Neoproterozoic to Paleozoic Geology of the Altai Orogen, NW China: New Zircon Age Data and Tectonic Evolution

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ABSTRACT

We present a synthesis and a new account of the geological and tectonic history of the terranes of the Chinese Paleozoic Altai orogen together with new, single zircon ages for granitic and rhyodacitic rocks. A central terrane consists of Neoproterozoic to Silurian, amphibolite facies, metasedimentary rocks, and abundant Devonian-Carboniferous granites. The presence of Precambrian basement is indicated by Sinian fossils, our xenocryst ages, and published Nd mean crustal residence ages of granites. Felsic arc-type lavas on the southern margin of the terrane have a mean $^{207}Pb/^{206}Pb$ zircon age of 505 Ma, reflecting the time of arc volcanism, and the presence of xenocysts with ages between 614 and 921 Ma suggests derivation by intracrustal melting. Accordingly, we suggest that a Cambro-Ordovician continental magmatic arc was built on the southern margin of the central terrane by northward subduction. A low-grade Ordovician Andean-type arc with a continental basement is situated above a normal fault on the northern side of the central terrane, and a low-grade Late Silurian to Early Devonian island arc on its southern side is succeeded southward by a terrane with Proterozoic basement overlain by Devonian to Carboniferous basins. During continent-arc collision high-grade gneisses of the central terrane were thrust southward over the Late Silurian to Early Devonian island arc with formation of inverted, Barrovian-type metamorphic isograds. The collisional processes caused exhumation of the high-grade central terrane and consequent emplacement of abundant granites derived by mixed arc-crust melting. This new model has major implications for the crustal and tectonic evolution of the Altaids.

Introduction

In contrast to orogens like the Himalayas that formed as a result of the collision between two continental blocks, some, like the Central Asian mobile belt (Mossakovsky et al. 1993) or Altaid collage of Central Asia (Sengör et al. 1993), formed by a continuous, long-lived process of subduction accretion (Rotarash et al. 1982; Coleman 1989). The Altaids extend from the Urals to the Pacific Ocean and from the Tianshan to the Aldan Shield. Other subduction-accretion orogens include Japan, the Cordillera of North America, and the Neoproterozoic Arabian-Nubian Shield (Windley 1995). Although it is clear that such orogens form by the accretion of different types of allochthonous fragments such as island arcs, ophiolites, accretionary prisms, seamounts, oceanic plateaus, and continental blocks, their mechanisms of formation are poorly understood. For example, Sengör et al. (1993) and Sengör and Natal'in (1996) based their tectonic interpretation of the Altaids on the single-subduction-zone, accretionary model of Japan. However, this interpretation was challenged by the accretion-collision, multiple subduction zone model for Japan of Charvet et al. (1990). Isozaki (1996) and Maruyama (1997) contrasted the Miyashiro-type orogen of Japan that depended on the episodic culmination of ridge subduction from the Cordilleran-type orogen that formed as a result of a steady state, long-term process related to subduction of normal oceanic floor.

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The Altai is one of the major orogens of Central Asia and is the type region of the Altaids. It extends for about 2500 km from Russia and East Kazakhstan, through Northern Xinjiang of China (Xiao et al. 1992) to southwestern and southern Mongolia, and it is situated between the Sayan and associated belts to the north (Zorin et al. 1993; Federovskii et al. 1995) and the Junggar belt to the south (Zhang et al. 1993). However, the Altaids is one of the least known Phanerozoic orogens in the world. Most publications are in the Russian and Chinese languages, but most are brief, and very few parts of the orogen are described in English. The aim of this article is to present a much-needed account in the English language of the geology of the Chinese segment of the Altai orogen, our new single zircon ages, and a new model to explain the tectonic evolution of the Altai. Chen and Jahn (in press) present many new geochemical and isotopic data on the sedimentary and granitic rocks of the Altai, which complement our data and which have major implications for the continental growth of Central Asia (see also Jahn et al. 2000*a*, 2000*b*). The metallogenesis of the Altai was reviewed by Wang et al. (2000).

Analytical Procedures

Zircons were separated from samples of approximately 5-kg weight using standard techniques of density and magnetic separation described in Kröner et al. (1999*a*). Single grains were then handpicked under a microscope and analyzed by the evaporation method (Kober 1986, 1987) using a technique detailed in Kröner and Hegner (1998).

During the course of this study, we have repeatedly analyzed fractions of large zircon grains from the Palabora Complex, South Africa, our internal standard. These zircons are completely homogeneous when examined under cathodoluminescence. Conventional U-Pb analyses of six separate grain fractions from this sample yielded a ^{207}Pb/^{206}Pb age of 2052 ± 1 Ma (2σ) (W. Todt, unpub. data), whereas the mean ^{207}Pb/^{206}Pb ratio for 18 grains, evaporated individually over a period of 12 months, is 0.126634 ± 0.000027 (2σ error of the population), corresponding to an age of 2052 Ma, which is identical to the U-Pb age. The above error is considered the best estimate for the reproducibility of our evaporation data. In the case of pooled analyses, the 2σ (mean) error may become very low, and whenever this error was less than the reproducibility of the internal standard, we have used the latter value, i.e., an assumed 2σ error of 0.000027.

Since the evaporation technique only provides Pb isotopic ratios, there is no a priori way to determine whether a measured ^{207}Pb/^{206}Pb ratio reflects a concordant age. Thus, principally, all ^{207}Pb/^{206}Pb ages determined by this method are necessarily minimum ages. However, it has been shown in many studies that there is a very strong likelihood that these data represent true zircon crystallization ages when (1) the ^{207}Pb/^{206}Pb ratio does not change with increasing temperature of evaporation and/or (2) repeated analysis of grains from the same sample at high evaporation temperatures yields the same isotopic ratios within error. The rationale behind this is that it is highly unlikely that each grain in a zircon population has lost exactly the same amount of Pb and that grains with Pb-loss appreciably before the present would therefore yield highly variable ^{207}Pb/^{206}Pb ratios and ages. Comparative studies by single-grain evaporation, conventional U-Pb dating, and ion-microprobe analysis have shown this to be correct (e.g., Cocherie et al. 1992; Jaeckel et al. 1997; Karabinos 1997; Kröner et al. 1999, 2000). The analytical data are shown in table 1 and are plotted in the histograms of figure 2.

Terranes and Major Faults

The main period of evolution of the orogen was between the Neoproterozoic and the late Paleozoic. In the late Cenozoic, there was compression and uplift giving rise to the current mountain range. We divide the orogen into five fault-bound terranes (fig. 1) that have mutually different stratigraphy, metamorphism, deformation patterns, and age relations (He et al. 1990; Qu 1991). The geological history of the terranes is sufficiently different to warrant separation for descriptive purposes and tectonic interpretation. For each terrane, we give its geological makeup, and where appropriate, we give our new zircon age data and our interpretation of the geological evolution. Much of the following information comes from He et al. (1990), Qu (1991), and Zhuang (1993). The terranes are described from north to south.

Altaishan Terrane 1. This terrane consists largely of Late Devonian to Early Carboniferous metasediments. The oldest rocks are greenschist facies, weakly deformed Middle to Late Devonian andesites and dacites that host gold mineralization in quartz veins. These rocks are overlain conformably by thick metagreywackes and metasandstones, carbon-rich cherts, cordierite slates, and sericite-chlorite-quartz schists. Conformably on these rocks rest Late Devonian to Early Carboniferous

Table 1. Pb Isotopic Data from Single-Grain Zircon Evaporation

Grain and sample numbers	Mass scans[a]	Evaporation temperature (°C)	Mean $^{207}Pb/^{206}Pb$ ratio and 2-σm error[b]	$^{207}Pb/^{206}Pb$ age and 2-σm error
A5 (granite):				
1	77	1599	.054209 ± 27	379.8 ± 1.1
2	99	1603	.054198 ± 21	379.3 ± .9
3	99	1601	.054232 ± 14	380.7 ± .6
4	99	1599	.054218 ± 13	380.2 ± .5
5	121	1600	.054228 ± 12	380.6 ± .5
Mean of 5 grains (1–5)	495		.054218 ± 8	380 ± 1[c]
A50 (granitic orthogneiss):				
1	66	1599	.055061 ± 31	414.7 ± 1.3
2	88	1600	.055078 ± 25	415.4 ± 1.0
3	132	1602	.055058 ± 13	414.6 ± .5
4	99	1598	.055066 ± 20	414.9 ± .8
Mean of 4 grains (1–4)	385		.055065 ± 10	415 ± 1[c]
5[d]	44	1600	.061605 ± 54	660.4 ± 1.9
6[d]	55	1598	.063512 ± 46	725.4 ± 1.5
A117 (rhyodacite):				
1	132	1598	.057356 ± 48	505.2 ± 1.9
2	88	1599	.057358 ± 61	505.3 ± 2.4
Mean of 2 grains (1 and 2)	220	1598	.057357 ± 38	505 ± 2[c]
3[e]	66	1598	.060302 ± 65	614.4 ± 2.3
4[e]	66	1598	.061883 ± 43	670.1 ± 1.5
5[e]	88	1600	.069743 ± 78	920.8 ± 2.3
A118 (tonalitic gneiss):				
1	88	1598	.054989 ± 36	411.8 ± 1.5
2	110	1601	.054997 ± 31	412.1 ± 1.2
3	110	1602	.054969 ± 18	411.0 ± .7
4	154	1600	.054974 ± 9	411.2 ± .4
5	88	1606	.054954 ± 23	410.4 ± .9
Mean of 5 grains (1–5)	550		.054977 ± 10	411 ± 1[c]
6[f]	88	1601	.062974 ± 49	707.4 ± 1.6

Note. Zircon color and morphology of grains are as follows: A5 (grains 1–5), clear to yellow brown, long prismatic, idiomorphic to slightly rounded terminations; A50 (grains 1–4), clear to light yellow brown, long prismatic, idiomorphic; A117 (grains 1 and 2), light to dark brown, stubby, idiomorphic; A118, short and long prismatic, ends slightly rounded, clear.
[a] Number of $^{207}Pb/^{206}Pb$ ratios evaluated for age assessment.
[b] Observed mean ratio corrected for nonradiogenic Pb where necessary. Errors based on uncertainties in counting statistics.
[c] Error based on reproducibility of internal standard.
[d] As grains 1–4, slightly rounded ends.
[e] Dark olive brown, stubby, ends little rounded.
[f] Long, clear, idiomorphic.

metasediments of the Kumasu Group (750 m thick), the lower part of which is termed the "Mangdaiqia subgroup," that contain shales, siltstones, greywackes, minor silicic shales, and, at the top, lenses of limestone containing *Barrandeophyllum* sp., *Eopteria* ? sp., *Lunulacardium* ? sp., and *Cyclocyclicus* ? sp.

In faulted contact with the Kumasu Group is the lower Carboniferous 700-m-thick Hongshanzui Formation, which has the following stratigraphy:

Upper: sandstone, slate, thin limestone (*Fenestella* ? sp., *Cyclocyclicus* sp.)

Middle: limestone, thin porphyritic andesite and quartz albite porphyry

Lower: intermediate-acidic volcanics, limestones (*Striatifera* sp., *Linoproductus* sp., *Dictyoclostus* sp., *Spirifer* sp., *Syrongopora* cf. *ramulosa* Gold)

These rocks were intruded by biotite granite plutons that are undeformed.

This terrane contains the remains of two island arcs of mid-late Devonian and Early Carboniferous age. The sedimentary rocks of terrane 1 were deposited conformably on the island arcs; they were probably laid down on the flanks of volcanoes. An orogenic epithermal Au deposit occurs at Aketishikan (fig. 1).

NW Altaishan Terrane 2. This terrane contains sedimentary and volcanic rocks that range in age from Neoproterozoic (Sinian) to Early Devonian. It consists predominantly of the Habahe Group (Sinian to Middle Ordovician), which has the following continuous sedimentary sequence:

Upper: 2000 m metasandstone, -siltstone, -shale; marble and chert lenses

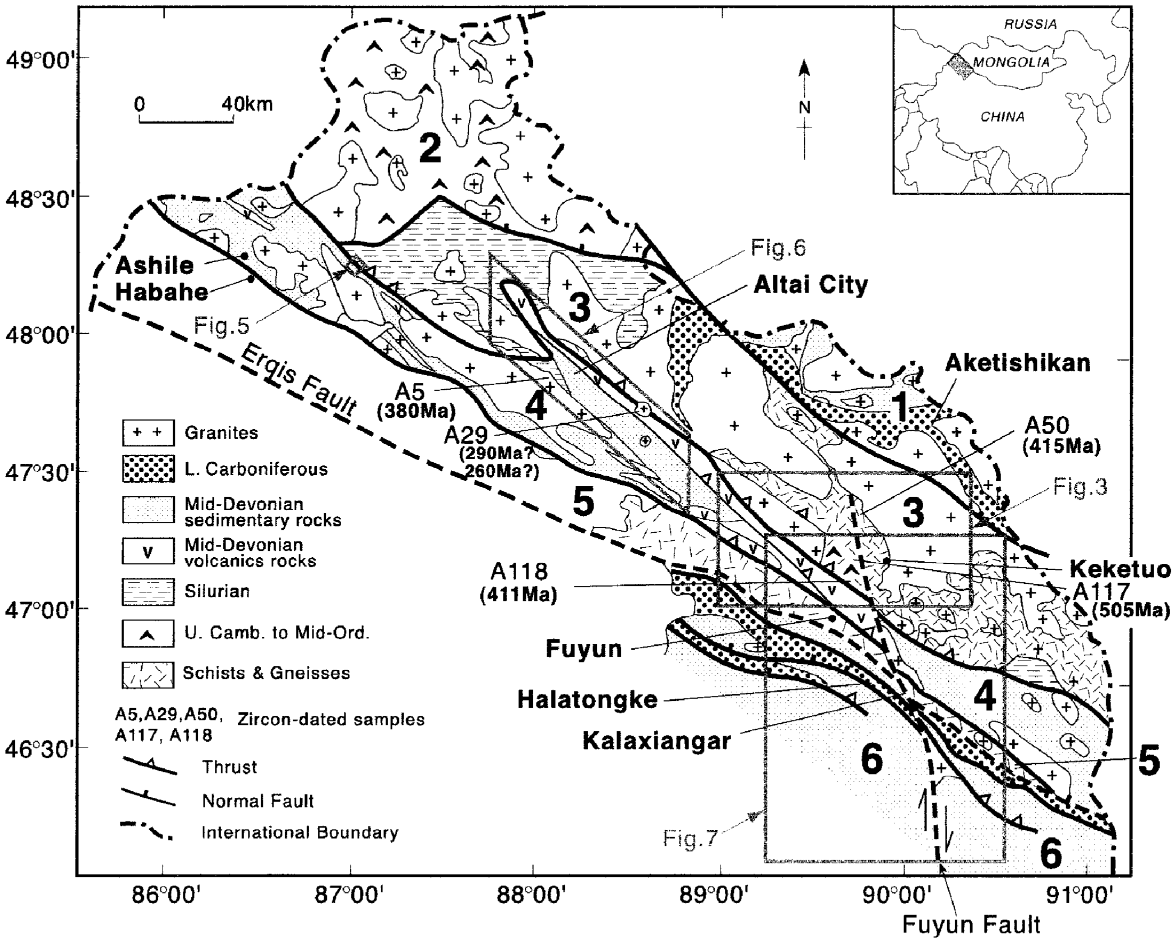


Figure 1. Geological map of the Chinese Altai showing main terranes referred to by number in the text. Positions of figures 3, 5, 6, and 7 are marked.

Middle: 2000 m schist, minor metasandstone and -siltstone
Lower: 1500–2000 m metasandstone, -siltstone; thin schists

The Habahe Group consists largely of continental-derived quartzo-feldspathic clastic turbidites. Marine rhythmic turbiditic beds typically 10–30 cm thick are prominent throughout. Micropaleoflora are common (Yan et al. 1989). Rocks of the Habahe Group have been isoclinally folded with steep axial planes and metamorphosed to low greenschist facies. Biotite- and biotite-muscovite granites are common. The following mineral assemblages are typical in the schists:

Chlorite-sericite-quartz ± epidote
Chlorite-epidote-albite ± actinolite
Chlorite-sericite-biotite

Middle Ordovician fossiliferous sediments of the Habahe Group are overlain unconformably by Late Ordovician sediments and volcanics of the Baihaba Formation. For this reason, the age of the metamorphism is estimated to be end-Ordovician, although no isotopic ages are available. The Baihaba Formation, which has a limited distribution, has the following stratigraphy:

Upper: 800 m shale, limestone
Lower: 1150 m tuff, albite and plagioclase porphyry, chert, andesite, andesitic agglomerate, andesitic breccia

The limestones in the upper sediments contain the following Late Ordovician fossils: *Plasmoporella* sp., *Propora* sp., *Palaeophyllum* sp., and *Madiolopsis* sp. The whole Baihaba Formation is only weakly deformed into open synclines. The intermediate volcanic and volcaniclastic rocks of the Lower Baihaba Formation, together with associated tonalite, granodiorite, and hornblende-granite plutons, constitutes an andesitic arc of Late Ordovician age. Because the arc developed on top of a major clastic basin, we interpret it as a continental magmatic arc. We suggest that the Upper Baihaba Formation of well-bedded sediments was deposited on the volcanic rocks in a fore-arc environment.

In a small area (ca. 40 × 10 km), unfossiliferous rocks of presumed Early Devonian age with a thickness of 2300 m contain sandstone, quartz porphyry, quartz albite porphyry, and tuff that rest unconformably on the Habahe Formation. These sedimentary and volcanic rocks most likely represent a late minor development of arc magmatism.

The granites in terrane 2 are largely undated. One granite (Hanas) has a Sm/Nd isochron age of 390 Ma (Zhao et al. 1993). It has I_{Sr} of 0.7092 and 0.7134 and mean crustal residence ages of 1.36 and 1.57 Ga, respectively, reflecting a major source from old continental crust, which is present in this terrane (Chen and Jahn, in press).

Central Altaishan Terrane 3. This terrane forms the central part of the Altai orogen in China. It contains widespread high-grade metamorphic rocks and abundant granites, some Neoproterozoic to Silurian metasediments but no island arcs.

Its northern boundary is well defined in the northeast by the steep, north-dipping Tuergen normal fault, which has placed low-grade rocks of terrane 1 against high-grade rocks of terrane 3 (fig. 1). In the western Altai, this boundary is poorly defined because of similarity of rock types on either side, although they are higher grade on the southern side.

Although the rocks in terrane 3 have been commonly metamorphosed to high grade, there are sufficient, locally well-preserved, fossiliferous sediments to indicate that the rocks mostly range in age from Neoproterozoic to Silurian. Just west of the Fuyun Fault there is a 10-km-wide belt of gneiss, migmatite, and relict quartzite and marble. In the marble, there are microplant fossils (*Plyoporota obsoleta*, *Lamnarites* sp., *Turuchania* sp., and *Trematosphaeridium* sp.), which are Neoproterozoic in age (He et al. 1990). These rocks belong to the Habahe Group, which also contains similar mid-Ordovician sediments and micropaleoflora as does this group in terrane 2 (Yan et al. 1989).

The Habahe Group is overlain by the fossiliferous Silurian Kulumutu Group, which has the following stratigraphy:

Upper: 2600 m metasandstone, -siltstone, phyllite, schist, gneiss

Lower: 5300 m mica-quartz-schist, migmatitic gneiss, minor metasandstone and -siltstone

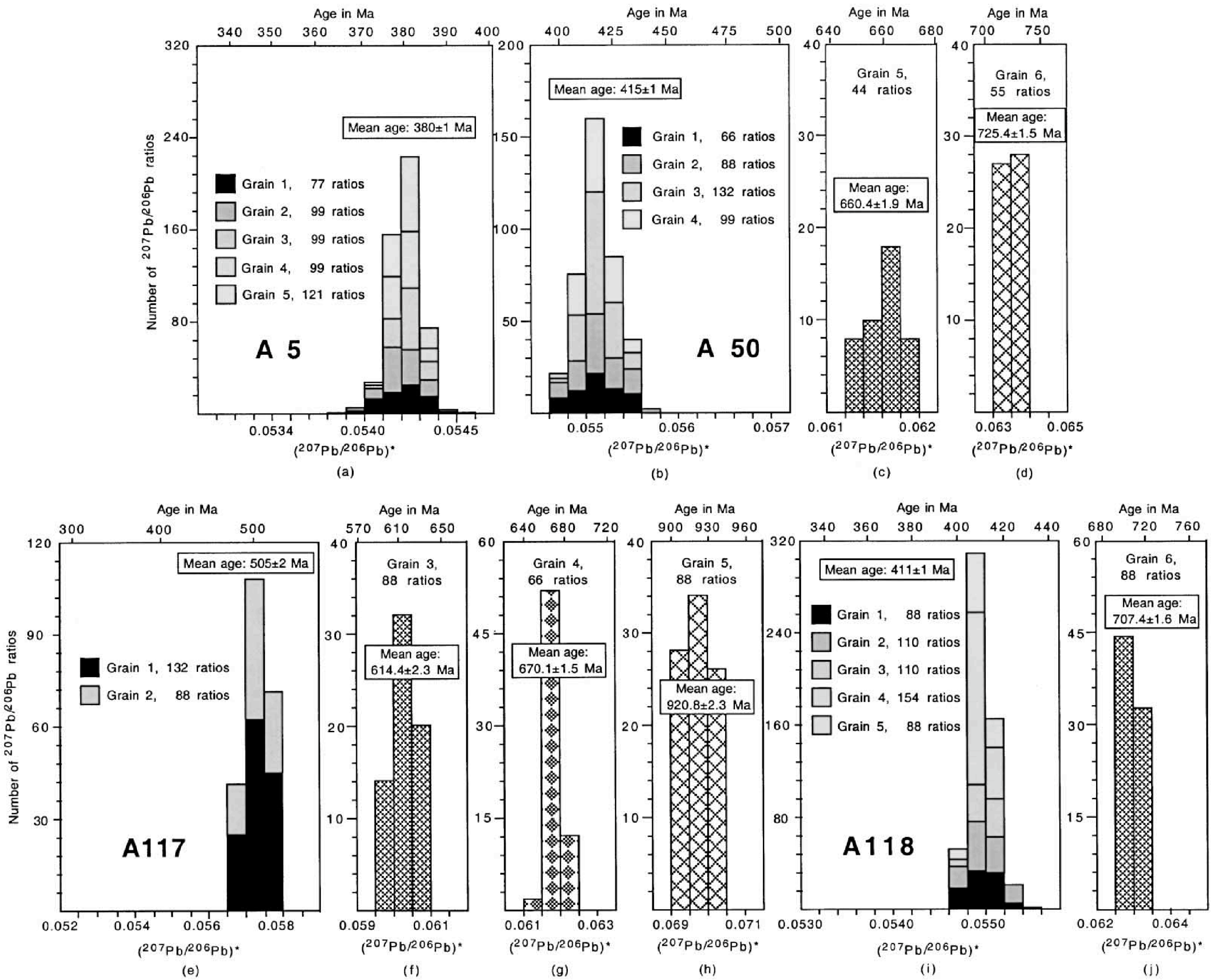
This group of turbiditic continental clastic rocks crops out extensively in the central Altai. However, regional metamorphism and associated deformation obscure many of the original stratigraphic relationships. The low-grade and the medium- to high-grade metamorphism have given rise to two major metamorphic belts of different baric type:

a) In the eastern Altai a low-pressure belt that extends from Keketuohai for about 80 km to the northwest contains the following metamorphic zones: chlorite-biotite-garnet-staurolite-andalusite-sillimanite-cordierite.

b) The west-central Altai, a higher pressure belt, extends NW-SE for about 50 km and contains the following zones of metamorphism: garnet-staurolite-kyanite-sillimanite.

Sample A50 is an orthogneiss collected from a small body within schists and gneisses about 2 km southwest of the main granite body of the region (fig. 1). The zircons are clear to light yellow brown and long prismatic, typical of magmatic growth. Most grains are idiomorphic, but some have slightly rounded terminations. Four grains of the idiomorphic type were evaporated separately and yielded identical $^{207}Pb/^{206}Pb$ ratios that combine to a mean age of 415 ± 1 Ma (table 1; fig. 2*b*). We interpret this to reflect the emplacement age of the precursor of the gneiss. Two grains with rounded terminations produced significantly older $^{207}Pb/^{206}Pb$ ages of 660.4 ± 1.9 and 725.4 ± 1.5 Ma, respectively (table 1; fig. 2*c*, 2*d*), that are probably xenocrysts inherited from the source terrain from which the orthogneiss precursor was derived by intracrustal melting.

Sample A117 is a rhyodacite, collected from a sequence of felsic metavolcanic rocks along the road from Fuyun to Kekertouhai (figs. 1, 7). The zircons are light brown to dark brown in color, short prismatic, and mostly idiomorphic, with some grains showing slight to significant rounding at their terminations. Five grains were evaporated, of which two idiomorphic grains yielded identical $^{207}Pb/^{206}Pb$ ratios with a mean age of 505 ± 2 Ma, while three grains of the rounded population produced significantly different isotopic ratios that translate to ages of 614.4 ± 2.3, 670.1 ± 1.5, and 920.8 ± 2.3 Ma, respectively (table 1; fig. 2*e*–2*h*). We interpret the age of 505 Ma as reflecting the time of felsic arc volcanism, whereas the older zir-


A 5
Mean age: 380±1 Ma
Grain 1, 77 ratios
Grain 2, 99 ratios
Grain 3, 99 ratios
Grain 4, 99 ratios
Grain 5, 121 ratios
A 50
Mean age: 415±1 Ma
Grain 1, 66 ratios
Grain 2, 88 ratios
Grain 3, 132 ratios
Grain 4, 99 ratios
Grain 5, 44 ratios
Mean age: 660.4±1.9 Ma
Grain 6, 55 ratios
Mean age: 725.4±1.5 Ma
A117
Mean age: 505±2 Ma
Grain 1, 132 ratios
Grain 2, 88 ratios
Grain 3, 88 ratios
Mean age: 614.4±2.3 Ma
Grain 4, 66 ratios
Mean age: 670.1±1.5 Ma
Grain 5, 88 ratios
Mean age: 920.8±2.3 Ma
A118
Mean age: 411±1 Ma
Grain 1, 88 ratios
Grain 2, 110 ratios
Grain 3, 110 ratios
Grain 4, 154 ratios
Grain 5, 88 ratios
Grain 6, 88 ratios
Mean age: 707.4±1.6 Ma
Age in Ma
Number of 207Pb/206Pb ratios
(207Pb/206Pb)*
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)

cons are interpreted as xenocrysts derived from the source region from which the rhyodacite was derived by intracrustal melting. This suggests that a continental magmatic arc was built on the southern margin of terrane 3. The age of 920.8 Ma is within the tight range of 915–948 Ma reported by Hu et al. (2000) for Nd mean crustal residence ages of six amphibolites with "low" $^{147}Sm/^{144}Nd$ ratios (ca. 0.14). The samples come from the high-grade region of terrane 3 about 40 km ENE of Fuyun, and these authors considered the ages to represent the time of their protolith formation. Hu et al. (2000) quoted several earlier-published, older ages from terrane 3, but lack of precise location and of details of the isotope systematics prevent us from quoting them.

Sample A118 is a strongly foliated, almost mylonitic, tonalitic gneiss, a little migmatitic in places, that is tectonically interlayered with metasediments. Its location is marked on figure 1. The zircons are clear, short and long prismatic, with slightly rounded terminations, probably the result of metamorphic "corrosion" (Silver 1969; Kröner et al. 1994). Six grains were evaporated, of which five produced identical $^{207}Pb/^{206}Pb$ ratios with a mean age of 411 ± 1 Ma, while one identical grain has a much higher age of 707.4 ± 1.6 Ma (table 1; fig. 2*i*, 2*j*). Here again we interpret the younger age as reflecting the time of emplacement of the original tonalite, whereas the Neoproterozoic xenocryst age probably reflects a basement component of the continental arc.

A Rb-Sr whole rock isochron on metamorphic rocks of the Habahe Group yielded a Late Devonian age of 365 Ma (Zhuang 1993). We interpret this as the age of metamorphism that took place after deposition of the Kulumutu Group and which therefore affected the earlier Habahe Group.

Terrane 3 contains abundant biotite/two-mica granites often with garnet of mixed-arc/crust-melt origin (see later in Chen and Jahn, in press). In some regions such as near Keketuohai, the bulk of the surface area consists of such granites. According to Zou et al. (1988), 40% of the exposed rocks in the Altai mountains are granitic. The majority of granites in the west-central Altai in this terrane are foliated and occur in the belt of high-pressure metamorphism (kyanite), whereas most granites in the eastern Altai are undeformed and are in the belt of low-pressure metamorphism (andalusite-cordierite). The undeformed Keketuohai granite has a U-Pb zircon (SHRIMP) age of 387 ± 6 Ma by S. A. Wilde (unpub. data), a Sm-Nd age of 390 Ma by Chen and Jahn (in press), and Sm-Nd ages of 390 Ma and 330 Ma by Zhao et al. (1993). One foliated granite 40 km NW of Keketuohai has a Rb-Sr whole rock isochron age of 377 ± 18 Ma (Zou et al. 1988), and this granite has intruded rocks of the Silurian Kulumutu Group. Two more reliable, but poorly documented, U-Pb zircon dates and several whole rock Rb-Sr isochrons suggest that most granites have Late Devonian to Early Carboniferous ages. The Alaer (or Aral) granite has a Late Permian, whole rock Rb-Sr isochron age of 250.9 Ma (Liu 1990). This granite has been intensively studied by trace element modeling (Liu et al. 1997) and oxygen and hydrogen isotope systematics (Liu et al. 2000), indicating that the granite underwent composite mixing-fractional cystallization processes and two stages of isotopic exchange with aqueous fluids.

In the Keketuohai region, five major pegmatite fields are associated with garnet-bearing, posttectonic granites (Kremenetsky 1996) (fig. 3). They commonly occur in or near amphibolite bodies close to the granite contacts. Several of the larger pegmatites have been mined for muscovite, spodumene, beryl, and rare earth elements; the biggest near Keketuohai town (fig. 4; Wang et al. 1981) has the largest muscovite deposit in Asia, with prominent LiBeNbTa mineralization. The present inactive open quarry can still be visited to study the pegmatite and its mineralogy. This spectacular pegmatite is one of the largest in the world. It has the shape of a vertical pipe (2 × 1.5 km diameter), which at a depth of 0.5 km flattens out to a subhorizontal sheet that is at the contact of biotite-garnet granite and host-rock amphibolite. Although this figure was published in the Chinese-language

Figure 2. Histograms showing distribution of radiogenic lead isotope ratios derived from evaporation of single zircons from felsic rocks of the Altai Mountains, Xinjiang Province, NW China. *a*, Spectrum for five grains from granite-gneiss sample A5, integrated from 495 ratios. *b*, Spectrum for four grains from granitoid orthogneiss sample A50, north of Keketuohai town, integrated from 385 ratios and interpreted to reflect age of emplacement of gneiss precursor. *c*, *d*, Spectra for xenocrystic grains. *e*, Spectrum for two grains from rhyodacite sample A117, Fuyun area, integrated from 220 ratios and interpreted to reflect age of volcanism. *f–h*, Spectra for xenocrystic grains. *i*, Spectrum for five grains from granite gneiss sample A118, Fuyun area, integrated from 550 ratios and interpreted to reflect age of gneiss precursor. *j*, Spectrum for xenocrystic grain.

monograph of Wang et al. (1981), we reproduce it here in its geological context because it warrants international exposure.

The southern boundary of terrane 3 is a well-defined, north-dipping thrust on which high-grade rocks of terrane 3 have been transported southward over low-grade rocks of terrane 4 within a 1.5-km-thick metamorphic-thrust stack. An example of this relationship is shown in figure 5 near Qiongkuer, where inverted metamorphic isograds increase in grade upward from sericite, biotite, garnet, staurolite-kyanite to sillimanite, above which there are partial melt migmatites and granites (Yang et al. 1992). The figure shows nappes within the biotite zone that have been truncated by the basal thrust. O'Hara et al. (1997) undertook an oxygen isotope study of syntectonic gold-bearing quartz veins in schists, gneisses, migmatites, and mylonites within this inverted metamorphic sequence and concluded that seawater was tectonically ingested into the rocks to a depth of 5–10 km. In their model, the rocks belonged to an accretionary prism. In contrast, we suggest that these inverted metamorphic isograds and associated thrusts and the late granites in terrane 3 formed in association with postcollisional thrust tectonics. Sengör et al. (1993, p. 303) were incorrect in stating that "no Himalayan-type crystalline nappe complexes imbricating preexisting continental crust can be recognized within the Altaid collage."

Qiongkuer-Abagong Terrane 4. This terrane contains two formations: the Kangbutiebao Formation and the Altai Formation. The predominant Kangbutiebao Formation consists of upper Silurian to lower Devonian arc-type volcanic and pyroclastic rocks that are 1–2 km thick and minor basic volcanic rocks and spilites. In the far eastern Altai, this formation consists mostly of meta-andesite.

Two Rb-Sr whole rock isochrons on metavolcanic rocks yielded ages of 307 and 284.6 Ma (Yu et al. 1990). Volcanic rocks are intruded by many granites, some of which have K-Ar ages in the range 300–330 Ma (He et al. 1990). We record these ages but attach little significance to them because of their unconstrained field relations; the isotopic systems were apparently affected by post-Altai events.

The Middle Devonian Altai Formation rests on the Kangbutiebao Formation. It is well preserved in a low-grade metamorphic window, where it consists predominantly of a turbiditic sandstone-shale sequence, together with minor pillow-bearing basalts and siliceous volcanics. Fossils in thin limestones give a mid-Devonian age: *Cymostrophia* cf. *stephani*, *Cymostrophia* aff. *guadrata*, *Megastrophia* sp., *Stropheodonta* sp., *Euryspirifer* sp., *Acrospirifer* sp., *Brachyprion* sp., *Cyrtospirifer*, sp., *Favosites goldfussi*, *Pachyfavosites palymorphus*, *Pachyfavosites yui*, *Pachyfavosites vilvaensis*, *Calceola sandalina* subsp. *sinensis*. We suggest that the Altai Formation was deposited in a fore-arc basin.

Sample A5 is a foliated homogeneous granite intruded into the metavolcanic rocks (fig. 6). The zircons are clear to yellow brown, long prismatic, and idiomorphic to slightly rounded at their terminations. Five grains were evaporated individually and produced consistent results with a mean age of 380 ± 1 Ma (table 1; fig. 2*a*). No xenocrysts were detected. We interpret this as reflecting the time of granite intrusion; this is comparable to the fossiliferous age of the Kangbutiebao Formation.

At Lamazhao a prominent, circular posttectonic granitic pluton truncates regional thrusts (fig. 6). Sample A29 from the Lamazhao pluton is a homogeneous, undeformed, two-mica leucocratic granite. The zircons are dark brown, and the population separated from this sample consists of broken crystal fragments. All grains analyzed contain an unusually high amount of common Pb that did not disappear during continuous evaporation of the zircons. Therefore, we were not able to calculate a reliable $^{207}Pb/^{206}Pb$ age and we therefore do not provide analytical data for this sample. All we can say is that the zircons have a minimum age of 290 Ma. Liu (1993) reported a Rb-Sr whole rock isochron of 256 ± 5 Ma from the Lamazhao pluton.

The Altai Formation contains considerable gold mineralization. Alt means gold in the Mongolian language. There is a working gold mine in siliceous volcanics ca. 25 km northwest of Fuyun City. Alluvial gold occurs in most rivers of the Altai range, and many minor alluvial gold workings are still in operation. Some gold may have been derived by erosion of the siliceous island arc volcanics of the Kangbutiebao Formation. Dong (2000) and Rui et al. (in press) point out the spatial relationship between most gold deposits in the Altai with the major northeasterly dipping faults and thrusts. We agree with this observation, but emphasize the fact that the thrusts are sited on suture zones between arcs and on former subduction zones which were the ultimate control on the generation of magmatic rocks and fluids responsible for the gold mineralization.

At Ashile (fig. 1) an important Kuroko-type massive sulphide Zn-Cu deposit is hosted by rhyolite, andesite, and basalt of the Kangbutiebao arc (Cheng 1990; Yang 1994). The deposit has a Sm-Nd age of 372 Ma (Wang et al. 2000). Rui et al. (in press) consider that 360 Ma is the most probable age of the

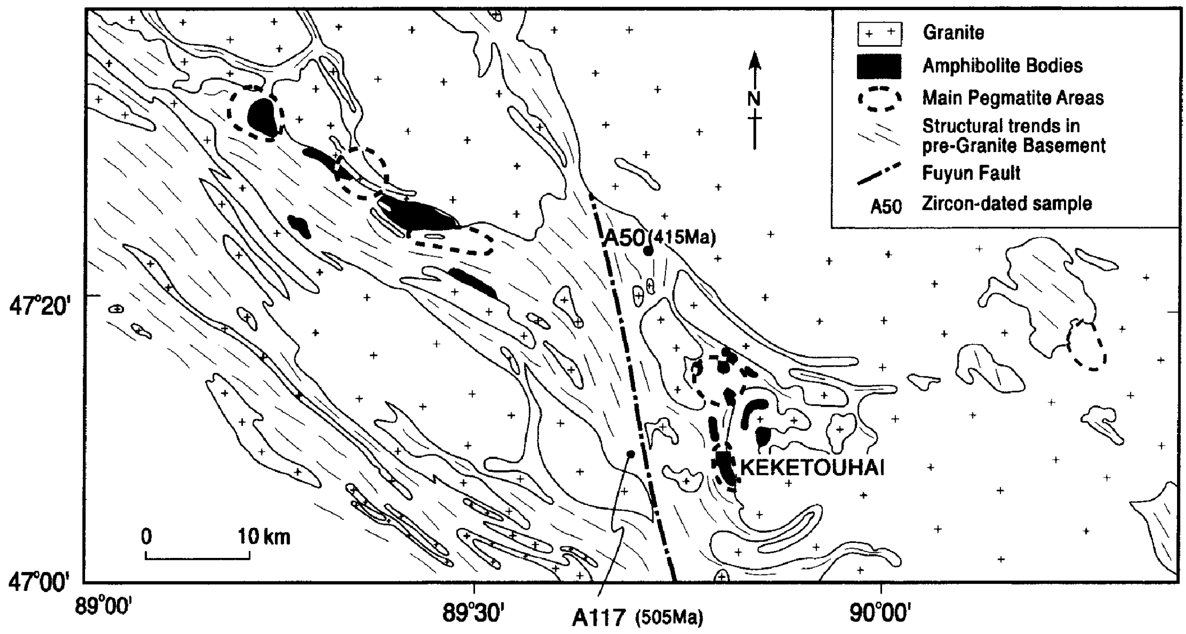


Figure 3. Geological sketch map of the Keketuohai region within terrane 3. Five main pegmatite fields are located at the contact zone between posttectonic granites and their wall rocks, which are mostly amphibolites. The major muscovite pegmatite mine is at Keketuohai. The position of zircon-dated samples A50 and A117 is indicated.

sea-floor hydrothermal activity that gave rise to the Ashile deposit.

Erqis Terrane 5. This terrane is situated between terrane 4 and the Erqis Fault. It thins eastward with the result that on the eastern side of the Fuyun Fault it has a maximum width of 10 km (figs. 1, 7). In the far west, it is covered by Quaternary sediments of the northern Junggar Basin. This terrane contains a Precambrian basement of high-grade gneisses and schists with $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ feldspar model ages of 1849 Ma and 1791 Ma (Qu and Chong 1991). Near the Kala-Erqus River the basement rocks are overlain unconformably by a Devonian fossiliferous succession of six formations, which themselves are overlain tectonically by the Late Carboniferous, sedimentary Kala-Erqis Formation and intruded by Permian postorogenic granites. Slates with a Sm-Nd isochron age of 340 Ma have Nd mean crustal residence ages ranging from 0.9 to 0.61 Ga (Chen and Jahn, in press); this is consistent with a source from the underlying Precambrian basement of this terrane, the isotopic age range of which is not known.

Little modern structural detail is known about this high-grade terrane and why it is so narrow. We can speculate that it was subducted and thrust under the arcs to the north, and the strike-slip Erqis Fault may have removed a significant part of its original southern margin. The Erqis Fault on the south side of terrane 5 is a major crustal structure deserving detailed description.

The Erqis Fault. The Erqis Fault (or Irtys in China; Qu and Zhang 1991) (fig. 1) is one of the largest transcurrent faults of Asia (Zhang et al. 1996); its extension in Kazakhstan is termed the "Irtish (or Irtysh) Fault," and in Mongolia the Bulgan Fault. In the Altai of China on its northern side, there are uplifted mountain ranges in which there are common high-grade metamorphic rocks, abundant two-mica-garnet granites, a paucity of A-type granites, many pre-Devonian rocks, and very few Mesozoic to Cenozoic sediments.

To the south of the fault, there are low hills and depressed basins in which the rocks are either unmetamorphosed or recrystallized to greenschist facies, there are few two-mica-garnet granites, and many A-type granites. The rocks are Early Devonian in age and younger, and there are abundant Carboniferous island arc volcanic rocks (in western Junggar) and Early Carboniferous clastic sediments and many Mesozoic and Cenozoic basins. These relations indicate that the northern (Altai) and southern (Junggar) crustal blocks contain rocks of

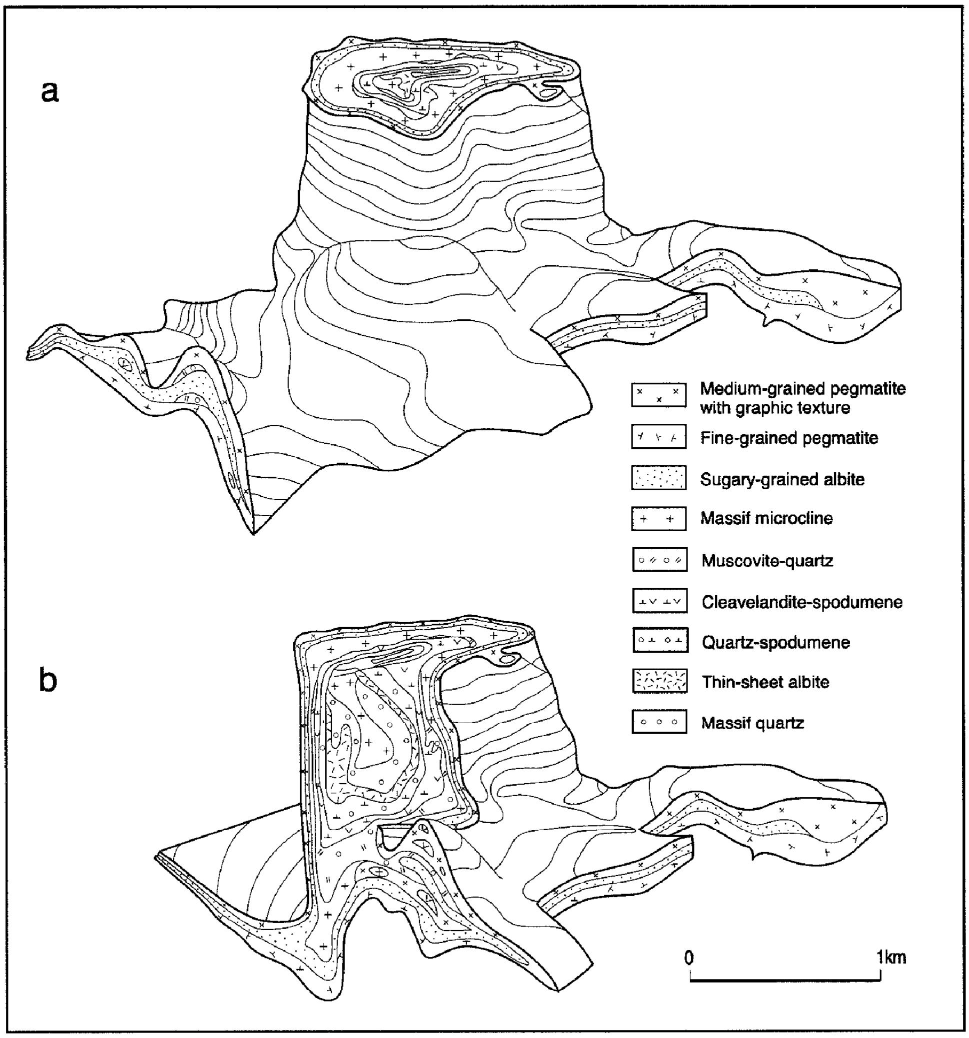


Figure 4. Three-dimensional structure of the Keketuohai pegmatite showing its nine internal zones (after Wang et al. 1981). This is one of the largest pegmatites in the world, which has its total shape well defined.

different age and type, different metamorphic regimes, and granitic rocks.

In China, the fault dips steeply northward, has a prominent subhorizontal rodding lineation, and a 10-km-wide mylonite zone. It is only exposed in the eastern half of the Altai (fig. 1, 7); in the west, it passes under Quaternary sediments of the northern Junggar basin. It is characterized by finely banded mylonites, individual bands being about 1 cm wide. Bands of mylonitic quartz alternate with bands of different compositions depending on their original lithology. Along the fault in China, there are many 10–100-m-long lenses of gabbro with minor nickel mineralization. The fault is a major gold metallogenic zone, the gold deposits occurring in ductile or ductile-brittle shear zones especially in segments with I-type granites (Wang et al. 2000). The fault contains ophiolitic mélanges, and in Mongolia and Russia, there are several large ophiolitic complexes. The fault commonly separates almost unmetamorphosed basalts and sandstones to the south from high-grade amphibolites and gneisses to the north. In places, there is a spectacular northward increase in metamorphic grade within the fault from chloritic, slaty, flinty mylonites through medium-grade muscovite-rich phyllonites and biotite schists locally with garnet, to high-grade biotite-bearing quartzo-feldspathic gneisses and

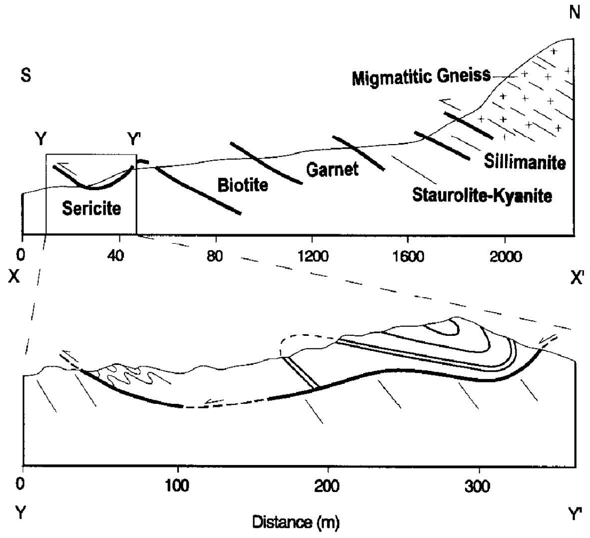


Figure 5. Sections across the north-dipping contact between terranes 3 and 4, 3 km NE of Qiongkuer town. Terrane 3 gneisses have been thrust southward over lower grade metavolcanics and metasediments of terrane 4. Inverted metamorphic isograds are seen in section XX′, and early nappes truncated by the main thrust in section YY′ are in the biotite zone.

hornblende-bearing amphibolite-facies mylonites. Along the southern margin of the zone, sandstones have been extensively shattered by brittle fracture, whereas in the northern marginal zone, gneisses and amphibolites have been ductily sheared. Throughout the mylonite zone, all original rocks have been thoroughly refoliated except for rare low-strain zones up to a few tens of meters across in which original rocks and textures such as volcanic breccias can be recognized. Centimeter-sized intrafolial folds increase in number northward across the fault zone.

The fault is seismically active. In 1957 in Mongolia, an earthquake with a magnitude of 8.3 caused a dextral offset of 8.7 m, and a 7.3-magnitude earthquake on it occurred in Russia on June 16, 1990 (S. Ge Shumo, pers. comm.). Seismic images indicate that the Erqis Fault is listric, becoming on its northern side a regional low-angle reflector at a depth of 10–15 km (Zhang et al. 1992). Sengör et al. (1993) proposed that the Erqis Fault is the major strike-slip fault bounding the northern side of the Kazakhstan orocline and that it has accommodated at least 1500 km of right-lateral motion. From their detailed paleostress analysis of the fault in Kazakhstan, Delvaux et al. (1998) concluded that it underwent right-lateral movement in the Late Carboniferous–Early Permian, its main deformation period, when ductile movements were associated with metamorphism and magmatism. Ductile deformation on the fault in Kazakhstan ceased by ca. 270 Ma (Travin et al. 1998).

Perkin-Ertai Terrane 6. This terrane is situated south of the Erqis Fault (fig. 1) and strictly belongs to the eastern Junggar. The bulk of it is occupied by a Devonian island arc that consists predominantly of felsic-intermediate basic lavas and tuffs, andesitic and dacitic porphyries, and contemporaneous calc-alkaline granitic plutons (Mei et al. 1993; Yu et al. 1993), together with fossiliferous shales (*Acrospirifer*, *Megastrophia*), sandstones, conglomerates, and limestones. Within the Devonian volcanics, many small blocks of very fossiliferous limestones have an upper Ordovician age.

A minor Carboniferous island arc in terrane 6 has the following stratigraphy and fauna, with the limestones being especially rich in fossils:

Top

Batamayneishan Formation: 5000 m andesitic tuff, tuff breccia, porphyritic andesite, sandstone, limestone lenses. *Calamites* sp., *Lepidodendro* sp., *Noeggerathiopsis* sp., *Sphenopteris* sp., *Pacopteris* sp.

Nanmingshui Formation: 2600 m sandstone, conglomerate, siltstone, tuff, sandstone, limestone lenses. *Dictyoclostus* sp., *Productus* sp., *Linoproductus* sp., *Davidsonia* (?) sp., *Kueichouphyllum* sp., *Caninia* sp., *Gangamophyllum* sp., *Paleosmilia* sp., *Spirifer subgrandis*, *Dictyoclostus* sp.

Heishantou Formation: 4500 m porphyritic andesite, rhyolite, basalt, trachyte, tuff, sandstone, siltstone, shale. *Neoggerathiopsis* (?) sp., *Lepidodendropsis*, sp., *Sublepidodendron* (?) sp., *Knorria* sp., *Phillipsiidae*.

Fine-grained clastic Carboniferous and Devonian sediments were weakly deformed and metamorphosed to phyllites and slates. Common assemblages are as follows (He et al. 1990):

Prehnite-sericite-pumpellyite-chlorite-carbonate
Prehnite-chlorite-actinolite-albite
Pumpellyite-epidote-albite-quartz-chlorite

The Carboniferous rocks were intruded by several small Permian granitic plutons up to 10 km across and gabbro-norite-diorite bodies, one of which hosts the Halatongke nickel-copper deposit (Feng 1987; Zhou 1987). The mineralization occurs in veins and massive ore in 11 gabbro-norite bodies that intruded anticlines of folded middle-upper Carboniferous siltstones, which have the following stratigraphy (Zhou 1987):

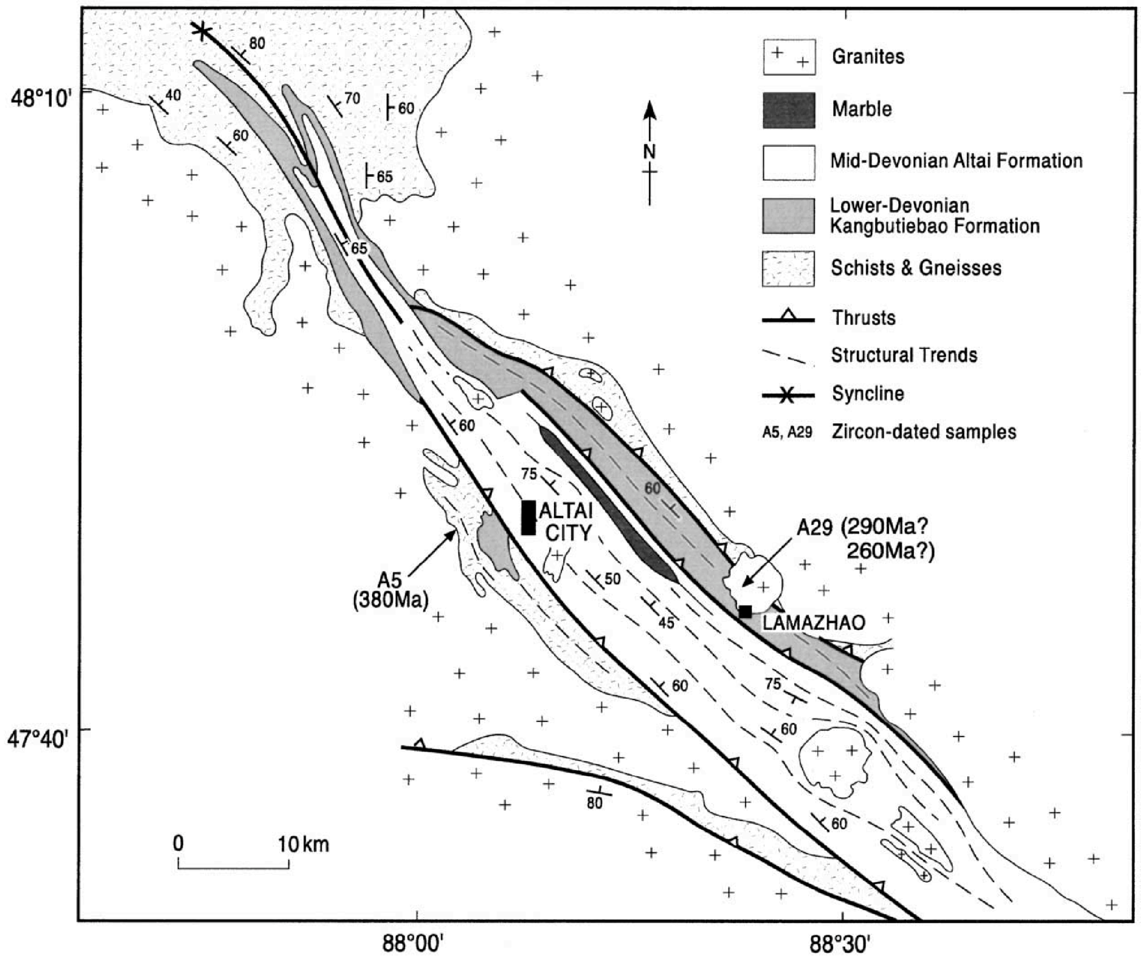


Figure 6. Geological map of the region around Altai City. The Altai Formation of terrane 4 occurs here in an isoclinal fold within narrow thrust slivers of terrane 5 schists and gneisses (not shown in fig. 1). The position of samples A5 and A29 is indicated.

Middle upper Carbonferous: siltstone; host to the gabbros

Lower upper Carboniferous: sandstone, siltstones shale, felsite, dacite, albite porphyry

Middle Carboniferous: tuff, tuff siltstone, andesite, sandstone, shale, siltstone

Lower Carboniferous: limestone, calc-sandstone, shale, sandstone, conglomerate, *Hypselentoma*, *Peychopteria*

The small granitic plutons are alkaline A-type granites and syenites containing Mg-biotite, orthoclase, arfvedsonite, and riebeckite and have Permian Rb-Sr and K-Ar ages (Zou et al. 1988). The peralkaline, A-type granites described by Han et al. (1997) are in terrane 6 close to the southern edge of the map of figure 1.

The Fuyun Fault. The NNW-trending, right-lateral, 180-km-long Fuyun Fault is clear on Landsat imagery. It is important to note the occurrence of this recent fault because it has displaced the Paleozoic rock terranes, and the amount of displacement and thus correlation is controversial. A magnitude 8 earthquake took place on the fault on August 10, 1931. Baljinnyam et al. (1992) reported that the average measured displacements on the 1931 rupture were 8 m and that west-flowing streams were displaced right laterally by up to 3 km. Kalaxiangar is a hill close to the intersection of the Fuyun and Erqis (fig. 7). The top of the hill was downfaulted in a graben, one fault of which has a well-preserved, very high fault scarp. From ^{14}C dating of material obtained from large-scale ex-

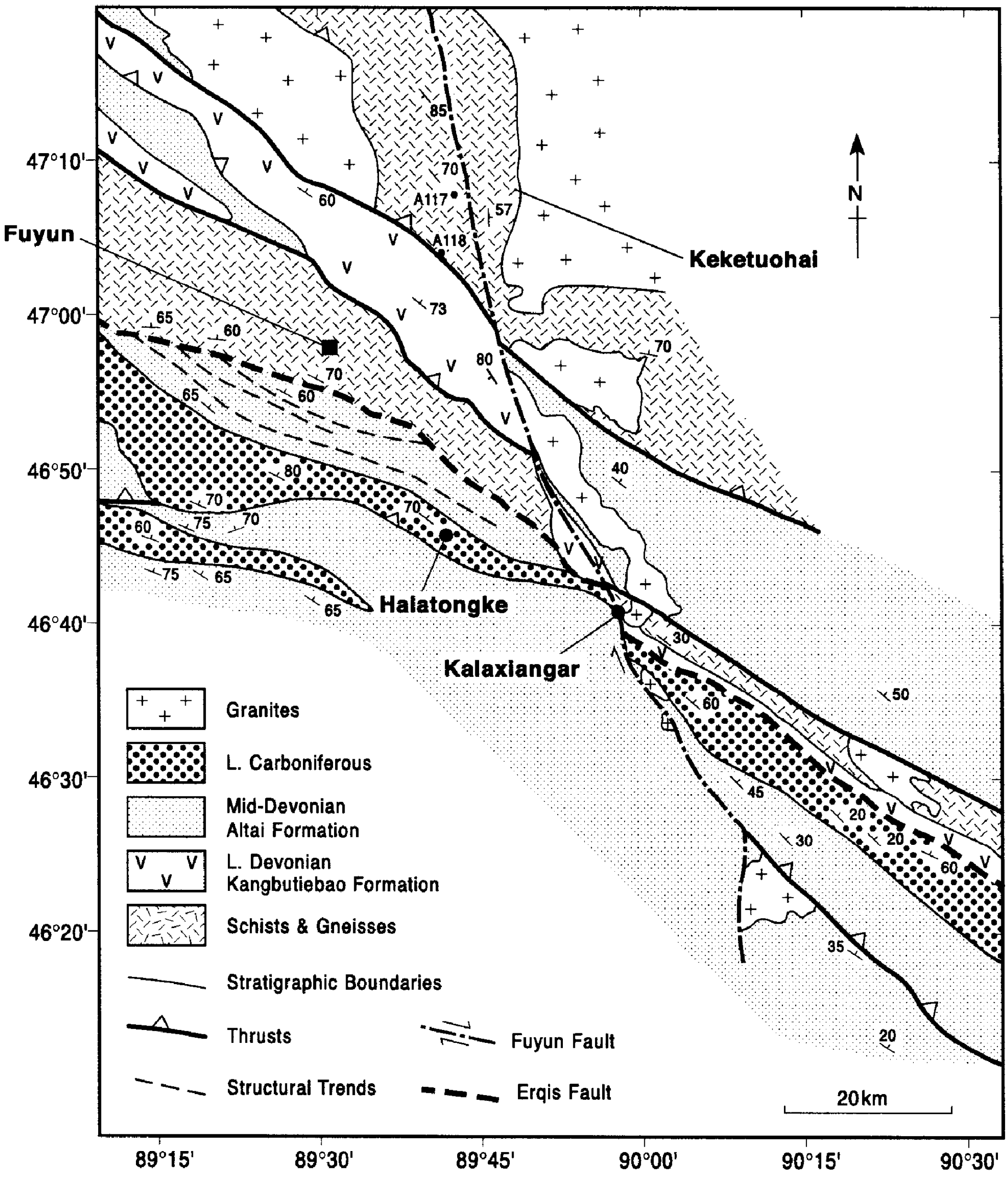


Figure 7. Map of the right-lateral Fuyun fault, which has displaced the Erqis fault about 8 km. Kalaxiangar, the epicenter of the 1931 earthquake, is close to the intersection of the two faults.

cavations, Ge et al. (1986) determined that five paleo-earthquakes have taken place in the last 10,000 yr, for which the average recurrence interval was 3150 yr. According to the Chinese geological map of Baljinnyam et al. (1992), the total displacement on the Fuyun Fault is 25–30 km. Our figure 7 presents a more detailed map of the region, including specific Paleozoic formations. Estimation of the fault displacement is made difficult by the obliquity of these formations and by the presence of several granites and earlier faults (Qu and Zhang 1994). We suggest that the only reliable earlier structure that can be used to calculate the offset is the Erqis Fault because this has some 10 km of mylonite, in contrast to all other displaced faults that are relatively weakly mylonitized. We have used this criterion to indicate in figure 7 that the Fuyun Fault has displaced the Paleozoic rocks by about 7–8 km.

Granitic Rocks in the Altai

Granitic rocks occupy at least 40% of the present area of the Chinese Altai (Zou et al. 1988); however, terrane 5 has hardly any, and terrane 3 has probably more than this value. Many of the gneisses in terrane 3 (fig. 1) may be orthogneisses, like our sample A50, derived by deformation and metamorphism of granitic rocks. If so, this terrane consists of more than 70% granitic rocks. Although the generation of granitoids in Central Asia is generally high, it is probably higher in the Chinese Altai than elsewhere. Consequently, Jahn et al. (2000*a*, 2000*b*) and in particular Chen and Jahn (in press) have made detailed geochemical and isotopic studies of the granitoids in order to understand the processes of continental growth. However, these studies were not made in relation to the different terranes and their makeup, and therefore, it is useful here to put their data into a geological framework outlined in this article.

Zhao et al. (1993) published many chemical and isotopic data on several Altai granites. Most granites analyzed by Chen and Jahn (in press), which are weakly metaluminous to weakly peraluminous, have $\varepsilon_{Nd(t)} = +2.1$ to -4.3, $I_{Sr} = 0.705$ to 0.714, and $T_{DM} = 0.7$ to 1.6 Ga, and on a diagram of $\varepsilon_{Nd(t)}$ versus intrusive age, they all plot between the fields of Paleozoic juvenile crust and Middle Proterozoic crust, and therefore, the above authors conclude that the granites were derived from a mixture of arc material and old continental crust. This conclusion is consistent with, and complements our information on, the geological history. However, some specific relationships are useful.

From a synthesis of the more reliable, published ages of the Altai granites, Chen and Jahn (in press) consider that emplacement of the granites took place in two broad internals: 408–377 Ma (Zou et al. 1988; Liu 1993) and 344–290 Ma (Zou et al. 1988; Liu 1990; Zhang et al. 1996), the mean emplacement ages being 390 and 330 Ma. These ages mostly refer to the granites in terrane 3, the only terrane with abundant granites (fig. 8). The Keketuohai granite (four samples of Zhao et al. [1993] and Chen and Jahn [in press]) has Nd mean crustal residence ages between 1.63 and 1.14 Ma, and initial Sr values (I_{Sr}) of 0.715, indicating a purely crustal melt origin, 0.709 suggesting a high continental crust component, and 0.707–0.705 indicating a significant component of juvenile/arc crust. Likewise, a granite about 15 km east of Altai City just within our terrane 3 has a Nd mean crustal residence age of 1.29 Ga but an I_{Sr} of 0.704, suggesting a major juvenile source. All these data are consistent with our conclusion that terrane 3 has a basement of Proterozoic to Cambrian age through which an Andean-type, continental magmatic arc was emplaced.

The Jiangjunshan A-type granite pluton is situated about 15 km south of Altai City within terrane 4. It has a Sm-Nd isochron age and a SHRIMP zircon age of 151 ± 3 Ma (Chen and Jahn, in press; S. A. Wilde, unpub. data, respectively). Why is there a late Jurassic granite in this Silurian-Devonian island arc? Could it be related to a hitherto unrecognized, westerly extension of the zone of 160–100 Ma orogen collapse in Central Asia that was located on arcs accreted in the Paleozoic (Johnson et al. 2001)?

Discussion and Conclusions

In this synthesis of the essential elements of the geology of the Chinese Altai, we have integrated the main information from Chinese and international literature with our own field and laboratory results. We regard our interpretations of the tectonic environments of the different terranes as preliminary and frame them in terms of current plate tectonic models that are testable. The data also provide constraints on the model of Sengör et al. (1993) insofar as the Altai forms an important part of the Altaid collage of Central Asia.

North of the Erqis Fault several terranes record the growth and tectonic accretion of island arcs (fig. 8). However, the arcs do not consistently young southward, as might be expected in the southward (present coordinates) accretionary model of Sengör et al. (1993).

Terranes 2 and 3 have Proterozoic basements; it is not known whether they originally belonged to the same terrane. The pre–Middle Ordovician rocks of terrane 2 are low-grade sediments, whereas in terrane 3, there are low-grade pre–Late Silurian metasediments, but many high-grade schists and gneisses, and we do not know the structural-tectonic relations between the rocks in these terranes. Therefore, at the moment, we prefer to keep them separate as terranes 2 and 3 until further work clarifies their relationships. The deformation events before the mid-Ordovician unconformity in terrane 2 and before the continental arc in terrane 3 presumably record accretion or collision events, but we have no evidence of their cause. According to Chang et al. (1995), the Altai contains many terrigenous clastic sedimentary rocks, which they suggest formed on a passive continental margin.

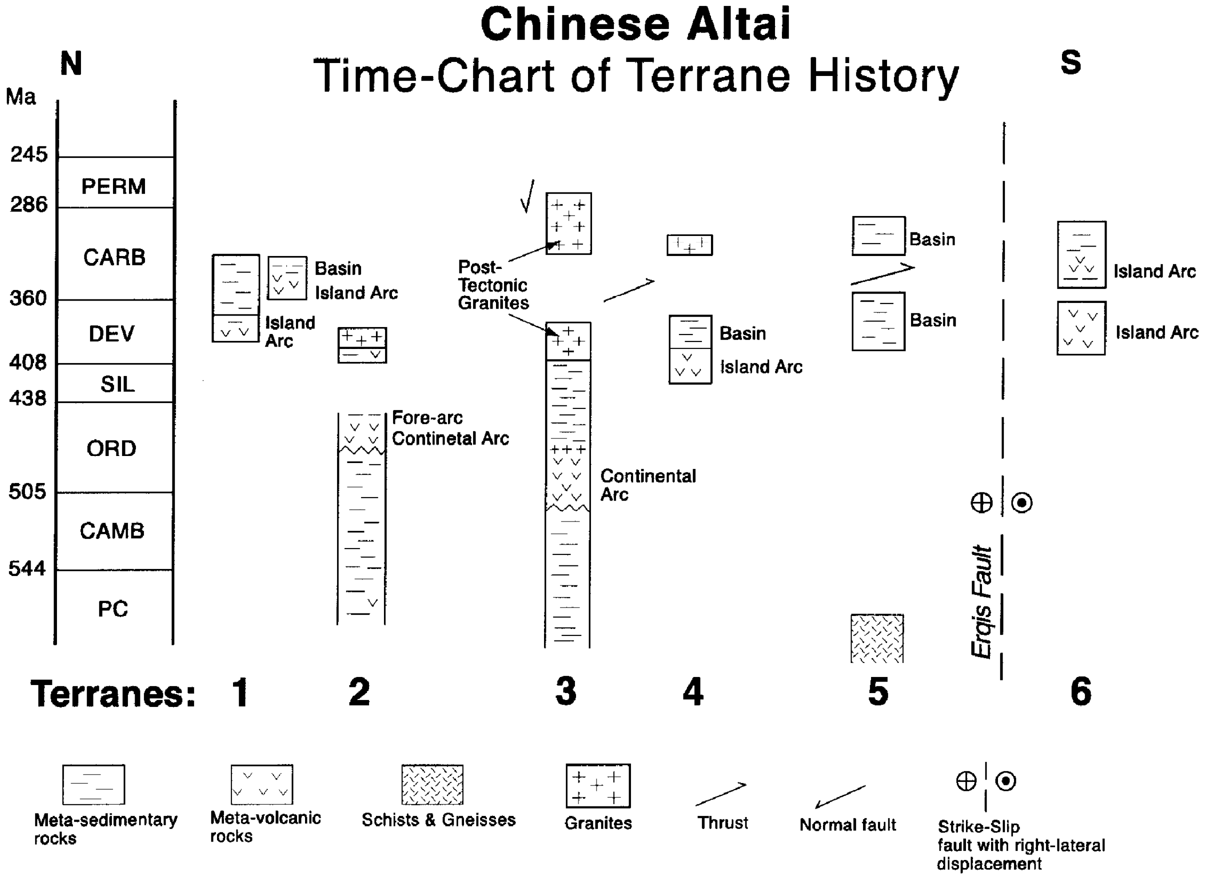


Figure 8. Time chart of the terranes of the Chinese Altai. This chart summarizes the main information in the text, plotting types of geological development against time. This provides an overall picture not so readily available from the details in the text. It shows that terranes 2 and 3 have a long history extending from the Precambrian to the mid-late Paleozoic. In terrane 5, there was a marked hiatus in evolution between the Precambrian and the Devonian. Terranes 1, 4, and 6 started as intraoceanic island arcs with no earlier basement, whereas in terranes 2 and 3, continental magmatic arcs developed on earlier continental basement. Most terranes have late sedimentary basins. Terrane 3 is unique in having a basement of sedimentary rocks that were widely metamorphosed to a high-metamorphic grade, an Andean-type continental magmatic arc, and, most importantly, voluminous posttectonic granites; the ages of the two main periods of granites are from Chen and Jahn (in press). The time chart also shows that terrane 3 was thrust southward over terrane 4 and that it is bounded on its northern side by a late normal fault. The right-lateral Erqis fault formed in the Late Carboniferous to Early Permian and separates terranes 1–5 of the Altai from terrane 6, which strictly belongs to the Eastern Junggar.

This can only refer to the sediments in terranes 2 and 3. However, we know of no evidence that indicates such a setting because there are no mapped continental margins. They could have been deposited in clastic sedimentary basins on Precambrian continental basement.

Terrane 2 contains Late Ordovician arc-type lavas, volcaniclastic rocks, and granitic plutons with some sediments that lie unconformably on a basement of deformed and metamorphosed sediments. Accordingly, we interpret this is as a continental magmatic arc, but there are no data to indicate whether it was derived by southward or northward subduction below this terrane. If terranes 2 and 3 belonged to the same terrane, then the late Ordovician arc of terrane 2 would have formed by southward subduction.

Our new zircon ages indicate that a Cambro-Ordovician continental arc of felsic lavas and plutons is situated on the southern margin of terrane 3. From this, we can infer northward subduction of terrane 4 below terrane 3. The rocks of terrane 3 have commonly been metamorphosed to a high grade, undergone partial melting, and intruded by voluminous posttectonic granites mostly of Late Devonian to Early Carboniferous age. The considerable volumes of late magmatic fluids associated with these granites gave rise to extensive pegmatite fields and the largest muscovite deposit in Asia.

On its southern side, terrane 3 has been transported in thrust nappes southward over terrane 4, producing classic inverted Barrovian-type metamorphic isograds. Barrovian isograds are typical of the peak metamorphism of collisional orogens but do not form in the trench environment of accretionary orogens. Our discovery of Barrovian metamorphism in the Altaids usefully places the metamorphism in its tectonic context in a collisional zone between a continental terrane and a colliding arc. The southward thrusting most likely produced crustal thickening, which was probably the cause of crustal melting at depth, giving rise to the voluminous posttectonic granites. The southward thrusting must have taken place after the northward attachment of the Kangbutiebao-Altai arc of terrane 4. The north-dipping normal fault on the northern side of terrane 3 has the character of an extensional collapse fault that formed as a result of the crustal thickening and exhumation of terrane 3. Within the Chinese Altai, terrane 3 stands out because it has been more highly exhumed than adjacent island arcs. The underlying cause of the exhumation was probably the accretion and collision of this terrane with the surrounding arcs.

Terrane 4 is an intraoceanic island arc of upper Silurian to lower Devonian age overlain by Middle Devonian fore arc? sediments; no older rocks are known in this terrane. Metasedimentary schists with Sm-Nd ages of 400 and 385 Ma from terrane 4 have Nd mean crustal residence ages ranging from 1.56 to 1.25 Ga (Chen and Jahn, in press). These samples were probably from postarc clastic sediments. Because there is no Precambrian basement below this island arc, the data may indicate that at the time of deposition the arc was already accreted to either terranes 3 or 5, which could provide a Precambrian source for the terrigenous detritus.

Terrane 5 has a high-grade gneissic basement about which little is known in detail. The narrowness of this terrane may have been caused by its partial subduction under terrane 4 to the north and/or by slicing by the major strike-slip Erqis Fault to the south.

Terrane 6 is situated south of the Erqis fault and strictly belongs to the eastern Junggar block rather than the Altai. Mei et al. (1993) and Chen and Jahn (in press) envisaged that the Altai orogen as a whole constituted a passive continental margin in the Early Paleozoic, which was converted to an active margin in the earliest Devonian because of north-dipping subduction of the Junggar Ocean. This model cannot be correct because the Altai and the Junggar are separated by the Late Carboniferous–Early Permian Erqis Fault, which with a 10-km-wide mylonite zone has a displacement of many hundreds of kilometers (Sengör et al. 1993). Therefore, the Junggar terrane 6 cannot be related genetically to terranes 1–5 of the Altai.

The Altai is rich in mineralization. The various terranes of the orogen have different and characteristic mineralization types. Terrane 3 with its crustal melt granites and pegmatites is rich in muscovite, beryl, tantalum, and niobium deposits. To the south, the island arcs are enriched in Au, Pb, Zn, and Cu. To the north, the arcs of terrane 1 contain notable Au, and just across the border in Mongolia, there is Pb and Zn mineralization and one of the largest Ag deposits in Asia (at Asgat). The many island arcs provided the source for the widely distributed gold in the Altai.

In this article, we have described what is known and what is little known. We have tried not to overspeculate as in a model-driven synthesis. From the details so far, it appears that the tectonic evolution of the Chinese Altai was more complicated in both time and space than most previous work has appreciated.

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