Journal of the Geological Society, *London*, Vol. **161**, 2004, pp. 339–342. Printed in Great Britain.

SPECIAL

Palaeozoic accretionary and convergent tectonics of the southern Altaids: implications for the growth of Central Asia

W. XIAO[1], B. F. WINDLEY[2], G. BADARCH[3], S. SUN[1], J. LI[1], K. QIN[1] & Z. WANG[1]

[1]*Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China (e-mail: wj-xiao@mail.igcas.ac.cn)*
[2]*Department of Geology, University of Leicester, Leicester LE1 7RH, UK*
[3]*Institute of Geology and Mineral Resources, Mongolian Academy of Sciences, 63 Peace Avenue, Ulaanbaatar 210357, Mongolia*

The southern Altaids present a unidirectional section from Mongolia to China through an accretionary orogen that youngs progressively from Neoproterozoic in the north to Permian in the south. The orogen formed by forearc accretion of island arcs, accretionary wedges, ophiolites and Precambrian microcontinents. This regularity was upset by early growth within the ocean of arcs that later collided at the accreting continental margin, by imbrication of old ophiolites with young arcs, and by Himalayan-style thrust–nappe tectonics when an arc collided into a microcontinent. Lateral growth of the Southern Altaids represents a massive addition of juvenile material to the Palaeozoic crust.

Keywords: Altay, Eastern Junggar, Altaids, Central Asia, tectonostratigraphic units.

Central Asia is an important natural laboratory for the analysis of accretionary tectonics and crustal growth (Sengör *et al*. 1993; Dobretsov *et al*. 1995; Jahn *et al*. 2000). However, there is a strong debate about the mechanism of orogenesis; forearc accretion and oroclinal bending of a long-lived, single subduction system (Sengör *et al*. 1993) or a collage of terranes (Coleman 1989; Mossakovsky *et al*. 1994; Badarch *et al*. 2002).

The southern Altaid orogen connects the Altay and Eastern Junggar belts of China with the Altay belt in Mongolia (Fig. 1). The orogen contains island arcs, accretionary wedges, ophiolites and Precambrian blocks, and records accretionary processes associated with the consumption of the Altay Ocean (Heubeck 2001). The geology of the Chinese Altay (Windley *et al*. 2002) and Mongolian Altay (Badarch *et al*. 2002) was synthesized in terms of terranes, but no sections were constructed across the tectonic belts and no correlations were made across the international border. This paper presents a new comparative correlation of the tectonostratigraphic units across the China–Mongolia border and new sections to illustrate the tectonic evolution of the southern Altaids. We propose a new dynamic model in order to help reconcile the long-standing controversy in Central Asia.

Tectonostratigraphic units. In our new tectonic map of Fig. 1 we show how the tectonostratigraphic units in China and Mongolia mutually correlate along strike. Because the oldest Proterozoic rocks are in the far north, the youngest Permian rocks in the far south, and because the rock units generally young from north to south, our section provides a valuable insight into the sequential accretionary processes. Rock assemblages in the 11 units are listed in Table 1. The belts are described below from north to south.

In the NE corner of Figure 1 the Zavhan microcontinent (unit 1) contains epidote amphibolite and greenschist facies rocks including a granite-gneiss dome that has a Pb–Pb zircon age of 1868 ± 3 Ma (Badarch *et al*. 2002). On its SW side (Fig. 1) the block is overlain by slices of ophiolitic rocks and is bordered by Neoproterozoic–Cambrian shelf sediments that include carbonates with phosphatic beds, sandstone, conglomerate, shale, and diamictite.

Lake unit 2 contains Cambrian to early Ordovician calc-alkaline lavas, tuffs and granitic rocks, limestone with archaeocyathids, and trilobites, and is regarded as an island arc (Badarch *et al*. 2002). Table 1 shows that assemblages and structures of Unit 3 (Hovd) are indicative of an accretionary wedge active from the Cambrian to Silurian, that the features of unit 4 suggest a long-lived arc with forearc clastic detritus, and that unit 5 has assemblages diagnostic of a Devonian accretionary wedge that contains Cambrian, Ordovician and Devonian debris and succeeded by a minor Devonian–early Carboniferous arc. Unit 6 is a microcontinental block that contains high-grade gneisses in Mongolia and China. Berzin *et al*. (1994) showed the Altay Mountains as a microcontinent with possible Precambrian basement (Wang *et al*. 2003*a*). From zircon geochronology Windley *et al*. (2002) demonstrated that a 505 Ma rhyolite in the Chinese Altaishan contains 920–614 Ma xenocrysts suggesting the presence of a continental magmatic arc on the southern margin of the block. The presence within unit 6 of Be–Nb–Ta–Li mineralization in the NE, VMS-type Zn–Pb–Cu in the middle, and Cu–Ni–Au and Cu–Au in the SW (Qin *et al.* 2002) also indicates a Cordilleran-type margin above a northeast-dipping subduction zone of roughly similar age. Thrust nappes and inverted metamorphic isograds on this southern margin demonstrate that the block underwent collisional tectonics when unit 7, a Silurian–early Devonian island arc, accreted to it in the late Devonian–early Carboniferous (Windley *et al*. 2002).

Erqis unit 8 is a narrow sliver on the northern side of the Erqis–Bulgan fault (Zhang *et al*. 1996) that contains 10 km wide mylonites and underwent at least 1000 km of sinistral displacement mainly at 290–280 Ma (Laurent-Charvet *et al*. 2003). In China on the Erqis fault there is an ophiolite with a 390 Ma U–Pb age (Wang *et al*. 2003*b*). In unit 8 some gneisses contain 1849–1791 Ma feldspar Pb–Pb model ages (Qu & Chong 1991). Some pillow basalts (more than 1 km thick) show MORB and island arc tholeiitic chemical signatures (Yu *et al*. 2000), and are imbricated with Ordovician–Silurian radiolarian chert and Silurian–Devonian turbidites (Xiao *et al*. 1992); the presence of high-Mg andesites and boninites suggests a forearc setting (Niu *et al*. 1999). We propose the Erqis fault helped to dismember the discontinuous Erqis unit.

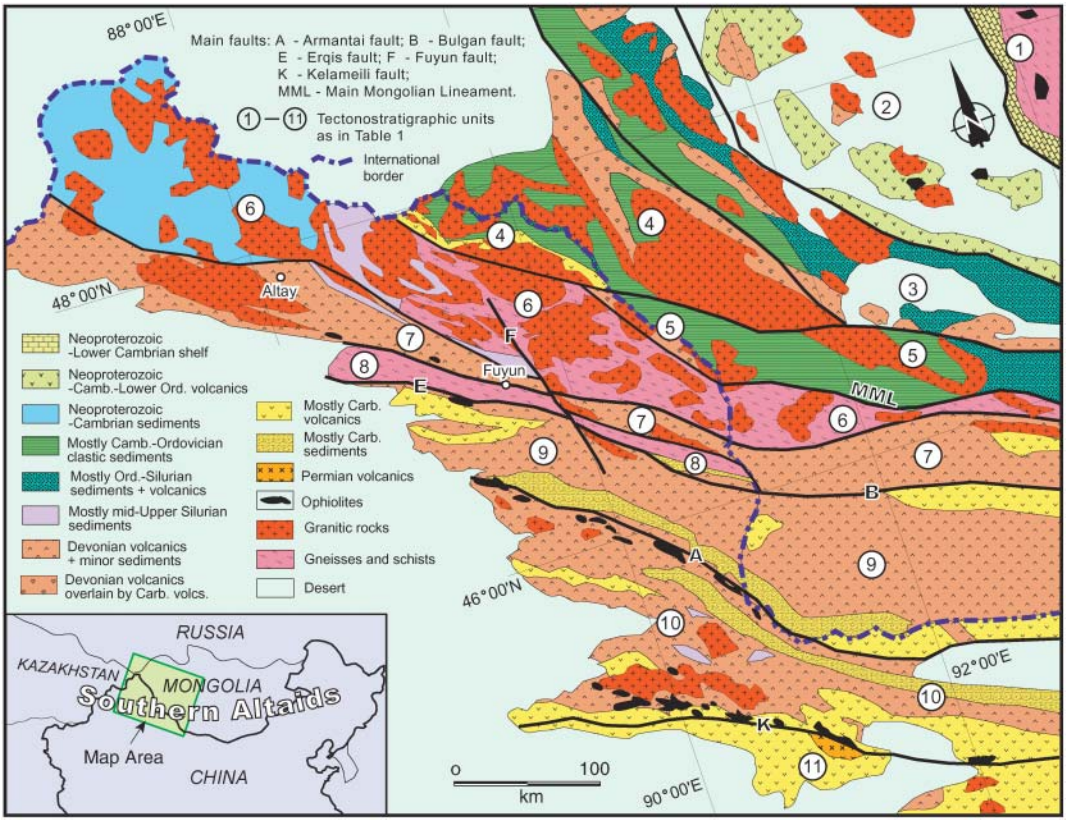

Fig. 1. Tectonic map of the southern Altaids that crosses the Chinese–Mongolian border showing main tectonostratigraphic units (modified after Badarch *et al*. 2002, Windley *et al*. 2002 and our own data). Inset is a map showing the tectonic position of the southern Altaids.

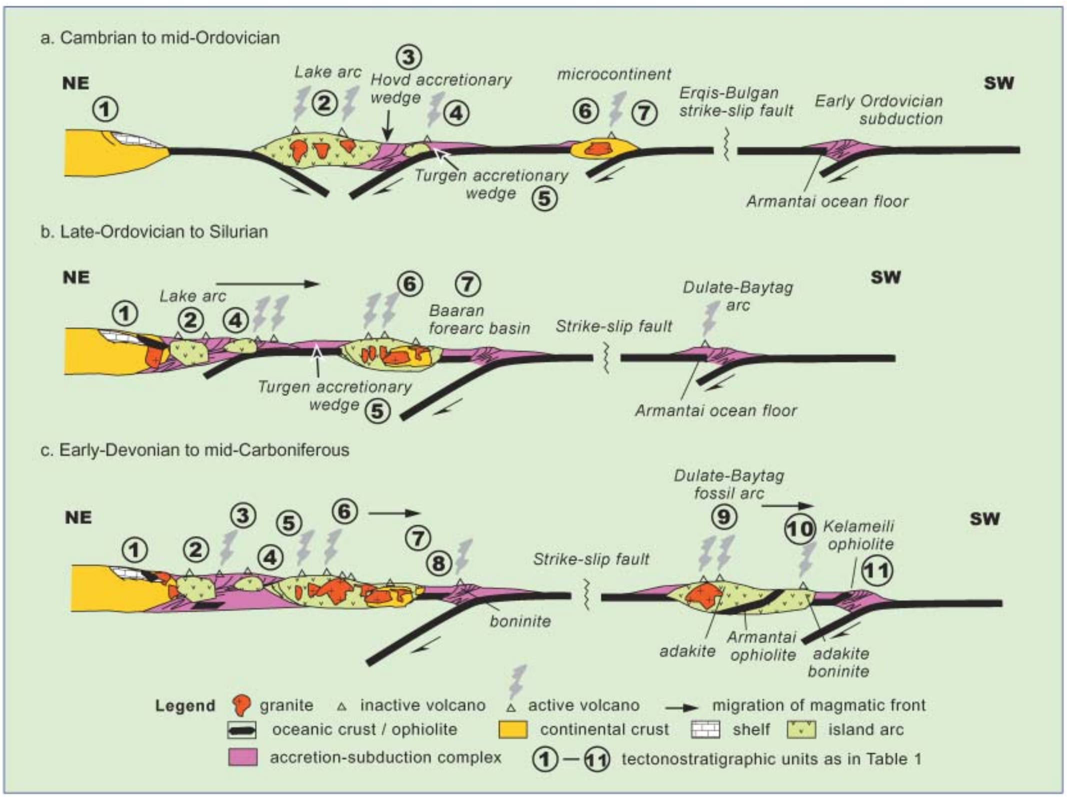

Fig. 2. Schematic sections demonstrating the tectonic evolution of the southern Altaids. (**a**) Cambrian to mid-Ordovician; (**b**) late Ordovician to Silurian; (**c**) early Devonian to mid-Carboniferous. The cross-sectional directions are present-day coordinates.

Table 1. *Characteristic rock assemblages and structures of the 11 tectonostratigraphic units in the Chinese and Mongolian Altay with their correlations and interpretations of tectonic environment and evolution*

Unit	China	Mongolia	Interpretation
1		**ZAVHAN**: Microcontinent of gneisses & schists (1868 Ma Pb–Pb zircon). Ophiolites on continental margin. Neoprot.–early Camb. shelf containing lst. with phosphate beds, sst., shale, cong. & diamictite.	Precambrian craton overlain by obducted ophiolites and bordered by shelf sediments with Neoproterozoic glacial deposits.
2		**LAKE**: 573–522 Ma ophiolites. Camb.–early Ord. calc-alkaline lavas, tuffs, volcaniclastics, lst. with archeachyathes & trilobites, granodiorites, granites.	Subduction of ocean floor led to Cambrian–early Ordovician island arc.
3		**HOVD**: Camb. sst., silt., phyllite, tuff. Ord. cong., sst., shale. Sil. basalt, sst., shale, tuff, ophiolite relics; all in melanges & blocks. S-vergent thrusts. Granodiorite plutons.	Evolving accretionary wedge with Cambrian, Ordovician, Silurian debris.
4	**ALTAISHAN**: Mid–late Dev. andesites, dacites. Late Dev. to early Carb. shale, silt., greywacke, sst., lst., andesite,. Mainly Carb. granites	**ALTAY**: Camb.–Ord. inter–mafic volcanics & volcaniclastics, & marine clastics intruded by calc-alkaline diorites & granodiorites. Sil.–Dev.–early Carb. volcanics & shallow marine seds. Late Dev. to Permian granites.	Camb.–Ord. arc and clastic basin succeeded by Silurian to early Carboniferous arc volcanism and forearc basins.
5	**NO NAME**: Mid–late Devonian andesite overlain by early Carb. dacite, rhyolite. Carb. granites.	**TURGEN**: Camb. turbidite, Ord.–Dev. sst., silt., phyllite, minor basalt, andesite, lst., all in melanges and blocks. S-vergent thrusts. Dev.–Carb. granites.	Dev. accretionary wedge containing older debris and overlain by a minor Dev.–early Carb. arc.
6	**HALONG**: Mostly gneisses & schists. In W. low-grade Neoprot.–Camb. seds. In E. Neoprot. microplants, 920–614 Ma zircon xenocrysts in mid-Camb. felsic lava. Mid-Ord. to Sil. turbidite. Late Dev. crustal melt granites & regional metamorphism.	**TSEEL**: Gneiss, migmatite, amphibolite, schist, granulite, 2200 Ma zircons. Mid-Devonian granitic plutons.	Precambrian microcontinent. Cambrian Andean-type arc on its southern side. Ordovician–Silurian back-arc? clastics. Late Devonian collision with arc to S., metamorphism, crustal melting.
7	**ABAGONG**: Late Sil.–early Dev. calc-alkaline lavas and pyroclastics overlain by mid-Dev. turbidite. Permian post-orogenic granites.	**BAARAN**: Greenschist-grade Dev. sst., silt., chert, tuff, lst, gabbro, and early Carb. sst., silt., trachyandesite, tuff, chert, lst. Thrust sheets. Carb. granites, granosyenites & picrite intrusions.	Late Silurian–early Dev. island arc passing into mid-Devonian–early Carb. fore-arc basins. Accretion to unit 6 in the late Devonian.
8	**ERQIS**: Proterozoic gneisses. Ord.–Sil. basalts, andesites, boninites, Sil.–Dev. turbidites. Thrusted late Carb. clastic basin. Permian granites.		Narrow sliver on N. side of Erqis fault. Remnant Precambrian gneisses, Ord.–Sil. arc, Sil.–Dev. forearc basin. Thrusted Carb. foreland basin.
9.	**DULATE**: Dev. felsic–inter. lavas, tuffs, calc-alkaline granites, shale, sst., cong., lst. Early–Dev. adakite, mid-Dev. boninite. Early Carb. andesite & clastic seds. Permian A-type granites.	**BAYTAG**: Early Dev. calc-alkaline lavas & tuffs. Mid–Upper Dev. sst., silt., chert, lst. Early Carb. lst, mudstone. Late Carb. granites and granosyenites.	Major Devonian island arc with boninites and sediments in the forearc, minor early Carboniferous mature island arc.
10	**YEMAQUAN**: Early Ord. ophiolite on Armantai fault. Early to late Dev. andesite, trachyandesite, basalt, trachybasalt, basanite, Carb. volcanics, granitic plutons. Dev. ophiolite on Kelameili fault.		Many remnants of ocean floor preserved on both sides of this major Devonian mature island arc.
11	**JIANGJUN**: Minor Dev. andesite, boninite, adakite. Major mid-Carb. andesite, trachyandesite. Minor Permian andesite, dacite, & rhyolite.		A progressive accretion of Devonian, Carboniferous and Permian island arcs with evolved chemistry.

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.

Units 9, 10 and 11 are mature Devonian to Permian island arcs (Li 1995) with progressively evolved chemistry, the youngest being furthest south. Notable in units 9 and 11 are boninites suggestive of forearc environments (Wang *et al*. 2003*b*; Liu *et al*. 1993). On the Armantai fault an ophiolite (Sm–Nd isochron age of 479 ± 27 Ma) is associated with arc-related adakites, and on the Kelameili fault an ophiolite contains early to mid-Devonian radiolaria (Wang *et al*. 2003*b*).

A new model for the southern Altaids. All these disparate tectonic units are separated by steep faults along which mylonitic fabrics commonly indicate strike-slip and multiphase motion. All thrusting took place during subduction–accretion or oblique strike-slip (Sengör & Natal'in 1996). Overall, most units developed by subduction-related processes and accreted in a southward (present coordinates) direction from the Cambrian to the Permian. This unidirectional growth of the orogen is confirmed by orogenic gold deposits in the Chinese Altay which young progressively to the south (Rui *et al*. 2002). Precambrian unit 1 acted as a northerly back-stop to the accretion, unit 6 is a Precambrian microcontinent that docked northwards into the accreting collage, and unit 8 contains a Precambrian remnant that is either another microcontinent or is an old crustal fragment of unknown origin on the Erqis fault.

From the above data and observations we propose that the southern Altaid orogen was generated by the following tectonic processes from north to south and with time, illustrated in Figure 2. On the margin of the Zavhan Precambrian back-stop a carbonate shelf formed in the Neoproterozoic to early Cambrian probably within 30° of the palaeo-equator (Briden & Irving 1964), and glacial diamictites were deposited during the snowball earth (Hoffman *et al*. 1998). Lack of an arc in the Zavhan microcontinent requires that south-directed subduction generated the Cambrian–early Ordovician Lake arc (unit 2) to the south, caused it to collide with the shelf, and was responsible for the obduction of ophiolites northwards onto the margin of the Zavhan microcontinent. A north-dipping subduction zone started on the southern side of the Lake arc in the Cambrian and continued to the Silurian, as indicated by the Hovd accretionary wedge. The double subduction under the Lake arc may explain its anomalous width of nearly 200 km in its present shortened state. Meanwhile in the early Palaeozoic within the ocean to the south subduction gave rise to the Cambrian island arc of unit 4, the Precambrian microcontinent of unit 6 was drifting and a Cambrian Andean-type arc was generated on its southern side, and early Ordovician oceanic crust (the Armantai ophiolite) was generated with a contemporaneous adakite-bearing arc. Semi-continuous subduction caused the arc of unit 4 to be overprinted by arcs from the Silurian to the early Carboniferous. This subduction also gave rise to the coeval accretionary wedge of unit 5. Unit 6 accreted to unit 4 arc and unit 5 accretionary wedge probably by the Ordovician, and the late Silurian to early Devonian island arc of unit 7 collided into unit 6 in the late Devonian causing thrust–nappe tectonics, inverted isograd metamorphism (Windley *et al*. 2002), and voluminous crustal granites in the microcontinent (Jahn *et al*. 2000). Erqis unit 8 contains Proterozoic gneisses imbricated with Ordovician–Silurian island arcs. A foreland basin was thrusted on the Erqis unit. The Erqis–Bulgan fault marks a major boundary between the accretionary processes to its north and south.

South of that fault island arcs grew in Dulate–Baytag unit 9 and Yemaquan unit 10 in the Devonian–early Carboniferous and Devonian respectively. The former generated forearc boninites and was probably accreted by the late Carboniferous. The latter evolved further to produce trachyandesites and basanites and during accretion was imbricated with early Ordovician ophiolites on its northern flank, and with Devonian ophiolites on its southern margin. Unit 11 Jiangjun island arc started growth in the Devonian, evolved largely in the Devonian, and continued to the Permian, when the late Palaeozoic ocean was finally consumed (Carroll *et al*. 1990).

Our model for the southern Altaid orogen supports the general concept of long-lived subduction and growth by roll-back forearc accretion of Sengör & Natal'in (1996) based on the forearc accretionary part of Japanese orogenesis. However, several old (Proterozoic) and young (oceanic) units also accreted from the ocean to the growing Altaid orogen, thus the evolutionary process was more complicated than that envisaged by the above authors. It is known today that Japan has grown not only by forearc accretion, but also by collision and incorporation of terrane-type oceanic plateaus, seamounts and ridge-subducted oceanic crust derived from the Pacific Ocean (Isozaki 1997). Likewise, the Altaid orogen can only be explained by a combination of accretionary and convergent (collisional) processes as in palaeo-Japan, and under operation today in the Indonesian archipelago (Xiao *et al*. 2001). Further stratigraphic–structural–metamorphic data integrated with isotopic and palaeontological constraints are required to refine understanding of the accretionary processes in this classic orogen.

We appreciate critical reviews by A. Kröner, R. England and R. G. Coleman, and funding by the China 973 Programme (2001CB409801) and NSFC (40172080).

References

Badarch, G., Cunningham, W.D. & Windley, B.F. 2002. A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia. *Journal of Asian Earth Sciences*, **21**, 87–110.

Berzin, N.A., Coleman, R.G., Dobretsov, N.L., Zonenshain, L.P., Xiao, X. & Chang, E.Z. 1994. Geodynamic map of the western part of the Paleoasian ocean. *Russian Geology and Geophysics*, **35**(7–8), 5–22.

Briden, J.C. & Irving, E. 1964. Palaeolatitude spectra of sedimentary palaeoclimatic indicators. *In:* Nairn, A.E.M. (ed.) *Problems in Palaeoclimatology.* Wiley, New York, 199–224.

Carroll, A.R., Liang, Y., Graham, S.A., Xiao, X., Hendrix, M.S., Chu, J. & McKnight, C.L. 1990. Junggar basin, northwestern China: trapped Late Paleozoic ocean. *Tectonophysics*, **181**, 1–14.

Coleman, R. 1989. Continental growth of Northwest China. *Tectonics*, **8**, 621–635.

Dobretsov, N.L., Berzin, N.A. & Buslov, M.M. 1995. Opening and the tectonic evolution of Paleo-Asian ocean. *International Geology Review*, **35**, 335–360.

Heubeck, C. 2001. Assembly of central Asia during the middle and late Paleozoic. *In:* Hendrix, M.S. & Davis, G.A. (eds) *Paleozoic and Mesozoic Tectonic Evolution of Central and Eastern Asia*. Geological Society of America Memoirs, **194**, 1–22.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P. & Schrag, D.P. 1998. A Neoproterozoic snowball earth. *Science*, **281**, 1342–1346.

Isozaki, Y. 1997. Contrasting two types of orogen in Permo-Triassic Japan: accretionary versus collisional. *The Island Arc*, **6**, 2–24.

Jahn, B-M., Wu, F. & Chen, B. 2000. Granitoids of the Central Asian orogen and continental growth in the Phanerozoic. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **91**, 181–193.

Laurent-Charvet, S., Charvet, J., Monié, P. & Shu, L. 2003. Late Paleozoic strike-slip shear zones in eastern central Asia (NW China): new structural and geochronological data. *Tectonics*, **22**, doi 10.1029/2001TC901047.

Li, J. 1995. Main characteristics and emplacement processes of the East Junggar ophiolites, Xinjiang, China. *Acta Petrologica Sinca*, **11**, 73–84.

Liu, D., Tang, Y. & Zhou, R. 1993. The Devonian intra-oceanic arc and boninite in the North Junggar, Xinjiang. *Xinjiang Geology*, **11**, 1–12.

Mossakovsky, A.A., Ruzhentsov, S.V., Samygin, S.G. & Kheraskova, T.N. 1994. The Central Asian fold belt: geodynamic evolution and formation history. *Geotectonics*, **26**, 455–473.

Niu, H., Xu, J., Yu, X., Chen, F. & Zheng, Z. 1999. Discovery of the Mg-rich volcanics in Altay, Xinjiang, and its geological implications. *Chinese Science Bulletin*, **44**, 1685–1688.

Qin, K.Z., Sun, S., LI, J.L., Fang, T.H., Wang, S.L. & Liu, W. 2002. Paleozoic epithermal Au and Cu deposits in North Xinjiang, China: epochs, features, tectonic linkage and exploration significances. *Resource Geology*, **52**, 291–300.

Qu, G. & Chong, M. 1991. Lead isotope geology and its tectonic implications in the Altaids. *China Geoscience*, **5**, 100–110.

Rui, Z., Goldfarb, R., Qiu, Y., Zhou, T., Chen, R., Pirajno, F. & Yun, G. 2002. Paleozoic–early Mesozoic gold deposits of the Xinjiang Autonomous Region, northwestern China. *Mineralium Deposita*, **37**, 393–418.

Sengör, A.M.C., Natal'in, B.A. & Burtman, V.S. 1993. Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia. *Nature*, **364**, 209–304.

Sengör, A.M.C. & Natal'in, B. 1996. Turkic-type orogeny and its role in the making of the continental crust. *Annual Reviews of Earth and Planetary Sciences*, **24**, 263–337.

Wang, Y., Mooney, W.D., Yuan, X. & Coleman, R.G. 2003*a*. The crustal structure from the Altai mountains to the Altyn Tagh fault, northwest China. *Journal of Geophysical Research*, **108B**, doi 10.1029/2001JB000552.

Wang, Z., Sun, S., Li, J., Hou, Q., Qin, K., Xiao, W. & Hao, J. 2003*b*. Paleozoic tectonic evolution of northern Xinjiang, China: geochemical and geochronological constraints from the ophiolites. *Tectonics*, **22**, doi 10.1029/2002TC001396.

Windley, B.F., Kröner, A., Guo, J., Qu, G., Li, Y. & Zhang, C. 2002. Neoproterozoic to Paleozoic geology of the Altai orogen, NW China: New zircon age data and tectonic evolution. *Journal of Geology*, **110**, 719–739.

Xiao, W., Sun, S., Li, J. & Chen, H. 2001. South China archipelago orogenesis. *In:* Briegel, U. & Xiao, W.J. (eds) *Paradoxes in Geology.* Elsevier, Amsterdam, 15–37.

Xiao, X., Tang, Y., Feng, Y., Zhu, B., Li, J. & Zhao, M. 1992. *Tectonic Evolution of Northern Xinjiang and its Adjacent Regions*. Geological Publishing House, Beijing.

Yu, X., Niu, H., Xu, J., Chen, F. & Zheng, Z. 2000. *On the Fluid System of the Paleozoic Volcano-Sedimentary Basins and Associated Mineralisation*. Chinese National 305 Project, Urumqi, Xinjiang, China, **305**.

Zhang, B., Sui, J., Li, Z., Liu, W., Yang, X. & Liu, S. 1996. *Tectonic Evolution of the Erqis Belt and Its Mineral Deposit Series*. Science in China Press, Beijing.

Received 28 October 2003; revised typescript accepted 6 January 2004.
Scientific editing by Richard England