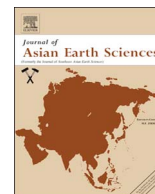




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Geometry, kinematics and tectonic models of the Kazakhstan Orocline, Central Asian Orogenic Belt

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ABSTRACT

The Central Asian Orogenic Belt (CAOB) is one of the largest accretionary orogens on Earth and is characterized by the occurrence of tight oroclines (Kazakhstan and Tuva-Mongolian oroclines). The origin of these large-scale orogenic curvatures is not quite understood, but is fundamentally important for understanding crustal growth and tectonic evolution of the CAOB. Here we provide an outline of available geological and paleomagnetic data around the Kazakhstan Orocline, with an aim of clarifying the geometry, kinematics and geodynamic origin of the orocline. The Kazakhstan Orocline is evident in a total magnetic image, and can be traced by the continuation of high magnetic anomalies associated with the Devonian Volcanic Belt and the Late Devonian to Carboniferous Balkhash-Yili arc. Paleomagnetic data show $\sim 112\text{--}126^\circ$ clockwise rotation of the northern limb relative to the southern limb in the Late Devonian to Early Carboniferous, as well as $\sim 15\text{--}28^\circ$ clockwise rotation of the northern limb and $\sim 39\text{--}40^\circ$ anticlockwise rotation of the southern limb relative to the hinge of the orocline during the Late Carboniferous to Permian. We argue that the Kazakhstan Orocline experienced two-stage bending with the early stage of bending (Late Devonian to Early Carboniferous; $\sim 112\text{--}126^\circ$) driven by slab rollback, and the later stage (Late Carboniferous to Permian; $54\text{--}68^\circ$) possibly associated with the amalgamation of the Siberian, Tarim and Baltic cratons. This new tectonic model is compatible with the occurrence of rift basins, the spatial migration of magmatic arc, and the development of large-scale strike-slip fault systems during oroclinal bending.

1. Introduction

Curved mountain belts, commonly referred to as oroclines, result from bending of quasi-linear orogenic belts, and have fascinated generations of geologists since the pioneering work by Carey (1955). Such structures are recognized in both modern and ancient orogens, and their origin is fundamentally important for understanding the geodynamics of convergent plate boundaries and the driving mechanisms of the orogenesis (Marshak, 2004; Van der Voo, 2004; Gutiérrez-Alonso et al., 2012; Weil et al., 2013; Rosenbaum, 2014). How and why orogenic belts become curved has been in debate. Some authors have demonstrated that oroclinal bending can occur in response to the occurrence of obstacles in the front of fold thrust belts (e.g. Hindle and Burkhard, 1999; Marques and Cobbold, 2002, 2006; Marshak, 2004),

while others propose mechanisms associated with lithospheric buckling around a sub-vertical axis (Gutiérrez-Alonso et al., 2008; Pastor-Galán et al., 2012a; Johnston et al., 2013). Alternatively, the formation of many oroclines has been attributed to along-strike variations in plate boundary migration, promoted for example, by slab rollback (Loiselet et al., 2009; Rosenbaum, 2014). In addition, oroclinal bending can be associated with the indentation of rigid blocks along convergent plate boundaries (Tapponnier et al., 1982). Actually, oroclinal bending may involve a combination of the above mechanisms (e.g. Li et al., 2012; Rosenbaum et al., 2012; Li and Rosenbaum, 2014; Moresi et al., 2014), but in many cases (particularly in ancient oroclines), the scarcity of geological constraints has resulted in ambiguous and even contradictory explanations. For example, the Cantabrian Orocline has been attributed to either orogenic buckling (Gutiérrez-Alonso et al., 2008) or

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indentation of a rigid block (Şengör, 2013).

Here we focus on the tightly curved Kazakhstan Orocline in the western Central Asian Orogenic Belt (CAOB). The formation of this oroclinal structure had a significant effect on the architecture of the CAOB. Understanding its geometry, kinematics, and geodynamic processes is fundamentally important for tectonic reconstructions of the CAOB, and has general implications for the geodynamics of oroclinal bending in accretionary orogens. The Kazakhstan Orocline is defined by U-shaped arc systems (Fig. 1) (Şengör et al., 1993), which, according to paleomagnetic studies, were quasi-linear prior to the Middle Devonian (Levashova et al., 2012 and references therein). The formation of this oroclinal structure was attributed to the bucking of an originally linear orogenic belt in response to the convergence of the Siberian and Tarim cratons (Fig. 1) (e.g. Abrajevitch et al., 2008; Xiao et al., 2015). This model, however, is conceptual and is not entirely supported by geological data. For example, Li et al. (2017) have recently demonstrated a latest Carboniferous constraint for the collision of the Siberian Craton with the orogenic system around the Kazakhstan Orocline. Such a time constraint postdated the major phase of oroclinal bending in the Late Devonian to Early Carboniferous (e.g. Levashova et al., 2012; Yi et al., 2015), indicating that oroclinal bending may have occurred during subduction. In this contribution, we firstly highlight the geometry and kinematics of the Kazakhstan Orocline by outlining tectonic elements and integrating paleomagnetic data. This is followed by a discussion on tectonic models for oroclinal bending as constrained by available geological data.

2. Major tectonic elements in the western CAOB

The CAOB experienced a prolonged history of accretion since the Neoproterozoic, which was terminated, in the Late Paleozoic to Early Mesozoic, by a collisional orogenic phase driven by the convergence of the Siberian, North China and Tarim cratons (Filippova et al., 2001; Khain et al., 2002; Yakubchuk, 2004; Windley et al., 2007; Wilhem et al., 2012; Seltmann et al., 2014; Xiao et al., 2015). The giant CAOB has been divided into several sub-orogenic collages (e.g. Wilhem et al., 2012; Xiao et al., 2015), termed here as the peri-Siberian orogenic system (PSOS) in the north, the Xing'an-South Mongolian-East Junggar orogenic system (XSMEJOS) in the southeast, and the West Junggar-Kazakhstan-Tianshan orogenic system (WJKTOS) in the southwest (Fig. 1). The PSOS represents progressive accretion along the Siberian margin, and is separated from the WJKTOS by the Irtysh/Char Shear Zone. The latter includes various arcs and continental blocks, and is spatially distributed around the U-shaped Kazakhstan Orocline (Şengör et al., 1993; Van der Voo, 2004; Windley et al., 2007; Levashova et al., 2012; Xiao et al., 2015; Yi et al., 2015). Farther east, the XSMEJOS was considered by some authors to be part of the PSOS (e.g. Xiao et al., 2015).

In the following sections, we review major tectonic units around the Kazakhstan Orocline in the western CAOB. Some confusion exists for the tectonic nomenclature within the WJKTOS across the Chinese-Kazakhstan-Kyrgyzstan borders. The North Tianshan in Kyrgyzstan and southern Kazakhstan (here termed the Kokchetav-North Tianshan belt) is equivalent to the Chinese Central Tianshan and the southern part of the Yili block in NW China (Fig. 1) (e.g. Rojas-Agramonte et al., 2014; Alexeiev et al., 2016). The Chinese North Tianshan does not extend into Kazakhstan farther west. The Kyrgyzstan Middle Tianshan (here termed the Ishim-Middle Tianshan block) wedges out near the Kyrgyzstan-Chinese border and may not be present in NW China (e.g. Rojas-Agramonte et al., 2014; Alexeiev et al., 2016). The South Tianshan Belt was equivalent across different nations.

2.1. Kazakhstan microcontinent and Early Paleozoic island arc systems

The Kazakhstan microcontinent (also termed the Kazakhstan composite continent) occupies a large part of the WJKTOS, and includes two

Precambrian units of the Ishim-Middle Tianshan block in the southwest and the Aktau-Junggar block in the north, as well as a structurally complex Kokchetav-North Tianshan belt in between (Fig. 1) (e.g. Alexeiev et al., 2011). The Kokchetav-North Tianshan belt comprises smaller blocks of Proterozoic continental crust (e.g. Chu-Yili block), as well as early Paleozoic ophiolite, HP/UHP metamorphic complexes, island arc rocks (e.g. Stepnyak arc), continental arc rocks (e.g. Kokchetav-North Tianshan arc) and accretionary wedge complexes (e.g. Erementau-Yili belt, Fig. 1) (Zonenshain et al., 1990; Windley et al., 2007; Biske and Seltmann, 2010; Alexeiev et al., 2011; Glorie et al., 2015; Klemd et al., 2015; Degtyarev et al., 2017). In the Chinese western Tianshan, two tectonic units, Yili and Central Tianshan blocks, have been defined. The northern part of the Yili block possibly represents the eastern segment of the Aktau-Junggar block, whereas the southern part of the Yili block and the Central Tianshan block are likely correlated to the Kokchetav-North Tianshan belt (Fig. 1) (e.g. Rojas-Agramonte et al., 2014). The tectonic boundary between the northern and southern Yili block in the Chinese western Tianshan is poorly exposed and remains unclear (e.g. Wang et al., 2014b).

Early Paleozoic island arc systems, Boshchekul-Chingiz (also referred to as Bozshakol-Chngiz) and Baydaulet-Akbastau arcs, occur along the northern limb of the Kazakhstan Orocline. The Boshchekul-Chingiz arc extends from central Kazakhstan to NW China (West Junggar, Fig. 1), and is characterized by Cambrian to Silurian volcanic and siliciclastic sequences (Chen et al., 2010; Shen et al., 2012, 2015; Degtyarev et al., 2015). The Baydaulet-Akbastau arc occurs to the south of the Boshchekul-Chingiz arc, and is dominated by Ordovician volcanic and volcano-sedimentary complexes (Degtyarev, 2011).

The continental blocks and arc systems as mentioned above were likely amalgamated in the early Paleozoic (e.g. Degtyarev and Ryazantsev, 2007; Biske and Seltmann, 2010; Alexeiev et al., 2011, 2016; Bazhenov et al., 2012; Rojas-Agramonte et al., 2013; Glorie et al., 2015). The Ishim-Middle Tianshan block may have been jointed with the Kokchetav-North Tianshan belt in the Ordovician, and an active marginal arc system of the Kokchetav-North Tianshan arc was subsequently developed during the middle Ordovician (Bazhenov et al., 2012). This subduction system was considered by some authors to extend laterally into the Paleo-Asian ocean to generate the Boshchekul-Chingiz island arc, similarly as the Alaska-Aleutian-type arc system (Bazhenov et al., 2012; Xiao and Santosh, 2014). Alternatively, the Boshchekul-Chingiz arc represents an independent Ordovician island arc system, which subsequently collided with the Kokchetav-North Tianshan arc (Fig. 2). This alternative interpretation is supported by the present-day tectonic configuration with the westernmost segment of the Boshchekul-Chingiz arc separated from the Kokchetav-North Tianshan arc by a suture zone and the Cambrian Selety island arc (Fig. 1). A paleomagnetic study by Levashova et al. (2009) showed that the Boshchekul-Chingiz arc likely resided in a low latitude ($\sim 0\text{--}10^\circ$ south) during the Ordovician. Farther north, the Aktau-Junggar block and Baydaulet-Akbastau island arc were inferred close to the equator based on the occurrence of equatorial fauna (Fig. 2) (Popov et al., 2009; Bazhenov et al., 2012). In the latest Ordovician, arc magmatism of the Kokchetav-North Tianshan arc became waning, indicating that the Kokchetav-North Tianshan belt together with the Boshchekul-Chingiz arc and the Ishim-Middle Tianshan block, may have been collided with the Aktau-Junggar block and Baydaulet-Akbastau arc (Figs. 1 and 2) (Bazhenov et al., 2012), to terminate the subduction and to form the prototype of the WJKTOS. The whole orogenic system moved northward in the Silurian and changed its orientation from $\sim E\text{--}W$ to $\sim NW\text{--}SE$ (Abrajevitch et al., 2007; Bazhenov et al., 2012).

2.2. Late Paleozoic arc systems around the Kazakhstan Orocline

Late Paleozoic arc systems around the Kazakhstan Orocline mainly include the external Devonian Volcanic Belt (DVB) and the internal Balkhash-Yili arc, which were built on the margin of the Kazakhstan

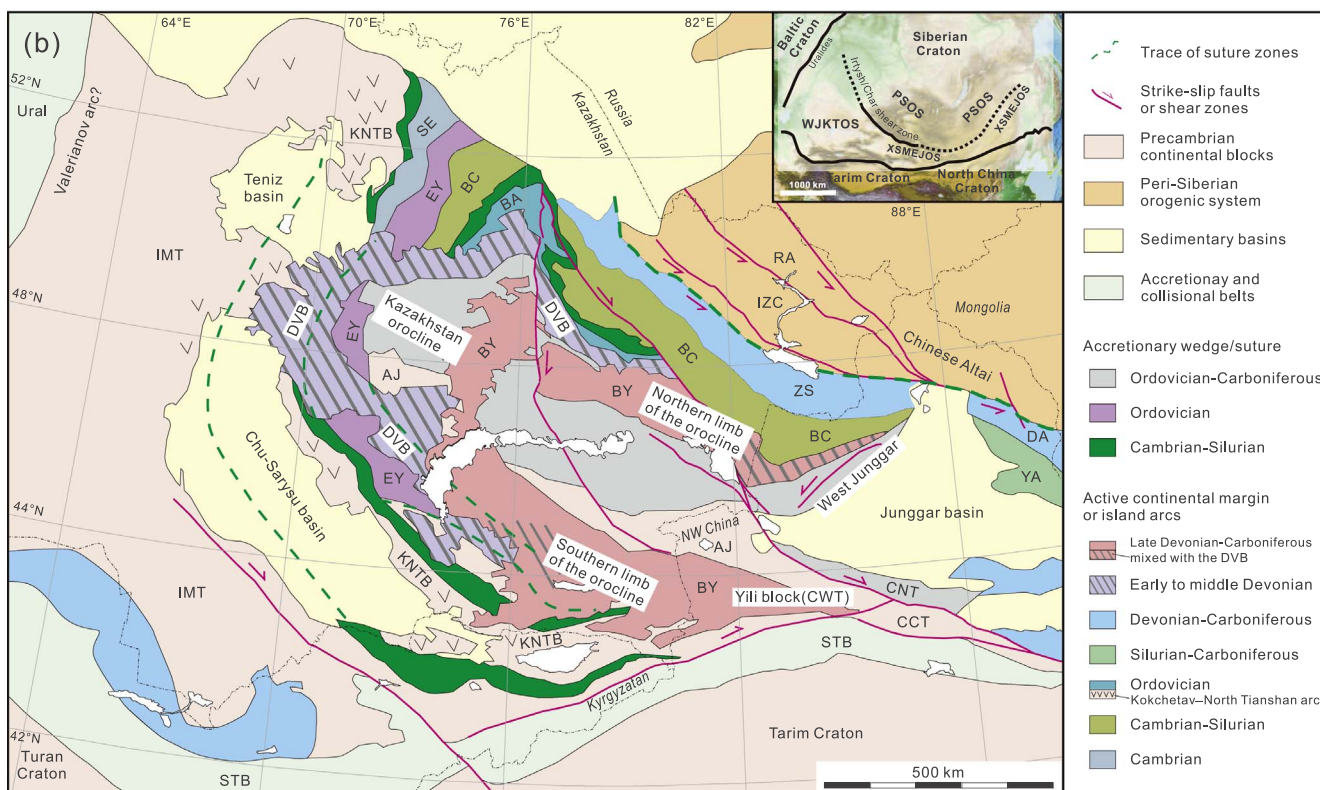
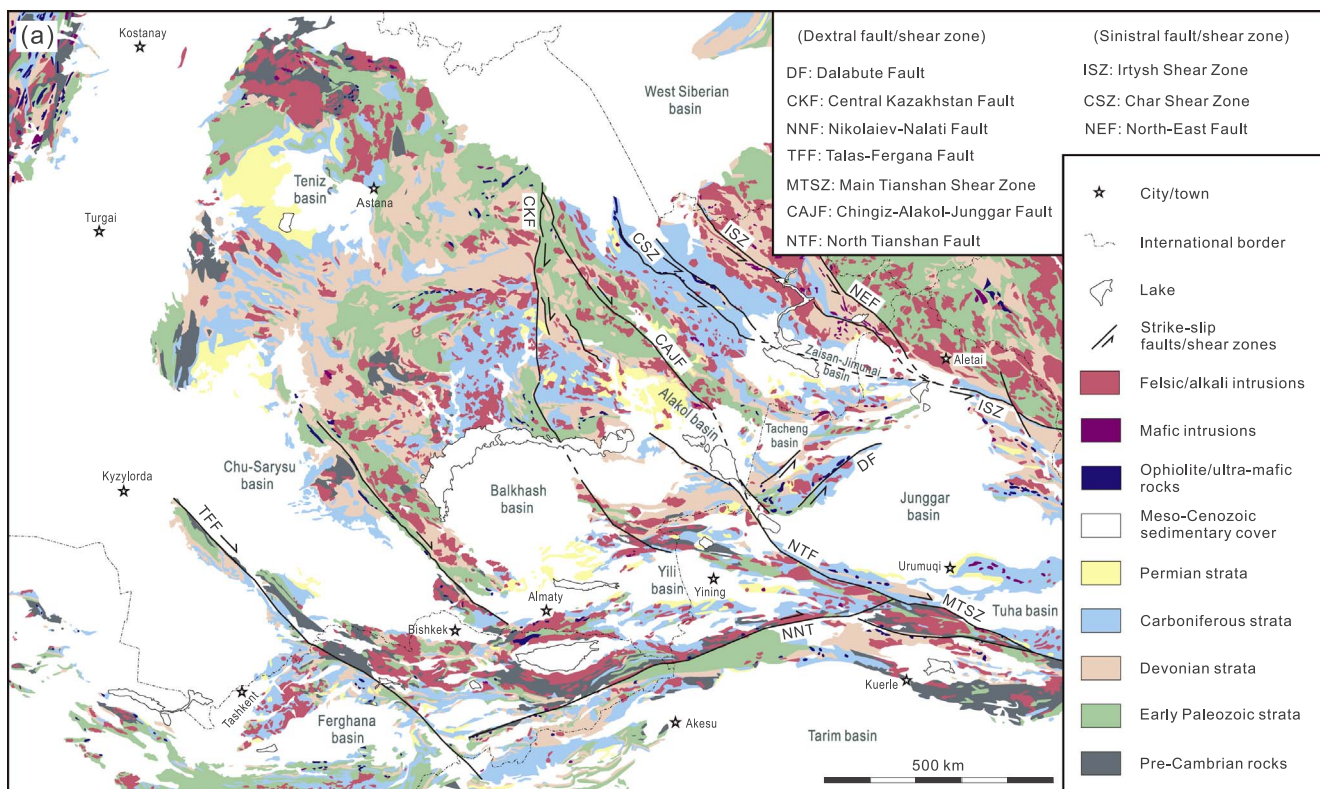


Fig. 1. (1) A simplified geological map in the western CAOB (after Li et al., 2008). (b) Tectonic map showing major tectonic units of the western CAOB (after Windley et al., 2007; Alexeiev et al., 2011). The topographic image is from Amante and Eakins (2009). The Xing'an-South Mongolian-East Junggar orogenic system (XSMEJOS) refers to arc systems in the East Junggar, southern Mongolia and NE China, whereas the West Junggar-Kazakhstan-Tianshan orogenic system (WJKTOS) and the peri-Siberian orogenic system (PSOS) represent arc systems to the south and north of the Irtysh/Char shear zones, respectively. Note that both the Char Shear Zone (CSZ) and the North-East Fault (NEF) merge into the Irtysh Shear Zone (ISZ) in NW China. The tectonic boundary between the WJKTOS and the PSOS is denoted by the ISZ in NW China and the CSZ in eastern Kazakhstan, respectively. RA: Rudny Altai; IZC: Irtysh-Zaisan Complex; ZS: Zharma-Saur arc; BC: Boshchekul-Chingiz arc; BA: Baydaulet-Akbastau arc; EY: Erementau-Yili belt; SE: Seley arc; DA: Dulate arc; YA: Yemaquan arc; BY: Balkhash-Yili arc; DVB: Early to Middle Devonian volcanic belt; KNTB: Kokchetav-North Tianshan belt; IMT: Ishim-Middle Tianshan block; AJ: Aktau-Junggar block; CCT: Chinese Central Tianshan block; CNT: Chinese North Tianshan belt; STB: South Tianshan belt; CWT: Chinese western Tianshan.

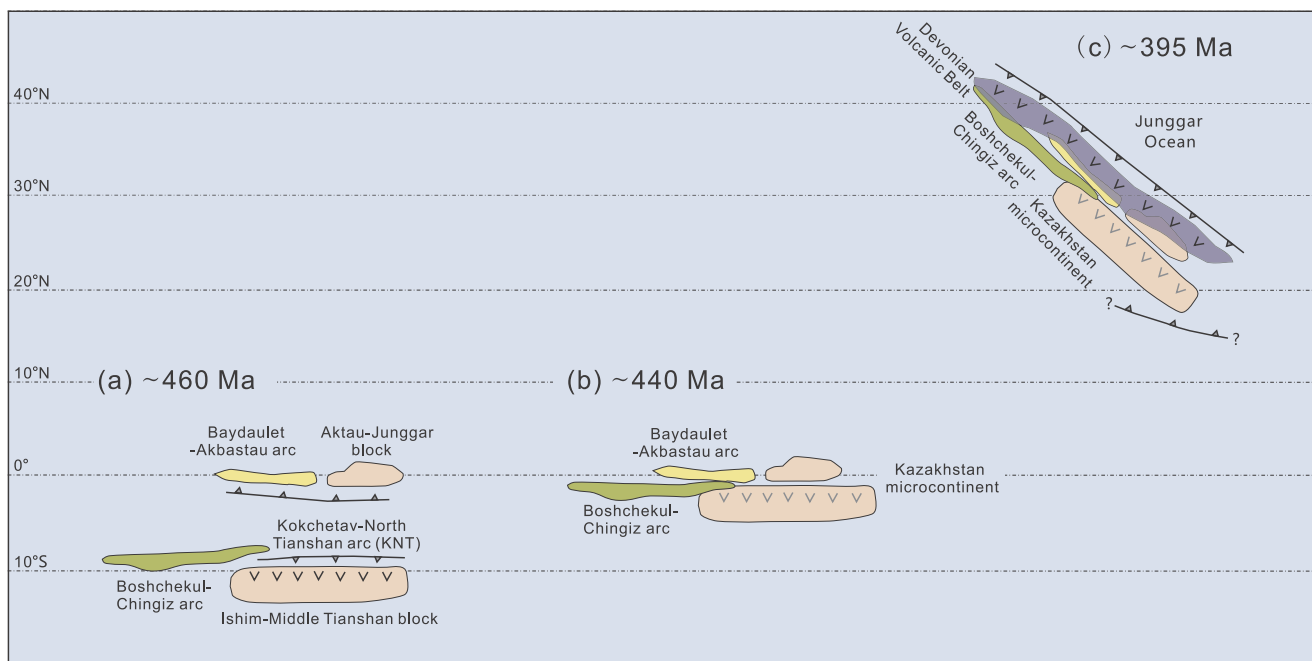


Fig. 2. Schematic reconstruction for the western CAOB in the early Paleozoic (after Bazhenov et al., 2012).

microcontinent and the Boshchekul-Chingiz arc (Figs. 1 and 2). The development of these arc systems was associated with the subduction of the Junggar oceanic plate (Fig. 2) (Windley et al., 2007). The DVB is mainly composed of Early and Middle Devonian volcanic and clastic rocks that represent an Andean-type volcanic arc (Fig. 2c) (Golubovskiy, 1976; Abrajevitch et al., 2008; Degtyarev, 2011; Bazhenov et al., 2012). In the Late Devonian to Carboniferous, arc magmatism shifted towards the core of the orocline forming the Balkhash–Yili arc (Figs. 1 and 3). Volcanic rocks in the Balkhash–Yili arc are calc-alkaline in composition ranging from rhyolite to andesite–dacite and andesite–basalt (BGMRX, 1993; Levashova et al., 2003a; Windley et al., 2007). In the Chinese western Tianshan (Fig. 1), the Balkhash–Yili arc along the southern limb of the Kazakhstan Orocline, is characterized by ~366–345 Ma volcanic/plutonic rocks with a geochemical affinity of the continental marginal arc magmatism (Tang et al., 2010). This was followed by a magmatic quiescent period at ~345–320 Ma, and a reactivation of arc-related magmatism at ~317–306 Ma (Wang et al., 2007b; Tang et al., 2010). In the Early Permian, terrestrial sedimentary deposits and volcanic rocks with an intra-plate origin (such as alkaline basalt and continental tholeiites) extruded on top of Carboniferous rocks, marking the termination of the Balkhash–Yili arc in this region (Wang et al., 2007b). Farther north, the Balkhash–Yili arc extends into the West Junggar (NW China), in which Late Devonian to Early Carboniferous arc magmatism becomes younger towards the core of the Kazakhstan Orocline, and a latest Carboniferous transition from calc-alkaline arc magmatism to alkaline intraplate composition was also detected (Choulet et al., 2012a and reference therein).

An additional late Paleozoic island arc system (the Zharma-Saur arc) occurs to the north of the Boshchekul-Chingiz arc (Fig. 1). It mainly consists of Devonian to Carboniferous arc-related magmatic rocks and sedimentary sequences (Chen et al., 2010, 2016). This arc system may have collided with the Boshchekul-Chingiz arc in the Late Carboniferous, as indicated by the waning of arc-related magmatism in the Zharma-Saur arc during this period (Zhou et al., 2008; Chen et al., 2010; Li et al., 2015a). Moreover, patches of Devonian to Early Carboniferous island arc rocks were recognized within the Char Shear (Suture) Zone along the northern margin of the Zharma-Saur arc, and

they were probably juxtaposed during the collision between the WJKTOS and the PSOS (Ermolov et al., 1981; Safonova et al., 2012, 2017; Kurganskaya et al., 2014).

2.3. Late Paleozoic basin systems around the Kazakhstan Orocline

Two late Paleozoic basins, Chu-Sarysu and Teniz basins, are aligned subparallel to the Devonian Volcanic Belt and the Balkhash–Yili arc (Fig. 1). The Chu-Sarysu basin consists of a ~3–6 km-thick Lower Devonian to Upper Permian stratigraphic sequence with basal Early to Middle Devonian intermediate volcanic and volcanoclastic rocks grading upward into Late Devonian red beds (Box et al., 2012; Zhao et al., 2016). The deposition of lagoonal to marginal-marine salt-bearing strata characterizes the Chu-Sarysu basin in the Early Carboniferous, and is overlain by Late Carboniferous to Permian alluvial-lacustrine red beds, and a shale–limestone sequence (Bykadorov et al., 2003; Alexeiev et al., 2009; Box et al., 2012). The Teniz basin occurs to the north of the Chu-Sarysu basin, and is characterized by a similar sedimentary evolution that involved a continental–marine–continental depositional cycle from Devonian to Permian (Cossette et al., 2014). Graben-like structures within the basins indicate that the Late Devonian to Early Carboniferous rocks were likely deposited in a rift system (Levashova et al., 2012 and reference therein; Zhao et al., 2016). Rocks in both Chu-Sarysu and Teniz basins were folded in the Permian, producing dome-and-basin interference patterns (Allen et al., 2001; Alexeiev et al., 2009; Cossette et al., 2014; Zhao et al., 2016).

The Zaisan–Jimunai, Alakol and Tacheng basins occur along the northern limb of the Kazakhstan Orocline (Figs. 1 and 3). The Zaisan–Jimunai basin was developed from Permian to Paleogene, and Li et al. (2015a) inferred a possible extensional origin for low Permian terrestrial volcano-sedimentary rocks given the increasing deposition thickness towards the basin center. Farther south, the Alakol basin is filled by Permian to Cenozoic sedimentary rocks, in which Early Permian strata are dominated by volcanic rocks and are overlain by the Upper Permian red beds (Allen et al., 1995). The Tacheng basin contains a ~4 km thick Carboniferous to Cenozoic sedimentary sequence, in which Carboniferous deep to shallow marine sedimentary rocks are unconformably overlain by Early Permian terrigenous volcanic and

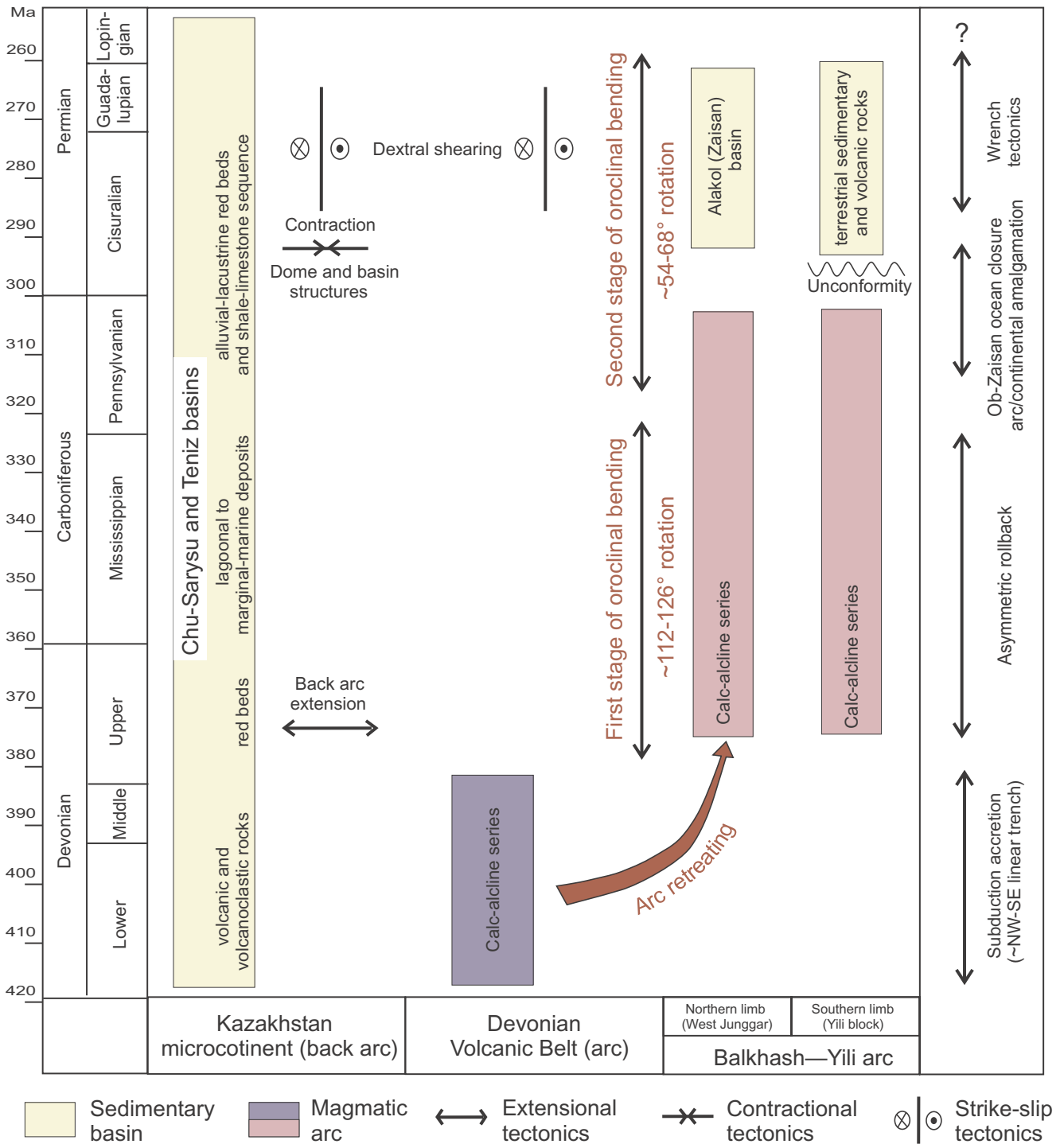


Fig. 3. Spatial and temporal diagram for the western CAOB in the late Paleozoic.

sedimentary rocks (Li et al., 2015b).

The Junggar Basin, which occurs in the core area of the Kazakhstan Orocline (Fig. 1), is characterized by a thick Permian to Cenozoic sedimentary sequence (Coleman, 1989; Allen et al., 1995; He et al., 2013; Yang et al., 2014b; Li et al., 2016a). The basement of the Junggar Basin is not exposed, and has been interpreted as a Precambrian microcontinent (e.g. Zhang et al., 1984), trapped oceanic crust (e.g. Carroll et al., 1990), or Paleozoic arc systems that bridge the East and West Junggar island arc systems (e.g. Zheng et al., 2007; He et al., 2013; Li et al., 2014, 2016a).

2.4. Siberian marginal arc systems

The Chinese Altai, as part of the PSOS, represents a continental marginal arc system along the Siberian margin (Fig. 1). It records the accretion history along the Siberian margin in the Paleozoic and subsequent collision with the WJKTOS (Fig. 1) (Windley et al., 2002, 2007; Xiao et al., 2004, 2009; Yuan et al., 2007). Most of rocks in the Chinese Altai are Ordovician turbiditic and pyroclastic sequences of the Habahe Group (Windley et al., 2002; Long et al., 2007, 2008; Jiang et al., 2011). Devonian arc-related igneous and sedimentary rocks occur farther south (Windley et al., 2002; Chai et al., 2009; Wan et al., 2010), and

can be correlated with the Rudny Altai in Kazakhstan and Russia (Fig. 1) (Li et al., 2016b). The Irtysh Complex represents the southernmost tectonic unit of the Chinese Altai. Rocks in this unit are characterized by a heterogeneous sequence of foliated amphibolite-facies schists, para- and ortho-gneisses, amphibolites and metacherts (Qu and Zhang, 1991; Briggs et al., 2007; Li et al., 2015c), interpreted as an accretionary complex associated with a north-dipping subduction system (O'Hara et al., 1997; Xiao et al., 2009; Li et al., 2017). The Irtysh Complex can be traced into eastern Kazakhstan (Fig. 1), termed as the Irtysh-Zaisan Complex or the Kalba-Naryn terrane (Buslov et al., 2001, 2004a; Windley et al., 2007; Vladimirov et al., 2008; Safonova, 2014; Kotler et al., 2015).

The tectonic boundaries between the Siberian marginal arc system (i.e. the Chinese Altai and its counterpart in Kazakhstan) and the Zharmasaur arc of the WJKTO are represented by the Irtysh Shear Zone in NW China and the Char Shear (Suture) Zone in Kazakhstan (Fig. 1). The suturing time of these two tectonic units has been constrained in the latest Carboniferous (Buslov et al., 2004a; Vladimirov et al., 2008; Cai et al., 2012; Kurganskaya et al., 2014; Safonova, 2014; Yang et al., 2014a; Kuibida et al., 2016; Li et al., 2017).

2.5. South Tianshan belt

The South Tianshan Belt extends for ~2000 km along the southwestern margin of the CAOB, and separates the southern limb of the Kazakhstan Orocline from the Tarim Craton (Fig. 1). It represents a late Paleozoic accretionary and collisional fold-and-thrust belt and is mainly composed of middle to late Paleozoic marine sedimentary rocks, subordinate ophiolites, and volcanic rocks, which are imbricated and stacked together along a series of thrusts (Brookfield, 2000; Burtman, 2006; Gao et al., 2009; Biske and Seltmann, 2010; Han et al., 2011; Wang et al., 2011; Xiao et al., 2013; Jiang et al., 2014; Alexeiev et al., 2015). The tectonic origin of the South Tianshan Belt is controversial. It has been interpreted to form in a fore-arc position in response to either northward subduction of the south Tianshan oceanic plate beneath the Tianshan belt, or southward subduction beneath the Tarim Craton (Charvet et al., 2011; Lin et al., 2013; Xiao et al., 2013; Han et al., 2015, 2016). The closure of the South Tianshan Ocean likely occurred in the Late Carboniferous, but a later closure (Early Triassic) has also been suggested (Han et al., 2011 and the references therein).

2.6. Late Paleozoic strike-slip fault systems in the western CAOB

A series of very large (> 1000 km) strike-slip fault systems were developed in the western CAOB (Fig. 1). Three left-lateral fault systems, Char Shear Zone, Irtysh Shear Zone and North-East Fault, occur along the boundary of the PSOS with the WJKTOS (Qu and Zhang, 1991, 1994; Laurent-Charvet et al., 2003; Buslov et al., 2004b; Briggs et al., 2007; Liu et al., 2013; Hong et al., 2015; Li et al., 2015c, 2016b, 2016c). Both the Char Shear Zone and the North-East Fault are merged into the Irtysh Shear Zone in NW China (Fig. 1). Geochronological data show that the major phase of sinistral shearing occurred at ~286–253 Ma, with a likely reactivation during the Meso-Cenozoic (Buslov et al., 2004b; Briggs et al., 2007; Glorie et al., 2012; Li et al., 2017). Local evidence for dextral shearing has also been demonstrated along the Irtysh Shear Zone in NW China, but the time of deformation is poorly constrained (Laurent-Charvet et al., 2003; Liu et al., 2013).

Farther south, three major strike-slip fault systems of the Central Kazakhstan Fault, the Chingiz–Alakol–Junggar Fault and the Dalabute Fault were developed along/across the northern limb of the Kazakhstan Orocline (Fig. 1) (Shu et al., 1999; Laurent-Charvet et al., 2003; Wang et al., 2008, 2010, 2014a; Lin et al., 2009). The ~N-S trending Central Kazakhstan Fault is characterized by dextral kinematics, and show ~120 km offset (Fig. 4). The Chingiz–Alakol–Junggar Fault shows ~100 km dextral offset (Fig. 4), and is likely connected to the North Tian Shan Fault and the Main Tianshan Shear Zone farther east (Fig. 1).

Geochronological data indicate that the age of dextral shearing is in the range of ~290–240 Ma (Shu et al., 1999; Laurent-Charvet et al., 2003; Wang et al., 2014a). The Dalabute Fault in the West Junggar, which was possibly active in the Permian, is dominated by sinistral kinematics (Allen et al., 1995).

An additional NW-SE trending strike-slip fault (the Talas-Fergana Fault) extends ~2000 km along the southern limb of the Kazakhstan Orocline (Fig. 1), and exhibits a maximum dextral offset of ~200 km since the late Paleozoic (Allen et al., 2001; Alexeiev et al., 2009; Rolland et al., 2013). Geochronological data show that major phase of dextral motion along the entire fault occurred at ~290–260 Ma (Rolland et al., 2013).

3. Geometry of the Kazakhstan Orocline

The tectonic trending of the western CAOB is obliterated by Mesozoic to Cenozoic rocks (Fig. 1a). Here we trace the tectonic orientation via combining the surface geology with the magnetic image of EMAG2 (Earth Magnetic Anomaly Grid; 2-arc-minute resolution). The acquisition and processing of magmatic data are documented in the Geomagnetism website (<http://www.geomag.org/models/emag2.html>). The curved structure of the Kazakhstan Orocline is evident from high-amplitude magnetic anomalies in the total magnetic image, which delineate a U-shaped curvature (Fig. 4a). Such magnetic anomalies are spatially overlapped with arc magmatic rocks in the surface geological map (Fig. 1), likely corresponding to the Devonian Volcanic Belt (Early-Middle Devonian age) and Late Devonian to Late Carboniferous Balkhash-Yili arc, respectively (Fig. 4a and b). The spatial distribution of the Balkhash-Yili arc exposed in the surface geological map matches well with the high-amplitude anomaly around the inner part of the Kazakhstan Orocline (Fig. 4). In contrast, the DVB along the southern limb of the orocline, which is interpreted from the total magnetic image, is slightly biased from the DVB in the surface geological map (Fig. 4). This discrepancy is possibly due to the deviation of the subsurface magnetic anomaly from geological units on the surface. Overall, both the DVB and the Balkhash-Yili arc can be traced around the Kazakhstan Orocline, and are characterized by the shifting of arc magmatism towards the core of the orocline (Figs. 2 and 3).

The Cambrian to Silurian Boshchekul-Chingiz arc, occurs along the northern limb of the Kazakhstan Orocline (Fig. 1), and paleomagnetic data show that it underwent ~180° clockwise rotation (Levashova et al., 2009). Therefore, the Boshchekul-Chingiz arc has been considered to represent the northern limb of the Kazakhstan Orocline (Levashova et al., 2012 and reference therein), which together with the Kazakhstan microcontinent, defines a belt that was quasi-linear prior to oroclinal bending (Fig. 2). A Devonian to Carboniferous arc system (the Zharmasaur arc) occurs to the north of the Boshchekul-Chingiz arc, and cannot be traced around the Kazakhstan Orocline (Fig. 1). Li et al. (2017) have shown that the Zharmasaur arc is dominated by Devonian to Carboniferous detrital zircon grains (Fig. 10D), whereas early Paleozoic detrital zircon grains are abundant in the Boshchekul-Chingiz arc. This contrast in zircon populations suggests that during the Devonian-Carboniferous, the Zharmasaur arc was likely separated from the Boshchekul-Chingiz arc by an oceanic basin. Thus, the Zharmasaur arc does not represent the northern limb of the Kazakhstan Orocline (Li et al., 2017).

A second-order curved structure (here termed the West Junggar orocline) can be recognized along the northern limb of the Kazakhstan Orocline (Fig. 4), where the structural trend varies from ~NW-SE to ~NE-SW. A series of strike-slip faults are developed around the West Junggar orocline with dextral movement along the western limb (e.g. the Chingiz-Alakol-Junggar Fault) and sinistral kinematics along the eastern limb (e.g. the Dalabute Fault). On a larger scale, the Kazakhstan Orocline was cut and overprinted by late Paleozoic strike-slip fault systems (Figs. 1 and 4), and some faults cut through both the northern and southern limbs of the orocline (Figs. 1 and 4). For example, the

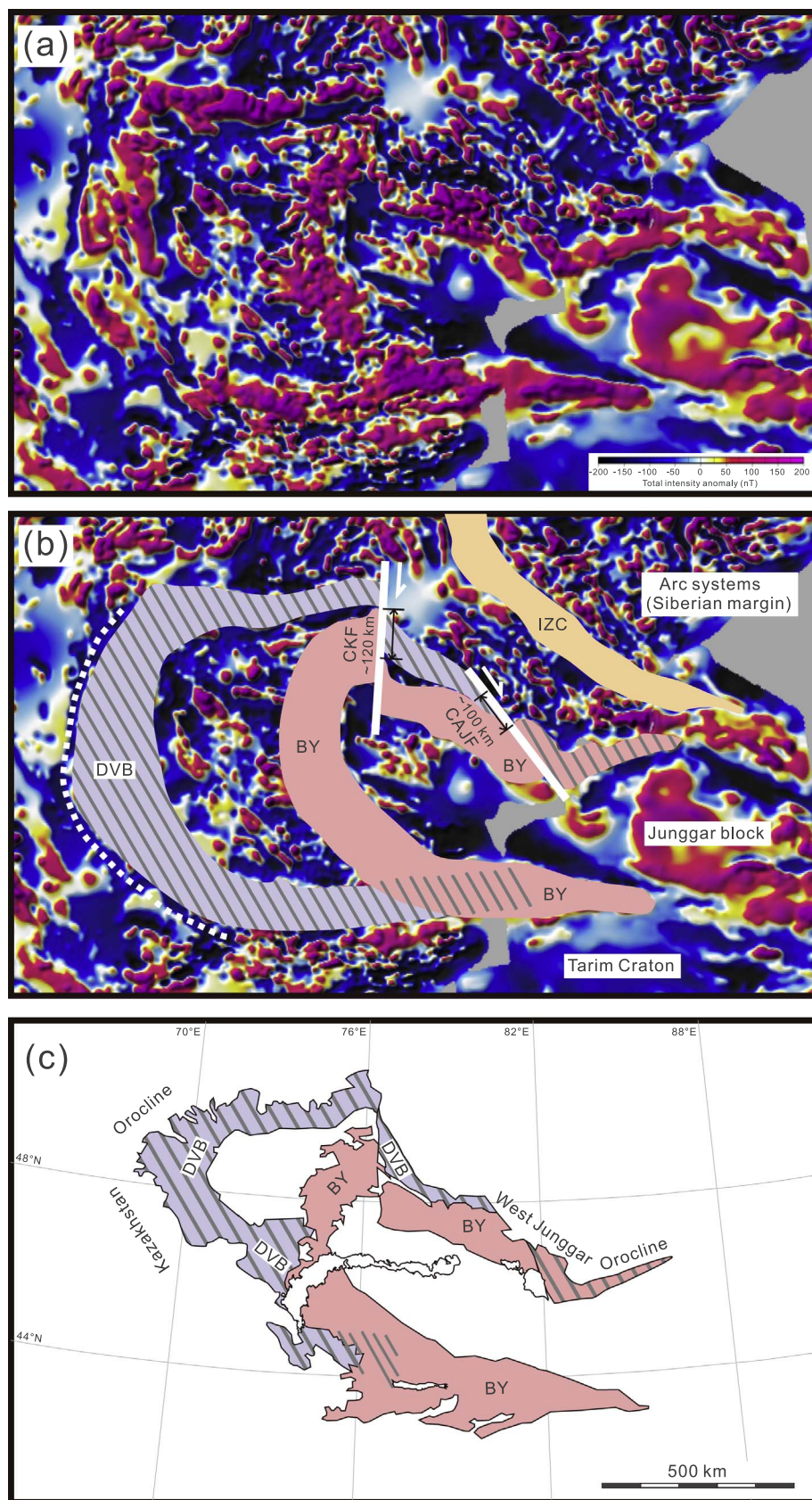


Fig. 4. Geometry of the Kazakhstan Orocline. (a) Total magnetic image around the Kazakhstan Orocline. (b) Interpretation of the total magnetic image, with high magnetic anomaly showing the curved distribution of the Devonian Volcanic Belt (DVB) and the Balkhash-Yili arc (BY) that defines the Kazakhstan Orocline. The Irtysh-Zaisan Complex (IZC), which is located in the boundary area between the Siberian marginal arc system and the WJKTOS, is highlighted by low magnetic anomaly. The dash line illustrates the regional structural trending. (c) The distribution of the Devonian Volcanic Belt (DVB) and the Balkhash-Yili arc (BY) inferred from the geological/tectonic map (Fig. 1). Note that a second-order curved structure (here termed the West Junggar orocline) can be recognized along the northern limb of the Kazakhstan Orocline, where structural trending varies for $\sim 90^\circ$ from \sim NW-SE to \sim NE-SW. The offset of the Central Kazakhstan Fault (CKF) and the Chingiz-Alakol-Junggar Fault (CAJF) is estimated based on the displacement of the magnetic anomaly. The magnetic image of EMAG2 (Earth Magnetic Anomaly Grid; 2-arc-minute resolution), is adapted from the Geomagnetism website (<http://www.geomag.org/models/emag2.html>).

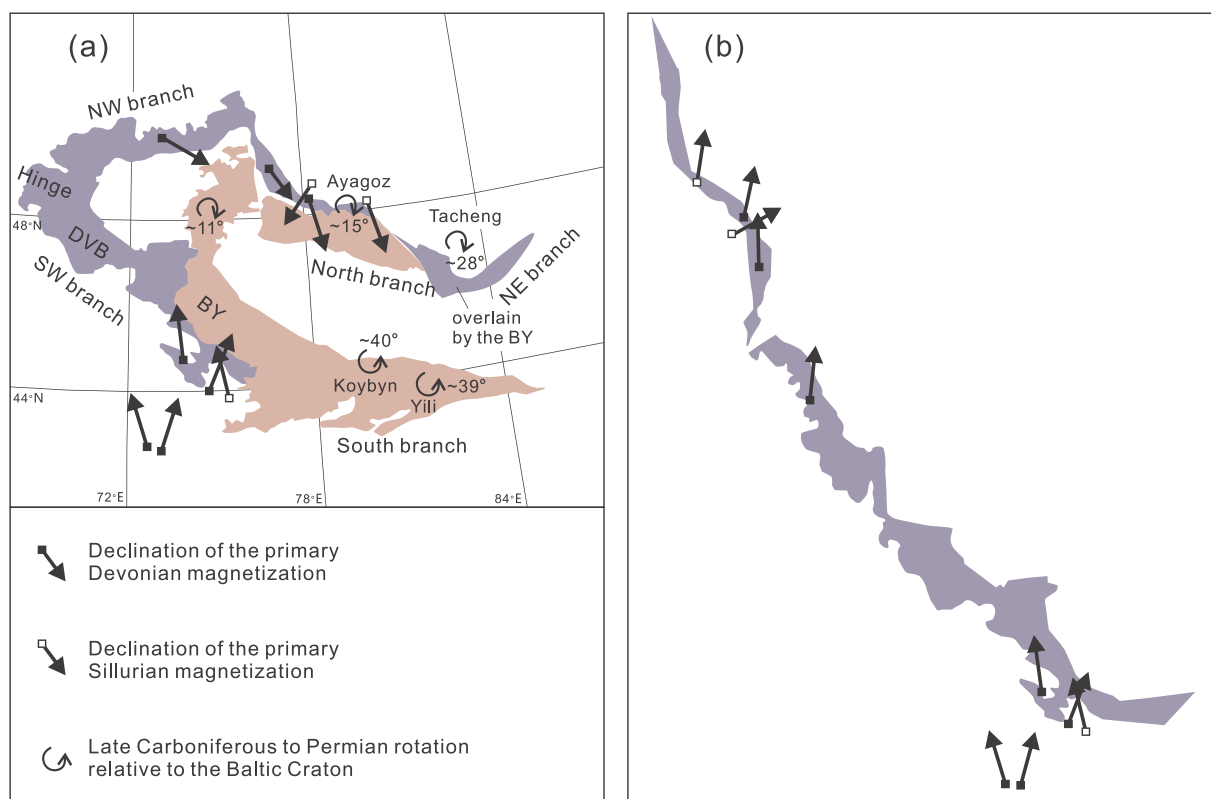


Fig. 5. (a) Paleomagnetic data around the Kazakhstan Orocline (after [Abrajevitch et al., 2007](#); [Wang et al., 2007a](#); [Levashova et al., 2012](#); [Yi et al., 2015](#)). Also see the synthesis of Late Carboniferous to Permian paleomagnetic data in [Appendix Table 1](#). (b) Quasi-linear distribution of the Devonian Volcanic Belt (DVB) after restoring the orocline (based on [Abrajevitch et al., 2007](#); [Bazhenov et al., 2012](#); [Levashova et al., 2012](#)). BY: Balkhash-Yili arc.

~NW-SE Chingiz-Alakol-Junggar Fault cut through the northern limb of the orocline, and is connected to the steeply dipping North Tianshan Fault that truncates through the southern limb of the orocline ([Fig. 1](#)).

4. Kinematics of the Kazakhstan Orocline

The development of the U-shaped Kazakhstan Orocline from an original quasi-linear orogen is supported by paleomagnetic data ([Levashova et al., 2009, 2003b](#); [Van der Voo et al., 2006](#); [Abrajevitch et al., 2007, 2008](#); [Choulet et al., 2011](#); [Bazhenov et al., 2012](#); [Levashova et al., 2012](#); [Yi et al., 2015](#)). In this section, we use paleomagnetic data compiled by [Levashova et al. \(2012\)](#) and [Yi et al. \(2015\)](#), to plot the pre-Late Carboniferous paleomagnetic declination against the orogenic strike and to calculate the rotation of various sites around the orocline with respect to the Baltica during the Late Carboniferous to Permian ([Fig. 5](#)). In order to describe the rotation of each segment of the orocline, we further divide two limbs of the orocline into several branches, namely the NE, North, NW, SW and South branches ([Fig. 5](#)).

The hinge area of the Kazakhstan Orocline was supposedly collided with the Baltica in the Late Carboniferous ([Puchkov, 1997](#); [Filippova et al., 2001](#)), and thus this part of the orocline had been fixed relative to the Baltica since then. We recalculated Late Carboniferous to Permian poles for the Baltica to the site of paleomagnetic samples, from which we calculate a reference declination in the sample site ([Appendix Table 1](#)). The variation between this reference declination and the measured declination gives the rotation of the sample sites with respect to the Baltica ([Levashova et al., 2012](#)). In addition, a series of strike-slip faults were developed during the Permian (Section 2.6), which may have been associated with the block rotation. Indeed, various sites in the SW and South branches of the orocline show either non-rotation or variable amount of rotation in the Middle Permian to Early Triassic, which has been attributed to the local rotation associated with the development of large-scale strike-slip faults/shear zones ([Van der Voo](#)

[et al., 2006](#)). Following [Levashova et al. \(2012\)](#), the rotation amount during/after the Middle-Late Permian, which may represent local rotation associated with strike-slip faulting, was deduced when calculating the rotation amount of each branch of the orocline relative to the Baltica during the Late Carboniferous to Early Permian (see [Appendix Table 1](#)).

Paleozoic data from Ayagoz and Tacheng areas ([Fig. 5](#)) along the North branch show $\sim 15^\circ$ and $\sim 28^\circ$ clockwise rotations relative to the Baltica during the Late Carboniferous to Early Permian ([Appendix Table 1](#)). Another site in the NW branch shows $\sim 11^\circ$ clockwise rotation during this period, which is close to the error of the paleomagnetic method (e.g. [Levashova et al., 2012](#)). In the south branch of the orocline (Koybyn area), a $\sim 40^\circ$ counterclockwise rotation relative to the Baltica was inferred ([Fig. 5](#)) after deducing the rotation amount during/after the Middle to Late Permian ([Appendix Table 1](#)) ([Levashova et al., 2012](#)). Farther east in NW China, paleomagnetic data in the Yili block show $\sim 39^\circ$ counterclockwise rotation relative to the Baltica from Late Carboniferous to Middle Permian ([Appendix Table 1](#)) ([Wang et al., 2007a](#)), consistently with the amount of rotation in the Koybyn area.

Silurian to Devonian declinations are approximately north-oriented in SW and South branches of the orocline, and south-oriented in the North branch ([Fig. 5](#)) ([Abrajevitch et al., 2007](#); [Bazhenov et al., 2012](#); [Levashova et al., 2012](#)), which indicates $\sim 180^\circ$ relative rotation of the North branch relative to the South branch. After deducing $\sim 15\text{--}28^\circ$ clockwise rotation of the North branch and $\sim 39\text{--}40^\circ$ anticlockwise rotation of the South branch in the Late Carboniferous to Early Permian, we obtain $\sim 112\text{--}126^\circ$ rotation for the North branch with respect to the South branch in the Late Devonian to Early Carboniferous.

In a summary, oroclinal bending likely occurred during the Late Devonian to Permian, with $\sim 112\text{--}126^\circ$ bending in the Late Devonian to Early Carboniferous. A further $\sim 15\text{--}28^\circ$ rotation of the northern limb and $\sim 39\text{--}40^\circ$ rotation of the southern limb with respect to the hinge of the orocline were developed during the Late Carboniferous to Permian.

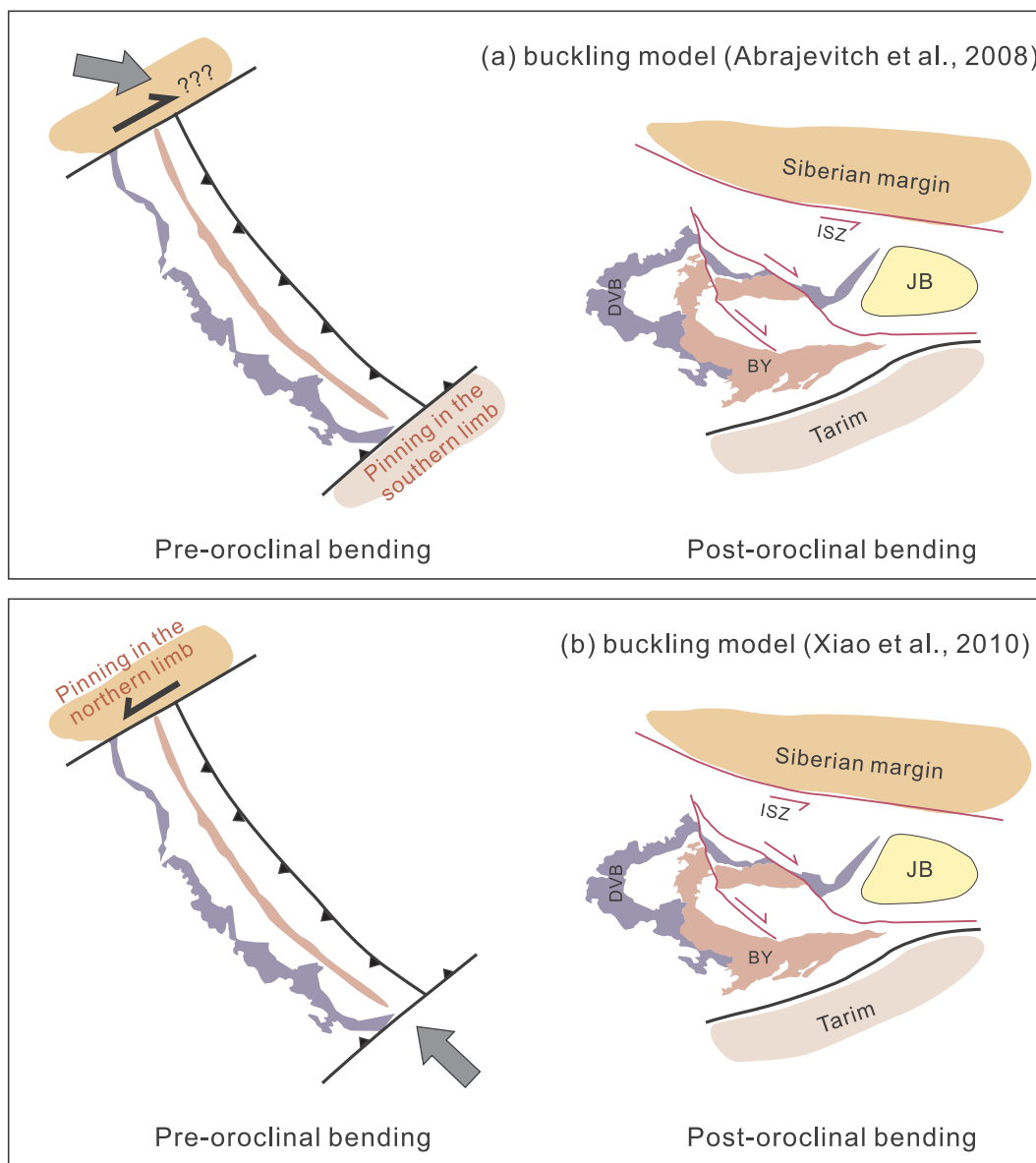


Fig. 6. Schematic diagrams showing the buckling model for the Kazakhstan Orocline. (a) The formation of the orocline resulted from the pinning of the southern limb, but the clockwise rotation of the northern limb that was driven by dextral shearing and dragging in response to movement of the Siberian Craton with respect to the WJKTS (Abrajevitch et al., 2008). (b) The northern limb of the Kazakhstan Orocline was blocked along the sinistral Irtysh Shear Zone, and the northward subduction of the South Tianshan oceanic plate buckled the WJKTS to form the Kazakhstan Orocline (Xiao et al., 2010). See the abbreviation in Figs. 1 and 7.

Prior to oroclinal bending, the arc system was quasi-linear with a ~NW-SE strike, which is compatible with the north-oriented declination (Fig. 5).

5. Tectonic models

5.1. Buckling of a linear orogenic belt

The origin of the Kazakhstan Orocline is commonly attributed to buckling of a relatively linear belt (WJKTS) in response to the assembly of Siberian and Tarim cratons (Fig. 6) (Van der Voo, 2004; Abrajevitch et al., 2008; Xiao et al., 2010). One scenario involves pinning of the southern limb and clockwise rotation of the northern limb driven by the dextral shear and dragging in response to the relative movement between the Siberian Craton and the WJKTS (Fig. 6a) (Abrajevitch et al., 2008). According to this tectonic model, the convergence of Siberian and Tarim cratons was responsible for buckling the linear belt of WJKTS. A slightly different model by Xiao et al. (2010) assumes that

the northern limb of the Kazakhstan Orocline was pinned along the sinistral Irtysh Shear Zone, and that buckling of the WJKTS was controlled by northward subduction of the South Tianshan oceanic plate (Fig. 6b).

The buckling model, which involves deformation of the whole lithosphere around a sub-vertical axis in response to orogen-parallel shortening, has been applied to explain the origin of other oroclines (e.g. the late Paleozoic Iberian-Armorican Orocline) (Gutiérrez-Alonso et al., 2012; Pastor-Galán et al., 2012b; Johnston et al., 2013; Weil et al., 2013). However, in the Kazakhstan Orocline, the assumption that bending occurred simultaneously with the convergence of the Siberian Craton, the WJKTS and the Tarim Craton is problematic. Li et al. (2017) have found that the closure of the Ob-Zaisan Ocean (or Irtysh-Zaisan Ocean) along the Irtysh/Char Shear Zone occurred in the latest Carboniferous, which is later than the major phase of oroclinal bending (Late Devonian to Early Carboniferous). Furthermore, the map-view length of the Balkhash-Yili arc is much shorter than the DVB around the Kazakhstan Orocline (Fig. 4), which indicates that bending of the

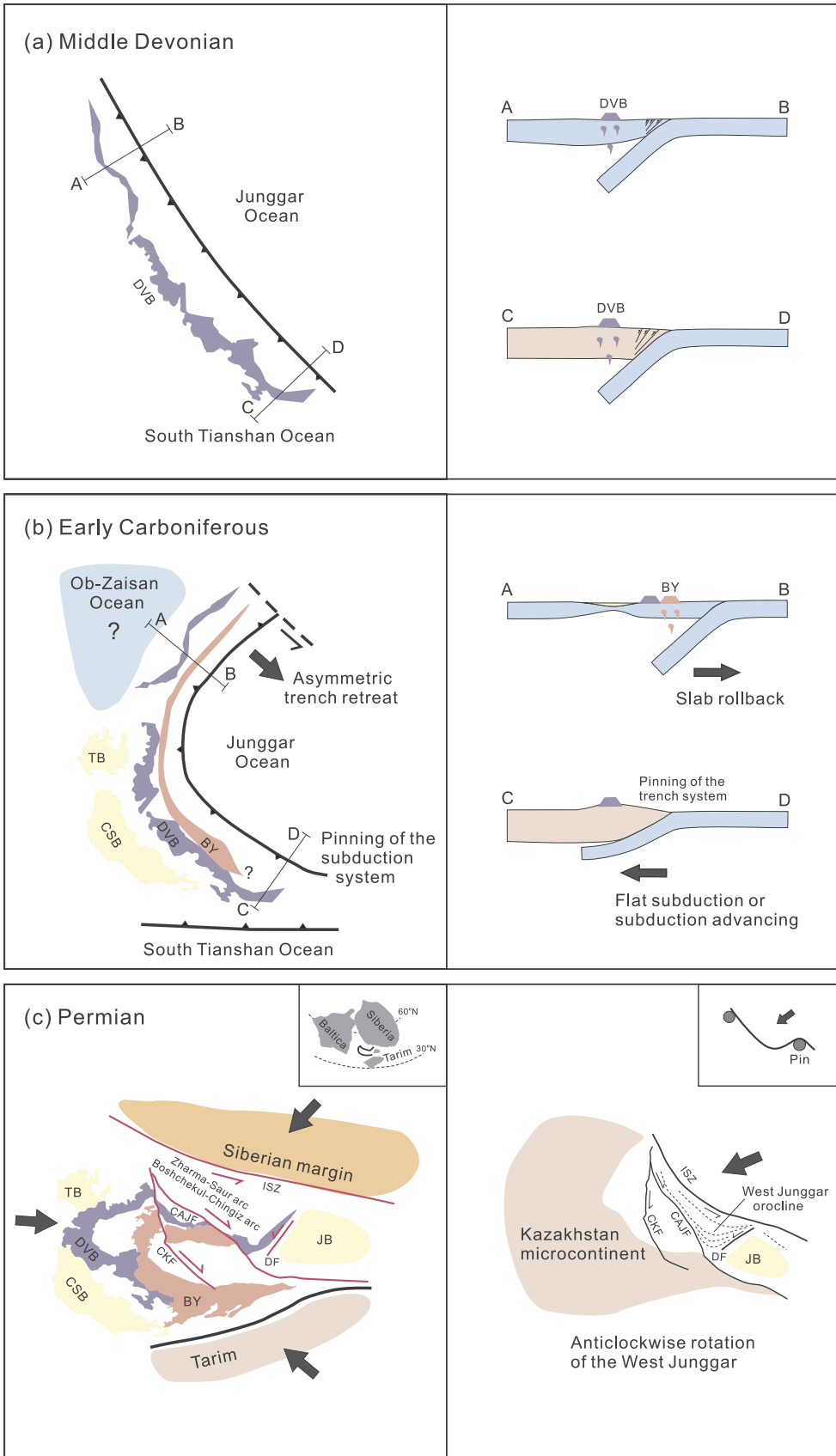


Fig. 7. A rollback-related tectonic model for the Kazakhstan Orocline (after Li et al., 2017). (a) ~NW-SE quasi-linear subduction system in the Early Devonian. (b) Schematic tectonic reconstruction of the western CAOB in the Early Carboniferous. Oroclinal bending as a result of along-strike variation in trench migration, was possibly associated with the pinning of the subduction system in the southern limb and the asymmetric rollback along the northern limb. The bending of the subduction system was accompanied by the development of back-arc basins (Chu-Sarysu and Teniz basins), as well as the migration of the magmatic arc towards the core of the orocline. Note that a larger back-arc basin would be expected to develop north of the Teniz Basin (Fig. 7), which might be represented by the Ob-Zaisan Ocean that was consumed during the subsequent convergence of the Siberian Craton with the WJKTOS. (c) Schematic reconstruction of the western CAOB in the Permian. Note that the second stage of orocline bending was associated with the convergence of Siberian and Tarim cratons, during which strike-slip faults/shear zones cut through the orocline structure. The inset figure in the left is based on Yi et al. (2015). The right figure shows that the triangle Junggar block (JB) possibly obstructed the southward movement of the northern limb of the Kazakhstan Orocline, and led to the anticlockwise rotation of the easternmost segment of the northern limb (West Junggar) and the formation of the second-order West Junggar orocline. The development of the West Junggar Orocline may have been assisted by the sinistral Dalabute Fault (DF) and the dextral Chingiz-Alakol-Junggar Fault (CAJF). The dash line mimics the structural orientation around the West Junggar orocline. TB: Teniz basin; CSB: Chu-Sarysu basin; DVB: Devonian Volcanic Belt; BY: Balkhash-Yili arc; ISZ: Irtysh Shear Zone; CKF: Central Kazakhstan Fault.

subduction system along the WJKTOS must have initiated during or prior to the development of the Balkhash-Yili arc.

5.2. Rollback-related tectonic model for oroclinal bending

The recognition that bending of the WJKTOS occurred during subduction implies that the process of oroclinal bending was likely linked to dynamic interactions within the subduction system. Here, we follow Li et al. (2017) to propose a conceptual reconstruction model, in which Late Devonian to Early Carboniferous rollback-driven oroclinal bending was further tightened during arc/continental amalgamation of the western CAOB in the Late Carboniferous to Permian. We emphasize that the reconstruction is only constrained by limited geological and paleomagnetic data, and likely incorporates errors. However, the reconstruction provides a testable model that highlights the role of slab rollback in the formation of the Kazakhstan Orocline.

The reconstruction assumes a relatively linear subduction zone in the Early to Middle Devonian as inferred from the paleomagnetic data (Section 4). The southwestward subduction of the Junggar oceanic plate formed the Devonian Volcanic Belt (DVB) over the Kazakhstan microcontinent and the Boshchekul-Chingiz arc (Figs. 3 and 7). The ~NW-SE orientation of the DVB in the Early to Middle Devonian is reconstructed based on paleomagnetic data (Section 4). In the Late Devonian to Early Carboniferous, the subduction zone was subjected to slab rollback, as indicated by the retreat of the Balkhash-Yili arc towards the Junggar Ocean with respect to the DVB (Windley et al., 2007). The development of the Chu-Sarysu and Teniz basins likely resulted from overriding plate extension association with trench retreat, as indicated by the occurrence of rift-related grabens in these basins (Section 2.3; Fig. 3). We argue that the ~112–126° bending of the subduction system during the Late Devonian to Early Carboniferous was possibly attained by the asymmetric slab rollback, with pinning of the subduction system along the southern limb of the Kazakhstan Orocline and rapid rollback along the northern limb (Fig. 7b). The along-strike variations in trench migration gave rise to the progressive curvature of the subduction zone, similarly to the formation of the curved New Hebrides arc in the Cenozoic southwest Pacific Ocean (Fig. 8) (Schellart et al., 2002). Indeed, the along-strike variation in the trench migration in the western CAOB is supported by available geological data. The spatial-temporal distribution of arc magmatism in the Yili block (southern limb of the Kazakhstan Orocline, Fig. 1), is indicative of a relatively flat subduction and/or trench advance during the Late Devonian to Early Carboniferous (Tang et al., 2010; Cao et al., 2017). In contrast, the subduction system along the northern limb of the orocline (West Junggar) may have been dominated by rollback of the Junggar oceanic plate as indicated by the oceanward retreat of arc magmatism

(Fig. 7b) (Choulet et al., 2015 and reference therein). In addition, the asymmetric rollback model proposed in this study would expect a larger back-arc basin occurring to the north of the Teniz Basin (Fig. 7). We think that such a large back-arc basin is likely represented by the Ob-Zaisan Ocean that was consumed during the late Paleozoic convergence of the Siberian Craton with the WJKTOS (Fig. 7).

Paleomagnetic data show further bending of ~54–68° in the Late Carboniferous to Permian, which overlapped in time with the amalgamation of arc systems and continental blocks in the western CAOB. In the north, the Siberian marginal arc system (i.e. Russian, Kazakhstan and Chinese Altai) may have been collided with the Zharma-Saur arc along the Irtysh/Char Shear Zone following the closure of the Ob-Zaisan Ocean in the Late Carboniferous (Buslov et al., 2004a; Vladimirov et al., 2008; Cai et al., 2012; Safonova, 2014; Yang et al., 2014a; Kuibida et al., 2016; Li et al., 2017). The Zharma-Saur arc was likely attached to the Boshchekul-Chingiz arc (the northern limb of the Kazakhstan Orocline) during the Late Carboniferous (Section 2.2; Fig. 1). In the south, the South Tianshan Ocean between the WJKTOS and the Tarim Craton was likely closed in the Late Carboniferous (e.g. Han et al., 2011) though some authors suggested a later closure in the Late Permian to Early Triassic (e.g. Xiao et al., 2013). Here, we argue that the convergence of Siberian and Tarim cratons since the Late Carboniferous may have sandwiched the curved WJKTOS, thus leading to a second phase of bending accompanied by the consumption of the Junggar oceanic plate in the core area of the Kazakhstan Orocline (Fig. 7c). In the context of this interpretation, the closure of the Junggar Ocean could be passive and driven by the progressive convergence of Siberian and Tarim cratons if the convergence was faster than the retreat of the Junggar oceanic plate. Alternatively, it is possible that the rate of retreat of the Junggar oceanic plate was higher than the convergence rate of the Siberian and Tarim cratons, thus leading to the occurrence of back-arc extensional basins (Alakol and Zaisan-Jimunai basins?). According to this interpretation, the closure of the Ob-Zaisan Ocean and the second phase of bending of the WJKTOS was driven by a combination of rollback and plate convergence.

The closure of the Junggar Ocean has likely occurred prior to/ during the development of large-scale strike-slip fault systems, which cut through both limbs of the Kazakhstan Orocline (Sections 2.6 and 3; Fig. 1). Available chronological data indicate that these faults were active during a period of ~290–240 Ma (Section 2.6). The Junggar block, which is here assumed to have a rigid basement as suggested by Zhang et al. (1984), was trapped in the core area of the Kazakhstan Orocline following the closure of the Junggar Ocean (Fig. 7c). The triangle shape of this rigid block may obstruct the southward movement of the northern limb of the Kazakhstan Orocline, leading to an anticlockwise rotation of the easternmost segment of the northern limb

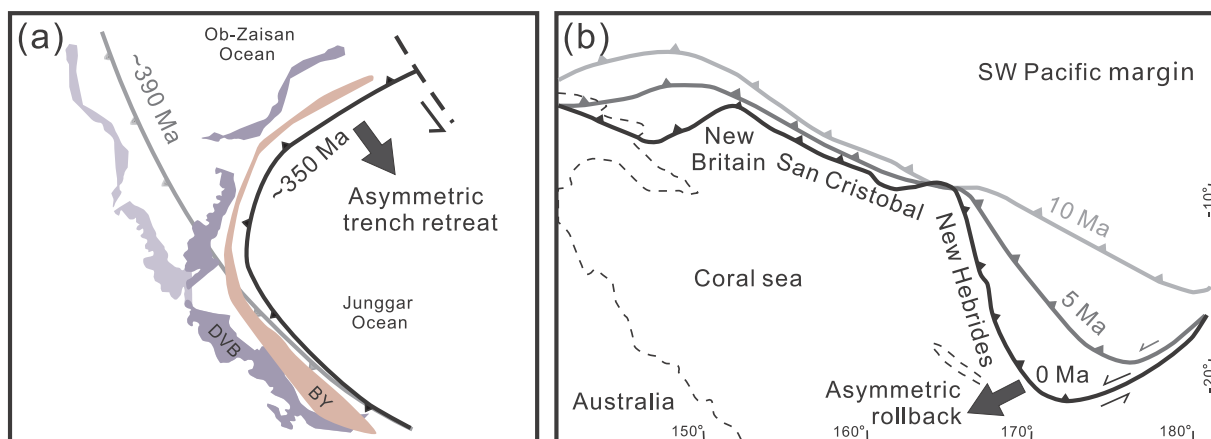


Fig. 8. A comparison between new model for early stage of oroclinal bending in the western CAOB (a) and the development of the curved New Hebrides arc in the SW Pacific margin (b). The tectonic reconstruction for the New Hebrides arc is after Schellart et al. (2007). Note that the map-view curvature of subduction systems is driven by asymmetric slab rollback.

(West Junggar) and the formation the second-order West Junggar orocline (Fig. 7c). The formation of this second-order orocline may have been assisted by the development of the sinistral Dalabute Fault and the dextral Chingiz-Alakol-Junggar Fault (Fig. 7c) (e.g. Choulet et al., 2012b).

Both buckling and rollback models have been proposed to explain the origin of oroclines (Van der Voo, 2004; Johnston et al., 2013; Rosenbaum, 2014). The buckling model involves orogen-parallel shortening (e.g. Gutiérrez-Alonso et al., 2012; Pastor-Galán et al., 2012b), which must be accompanied by the consumption of oceanic lithosphere adjacent to orogenic belts in order to accommodate the space around the core of the orocline. In contrast, the orogen-perpendicular plate boundary migration (e.g. trench retreat) provides ample space for rotations of orogenic segments (e.g. Schellart et al., 2007; Moresi et al., 2014). For example, the bending of the Mariana arc could result from variable amount of trench retreat in response to pinning at northern and southern sides due to aseismic ridge subduction, which was accompanied by the opening of the back-arc basin (e.g. Rosenbaum and Mo, 2011). In the SE Asia, the map-view curvature of the Seram-Timor subduction belt was attributed to variable trench retreat along a continental embayment, and the bending of subducted slab was compatible with the back-arc extension (Spakman and Hall, 2010). In the case of the Kazakhstan Orocline, the benefit of the rollback-related model is to build the link of oroclinal bending with the spatial and temporal variation of arc-related magmatism (the DVB and Balkhash-Yili arc) and the occurrence of rift basins (Chu-Sarysu and Teniz basins) (Fig. 3).

6. Conclusions

- (1) The U-shaped Kazakhstan Orocline can be traced by the Devonian Volcanic Belt and the Late Devonian to Carboniferous Balkhash-Yili arc. A second-order West Junggar orocline is also recognized along the northern limb of the Kazakhstan Orocline.
- (2) The orogenic system around the Kazakhstan Orocline was originally quasi-linear and underwent $\sim 112\text{--}126^\circ$ rotation during the Late Devonian to Carboniferous. This was followed by $\sim 54\text{--}68^\circ$ further rotation in the Late Carboniferous to Permian.
- (3) The Kazakhstan Orocline was likely subjected to two stages of bending. Oroclinal bending in the Late Devonian to Early Carboniferous was likely driven by along-strike variations in the rollback rate of the Junggar oceanic plate, which was accompanied by the spatial migration of magmatic arc and the occurrence of rift basins. The second stage of bending was possibly associated with the Late Carboniferous to Permian continental/arc amalgamation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.jseas.2017.07.029>.

References

- Abrajvitch, A., Van der Voo, R., Levashova, N.M., Bazhenov, M.L., 2007. Paleomagnetic constraints on the paleogeography and oroclinal bending of the Devonian volcanic arc in Kazakhstan. *Tectonophysics* 441, 67–84.
- Abrajvitch, A., Van der Voo, R., Bazhenov, M.L., Levashova, N.M., McCausland, P.J.A., 2008. The role of the Kazakhstan orocline in the late Paleozoic amalgamation of Eurasia. *Tectonophysics* 455, 61–76.
- Alexeiev, D., Kröner, A., Hegner, E., Rojas-Agramonte, Y., Biske, Y.S., Wong, J., Geng, H., Ivleva, E., Mühlberg, M., Mikolaichuk, A., 2016. Middle to Late Ordovician arc system in the Kyrgyz Middle Tianshan: from arc-continent collision to subsequent evolution of a Palaeozoic continental margin. *Gondwana Res.* 36, 261–291.
- Alexeiev, D.V., Cook, H.E., Buvtyshkin, V.M., Golub, L.Y., 2009. Structural evolution of the Ural-Tian Shan junction: a view from Karatau ridge, South Kazakhstan. *C.R. Geosci.* 341, 287–297.
- Alexeiev, D.V., Ryazantsev, A.V., Kröner, A., Tretyakov, A.A., Xia, X., Liu, D.Y., 2011. Geochemical data and zircon ages for rocks in a high-pressure belt of Chu-Yili Mountains, southern Kazakhstan: Implications for the earliest stages of accretion in Kazakhstan and the Tianshan. *J. Asian Earth Sci.* 42, 805–820.
- Alexeiev, D.V., Biske, Y.S., Wang, B., Djenchuraeva, A.V., Getman, O.F., Aristov, V.A., Kröner, A., Liu, H., Zhong, L., 2015. Tectono-Stratigraphic framework and Palaeozoic evolution of the Chinese South Tianshan. *Geotectonics* 49, 93–122.
- Allen, M.B., Şengör, A.M.C., Natal'in, B.A., 1995. Junggar, Turfan and Alakol basins as Late Permian to Early Triassic extensional structures in a sinistral shear zone in the Altaid orogenic collage, Central Asia. *J. Geol. Soc.* 152, 327–338.
- Allen, M.B., Alsop, G.I., Zhemchuzhnikov, V.G., 2001. Dome and basin refolding and compressive inversion along the Karatau Fault System, southern Kazakhstan. *J. Geol. Soc.* 158, 83–95.
- Amante, C., Eakins, B.W., 2009. ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19pp.
- Bazhenov, M.L., Levashova, N.M., Degtyarev, K.E., Van der Voo, R., Abrajvitch, A.V., McCausland, P.J.A., 2012. Unraveling the early-middle Paleozoic paleogeography of Kazakhstan on the basis of Ordovician and Devonian paleomagnetic results. *Gondwana Res.* 22, 974–991.
- BGMRX, 1993. Bureau of Geology and Mineral Resources of Xinjiang Autonomous Region, Regional Geology of Xinjiang Autonomous Region (in Chinese with English abstract). Geological Publishing House, Beijing, pp. 841.
- Biske, Y.S., Seltmann, R., 2010. Paleozoic Tian-Shan as a transitional region between the Rheic and Urals-Turkestan oceans. *Gondwana Res.* 17, 602–613.
- Box, S.E., Syusyura, B., Seltmann, R., Creaser, R.A., Dolgoplova, A., Zientek, M., 2012. Dzhuzkazgan and associated sandstone copper deposits of the Chu-Sarysu basin, central Kazakhstan. *Soc. Econ. Geol.* 303–328.
- Briggs, S.M., Yin, A., Manning, C.E., Chen, Z.-L., Wang, X.-F., Grove, M., 2007. Late Paleozoic tectonic history of the Ertix Fault in the Chinese Altai and its implications for the development of the Central Asian Orogenic System. *Geol. Soc. Am. Bull.* 119, 944–960.
- Brookfield, M., 2000. Geological development and Phanerozoic crustal accretion in the western segment of the southern Tien Shan (Kyrgyzstan, Uzbekistan and Tajikistan). *Tectonophysics* 328, 1–14.
- Burtman, V., 2006. The Tien Shan Early Paleozoic tectonics and geodynamics. *Russ. J. Earth Sci.* 8, 1–23.
- Buslov, M.M., Saphonova, I.Y., Watanabe, T., Obut, O., Fujiwara, Y., Iwata, K., Semakov, N., Sugai, Y., Smirnova, L., Kazansky, A.Y., 2001. Evolution of the Paleo-Asian Ocean (Altai-Sayan Region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent. *Geosci. J.* 5, 203–224.
- Buslov, M.M., Fujiwara, Y., Iwata, K., Semakov, N.N., 2004a. Late Paleozoic-Early Mesozoic Geodynamics of Central Asia. *Gondwana Res.* 7, 791–808.
- Buslov, M.M., Watanabe, T., Fujiwara, Y., Iwata, K., Smirnova, L.V., Safonova, I.Y., Semakov, N.N., Kiryanova, A.P., 2004b. Late Paleozoic faults of the Altai region, Central Asia: tectonic pattern and model of formation. *J. Asian Earth Sci.* 23, 655–671.
- Bykadorov, V., Bush, V., Fedorenko, O., Filippova, I., Miletchenko, N., Puchkov, V., Smirnov, A., Volozh, B.U.A., 2003. Ordovician–Permian palaeogeography of Central Eurasia: development of Palaeozoic petroleum-bearing basins. *J. Pet. Geol.* 26, 325–350.
- Cai, K., Sun, M., Yuan, C., Xiao, W., Zhao, G., Long, X., Wu, F., 2012. Carboniferous mantle-derived felsic intrusion in the Chinese Altai, NW China: implications for geodynamic change of the accretionary orogenic belt. *Gondwana Res.* 22, 681–698.
- Cao, Y., Wang, B., Jahn, B.-M., Cluzel, D., Shu, L., Zhong, L., 2017. Late Paleozoic arc magmatism in the southern Yili Block (NW China): insights to the geodynamic evolution of the Balkhash – Yili continental margin, Central Asian Orogenic Belt. *Lithos* 278–281, 111–125.
- Carey, S.W., 1955. The orocline concept in geotectonics. *Pap. Proc. Roy. Soc. Tas.* 89, 255–288.

- Carroll, A.R., Yunhai, L., Graham, S.A., Xuchang, X., Hendrix, M.S., Jinchi, C., McKnight, C.L., 1990. Junggar basin, northwest China: trapped Late Paleozoic ocean. *Tectonophysics* 181, 1–14.
- Chai, F., Mao, J., Dong, L., Yang, F., Liu, F., Geng, X., Zhang, Z., 2009. Geochronology of metarhyolites from the Kangbutiebao Formation in the Kelang basin, Altay Mountains, Xinjiang: implications for the tectonic evolution and metallogeny. *Gondwana Res.* 16, 189–200.
- Charvet, J., Shu, L., Laurent-Charvet, S., Wang, B., Faure, M., Cluzel, D., Chen, Y., Jong, K., 2011. Paleozoic tectonic evolution of the Tianshan belt, NW China. *Sci. China Earth Sci.* 54, 166–184.
- Chen, J.-F., Han, B.-F., Ji, J.-Q., Zhang, L., Xu, Z., He, G.-Q., Wang, T., 2010. Zircon U-Pb ages and tectonic implications of Paleozoic plutons in northern West Junggar, North Xinjiang, China. *Lithos* 115, 137–152.
- Chen, Y., Xiao, W., Windley, B.F., Zhang, J.E., Zhou, K., Sang, M., 2016. Structures and detrital zircon ages of the Devonian-Permian Tarbagatay accretionary complex in west Junggar, China: imbricated ocean plate stratigraphy and implications for amalgamation of the CAOB. *Int. Geol. Rev.* 1–19.
- Choulet, F., Chen, Y., Wang, B., Faure, M., Cluzel, D., Charvet, J., Lin, W., Xu, B., 2011. Late Paleozoic paleogeographic reconstruction of Western Central Asia based upon paleomagnetic data and its geodynamic implications. *J. Asian Earth Sci.* 42, 867–884.
- Choulet, F., Cluzel, D., Faure, M., Lin, W., Wang, B., Chen, Y., Wu, F.Y., Ji, W., 2012a. New constraints on the pre-Permian continental crust growth of Central Asia (West Junggar, China) by U-Pb and Hf isotopic data from detrital zircon. *Terra Nova* 24, 189–198.
- Choulet, F., Faure, M., Cluzel, D., Chen, Y., Lin, W., Wang, B., 2012b. From oblique accretion to transpression in the evolution of the Altaid collage: new insights from West Junggar, northwestern China. *Gondwana Res.* 21, 530–547.
- Choulet, F., Faure, M., Cluzel, D., Chen, Y., Lin, W., Wang, B., Xu, B., 2015. Toward a unified model of Altaids geodynamics: Insight from the Paleozoic polycyclic evolution of West Junggar (NW China). *Sci. China Earth Sci.* 59, 25–57.
- Coleman, R.G., 1989. Continental growth of northwest China. *Tectonics* 8, 621–635.
- Cossette, P.M., Bookstrom, A.A., Hayes, T.S., Robinson, G.R., Wallis, J., John, C., Zientek, M.L., 2014. Assessment Sandstone Copper Assessment of the Teniz Basin, Kazakhstan. In: Zientek, M.L., Hammarstrom, J.M., Johnson, K.M., (Eds.), *Global Mineral Resource Assessment*, 42pp.
- Degtyarev, K., Ryazantsev, A., 2007. Cambrian arc-continent collision in the Paleozooids of Kazakhstan. *Geotectonics* 41, 63–86.
- Degtyarev, K., 2011. Tectonic evolution of Early Paleozoic Island-arc systems and continental crust formation in the Caledonides of Kazakhstan and the North Tien Shan. *Geotectonics* 45, 23–50.
- Degtyarev, K., Shatagin, K., Kovach, V., Tretyakov, A., 2015. The formation processes and isotopic structure of continental crust of the Chingiz Range Caledonides (Eastern Kazakhstan). *Geotectonics* 49, 485–514.
- Degtyarev, K., Yakubchuk, A., Tretyakov, A., Kotov, A., Kovach, V., 2017. Precambrian geology of the Kazakh uplands and Tien Shan: an overview. *Gondwana Res.* (in press).
- Ermolov, P.V., Dobretsov, N.L., Polyansky, N.V., Klenina, N.L., Khomyakov, V.D., Kuzebny, V.S., Revyakin, P.S., Bortsov, V.D., 1981. Ophiolites of the Chara zone. In: Abdulin, A.A., Patalakha, E.I., (Eds.), *Ophiolites: Nauka KazSSR, Alma-Ata*, pp. 103–178 (in Russian).
- Filippova, I., Bush, V., Didenko, A., 2001. Middle Paleozoic subduction belts: the leading factor in the formation of the Central Asian fold-and-thrust belt. *Russ. J. Earth Sci.* 3, 405–426.
- Gao, J., Long, L., Klemd, R., Qian, Q., Liu, D., Xiong, X., Su, W., Liu, W., Wang, Y., Yang, F., 2009. Tectonic evolution of the South Tianshan orogen and adjacent regions, NW China: geochemical and age constraints of granitoid rocks. *Int. J. Earth Sci.* 98, 1221–1238.
- Glorie, S., De Grave, J., Delvaux, D., Buslov, M.M., Zhimulev, F.I., Vanhaecke, F., Elburg, M.A., Van den haute, P., 2012. Tectonic history of the Irtysh shear zone (NE Kazakhstan): new constraints from zircon U/Pb dating, apatite fission track dating and palaeostress analysis. *J. Asian Earth Sci.* 45, 138–149.
- Glorie, S., Zhimulev, F., Buslov, M., Andersen, T., Plavsa, D., Izmer, A., Vanhaecke, F., De Grave, J., 2015. Formation of the Kokchetav subduction–collision zone (northern Kazakhstan): insights from zircon U-Pb and Lu-Hf isotope systematics. *Gondwana Res.* 27, 424–438.
- Golubovskiy, V.A., 1976. The Devonian volcanic belt of Central Kazakhstan: structural and historical position. *Int. Geol. Rev.* 18, 1155–1159.
- Gutiérrez-Alonso, G., Fernández-Suárez, J., Weil, A., Murphy, J., Nance, R., Corfú, F., Johnston, S., 2008. Self-subduction of the Pangaea global plate. *Nat. Geosci.* 1, 549–553.
- Gutiérrez-Alonso, G., Johnston, S.T., Weil, A., Pastor-Galán, D., Fernández-Suárez, J., Autin, W.J., Holbrook, J.M., 2012. Buckling an orogen: the Cantabrian Orogen. *GSA Today* 22, 4–9.
- Han, B.-F., He, G.-Q., Wang, X.-C., Guo, Z.-J., 2011. Late Carboniferous collision between the Tarim and Kazakhstan-Yili terranes in the western segment of the South Tian Shan Orogen, Central Asia, and implications for the Northern Xinjiang, western China. *Earth Sci. Rev.* 109, 74–93.
- Han, Y., Zhao, G., Sun, M., Eizenhöfer, P.R., Hou, W., Zhang, X., Liu, D., Wang, B., Zhang, G., 2015. Paleozoic accretionary orogenesis in the Paleo-Asian Ocean: insights from detrital zircons from Silurian to Carboniferous strata at the northwestern margin of the Tarim Craton. *Tectonics* 34. <http://dx.doi.org/10.1002/2014TC003668>.
- Han, Y., Zhao, G., Sun, M., Eizenhöfer, P.R., Hou, W., Zhang, X., Liu, Q., Wang, B., Liu, D., Xu, B., 2016. Late Paleozoic subduction and collision processes during the amalgamation of the Central Asian Orogenic Belt along the South Tianshan suture zone. *Lithos* 246–247, 1–12.
- He, D.-F., Li, D., Fan, C., Yang, X.-F., 2013. Geochronology, geochemistry and tectonostratigraphy of Carboniferous strata of the deepest Well Moshen-1 in the Junggar Basin, northwest China: insights into the continental growth of Central Asia. *Gondwana Res.* 24, 560–577.
- Hindle, D., Burkhard, M., 1999. Strain, displacement and rotation associated with the formation of curvature in fold belts; the example of the Jura arc. *J. Struct. Geol.* 21, 1089–1101.
- Hong, T., Xiang, P., You, J., Zhang, L., Wu, C., Wu, Q., Xu, X., 2015. Texture and formation age of the eastern Irtysh collision belt. *Acta Petrol. Sin.* 31, 571–593.
- Jiang, T., Gao, J., Klemd, R., Qian, Q., Zhang, X., Xiong, X., Wang, X., Tan, Z., Chen, B., 2014. Paleozoic ophiolitic mélanges from the South Tianshan Orogen, NW China: geological, geochemical and geochronological implications for the geodynamic setting. *Tectonophysics* 612, 106–127.
- Jiang, Y., Sun, M., Zhao, G., Yuan, C., Xiao, W., Xia, X., Long, X., Wu, F., 2011. Precambrian detrital zircons in the Early Paleozoic Chinese Altai: their provenance and implications for the crustal growth of central Asia. *Precamb. Res.* 189, 140–154.
- Johnston, S.T., Weil, A.B., Gutiérrez-Alonso, G., 2013. Oroclines: thick and thin. *Geol. Soc. Am. Bull.* 125, 643–663.
- Khain, E., Bibikova, E., Kröner, A., Zhuravlev, D., Sklyarov, E., Fedotova, A., Kravchenko-Berezhnoy, I., 2002. The most ancient ophiolite of the Central Asian fold belt: U-Pb and Pb–Pb zircon ages for the Duzhugur Complex, Eastern Sayan, Siberia, and geodynamic implications. *Earth Planet. Sci. Lett.* 199, 311–325.
- Klemd, R., Gao, J., Li, J.-L., Meyer, M., 2015. Metamorphic evolution of (ultra)-high-pressure subduction-related transient crust in the South Tianshan Orogen (Central Asian Orogenic Belt): Geodynamic implications. *Gondwana Res.* 28, 1–25.
- Kotler, P.D., Khromykh, S.V., Vladimirov, A.G., Navozov, O.V., Travin, A.V., Karavaeva, G.S., Kruk, N.N., Murzintsev, N.G., 2015. New data on the age and geodynamic interpretation of the Kalba-Narym granitic batholith, eastern Kazakhstan. *Dokl. Earth Sci.* 462, 565–569.
- Kuibida, M., Safonova, I.Y., Yermolov, P., Vladimirov, A., Kruk, N., Yamamoto, S., 2016. Tonalites and plagiogranites of the Char suture-shear zone in East Kazakhstan: implications for the Kazakhstan-Siberia collision. *Geosci. Front.* 7, 141–150.
- Kurganskaya, E., Safonova, I.Y., Simonov, V., 2014. Geochemistry and petrogenesis of suprasubduction volcanic complexes of the Char shear zone, eastern Kazakhstan. *Russ. Geol. Geophys.* 55, 62–77.
- Laurent-Charvet, S., Charvet, J., Monié, P., Shu, L., 2003. Late Paleozoic strike-slip shear zones in eastern Central Asia (NW China): new structural and geochronological data. *Tectonics* 22. <http://dx.doi.org/10.1029/2001TC901047>.
- Levashova, N.M., Degtyarev, K.E., Bazhenov, M.L., Collins, A.Q., Van der Voo, R., 2003a. Permian palaeomagnetism of East Kazakhstan and the amalgamation of Eurasia. *Geophys. J. Int.* 152, 677–687.
- Levashova, N.M., Degtyarev, K.E., Bazhenov, M.L., Collins, A.Q., Van der Voo, R., 2003b. Middle Paleozoic paleomagnetism of east Kazakhstan: Post-Middle Devonian rotations in a large-scale orocline in the central Ural-Mongol belt. *Tectonophysics* 377, 249–268.
- Levashova, N.M., Van der Voo, R., Abrajevitch, A.V., Bazhenov, M.L., 2009. Paleomagnetism of mid-Paleozoic subduction-related volcanics from the Chingiz Range in NE Kazakhstan: the evolving paleogeography of the amalgamating Eurasian composite continent. *Geol. Soc. Am. Bull.* 121, 555–573.
- Levashova, N.M., Degtyarev, K., Bazhenov, M., 2012. Oroclinal bending of the Middle and Late Paleozoic volcanic belts in Kazakhstan: Paleomagnetic evidence and geological implications. *Geotectonics* 46, 285–302.
- Li, D., He, D., Yang, Y., Lian, Y., 2014. Petrogenesis of mid-Carboniferous volcanics and granitic intrusions from western Junggar Basin boreholes: geodynamic implications for the Central Asian Orogenic Belt in Northwest China. *Int. Geol. Rev.* 56, 1668–1690.
- Li, D., He, D., Ma, D., Tang, Y., Kong, Y., Tang, J., 2015a. Carboniferous-Permian tectonic framework and its later modifications to the area from eastern Kazakhstan to southern Altai: insights from the Zaysan-Jimunai Basin evolution. *J. Asian Earth Sci.* 113, 16–35.
- Li, D., He, D., Qi, X., Zhang, N., 2015b. How was the Carboniferous Balkhash-West Junggar remnant ocean filled and closed? Insights from the Well Tacan-1 strata in the Tacheng Basin, NW China. *Gondwana Res.* 27, 342–362.
- Li, D., He, D., Tang, Y., 2016a. Reconstructing multiple arc-basin systems in the Altai-Junggar area (NW China): implications for the architecture and evolution of the western Central Asian Orogenic Belt. *J. Asian Earth Sci.* 121, 84–107.
- Li, P., Rosenbaum, G., Donchak, P.J.T., 2012. Structural evolution of the Texas Orocline, eastern Australia. *Gondwana Res.* 22, 279–289.
- Li, P., Rosenbaum, G., 2014. Does the Manning Orocline exist? New structural evidence from the inner hinge of the Manning Orocline (eastern Australia). *Gondwana Res.* 25, 1599–1613.
- Li, P., Sun, M., Rosenbaum, G., Cai, K., Yu, Y., 2015c. Structural evolution of the Irtysh Shear Zone (northwestern China) and implications for the amalgamation of arc systems in the Central Asian Orogenic Belt. *J. Struct. Geol.* 80, 142–156.
- Li, P., Sun, M., Rosenbaum, G., Cai, K., Chen, M., He, Y., 2016b. Transpressional deformation, strain partitioning and fold superimposition in the southern Chinese Altai, Central Asian Orogenic Belt. *J. Struct. Geol.* 87, 64–80.
- Li, P., Sun, M., Rosenbaum, G., Jiang, Y., Cai, K., 2016c. Structural evolution of zonal metamorphic sequences in the southern Chinese Altai and relationships to Permian transpressional tectonics in the Central Asian Orogenic Belt. *Tectonophysics* 693, 277–289.
- Li, P., Sun, M., Rosenbaum, G., Jourdan, F., Li, S., Cai, K., 2017. Late Paleozoic closure of the Ob-Zaisan Ocean along the Irtysh Shear Zone (NW China): implications for arc amalgamation and oroclinal bending in the Central Asian Orogenic Belt. *Geol. Soc. Am. Bull.* <http://dx.doi.org/10.1130/B31541.31541>.
- Li, T., Daukeev, S., Kim, B., Tomurtogoo, O., Petrov, O., 2008. Atlas of geological maps of Central Asia and adjacent areas (1:2500000). Geological Publishing House, Beijing, China.

- Lin, W., Faure, M., Shi, Y., Wang, Q., Li, Z., 2009. Palaeozoic tectonics of the south-western Chinese Tianshan: new insights from a structural study of the high-pressure/low-temperature metamorphic belt. *Int. J. Earth Sci.* 98, 1259–1274.
- Lin, W., Chu, Y., Ji, W., Zhang, Z., Shi, Y., Wang, Z., Li, Z., Wang, Q., 2013. Geochronological and geochemical constraints for a middle Paleozoic continental arc on the northern margin of the Tarim block: implications for the Paleozoic tectonic evolution of the South Chinese Tianshan. *Lithosphere* 5, 355–381.
- Liu, F., Wang, Z., Lin, W., Chen, K., Jiang, L., Wang, Q., 2013. Structure deformation and tectonic significance of Erqis fault zone in the southern margin of Chinese Altay. *Acta Petrol. Sin.* 29, 1811–1824 (in Chinese with the English abstract).
- Loiselet, C., Husson, L., Braun, J., 2009. From longitudinal slab curvature to slab rheology. *Geology* 37, 747–750.
- Long, X., Sun, M., Yuan, C., Xiao, W., Lin, S., Wu, F., Xia, X., Cai, K., 2007. Detrital zircon age and Hf isotopic studies for metasedimentary rocks from the Chinese Altai: implications for the Early Paleozoic tectonic evolution of the Central Asian Orogenic Belt. *Tectonics* 26. <http://dx.doi.org/10.1029/2007TC002128>.
- Long, X., Sun, M., Yuan, C., Xiao, W., Cai, K., 2008. Early Paleozoic sedimentary record of the Chinese Altai: implications for its tectonic evolution. *Sed. Geol.* 208, 88–100.
- Marques, F.O., Cobbold, P.R., 2002. Topography as a major factor in the development of arcuate thrust belts: insights from sandbox experiments. *Tectonophysics* 348, 247–268.
- Marques, F.O., Cobbold, P.R., 2006. Effects of topography on the curvature of fold-and-thrust belts during shortening of a 2-layer model of continental lithosphere. *Tectonophysics* 415, 65–80.
- Marshak, S., 2004. Salientes, recesses, arcs, oroclines, and syntaxes - a review of ideas concerning the formation of map-view curves in fold-thrust belts. *AAPG Memoir* 82, 131–156.
- Moresi, L., Betts, P.G., Miller, M.S., Cayley, R.A., 2014. Dynamics of continental accretion. *Nature* 508, 245–248.
- OHara, K.D., Yang, X.-Y., Guoyuan, X., Li, Z., 1997. Regional $\delta^{18}\text{O}$ gradients and fluid-rock interaction in the Altay accretionary complex, northwest China. *Geology* 25, 443–446.
- Pastor-Galán, D., Gutiérrez-Alonso, G., Mulchrone, K.F., Huerta, P., 2012a. Conical folding in the core of an orocline. A geometric analysis from the Cantabrian Arc (Variscan Belt of NW Iberia). *J. Struct. Geol.* 39, 210–223.
- Pastor-Galán, D., Gutiérrez-Alonso, G., Zulauf, G., Zanella, F., 2012b. Analogue modeling of lithospheric-scale orocline buckling: Constraints on the evolution of the Iberian-Armorican Arc. *Geol. Soc. Am. Bull.* 124. <http://dx.doi.org/10.1130/b30640.30641>.
- Popov, L.E., Bassett, M.G., Zhemchuzhnikov, V.G., Holmer, L.E., Klishkevich, I.A., 2009. Gondwanan faunal signatures from Early Paleozoic terranes of Kazakhstan and Central Asia: evidence and tectonic implications. *Geol. Soc., Lond., Spec. Publ.* 325, 23–64.
- Puchkov, V.N., 1997. Structure and geodynamics of the Uralian orogen. *Geol. Soc., Lond., Spec. Publ.* 121, 201–236.
- Qu, G., Zhang, J., 1991. Irtyz structural zone. *Geosci. Xinjiang* 3, 115–131 (in Chinese with the English abstract).
- Qu, G., Zhang, J., 1994. Oblique thrust systems in the Altay orogen, China. *J. SE Asian Earth Sci.* 9, 277–287.
- Rojas-Agramonte, Y., Herwardt, D., García-Casco, A., Kröner, A., Alexeiev, D.V., Klemm, R., Buhre, S., Barth, M., 2013. Early Palaeozoic deep subduction of continental crust in the Kyrgyz North Tianshan: evidence from Lu–Hf garnet geochronology and petrology of mafic dikes. *Contrib. Miner. Petrol.* 166, 525–543.
- Rojas-Agramonte, Y., Kröner, A., Alexeiev, D.V., Jeffreys, T., Khudoley, A.K., Wong, J., Geng, H., Shu, L., Semiletin, S.A., Mikolaichuk, A.V., Kiselev, V.V., Yang, J., Seltmann, R., 2014. Detrital and igneous zircon ages for supracrustal rocks of the Kyrgyz Tianshan and palaeogeographic implications. *Gondwana Res.* 26, 957–974.
- Rolland, Y., Alexeiev, D.V., Kröner, A., Corsini, M., Loury, C., Monié, P., 2013. Late Palaeozoic to Mesozoic kinematic history of the Talas-Ferghana strike-slip fault (Kyrgyz West Tianshan) as revealed by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of syn-kinematic white mica. *J. Asian Earth Sci.* 67–68, 76–92.
- Rosenbaum, G., Mo, W., 2011. Tectonic and magmatic responses to the subduction of high bathymetric relief. *Gondwana Res.* 19, 571–582.
- Rosenbaum, G., Li, P., Rubatto, D., 2012. The contorted New England Orogen (eastern Australia): new evidence from U–Pb geochronology of early Permian granitoids. *Tectonics* 31, TC1006 doi: 10.1029/2011tc002960.
- Rosenbaum, G., 2014. Geodynamics of oroclinal bending: insights from the Mediterranean. *J. Geodyn.* 82, 5–15.
- Safonova, I., Simonov, V., Kurganskaya, E., Obut, O., Romer, R., Seltmann, R., 2012. Late Paleozoic oceanic basalts hosted by the Char suture-shear zone, East Kazakhstan: geological position, geochemistry, petrogenesis and tectonic setting. *J. Asian Earth Sci.* 49, 20–39.
- Safonova, I., 2014. The Russian-Kazakh Altai orogen: an overview and main debatable issues. *Geosci. Front.* 5, 537–552.
- Safonova, I., Kotlyarov, A., Krivonogov, S., Xiao, W., 2017. Intra-oceanic arcs of the Paleozoic-Asian Ocean. *Gondwana Res.* in press.
- Schellart, W.P., Lister, G.S., Jessell, M.W., 2002. Analogue modeling of arc and backarc deformation in the New Hebrides arc and North Fiji Basin. *Geology* 30, 311–314.
- Schellart, W.P., Freeman, J., Stegman, D.R., Moresi, L., May, D., 2007. Evolution and diversity of subduction zones controlled by slab width. *Nature* 446, 308–311.
- Seltmann, R., Porter, T.M., Pirajno, F., 2014. Geodynamics and metallogeny of the central Eurasian porphyry and related epithermal mineral systems: a review. *J. Asian Earth Sci.* 79, 810–841.
- Şengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature* 364, 299–307.
- Şengör, A.M.C., 2013. The Pyrenean Hercynian Keirogen and the Cantabrian Orocline as genetically coupled structures. *J. Geodyn.* 65, 3–21.
- Shen, P., Shen, Y., Li, X.-H., Pan, H., Zhu, H., Meng, L., Dai, H., 2012. Northwestern Junggar Basin, Xiemisitai Mountains, China: a geochemical and geochronological approach. *Lithos* 140, 103–118.
- Shen, P., Pan, H., Seitmuratova, E., Yuan, F., Jakupova, S., 2015. A Cambrian intra-oceanic subduction system in the Bozshakol area, Kazakhstan. *Lithos* 224–225, 61–77.
- Shu, L., Charvet, J., Guo, L., Lu, H., Laurent-Charvet, S., 1999. A large-scale Palaeozoic dextral ductile strike-slip zone: the Aqqikkudug-Weiya zone along the northern margin of the central Tianshan Belt, Xinjiang, NW China. *Acta Geol. Sin.* 73, 148–162.
- Spakman, W., Hall, R., 2010. Surface deformation and slab-mantle interaction during Banda arc subduction rollback. *Nat. Geosci.* 3, 562–566.
- Tang, G.-J., Wang, Q., Wyman, D.A., Sun, M., Li, Z.-X., Zhao, Z.-H., Sun, W.-D., Jia, X.-H., Jiang, Z.-Q., 2010. Geochronology and geochemistry of Late Paleozoic magmatic rocks in the Lamasu-Dabate area, northwestern Tianshan (west China): evidence for a tectonic transition from arc to post-collisional setting. *Lithos* 119, 393–411.
- Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology* 10, 611–616.
- Van der Voo, R., 2004. Paleomagnetism, oroclines, and growth of the continental crust. *GSA Today* 14, 4–9.
- Van der Voo, R., Levashova, N.M., Skrinnik, L.I., Kara, T.V., Bazhenov, M.L., 2006. Late orogenic, large-scale rotations in the Tien Shan and adjacent mobile belts in Kyrgyzstan and Kazakhstan. *Tectonophysics* 426, 335–360.
- Vladimirov, A., Kruk, N., Khromykh, S., Polyansky, O., Chervov, V., Vladimirov, V., Travin, A., Babin, G., Kuibida, M., Vladimirov, V., 2008. Permian magmatism and lithospheric deformation in the Altai caused by crustal and mantle thermal processes. *Russ. Geol. Geophys.* 49, 468–479.
- Wan, B., Zhang, L., Xiang, P., 2010. The Ashele VMS-type Cu–Zn Deposit in Xinjiang, NW China Formed in a Rifted Arc Setting. *Resource Geol.* 60, 150–164.
- Wang, B., Chen, Y., Zhan, S., Shu, L., Faure, M., Cluzel, D., Charvet, J., Laurent-Charvet, S., 2007a. Primary Carboniferous and Permian paleomagnetic results from the Yili Block (NW China) and their implications on the geodynamic evolution of Chinese Tianshan Belt. *Earth Planet. Sci. Lett.* 263, 288–308.
- Wang, B., Shu, L.S., Cluzel, D., Faure, M., Charvet, J., 2007b. Geochemical constraints on Carboniferous volcanic rocks of the Yili Block (Xinjiang, NW China): implication for the tectonic evolution of Western Tianshan. *J. Asian Earth Sci.* 29, 148–159.
- Wang, B., Faure, M., Shu, L., de Jong, K., Charvet, J., Cluzel, D., Jahn, B.M., Chen, Y., Ruffet, G., 2010. Structural and geochronological study of high-pressure metamorphic rocks in the Kekesu section (northwestern China): implications for the late Paleozoic tectonics of the Southern Tianshan. *J. Geol.* 118, 59–77.
- Wang, B., Shu, L., Faure, M., Jahn, B.-M., Cluzel, D., Charvet, J., Chung, S.-L., Meffre, S., 2011. Paleozoic tectonics of the southern Chinese Tianshan: insights from structural, chronological and geochemical studies of the Heiyingshan ophiolitic mélange (NW China). *Tectonophysics* 497, 85–104.
- Wang, B., Cluzel, D., Jahn, B.-M., Shu, L., Chen, Y., Zhai, Y., Branquet, Y., Barbanson, L., Sizaret, S., 2014a. Late Paleozoic pre- and syn-kinematic plutons of the Kangguer-Huangshan Shear zone: Inference on the tectonic evolution of the eastern Chinese north Tianshan. *Am. J. Sci.* 314, 43–79.
- Wang, B., Shu, L., Liu, H., Gong, H., Ma, Y., Mu, L., Zhong, L., 2014b. First evidence for ca. 780 Ma intra-plate magmatism and its implications for Neoproterozoic rifting of the North Yili Block and tectonic origin of the continental blocks in SW of Central Asia. *Precamb. Res.* 254, 258–272.
- Wang, Y., Li, J., Sun, G., 2008. Postcollisional Eastward Extrusion and Tectonic Exhumation along the Eastern Tianshan Orogen, Central Asia: Constraints from Dextral Strike-Slip Motion and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological evidence. *J. Geol.* 116, 599–618.
- Weil, A.B., Gutiérrez-Alonso, G., Johnston, S.T., Pastor-Galán, D., 2013. Kinematic constraints on buckling a lithospheric-scale orocline along the northern margin of Gondwana: a geologic synthesis. *Tectonophysics* 582, 25–49.
- Wilhelm, C., Windley, B.F., Stampfli, G.M., 2012. The Altaids of Central Asia: a tectonic and evolutionary innovative review. *Earth Sci. Rev.* 113, 303–341.
- Windley, B.F., Kröner, A., Guo, J., Qu, G., Li, Y., Zhang, C., 2002. Neoproterozoic to Paleozoic Geology of the Altai Orogen, NW China: New Zircon Age Data and Tectonic Evolution. *J. Geol.* 110, 719–737.
- Windley, B.F., Alexeiev, D., Xiao, W., Kroner, A., Badarch, G., 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *J. Geol. Soc.* 164, 31–47.
- Xiao, W., Windley, B.F., Badarch, G., Sun, S., Li, J., Qin, K., Wang, Z., 2004. Palaeozoic accretionary and convergent tectonics of the southern Altaids: implications for the growth of Central Asia. *J. Geol. Soc.* 161, 339–342.
- Xiao, W., Windley, B., Yuan, C., Sun, M., Han, C., Lin, S., Chen, H., Yan, Q., Liu, D., Qin, K., Li, J., Sun, S., 2009. Paleozoic multiple subduction-accretion processes of the southern Altaids. *Am. J. Sci.* 309, 221–270.
- Xiao, W., Huang, B., Han, C., Sun, S., Li, J., 2010. A review of the western part of the Altaids: a key to understanding the architecture of accretionary orogens. *Gondwana Res.* 18, 253–273.
- Xiao, W., Windley, B.F., Allen, M.B., Han, C., 2013. Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage. *Gondwana Res.* 23, 1316–1341.
- Xiao, W., Santosh, M., 2014. The western Central Asian Orogenic Belt: a window to accretionary orogenesis and continental growth. *Gondwana Res.* 25, 1429–1444.
- Xiao, W., Windley, B., Sun, S., Li, J., Huang, B., Han, C., Yuan, C., Sun, M., Chen, H., 2015. A Tale of Amalgamation of Three Collage Systems in the Permian-Middle Triassic in Central-East Asia: Oroclines, Sutures, and Terminal Accretion. *Annu. Rev. Earth Planet. Sci.* 43. <http://dx.doi.org/10.1146/annurev-earth-060614-105254>.
- Yakubchuk, A., 2004. Architecture and mineral deposit settings of the Altaid orogenic

- collage: a revised model. *J. Asian Earth Sci.* 23, 761–779.
- Yang, G., Li, Y., Safonova, I., Yi, S., Tong, L., Seltmann, R., 2014a. Early Carboniferous volcanic rocks of West Junggar in the western Central Asian Orogenic Belt: implications for a supra-subduction system. *Int. Geol. Rev.* 56, 823–844.
- Yang, Y.-T., Song, C.-C., He, S., 2014b. Jurassic tectonostratigraphic evolution of the Junggar basin, NW China: a record of Mesozoic intraplate deformation in Central Asia. *Tectonics*, 2014TC003640, <http://dx.doi.org/10.1002/2014TC003640>.
- Yi, Z., Huang, B., Xiao, W., Yang, L., Qiao, Q., 2015. Paleomagnetic study of Late Paleozoic rocks in the Tacheng Basin of West Junggar (NW China): implications for the tectonic evolution of the western Altids. *Gondwana Res.* 27, 862–877.
- Yuan, C., Sun, M., Xiao, W., Li, X., Chen, H., Lin, S., Xia, X., Long, X., 2007. Accretionary orogenesis of the Chinese Altai: insights from Paleozoic granitoids. *Chem. Geol.* 242, 22–39.
- Zhang, Z., Liou, J., Coleman, R., 1984. An outline of the plate tectonics of China. *Geol. Soc. Am. Bull.* 95, 295–312.
- Zhao, Z., Pang, X., Li, Q., Hu, T., Wang, K., Li, W., Guo, K., Li, J., Shao, X., 2016. Depositional environment and geochemical characteristics of the Lower Carboniferous source rocks in the Marsel area, Chu-Sarysu Basin, Southern Kazakhstan. *Mar. Pet. Geol.* 81, 134–148.
- Zheng, J., Sun, M., Zhao, G., Robinson, P.T., Wang, F., 2007. Elemental and Sr–Nd–Pb isotopic geochemistry of Late Paleozoic volcanic rocks beneath the Junggar basin, NW China: implications for the formation and evolution of the basin basement. *J. Asian Earth Sci.* 29, 778–794.
- Zhou, T., Yuan, F., Fan, Y., Zhang, D., Cooke, D., Zhao, G., 2008. Granites in the Sawuer region of the west Junggar, Xinjiang Province, China: geochronological and geochemical characteristics and their geodynamic significance. *Lithos* 106, 191–206.
- Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., Page, B.M., 1990. *Geology of the USSR: a plate-tectonic synthesis*. American Geophysical Union pp. 242.