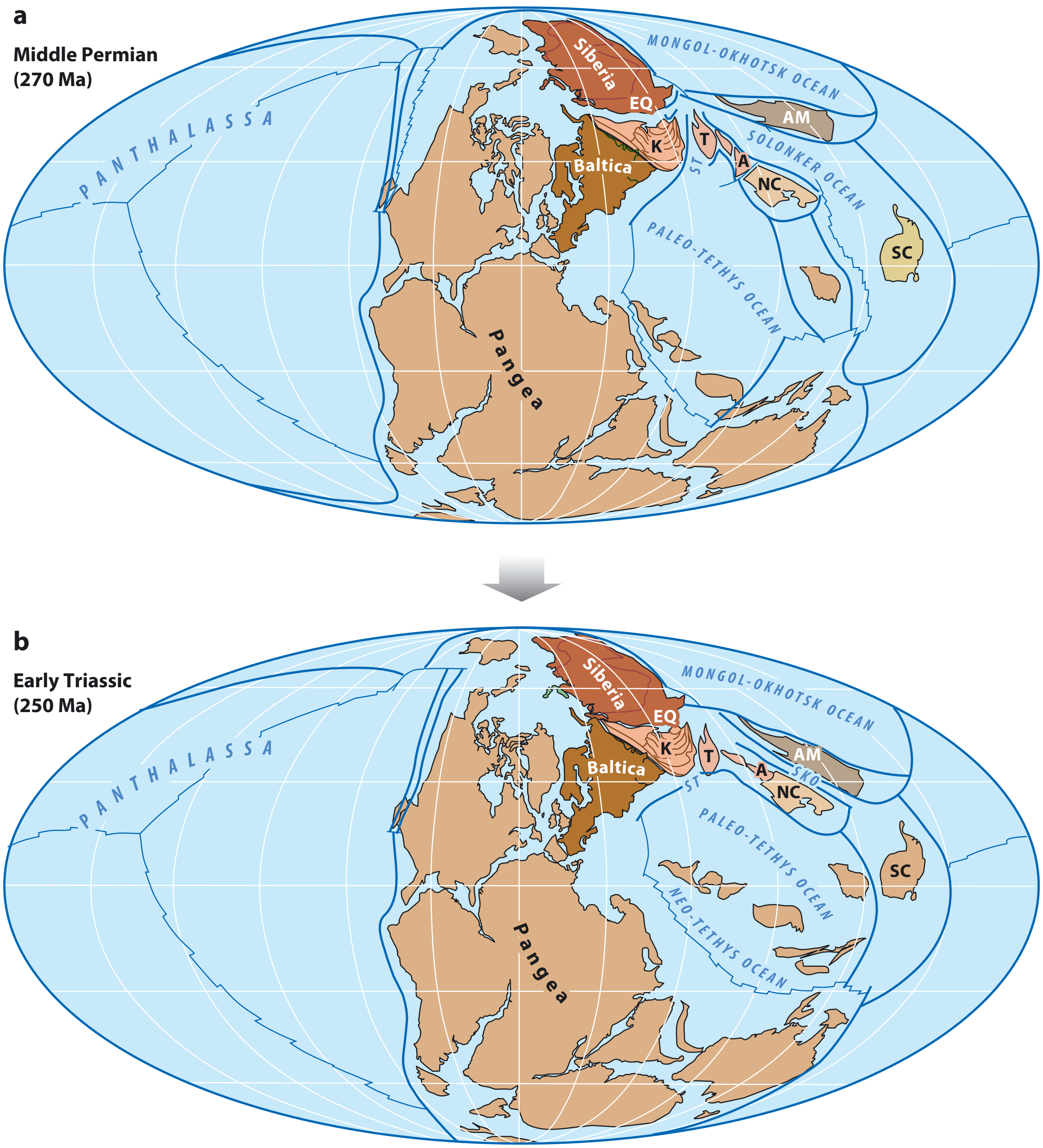


**Figure 11**

(*a*) Early Permian (290–260 Ma) and (*b*) End-Permian to Early Triassic (255–246 Ma) paleogeographic reconstructions showing simplified plate boundaries and labels of some major features of the Central Asian Orogenic Belt (modified after Natal'in & Şengör 2005). The Silk Road arc is modified after Natal'in & Şengör (2005). Red stars indicate the localities of high-pressure/ultrahigh-pressure rocks in Atbashi and Southwest Tianshan (see **Figure 2**). The distributions of floras are based on those in **Figure 1**. Present-day north is indicated by an arrow for the Siberia, Tarim, and North China cratons. Figure modified after Natal'in & Şengör (2005), with permission from Elsevier. Abbreviations: E-MORB, enriched mid-ocean ridge basalt; OIB, ocean island basalt; WJ, West Junggar.


a
Middle Permian
(270 Ma)
PANTHALASSA
Siberia
EQ
MONGOL-OKHOTSK OCEAN
AM
K
T
SOLONKER OCEAN
A
NC
ST
Baltica
PALEO-TETHYS OCEAN
SC
Pangea
b
Early Triassic
(250 Ma)
PANTHALASSA
Siberia
EQ
MONGOL-OKHOTSK OCEAN
AM
K
T
A
SKO
NC
ST
Baltica
PALEO-TETHYS OCEAN
NEO-TETHYS OCEAN
SC
Pangea

The late Paleozoic orogens of North Xinjiang and adjacent areas developed by continuous southward accretion along the wide southern active margin of Siberia, with the formation of an Alaska-type arc (Kokchetav–North Tianshan), some Japan-type arcs (Altai, Chinese Central Tianshan), and Mariana-type arcs (Balkash, West Junggar, and East Junggar).

In the Mongolia collage system, the oldest accretionary event has an age of ~1.0 Ga (Khain et al. 2002). In West Junggar of the Kazakhstan collage system, zircons from an isotropic gabbro in the Mayile ophiolitic mélange yield an LA-ICP-MS U-Pb age of 572 ± 9 Ma (Yang et al. 2012b). Geochemically, basalts from the Mayile ophiolitic mélange display OIB-type alkali basalt and E-MORB-type tholeiitic features with a within-plate affinity, and they are geochemically similar to the Hawaii and Xigaze seamounts, suggesting an intraoceanic seamount setting. Yang et al. (2012b) proposed a model in which subduction of the oceanic lithosphere commenced during the late Cambrian to Early Ordovician, and finished with eventual accretion of Neoproterozoic–early Cambrian seamounts in a forearc together with oceanic fragments, thus forming the Mayile ophiolitic mélange.

Alaskan-type, zoned mafic-ultramafic complexes with arc-related chemical signatures intruded in the Beishan near the Tianshan-Tarim suture in the Early Permian (Ao et al. 2010, Xiao et al. 2008b) and in the Central Tianshan in the Ordovician and late Carboniferous (Su et al. 2014). The final amalgamation of the margin of the Tarim craton with the huge accretionary system to the north seems to have continued to the late Permian and even to the Early–Middle Triassic (Xiao et al. 2003, 2004a,b).

The youngest orogenic events are also indicated in the time of final formation of the oroclines in the Central Asian Orogenic Belt. The formation and tightening of the Kazakhstan orocline, the early-stage of formation of the Mongol-Okhotsk orocline, and the suturing of the Southern Tianshan, Beishan, and Solonker sutures all indicate that the termination of the southern Central Asian Orogenic Belt was in the Permo-Triassic. Combined with the earlier subduction history of seamounts and/or ophiolitic fragments imbricated in accretionary complexes and sutures, the accretionary orogenesis in the southern Central Asian Orogenic Belt clearly lasted from the Neoproterozoic to the Middle Triassic.

## Architecture of the Altaids

The present-day Circum-Pacific Ocean is characterized either by archipelagos with multiple arcs and other terranes (West Pacific) or largely by a single active margin (East Pacific). The West Pacific active margins also began with archipelagos in their early tectonic history (Johnston 2004). These active margins behaved tectonically like an accordion, with episodic opening and closure of small oceans; that was the fundamental tectonic idea of Şengör et al.'s (1993) single Kipchak arc model. However, that work considered only the simplest single-arc situation for the tectonic evolution of the orogens. We now know that the Central Asian Orogenic Belt clearly has a far more complicated tectonic framework and underwent a very complex series of tectonic events to arrive

**Figure 12**

(*a*) 270 Ma (middle Permian) paleogeographic reconstruction, showing simplified plate boundaries and labels of some major features. (*b*) 250 Ma (Early Triassic) paleogeographic reconstruction, showing simplified plate boundaries and labels of some major features. Reconstruction of the relative position of the Alxa block and North China craton is from Yuan & Yang (2015a,b). Figure modified after Domeier & Torsvik (2014), with permission from Elsevier. Abbreviations: A, Alxa block; AM, Amuria; B, Baltica craton; EQ, Erqis; K, Kazakhstan; NC, North China craton; SC, South China craton; SKO, Solonker Ocean; ST, Southern Tianshan Ocean; T, Tarim craton.

at its present state; for example, some active margins joined together to form complicated orogenic collages (Xiao et al. 2010a). In present-day southeast Asia there is an overall convergent tectonic system with two large families of archipelagos. One is north of the Sumatra-Timor trench, and the other is south of the Ontong Java and southeast of the Tonga trench; both of these archipelagos are currently being amalgamated by convergence. The Central Asian Orogenic Belt was constructed by three families of archipelagos, and their terminal amalgamation was in the end-Permian to Middle Triassic (**Figures 11** and **12**).

The development of the southern Central Asian Orogenic Belt was characterized by multiple periods of convergence and accretion, which in the early Paleozoic generated extensive, long orogenic collages that were bent into oroclines in the late Paleozoic and Early Triassic (**Figure 12**). Advanced accretionary orogenesis was achieved by multiple amalgamations of several collage systems, which were accompanied by multiple phases of parallel amalgamation and orocline rotation.

Therefore, regarding the two major questions to be answered—the duration and architecture of the accretionary orogenesis—we envisage that the construction of the Central Asian Orogenic Belt was far more complicated than the processes responsible for collisional orogens. It is also clear that the duration of orogenesis was longer than previously recognized.

## Implications

Orogenic collages are connections of various orogenic components that generated supercontinents like the Central Asian Orogenic Belt in the Permian (**Figures 11*a*** and **12*a***) and Early Triassic (**Figures 11*b*** and **12*b***). The anatomy of the Central Asian Orogenic Belt indicates that nearly all accretionary orogeneses occurred along an active margin of the host continent, the core of which was subsequently enlarged by lateral growth (Şengör et al. 1993, Xiao & Santosh 2014).

Oroclines that develop in the oceans, like the New Caledonia–D'Entrecasteaux orocline (Johnston 2004) and the Banda arc in Indonesia (Milsom et al. 1996), are well known, but those that have already accreted into collisional and accretionary orogens are not so well understood (Johnston et al. 2013). Large-scale orogen-parallel movements, which produce an orocline, may take place along a linear convergent margin, as in the Alaskan and Vancouver Island oroclines (Johnston 2001, Johnston & Acton 2003) and along the Kipchak arc (Natal'in & Şengör 2005, Şengör et al. 1993). Because active margins tend to change their geometry with time, the inboard components may also change their orientations as a result of rotation during oroclinal bending; this happened in the Central Asian Orogenic Belt.

The North American Cordillera may provide a useful modern analog for the Central Asian Orogenic Belt. A long, originally linear strip of continental crust (i.e., a continental ribbon) was accreted and then buckled by coast-parallel northward movements into the Alaskan orocline (Johnston 2001) and the Vancouver Island orocline (Johnston & Acton 2003). Production of the two oroclines may have been fundamentally similar to that of the two oroclines and their collage systems in the Central Asian Orogenic Belt. The complicated development of orogens involving the growth of linear arc chains and/or continental ribbons, which are then rotated and buckled into oroclines, is undervalued and insufficiently understood.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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