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Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt

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[1] The Solonker suture records the termination of the central Asian Orogenic Belt (CAOB). However, tectonic development of the Solonker suture is poorly understood. We report new field data for the Ondor Sum melange in the Ulan valley, and present a new evaluation of the orogenic belt extending from the southern Mongolia cratonic boundary to the north China craton within the context of a new geological framework and tectonic model, which incorporates relevant data from the literature. The southern accretionary zone between the north China craton and the Solonker suture is characterized by the Mid-Ordovician-Early Silurian Ulan island arc-Ondor Sum subduction-accretion complex and the Bainaimiao arc. This zone was consolidated by the Carboniferous-Permian when it evolved into an Andean-type magmatic margin above a south dipping subduction zone. The northern accretionary zone north of the Solonker suture extends southward from a Devonian to Carboniferous active continental margin, through the Hegenshan ophiolite-arc accretionary complex to the Late Carboniferous Baolidao arc associated with some accreted Precambrian blocks. This northern zone had consolidated by the Permian when it developed into an Andean-type magmatic margin above a north dipping subduction zone. Final subduction of the central Asian ocean caused the two opposing active continental margins to collide, leading to formation of the Solonker suture in the end-Permian. Predominant northward subduction during final formation of the suture gave rise in the upper northern plate to a large-scale, postcollisional, south directed thrust and fold belt in the Triassic-Jurassic. In summary, the CAOB underwent three final stages of tectonic development: early Japanese-type accretion, Andean-type magmatism, and Himalayan-type collision. *INDEX TERMS:* 8102 Tectonophysics: Continental contractional orogenic belts; 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8110 Tectonophysics: Continental tectonics—general (0905); 0905 Exploration Geophysics: Continental structures (8109, 8110); *KEYWORDS:* Solonker suture, accretion, Permian, Paleo-Asian ocean, Inner Mongolia. **Citation:** Xiao, W., B. F. Windley, J. Hao, and M. Zhai, Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt, *Tectonics*, *22*(6), 1069, doi:10.1029/2002TC001484, 2003.

1. Introduction and Geological Background

[2] The central Asian orogenic belt (CAOB) extends from Kazakhstan in the west to eastern Siberia in the east (Figure 1). It is a 300 km wide belt separating the Siberian craton in the north from the Tarim and north China (or Sino-Korean) cratons in the south [*Zonenshain*, 1973; *Zonenshain et al.*, 1990; *Mossakovsky et al.*, 1994; *Jahn et al.*, 2000; *Badarch et al.*, 2002]. It mainly formed from the progressive subduction of the Paleo-Asian ocean and amalgamation of terranes of different types and derivation [*Coleman*, 1994; *Dobretsov et al.*, 1995; *Buslov et al.*, 2001; *Heubeck*, 2001; *Badarch et al.*, 2002]. Following *Şengör et al.* [1993] and *Şengör and Natal'in* [1996] we use the term 'Solonker' for the suture that extends from Solonker (also called Solon Obo, Figure 1) via Sonid Yuoqi to Linxi in Inner Mongolia and further west and northeast (Figure 1). It marks the final closure of the Paleo-Asian ocean. It has been alternatively called the Suolun-Linxi or Suolun suture [*Wang and Mo*, 1995; *Davis et al.*, 2001], the Tian Shan-Ying Shan suture [*Yin and Nie*, 1996], the Suolunshan-Hegenshan suture, the Hegenshan-Nenjiang-Heihe suture [*Wu et al.*, 2002], and the Solon Obo-Linxi suture [*Wang and Liu*, 1986].

[3] The terms Altaid Tectonic Collage [*Şengör et al.*, 1993], Altaides [*Şengör et al.*, 1994] and Altaids [*Şengör*

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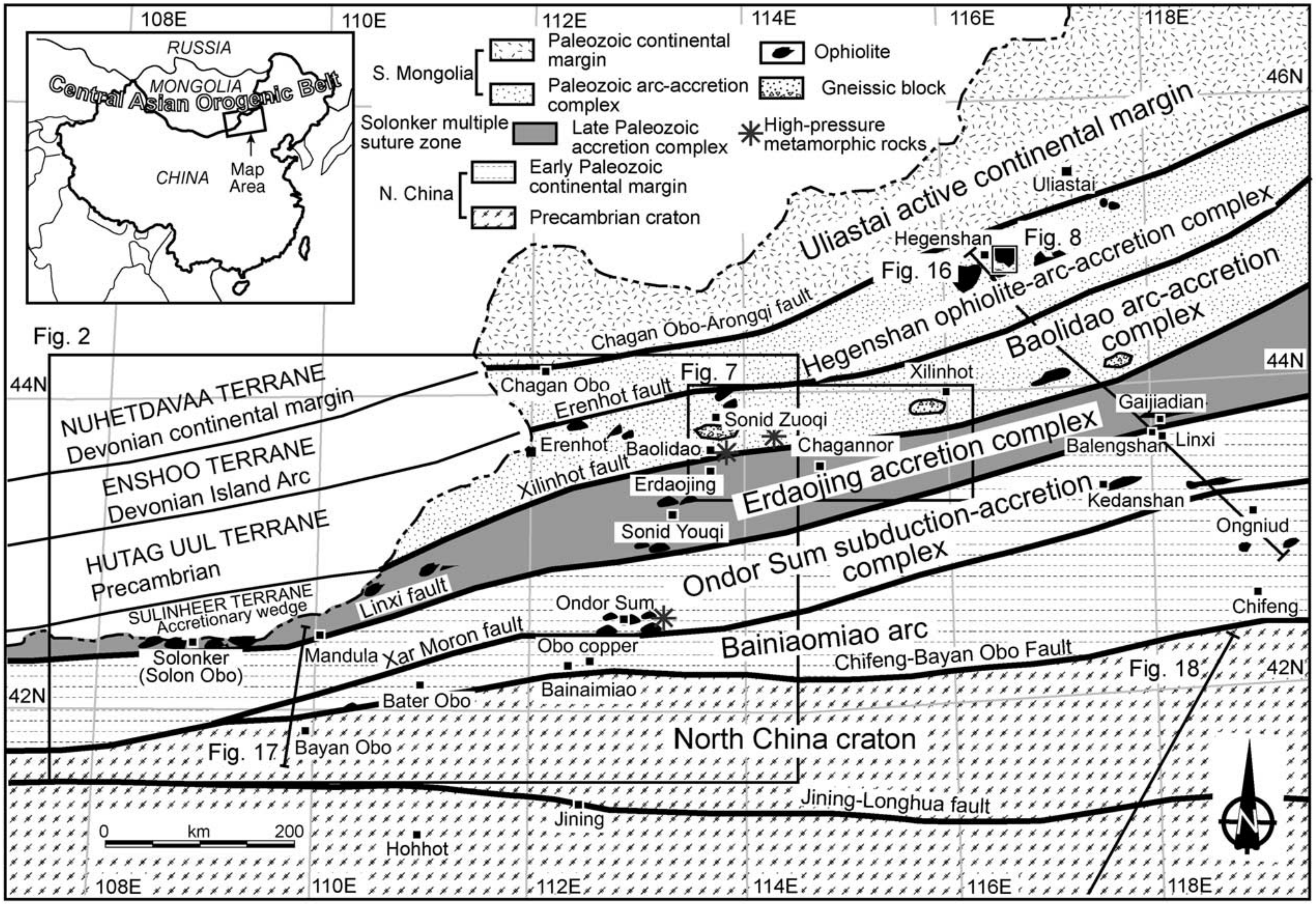


Figure 1. Tectonic map of central Inner Mongolia showing its structures and tectonics (compiled from *Wang and Liu* [1986], *Shao* [1989], *Tang* [1990], *Hsü et al.* [1991], *BGMRIM* [1991], *Tang and Yan* [1993], *Chen et al.* [2000], *Badarch et al.* [2002] and from our own observations). For clarity, Late Mesozoic-Cenozoic strata are not shown. Insert is a simplified map of Asia showing the CAOB and the study area. Locations marked of Figures 2, 5, 7, 16, 17, and 18.

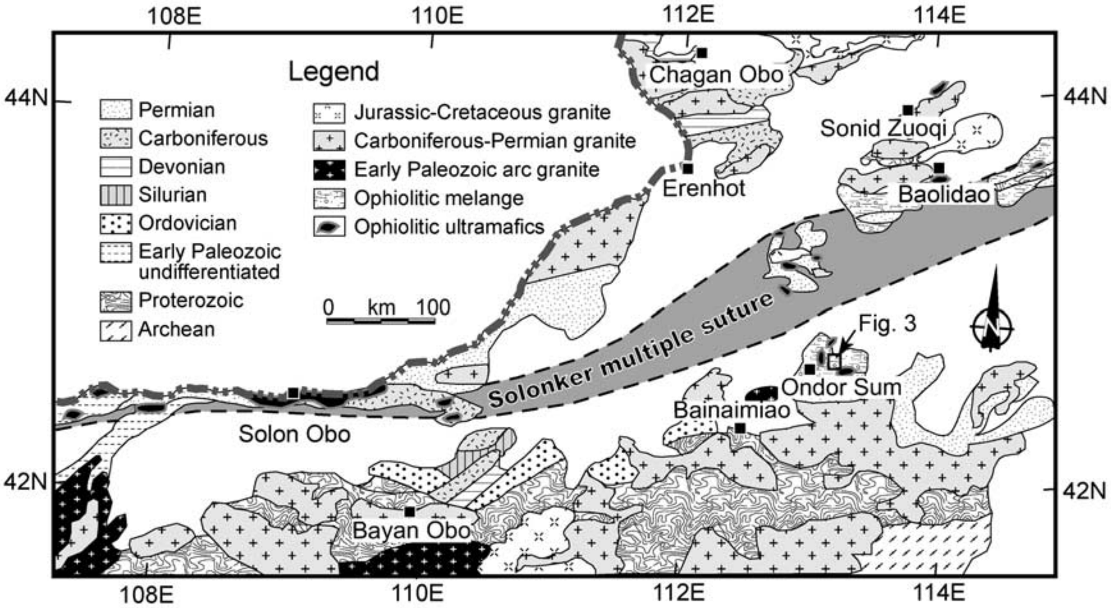


Figure 2. Geological map of the Sonid Zuoqi area in Inner Mongolia, China and the Mongolian border area mainly illustrating the distribution of Early and Late Paleozoic arc-accretion complexes (modified after *Wang and Liu* [1986], *Shao* [1989], *Tang* [1990], *Hsü et al.* [1991], *BGMRIM* [1991], *Tang and Yan* [1993], *Chen et al.* [2000], and *Badarch et al.* [2002], incorporated with our own work). Position shown in Figure 1. The location of Figure 3 is shown.

and Natal'in, 1996] are almost, but not exactly, equivalent to the CAOB. They cover the area from the Siberian craton to the Solonker suture within Inner Mongolia (Nei Mongol). This suture separates the Altaids from the Manchurides of *Şengör and Natal'in* [1996], who considered these to be "two entirely different orogenic systems of different (subduction) polarity' although both are subduction-accretion complexes." They formed by accretion against the continental margins of the two opposing cratons, and thus represent the two parts of the orogenic belt separated by a suture, and so we choose to employ the more widely used term 'CAOB' for the whole orogenic belt between its opposing margins. According to *Yakubchuk et al.* [2001] the Altaids lies between the Siberian and north China cratons, and thus is equivalent to the CAOB.

[4] *Hsü et al.* [1991] and *Hsü and Chen* [1999] introduced the term 'Neimonides' for the orogenic belt situated in Inner Mongolia. However, because the Mongolian-Chinese border is highly curved, the "Neimonides" includes different tectonic belts in different places, and therefore we consider it is inappropriate to define an orogenic belt on such variable geography, and so prefer to use "CAOB," which includes the tectonic belts of Inner Mongolia as far south as the border of the north China craton.

[5] The timing of collision and formation of the Solonker suture has long been controversial: Latest Silurian to Devonian [*Yue et al.*, 2001], Late Devonian to Early Carboniferous [*Shao*, 1991; *Hong et al.*, 1995; *Shao and Zhan*, 1998], Middle to Late Devonian [*Tang*, 1990; *Xu and Chen*, 1997], Late Permian [*Wang and Liu*, 1986; *Ruzhentsev et al.*, 1989; *Tang*, 1990; *Hsü et al.*, 1991; *Muller et al.*, 1991; *Wang et al.*, 1991; *Şengör et al.*, 1993; *Zorin et al.*, 1993; *Bao et al.*, 1994; *Ruzhentsev*, 2001], Permian-Triassic [*Zhang et al.*, 1984; *Ruzhentsev et al.*, 1985; *Ruzhentsev and Pospelev*, 1992; *Chen et al.*, 2000], Middle-Late Triassic [*Dorjnamjaa et al.*, 1993; *Badarch and Orolmaa*, 1998], or Cretaceous [*Nozaka and Liu*, 2002]. These variations partly reflect different availability of isotopic ages and partly differences in interpretation of the geological environments of key rock groups.

[6] One problem with understanding the tectonic development of Inner Mongolia is that many papers have been published on specific subjects in small areas, but often without any relationships to regional tectonics. For example, the excellent metamorphic petrological studies were made without reference to any fabrics and local structural history [*Shao*, 1989; *Tang*, 1990; *Tang and Yan*, 1993].

[7] There are several papers on the overall tectonic evolution of Inner Mongolia. However, earlier papers by *Wang and Liu* [1986], *Tang* [1990], and *Hsü et al.* [1991] need considerable revision in view of more recent developments in the sciences. *Şengör and Natal'in* [1996] discussed the whole of Inner Mongolia in terms of accretionary tectonics, but provided few details. *Wu et al.* [2002] gave an overview of the eastern extension of central Inner Mongolia in NE China and they produced an innovative model of tectonic evolution.

2. Present Studies

[8] In order to understand the final stages of development of the CAOB, we have made some detailed studies and a

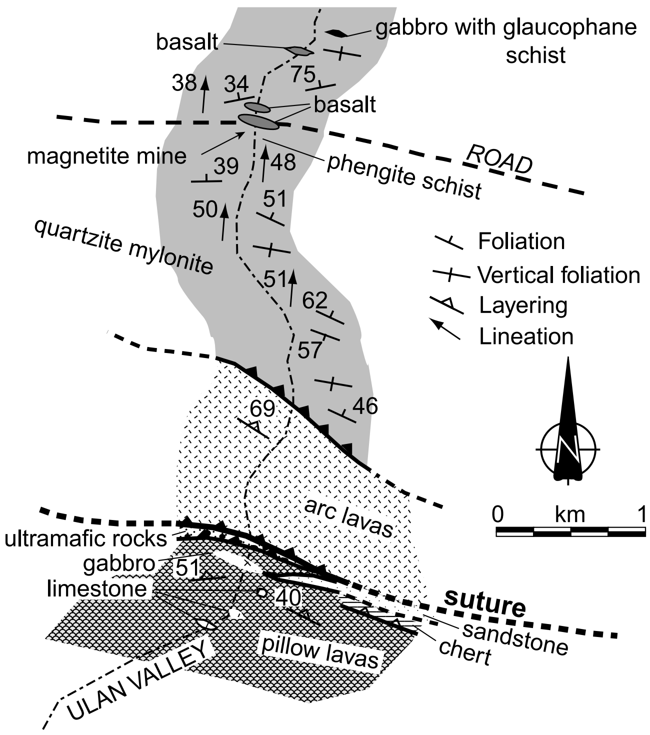


Figure 3. New geological map of the Ulan Valley showing major litho-tectonic units and structures of the Ulan subduction-accretion complex. Based on our mapping and structural observations. Position shown in Figure 2. Pillow lavas at N42°35′46″E113°04′08″.

long geotraverse across Inner Mongolia. The Ondor Sum melange is much quoted in the literature, but there is no detailed geological map of this key accretion-subduction complex. Therefore we have made the first geological-structural map of the melange in the well-exposed Ulan valley (Figures 2 and 3). In order to obtain a larger perspective, we have made a 1200 km-long traverse in two sections across the orogenic belt from the north China craton, to Bainaimiao, Sonid Youqi, Sonid Zuoqi, Hegenshan, Xilinhot, Kedanshan, and southward to the north China craton (Figure 1). During this traverse we reevaluated all major rock groups in terms of their position in the evolving orogen by taking account of all relevant data from earlier literature and integrating them with our new geological and structural observations of all the main tectonic belts across the orogen.

[9] To analyse the tectonic settings of various tectonic entities in this complicated orogenic belt, we use the tectonic facies approach [*Robertson*, 1994] which bridges the gap between regional tectonics and local structure. We map local field structural data and spatial distribution of key tectonic entities key areas to define thrust vergence and subduction polarities. As arc volcanics, accretionary complex, and ophiolitic melange are the main components of this vast area, in particular the accretionary complex plays significant role in the architecture of the orogen [*Şengör et al.*, 1993], we pay special attention to the comparison of various tectonic entities with that of the accretionary orogens in the Japanese Island Arc [*Isozaki et al.*, 1990], SW Pacific [*Huang et al.*, 2000], and that of some ancient examples, such as the western Kunlun in central Asia [*Şengör and Okurogullari*, 1991]. At the same time, we use the ophiolite-arc-accretionary complex which corresponds to the boundary between Angaran and Cathaysian faunas trace the final suturing belt. We also combine all these geological aspects with published geophysical transect profiles to constrain the substructure and possible key tectonic boundaries such as suture zone.

[10] The aim of the present paper is to provide a reassessment of the orogen, and a new model of evolution from early subduction-accretion, via an Andean-stage of development, to the final continent-continent collision that led to the Solonker suture and termination of the CAOB. We produce the first account of the Ondor Sum melange in the Ulan valley. Also we have made a new correlation of the tectonic belts of Inner Mongolia of China with those along strike in southern Mongolia. This helps to resolve some of the major problems of the geological development of Inner Mongolia.

3. Regional Geology and Main Place-Time Units

[11] Inner Mongolia is an accretionary orogen that has one terminal suture zone passing through Solonker, which contains many lenses of melange, ophiolites and blueschists (Figure 1). In the past it was popular to join up many of these lenses to outline several extensive suture zones. However, we regard most of these as small bodies formed during the semi-continuous process of formation of the accretionary orogen. To ease description of such diverse geology, we outline the geology in terms of six place-time units:

3.1. Between the North China Craton and the Solonker Suture

[12] The basement of the north China craton consists of Archaean and Lower Proterozoic rocks, covered by passive margin sediments of Neoproterozoic to early Paleozoic age [*Hsü et al.*, 1991]. However, the Archaean rocks of the craton in this part of Inner Mongolia are not overlain everywhere by such passive margin sediments. There are metamorphic rocks with isotopic ages of 1150–1350 Ma, which were previously thought to be continental rifts composed of thick sedimentary sequences intercalated with continental volcanic rocks [*Wang and Liu*, 1986; *Tang and Yan*, 1993]. *Şengör and Natal'in* [1996] suggested that the EW trending Jining-Longhua fault is the northern boundary of the north China craton. However, because Archaean-Early Proterozoic rocks occur on both sides of this fault (Figure 2), we prefer to use the Chifeng-Bayan Obo fault as the northern boundary of the Precambrian north China craton [*Shao*, 1989; *Tang and Yan*, 1993; *Bai et al.*, 1993a, 1993b].

3.1.1. Bianaimiao Arc

[13] On the northern side of the Chifeng-Bayan Obo fault is the Mid-Ordovician to Early Silurian Bianaimiao arc [*Hu*

et al., 1990], which contains calc-alkaline tholeiitic basalts to minor felsic lavas, alkaline basalts, and agglomerates, volcanic breccias, tuffs, granodiorites, and granites. In Bainiaomiao village (Figures 1 and 2) granodiorite, quartz-diorite, and homogeneous hornblende gabbro are intruded by feldspar quartz porphyry and veins of aplite. In the Obo copper mine (N42°12′05″, E112°30′40.6″), andesitic volcanics, rhyolite, chert, sandstone, and conglomerate occur in a northward vergent imbricate zone. The Bianaimiao arc has commonly been thought to be an island arc [*Tang and Yan*, 1993], but the high initial strontium isotope ratio (0.7146) of granites [*Shao*, 1989] and the discovery by *Nie and Bjørlykke* [1999] that the Bainaimiao granodiorite has a Sm-Nd isochron age of 429 ± 100 Ma with an ε Nd value of 2.4 ± 1.7 suggests formation by mixing between mantle-derived and crustal rocks, in which case an active continental margin setting would be more appropriate. This would be consistent with the presence at Bainaimiao of mid-Proterozoic and late Proterozoic rocks [*Nie and Bjørlykke*, 1999]. A granodiorite porphyry at Bainaimiao yielded a U-Pb zircon age of 466 Ma [*Tang and Yan*, 1993], a greenschist has a metamorphic Rb-Sr whole rock isochron age of 428 ± 17 Ma, and a muscovite granite has a K-Ar age on muscovite of 430 Ma [*Zhang and Tang*, 1989; *Tang and Yan*, 1993]. A granodiorite porphyry contains arc-type porphyry copper-gold deposits [*Hu et al.*, 1990]. There is no evidence of subduction zone rocks or a suture zone south of Bainaimiao to allow northward subduction to create this arc, and therefore we suggest southward subduction was responsible.

[14] An Ordovician island arc occurs almost along strike to the east in the Linxi-Bairin Youqi area [*Shao*, 1989]. Much further west (at about longitude 110′30°E) near Bater Obo an Ordovician island arc with basalt, granodiorite and diorite is surrounded by a paleo-island of Upper Silurian limestones that contains conodonts with a mid-Ludlovian age, circa 421 Ma [*Johnson et al.*, 2001].

3.1.2. Ondor Sum Subduction-Accretion Complex

[15] To the north of Bainaimiao a melange at Ondor Sum may be the western extension of the Xilamulunhe (Xar Moron River)-Changchun suture zone of *Wu et al.* [2002], but with the paucity of rocks available for such a long-range extrapolation of a suture zone, we prefer to regard this melange as a local feature within the overall accretionary development of the orogen. Approximately along strike to the east is the isolated Kedanshan ophiolite (Figure 1), which is overlain by chert containing Ordovician brachiopods, foraminifera, radiolaria and conodonts [*Shao*, 1989; *Tang*, 1990]. This dismembered ophiolite contains thrust slices of peridotite, gabbro and basalt, and is in fault contact with Silurian meta-sediments.

[16] Formerly called the Ondor Sum Group [*Zhang and Wu*, 1998], Ondor Sum Ophiolite Belt [*Wang and Liu*, 1986], the Wentermiao Group [*Tang et al.*, 1983] or Wendurmiao Group [*Hu et al.*, 1990], the main outcrop of this heterogeneous melange is in the Ondor Sum region (Figure 2), the best section of which is along the Ulan valley (Ulangou, Wulan valley, or Wulangou); see below. According to *Wang and Liu* [1986] a melange belt extends discontinuously for about 700 km from north of Bayan Obo in the west to the Xar Moron River south of Linxi in the east (Figure 1). However this notion is not in accordance with the age differences between the rocks in the west where the Bayan Obo strata are mainly Late Precambrian and those in the east where the Linxi and Kedanshan ophiolites are of Paleozoic or even Late Paleozoic age [*Wang and Liu*, 1986; *Li*, 1986; *Shao*, 1989; *Tang*, 1990; *Wang and Fan*, 1997]. The majority of Bayan Obo rocks clearly belong to the north China craton (Figure 1) [*Bureau of Geology and Mineral Resources of Inner Mongolia* (*BGMRIM*), 1991; *Shao*, 1991].

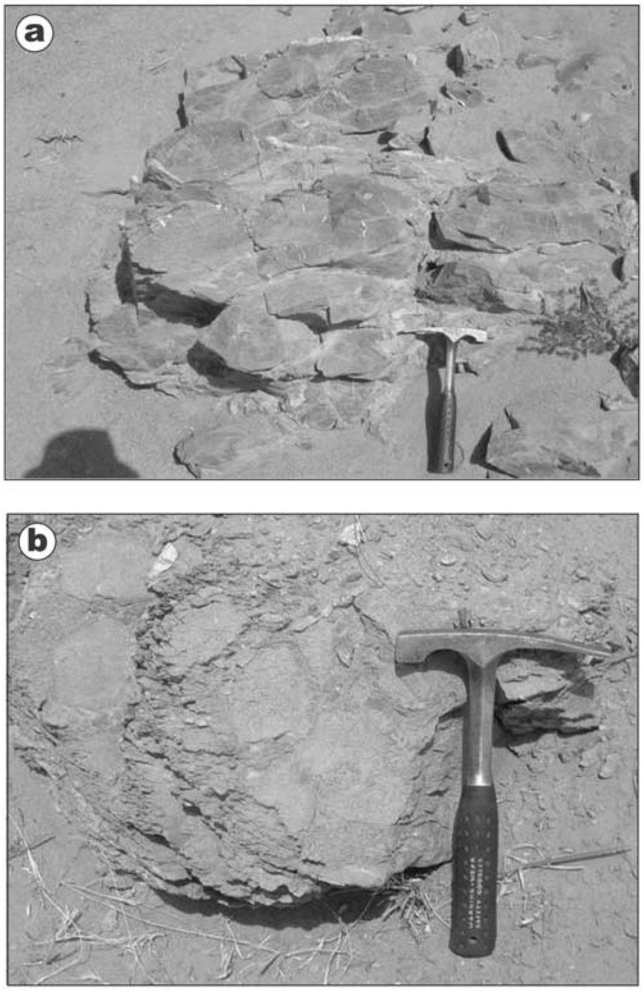


Figure 4. (a) Elongate pillow lavas in southern Ulan valley, see Figure 3. (b) Pillow breccia within the lower pillow lava succession in southern Ulan valley of Figure 3. Several pillow fragments have partial chilled margins. Matrix is bedded basalt. Hammer for scale. By B. F. Windley. See color version of this figure at back of this issue.

[17] The main detailed published work on the Ondor Sum melange is on metamorphic petrology [*Wang and Liu*, 1986; *Yan et al.*, 1989; *Tang and Yan*, 1993]. High-pressure phases include ferroglaucophane-crossite, ribeckite, lawsonite,

phengite, pumpellyite, aragonite, jadeitic pyroxene, and stilpnomelane. Lawsonite occurs mainly in the cores of pillows and decreases in abundance outward. The pillow matrix has the assemblage calcite-haematite-quartz-lawsonite. Quartzitic mylonites contain glaucophane, stilpnomelane, deerite, minnesotaite, and piedmontite. According to *Tang and Yan* [1993] phase equilibria indicate temperatures of 250°–350°C and pressures of 6–7.5 kbar for the subduction metamorphism of these Ondor Sum rocks. Our new mineral analyses of blueschists in the Ulan valley (see below; B. F. Windley, manuscript in preparation) show that the cores of Na-amphiboles are high-Al, ferro-glaucophane and their rims are largely of less aluminous crossite. This change in the alumina content with time indicates decrease in pressure that may be correlated with progressive exhumation [*Maruyama et al.*, 1986].

[18] We now present a new geological map (Figure 3) of the Ondor Sum rocks where best exposed in the Ulan valley, together with a brief description. The map shows a tripartite structural division—an undeformed ophiolite in the south, a folded island arc in the centre, and a thrusted mylonitic high-pressure subduction complex in the north. We describe the rocks from the least deformed in the south to the most deformed in the north. The lowermost unit consists of north dipping undeformed pillow basalts (Figure 4a), the shapes of which indicate that the rocks face upward to the north. The bedding dips moderately to the north, and the stratigraphic thickness is about 0.6 km. Pillows are up to 30–50 long and have vesicular chilled margins. Many lavas have a shear foliation parallel to the bedding of the pillows. Near the bottom of the lavas are pillow breccias (Figure 4b), and hyaloclastites with centimeter-size fragments of lava. Above the basalts is a thrust-imbricated, but stratigraphically intact succession of chert overlain by sandstone, representing the ridge-trench transition in ocean plate stratigraphy. One chert contains lenses of serpentinite, magnetite-pyrolusite-quartz rock (Figure 5), and conglomerate with pebbles of quartz and chert. Above this thrust duplex of ophiolitic rocks are well-folded, weakly thrusted calc-alkaline basalts, andesites, dacites, rhyolites, and bedded pyroclastic tuffs. We interpret these rocks as a tectonic remnant of an island arc that has been highly dismembered and incorporated into the accretionary complex. Further north above a north dipping thrust is a 2.5 km-long section of phengite-bearing quartzite mylonite (Figure 3), much of which is reddened with haematite (Figure 6). The regional foliation of the quartzite mylonites contains a strong mineral lineation that plunges moderately to the north, in places in pencil-lineated schists, and the foliation is folded into 50 m-wavelength, open anticlines and synclines that plunge shallowly to the north and south. The mylonite contains lenses of several different lithologies such as meta-basaltic greenschist up to 100–200 m across, magnetite-pyrolusite-quartz rock (with a disused magnetite mine, Figure 3), quartzitic meta-chert, marble, quartz-pyrite-haematite rock, quartz-sericite schist, muscovite-rich quartzitic schist, chlorite schist, and chlorite-magnetite-epidote schist. One 70 m-wide lens of meta-gabbro/leucogabbro has a margin of highly foliated and lineated greenschist that contains glaucophane.

Figure 5. Photograph showing a 2 m-size block of magnetite-pyrolusite-quartz within purple chert on northern side of ultramafic rocks. Southern Ulan valley (Figure 3). Looking northeast. By B. F. Windley. See color version of this figure at back of this issue.

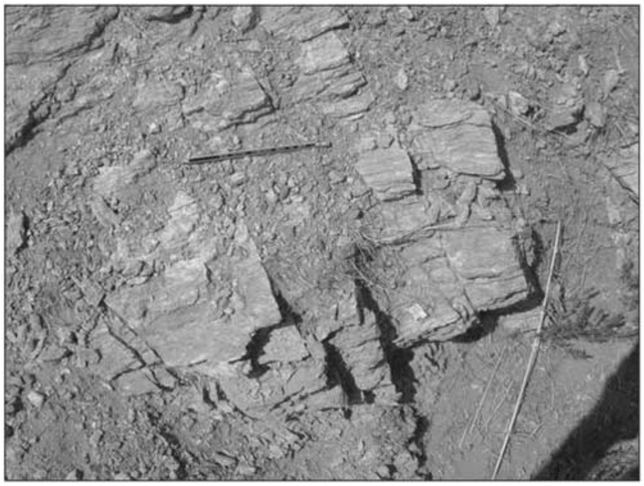


Figure 6. Photograph of red phengite/haematite-bearing quartzitic mylonite in northern Ulan valley of Figure 3. Pencil for scale. By B. F. Windley. See color version of this figure at back of this issue.

[19] We consider that the quartzitic mylonites were derived from ocean floor chert enriched in Fe and Mn and imbricated with slices of oceanic basalt and gabbro. They have been subducted to stability depths of glaucophane and phengite, exhumed and thrust southward from a suture zone. The northward upright stratigraphic succession of the ophiolite from basalt to chert and sandstone, the upward facing pillows, and the consistent northward dip of the whole Ulan valley section indicate that the rocks have not been overturned, and that southward accretion took place on a north dipping subduction zone.

[20] According to *Wang and Liu* [1986] the top of the ophiolite is often marked by a pelagic siliceous rock containing fossil sponge spicules, Hyolithes, Monoplaco-

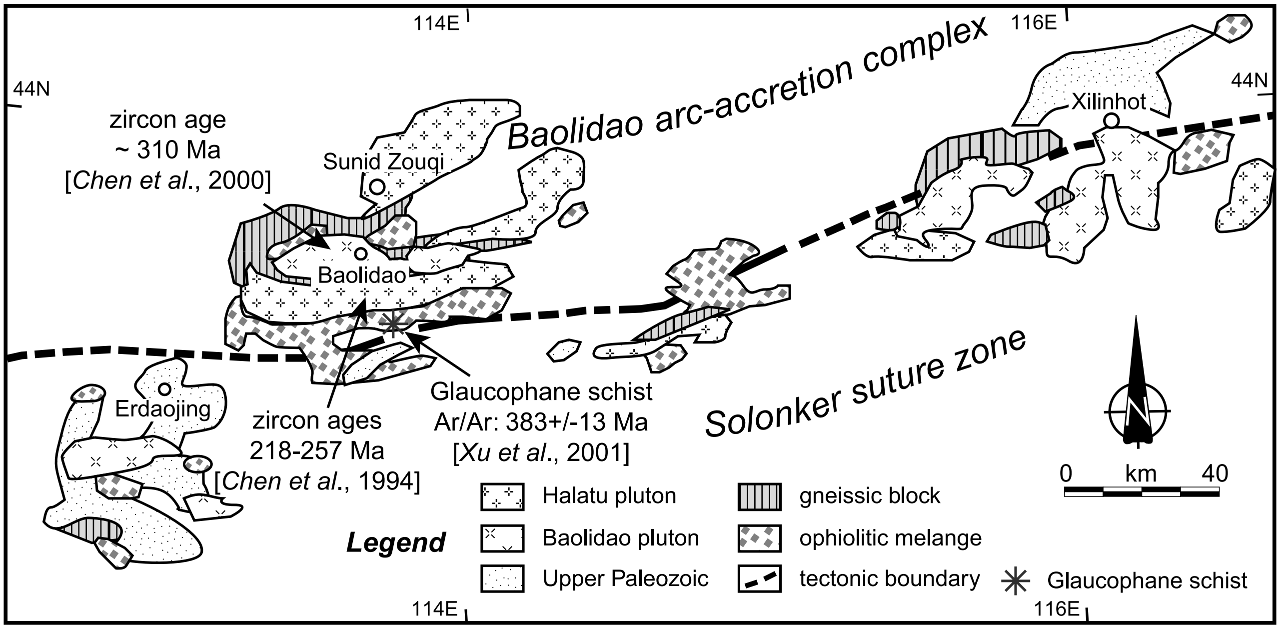


Figure 7. Geological map of the Baolidao area showing major granitic rocks and their ages, together with other tectonic lithologies and structures (modified after *Chen et al.* [1994, 2000]). Position shown in Figure 1.

phora, radiolaria, acritarchs and spores, the age of which is Late Precambrian to Cambrian [*Peng*, 1984; *Wang and Liu*, 1986]. A meta-basalt has a Rb/Sr isochron of 509 ± 40 Ma [*Yan et al.*, 1989; *Tang*, 1990]. Glaucophane from the Ulan valley has ^{39}Ar/^{40}Ar isochrons of 446 ± 15 Ma and 426 ± 15 Ma [*Zhang and Liou*, 1987; *Yan et al.*, 1989; *Tang and Yan*, 1993; and references therein]. Five meta-basic volcanic rocks from the Ondor Sum Group have controversial Sm-Nd and Rb-Sr isochron ages of 961 ± 66 Ma and 624 ± 110 Ma respectively [*Zhang and Wu*, 1998]. In the western Ondor Sum region Upper Silurian shallow-marine clastic and carbonate sediments overlie unconformably early Palaeozoic granites [*Wang and Liu*, 1986], in the central part of the region the Wentermiao Group with its ophiolites and blueschists is overlain unconformably by Upper Silurian sediments containing the corals *Cladopora* sp. and *Tryplasma* sp. [*Tang et al.*, 1983], and near the type locality the Ondor Sum melange is overlain unconformably by Carboniferous strata [*Hsü et al.*, 1991].

[21] In summary, the Ondor Sum assemblage north of the Xar Moron fault contains remnants of multiple subduction-accretion complexes that range in age from Late Precambrian to mid-Paleozoic. The original rocks have been intensely shredded by tectonic processes partly during accretion, and partly during subduction and exhumation.

3.2. Between the Solonker Suture and the Mongolian Border

3.2.1. Baolidao Arc and Precambrian Blocks

[22] A north dipping thrust belt extends for at least 250 km from Baolidao to Xilinhot (Figures 1 and 7) immediately north of the Solonker suture zone [*Chen et al.*, 2000; *Xu et al.*, 2001]. It was produced as a result of the northward subduction and postcollision convergence between the Baolidao magmatic arc and the Ondor Sum subduction complex [*Xu and Chen*, 1997]. This thrust belt consists mainly of the Baolidao arc-accretion complex. Ophiolites and blueschists between Sunid Zouqi and Xilinhot (Figures 1 and 7) occur as lenses in north dipping Carboniferous and Early Permian clastic sediments, and are overlain unconformably by Upper Permian conglomerates [*Wang and Liu*, 1986].

[23] The Baolidao arc is only known in detail near Baolidao town [*Chen et al.*, 2000]. It is composed of variably deformed, metaluminous to weakly peraluminous, hornblende-bearing gabbroic diorite, quartz diorite, tonalite and granodiorite [*Chen et al.*, 2000]. U-Pb zircon ages indicate that the bulk of the Baolidao rocks were emplaced in Late Carboniferous time at circa 310 Ma. Contemporaneous volcano-sedimentary rocks to the north formed in island arc and back arc settings [*Nan and Guo*, 1992]. *Tang and Yan* [1993] reported metamorphosed sandstone and mudstone intercalated with marble, chert, basalt and dacite, and intruded by high δ^{18}O granitic rocks generated by ultrametamorphism of turbidite and volcanic rocks.

[24] Several blocks up to $\sim$60 km long of amphibolite facies gneissic rocks occur south and southeast of Xilinhot and south of Sonid Zuoqi (Figures 1 and 7). *Hsü et al.* [1991] described these as quartz-feldspar gneisses and plagioclase amphibolites. A possible extension of the Xilinhot gneiss near the Chinese-Mongolian border in the west has a U-Pb zircon age of 916 ± 16 Ma [*Wang et al.*, 2001]. Southwest of Xilinhot a block consists of mica schist containing kyanite, staurolite and garnet [*Tang*, 1990], chlorite schist, quartzite and marble [*Hsü et al.*, 1991]. Along strike to the west across the border in Mongolia

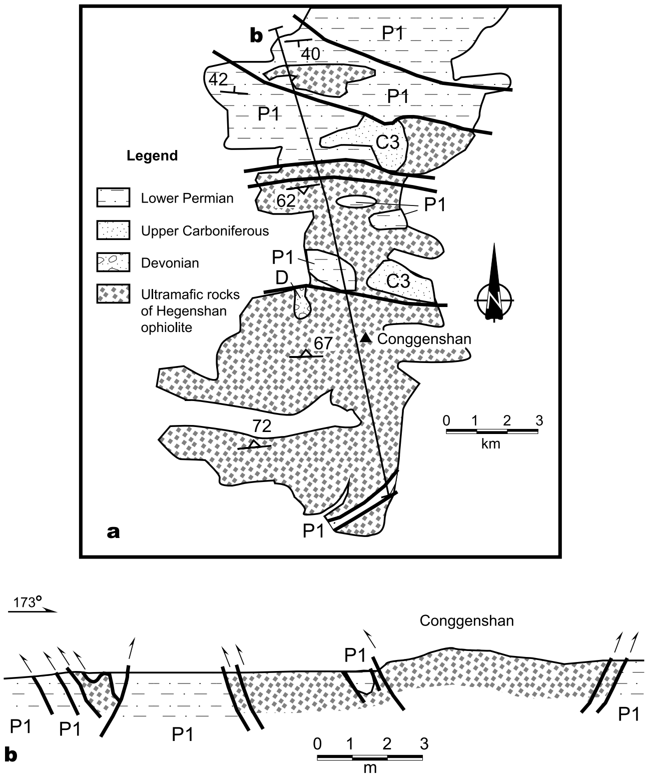


Figure 8. Geological map and cross section of the Hegenshan area showing major ophiolitic blocks and structures (modified after *BGMRIM* [1991]; *Wang* [1996]). Position shown in Figure 1.

the Hultag Uul terrane consists of Proterozoic granitic gneiss, quartzite, marble, stromatolitic limestone, and meta-sandstone [*Badarch et al.*, 2002]. A garnet-bearing aplite within the gneiss has a Pb-Pb zircon age of 770 Ma [*Kozakov et al.*, 1999]. These gneissic blocks are isolated bodies or tectonic slices in fault contact with ophiolitic melange, blueschist, greenschist, meta-sandstone, and meta-volcanic rocks, some of which are Late Devonian-Early Permian in age [*Xu et al.*, 2001]. ^{40}Ar-^{39}Ar dating on Na-amphibole from the blueschist yields 383 ± 13 Ma [*Xu et al.*, 2001]. We suggest that these Precambrian rocks belong to blocks that were accreted to the margin of the CAOB and incorporated into the subduction-accretion complex before the terminal closure of the central Asian ocean and formation of the Solonker suture.

3.2.2. Hegenshan Ophiolite-Arc-Accretionary Complex

[25] At Hegenshan north of Xilinhot (Figures 1 and 8) there are up to 30 outcrops of ophiolitic rocks, the largest of which is up to 20 km across. Poor exposure often prevents observation of their host rocks, but drill cores and a magnetotelluric study show that the outcrops belong to one giant ophiolite [*Hsü et al.*, 1991; *Bai et al.*, 1993a, 1993b]. The best preserved body is 5 km thick and has an upward stratigraphy from tectonized harzburgite and dunite to ultramafic and mafic cumulates, basalt and chert. Ophiolitic rocks have an Early Devonian whole rock Sm-Nd isochron age of 403 ± 27 Ma [*Bao et al.*, 1994]. On top of the ophiolite are Middle and Late Devonian coral-rich limestones, which are overlain unconformably by flat-lying Lower Permian sediments rich in brachiopods [*Wang and Liu*, 1986]. Cherts interbedded with turbidites contain Late Devonian radiolaria [*Hsü et al.*, 1991, and references therein]. Permian breccias containing pebbles of chert and ophiolitic rocks rest unconformably on the ophiolite [*Hsü et al.*, 1991], suggesting erosion of the ocean floor before obduction. Chromite mineralogy and geochemistry of mafic rocks suggested to *Robinson et al.* [1999] that the Hegenshan ophiolite formed in a back arc basin setting [*Robinson et al.*, 1995]. The section, however, could suggest a transform fault, or a very slow-spreading magma-starved crustal section. Chemical compositions alone cannot serve as a reliable indicator of tectonic environment of ophiolite origin, and they must be used in concert with data from structural geology and regional stratigraphy [*Moores et al.*, 2000; *Sturm et al.*, 2000]. South verging thrusts have locally transported the lower part of the ophiolite sequence over the upper part [*Tang*, 1990; our observations]. The ophiolite blocks mostly occur with Carboniferous strata or beneath the Lower Permian, and were found to be juxtaposed with some Early to Middle Devonian limestones, cherts, volcanics, and silty argillaceous sediments [*Tang*, 1990]. Sediments in exotic blocks north of the Hegenshan ophiolite contain radiolaria and coral fossils of Middle to Late Devonian age [*Wang and Liu*, 1986; *Tang*, 1990]. *Hsü et al.* [1991] pointed out that drilling has shown that the ophiolite has been thrust southward over Lower Permian volcanic rocks and Lower to mid-Jurassic conglomerates and sandstones belonging to a foreland basin (Figure 9). Structural transects and magnetotelluric studies reveal that the ultrabasic rocks occur in allochthonous klippen [*Lu and Xia*, 1993; *Bai et al.*, 1993a, 1993b]. Immediately south of the Uliastai continental margin (see below) are Carboniferous and Lower Permian interbedded hemipelagic shales, turbidites and conglomerates with pebbles of chert [*Hsü and Chen*, 1999]. Bedding parallel thrusts have broken up the beds, so that turbidites occur as blocks in sheared shale. We interpret these as a coherent-type accretionary wedge, because similar lithologies with bedding-parallel structures are characteristic of Triassic to Tertiary accretionary wedges in Japan [*Isozaki et al.*, 1990]. Such an accretionary wedge would be expected along the subduction zone at the foot of the Uliastai active continental margin, and would be consistent with the presence of similar rocks in exotic blocks within the Hegenshan melange. Along strike in Mongolia the Enshoo terrane (Figure 1) of *Badarch et al.* [2002] contains a major Devonian island arc made up of calc-alkaline basalt, andesite, dacite and volcaniclastic rocks.

[26] We propose that the whole belt located between the Baolidao arc-accretion complex and the Uliastai active continent margin to the north is an arc-accretion complex that contains allochthonous slices of ophiolitic rocks.

[27] In a very controversial paper, *Nozaka and Liu* [2002] reported that metamorphic amphiboles in meta-basalts in the Hegenshan ophiolite have K-Ar ages of 110–130 Ma, and concluded that the metamorphism was caused by continen-

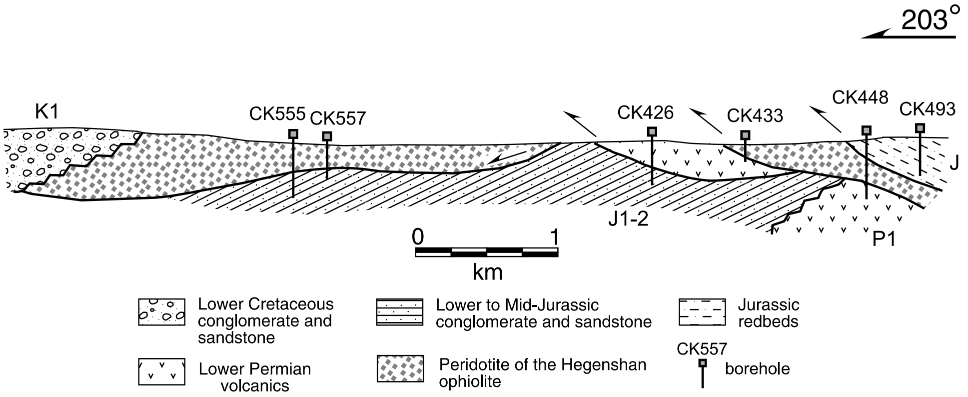


Figure 9. Structural section of the Hegenshan ophiolite. Borehole data show that the peridotites of the ophiolite have been thrust over Lower Permian volcanic rocks and Jurassic red beds (modified after *Hsü et al.* [1991]). Position shown in Figure 1.

tal collision, and therefore that the continental collision between the Siberian and north China blocks took place in middle Mesozoic time. In our opinion current knowledge of the K-Ar systematics of amphiboles suggests that the Cretaceous age results from cooling and uplift of the ophiolite, and has nothing to do with peak metamorphism. This would be consistent with the formation of Cretaceous extensional basins on top of the ophiolite.

3.2.3. Uliastai Active Continental Margin

[28] The Uliastai active continental margin extends along the northern border of Inner Mongolia from Chagan Obo to Uliastai (Figures 1 and 10). Cambrian limestones and siltstones about 100 m thick were deposited on a passive continental margin of Proterozoic gneiss, schist and quartzite. Two kilometer thick Ordovician calc-alkaline andesites, tuffs, tuffaceous slates and sandstones represent the initial change from a passive to an active continental margin, and they are succeeded by Silurian sandstones and siltstones [*Hsü et al.*, 1991]. Devonian andesites, basalts, porphyries, tuffs and pyroclastics define a major mid-late Devonian active continental margin [*Shao*, 1989]. The basal Devonian overlies a granitic basement and contains a complete fossiliferous Devonian stratigraphic succession about 5 km thick dominated by shallow marine to continental limestones, siltstones, sandstones and arkoses [*Shao*, 1989]. Carboniferous rocks include interbedded terrigenous clastics, volcanic rocks and shallow marine limestones. In the Lower Permian a major continental volcanic arc is represented by andesites, tuffs, and tuff breccias with sandstones, siltstones and conglomerates, in all several kilometres thick [*Wang*, 1996; *BGMRIM*, 1991]. The Devonian, Carboniferous and Permian lavas are accompanied by many calc-alkaline granitic Andean-type plutons and batholiths.

[29] The southeastern side of the Uliastai active continental margin is marked by the major, northwest dipping Chagan Obo-Arongqi thrust (Figure 1) [*Wang et al.*, 1991]. We envisage that a north dipping Devonian-Permian subduction zone under the Uliastai continental margin enabled the Early Devonian Hegenshan ophiolite to be obducted southward over the forearc; it was later thrust southward over Jurassic sediments with similar polarity in postcollisional times (Figure 9). Fauna in Silurian to early Early Permian sediments are cold-water types, middle Early Permian ones are cold-water mixed with some warm-water assemblages, and late Early Permian fauna are warm-water types [*Hsü et al.*, 1991]. These differences reflect the southward drift of this continental margin.

[30] The Uliastai continental arc continues along strike to the west in Mongolia as the Nuhetdavaa terrane of *Badarch et al.* [2002], which consists of Neoproterozoic gneiss, schist, quartzite, and stromatolitic marble overlain by Cambrian sandstone, siltstone and olistostromes. In Ordovician-Silurian times clastic sediments were deposited, but no incipient arc was generated as in Uliastai. In the Devonian, as in Uliastai, basalts, andesites and pyroclastics formed in an active continental margin. In the Carboniferous-Permian arc-type granitic plutons were intruded into the continental margin.

3.3. Late Paleozoic Andean-Type Magmatism

[31] Late Carboniferous to Upper Permian calc-alkaline to alkaline magmatic rocks have been singled out for special treatment because of their importance in defining a key phase in the tectonic development. Andesites and associated lavas and plutons are widespread in the areas between the Solonker suture and the north China craton and the Mongolian border (Figure 10).

[32] We emphasize the fact that *BGMRIM* [1991], the very detailed account of what is where in Inner Mongolia (unbiased by model-driven perspectives), described volcanic rocks of Andean-type of both Lower and Upper Permian age (interbedded with fossiliferous sediments) in several parts of Inner Mongolia. Examples are as follows:

[33] 1. On the south side of the suture ~2 km east of Kedanshan (Figure 1) the Lower Permian succession is 665 m thick and is dominated by andesites with minor basalts, rhyolites and tuffs, and the Upper Permian succession contains dacites, rhyolites, tuffs and conglomerates with volcanic pebbles.

[34] 2. At Keshitengqi about 20 km NE of Kedanshan the Upper Permian succession contains 20 m of andesites, 40 m of tuffs associated with sandstones and conglomerates.

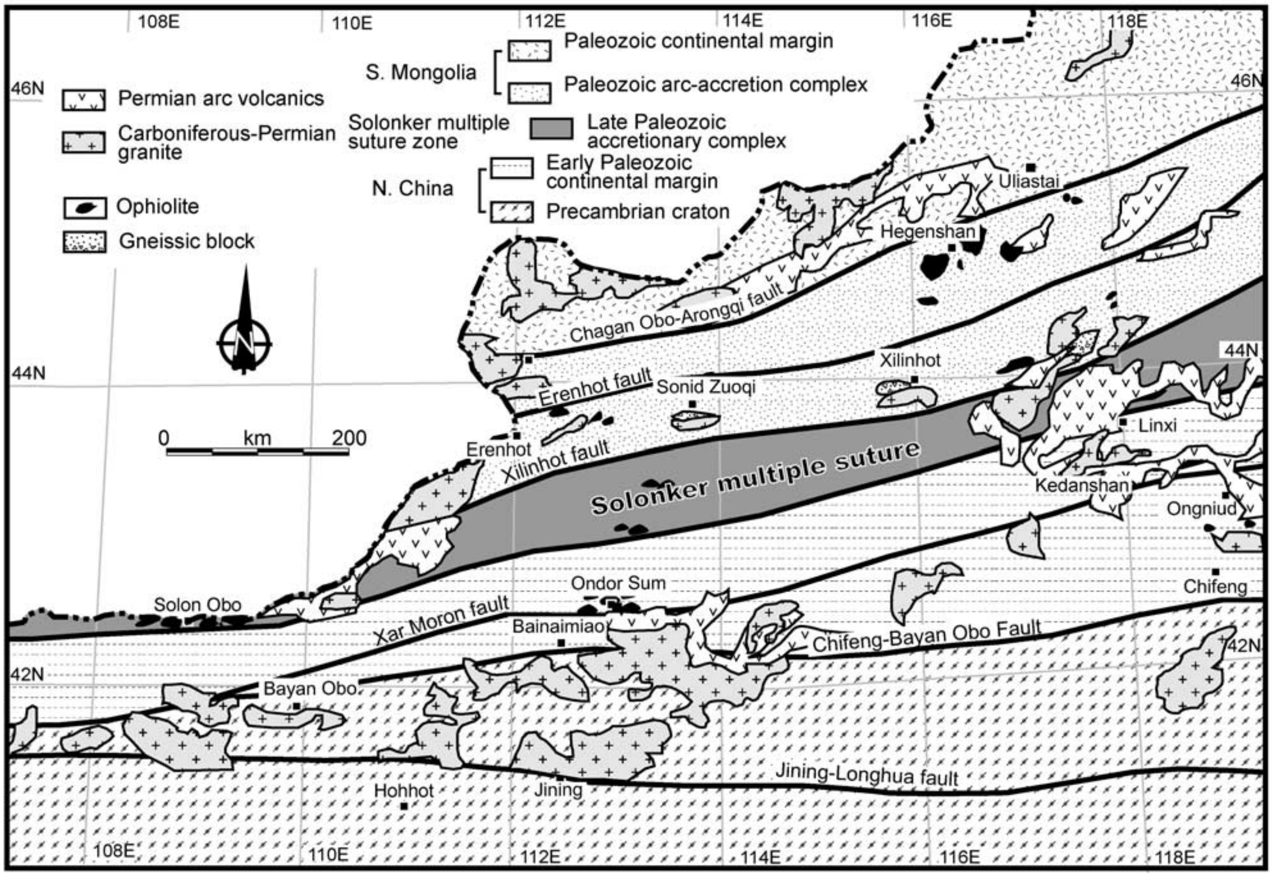


Figure 10. Geological map of central Inner Mongolia to show the distribution of Carboniferous-Permian granites and Permian arc volcanic rocks with respect to the tectonic belts, their boundaries and the Solonker suture zone (modified after *BGMRIM* [1991]).

[35] 3. On the north side of the suture ~100 km west of Uliastai the Lower Permian succession contains three beds of andesite totalling 1130 m in thickness, a rhyolite more than 115 m thick, together with tuffs and sandstones, and the Upper Permian has several beds of tuff totaling about 100 m in thickness, with tuffaceous sandstones, siltstones, shales and limestones. Lower Permian andesites and dacites occur in the Hutag Uul terrane of Mongolia (Figure 1) [*Badarch and Orolmaa*, 1998].

[36] Some Permian arc lavas and Carboniferous-Permian arc granites, shown in Figure 10, crosscut either the northern or southern margins of the Solonker suture zone, but not both margins. They were derived from northward or southward subduction, respectively.

[37] Many calc-alkaline granitic plutons were intruded into Paleozoic rocks just north of the north China craton, and also into the northern margin of the craton itself during the Late Carboniferous to Early Permian [*Hong et al.*, 1995]. Figure 10 shows that they are concentrated in the area south of Bayan Obo and Bainaimiao, from where they extend southward for about 150–200 km into the border zone of the north China craton.

[38] A narrow belt of undeformed granites of mostly Early Permian age extends on the northern side of the suture from NE China in the Great Xing'an Range, through central Inner Mongolia, to eastern Junggar in northern Xinjiang [*Hong et al.*, 1995]. About 20 Early Permian A-type monzogranites, syenogranites, and alkaline granites were intruded into, and are spatially associated with mid-late Carboniferous continental felsic lavas on the active continental margin of the Uliastai belt. They are associated with porphyry dyke swarms, and some have contact metamorphic aureoles over 1 km wide, and miarolitic cavities suggesting a very high level of intrusion [*Hong et al.*, 1995]. Those in the Great Xing'an Range were intruded in the period 290–260 Ma [*Wu et al.*, 2002]. The geological environment in which they were emplaced is that of an Andean-type continental margin, and their A-type geochemical signature requires some component of melted continental crust, which such an environment would provide, and we agree with *Wu et al.* [2002] that their emplacement was coeval with subduction of the ocean.

3.4. Solonker Suture

[39] The Solonker suture zone is marked by a belt of melanges, blueschists and ophiolites that is 700 km long and 60 km wide (Figure 1). It contains blocks of dolomite, quartzite, mafic and ultramafic rocks, marble and blueschist

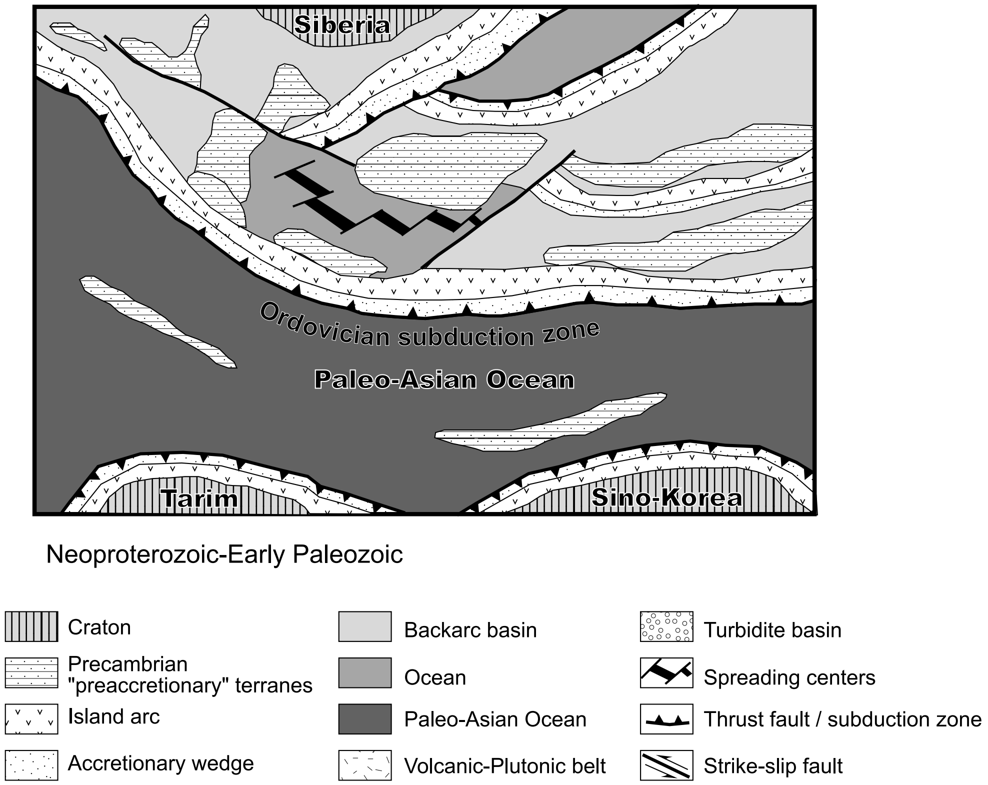


Figure 11. Paleogeographic map for the Neoproterozoic-Early Paleozoic for the southern CAOB based on terrane analyses in Mongolia (modified after *Badarch et al.* [2002]), demonstrating the southward (present day coordinates) growth of the southern margin of the Siberian continent.

[*Tang*, 1990; *Xu et al.*, 2001]. This accretionary wedge, which is called here the Erdaojing complex (Figure 1), is composed of tectonic melanges typical of a modern accretionary wedge [*Tang*, 1990]. A structurally higher unit of the melange mainly in the north consists of coherent turbidites that contain exotic blocks of ophiolitic rocks, chert, marble, and arc volcanics [*Wang and Liu*, 1986; *Tang and Yan*, 1990]. A structurally lower unit of the melange in the south is characterized by lenses of oceanic mafic-ultramafic rocks within an argillite matrix. Blueschist, which occurs as blocks up to 20 m wide and 40 m long, has a mid-Devonian, ^{40}Ar/^{39}Ar age on Na-amphibole of 383 ± 13 Ma [*Xu et al.*, 2001], which reflects the time of uplift and cooling of high-pressure rocks in the subduction zone. There is a discontinuous belt of ophiolitic lenses extending from Sunid Youqi to Linxi [*Wang and Liu*, 1986]. At the western end the ophiolites consist of harzburgite, dunite, gabbroic cumulate, mafic pillow lavas and chert, and they are overlain by Lower Permian clastic sediments. At the eastern end, near Linxi, ophiolitic lenses up to 1.1 km thick occur in Lower Permian clastic sediments and comprise pyroxenite, layered gabbro, sheeted mafic dykes, basalt and chert that contains Early Paleozoic conodonts such as Panderodus sp.

[40] FromBalengshannortheastwardtoGaijiadian(Figure1) Early Paleozoic ophiolites were thrust northward over Lower Permian sandstone and shale which in turn were under-thrust by Permian ophiolites composed of cumulate gabbro, sheeted diabase, pillow spilites, and quartz keratophyre with a Rb-Sr isochron age of 262 Ma [*Wang and Liu*, 1986]. The northward younging in the ophiolitic melanges from the Early Paleozoic ophiolites in the south to the Permian ophiolites in the north, together with the fact that both these ophiolites were imbricated with the Lower Permian sediments, containing the Early Permian fossil Streblascopora sp. [*Li*, 1986, 1987], suggests that the whole section represents a northward growing accretionary complex which may have been resulted from seaward retreat (northward) of a south dipping trench along which the Paleo-Asian ocean was subducted beneath the north China craton in the Late Paleozoic.

[41] Between Linxi and Solon Obo (Figure 1) there is an ENE trending boundary between two Permian biogeographic provinces [*Zhan and Li*, 1979; *Wang and Liu*, 1986]. Although *Şengör and Natal'in* [1996] did not agree with the distribution of the Cathaysian and Angaran fossil plants of *Wang and Liu* [1986], we suggest that, because the suturing of the Paleo-Asian ocean continued to the end of the Permian [*Wang and Liu*, 1986; *Ruzhentsev et al.*, 1989; *Şengör and Natal'in*, 1996; *Badarch et al.*, 2002], the Permian distribution of Angaran and Cathaysian fossil plants across the Solon Obo-Linxi line, which corresponds to the Linxi Fault (Figure 1) [*Wang and Liu*, 1986], should define, at least locally, the final position of suture zone. This is consistent with the fact that ophiolites or oceanic crust fragments containing Permian radiolarian and bryozoan

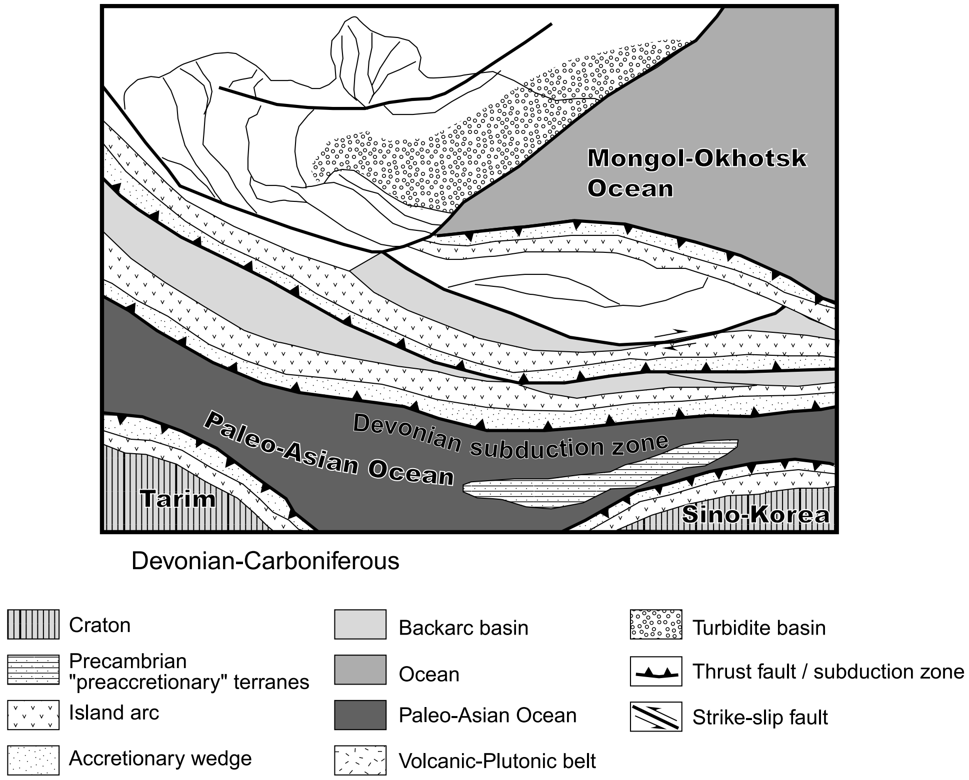


Figure 12. Devonian-Carboniferous paleogeographic map for the southern CAOB based on terrane analyses in Mongolia (modified after *Badarch et al.* [2002]).

fossils have been found along the Lixi fault [*Wang and Fan*, 1997; *Li*, 1986]. The Erdaojing accretion complex contains the youngest ophiolites among the four ophiolitic belts [*Wang and Liu*, 1986; *Li*, 1987] in this portion of the central Asian orogenic collage. Accordingly, the Solonker suture may be better interpreted not as a single line, but as a multiple suture zone within the Erdaojing accretion complex.

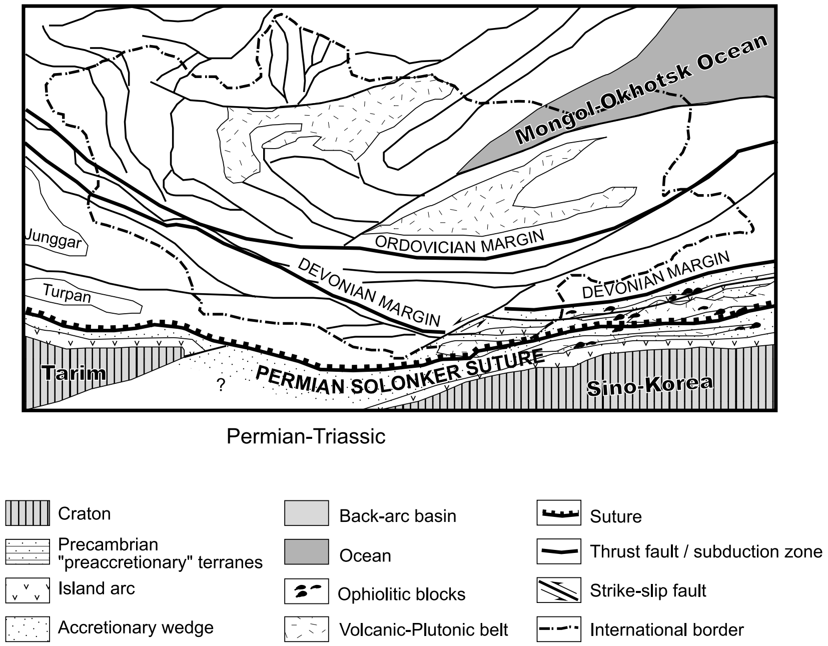


Figure 13. Permian-Triassic paleogeographic map for the southern CAOB based on terrane analyses in Mongolia (modified after *Badarch et al.* [2002]). See text for discussion.

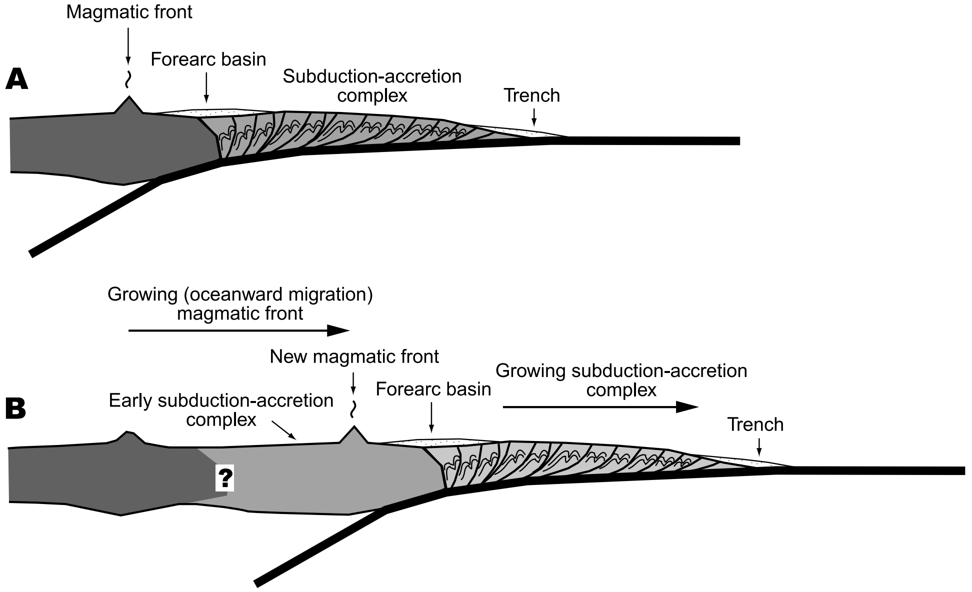


Figure 14. A tectonic model modified after *Şengör and Okurogullari* [1991] to show the overlap of magmatic arcs and subduction-accretion wedges as a magmatic front (active arc) migrates oceanward from stage A to stage B. See text for discussion.

[42] The Solonker suture in Inner Mongolia has a multiple character, because it occurs within two opposing subduction-accretion complexes between the South Mongolian active margin and the north China craton. The South Mongolian margin grew southward as an accretionary collage. Figures 11, 12, and 13 are paleogeographic reconstructions for southern Mongolia [*Badarch et al.*, 2002], which we have modified for the development of the Solonker suture. Arcs and their associated accretionary complexes grew southward (present-day coordinates) from the Ordovician, through the Devonian-Carboniferous, to the Permian-Triassic, when they collided with the active accretionary margin developed on the northern side of the north China craton. The accretionary processes in these two opposing active margins are similar to those in so-called Turkic-type orogens described by *Şengör and Okurogullari* [1991]; see Figure 14. The final amalgamation of the two accretionary collages can be well explained

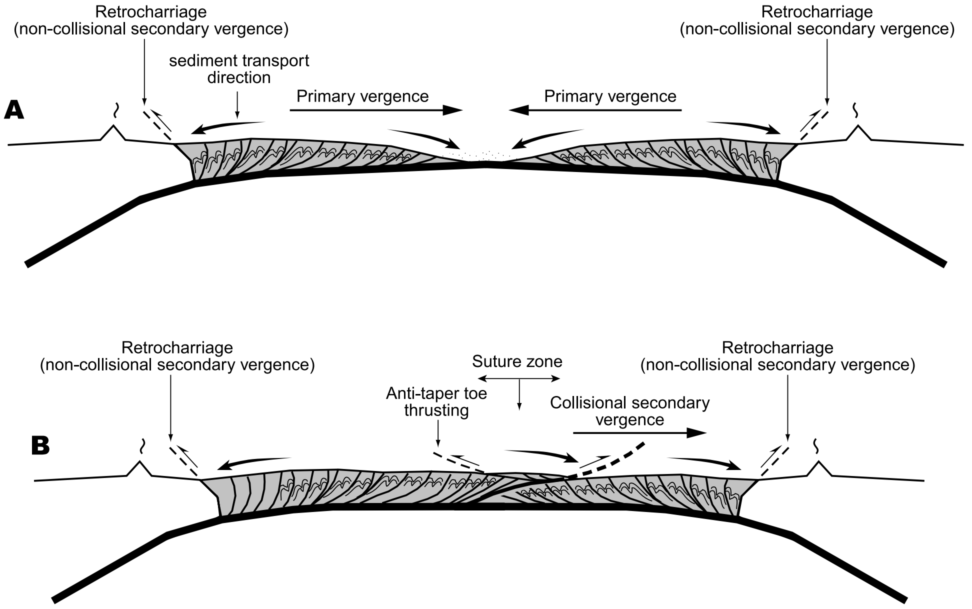


Figure 15. Diagrammatic collision of two accretionary wedges (modified after *Şengör and Okurogullari* [1991]). (a) The situation just before collision; (b) after collision.

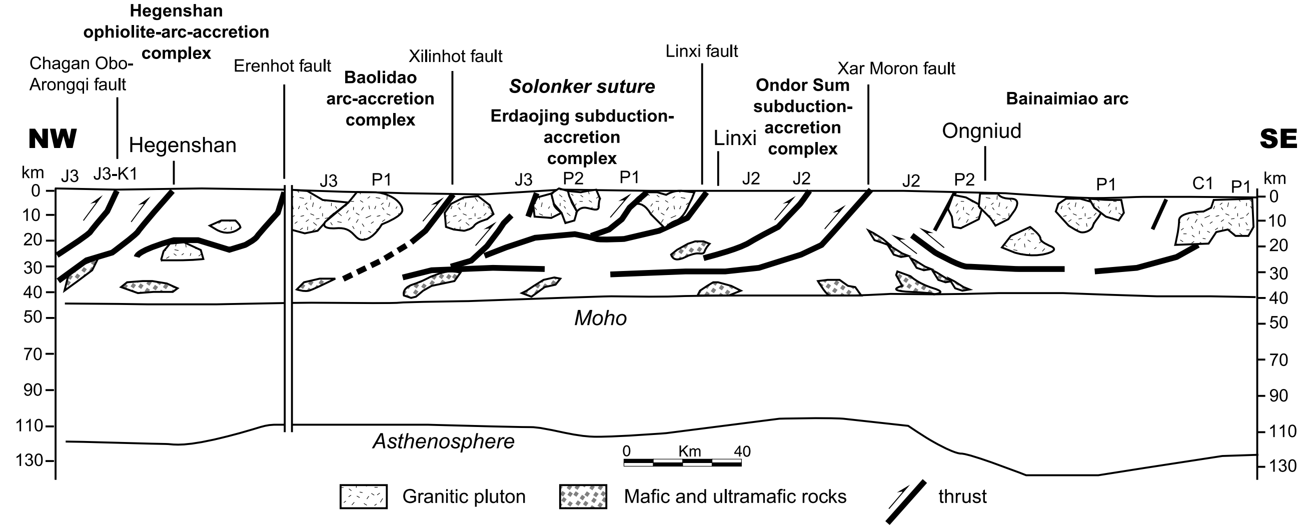


Figure 16. Cross section from Hegenshan to Ongniud. The deep structure is based on the interpretative geophysical section of *Lu and Xia* [1993], and the surface structure is based on our own work and that of *Wang and Liu* [1986], *Hsü et al.* [1991], *BGMRIM* [1991], *Tang and Yan* [1993], and *Wang* [1996]. Position shown in Figure 1.

by the model of wedge-wedge-collision of *Şengör and Okurogullari* [1991] which is illustrated in Figure 15. This scenario is inconsistent with the reconstruction of *Şengör and Natal'in* [1996] which shows that in Carboniferous-Permian time the Solonker Ocean was trapped between the South Mongolia and north China cratons, while the Mongol-Okhotsk ocean opened further north. These two wedge systems amalgamated into a subduction-accretion complex zone in which first order (primary) vergence cannot be used to distinguish where exactly the suture zone is situated. This is one of the main reasons for the many divergent opinions concerning the position of the suture zone between the north China craton and South Mongolia active margin.

[43] Geophysical transects help to define the subsurface structure of mountain belts, and they provide constraints on their tectonic development. We use three seismic sections to help resolve the structural fabric and evolution of Inner Mongolia. One crosses from Hegenshan through Ongniud (Figures 1 and 16), another from Mandula (Figure 1, east of Solon Obo) through Bayan Obo to the north China craton (Figure 17), and a third from Beijing to Kalaqinqi just south of Chifeng (Figure 18). The first two sections show that to the south of the Solonker suture (the Solon Obo-Linxi line) an early south dipping fabric (with ophiolitic lenses) is cut by a later north dipping fabric (with ophiolitic lenses). When these relations are correlated with the surface geology and structures, we infer that an early subduction-accretion complex together with ophiolitic rocks was subducted southward (and may have given rise to the Bainaimiao arc). We interpret the later north dipping structures, which extend across the Solonker suture, as late to postcollisional, south directed thrusts, which are prominent on the surface, where they have transported, for example, the Hegenshan ophiolite over a Jurassic basin [*Hsü et al.*, 1991]. Figure 18 shows that, on a larger scale from Kalaqinqi southward into the north China craton, all main structures dip to the north. The

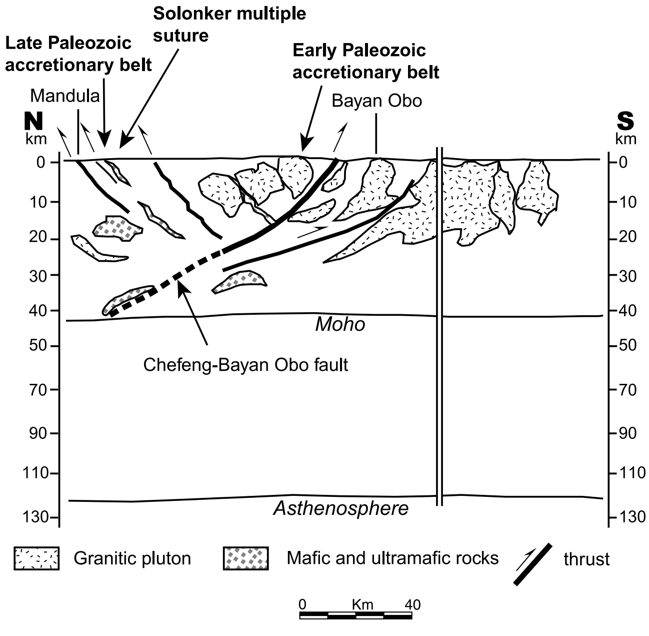


Figure 17. Cross section from Madula through Bayan Obo to Xiaoshetai. The deep structure is based on the interpretative geophysical section of *Ma et al.* [1991], and the surface structure is based on our own work and that of *Wang and Liu* [1986], *Hsü et al.* [1991], *BGMRIM* [1991], *Tang and Yan* [1993], and *Wang* [1996]. Position shown in Figure 1.

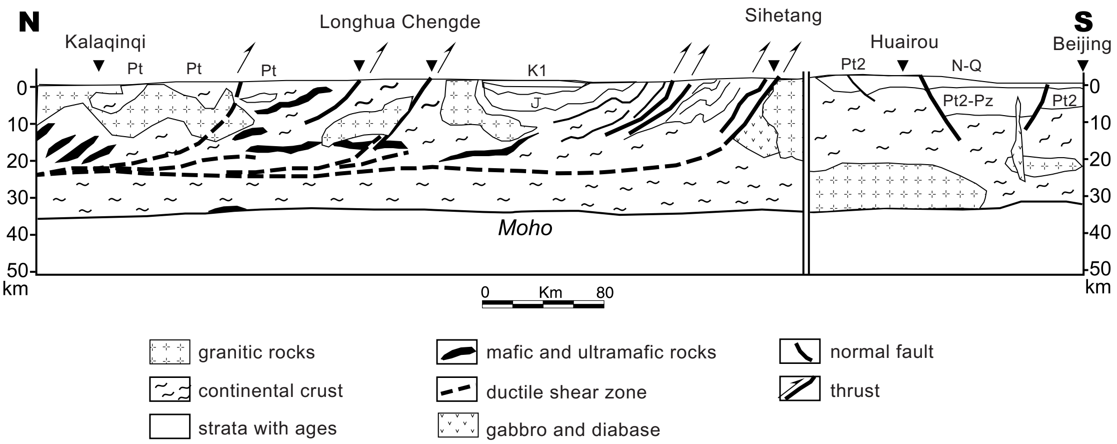


Figure 18. Cross section from Beijing to Kalaqinqi. The deep structure is based on the interpretative seismic section of *Sun et al.* [1992] and *He et al.* [1998], and the surface structure is based on our own work and that of *Wang and Liu* [1986], *Tang* [1990], *Hsü et al.* [1991], *BGMRIM* [1991], *Tang and Yan* [1993], and *Chen et al.* [2000].

subsurface structures on these seismic sections are largely continuous with those on the surface, and we suggest that they are consistent with two-way terminal subduction of the Paleo-Asian ocean, followed by southward postcollisional thrusting.

[44] At longitude 109° at the western end of Figure 1 the Solonker suture passes along the Chinese-Mongolian border where an accretionary wedge occurs in the Solonshan belt of China and in the Sulinheer terrane of Mongolia [*Badarch et al.*, 2002]. A melange contains blocks of pillow basalt, chert, tuff and limestone. Straddling the international border are fragments of dismembered ophiolites, which consist of serpentinite, dunite and gabbro. These rocks belong to the Carboniferous Enger Us ophiolite in China [*Wu*, 1993] and the Sulinheer ophiolite of presumed Upper Devonian-Lower Carboniferous age in Mongolia [*Badarch and Orolmaa*, 1998; *Badarch et al.*, 2002].

[45] In our opinion the best three pieces of evidence for determining the time of formation of the Solonker suture are (1) Andean-type magmatism was still developing in the Late Permian, suggesting that the central Asian ocean was still in existence (discussed previously), (2) mid-late Triassic S-type, crustal melt granites were intruded into and across the suture zone [*Chen et al.*, 2000] (next section), (3) significantly, there are no Triassic sediments in central Inner Mongolia [*BGMRIM*, 1991]. Our interpretation of this fact is that collision had uplifted the region in the Triassic, preventing deposition of sediments. Terrestrial sediments of Early Jurassic age were deposited across the entire suture zone and region. Accordingly we believe that the best documented time of formation of the Solonker suture is end-Permian. This is in accordance with the regional paleomagnetic investigations of [*Zhao et al.*, 1990]. *Chen et al.* [1997] wrongly suggested that the Uliastai block and the whole of Mongolia had north China affinities only because they had a paleolatitude similar to that of north China. However, only the well-defined boundary between the Angaran and Cathaysian floras can define the position of the suture zone, as discussed above, and therefore we suggest that in the Late Carboniferous the two continents (Siberia and north China) approached each other to collide in the end-Permian.

3.5. Postorogenic and Postcollisional Granites

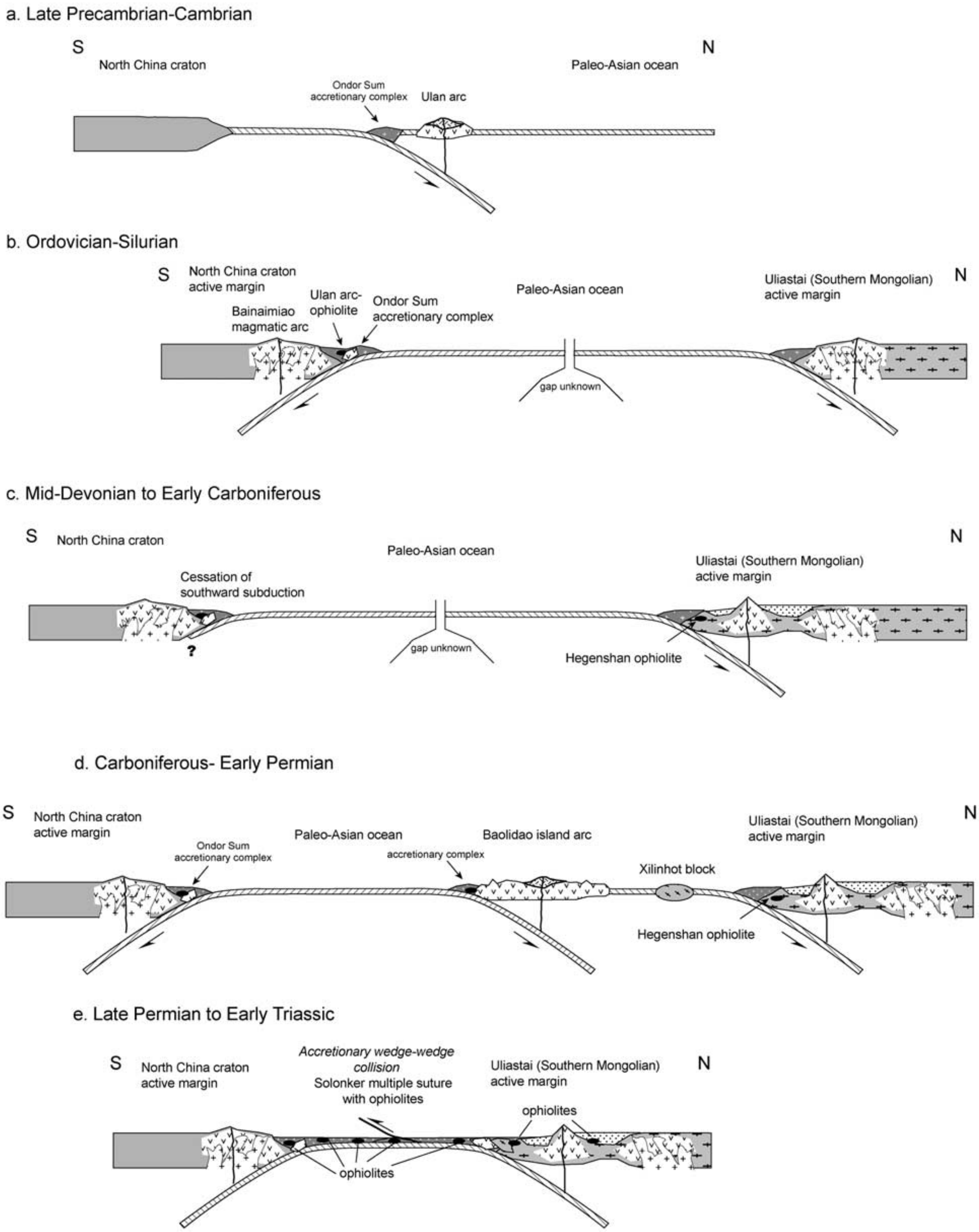
[46] A variety of postorogenic granites were intruded after the formation of the suture. Although they may defined on geochemical criteria as I-type, S-type or A-type, it is often difficult to understand the tectonic environment in which they were emplaced with respect to the time of closure of the ocean, of formation of the suture and of the postcollisional structures. In view of previous uncertainties about the time when the Solonker suture was created, it has been difficult to produce tectonic models to explain the production and emplacement of these different types of granites, and thus there is much confusion in the literature.

[47] Mid-late Triassic S-type granites were intruded into and across the suture zone in the region between Erdaojing and Xilinhot (Figure 7) [*Chen et al.*, 2000]. These Halatu granites have a whole rock Rb-Sr age of circa 230 Ma, are weakly metaluminous to peraluminous, and have the geochemical features of crustal melt granites, that were derived from a mixed source including juvenile material such as acid to intermediate igneous rocks, and older continental crust such as the Xilinhot gneisses.

[48] In NE China postcollisional compression ended in the late Triassic. Late Triassic to early Jurassic A-type granites are widespread in the region and were related by *Wu et al.* [2002] to postorogenic processes of lithospheric delamination.

3.6. Postcollisional Structures

[49] Postcollisional structures are widespread in Inner Mongolia. However different types of structures are variably developed along the length of the orogen and they are



a. Late Precambrian-Cambrian

b. Ordovician-Silurian

c. Mid-Devonian to Early Carboniferous

d. Carboniferous- Early Permian

e. Late Permian to Early Triassic

Figure 19. Schematic cartoons demonstrating the tectonic evolution of the Paleo-Asian ocean and the eventual formation of the Solonker suture zone. (a) Late Precambrian-Cambrian; (b) Ordovician-Silurian; (c) Middle Devonian-Early Carboniferous; (d) Carboniferous-Permian; (e) Late Permian to Early Triassic. Positions of Uliastai active margin in Figures 19b to 19d after *Badarch et al.* [2002]. The cross-sectional directions are present day coordinates. See text for discussion.

different on the two sides of the suture zone. Although many authors have related the pre-Permian structures to the progressive closure of the ocean and formation of the Solonker suture [e.g., *Wang and Liu*, 1986], few have related the post-Permian structures to the postcollisional tectonic development of the orogen. Recent studies of many Mesozoic-Cenozoic orogens have demonstrated how postcollisional thrusts thicken an orogen and lead to later extensional faults and detachments, and even to metamorphic core complexes. We describe the following structures in the light of these advances.

[50] A major problem with all previous publications on Inner Mongolia was the lack of a N-S seismic section which could potentially image the suture zone or the dominant vergence of crustal structures at depth. Therefore we produce in Figure 18 a slightly modified version of the crustal section [*Ma et al.*, 1991; *Sun et al.*, 1992; *Lu and Xia*, 1993; *Wang*, 1996; *He et al.*, 1998]. The northern boundary of the north China craton is roughly marked at Longhua by a south directed thrust, which is near and south of the Chifeng-Bayan Obo fault. A south directed thrust at Chengde is consistent with the Chengde thrust described by *Davis et al.* [2001]. The Solonker suture was not on the section by *Sun et al.* [1992] (Figure 18) and *He et al.* [1998] (they were concerned with the Yanshan-Yinshan orogen to the south), and therefore we have marked the position of the suture in the appropriate position on Figures 16 and 17. The sections clearly show the dominant northward dip of the crustal structure on both north and south sides of the suture. All the faults are listric rooting on a detachment at about 23 km depth which surfaces at Sihetang (Figure 18) within the Yanshan-Yinshan thrust belt in the north China craton. The northwest dipping Chagan Obo-Arongqi thrust which marks the southeastern border of the Uliastai continental margin is north of Hegenshan (Figure 16). Lenses of ultramafic and mafic rocks are marked by *Ma et al.* [1991] and *Lu and Xia* [1993] in the footwall or lower plate of the Solonker suture which is consistent with their presence near Linxi and in the Kedanshan and Ondor Sum ophiolites. In the hanging wall, upper plate mafic and ultramafic rocks at depth are below the surface position of the Hegenshan ophiolite.

[51] *Hsü et al.* [1991] showed that drilling had confirmed that the Hegenshan ophiolite was thrust southward over Jurassic foreland basin sediments (Figure 9). From their magnetotelluric study *Bai et al.* [1993a, 1993b] also proposed the allochthonous nature of the Hegenshan ophiolite. We suggest that the slab of oceanic crust was derived from the accretionary wedge sited on the Chagan Obo-Arongqi thrust below the Uliastai continental margin, that it was obducted in the Devonian-Carboniferous [*Wang and Liu*, 1986], and thrust further southward in postcollisional times. Such thrust kinematics would be expected in the hanging wall of the Solonker suture.

[52] Further west in Mongolia just north of the Solonker suture several nappes were thrust northward onto the margin of the Tsagan Uul terrane in the Late Permian and Lower Triassic with a displacement of at least 40 km [*Ruzhentsev*, 2001]. We interpret these as back-thrusts developed in the hanging wall of the suture.

4. Discussion

[53] We have integrated our new local and regional data with a synthesis of published information from central Inner Mongolia, and this leads us to produce a new tectonic model for the evolution of the terminal stages of the CAOB.

[54] Figure 19 shows that the continental margin of the CAOB had moved progressively southward (present coordinates) from the Ordovician in central Mongolia to the Devonian in southern Mongolia [*Badarch et al.*, 2002] and northern Inner Mongolia [*Wang*, 1996]. This margin in the Uliastai belt underwent Andean-type magmatism in the Devonian and Carboniferous [*Lamb and Badarch*, 1997]. The trench on the southeast side of the margin is marked by the Chagan Obo-Arongqi thrust on which there are Carboniferous and Lower Permian interbedded hemipelagic shales, turbidites and conglomerates with pebbles of chert, that belong to the accretionary wedge in that trench. The blocks of Precambrian gneiss at Xilinhot and in the Hutag Uul terrane of Mongolia were then accreted from the south, and the Baolidao island arc was attached to the collage in the Late Carboniferous. This completes the accretionary stage on this northern side of the suture. A new stage of development took place throughout the Permian, when Andean-type lavas were extruded, tuffs were deposited and I-type granitic rocks were intruded into the consolidated accretionary rocks on this leading southern margin of the CAOB.

[55] On the southern side of the suture similar stages of development took place from early accretion to active continental margin, as progressive consolidation of the accreted terranes (mostly early Paleozoic) enabled an Andean-type margin to develop in the Permian. In the Early Paleozoic the Ulan arc formed within the Ondor Sum subduction-accretion complex, as part of a north dipping subduction system on the northern margin of the north China craton. We infer that a new south dipping subduction zone was generated near the present position of the Ondor Sum melange in the Ordovician and gave rise to the Bainaimiao arc, which was attached at an unknown time to the northern margin of the north China craton. The Kedanshan ophiolite represents a piece of Ordovician ocean floor, and island arcs were generated in the Ordovician at Linxi-Bairin Youqi and Bater Obo (Figure 1). No arcs were generated or accreted on this northern margin in the Silurian, Devonian and Carboniferous. Instead, at this time fossiliferous shallow water limestones and some sandstones were deposited unconformably on earlier rocks. By the end of the Carboniferous this southern accreted margin had consolidated into an active continental margin into which Andean-type granites were intruded and on which andesites, basalts, dacites, rhyolites were extruded, and tuffs were deposited during the Lower and Upper Permian. The presence of both northward and southward facing active continental margins in the Permian suggests that the Paleo-Asian ocean closed at this stage by double or two-way

subduction rather like the Molucca islands in the SW Pacific.

[56] Although it is well established that the Paleo-Asian ocean began to form in the late Proterozoic [*Şengör and Natl'in*, 1996; *Khain et al.*, 2002], the time of its termination and of completion of the CAOB is much discussed and poorly understood. Our evidence indicates that the Solonker suture formed at the end of the Permian. The Triassic period was marked by consequent uplift and absence of sedimentation. Some crustal melt granites were intruded into the suture zone in the mid-late Triassic, having been generated from presumed thrust-thickened crust. From the early Jurassic terrestrial sediments were deposited across the suture and entire orogen.

[57] Thrusting began in the Ufimian (mid-Permian) and continued in the late Permian in southern Mongolia transporting nappes northward perhaps during final stages of closure of the ocean. In central Inner Mongolia south directed postcollisional thrusting took place throughout the Jurassic transporting the Hegenshan ophiolite over Jurassic sediments. A-type granites were widely emplaced on the north side of the suture in the late Triassic to early Jurassic, perhaps as a result of the more intense thrusting on this margin. The seismic profiles show that the present crust across Inner Mongolia is dominated by northward dipping structures, which means that after collision the northward dipping subduction zone was the more prominent in controlling the postcollisional structures.

5. Modern Analogs

[58] Our results suggest that the CAOB underwent several progressive stages of growth in its terminal history. It is useful here to consider to what extent the various tectonic environments are comparable to equivalents in more recent and ancient orogenic belts, because it is important to understand the different ways orogenic belts are constructed.

[59] The early formation of the Ulan arc above an oceanward directed subduction zone and its accretion to the north China craton with the accretionary Ondor Sum complex between them (Figure 19a) has similarities to the initial arc-continent collision in Taiwan, when the North Luzon arc formed above an oceanward directed subduction zone and was accreted to the Eurasian continent with the accretionary wedge of the Central Range between them [*Huang et al.*, 2000]. As pointed out by *Dewey and Mange* [1999], the fate of intraoceanic arcs whose polarity is continentward is likely to be collision with a continental margin. Like the Ulan arc, the initial collision between the Timor arc with the continental margin of North Australia [*Huang et al.*, 2000] involved subduction polarity flip [*Dewey and Mange*, 1999]. Likewise, the Cretaceous Kohistan arc may have formed as a result of southward subduction, and consequent collision with Eurasia created a new north dipping subduction [*Khan et al.*, 1997]. An inevitable result of subduction polarity flip in Inner Mongolia was the generation of the Bainaimiao magmatic arc in the continental margin of the north China craton (Figure 19b). Further advanced stages of arc-continent collision are represented by Papua New Guinea and the Urals [*Huang et al.*, 2000].

[60] Material accreted in the early-middle Paleozoic to the two opposing margins became sufficiently consolidated by the Permian for two Andean-type continental margins to develop. From the literature we are not aware of similar two-way, symmetrical Andean-type magmatic arcs developing just before closure of an ocean. Inner Mongolia may be instructive in this regard. Two-way subduction caused final closure of the Paleo-Asian ocean, leading to terminal collision and formation of the Solonker suture by the end-Permian. The massive postcollisional thrusting across the suture zone has similarities with the postcollisional thrusting of collisional orogenic belts like the Himalayas.

[61] Therefore, the COAB underwent several stages of development: island arc formation and collision to north China block—Japan-style state with a Taiwan-style (West Luzon-East China) collision, development of multiple Andean-style magmatism, and Himalayan-type collision. Although more complicated, the scenario we outline here is similar to that described in the Appalachians-Hercynian, Caledonide, and other ancient orogens [*Hatcher*, 1987; *Hall and Roberts*, 1988; *Dewey and Mange*, 1999; *Huang et al.*, 2000]. Paraphrasing *Dewey and Mange* [1999] in their discussion of the Grampian orogeny, obduction of the huge Hegenshan ophiolite sheet would have prevented orographic expression during early phases of crustal thickening, while the ophiolite nappe was preserved to depress the orogen. This would explain the preservation of Cretaceous basin sediments above the ophiolite (Figure 9).

[62] The tectonic framework of the original ocean is still an open question. There is no definitive evidence that north China and East Siberia rifted from each other, and this model is at variance with the reconstruction of *Li et al.* [1996] which shows the southern (present coordinates) margin of Siberia against the Arctic margin of Laurentia, and north China along the Verkhoyansk margin of Siberia. However, in an updated version of their reconstruction involving north China and Siberia [*Zhang et al.*, 2000], Siberia had rotated to a position against the north China craton by circa 650 Ma, enabling convergence between these two continents from that time. This is consistent with our current tectonic model, but a full discussion of supercontinent reconstruction is beyond the scope of this paper.

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Figure 4. (a) Elongate pillow lavas in southern Ulan valley, see Figure 3. (b) Pillow breccia within the lower pillow lava succession in southern Ulan valley of Figure 3. Several pillow fragments have partial chilled margins. Matrix is bedded basalt. Hammer for scale. By B. F. Windley.

Figure 5. Photograph showing a 2 m-size block of magnetite-pyrolusite-quartz within purple chert on northern side of ultramafic rocks. Southern Ulan valley (Figure 3). Looking northeast. By B. F. Windley.

Figure 6. Photograph of red phengite/haematite-bearing quartzitic mylonite in northern Ulan valley of Figure 3. Pencil for scale. By B. F. Windley.