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PALEOZOIC MULTIPLE SUBDUCTION-ACCRETION PROCESSES OF THE SOUTHERN ALTAIDS

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ABSTRACT. The formation and development of the southern Altaids is controversial with regard to its accretionary orogenesis and continental growth. The Altay-East Junggar orogenic collage of North Xinjiang, China, offers a special natural laboratory to resolve this puzzle. Three tectonic units were juxtaposed, roughly from North to South, in the study area. The northern part (Chinese Altay), composed of variably deformed and metamorphosed Paleozoic sedimentary, volcanic, and granitic rocks, is interpreted as a Japan-type island arc of Paleozoic to Carboniferous-Permian age. The central part (Erqis), which consists of ophiolitic mélanges and coherent assemblages, is a Paleozoic accretionary complex. The southern part (East Junggar), characterized by imbricated ophiolitic mélanges, Nb-enriched basalts, adakitic rocks and volcanic rocks, is regarded as a Devonian-Carboniferous intra-oceanic island arc with some Paleozoic ophiolites, superimposed by Permian arc volcanism. A plagiogranite from an imbricated ophiolitic mélange (Armantai) in the East Junggar yields a new SHRIMP zircon age of 503 ± 7 Ma. Using published age constraints, we propose the presence of multiple subduction systems in this part of the Paloasian Ocean in the Paleozoic. The intraoceanic arcs became accreted to the southern active margin of the Siberian craton in the middle Carboniferous-Permian. During the long accretionary processes, in addition to large-scale southward-directed thrusting, large-scale, orogen-parallel, strike-slip movements (for example, Erqis fault) in the Permian translated fragments of these intraoceanic arcs and associated accretionary wedges. This new tectonic model has broad implications for the architecture and crustal growth of Central Asia and for other ancient orogens.

INTRODUCTION

The Altaids (Şengör and others, 1993; Şengör and Natal'in, 1996a; Xiao and others, 2004a, 2004b) or the Central Asian Orogenic Belt (CAOB) (Carroll and others, 1990, 1995; Ruzhentsev and Mossakovskiy, 1996; Jahn and others, 2000; Jahn, 2001; Dobretsov, 2003), one of the world's largest accretionary orogens, was largely formed by subduction and accretion of juvenile material from the Neoproterozoic through the Paleozoic (Şengör and others, 1993; Şengör and Natal'in, 1996a; Yin and Nie, 1996; Xiao and others, 2004a, 2004b; Jahn and others, 2004). However, there is a strong debate about the orogenic processes, in particular as to whether the orogenic collage was formed from one long-lived, single subduction system (Şengör and others, 1993; Şengör and Natal'in, 1996a, 1996b; Bazhenov and others, 2003; Collins and others, 2003; Abrajevitch and others, 2007; Levashova and others, 2007) or from many subduction systems with different polarities and ages (Coleman, 1989, 1994; Mossakovsky and others, 1993; Buslov and others, 2001, 2004).

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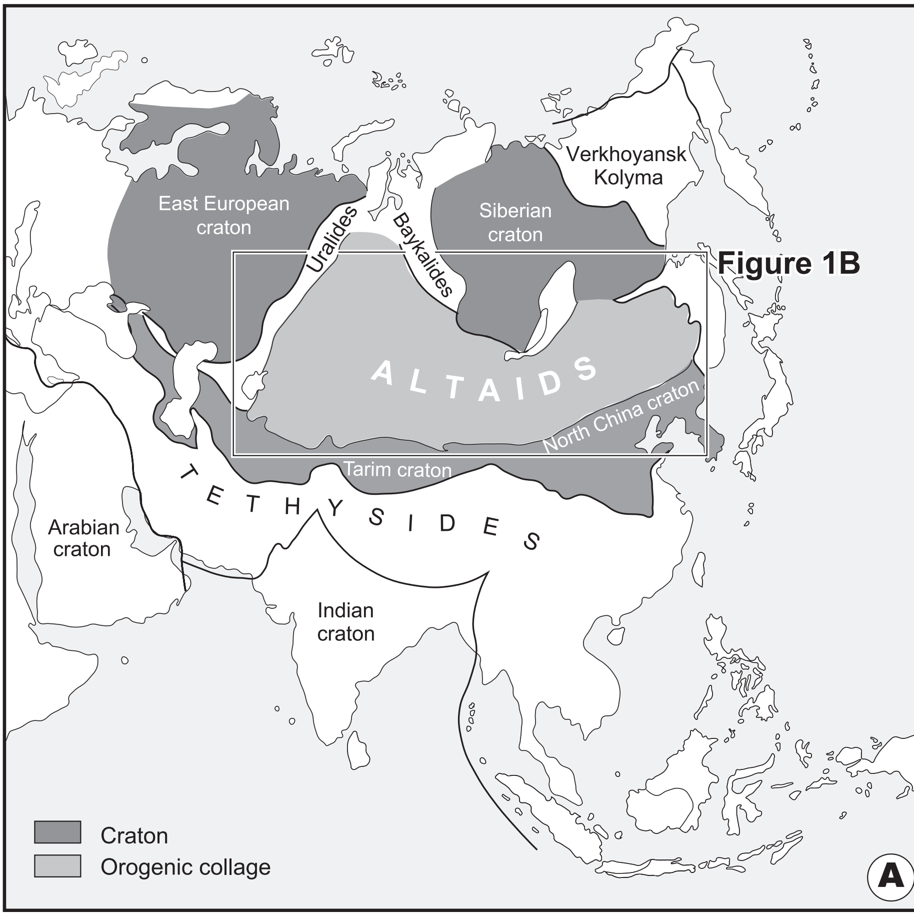

Fig. 1. (A) Simplified tectonic map of the Altaids, separating the East European and Siberian cratons to the north from the Tarim and North China cratons to the south (Şengör and others, 1993). Figure 1B is outlined. (B) Schematic tectonic map of the Altaids showing the major tectonic units and structures (modified after Şengör and others, 1993; Şengör and Natal'in, 1996a, 1996b, 2004). The tectonic units to the west of the Erqis fault zone are deformed by the "Kazakhstan Orocline", while those to the east are folded by the "Tuva-Mongolian Orocline". KOK: Kokchetav; TM: Tuva-Mongol. Figures 2 and 3 are outlined. Carb. = Carboniferous.

The Chinese Altay-East Junggar orogenic collage (CAEJ) of northern Xinjiang links the southern Altaids in Mongolia to the east with Kazakhstan in the west (figs. 1 and 2). According to Şengör and others (1993), the Altaids is characterized by two huge oroclines, Kazakhstan and Tuva-Mongol, which are mainly separated by the Erqis fault zone (fig. 1B). Accordingly, the CAEJ should record the basic features of the architecture of the Altaids, thus offering a special opportunity to resolve this puzzle in one area. The CAEJ is located in a remote area near the Chinese–Mongolian and Chinese–Kazakhstan border where excellent exposures of arc rocks and ophiolites crop out (Li and others, 1990, 2003). The CAEJ marks the site where one or more branches of the Paleoasian Ocean was consumed (Şengör and others, 1993; Filippova and others, 2001; Bykadorov and others, 2003), when the Altay and East Junggar tectonic segments approached and became accreted to the southern active margin of Siberia in the Late Paleozoic (Coleman, 1989, 1994; Mossakovsky and others, 1993;

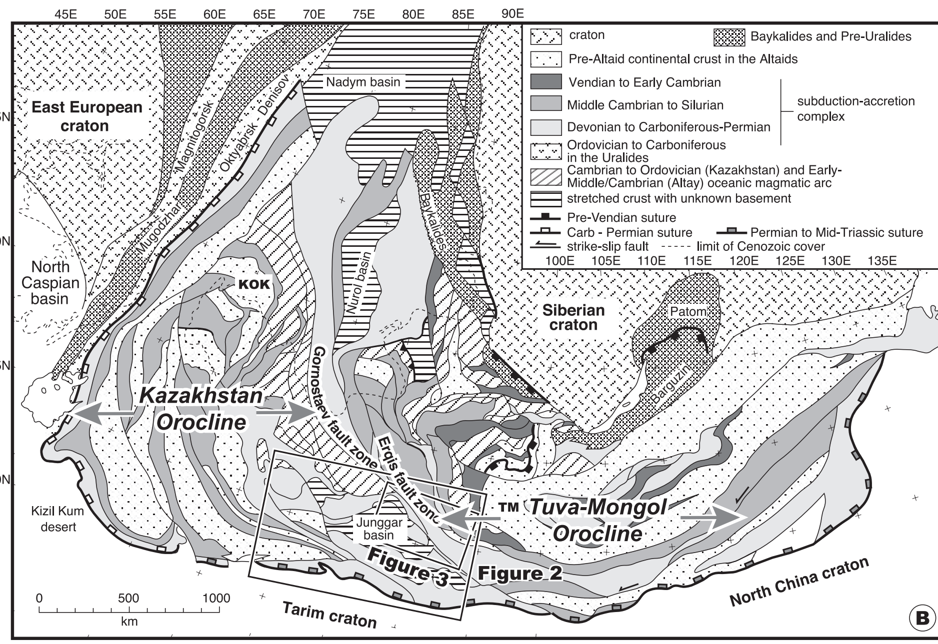

Fig. 1. (continued)

Buslov and others, 2001, 2004; Heubeck, 2001; Yakubchuk and others, 2001, 2002; Yakubchuk, 2002, 2004). Relics of the Paleoasian Ocean are now imbricated within the ca. 300-km-wide orogenic collage. Therefore, investigation of the Paleozoic tectonics of the CAEJ will not only help address the long-standing controversy of single (Rotarash and others, 1982; Şengör and others, 1993) versus multiple subduction systems (Coleman, 1989, 1994; Mossakovsky and others, 1993; Buslov and others, 2001, 2004; Rui and others, 2002), but it will also shed light on global reconstructions in the Paleozoic (Smethurst and others, 1998; Heubeck, 2001; Torsvik and Cocks, 2004; Cocks and Torsvik, 2007).

Although many studies have been carried out in the West Junggar, Tien Shan and other orogenic collages in Russia, Kazakhstan, and Mongolia (Feng and others, 1989; Windley and others, 1990; Lamb and Badarch, 1997; Lamb and others, 1999, 2008; Zhou and others, 2001; Yakubchuk, 2004; Van der Voo and others, 2006; Johnson and others, 2007; Abrajevitch and others, 2007), they were related only generally or partially to the CAEJ (Vincent and Allen, 2001; Windley and others, 2002; Laurent-Charvet and others, 2003; Briggs and others, 2007), and thus doubts remain on the precise location of sutures within the CAEJ and their continuity in the Altay-Mongolia region with other known sutures.

In this paper we present the results of our detailed field structural studies in this vast area during the past 6 field seasons. First, we describe some newly discovered mélanges and accretionary complexes that include ophiolitic fragments, and then, we document their structural characteristics. We integrate a new SHRIMP zircon age from an Armantai ophiolitic fragment with recently published high-resolution isotopic age data, in order to constrain the temporal development of the CAEJ. Combined with published geochemical, structural, geochronological, and geophysical data (Wang and others, 2003a), we define the key subduction-accretion complexes, and interpret their tectonic settings and paleogeographic significance. We discuss the many long-lived

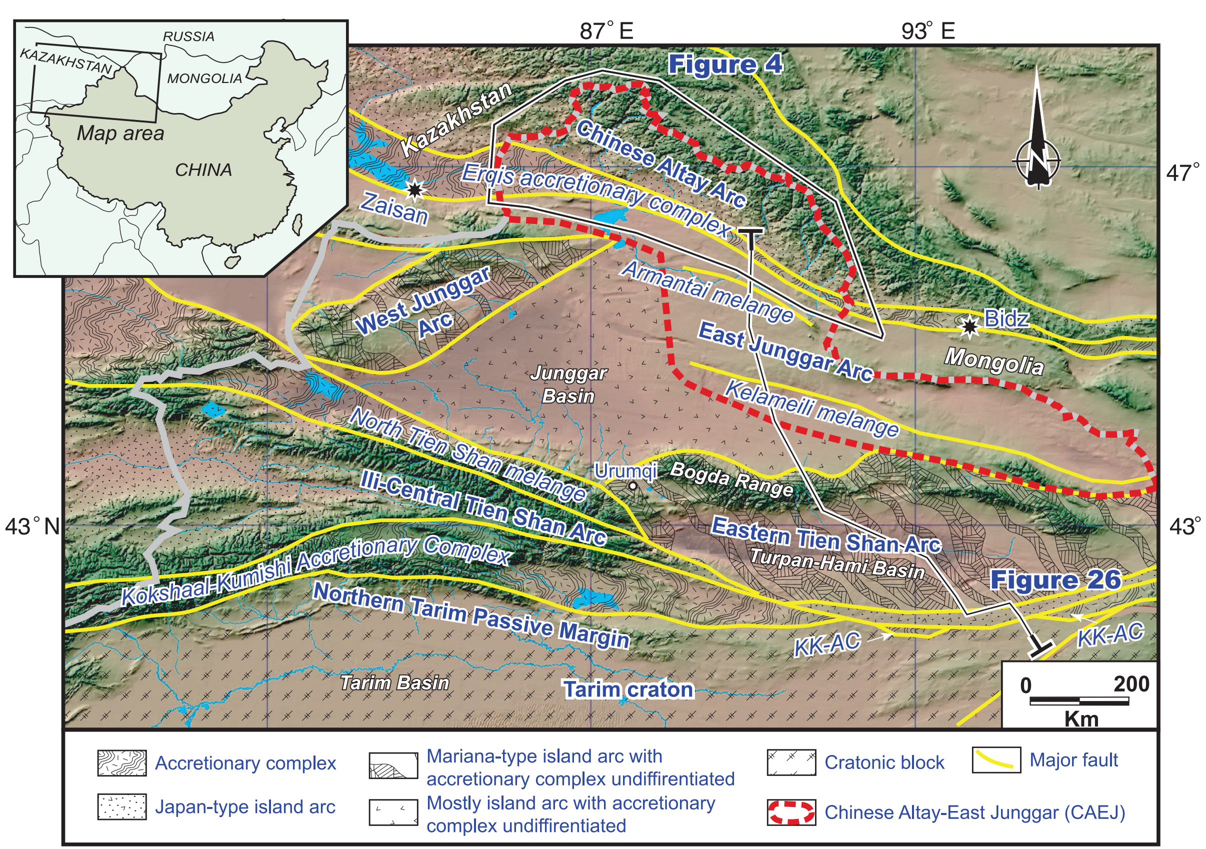

Fig. 2. Schematic tectonic map showing the Chinese Altay-East Junggar orogenic collage (CAEJ) (Xiao and others, 2004a, 2004b, 2008). Insert is a schematic map showing the tectonic position of Northern Xinjiang in the southernmost part of the Altaids. Black stars represent ophiolitic mélanges in the adjacent areas in Kazakhstan and Mongolia. The positions of figures 4 and 26 are marked. KK-AC = Kokshaal-Kumishi accretionary complex.

subduction-accretion events from the Cambrian to the Permian in terms of a new tectonic model that provides improved constraints on the crustal growth of Central Asia.

Regional Geology

Unlike the northern Altaids where some old continental fragments are juxtaposed against younger accretionary complexes, the geological and tectonic framework of the southern Altaids is characterized by multiple, linear, accretionary orogenic collages that contain Paleozoic arcs, ophiolites, accretionary wedges, and arc-related basin sediments, all formed as a result of accretion and subduction of the Paleoasian Ocean (Coleman, 1989, 1994; Windley and others, 1990; Xiao and others, 1992; Mossakovsky and others, 1993; Buslov and others, 2001, 2004; Heubeck, 2001; Buchan and others, 2001, 2002; Yakubchuk and others, 2001, 2002; Yakubchuk, 2002, 2004). It is generally accepted that the Paleoasian Ocean started at least by ca. 1.0 Ga (Khain and others, 2002) and that the general northward (present-day coordinates) subduction of the Paleoasian Oceanic plate until the Permian resulted in a huge accretionary orogen (Şengör and others, 1993; Şengör and Natal'in, 1996a, 1996b; Yin and Nie, 1996; Bazhenov and others, 2003; Collins and others, 2003; Abrajevitch and others, 2007; Levashova and others, 2007). Also some Vendian (Neoproterozoic)-Paleozoic metamorphic rocks have been variably interpreted as blocks, arc roots, or small components in accretionary complexes (Mossakovsky and others, 1993; Li and others, 2003; Dobretsov and others, 2004; Xiao and others, 2004a, 2004b, 2008; Sun and others, 2008); these rocks are an integral part of the Altaids.

The southern Altaids began its oceanic evolution and accretionary history mostly in the early Paleozoic, but its starting time is not well constrained. The CAEJ is situated in the southern Altaids (figs. 2 and 3). Its northern boundary is a Late Devonian-Early Carboniferous tectonic collage (Dobretsov and others, 2004; Buslov and others, 2004), and its southern boundary is separated from the late Paleozoic Eastern Tien Shan orogenic collage by mélanges, which include ophiolitic fragments that represent a branch of the Paleoasian Ocean that closed by double, two-way subduction (Xiao and others, 2004b). Farther south, a huge accretionary complex (Kokshaal-Kumishi) occupies the final suture zone along which the Tarim craton was accreted to what by then had become the southern Siberian accretionary collage (Xiao and others, 2004b, 2008, 2009).

We subdivide the CAEJ into three major tectonic units; the northern (Chinese Altay), Central (Erqis, or Irtysh, Irtish, Irtys, Erqisi, Ertix), and southern (East Junggar) (figs. 2 and 3, table 1). However, there are alternative views about this three-fold tectonic subdivision of the CAEJ (Xiao and Tang, 1991; Xiao and others, 1992, 1994; Coleman, 1994; Windley and others, 2002), and the ages, tectonic settings, and geodynamic significance of the three tectonic units remain controversial. The Chinese Altay has been regarded as a Precambrian block because of the presence of Sinian fossils and Neoproterozoic zircon xenocrysts, but the origin of some high-grade metamorphic rocks is still controversial; for this reason we have chosen some gneisses and schists for detailed study. The Erqis unit has long been interpreted as a large-scale strike-slip fault, but the components and the nature of the strike-slip faulting are unclear; therefore the components of the unit and their relationships with those of adjacent units require further study. The southernmost unit, East Junggar, has been interpreted for many years as a continental block together with some ophiolites in suture zones (Li and others, 2003; Li, 2006); however, the time of formation of rocks in the block and emplacement age of the ophiolites are still under debate. In this paper we describe the lithological components and structures of the three major tectonic units integrated with key data from the literature. With these data we construct a new

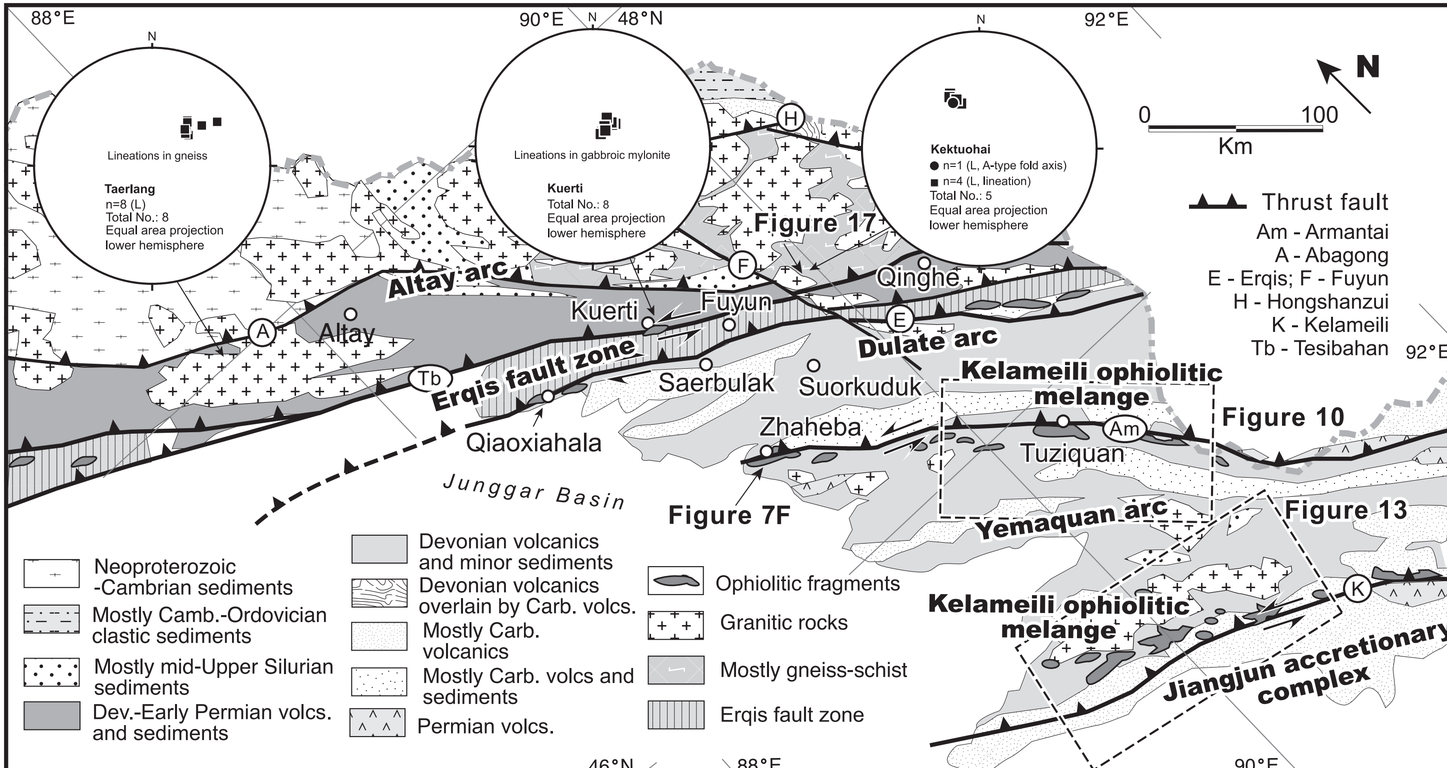

Fig. 3. Tectonic map of the Chinese Altay-East Junggar orogenic collage (CAEJ), showing its principal structures and tectonic units (modified after XBGMR, 1993; Hu and others, 2000; Windley and others, 2002; Buslov and others, 2002, 2003; Xiao and others, 2004a). Some lower hemisphere equal area projections are marked. Abbreviations: Camb. = Cambrian; Dev. = Devonian; Carb. = Carboniferous; Volcs. = volcanic rocks. The locations of figures 7F, 10, and 13 are shown.

tectonic model for the CAEJ and discuss the inherent implications for the evolution of the Paleoasian Ocean and construction of the southern Altaids.

NEW OBSERVATIONS OF MÉLANGES AND OPHIOLITIC FRAGMENTS

Chinese Altay Unit

In the northernmost part of the CAEJ the Chinese Altay occupies an area of ca. 600 by 180–200 km (fig. 2, table 1).

In the Kangbutiebao area, approximately 50 km SE of Altay city (for position see abbreviation "Kb" in fig. 4), we examined a representative section of a mélange that is composed of lenses of ultramafic, mafic and clastic rocks in a matrix of turbiditic sediment (fig. 5). In the north of the section lenses of ultramafic rocks up to several meters wide and 20 meters long are tectonically imbricated in a matrix of turbidites, farther south there are lenses of gabbro-diabases and minor ultramafic rocks, and in the far south lenses of massive basaltic rocks without pillow structures. Sandstone lenses in turbiditic sediment occur throughout the whole section. All the above rocks strike NW-SE and dip to the northeast. Along strike to the NW and SE the ultramafic and mafic lenses decrease and ultimately disappear.

In low hills north of Buerjin (fig. 4), we discovered a similar mélange composed of lenses of ultramafic, mafic, cherty, and clastic rocks in a turbiditic matrix; the best 3 km-long section is about 20 kilometers west of the main Buerjin-Kanas highway (fig. 6, for position see "Bu" in fig. 4). The northern boundary of this NW-trending mélange is a thrust that dips to the NE and strikes NW, along which granitic rocks and turbidites are thrust southwards over the mélange. The southern mélange boundary is represented by several northeast-dipping thrusts that dip moderately NE. In the north, a sandstone-rich turbiditic matrix contains lenses of pillow-bearing basalts up to 20m wide (fig. 7A). The central part of the mélange contains lenses of NE-dipping ultramafic-mafic rocks, turbidites, limestones, and cherts, and these are repeated by thrusts several times along the section (fig. 6). The ultramafic-mafic lenses are commonly 20 to 50 meters wide, whereas limestones and cherts are only a few meters. Towards the south, mafic-ultramafic lenses 80 to 150 meters wide and several hundred meters long are very common (fig. 6), together with small gabbro-diabase lenses 10 to 20 meters wide. This ophiolitic mélange extends along strike for about 10 to 15 kilometers, and is fault bound farther to the northwest and southeast.

Lens-in-matrix mélanges also occur west of Altay City. In northwestern Altay City, pillow-bearing basalts are imbricated with gabbroic rocks (fig. 7B). Lenses of gabbroic rocks in sheared metasediments are at Taerlang and northwest of Altay (figs. 4, 7C and 8). Some lenses of sandstones and limestones occur in a matrix of sandstones and siltstones (fig. 7D). The matrix of these mélanges has been assigned various ages ranging from Silurian to Devonian-Carboniferous; detrital zircon ages are required.

Along the Chinese Altay towards the east, at Kuerti ca. 30 km NW of Fuyun (figs. 2, 3, and 4), a few kilometers north of the Erqis fault, there is a 15 km-long section comprising a fault-bound, NW-trending, sub-vertical, imbricated, greenschist-grade ophiolitic zone with pillow basalts, gabbros, mafic dikes and cherts. In the northern part of the section, gabbroic rocks up to 200m wide and basalts up to 60 meters wide are juxtaposed against mafic dikes, cherts, sandstones, and metasediments. Basalts with slightly deformed pillows are juxtaposed against gabbros and cherts (fig. 7E). In the middle section, massive to foliated gabbros with plagiogranite dikes are predominant. Farther south, gabbros up to 4 to 5 m across are juxtaposed against mylonites, which in turn are thrust against pillow basalts. In the far south metamorphosed (high-grade, low-grade, greenschist or amphibolite facies?) volcano-sedimentary rocks several kilometers wide are thrust over an imbricated assemblage of sandstones (of possible

TABLE 1

Characteristic rock assemblages and structures of tectonostratigraphic units in the Chinese Altay-East Junggar orogenic units with correlations and interpretations of tectonic environment

Unit	Typical lithologies	Geochemical affinities of ophiolitic mélange	Nature of basement, if any	Fault/suture bound	Age with references	Younging direction	Interpretation
CHINESE ALTAY	Gneisses & schists. In W. low-grade Camb. seds. In E. Mid-Ord. to Sil. turbidite. Late Sil.-early Dev. calc-alkaline lavas and pyroclastics overlain by mid-Dev. turbidite. Mid-Dev. ophiolitic fragments. Mid-late Dev. andesites, dacites. Late Dev. to early Carb. shale, silt., greywacke, sst., lst., andesite. Mainly Ord. to Carb. -Permian granites. Early Carb. adakite. Late Dev. Carb. -Permian regional metamorphism.	MORB (Xu and others, 2003)	?	Bound by major faults and the Erqis AC (suture) on the S.	920-614 Ma zircon xenocrysts in mid-Camb. felsic lava (Windley and others, 2002). Kuerti plagiogranite, SHRIMP, 372±19 Ma (Zhang and others, 2003); Gneiss, SHRIMP, 281±3 Ma (Hu and others, 2006); Mafic granulite, SHRIMP, 279±6 Ma (Chen and others, 2006b); Metasediments, Chemical Th-U-total Pb isochron, 261–268 Ma (Zheng and others, 2007)	S-vergent thrusts; Mainly of S-ward younging direction	Camb.-Ord. arc and clastic basin succeeded by Silurian to early Permian arc volcanism and arc-related basins.
ERQIS	High-grade gneisses. & schists. Ophiolitic fragments. Ord.-Sil. basalts, andesites, Sil.-Dev. turbidites. Early Carb. ophiolitic fragment. Thrusted late Carb. clastic basin. Permian granites.	OIB, IAB, E-MORB (Wang and others, 2003; Wu and others, 2006)		Bound by major faults	Ordovician–Silurian radiolarian chert (Xiao and others, 1992). Basalt, SHRIMP, 352±4 Ma (Wu and others, 2003);	S-vergent thrusts; Strike-slip faults	Accretionary complex including ophiolitic melange, Ord.- Dev. forearc basin, thrusted Carb.-Permian forearc basin.
EAST JUNGGAR	**Dulate Arc**: Dev. felsic-inter. lavas, tuffs, calc-alkaline granites, shale, sst., cong., lst. Early-Dev. adakite, mid-Dev. boninite. Early Carb. andesite & clastic seds. Minor late Ord. limestone. Permian A-type granites.	Calc-alkaline	Ocean floor	Bound by major faults and the Erqis AC (suture) on the N.		S-vergent thrusts; Mainly S-ward younging direction with minor N-ward younging of arc volcanic rocks	Major Devonian island arc with boninites and sediments in the forearc, minor early Carb. mature island arc.

Table 1
(continued)

Unit	**Typical lithologies**	Geochemical affinities of ophiolitic mélange	Nature of basement, if any	Fault/suture bound	Age with references	Younging direction	Interpretation
	Aermantai OM: Early Ord. ophiolite on Armantai fault. Dev. – early Carb. ophiolite on Kelameili fault.	OIB, IAB, MORB, E-MORB (Wang and others, 2003; Jin and others, 2001)	Ocean floor	Bound by major faults	Ord. and mid-Dev. radiolarian fossils, chert (Li, 1991; He and others, 2001; Xiao and others, 1992). Plagiogranite, SHRIMP 503 ± 7 Ma (This study) Ophiolitic ultramafic rock, Sm-Nd, 479 ± 27 Ma (Liu and Zhang, 1993) Layered gabbro, SHRIMP, 489 ± 4 Ma Anorthosite vein, SHRIMP, 481 ± 5 Ma Massive gabbro, SHRIMP, 406 ± 4 Ma Plagiogranite pod, SHRIMP, 400 ± 5 Ma Fine-grained gabbro, SHRIMP, 385 ± 9 Ma (Ping and others, 2005)	S-vergent thrusts; No clear younging direction	Remnants of ocean floor, remnants of arc-related basin and seamount
	Yemaquan Arc: Early to late Dev. andesite, trachyandesite, basalt, trachybasalt, basanite, Carb. volcanics, granitic plutons.		Ocean floor	Bound by major faults and the Aermantai OM. on N.		S-vergent thrusts; Mainly S-ward younging direction	Dev. to Carb. mature island arc.
	Kelameili OM: Early Ord. ophiolite on Armantai fault. Dev. –early Carb. ophiolite on Kelameili fault.	IAB, MORB (Wang and others, 2003)	Ocean floor	Bound by major faults	Radiolarian chert, late Dev. to early Carb. (Shu and Wang, 2006) Plagiogranite, SHRIMP, 403± 9 Ma, with older ages of 497 ± 12 Ma (Ping and others, 2005) Gabbro, SHRIMP, 336 ± 4 Ma, 342 ± 3 Ma (Ping and others, 2005)	S-vergent thrusts; No clear younging direction	Remnants of ocean floor
	Jiangjun AC: Minor Dev. andesite, boninite, adakite. Major mid-Carb. andesite, trachyandesite. Minor Permian andesite, dacite, & rhyolite.		Ocean floor	Bound by major faults; the Kelameili OM on N.		S-vergent thrusts; Mainly S-ward younging direction	Accretionary complex with Devonian, Carboniferous and Permian forearc basins.

Abbreviations: seds. sediments; cong. conglomerate; lst. limestone; sst. sandstone; silt. siltstone; inter. intermediate; Neoprot. Neoproterozoic; Camb. Cambrian; Ord. Ordovician; Sil. Silurian; Dev. Devonian; Carb. Carboniferous. SSZ. suprasubduction-zone; MORB. mid-ocean ridge basalt; OIB. oceanic island basalt; IAB. island arc basalt; E-MORB. enriched mid-ocean ridge basalt; AC. accretionary complex; OM. ophiolitic mélange

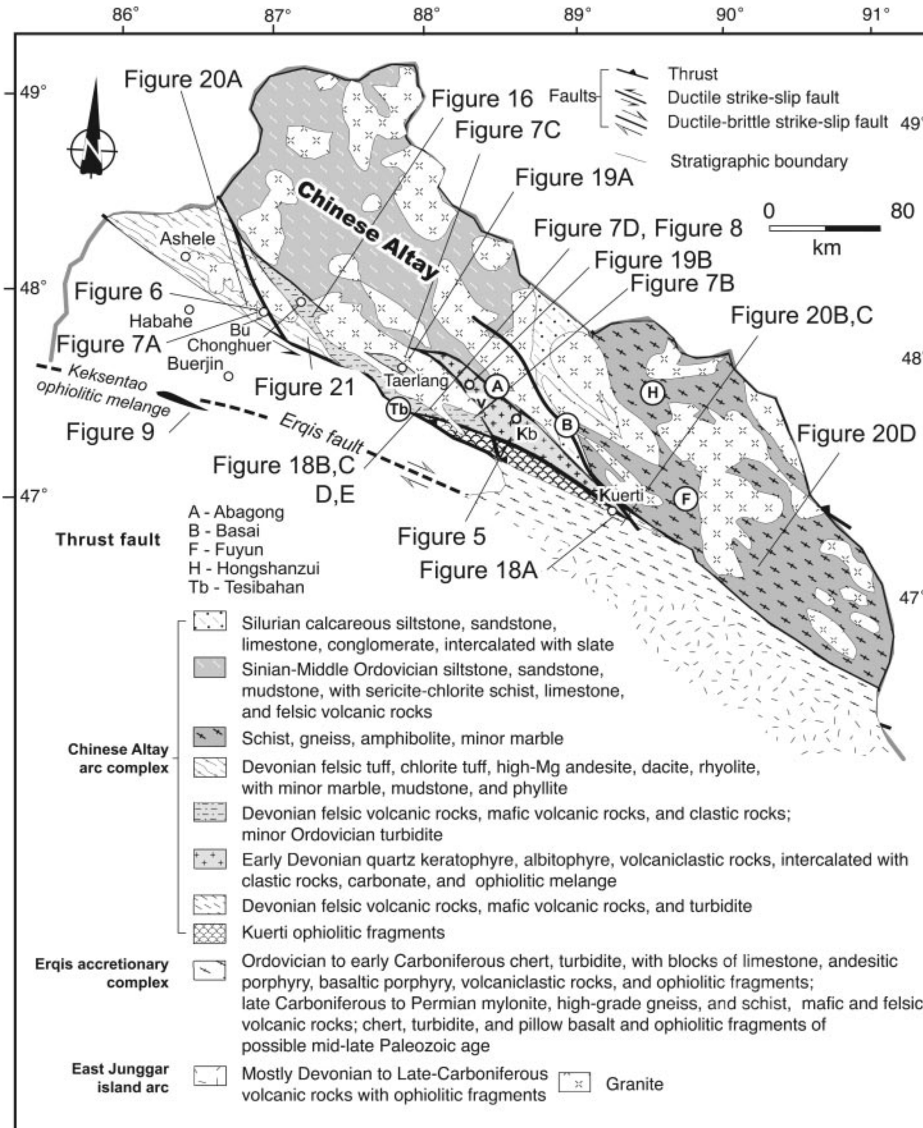

Fig. 4. Tectonic map of the Chinese Altay showing its main lithologies, tectonic units and structures (modified after XBGMR, 1993; Windley and others, 2002; Xiao and others, 2004a). Bu: Buerjin ophiolitic mélange. Kb: Kangbutiebao ophiolitic mélange. The positions of figures 5, 6, 7, 8, 9, 16, 18, 19, 20, 21 are marked.

Permian age), minor gabbro and basalt. Although Xu and others (2003) interpreted this mélange as a remnant of back-arc mantle-crust, the whole sequence and the presence of volcanic rocks with a forearc geochemical signature (Niu and others, 2006) to the northwest make an arc interpretation more likely. The discovery of Devonian high-Mg andesites and boninites suggests a forearc setting (Niu and others, 1999). According to the main geological map (XBGMR, 1993) and local geological

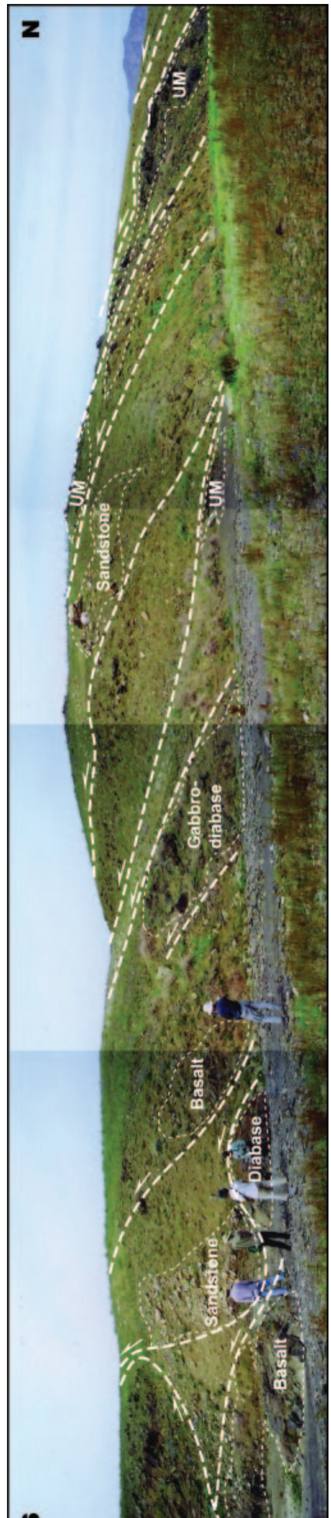

Fig. 5. Annotated photo of part of the Kangbutiebao accretionary complex showing major lithologies and structures, Kangbutiebao. Scientists for scale. Looking NW. Position shown in figure 4.

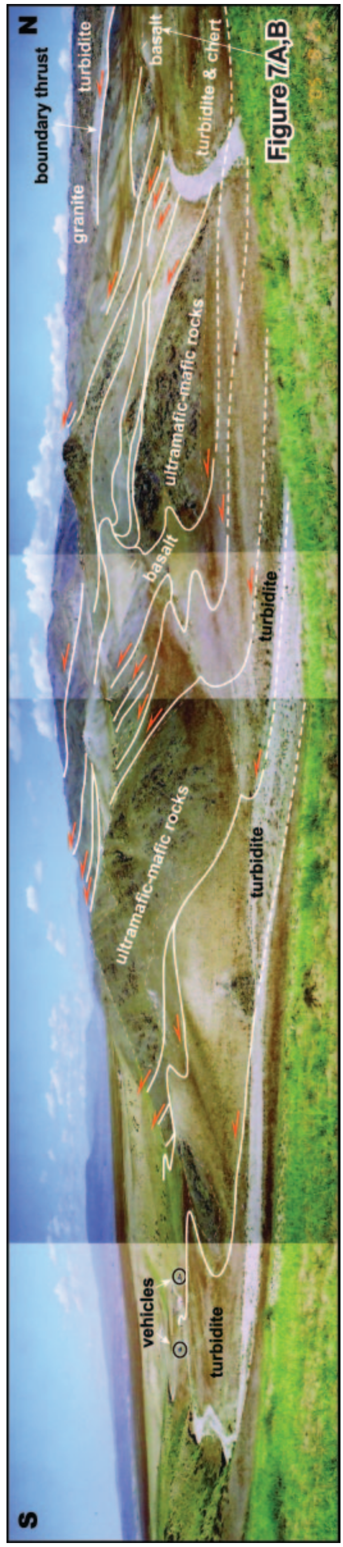

Fig. 6. Annotated photo of the Buerjin mélange showing major lithologies and structures, NW of Buerjin. See circled vehicles for scale. For position see "Bu" in figure 4. Looking NW.

Fig. 7. (A) Pillows in basalt of the Buerjin melange. Pen for scale. Looking NW. (B) Pillows in basalt, W of Altay. Hammer for scale. (C) Lenses of gabbroic rocks in a turbiditic matrix, indicating thrusting to SW, Taerlang. Hammer for scale. Looking W. (D) a sandstone lens in a matrix of turbidite. The cliff is about 20 m high. Looking W.

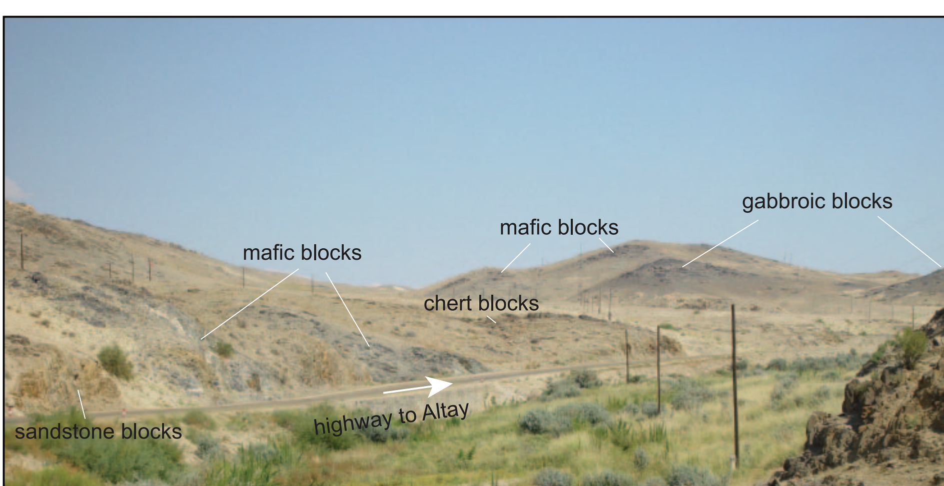

Fig. 8. Photo of the SW Altay melange showing different types of blocks in the melange. NW of Altay. Communication pole is 8 meters high for scale. Looking NE.

maps this imbricate zone extends for about 30 to 45 kilometers to the NW where it is bordered by Devonian-Carboniferous volcano-sedimentary rocks.

Erqis Unit

The Erqis fault has long been regarded as a strike-slip fault with a thick mylonite zone (Şengör and others, 1993). However, in addition to some mylonitic rocks, there are other kinds of rocks including ophiolitic fragments. Actually, the major components are ophiolitic fragments, volcanic rocks, some of which were deformed into mylonites, together with some high-grade gneisses. Along the Erqis fault some gneisses containing 1849 to 1791 Ma feldspar Pb–Pb model ages occur (Qu and Zhang, 1994). But the ages of many of these gneisses need to be further confirmed by high-resolution age data.

The ophiolitic fragments in the Erqis zone are mainly represented by the Keksantao mélange in the west, Qiaoxiahala mélange in the middle, and the southern Qinghe mélange in the east (figs. 3 and 4). The Kekesentao mélange is composed of ultramafic-mafic rocks, radiolarian cherts and volcaniclastic rocks which mostly occur as blocks in matrixes of sandstones, tuffaceous sandstones and siltstones of middle Devonian age. Peridotites can be identified in the Kekesentao area (Zhang and others, 1996). The compositions of olivine and chromian spinel indicate that the peridotites represent mildly-depleted mantle peridotites (Niu and others, 2006). Along the southern segment of these ophiolitic fragments basalts and cherts occur as blocks in a matrix of tuffaceous sandstones and siltstones (fig. 9A). About 500 m southeast of the basalt and chert blocks some coherent units of turbidites have been folded with cleavage (fig. 9B).

The Qiaoxiahala mélange (fig. 3) is represented by ultramafic-mafic rocks and cherts which are mostly blocks in matrixes of sandstones and tuffaceous sandstones and siltstones. Some pillow basalts (more than 1 km thick) show MORB and island arc tholeiitic chemical signatures (Yu and others, 2000), and are imbricated with Ordovician–Silurian radiolarian cherts and Silurian–Devonian turbidites (Xiao and others, 1992).

The southern Qinghe mélange is distributed along the southern part of the Qinghe area, which is in the eastern part of the Erqis fault zone (fig. 3). This mélange is represented by blocks of cherts, limestones, basalts, gabbros, serpentinized harzburgites and other ultramafic-mafic rocks in matrixes of siliceous and calcareous sandstones, tuffaceous sandstones and siltstones. Lenses of thin-bedded cherts, pillow basalts, massive basalts, basaltic conglomerates, foliated gabbros, cumulated gabbros occur in this mélange (Yang and others, 2005b; Wu and others, 2006). This mélange is juxtaposed against Carboniferous sandstones, siltstones, conglomerates, and phyllites. There are similar ophiolitic mélanges along the Erqis fault zone, northwest of Fuyun.

In these ophiolitic mélanges, lenses of cherts, turbidites, and pillow basalts and other ophiolitic fragments have possible mid-late Paleozoic ages. More high-resolution isotopic age dating is needed to better constrain the ages of these ophiolitic mélanges. In addition, some Ordovician to early Carboniferous cherts and turbidites contain lenses of limestones, andesitic porphyries, basaltic porphyries, volcaniclastic rocks, and ophiolitic fragments in the Erqis unit. Some high-grade gneisses, schists, mafic and felsic volcanic rocks are mutually imbricated. Late Carboniferous to Permian rocks are characterized by mafic and felsic volcanic and volcaniclastic rocks (Zhang and others, 1996). In the Erqis fault zone many rocks are strongly deformed into early Permian mylonites and/or ultramylonites.

East Junggar Unit

Armantai ophiolitic mélange.—The Armantai ophiolite, extending EW from Zhaheba to Tuziquan, and farther east to the China-Mongolia border (figs. 3 and 10), is

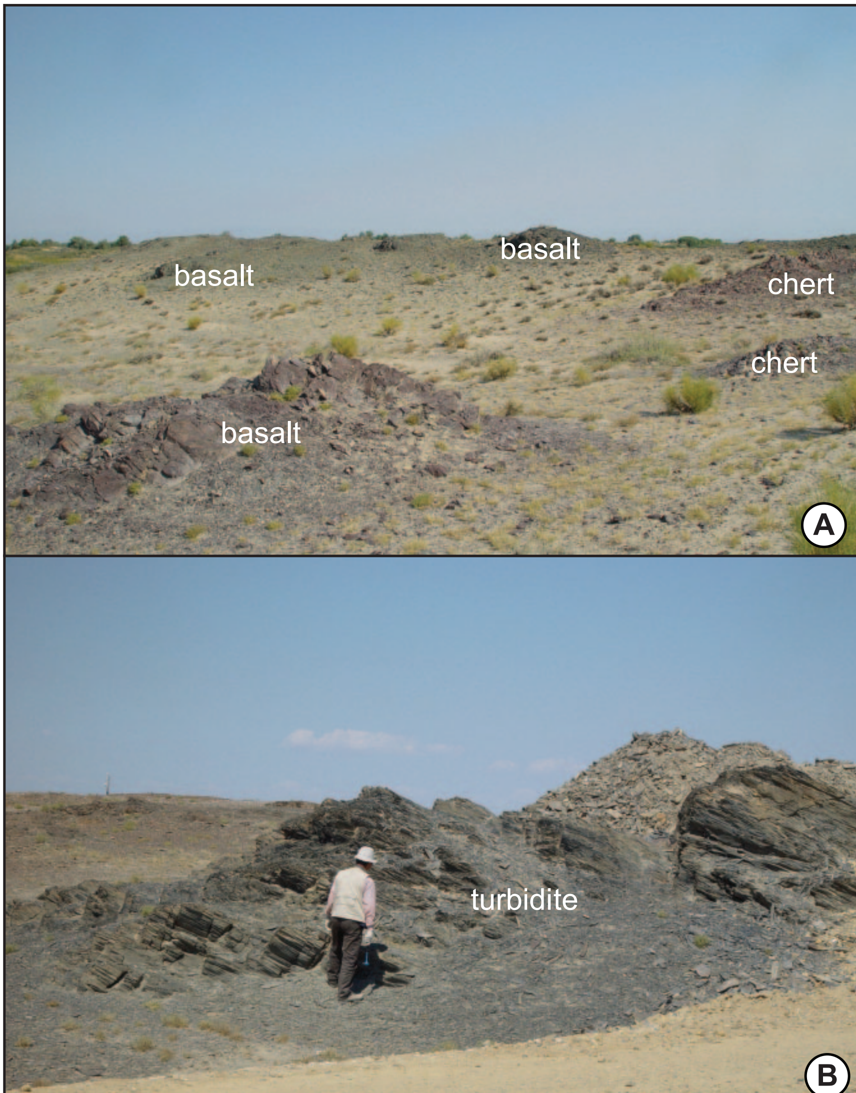

Fig. 9. Photos of the western Erqis fault zone. (A) Melange composed of chert and basalt lenses in a matrix of turbidite. The outcrop of basalt in the foreground is 5 m wide. Looking W. (B) coherent matrix of turbidite. Scientist for scale. Looking W.

composed of serpentinites, serpentinized peridotites, cumulate pyroxenites and gabbros, troctolites, rodingites, diabases, basalts and cherts. Field observations indicate that these components are in tectonic contact, and were emplaced against Devonian-Carboniferous arc-type volcanic-sedimentary rocks.

In the Zhaheba area, an extensive, NW-trending ophiolitic mélange several kilometers wide is composed of lenses of serpentinized peridotites, cumulate pyroxenites and gabbros, plagiogranites, troctolites, rodingites, diabases, basalts and cherts in a schistose serpentinite matrix. The ophiolitic mélange covers an area of about 10 km by 2–3 km, and trends NWW-SEE along the Armantai fault. Ultramafic rocks are wide-

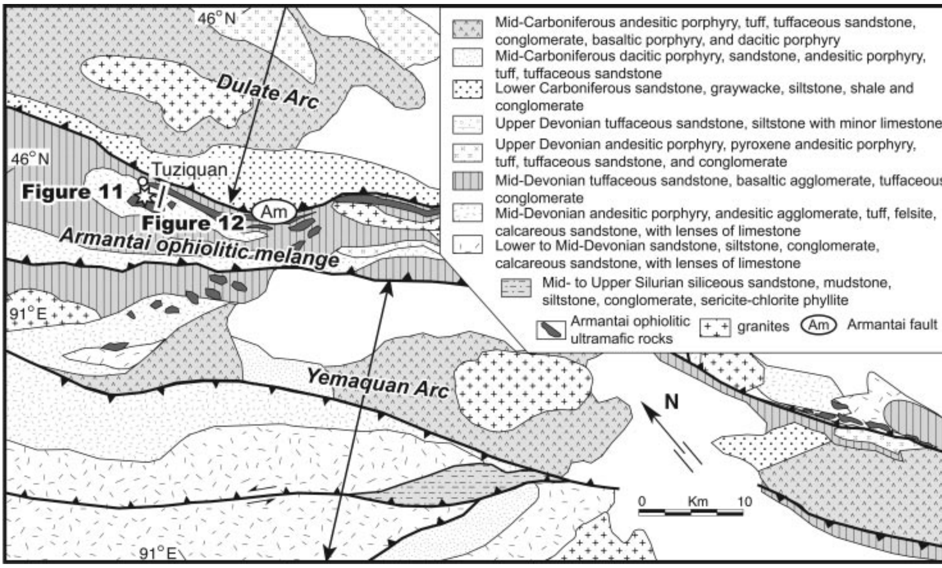

Fig. 10. Geological map of the Tuziquan area showing main Paleozoic lithologies, major tectonic units, and principal thrusts (modified after XBGMR, 1993). Position shown in figure 2. Figures 11 and 12 are marked.

spread in the northwestern and rare in the southwestern part of this ophiolitic mélange. These ultramafic rocks are strongly serpentinized, but contain sufficient relict olivine and pyroxene to indicate a peridotite or harzburgite parentage. Basalts are mostly massive, but locally pillow-bearing (fig. 7F). Red and green cherts also form lenses in the mélange.

Towards the east in the Tuziquan area, an ophiolitic mélange consists of lenses of serpentinized peridotites, cumulate pyroxenites and gabbros, diabases, olivine basalts, plagiogranites, basalts and cherts in a matrix of schistose serpentinites or turbidites (figs. 10, 11, and 12). In a NS-section illustrated in figure 12, ultramafic rocks including serpentinized peridotites are thrust southward over, or imbricated against, gabbros and olivine basalts. Gabbro-diabases are intruded by plagiogranite dikes. Locally dikes

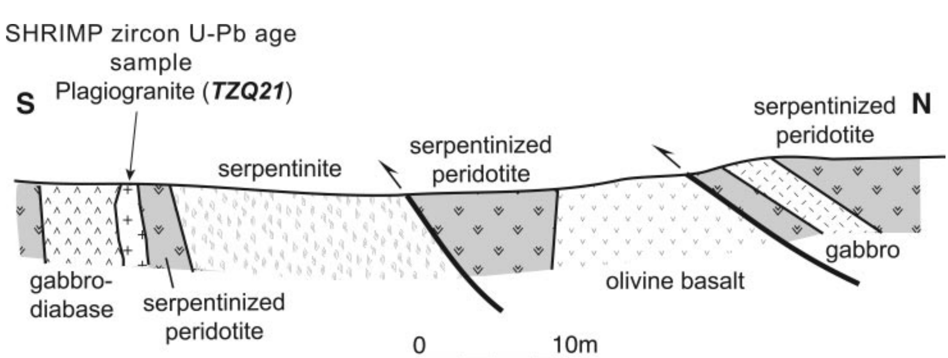

Fig. 11. Cross-section of part of the Armantai ophiolite showing SHRIMP zircon sampling site. The main units have been imbricated by thrusts. Position shown in figure 10.

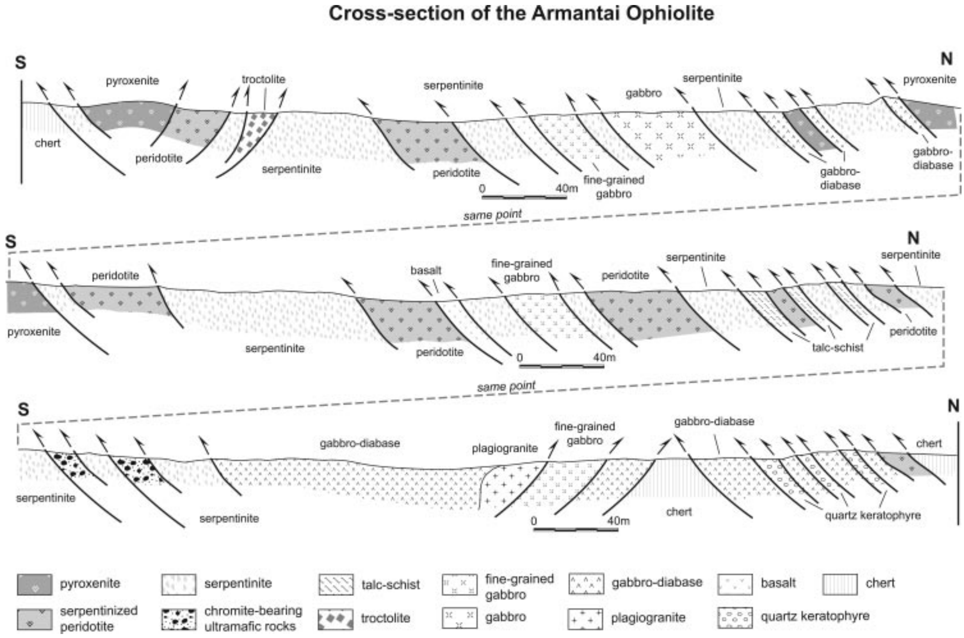

Fig. 12. Detailed cross-section of the Armantai ophiolite in the Tuziquan area showing the distribution of main rocks mostly imbricated by thrusts. Position shown in figure 10.

and bodies of plagiogranites and gabbro-diabases mutually intersect, suggesting contemporaneity. In addition, the mélange contains lenses and fragments of massive to pillow basalts, intercalated with lenses of turbidites, and radiolarian cherts, all within a tuffaceous to shaly matrix. The geological map shows that this mélange is at least 5 to 8 kilometers wide and 90 kilometers long.

Kelameili ophiolitic mélange.—In the Kelameili area (figs. 3, 13, 14, and 15), an ophiolitic mélange (Kelameili mélange, fig. 3) is composed of lenses of serpentinized peridotites, serpentinites, pyroxenites, gabbros, rodingites, basalts and cherts in a matrix of Devonian-Carboniferous volcanic-sedimentary rocks.

In the Sujiquan area, along the Kelameili fault (marked K in figs. 3 and 13), many lenses consist of serpentinized peridotites, cumulate pyroxenites and gabbros, diabases, olive basalts, plagiogranites, basalts and cherts (fig. 14). Ultramafic lenses are several tens of meters across, and basalt lenses are about 10 meters across, although a few are 20 meters long. Coherent units in the mélange are characterized by thick successions of Devonian-Carboniferous sandstones and tuffaceous sandstones.

In the Hongliuhe area between Sujiquan and Qingshui (star in fig. 13) in an area of about 20 km by 30 km dismembered ophiolitic complexes are made up of kilometer-sized lenses of serpentinized peridotites, gabbros, quartz diorites and volcanic rocks in a sheared and locally brecciated matrix of serpentinites and/or turbidites; similar dismembered ophiolitic complexes occur about 50 km east of Qingshui. As shown in a detailed section in figure 15, serpentinized peridotites are thrust southward over gabbroic rocks, which in turn are thrust southward over serpentinites. These imbricated thrust sheets are bounded by north-dipping thrusts; individual thrust sheets are usually about 25 meters thick.

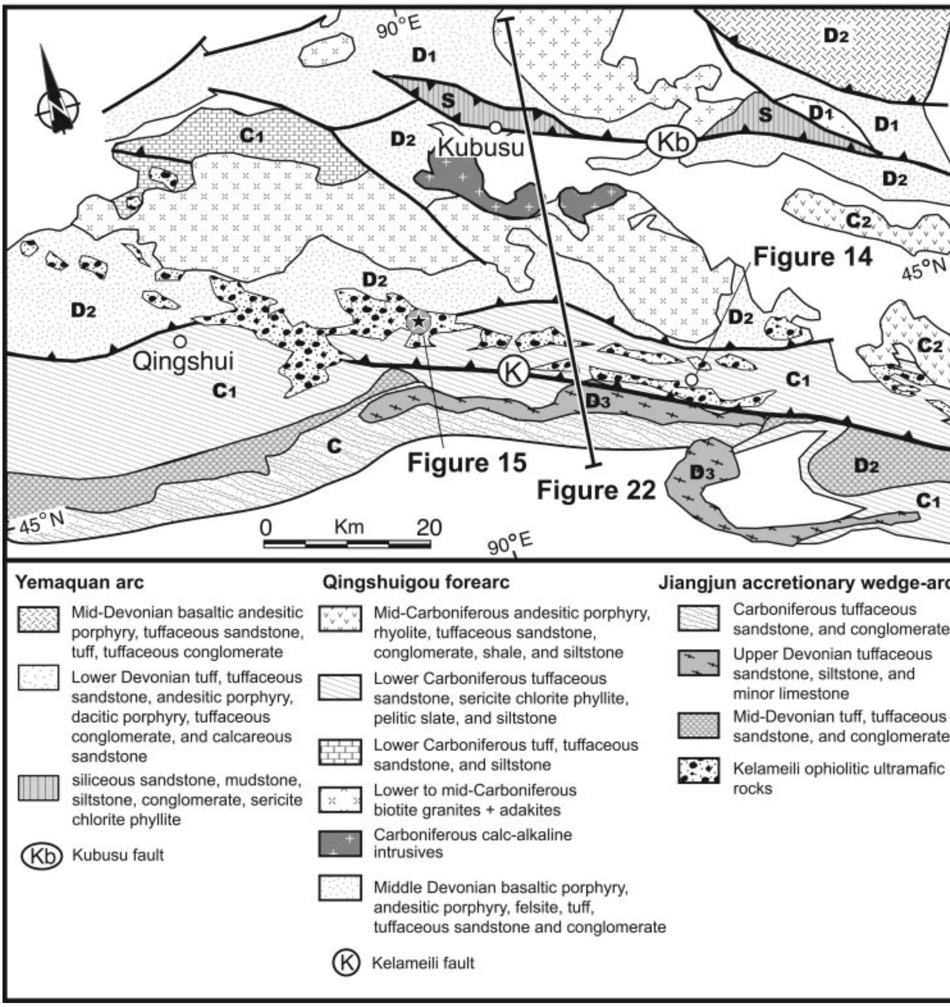

Fig. 13. Tectonic map of the Kelameili area showing major tectonic lithologies and structures (based on our own work and modified after XBGMR, 1993). Position shown in figure 3. The locations of figures 14 and 15, and the section line of figure 22 are shown.

NEW STRUCTURAL DATA

Major Thrust Tectonics in the Southern Chinese Altay and Erqis Units

There are several thrusts along the southern Chinese Altay (see fig. 4 for position), but the Tesibahan fault has long been thought to be the major boundary thrust that separates the Chinese Altay from the Erqis and East Junggar units to the south (Qu and Zhang, 1994; He and others, 1994). Within the mélanges or coherent components of different tectonic units there are some southward thrusts (figs. 5 and 6).

There is considerable evidence for major south-directed thrusting in the Chonghuer area (see fig. 4 for location), where northeast-dipping thrusts carry granitic gneisses over meta-sedimentary rocks that contain coarse porphyroblasts of staurolite (2-3 cm) and kyanite (5-7 cm) (fig. 16). The granitic gneisses have undergone multiple deformation phases including ptygmatic folding of quartz-feldspar veins. In the

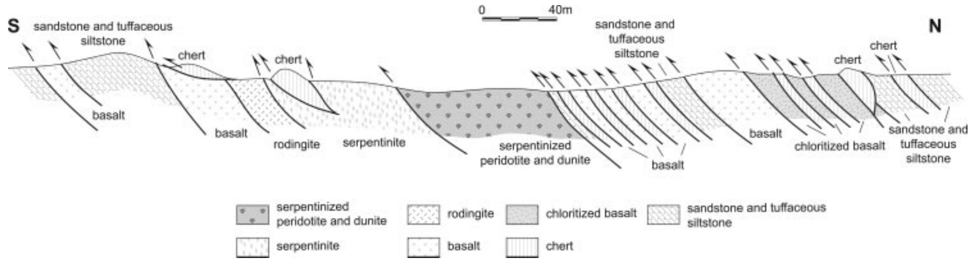

Fig. 14. Cross-section of the Sujiquan ophiolite showing details of the main rocks imbricated by south-vergent thrusts in the Kelameili ophiolitic melange. Sujiquan area. Position shown in figure 13.

Taerlang area (fig. 4), granites and granitic gneisses are thrust southward over mica-schists, which in turn are thrust southward over granitic gneisses. About 30 kilometers NE of Fuyuan, folds in granitic gneisses have fan-shaped, axial planar cleavages that indicate southward transport (fig. 17).

Along the Buerjin-Altay highway in the Kuerti area, gabbroic mylonite shows σ-type structures that indicate southwestward thrusting (fig. 18a). Southwest of Altay, asymmetrical σ-type structures and the vergence of small folds all indicate southwestward thrusting (figs. 18B, 18C, and 18D), and the kinematic relations between minor faults and chevron folds all point to southwestward or southward thrusting (figs. 18E and 18F).

The general trend of these thrusts is NWW-SEE, and their dip is commonly moderate, but locally may be steep or sub-vertical. The thrusts have commonly transported gneisses, schists, and migmatites of possible Devonian age over Carboniferous schists, volcanic rocks or other metasediments. About 8 km south of Altay city a minor duplex indicates that major thrusting was to the southwest (fig. 19A). In Taerlang, west of Altay city, well preserved lineations generally plunge to 040° (figs. 3 and 19B). Lineations in gabbroic mylonite in the Kuerti area plunge steeply to the NE (fig. 3). Lineations and A-type fold axes generally plunge NNW at about 50 degrees.

Large-scale Strike-slip Tectonics in the Southern Chinese Altay and Erqis Units

The Erqis fault zone has a mylonite that reaches 10 to 15 km in thickness, making it the largest fault in Central Asia (figs. 3 and 4). In the CAEJ the fault zone contains relicts of a wide variety of highly dismembered rocks, including gneiss, schist, arc volcanic rocks, ophiolites, and Silurian-Early Carboniferous metasedimentary and metavolcanic rocks (XBGMR, 1993; Windley and others, 2002). It is a major transpres-

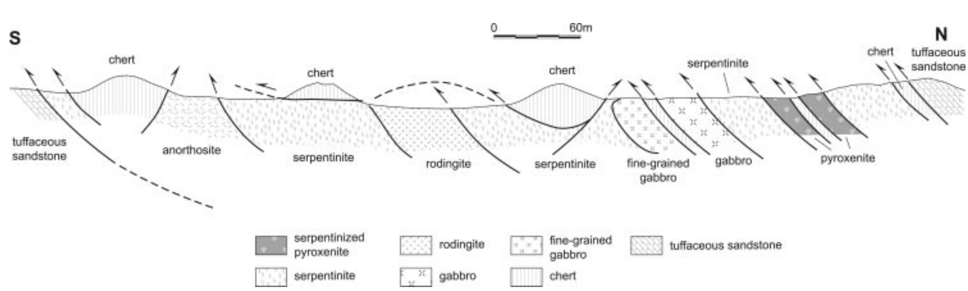

Fig. 15. Cross-section of the Kelameili ophiolite in the Hongliuhe area showing the distribution of rocks imbricated by two generations of thrusts. Position indicated in figure 13.

Fig. 16. Photo of the SW Altay thrust belt showing granitic gneiss thrust over staurolite-kyanite schist at Chonghuer. Scientists for scale. Looking NW. Position indicated in figure 4.

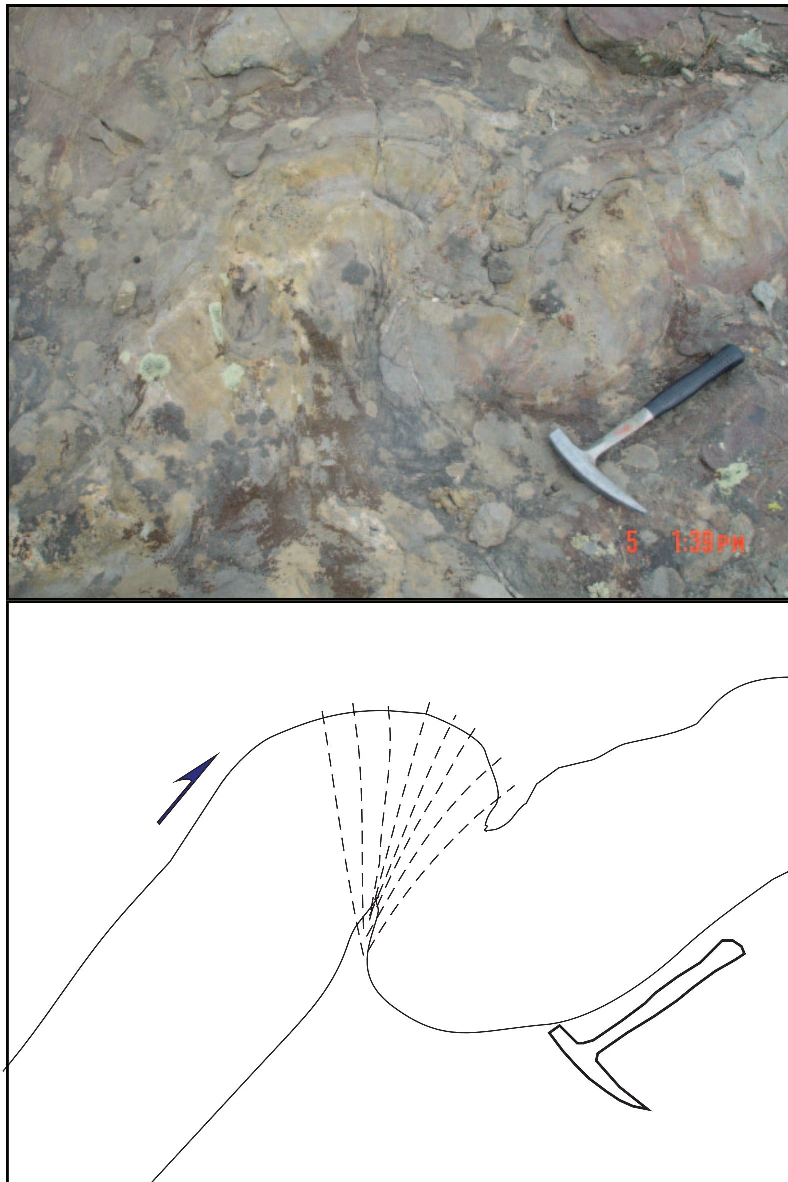

Fig. 17. Folds with axial planar, fan-shape cleavage in meta-sandstone, NW of Fuyun. Hammer for scale.

sional fault zone, but the movement direction of this strike-slip fault is highly controversial; sinistral or dextral (XBGMR, 1993; Şengör and others, 1993; Windley and others, 2002; Laurent-Charvet and others, 2003).

North of Fuyun the vergence of small folds in metasediments indicates sinistral strike-slip motion (fig. 20A). In the Kuerti area several gabbroic mylonites contain excellent σ-type and δ-type structures that indicate sinistral strike-slip movement (figs. 20B and 20C). Northwest of Fuyuan large staurolite porphyroblasts form σ-type structures that indicate sinistral strike-slip (fig. 20D). Sinistral ductile movements are

Fig. 18. Collage of photographs showing structures in ophiolitic mélanges. (A) Asymmetric kinematic indicators in gabbroic mylonite, indicating thrusting to SW, Kuerti. End of marker pen for scale. Looking SE. (B) σ-type porphyroclasts of feldspar in a shear zone, showing thrusting to SW, SW of Altay. Hammer for scale. Looking NW. (C) and (D) Asymmetric small folds in turbidites indicating thrusting to SW, NE of Altay. Hammer for scale. Looking SE. (E) Chevron folds and thrusts in turbidites, SW of Altay. Circled Hammer for scale. Looking NW. (F) Folded metasediments, SW of Altay. Circled 2.5-m-high tree for scale. Looking NE.

common along the southern Chinese Altay and northern Erqis units (Laurent-Charvet and others, 2002, 2003). However, north of Buerjin and Fuyun tight folds indicate ductile-brittle dextral deformation that is mainly concentrated in the central and southern parts of the Erqis fault zone (figs. 21A and 21B). The Erqis zone could be a triclinic shear zone, but this needs further investigation.

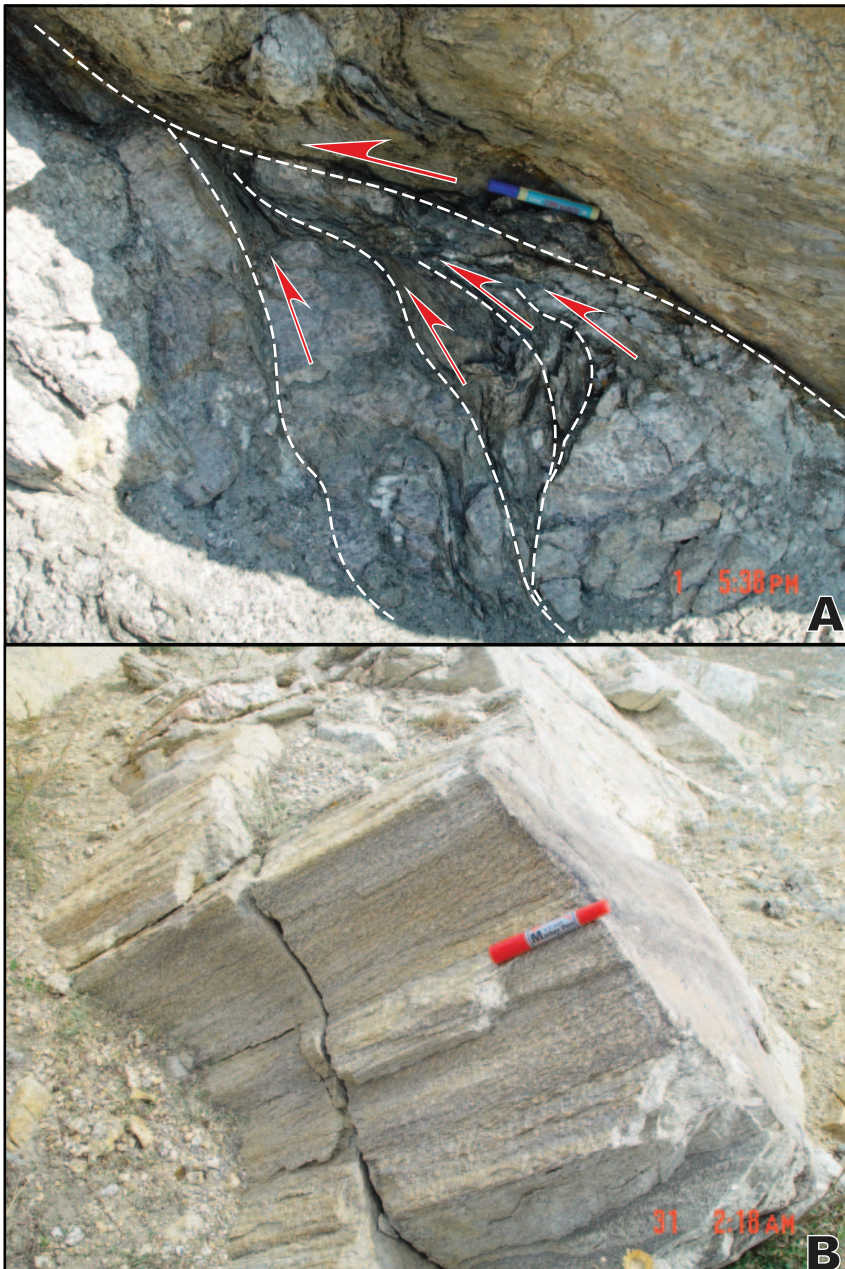

Fig. 19. (A) Photo of small duplex in a fault zone of the southern Altay, indicating thrusting to the SW. Marker pen for scale. Looking NW. Position shown in figure 4. (B) Photo of prominent NE-dipping rodding lineation in gneiss, indicating thrusting to SW. At Taerlang. Marker pen for scale. Looking E. Position shown in figure 4.

Thrust Imbrication in the East Junggar Arc

The major structures in East Junggar are mainly NW-trending thrusts and NNW-trending strike-slip faults (figs. 3, 10, and 13). Two ophiolitic mélange zones (Armantai

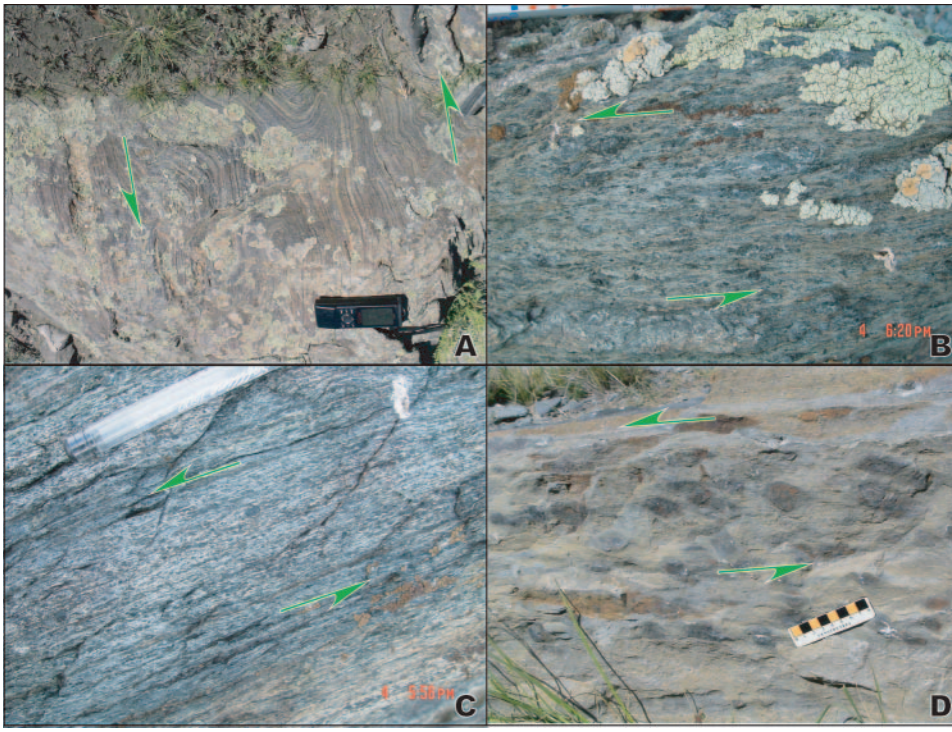

Fig. 20. Photographs of structures. (A) Complex folds, Erqis shear zone. Sinistral sense of shear is indicated. NE of Buerjin. GPS device for scale. (B) and (C) Asymmetric kinematic indicators in gabbroic mylonites in the Kuerti ophiolite, indicating sinistral sense of shear, Kuerti. End of marker pen for scale. Looking SE. (D) σ-type porphyroclasts of staurolite in a mylonite, NE of Fuyuan. Sinistral sense of shear is indicated. Cm-scale ruler for scale.

and Kelameili) form the major structural units, which are divided into the Dulate, Yemaquan, and Jiangjun subunits (figs. 3, 10, and 13). The Yamaquan arc occurs just south of the Armantai ophiolite (figs. 2, 3, and 10). Its northern part is characterized by pyroxene-bearing basalts imbricated with volcanic and pyroclastic rocks and minor tuffaceous conglomerates, crystal tuffs and tuffs. The southern part comprises quartz mica-schists juxtaposed with Early to Mid-Devonian pyroclastic rocks and siliceous andesites, dacites and minor rhyolites. Imbricated with these rocks are quartz mica-schists, meta-andesitic and meta-pyroclastic rocks of Late Silurian age (XBGMR, 1993) or mid-Silurian age (Li and others, 1990; Li, 1995). Devonian to Carboniferous volcanic and volcaniclastic rocks together with some granitic rocks form a 40 to 50 km-wide imbricate zone in the CAEJ. The thrusts generally dip moderately to the north or northeast, and are transected by several south-dipping thrusts (figs. 10 and 22).

GEOCHRONOLOGY

New SHRIMP Zircon Age

To obtain a "precise" age of formation of the Armantai ophiolite, we sampled a plagiogranite at Tuziquan (figs. 11, 23 and 24) and analyzed its zircons using SHRIMP II in the Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences.

Zircons from the plagiogranite are mostly clean, round and short (~100 μm) with some thin and long grains, but nearly all are prismatic (fig. 23). Analytic procedure for

Fig. 21. Photos of structures. (A) and (B) Z-type folds in meta-sandstones indicating dextral strike-slip shear, NW of Buerjin. Pen or ruler for scale.

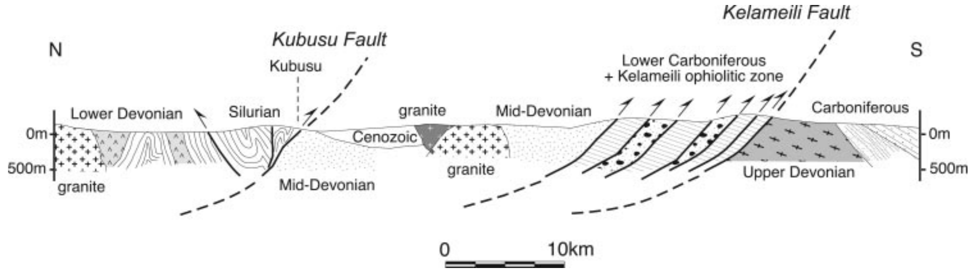

Fig. 22. Cross-section of the Kelameili area showing major tectonic units and structures in Silurian-Devonian-Carboniferous rocks belonging to the Yemaquan arc, Qingshuigou forearc and Jiangjun accretionary wedge-arc, as defined with the same lithologies in figure 13 (based on our own work and modified after Li and others, 1990; XBGMR, 1993). Position shown in figure 13.

SHRIMP U-Pb zircon dating is attached as an Appendix. The main results are presented in table 2 and figure 24. Nine zircons from the plagiogranite yielded U/Pb ages, and most analyses plot as a group straddling the Concordia and give a weighted mean ^{206}Pb/^{238}U age of 503 ± 7 Ma (n = 9, MSWD = 1.2).

Field observations show that plagiogranite dikes intrude gabbro-diabase; Jian and others (2003) described a similar relationship, although in places plagiogranite and gabbro-diabase dikes mutually transect. One gabbro has a U/Pb SHRIMP zircon age of 489 ± 4 Ma, and a 481 ± 5 Ma anorthosite intrudes another gabbro (Jian and others, 2003; Ping and others, 2005). The inter-relationships between the plagiogranite dikes and apparently older and younger gabbros in this ophiolite are complex. Many ophiolitic fragments of different age have been involved in formation of the accretionary complexes of the East Junggar unit. On the basis of these data, we regard 503 Ma as close to the formation age of the Armantai ophiolite.

Further Geochronological Constraints and Interpretations

Ages of ophiolitic fragments.—Several high-resolution SHRIMP zircon ages, recently obtained from ophiolitic fragments, provide firm constraints on the formation of the tectonic zones. A plagiogranite from the Kuerti ophiolitic fragment of the Chinese

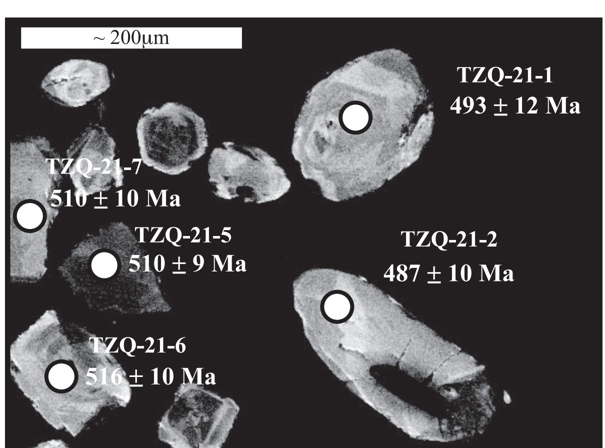

Fig. 23. CL image of zircons from dated plagiogranite from the Armantai ophiolite.

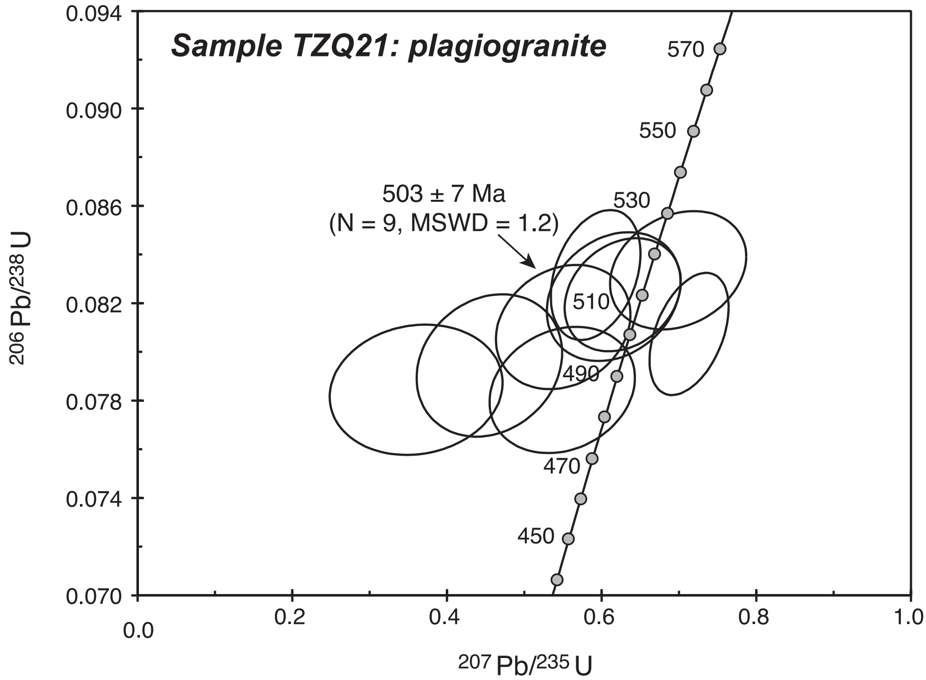

Fig. 24. Concordia plot of SHRIMP U-Pb data of zircons from plagiogranite TZQ21 from the Armantai ophiolite.

Altay arc, shown in figure 3, has a SHRIMP zircon age of 372 ± 19 Ma (Zhang and others, 2003a). Wu and others (2006) reported a SHRIMP zircon age of 352.1 ± 4.4 Ma for a basalt from the southern Qinghe ophiolitic mélange of the Erqis zone (fig. 25). Ping and others (2005) obtained an age as young as 403 ± 9 Ma for the Kelameili ophiolitic mélange (Jian and others, 2003; Ping and others, 2005) (fig. 25).

Ultramafic rocks from the Armantai ophiolitic fragment at Zhaheba have a Sm-Nd isochron age of 479 ± 27 Ma (Liu and Zhang, 1993). SHRIMP zircon dates by Jian and others (2003) of gabbros from Zhaheba yielded ages of 489 ± 4 Ma and 406 ± 4 Ma, and of an anorthosite of 481 ± 5 Ma (Jian and others, 2003; Ping and others, 2005). Jian and others (2003) interpreted the older ages (489, 481 Ma) to represent the age of formation, and the younger a later partial melting event (fig. 25), this is consistent with the presence of Ordovician radiolarian cherts (Li and others, 1990; Li, 1991; He and others, 2001), but other cherts yield Middle to Late Devonian radiolaria (Xiao and Tang, 1991; Xiao and others, 1992). Because the Armantai ophiolite is juxtaposed against arc-type, Late Devonian volcanic rocks and Early to Mid-Devonian boninites, adakites, and Nb-enriched basalts (fig. 3), we postulate that the Devonian arc was generated on old oceanic crust, and the younger age of 406 ± 4 Ma (Jian and others, 2003; Ping and others, 2005) is a record of this younger event (fig. 25). There is another possibility; these two parts of the ophiolite were displaced hundreds of kilometers on a strike-slip fault. This interpretation is in good agreement with the fact that Ordovician (Li and others, 1990; Li, 1991; He and others, 2001) and Mid-Late Devonian (Xiao and Tang, 1991; Xiao and others, 1992) radiolarian cherts are imbricated within this ophiolite-arc complex. Chromite mineralization occurs throughout almost one-third of the Armantai ultramafic rocks, suggesting that the majority of the ophiolite is a remnant of oceanic lithosphere. The above relations suggest that the

TABLE 2

Summary of U-Th-Pb SHRIMP data of zircons from the Armantai ophiolite

Grain spot	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	% $^{206}Pb_c$	$^{206}Pb/^{238}U$ Ages (in Ma)	$^{207}Pb/^{206}Pb$ Ages (in Ma)	$^{207}Pb^*/^{206}Pb^*$	±%	$^{207}Pb^*/^{235}U$	±%	$^{206}Pb^*/^{238}U$	±%
TZQ-21-1	77	39	0.53	5.39	2.10	493 ±12	-255 ±340	0.0415	13	0.455	14	0.0794	2.4
TZQ-21-2	60	24	0.41	4.10	1.79	487 ±10	230 ±256	0.0508	11	0.549	11	0.0784	2.2
TZQ-21-3	55	21	0.40	3.83	3.83	487 ±11	-850 ±584	0.0333	20	0.360	20	0.0784	2.3
TZQ-21-4	82	51	0.65	5.82	1.96	502 ±10	160 ±239	0.0493	10	0.550	10	0.0810	2.1
TZQ-21-5	136	53	0.40	9.77	1.29	510 ±9	422 ±171	0.0552	7.7	0.627	7.9	0.0823	1.9
TZQ-21-6	144	63	0.45	10.4	1.19	516 ±10	633 ±174	0.0608	8.1	0.699	8.3	0.0834	1.9
TZQ-21-7	73	30	0.42	5.23	0.87	510 ±10	382 ±203	0.0543	9.0	0.615	9.3	0.0823	2.1
TZQ-21-8	89	36	0.42	6.43	1.10	515 ±10	270 ±140	0.0517	6.1	0.592	6.5	0.0832	2.1
TZQ-21-9	68	24	0.37	4.74	0.38	501 ±10	743 ±90	0.0641	4.3	0.713	4.7	0.0807	2.1

Errors are 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.52%.
Common Pb corrected using measured ^{204}Pb.

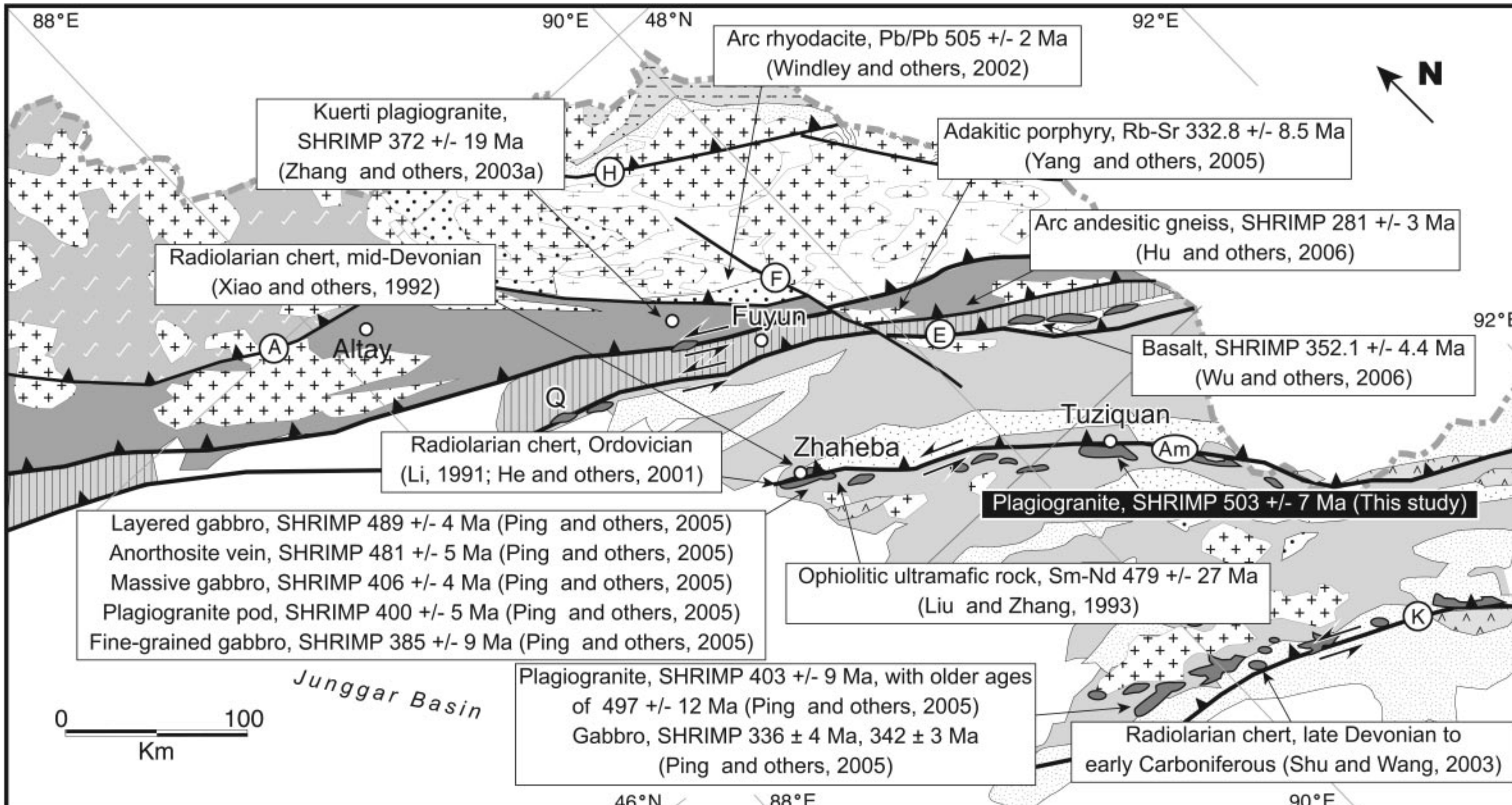

Fig. 25. Tectonic map of the Chinese Altay-East Junggar orogenic collage (CAEJ), showing published geochronological data (with references), and SHRIMP data from this study. Legend, fault names, and abbreviations as in figure 2.

final incorporation of the ophiolitic components into the East Junggar accretionary collage was in the Early Carboniferous.

Gabbros in the Kelameili ophiolitic fragments have island arc tholeiitic affinities (Wang and others, 2003b). The extrusive rocks plot in the fields of IAB and MORB (Wang and others, 2003b). Liang and others (1999) suggested they formed in a forearc setting based on their supra-subduction zone geochemical signature (Wang and others, 2003b). Associated cherts contain Early Devonian and Early Carboniferous radiolaria (Ma and others, 1997; Liang and others, 1999; Shu and Wang, 2003), and the ophiolitic rocks (containing 403 Ma plagiogranite, and gabbros with 336 Ma and 342 Ma U/Pb zircon ages) are imbricated with strongly deformed Devonian-Carboniferous arc volcanic rocks.

Ages of arc volcanic rocks and metasediments.—Many gneisses and schists in the Chinese Altay were previously assigned Precambrian ages on account of their high-grade metamorphism and of some Precambrian U-Pb and Sm-Nd age data. Zircons from banded paragneiss from the Altay and Chonghuer areas of the Chinese Altay, however, cluster predominantly between 466 and 528 Ma, and have some inherited Neoproterozoic, Paleoproterozoic and Archean ages (Sun and others, 2008). Zircons from gneissic granitoids from the southern Chinese Altay yield U-Pb ages between 380 and 453 Ma (Sun and others, 2008). The absence of Precambrian inherited zircons and the majority of positive ε_{Hf} values (ranging from -10 to $+15$) for these Paleozoic zircons (Sun and others, 2008) suggest little or no crustal contribution to the generation of the host granites. Recent geological and geochemical analyses have shown that the protoliths of some gneisses and schists, such as those situated SW of Fuyun, are actually arc-related volcanic rocks (fig. 25), and SHRIMP zircon ages of the gneisses and schists show that they formed at 281 $\pm$ 3 Ma (Hu and others, 2006).

U-Pb zircon data from six igneous and meta-igneous bodies (now gneisses and foliated plutons) in the hanging wall of the Erqis fault (fig. 4) indicate latest Ordovician (ca. 451-433 Ma) magmatism (Briggs and others, 2007). Systematic studies of U-Pb and Hf isotopes of detrital zircons separated from metasedimentary rocks from the Chinese Altay reveal that a predominant population has $^{206}Pb/^{238}U$ ages between 460 and 540 Ma and most grains of this population possess positive $\varepsilon_{Hf(t)}$ values (Long and others, 2007). These results suggest that the early Paleozoic melts were juvenile, implying that the Chinese Altay orogen was an active continental margin in the Early Paleozoic.

A felsic arc-type rhyodacite on the southern margin of the Chinese Altay has a mean $^{207}Pb/^{206}Pb$ zircon age of 505 $\pm$ 2Ma, reflecting the time of arc volcanism (fig. 25), but the presence of xenocrysts with ages between 614 and 921 Ma suggests derivation by intracrustal melting during formation of a continental magmatic arc (Windley and others, 2002).

Dacitic-rhyolitic rocks with a Rb-Sr isochron age of 405 $\pm$ 57 Ma and an arc geochemical signature were recently reported in the Ashele area in the southwestern Chinese Altay (Chen and others, 2006a). An adakitic porphyry located SE of Fuyun (fig. 25) has a Rb-Sr age of 332.8 $\pm$ 8.5 Ma (Yang and others, 2005a). A monazite from a schist with synkinematic garnets, dated using an *in situ* ion-microprobe Th-Pb technique, has ages ranging from 293 to 254 Ma with a weighted mean of 278 $\pm$ 9 Ma (Briggs and others, 2007). Muscovite from a granitic gneiss has a weighted mean age of 275 $\pm$ 8 Ma, while a metapelitic schist yielded biotite with a weighted mean age of 259 $\pm$ 10 Ma (Briggs and others, 2007).

The trace element geochemistry of a Permian basic granulite indicates that the protolith was a calc-alkaline basalt formed in an island arc environment (Li and others, 2004; Chen and others, 2006b). This granulite has SHRIMP zircon ages of 271$\pm$6, 279$\pm$5.6, 268$\pm$5.8 and 271$\pm$5.4 Ma (Li and others, 2004; Chen and others, 2006b).

In the Jiangjun area south of the Kelameili ophiolite muscovite-quartz schist, muscovite-garnet-quartz schist and minor amphibolite are intercalated with marbles. The schistosity mainly strikes ESE-WNW and dips steeply to vertical. A marble contains Early Paleozoic corals and crinods (He and others, 2001). Muscovite from a schist has a $^{40}Ar/^{39}Ar$ age of 460 Ma indicating Mid-Ordovician metamorphism (He and others, 2001). Silurian slates, sandstones, and pyroclastic rocks have been thickened by thrust imbrication (Carroll and others, 1990). These Ordovician-Silurian rocks are imbricated with Mid- to Upper Devonian metasediments.

Ages of granitic rocks.—Up to 60 percent of the present exposure-level of the Chinese Altay consists of granitic rocks (Windley and others, 2002). LA-ICP-MS zircon U-Pb dating and whole rock analyses for major, trace element and Nd-Sr isotopes of a comprehensive range of granitic rocks demonstrate that granitic intrusions took place in the Devonian, Late Carboniferous, and Permian (Wang and others, 2006b; Yuan and others, 2007). The study of Yuan and others (2007) also shows that the deep crust of the Chinese Altai may contain a considerable proportion of juvenile material, and that mantle-derived magma, probably in an extensional forearc setting, played an important role in the accretionary orogenesis, providing not only a heat source, but also a juvenile component for the vertical crustal growth of the Chinese Altai (Yuan and others, 2007).

Ages of strike-slip faults.—Many tectonic units in CAEJ have no foredeeps or foreland basins, and are separated by steep faults that have sub-horizontal mylonitic fabrics indicating strike-slip movements. Along many tectonic boundaries there is much evidence of multiphase strike-slip motion (Ruzhentsev and Mossakovskiy, 1996). Strike-slip movements on the Erqis fault have been dated as mid-late Permian by a variety of isotopic methods such as SHRIMP zircon and $^{40}Ar/^{39}Ar$ (Mossakovsky and others, 1993; Delvaux and others, 1998; Buslov and others, 2001, 2003, 2004; Laurent-Charvet and others, 2002, 2003; Dobretsov, 2003; Dobretsov and others, 2004). Laurent-Charvet and others (2003) reported $^{40}Ar/^{39}Ar$ ages of 290 to 247 Ma on biotite, muscovite, and amphibole from the Erqis fault in the Chinese Altay, and Melnikov and others (1998) reported $^{40}Ar/^{39}Ar$ ages of 290 to 265 Ma on micas along the western extension of this fault in Kazakhstan (Travin and others, 1998, 2001; Buslov and others, 2004). In combination with field data, Laurent-Charvet and others (2002, 2003) concluded that the sinistral strike-slip faults were mostly older (~ 290 Ma) in the northern side of the Erqis fault than in the center and southern side (ranging from 265-247 Ma). These movements predate Cenozoic strike-slip faulting (Cunningham and others, 1996, 2003).

NEW TECTONIC SUBDIVISION AND DEVELOPMENT

Our new data integrated with published literature above (figs. 2, 26, and 27, table 1) enable us to reinterpret the tectonic setting of several components of the CAEJ, and to suggest a novel tectonic development.

Chinese Altay: A Paleozoic Magmatic Arc with Accretionary Complexes

The Chinese Altay (figs. 2, 26, and 27) contains variably deformed and metamorphosed Neoproterozoic to Paleozoic sedimentary and volcanic rocks, which were intruded by granitic rocks of various ages ranging from 460 Ma to 270 Ma (He and others, 1994; Windley and others, 2002; Wang and others, 2006). Some previous studies (XBGMR, 1993) considered the Chinese Altay to be constructed by layer-cake deposition. However, the Chinese Altay is composed of volcanic, volcaniclastic, sedimentary and metamorphic rocks in thrust-bound ophiolitic melanges and coherent sedimentary accretionary packages, intruded by voluminous granitic rocks; in short a tectonic stratigraphy.

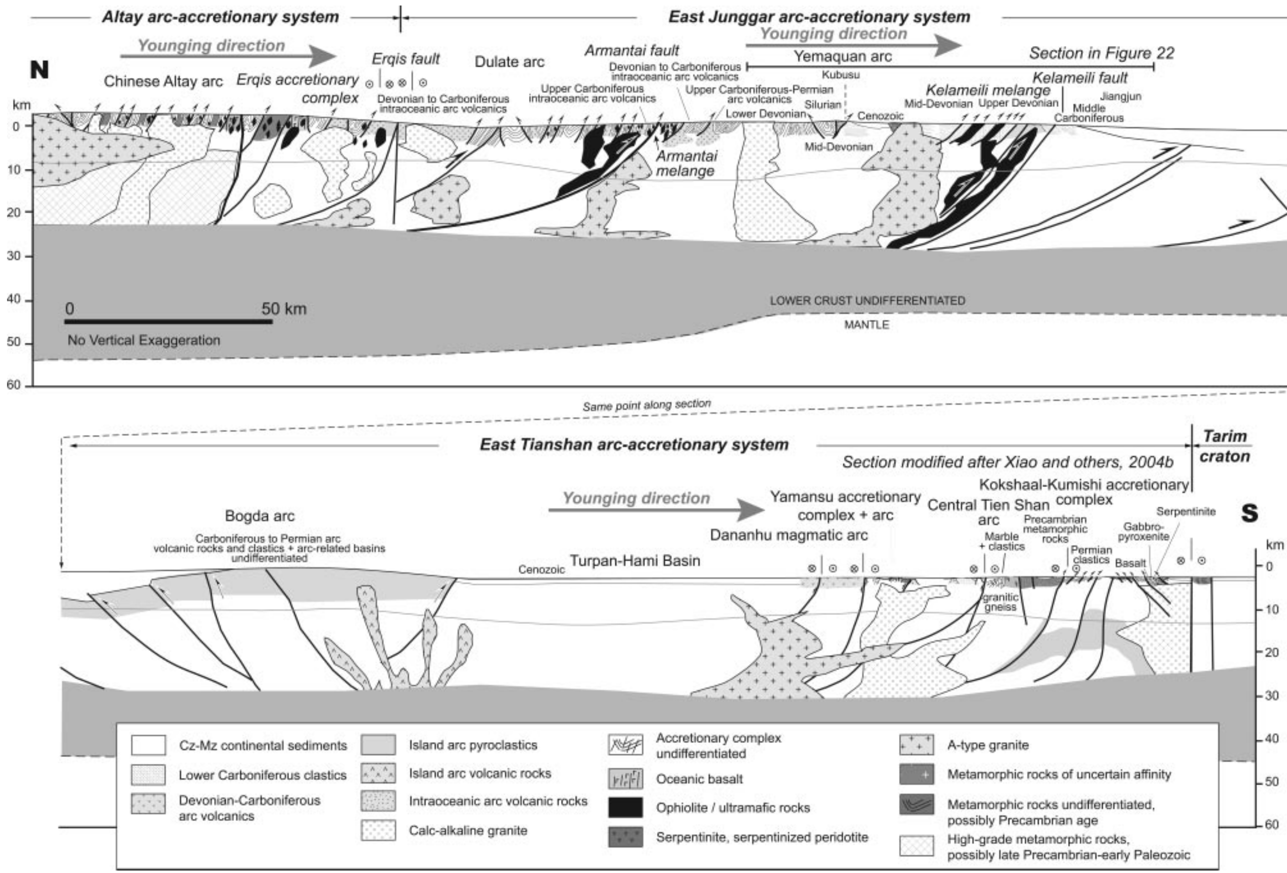

Fig. 26. Interpreted geophysical section from Altay to Bogdashan in Northern Xinjiang, China (modified after Yuan, 1999; Wang and others, 2003a). The section crosses the Altay, East Junggar and East Tianshan units of this paper. Surface structures and lithologies are based on our own observations and the literature. Section line is shown in figure 2. Cz = Cenozoic, Mz = Mesozoic. See text for discussion.

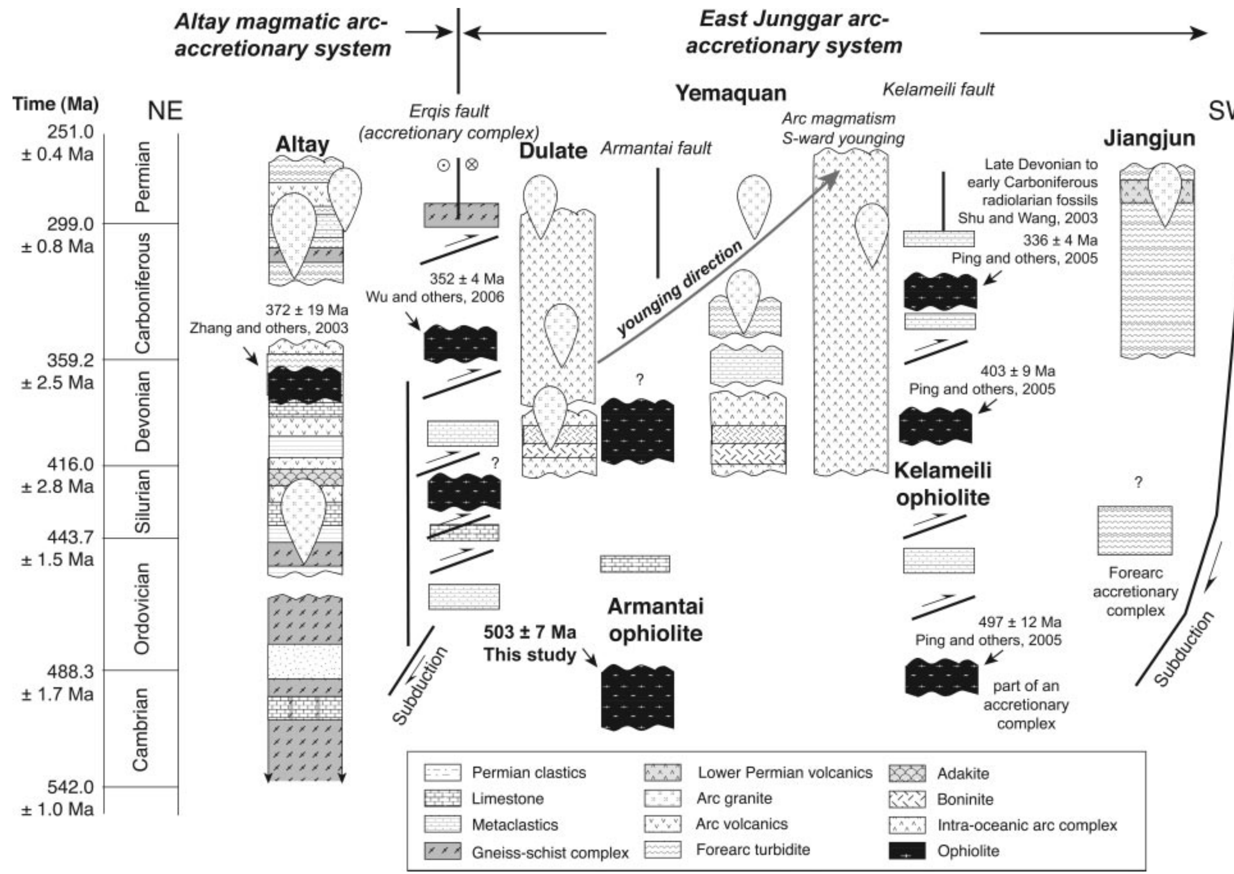

Fig. 27. Space-time diagram demonstrating the spatial and tectonic relationships between the tectonostratigraphic units of the Altay and East Junggar arc-accretionary collages (compiled from our own work, and incorporating that of Li and others, 1990; XBGMR, 1993; Windley and others, 2002). Published isotopic ages and the SHRIMP date of this study are shown in their tectonostratigraphic positions. See text for discussion.

The presence of high-Mg andesites and Nd-rich dacites suggests forearc components (Niu and others, 1999). These rocks were fault-sliced and mutually juxtaposed, and contain remnants of earlier deformed active margin sediments and Ordovician-Silurian accretionary complexes, which were thrust southwestwards over Devonian-Carboniferous arcs (He and others, 1994; Windley and others, 2002). Some ophiolitic mélanges, as at Kuerti, contain remnants of Middle-Late Devonian oceanic crust (Chen and others, 1997; Xu and others, 2003; Zhang and others, 2003a, 2003b, 2003c, 2005). Geochemical and isotopic studies show that these ophiolites have both arc- and MORB-related affinities, which led Xu and others (2003), Zhang and others (2003b, 2005), and Wu and others (2006) to conclude that the ophiolites were emplaced in an active continental margin setting. Geochemical studies on the newly found ophiolitic mélanges in figure 6 show that three are mid-ocean ridge basalts (MORB) and ocean island basalts (OIB-type) (Wong and others, 2008). These mélanges and different origins of ophiolitic fragments, which are imbricated against each other, show that there are parts of accretionary complexes in the Chinese Altay.

The Chinese Altay contains arc-accretionary complexes composed of variably deformed and metamorphosed Neoproterozoic to Paleozoic sedimentary and volcanic rocks, with granitic intrusions from which zircon U-Pb ages and Hf isotopic compositions suggest a progressive accretionary history in early to mid-Paleozoic times. Current data suggest that the Chinese Altay most likely represents a magmatic arc built on a continental margin dominated by Neoproterozoic rocks (Windley and others, 2002; Sun and others, 2008). Combined with tectonostratigraphic analysis (Windley and others, 2002; Xiao and others, 2004a), we interpret the Chinese Altay as a late Cambrian to carboniferous or even early Permian, Japan-type island arc orogen with some Neoproterozoic cratonic fragments.

The inferred development by multiple accretion of active margin rock packages and of planar sinistral strike-slip duplexes (fig. 4) indicates that forearc shaving or arc-parallel translation of active margin units possibly took place in a late stage of accretion.

Erqis: A Paleozoic Accretionary Complex

The Erqis fault has previously been considered to be a strike-slip zone with a thick mylonite (Şengör and others, 1993), and as a narrow sliver that contains 10 to 15 km-wide mylonites, and to have undergone at least 1000 km of sinistral displacement (Şengör and others, 1993; Laurent-Charvet and others, 2003). However, as shown above, this fault zone also contains many ophiolitic fragments. The ophiolites in or bordering this zone comprise lherzolite, IAT- and MORB-type basalt (Chen and others, 1997; Niu and others, 1999; Yu and others, 2000; Xu and others, 2003; Wang and others, 2003b; Wu and others, 2006) that represent the remains of oceanic crust/mantle derived from a major ocean largely subducted beneath the Chinese Altay and East Junggar intraoceanic subduction systems. Together with coherent units and thrust-imbricated forearc volcanic rocks and sediments, the material and structures within the Erqis zone indicate that it represents the remnants of a Paleozoic accretionary complex that includes neighboring active continental margin rocks. It developed along the southern accretionary margin of a Japanese-type arc represented by the present-day Altay Mountains in Kazakhstan, China and Mongolia, and it underwent southwestward thrusting and sinistral ductile strike-slip faulting, mostly in its northern side, followed by dextral strike-slip faulting, mainly in its present center and southern side.

East Junggar: A Paleozoic Intra-oceanic Island Arc with Accretionary Complexes

The main tectonic setting of East Junggar can be defined today as a Paleozoic Mariana-type intra-oceanic island arc, in contrast to an old continental block with some oceanic crust (Li, 2006).

The East Junggar (Dulate-Baytag) arc comprises boninites, Nb-enriched basalts, adakites, andesitic basalts, cherts, and minor gabbros (Liu and others, 1993). Boninites occur in the Saerbulake area south of the Erqis fault (fig. 4). The boninites occur as pillow lavas or pillow breccias (Niu and others, 2006). The primary magma composition of the boninites was generated from depleted sub-arc mantle fluxed by slab-derived fluids (Niu and others, 2006). The adakites in the Suoerkuduke area (fig. 4) most likely represent a low-degree of partial melting of subducted young oceanic crust, somewhat affected by interaction with mantle wedge peridotites and incorporated sediments (Niu and others, 2006).

A forearc setting is indicated (Stern and Bloomer, 1992; Polat and Kerrich, 2004) by massive and pillowed basalts, Nb-enriched basalts (Zhang and others, 2003b, 2003c, 2005; Yuan and others, 2007), boninites (Liu and others, 1993), and Lower Devonian adakites (Yu and others, 2000; Xu and others, 2001, 2003; Zhang and others, 2005), imbricated with Ordovician-Silurian radiolarian cherts, Silurian-Devonian turbidites, and Devonian-Carboniferous arc volcanic rocks and radiolarian cherts (Liu and Zhang, 1993; Mei and others, 1993; Liang and others, 1999; Yu and others, 2000; Qin and others, 2002). A mature arc is indicated by the presence of felsic tuffs, pyroxene-bearing basalts, andesites and porphyry-type copper ore deposits.

The Armantai ophiolite contains remnants of seamounts with minor limestones and island arc rocks (Jin and others, 2001); it was thrust southwards over pyroxene-bearing basalts belonging to the Early Devonian to mid-Carboniferous Yemaquan arc. These ophiolitic fragments are imbricated within forearc rocks including mid-Devonian boninites, adakites and Nb-enriched basalts and associated accretionary assemblages (Liu and Zhang, 1993; He and others, 1994; Wang and others, 2003b; Xu and others, 2003; Zhang and others, 2003a, 2003b, 2005). Cr-spinels in mantle peridotites of the Armantai ophiolitic mélange plot in the fields of arcs and back-arc basins (Wang and others, 2003b). Prominent alkali basalts have oceanic island basalt (OIB) geochemical signatures (Jin and others, 2001) like those in Hawaii (Xiao and others, 1992). But some geochemical data suggest a supra-subduction zone origin (Liang and others, 1999; Jin and others, 2001; Wang and others, 2003b); these components could belong to an earlier accretionary complex.

The geochemistry of granites and volcanic rocks from the Yamaquan arc suggests a calc-alkaline affinity (Li and others, 1990). Devonian-Early Carboniferous volcanic rocks in the Jiangjun area south of the Kelameili ophiolitic mélange are remnants of an arc and forearc. Lin and others (1997) considered that Permian volcanic rocks in the area southeast of Tuziquan formed in a subduction setting. Related accretionary complexes and associated forearc basins have recently been defined south of the Yemaquan arc based on their tectonic assemblages and structures (Xiao and others, 2004a, 2004b).

Discussion

Subduction Polarities

The CAEJ is composed of three major tectonic units, viz: Chinese Altay, Erqis, and East Junggar (Xiao and others, 2004a). Ophiolitic melanges, such as Armantai and Kelameili, divide the East Junggar into three major tectonic subunits. Extrusive rocks in the Paleozoic ophiolites or ophiolitic mélanges are mainly MORB-, OIB and IAB-type basalts, and minor back-arc basin basalts (BABB) (Wang and others, 2003b; Wu and others, 2006). Field relations and structural data indicate that they belonged to arcs, forearc accretionary complexes, and arc-related basins that were mutually juxtaposed by faulting. The present overall picture supports a series of convergent marginal processes in this part of the Altaids (Şengör and Natal'in, 1996b, 1996a; Şengör and Natal'in, 2004).

An interpreted geophysical profile across the Chinese Altay to the Eastern Tien Shan (Wang and others, 2003a), shown in figure 26, integrated with surficial geological structures, illustrates several structural anomalies, which correspond to the Erqis fault, Armantai, and Kelameili ophiolitic mélanges. Along the Erqis fault, the relatively steep Erqis accretionary complex is highly sheared. The Armantai and Kelameili ophiolitic mélanges, which mostly occur along the Aermantai and Kelameili faults respectively, are represented by north-dipping, listric thrust structures, which are occupied by thick and extensive ophiolite/ultramafic rocks that extend down to the upper boundary of the undifferentiated lower crust (fig. 26). From N to S, this major crustal section is characterized by a series of southward-younging, thrusted arcs, accretionary complexes, and minor ophiolitic mélanges together with high-grade metamorphic rocks of possible late Precambrian to early Paleozoic age, and calc-alkaline and A-type granites (fig. 26).

In so far as these geophysically defined subduction systems have a largely northward subduction polarity that can be traced upwards to geologically defined surface rocks and structures (Wang and others, 2003a), we think that they can be extrapolated to represent the tectonic events that amalgamated all the tectonic units in the CAEJ. Therefore we conclude that the subduction polarities in the Paleozoic CAEJ were mainly northward to northeastward.

Geological, geochemical, and geophysical data from the CAEJ indicate continuous subduction and accretion from at least the Devonian to the Early Carboniferous (Wang and others, 2003a) or even to the Permian prior to final amalgamation of these accreted systems with the Tarim craton along the Tien Shan suture (Xiao and others, 2004a, 2004b, 2008; Long and others, 2007; Briggs and others, 2007). Within the Chinese Altay and East Junggar units Paleozoic calc-alkaline intrusions formed above northward-dipping oceanic slabs (Wang and others, 2003a). Remnants of several intraoceanic arcs in the Chinese Altay and East Junggar units mainly have Late Cambrian-Early Ordovician to Late Paleozoic ages. Our new SHRIMP zircon age of 503 ± 7 Ma of the Armantai ophiolite, which was thrust imbricated between the intraoceanic Dulate and Yemaquan island arcs built by northward subduction, is close to the mean $^{207}Pb/^{206}Pb$ zircon age of 505 ± 2Ma of felsic arc lavas in the Chinese Altay (Windley and others, 2002). Based on the evidence of arc-related geochemistry of granites, regional tectonic correlations, and the presence of ophiolites to the south, we postulate that there is an early Paleozoic, N-dipping subduction system under the southern margin of the Chinese Altay. Combined with field mapping, detailed kinematic analysis, and geochronological dating of the Erqis fault zone in the Chinese Altay, Briggs and others (2007) favored a tectonic model that involves two episodes of subduction below the Altai arc: first, in the Ordovician along a south-dipping subduction zone; and second, in the late Carboniferous and early Permian along a north-dipping zone of subduction of the Junggar ocean. This is in good agreement with the conclusion that the final amalgamation time could be as young as Permian to mid-Triassic (Hendrix and others, 1996; Xiao and others, 2009). The major subduction polarity of the oceanic plates between the Chinese Altay and East Junggar was northward on the basis of southward younging, southwestward thrusting and the southwestward migration of deformation (Rotarash and others, 1982; Qu and Zhang, 1994; Windley and others, 2002; Qin and others, 2002; Goldfarb and others, 2003; Xiao and others, 2004a). All the above observations and data lead to the conclusion that a N-dipping subduction zone generated a mature island arc in the latest Cambrian-Early

Ordovician to the Devonian, and subduction beneath the southern CAEJ at least lasted to the Late Carboniferous-Early Permian (fig. 27).

Tectonic Model

We favor the following scenario for the Paleozoic accretionary tectonics of the CAEJ. Possible relations are depicted in figures 28 and 29.

During the mid-Cambrian to Early Ordovician the Junggar ocean, a branch of the Paleoasian Ocean, was probably subducted northeastward beneath the southern Altay margin (present-day coordinates, fig. 28A). At this time in the Paleoasian Ocean west of the Altay arc, there was an intra-oceanic northeast-dipping subduction zone (fig. 28A). Subduction of an oceanic plate generated nascent lithosphere above the subduction zone, forming a supra-subduction zone ophiolite (Kelameili). A volcanic arc was constructed above the suprasubduction zone adjacent to an accretionary prism (fig. 28B). A forearc accretionary prism was accreted southwest of the active Kelameili arc. Behind the subduction system there was a seamount composed of alkaline E-MORB and OIB basalts of the Armantai ophiolite (Jin and others, 2001) (figs. 28B and 29). In the Late Ordovician (fig. 28B) this seamount was capped by limestone subsequently off-scrapped as a slice in the Dulate arc. In the Silurian the subducting slab beneath the Kelameili ophiolite and Yemaquan arc became flat or very shallow-dipping because there was large-scale production of adakitic rocks in East Junggar (Zhao and others, 2006; Wang and others, 2006a, 2007), and there was no subduction-related volcanic or magmatic activity at this time, only growth of a forearc accretionary prism.

Continued convergence generated a new, N-dipping subduction zone beneath the Armantai seamount, resulting in a new intraoceanic arc (Dulate) containing Early to Mid-Devonian adakites (fig. 28C). In the Paleoasian Ocean this Dulate-Yemaquan arc (fig. 28C) had a paleogeography analogous to that of the present-day Mariana arc in the western Pacific (Macpherson and Hall, 2001; Hall, 2002; Hall and Spakman, 2002).

Through Late Devonian to Early Carboniferous times the Paleoasian Ocean was further consumed and subducted northeastward beneath the Dulate-Yemaquan intra-oceanic arcs (fig. 28C). Northeast-dipping thrusts led to emplacement of the Armantai ophiolite that was imbricated with Devonian-Early Carboniferous volcanic and sedimentary rocks. Trenchward thrusting may have imbricated the Kelameili ophiolite within the forearc accretionary prism.

This intra-oceanic composite arc gradually approached and accreted to the Chinese Altay active margin in the Mid-Carboniferous or even in the Permian, forming an Andean-type magmatic margin (figs. 28D and 28E). Probably at this time or later, the Erqis fault transported the intra-oceanic Dulate-Yamaquan arc-accretionary complexes southeastward (present-day coordinates) with respect to the Chinese Altay magmatic arc (fig. 29).

In the Late Carboniferous-early Permian the whole Chinese Altay-East Junggar region was transformed into a continental magmatic arc system, which was widened with its magmatic front shifting to the south into the Jiangjun accretionary prism (He and others, 2001). This above-mentioned process led to intense sinistral strike-slip faulting in the Permian in the Dulate arc, for example, along the Erqis fault (Zhang and others, 1996; Delvaux and others, 1998; Laurent-Charvet and others, 2002, 2003).

Implications for the Architecture of Central Asia

Many different models have been proposed to explain the tectonic evolution of the Central Asian Orogenic Belt, some speculative, and some based on detailed studies of the geology. Examples include: punctuated accretion by closure of multiple oceans (Coleman, 1989), accretion of arcs, new oceans, arcs, microcontinents (Mossakovsky

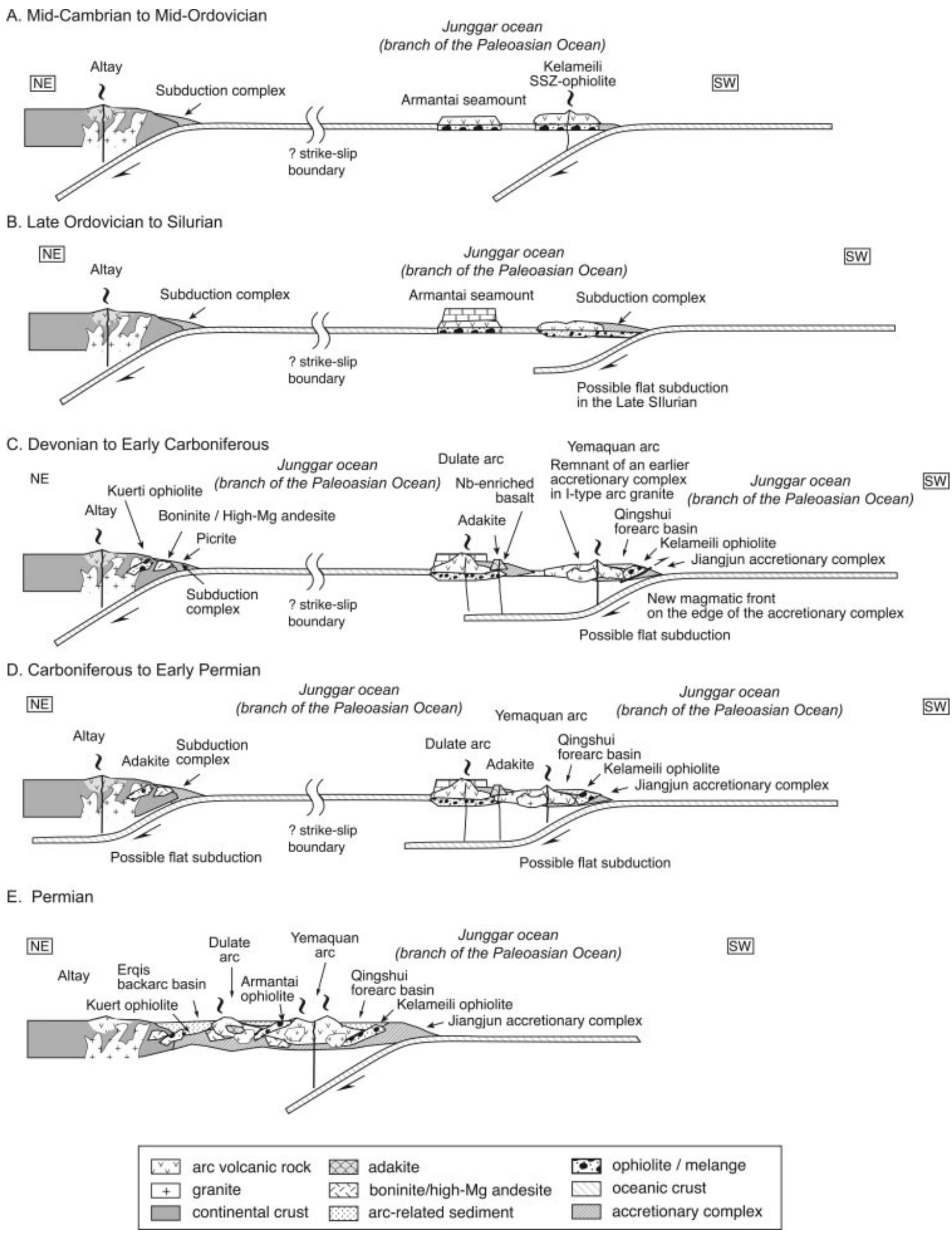

Fig. 28. Schematic time-diagrams illustrating the Paleozoic tectonic evolution of the East Junggar collage. (A) Mid-Cambrian to Mid-Ordovician; (B) Late Ordovician to Silurian; (C) Devonian to Early Carboniferous; (D) Carboniferous to Early Permian; and (E) Permian. The cross-sectional directions are in present-day coordinates. See text for discussion.

and others, 1993), and the Kipchak arc model that involved either continuous forearc accretion of a single subduction zone (Şengör and others, 1993; Şengör and Natal'in, 1996a), or forearc accretion punctuated by back-arc opening and closure (Yakubchuk and others, 2001, 2002; Yakubchuk, 2002). None of these competing models can fully

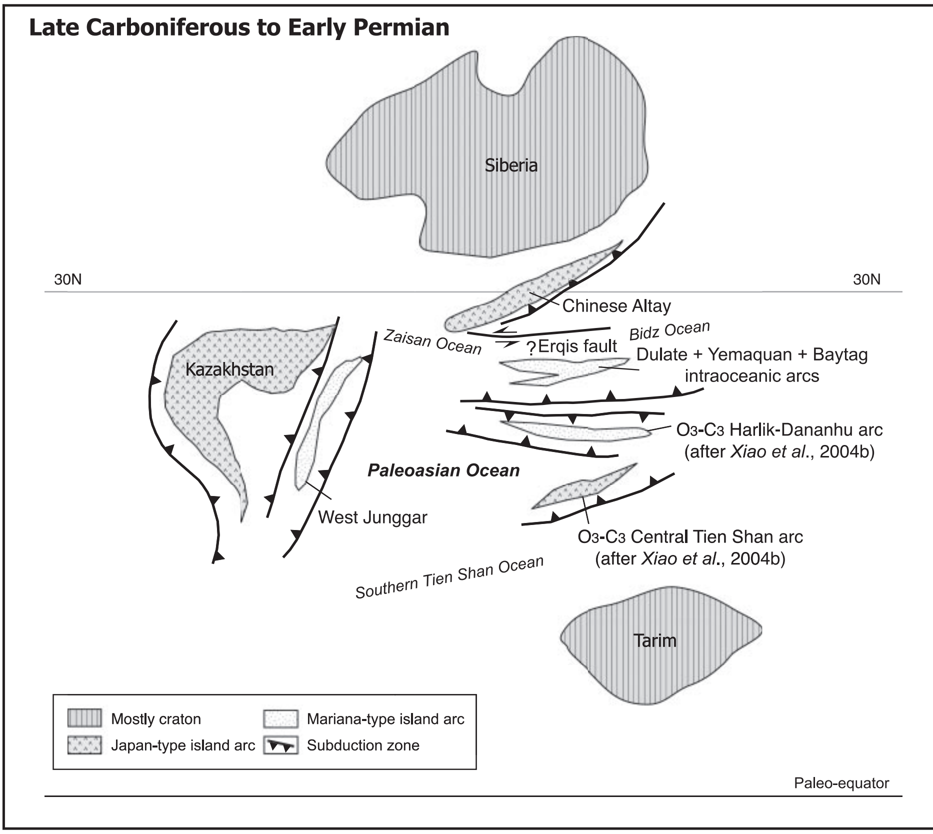

Fig. 29. Schematic map-view diagram illustrating the Late Carboniferous to Early Permian paleogeography of the East Junggar collage in the framework of the Paleoasian Ocean including the Siberia and Tarim cratons. The positions of six arcs are indicated in relation to the subduction zones that created them (based on our own understanding and modified after XBGMR, 1993; Ruzhentsev and Mossakovskiy, 1996; Smethurst and others, 1998; Li and Powell, 2001; Badarch and others, 2002; Li and others, 2003).

explain the tectonic architecture of Central Asia. The Kipchak arc model of Şengör and others (1993) has recently been invalidated by Windley and others (2007) because of a lack of evidence for migration of a magmatic front, a lack of similarity in lithology and history of adjacent arcs aligned in the single mega-arc, unsuitability of the model to explain the geology of Kazakhstan, and a lack of continuity of Siberia and Baltica at the start of the arc development and other necessary cratons. The early model of Coleman (1989) and Mossakovsky and others (1993) played an important role in the early development of ideas on the accretion of the Central Asian Orogenic Belt or Altaids, but they are inadequate today to provide a viable explanation for the evolution of Central Asia, because of the lack of knowledge at that time of many components of present subduction-accretion complexes, of the tectonic evolution of such complexes, and of the potential analogues of many arc systems known today.

Our tectonic model for the Chinese Altay-East Junggar region provides a robust explanation of available data and ideas about the development of the accretionary orogen in the southern Altaids from the Early Paleozoic to the Carboniferous-Permian. Our summary of the accretionary tectonics in the CAEJ sheds light on the tectonics of the Central Asian orogenic collages.

As exemplified by the southern Chinese Altay and Erqis units, forearc shaving or arc-parallel translation of active margin sequences occurred in the Paleoasian realm. The paleogeography may have been similar to that of the present-day Alaskan arc-oceanic system, which was translated by strike-slip faults during accretion (Patchett and Chase, 2002), and the arc-slicing and arc-shaving strike-slip faulting and duplexing that took place along strike of the "Silk Road Arc" in the Turan-Scythian region (Natal'in and Şengör, 2005). This kind of orogen-parallel strike-slip translation or oroclinal bending is also very common in accretionary orogens in Japan, Alaska, and western Ireland (Umhoefer, 1987; Monger and Price, 1996; Kusky, 1997; Kusky and others, 1997; Niocaill and others, 1998; Kusky and Bradley, 1999; Johnston, 2001; Taira, 2001; Sakashima and others, 2003), and many other modern arcs (McCaffrey, 1996; Taylor and others, 1998). Nevertheless, this could not have been the only mechanism responsible for the architecture of Central Asia, because different subduction systems existed in the Paleoasian Ocean (Mossakovsky and others, 1993; Coleman, 1994; Windley and others, 2002; Rui and others, 2002; Xiao and others, 2004a, 2004b; Ota and others, 2007).

Not only is the CAEJ characterized by an archipelago paleogeography with multiple subduction systems, but also the region south of the CAEJ, which has similar geology. In addition to the multiple accretionary systems in the CAEJ, figure 26 also shows a likely tectonic scenario for the Eastern Tien Shan arc that has several different components, namely from N to S, the Bogda arc, Dananhu magmatic arc, Yamansu arc-accretionary complex, Central Tien Shan arc, Kokshaal-Kumishi accretionary complex, and the Tarim craton (Xiao and others, 2004b). The seismic reflection anomalies on the northern side of the Bogda arc are southward dipping, but from the southern side of the Bogda arc to the northern side of the Tarim craton the anomalies mostly dip northwards, albeit at variable angles, and some listric (fig. 26). This is consistent with geological relationships that indicate a general southward younging direction from the Dananhu arc southwards via the Yamansu accretionary complex and arc, and Kokshaal-Kumishi accretionary complex (fig. 26).

Archipelago paleogeography, as exemplified today by Southeast Asia, played an important role in the architectural development and crustal growth of Central Asia in the Paleozoic (Li, 1980; Hsü and others, 1995; Filippova and others, 2001; Goldfarb and others, 2003; de Jong and others, 2006; Kröner and others, 2007; Windley and others, 2007; Jian and others, 2008; Xiao and others, 2009 and references therein). Some continental blocks or microcontinents, formerly thought to be Precambrian in age, have been partially or completely re-defined by high resolution isotopic dating as younger subduction-related orogenic collages in the Yenisey Ridge, Tuva-Mongolia and Kokchetav (Kaneko and others, 2000; Theunissen and others, 2000; Salnikova and others, 2001; Maruyama and others, 2002; Vernikovsky and others, 2003; Dobretsov and others, 2003), oceanic plateau-type meta-volcanic rocks occur in the Late Precambrian Gorny Altai of southern Siberia (Utsunomiya and Jahn, 2008), and numerous high-pressure eclogites and blueshists are now known throughout the CAOB (Volkova and Sklyarov, 2007). Taking these data into account, together with the evidence for multiple intra-oceanic island arcs and Andean-type active continental margin arcs in the CAEJ, as documented in this paper, the closure of the Paleoasian Ocean indubitably involved the production of multiple subduction systems, as schematically illustrated in figure 29 for the late Paleozoic.

Therefore, the Paleozoic tectonic framework and evolution of Central Asia is best characterized by juvenile accretion and amalgamation of arcs separated by intervening oceans (fig. 29). The general southward (present coordinates) accretion from the southern active margin of the Siberian Craton has been known as an important process since Zonenshain and others (1990). The final closure of the Paleoasian Ocean was in the end-Permian to mid-Triassic (Mossakovsky and others, 1993; Buslov and others, 2004; Xiao and others, 2009). The intervening development can be best understood in terms of multiple accretionary processes, similar to those in the Mesozoic-Cenozoic accretionary orogens around the Pacific, as in Japan (Maruyama, 1997; Taira, 2001) and Alaska (Plafker and others, 1989; Pavlis and Sisson, 1995; Kusky and others, 1997; Kusky and Young, 1999; Kusky and Bradley, 1999; Sisson and others, 2003), the Cordillera of the western America (Ingersoll, 2000; Wakabayashi and Dilek, 2003), Albania, Cyprus, Oman (Dilek and Flower, 2003), and in particular Indonesia (Hall, 2002) that involved divergent subduction zones and Precambrian fragments.

Major Sutures in the Southern Altaids

As mentioned before, the major suture zone for this CAEJ part of the southern Altaids is the subject of much debate, and the extension of some sutures towards the west and east is unclear. For example, the Armantai (He and others, 1994) and Kelamaili (Ma and others, 1997) ophiolites have been considered to be candidates for determination of a major suture zone. Furthermore, the Zaisan ophiolitic mélange in the Zaisan area of Kazakhstan (fig. 29) that hosts long slivers of Early-Middle Paleozoic ophiolites was thought not to continue into China (Zonenshain and others, 1990; Yakubchuk, 2004).

The Bidz ophiolite that forms a narrow, one hundred km-long sliver in southern Mongolia (Badarch and others, 2002) consists of tholeiitic pillow basalts, tuffs, cherts, sandstones, siltstones, argillites, and minor thin layers of limestones, intruded by gabbros and diorites. The age of volcanic and sedimentary rocks is presumed to be Ordovician to Devonian based on regional correlations (Ruzhentsev and Pospelov, 1992), but no high-resolution isotopic ages have been obtained for the ophiolitic components. Major and rare earth element data suggest that some basalts are MORB-type and formed at an oceanic ridge (Ruzhentsev and Pospelov, 1992; Ruzhentsev and Mossakovskiy, 1996). The Bidz ophiolite may contain displaced fragments of oceanic crust that can be correlated with ophiolitic fragments in the southern Chinese Altay and Erqis units (He and Han, 1991; Windley and others, 1994; Wu and others, 2006).

In the eastern part of the Bidz ophiolitic mélange quartz-chlorite-sericite schists contain lenses of igneous and sedimentary rocks, which may be components of a tectonic mélange or an olistostrome, and to their south there are extensive turbiditic sediments that probably were deposited in backarc or forearc basins (Badarch and others, 2002). The overall structure is dominated by SW-directed thrusts, and high-strain shear zones (Badarch and others, 2002). So the Bidz ophiolitic mélange is rather a sliver emplaced into an accretionary complex, which is adjacent to the Chinese Altay island arc that was active from the Ordovician to Permian (Windley and others, 2002; Xiao and others, 2004a, 2008, 2009). It is important to note that in Central Asia it is not possible to get ophiolites to be a "trinity". Instead most ophiolites in Central Asia are ophiolitic fragments in accretionary complexes or blocks in mélanges. This is true for all ophiolitic fragments in the CAEJ and adjacent area. We propose that the Bidz ophiolitic mélange and the associated accretionary complexes are most likely the eastern extension of the accretionary complexes in the southern Chinese Altay and Erqis units.

Some of the major island arcs in the Ob-Zaisan-Bidz Ocean may also be correlative, for instance, the East Junggar island arc may be the eastern equivalent of the Dulate-Baytag arc (Xiao and others, 2004a), which is illustrated in figure 29.

Accordingly, the Zaisan ophiolitic mélange zone was tectonically the western extension of the Erqis unit in CAEJ, and ophiolitic fragments in this major Erqis-Zaisan accretionary complex may have been part of an integrated suture zone that extends westwards to the Urals (Yakubchuk, 2004) and eastwards via important ophiolitic mélanges (Keksentao, then Armantai or Kelamaili ophiolites) in the CAEJ (Xiao and others, 1992; He and others, 1994; Buslov and others, 2004), and then continues farther east to southern Mongolia (for example, the Bidz ophiolite in fig. 4, Wu and others, 2006). A late Carboniferous ophiolitic mélange that occurs farther to the west in the Gobi Altay of southern Mongolia (Rippington and others, 2008) is possibly the eastern extension of the late Paleozoic ophiolitic mélange zone in CAEJ. The accretionary geology and convergent tectonic history of the CAEJ, and its counterparts in Mongolia (Lamb and Badarch, 2000; Lamb and others, 1999, 2008; Buchan and others, 2001; Windley and others, 2002; Badarch and others, 2002) and Kazakhstan (Heinhorst and others, 2000; Buslov and others, 2001, 2003), can best be explained by semi-continuous subduction with various subduction systems in the Neoproterozoic to late Carboniferous before development of a Cordilleran-type margin in the Permian, and terminal collision.

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APPENDIX

ANALYTIC PROCEDURE FOR SHRIMP U-PB ZIRCON DATING

Zircons for SHRIMP geochronology were separated using conventional heavy liquid and magnetic techniques. Representative zircons were hand-picked, together with several RSES (Research School of Earth Sciences, Australian National University) zircon-standard TEM, mounted in epoxy resin and sectioned approximately in half. The mount surface was polished to expose the grain interiors and then gold-coated.

Zircons were analyzed at the Chinese Geological Academy of Sciences using SHRIMP II. The SHRIMP data were reduced according to the method of Williams and Claesson (1987) and Compston and others (1992). The inter-element fractionation was undertaken relative to the RSES standard zircon TEM (417 Ma). The U, Th, and Pb concentrations were determined relative to those measured in the standard zircon SL13 (572 Ma; U, 238 ppm) (Claoue-Long and others, 1995). Corrections for common Pb were made using the measured $^{204}Pb/^{206}Pb$ ratios. Uncertainties in the isotopic ratios, in the ages in the data table (table 2) and in the error bars in the plotted data are reported at a 1σ level, but final ages of pooled data-sets are all $^{206}Pb/^{238}U$ ages reported as weighted means with 95 percent confidence limits. All age calculations and statistical assessments of the data have been made with the geochronological statistical software packages ISOPLT/EX (version 2.01) and SQUID 1.0 of Ludwig (1999, 2001).

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