The Central Asian Orogenic Belt and growth of the continental crust in the Phanerozoic

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Abstract: Asia is the world's largest composite continent, comprising numerous old cratonic blocks and young mobile belts. During the Phanerozoic it was enlarged by successive accretion of dispersed Gondwana-derived terranes. The opening and closing of palaeo-oceans would have inevitably produced a certain amount of fresh mantle-derived juvenile crust. The Central Asian Orogenic Belt (CAOB), otherwise known as the Altaid tectonic collage, is now celebrated for its accretionary tectonics and massive juvenile crustal production in the Phanerozoic. It is composed of a variety of tectonic units, including Precambrian microcontinental blocks, ancient island arcs, ocean island, accretionary complexes, ophiolites and passive continental margins. Yet, the most outstanding feature is the vast expanse of granitic intrusions and their volcanic equivalents. Since granitoids are generated in lower-to-middle crustal conditions, they are used to probe the nature of their crustal sources, and to evaluate the relative contribution of juvenile v. recycled crust in the orogenic belts. Using the Nd–Sr isotope tracer technique, the majority of granitoids from the CAOB can be shown to contain high proportions (60 to 100%) of the mantle component in their generation. This implies an important crustal growth in continental scale during the period of 500–100 Ma. The evolution of the CAOB undoubtedly involved both lateral and vertical accretion of juvenile material. The lateral accretion implies stacking of arc complexes, accompanied by amalgamation of old microcontinental blocks. Parts of the accreted arc assemblages were later converted into granitoids via underplating of basaltic magmas. The emplacement of large volumes of post-accretionary alkaline and peralkaline granites was most likely achieved by vertical accretion through a series of processes, including underplating of basaltic magma, mixing of basaltic liquid with lower-crustal rocks, partial melting of the mixed lithologies leading to generation of granitic liquids, and followed by fractional crystallization. The recognition of vast juvenile terranes in the Canadian Cordillera, the western US, the Appalachians and the Central Asian Orogenic Belt has considerably changed our view on the growth rate of the continental crust in the Phanerozoic.

In the last decade the Central Asian Orogenic Belt (CAOB) became celebrated for its orogenic style and the world's largest site of juvenile crustal formation in the Phanerozoic eon. Central Asia provides a prime example for study of accretionary tectonics and growth of the continental crust in the late part of the Earth's history. Asia has indeed grown in size, but a distinction must be made between the two terms commonly used in the discussion on the making of Asia:

(1) *amalgamation* of dispersed microcontinental fragments from the breakup of Gondwana. This process enlarged the size of Asia, but did not necessarily add a substantial amount of new (juvenile) crust to the continent and

(2) *growth* of the continental crust. This implies addition of juvenile crust and a net transfer of mantle-derived material to the continental crust. It is the latter process that is the focus of this article.

The CAOB, bounded by the Siberian and North China cratons (Fig. 1), represents a complex evolution of Phanerozoic orogenic belts (e.g. Tang 1990; Dobretsov *et al.* 1995). It has also been termed the Altaid tectonic collage by Sengör and his associates (Sengör *et al.* 1993; Sengör and Natal'in 1996). According to these authors, the CAOB was formed by successive accretion of arc complexes, accompanied by emplacement of immense volumes of granitic magmas (Fig. 2). In addition, they underlined the general absence of nappe complexes imbri-

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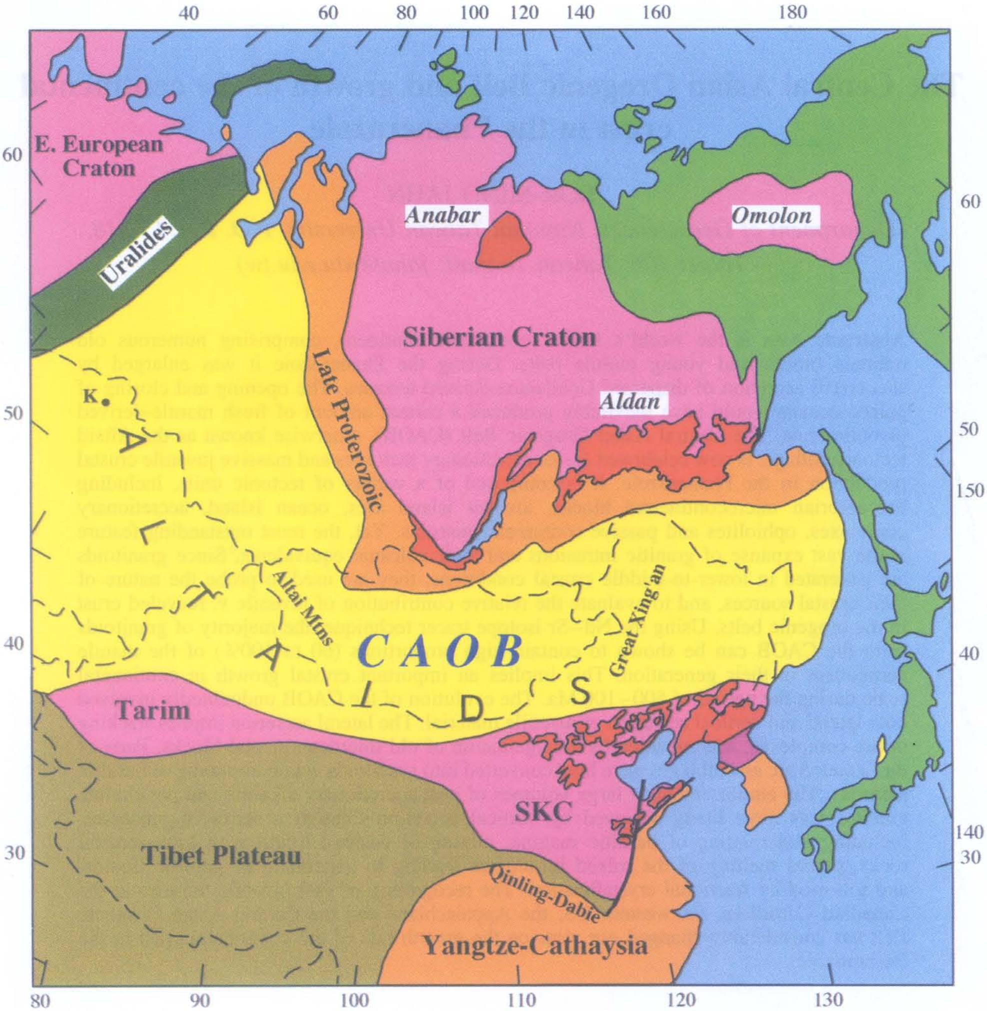


Fig. 1. Simplified tectonic divisions of Asia. The Central Asian Orogenic Belt (CAOB), also known as the Altaid tectonic collage (Sengör *et al.* 1993), is situated between two major Precambrian cratons: Siberian in the north and North China–Tarim in the south. Red areas are exposed Archaean to Early Proterozoic rocks. The light green pattern on the right-hand side, including the Japanese islands, represents Pacific fold-belts. The Hida Belt of Japan may belong tectonically to the CAOB. Abbreviation: K, Kokchetav (in northern Kazakhstan).

cating older continental crust as characteristic of the classic collisional orogenic belts. In general, the CAOB comprises a variety of tectonic units, including Precambrian cratonic blocks (=micro-continents), ancient island arcs, fragments of ocean island and seamount, accretionary complexes, ophiolites and passive continental margins (Sengör *et al.* 1993; Badarch *et al.* 2002; Dobretsov *et al.* 2004). However, it is the voluminous granitic intrusions, mostly of juvenile character, that distinguish the CAOB from other classic Phanerozoic orogenic belts, such as the Caledonides and Hercynides in Europe (e.g. Kovalenko *et al.* 1996, 2003; Jahn *et al.* 2000*a*, *b*, 2003; Wu *et al.* 2000, 2001, 2003*a*, *b*). Because granitoids are derived mainly by melting of the lower to middle crust, they can be used as an invaluable tool to probe the nature of their sources at deep crustal levels.

In the following, the contrasting Nd–Sr isotopic characteristics of granitic rocks from the classic orogens (e.g. Caledonian and Hercynian in Europe, Cathyasia in SE China, South Korea, and eastern Australia) and from the CAOB will

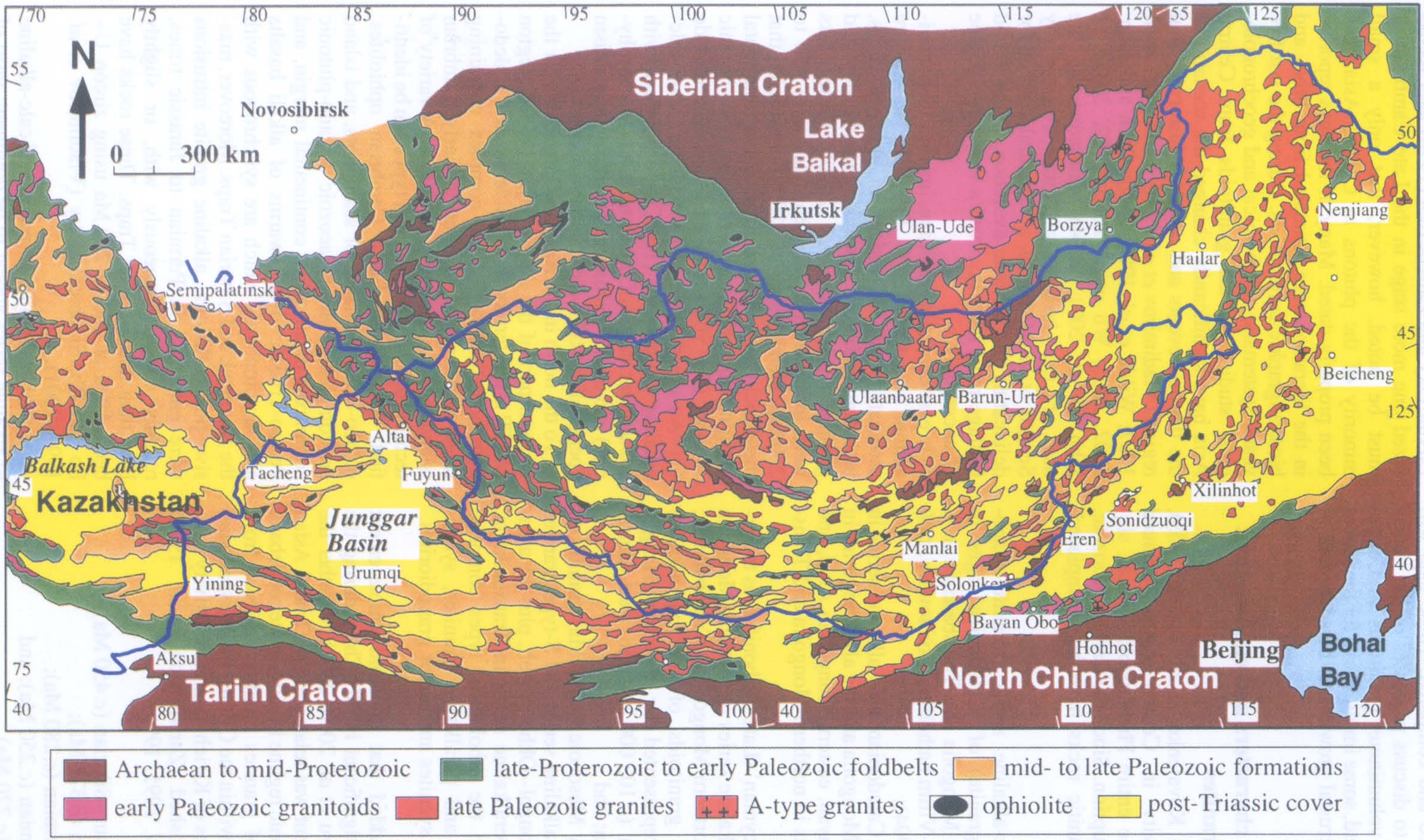


Fig. 2. Areal distribution of granitoids in the CAOB. The national boundaries between Russia, Mongolia, China and Kazakhstan are shown by heavy blue lines. Mongolia is situated in the heartland of Central Asia. The northern belt of CAOB represents the area from central-northern Mongolia to Transbaikalia (east of Lake Baikal), and the southern belt from east-central Kazakhstan (region to the north of Lake Balkash), Northern Xinjiang (regions surrounding the Junggar Basin), Inner Mongolia to NE China (Manchuria), of which the Great Xing'an Mountains are shown. In Northern Xinjiang, the Altai terrane is situated to the north of the Junggar Basin, and the eastern and western Tianshan terranes to the south. The eastern and western Junggar terranes are found in the east and west of the Junggar Basin.

be summarized and compared. These data will then be used to discuss processes of the generation of the voluminous granitoids in Central Asia. At the end, some implications for the global Phanerozoic crustal growth will be addressed.

Lithological characters and emplacement periods of granites

According to Kovalenko *et al.* (1995, 2003), igneous activity in Central Asia continued throughout the entire Phanerozoic without significant interruption. Since the Early Palaeozoic, numerous granitic rocks have been emplaced. They include:

(1) the calc-alkaline series (tonalite–granodiorite–granite) of 'Caledonian' ages in northern Mongolia and Transbaikalia (e.g. Angara–Vitim batholith; Litvinovsky *et al.* 1992, 1994);
(2) the 'late Caledonian' calc-alkaline series in western Mongolia and the alkaline series in Tuva, Sayan, eastern Mongolian Altai, and vast areas in northern Mongolia and Transbaikalia;
(3) the 'Hercynian' (Late Carboniferous to Permian) alkaline series in southern Mongolia and in northern Mongolia to Transbaikalia; Permian granitoids of the calc-alkaline series, represented by the vast Hangay batholith (*c.*100 000 km^2) in west-central Mongolia; and
(4) the Early Mesozoic (*c.*200 Ma) granites of the calc-alkaline series and S-type granites in the Mongol–Okhotsk Belt, plus the alkaline to peralkaline series in Transbaikalia, of which the lithological types comprise alkaline and peralkaline granites, syenogranites, syenites and minor granodiorites.

It must be added that granitoid emplacement became very significant in NE China during the Cretaceous (Wu *et al.* 2000, 2002). Whether the Cretaceous event was related to the Central Asian or Pacific tectonic regime is still a matter of debate.

The ages of granites roughly decrease from north to south within the CAOB. In Transbaikalia, five main stages of K-rich magmatic activity have been distinguished (Zanvilevich *et al.* 1995; Wickham *et al.* 1995, 1996):

(1) Ordovician–Silurian (*c.*450 Ma);
(2) Devonian (*c.*375 Ma);
(3) Early Permian (*c.*280 Ma);
(4) Late Permian (*c.*250 Ma); and
(5) Triassic (*c.*220 Ma).

Litvinovsky and Zanvilevich (1998) later recognized one more stage in the Late Cambrian. It must be noted, however, that only a small minority of the plutons in Central Asia have been properly dated. Many of the ages reported in the literature were estimated from litho- and biostratigraphic correlations. During the last five years, systematic geochemical and geochronological studies on the granitoids from Central Asia have significantly changed the scenario of the thermal events and orogenic history of that region (Vladimirov *et al.* 1997; Yarmolyuk *et al.* 1997; Wilde *et al.* 1997, 2000; Chen and Jahn, 2002, 2003; Wu *et al.* 2000, 2002, 2003*a*, *b*; Jahn *et al.* 2001, 2004). Consequently, the use of the 'magmatic front' concept by Sengör *et al.* (1993) as a structural marker for delineating the tectonic evolution of the Altaid Collage must have involved a very large degree of uncertainty.

In east-central Kazakhstan, important mineralizations (Au, Cu, Mo–W, Sn, REE, Nb–Ta) are associated with a variety of igneous rocks, including gabbros, diorites, granodiorites and granites (Heinhorst *et al.* 2000). These rocks were intruded in several episodes from 450 to 250 Ma. Heinhorst *et al.* (2000) considered that these rocks were formed in an active continental margin which developed from back-arc oceanic settings (for volcanic-hosted massive sulphide Cu–Au ore deposits) to subduction zone calc-alkaline magmatism (for Cu porphyries), with subsequent stages of differentiation (Mo porphyries) and finally to continental rifting magmatism (peralkaline REE–Zr–Nb deposits).

To the north in the Russian Gorny Altai, or the western part of the Altai–Sayan Folded Region (ASFR), the terrane is considered as a Caledonian accretion–collisional complex containing large fragments of Vendian to Early Cambrian island arcs (Dobretsov *et al.* 2004). A variety of tectonic units and lithological types can be identified: Vendian to Early Cambrian ophiolites, palaeo-oceanic islands or seamounts, and island arc complexes, Mid-Palaeozoic volcano-plutonic complexes of an active continental margin, and Permo-Triassic dyke swarms of alkali basalts and lamprophyres which are synchronous with the Kuznetsk and Siberian Traps. Moreover, massive post-collisional alkaline granite intrusions were emplaced in Permian to Jurassic times, roughly contemporaneously with, or slightly later than, the Siberian Traps. These rocks have been dated at 250 to 200 Ma using zircon U–Pb and Rb–Sr chronometry (Vladimirov *et al.* 1997, 2001).

In northern Xinjiang, granites of calc-alkaline to alkaline series appear to be dominant; most of these were emplaced in the period of 400–200 Ma but culminated around 300 Ma. A-type granites of the Ulungur River area were intruded at about 300 Ma (Rb–Sr ages, Wang *et al.* 1994; Han *et al.* 1997) and those in Inner Mongolia were emplaced slightly later at *c.*280 Ma (whole-rock Rb–Sr, Hong *et al.* 1995). In Inner Mongolia, arc-type calc-alkaline granitoids were intruded at *c.*310 Ma, but they were overwhelmed by much more widespread late orogenic granites of *c.*230 Ma (Chen *et al.* 2000). Further east to NE China the existing age data indicate four episodes of granitic intrusion (Fang 1992; Jahn *et al.* 2000*a*, *b*; Wu *et al.* 2000, 2002, 2003*a*):

(1) Late Permian (270–250 Ma);
(2) Late Triassic–Early Jurassic (220–180 Ma);
(3) Middle Jurassic (170–150 Ma); and
(4) Cretaceous (*c.*120 Ma).

These data support a younging trend of granitic emplacement from the west to the east within the southern belt of the CAOB.

In addition to the apparent regional age variation, two other trends are present:

(1) a regular decrease in size for younger plutons, and
(2) an increase in the proportion of syenite and alkaline granite to granite (*s.s.*), as well as in the ratio of K-feldspar to plagioclase, in the younger plutons. That is, the younger plutons tend to be more alkaline in nature.

This is particularly well demonstrated in the granitoids from the Mongolian–Transbaikalian belt (Litvinovsky and Zanvilevich 1998). In Transbaikalia, peralkaline granites and syenites containing aegirine and arfvedsonite only occur in the younger Permian and Triassic suites (Kuzmin and Antipin 1993; Wickham *et al.* 1995, 1996). However, we note that in the southern belt (Xinjiang–Inner Mongolia–NE China) such an increase of alkalinity in granitoids with the decrease of intrusive ages is not as clearly documented as in Transbaikalia (Hong *et al.* 1996).

In short, according to Sengör *et al.* (1993), Central Asia grew by successive accretion of subduction complexes along a single but migratory magmatic arc now found contorted between Siberia and Baltica. They recognized the main difference between the Altaids (=CAOB) and other classic collisional orogens such as the Alps and the Himalayas, in that the Altaids show the paucity of extensive ancient gneiss terrains or Precambrian microcontinents. Besides, they underlined that no Alpine- or Himalayan-type crystalline nappe complexes inbricating pre-existing continental crust can be recognized within the Altaid collage, and that high-K granites were considered to be produced by anatexis, and only became abundant in the Permian. The above hypothesis on tectonic evolution and structural analyses has been a point of controversy in the last few years, and the model on the high-K granite genesis is not supported by the isotope data to be presented below. Nevertheless, the overall scheme for the growth of Central Asia by accretion of subduction complexes is probably correct, apart from the role of ancient microcontinents being greatly underestimated. The voluminous post-orogenic A-type granites could not be easily explained using a subduction model. It is argued that vertical accretion via basaltic underplating might be even more important than the horizontal accretion of subduction complexes for the growth of the Asian continent.

Nd–Sr isotopic data for Phanerozoic granitoids – a summary

The Nd–Sr isotope characteristics of granitoids from the world's classic Phanerozoic orogenic belts are summarized below using three types of diagrams: (1) initial Nd isotope composition $\varepsilon_{Nd}(T)$ v. intrusive ages; (2) $\varepsilon_{Nd}(T)$ v. depleted-mantle-based model age T_{DM}; and (3) $\varepsilon_{Nd}(T)$ v. initial Sr isotope composition I_{Sr} or $(^{87}Sr/^{86}Sr)_o$. For model ages, a linear Nd isotope evolution is assumed for the depleted mantle from $\varepsilon_{Nd} = 0$ at 4.56 Ga to $+10$ at the present, but the choice of a one- or two-stage model (DePaolo *et al.* 1991) is difficult, as each model has its own uncertainty and inconvenience. In the single-stage model, the main uncertainties are due to:

(1) Sm/Nd fractionation between granitic melts and their sources during partial melting;
(2) Sm/Nd fractionation during magma differentiation; and
(3) mixing of melts or sources in petrogenetic processes (Arndt and Goldstein 1987; Jahn *et al.* 1990).

Many peralkaline granitoids of Central Asia show highly fractionated REE patterns, sometimes with the tetrad effect leading to enhanced or greater than chondritic Sm/Nd ratios and negative model ages (Masuda *et al.* 1987; Masuda and Akagi 1990; Bau 1996; Jahn *et al.* 2001, 2004). For this type of granite, single-stage model ages are clearly not appropriate. On the other hand, the two-stage model assumes that all the sources for granites follow the same isotope evolution as the average continental crust, regardless of their true lithological characteristics. This cannot always be realistic. Adoption of this model will result in most granitoid data forming a quasi-linear array in the $\varepsilon_{Nd}(T)$ v. T_{DM} plots (e.g. Wu *et al.* 2000).

Concerning initial Sr isotope ratios, it is important to know the uncertainty derived from the correction of *in situ* radiogenic growth. This problem is most severe for granitoids of very high Rb–Sr ratios, such as A-type or peralkaline granites, which are very abundant in Central Asia. Figure 3 shows a plot of initial Sr isotopic ratios (I_{Sr}) as a function of $^{87}Rb/^{86}Sr$ ratios for some granitoids from the southern belt of the CAOB. High $^{87}Rb/^{86}Sr$ ratios (up to 400) often occur with A-type and highly differentiated *I*-type granitoids. Note that as the I_{Sr} values were individually calculated by subtracting the radiogenic components from the measured $^{87}Sr/^{86}Sr$ and Rb/Sr ratios, they may bear large uncertainties for high Rb–Sr rocks, and not uncommonly yield unreasonably low ratios ($\leq$0.700; Fig. 3). The Rb–Sr induced errors (ξ) for calculated initial $^{87}Sr/^{86}Sr$ ratios are related to three factors: Rb–Sr ratio, assigned uncertainty for the Rb/Sr ratio, and age (true or assumed), all related by the equation:

$$\xi = {}^{87}Rb/{}^{86}Sr \times (\%\ \text{error assigned}) \times (e^{\lambda t} - 1)$$

The error propagation envelope assuming $t = 200$ Ma (Fig. 3) shows that the Rb–Sr induced errors for $(^{87}Sr/^{86}Sr)_o$ are too large to have any petrogenetic significance for rocks with $^{87}Rb/^{86}Sr \geq 10$ or 20. Peralkaline rocks with ratios $\geq$100 do not provide a useful constraint to their genetic processes. Nevertheless, most I_{Sr} values for low Rb/Sr rocks seem to show a restricted range of $(^{87}Sr/^{86}Sr)_o$ of 0.705 ± 0.002, which is rather low for granitic rocks formed in Phanerozic orogenic belts. Relative to Sr, the

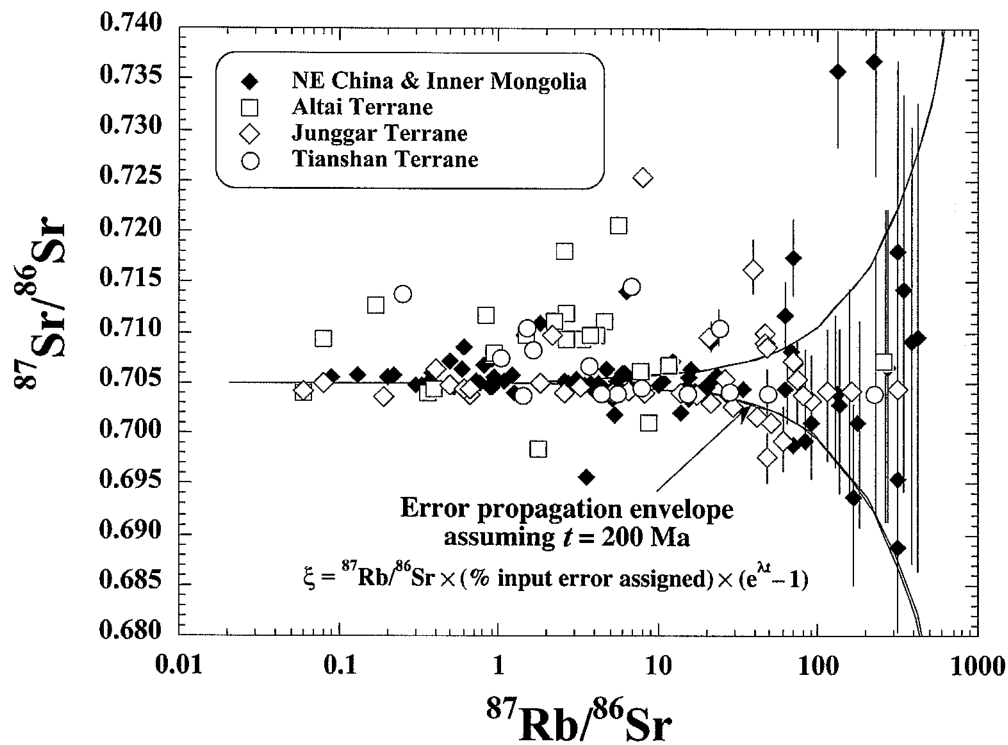


Fig. 3. Initial $^{87}Sr/^{86}Sr$ v. $^{87}Rb/^{86}Sr$ plot, only for young granitoids from the CAOB, showing the magnitude of uncertainty in $(^{87}Sr/^{86}Sr)_o$ induced by error in Rb/Sr ratio. More reliable $(^{87}Sr/^{86}Sr)_o$ for rocks with Rb/Sr ratios $\leq$20 range from 0.703 to 0.707. The $(^{87}Sr/^{86}Sr)_o$ calculated from rocks with high to very high Rb/Sr ratios, are too imprecise to have petrogenetic meanings. The grey area indicates the propagation of error in $(^{87}Sr/^{86}Sr)_o$ induced by 2% Rb/Sr uncertainty.

isotopic data of Nd are known to be more robust, and Sm/Nd ratios can be more accurately measured; thus they provide a much clearer and less ambiguous constraint to the origin of granitic rocks.

Classic Phanerozoic orogenic belts

European Caledonides and Hercynides and eastern Australia. Figures 4a and 4b show the available Sm–Nd isotope data for granitoids from the European Hercynides and Caledonides, and from the Lachlan Fold Belt (420–390 Ma) and New England Batholith (310–250 Ma) in eastern Australia. The data from young Himalayan leucogranites (*c.*20 Ma) are also shown for comparison, but their $\varepsilon_{Nd}(T)$ values are not adjusted to a Palaeozoic age and their T_{DM} were calculated using a two-stage model because most of them have f_{Sm-Nd} values higher than -0.2 (Fig. 4b). Note that almost all the Hercynian (450 data points) and Caledonian granitoids (80) and all Himalayan leucogranites (29) have negative $\varepsilon_{Nd}(T)$ values (Fig. 4a). This suggests that the granitoids were mainly generated from recycled sources containing large proportions of Precambrain crust. Most of the Hercynian granitoids with near-zero $\varepsilon_{Nd}(T)$ values represent the post-tectonic A-type granites from Corsica (Poitrasson *et al.* 1995). These rocks also have high Sm–Nd ratios, leading to very high T_{DM}, up to 3800 Ma (Fig. 4b), but their mantle component is significantly higher than the rest, as argued from the Nd isotope data. Figure 4b shows that if $f_{Sm/Nd}$ values are limited to -0.4 ± 0.2, then the majority of T_{DM} for the Hercynian and Caledonian granitoids would fall between 1000 and 2000 Ma. Note also that the Hercynian and Caledonian data-sets cannot be distinguished as a whole.

A significant proportion of Australian granitoids (black diamonds on Fig. 4) possess positive $\varepsilon_{Nd}(T)$ values, and their model ages (T_{DM}) are highly variable from *c.*500 Ma to >2000 Ma (Fig. 4a, b). The Australian granitoids differ from the European granites in their restricted range of f_{Sm-Nd} values for the same range of T_{DM}, which indicates their generation from sources of different mixing proportions between the mantle and crustal components. It has been estimated that in the Lachlan belt the added mantle component for the most primitive Moruya Suite ($\varepsilon_{Nd} = c.+4$) is *c.*40% (Keay *et al.* 1997), about 10% for the S-type Bullenbalong Suite, and between 10 and 40% for all other I-type granitoids (Collins, 1996, 1998). These estimates were based on a young crustal component with relatively high $\varepsilon_{Nd}(T)$ values, which is not the case for Central Asia.

SE China and South Korea. Cathaysia is a tectonic unit of the South China Block. It is a major Phanerozoic orogenic belt in East Asia. Like the CAOB, it is also characterized by voluminous Phanerozoic granitoids with rich mineralizations. Thus, a brief comparison of their isotopic signatures with those of the CAOB appears instructive for the understanding of their respective crustal development. Cathaysia has been considered as the easternmost part of the Tethyside orogen (Hsü *et al.* 1990; Sengör *et al.* 1993). Cathaysia and the CAOB are situated to the south and north of the North China craton, respectively, and they exhibit very contrasting styles of tectonic and crustal evolution. Their principal characteristics and differences are summarized in Table 1. A-type granites also occur in Cathaysia, but their Nd isotopic signatures are generally 'crustal' (Charoy and Raimbault 1994; Martin *et al.* 1994; Darbyshire and Sewell 1997). Most granitic rocks in Cathaysia were produced by remelting of Proterozoic crustal sources; only very few Cretaceous granitic bodies in coastal Fujian and Taiwan have a significant depleted mantle component in their magma genesis (Jahn *et al.* 1976, 1986, 1990; Huang *et al.* 1986; Lan *et al.* 1995b; Gilder *et al.* 1996; Chen and Jahn, 1998). The principal heat source is thought to come from basaltic underplating (Zhou and Li 2000).

The Phanerozoic granitoids of SE China (Yangtze craton, Cathaysia and Taiwan) show negative $\varepsilon_{Nd}(T)$ values, except a few cases (Fig. 5a, b, c). Some Cretaceous granites from Dabieshan possess the lowest $\varepsilon_{Nd}(T)$ values from -15 to -25, suggesting their derivation from a protolith of Archean to Early Proterozoic age (Fig. 5a). In the $\varepsilon_{Nd}(T)$ v. initial $^{87}Sr/^{86}Sr$ diagram, the data indicate a dominance of both upper and lower crust in the generation of granitic rocks. The mantle component is subordinate (Fig. 5b). Single-stage model ages range from 1000 to 2500 Ma for the majority of the granitoids (Fig. 5c). Besides, there is an apparent oceanward younging of T_{DM} and an increase of $\varepsilon_{Nd}(T)$ within the whole of SE China (Chen and Jahn 1998; Zhou and Li 2000).

With respect to the granitoids of SE China, the Late Palaeozoic to Cretaceous granitoids of South Korea are characterized by even lower $\varepsilon_{Nd}(T)$ values (Figs 5d, e, f) but comparable T_{DM} model ages (Fig. 5f). The basement gneisses and metasediments have very radiogenic initial Sr isotope ratios (up to 0.775) and old to very old Nd model ages (1500–3800 Ma). The Sr isotope

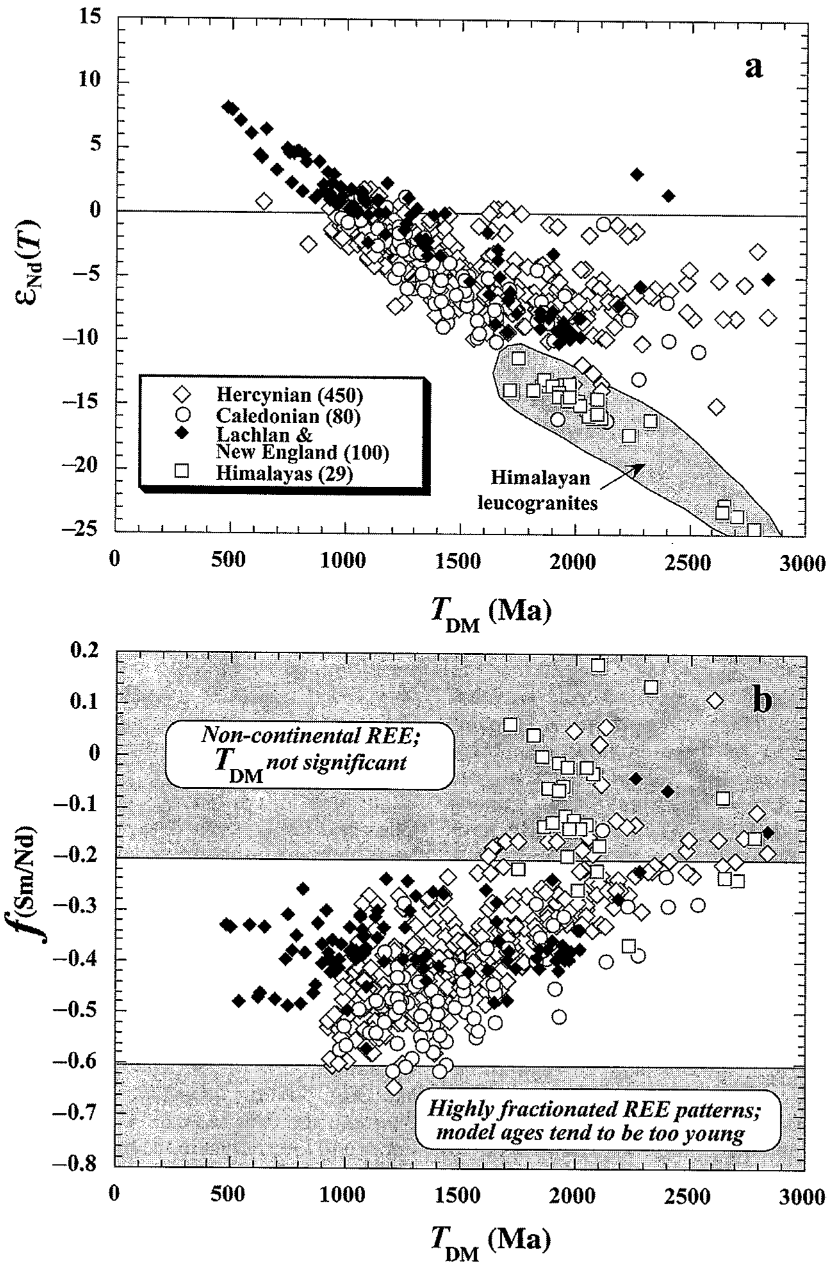


Fig. 4. Isotope diagrams for granitoids from European Hercynides and Caledonides, Australian Lachlan and New England fold-belts, and the Himalayas. Note that T_{DM} for Himalayan leucogranites shown in (a) are calculated using a two-stage model, because a large number of them have $f_{Sm-Nd} > -0.2$. Data sources: (a) **Caledonian Belt:** Hamilton *et al.* (1980), Halliday (1984), Frost and O'Nions (1985), Dempsey *et al.* (1990), Skjerlie (1992); (b) **Hercynian Belt:** Ben Othman *et al.* (1984), Bernard-Griffiths *et al.* (1985), Downes and Duthou (1988), Liew and Hofmann (1988), Liew *et al.* (1989), Pin and Duthou (1990), Turpin *et al.* (1990), Williamson *et al.* (1992), Cocherie *et al.* (1994), Darbyshire and Shepherd (1994), Dias and Leterrier (1994), Poitrasson *et al.* (1994, 1995), Moreno-Ventas *et al.* (1995), Siebel *et al.* (1995), Tommasini *et al.* (1995), Downes *et al.* (1997), Ajaji *et al.* (1998), Azevedo and Nolan (1998), Forster *et al.* (1999); (c) **Lachlan and New England Belts:** McCulloch and Chappell (1982), Hensel *et al.* (1985), Eberz *et al.* (1990), King *et al.* (1997), Keay *et al.* (1997), Mass *et al.* (1997); (d) **Himalaya:** Vidal *et al.* (1984), Deniel *et al.* (1987), Inger and Harris (1993), Gazis *et al.* (1998), Harrison *et al.* (1999).

Table 1. *Comparison of crustal evolution between the CAOB and Cathaysia of SE China*

	Central Asian Orogenic Belt	SE China (Cathaysia)
Type of orogen	Accretionary* (Altaid†)	Collisional* (Tethyside)
Characteristics	immense Phanerozoic granitic intrusions	immense Phanerozoic granitic intrusions
Period of intrusion	550 to 120 Ma ΔT *c.*400 Ma	400 (?) to 80 Ma ΔT *c.*300 Ma (mainly 180–90 Ma)
Total volume (area)	*c.*5.3 M km^{2}† (*c.*11% of Asian total)	*c.*0.4 M km^{2}‡
Granitic type	Mainly I- and A-types Calc-alkaline, alkaline and peralkaline granites	I- > S- ≫ A-type Calc-alkaline granites dominate
Crustal type	Mainly juvenile	Mainly reworked
$\varepsilon_{Nd}(T)$	Mostly positive (+8 to 0)	Mostly negative (−2 to −17)
Tectonics	Assembly of numerous arc complexes; intruded by vast granitic plutons and covered in places by their volcanic equivalent	Assembly of ancient continental blocks; vast granitic plutons and rhyolite formed by remelting of old basement rocks
Granitoid generation	Melting of wet mantle wedge + differentiation; Basaltic underplating (lithosphere delamination or plume activities?) and melting of lower crust	Melting of the lower crust via basaltic underplating (Zhou & Li 2000)
Structure	Nappe complexes rare or absent†; suture zones broad	Nappe complexes common; suture zones narrow and elongate
Basement rocks	Precambrian basement rocks comparatively rare†	Proterozoic basement dominates

*Terminology of Windley (1993, 1995)
†According to Sengör *et al.* (1993)
‡Late Mesozoic granites + rhyolites = 240 000 km^2 (Zhou and Li 2000)

data indicate that the granitoids have no direct genetic relationship with the metasediments or gneisses in the Ogcheon belt (Fig. 5e). On the other hand, the Early Tertiary (50 Ma) Namsan alkaline granite from the Kyongsang Basin in SE Korea is an exception. The chemical compositions indicate their A-type affinity, suggesting emplacement in a post-orogenic environment (Kim and Kim 1997). These rocks are characterized by low initial $^{87}Sr/^{86}Sr$ ratios of 0.704 to 0.705, and positive $\varepsilon_{Nd}(T)$ values of +3 to 0. Kim and Kim (1997) suggest that they were derived from a 'juvenile' source, presumably a young lower crust of underplated basalt with a small amount of old crustal material. As in the European Caledonides and Hercynides, the granitoids of SE China and South Korea, as a whole, are overwhelmed by the recycled continental crust (Jahn *et al.* 1990; Lan *et al.* 1995b; Chen and Jahn 1998).

Granitoids from the CAOB

NE China & Inner Mongolia. In NE China, ≥350 granitic bodies were intruded (mainly during the Mesozoic) in the Great Xing'an (or Khinggan), Lesser Xing'an and Zhangguangcai Ranges. Some of them were emplaced within the domain of the Jiamusi Massif, a Proterozoic microcontinental block whose metamorphic age has been precisely dated at 500 Ma by SHRIMP zircon analyses (Wilde *et al.* 1997, 2000). The granites are composed mainly of I-type and subordinate A-type granites (Wu *et al.* 2000, 2002, 2003a, b). They are accompanied by extensive Mesozoic and Tertiary acid volcanic rocks. Isotope tracer analysis and age determination of deep-drilled cores revealed that the Songliao Basin in central NE China is underlain by granitic rocks and deformed granitic gneisses of Phanerozoic ages; no Precambrian zircons have been identified (Wu *et al.* 2001). This suggests that the true volume of granitic rocks is much greater than shown in the present geological map. The tectonic setting for the emplacement of such an immense distribution of granitic rocks in NE China has not been resolved. It appears to have a connection with continental rifting and no relation with subduction zone processes.

In Inner Mongolia, several periods of granitic intrusion took place from Devonian to Jurassic times. The samples used in this study came from a Palaeozoic anorogenic A-type suite (280 Ma; Hong *et al.* 1995, 1996), an arc-related calc-alkaline magmatic belt composed of gabbroic diorite, quartz diorite, tonalite and granodiorite

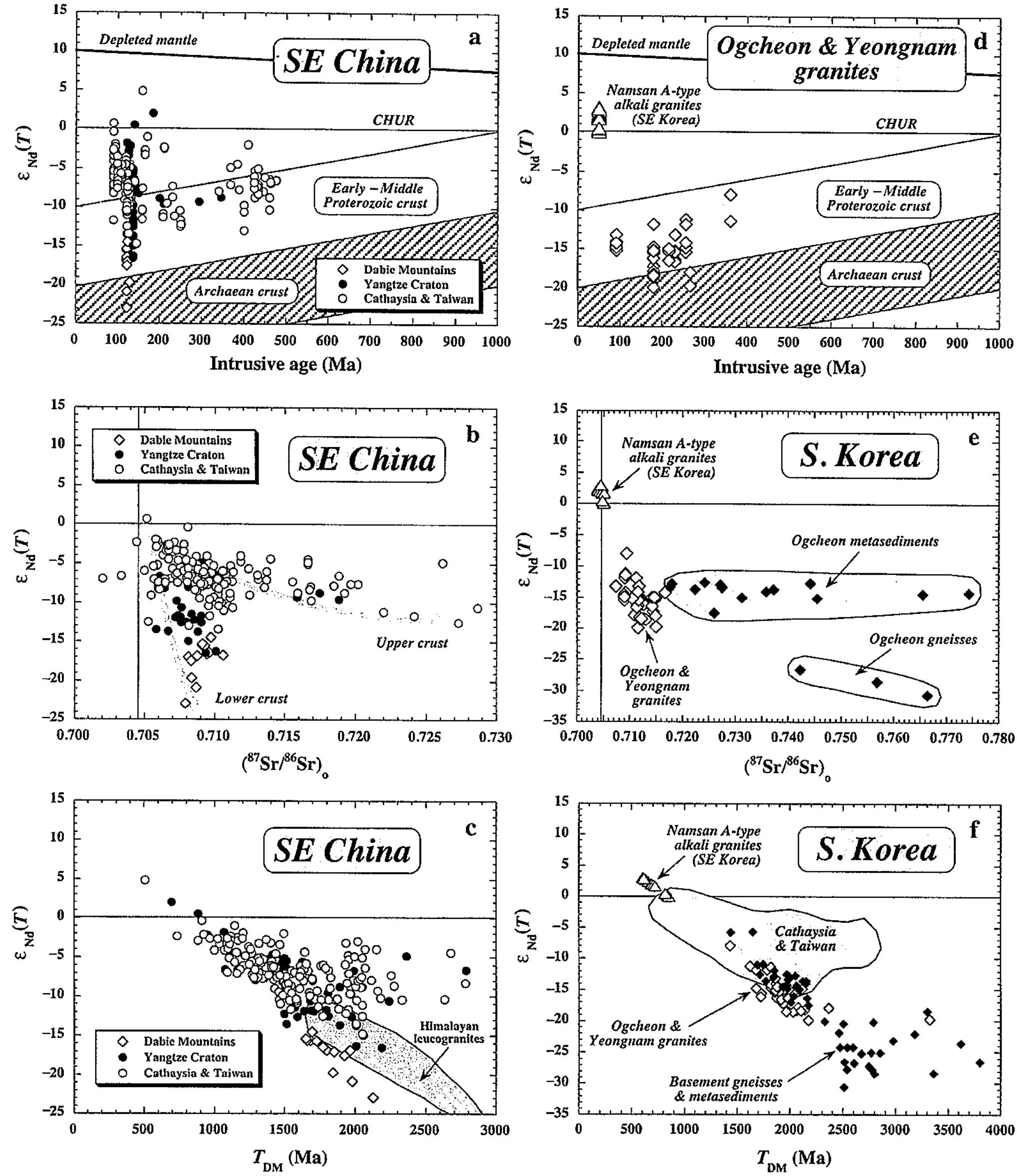


Fig. 5. Isotope diagrams for granitoids from SE China (**a**, **b** & **c**) and South Korea (**d**, **e** & **f**). Data sources: **SE China**: see references cited in Chen and Jahn (1998); **South Korea**: Lan *et al.* (1995a), Cheong and Chang (1997), Kim and Kim (1997), Lee *et al.* (1999).

(SHRIMP zircon age of 309 ± 8 Ma, Chen *et al.* 2000) and a Mesozoic collision-type granitic suite comprising adamellite, granodiorite and leucogranite (Rb–Sr isochron age of 230 ± 20 Ma; Chen *et al.* 2000).

The Nd–Sr isotope data, including all derivative parameters (intrusive and model ages, f_{Sm-Nd}) for the Phanerozoic granitic rocks from NE China, Inner Mongolia and the Hida Belt of Japan are presented in Figure 6. Figure 6a shows that the majority (75%) of the analysed samples have positive $\varepsilon_{Nd}(T)$ values. Most of the samples with negative $\varepsilon_{Nd}(T)$ values came from within the domain of the Precambrian Jiamusi Massif

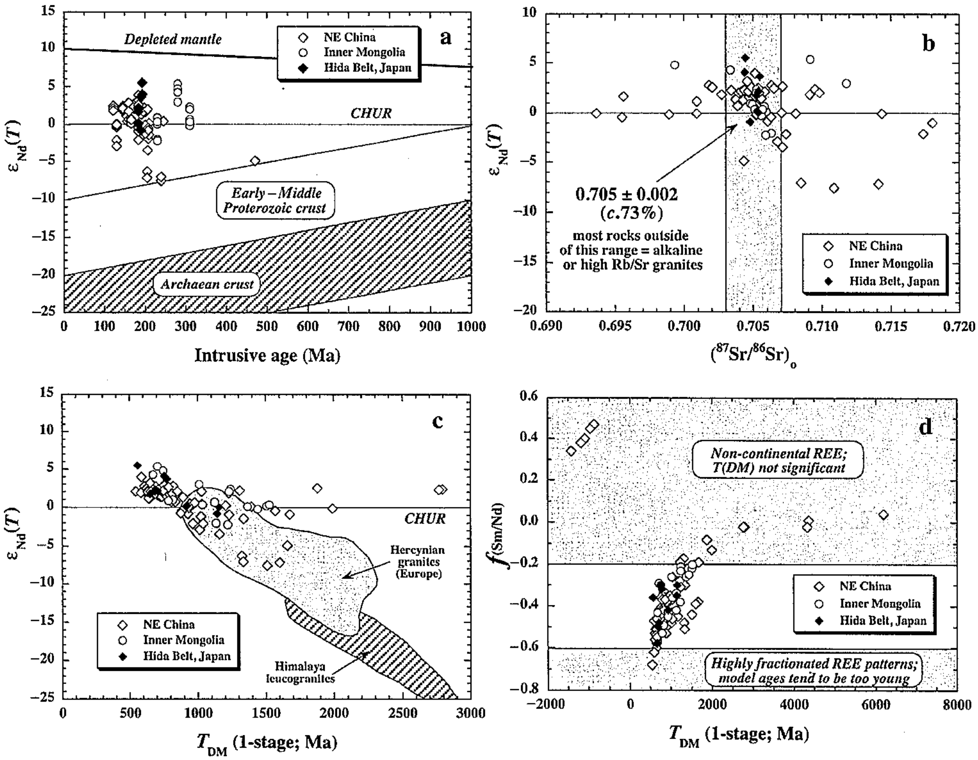


Fig. 6. Isotope diagrams for granitoids from NE China–Inner Mongolia–Hida Belt of Japan. (**a**) $\varepsilon_{Nd}(T)$ v. intrusive ages; (**b**) $\varepsilon_{Nd}(T)$ v. initial $^{87}Sr/^{86}Sr$ isotopic ratios; (**c**) $\varepsilon_{Nd}(T)$ v. T_{DM} (1-stage); and (**d**) f_{Sm-Nd} v. T_{DM} (1-stage). Data sources: **NE China**: Wu *et al.* (2000, 2002) and Jahn *et al.* (2001); **Inner Mongolia**: Chen *et al.* (2000), Jahn, unpubl.; **Hida Belt**: Arakawa and Shimura (1995), Arakawa *et al.* (2000).

(ε_{Nd}(200 Ma) = −7 to −12). Such a close relationship between the isotopic compositions of granitoids and the ages and nature of their intruded 'basement' rocks is also demonstrated by the granitoids from northern Xinjiang (Hu *et al.* 2000) and Mongolia (Kovalenko *et al.* 1996, 2004; Jahn *et al.* 2004). The lowering of the $\varepsilon_{Nd}(T)$ values was effected by the participation of old crustal rocks in their magma genesis.

Figure 6b shows a plot of initial Nd and Sr isotope ratios for the same suites of rocks. The Sr data are widely scattered, with I_{Sr} from 0.693 to 0.718. The scatter is due to the large correction of *in situ* radiogenic growth, as explained in the preceding section. However, the majority of the I_{Sr} appear to fall within a small range of 0.705 ± 0.002. This value is probably the most commonly found for granitoids of Central Asia. Figure 6c presents a $\varepsilon_{Nd}(T)$ v. model age plot with two reference fields (Hercynian and Himalayan granites). Much of the scatter in this plot results from the highly fractionated Sm–Nd ratios, whose effect would be reduced if a two-stage model were used (figure not shown). Figure 6d illustrates the effect of f_{Sm-Nd} values on the single-stage model age calculation. Aberrant model ages (negative or ≥4000 Ma) are produced due to strong Sm–Nd fractionation through crystallization and magma–hydrothermal interaction which led to a tetrad REE distribution pattern (Masuda *et al.* 1987; Masuda and Akagi 1990; Bau, 1996; Irber 1999; Jahn *et al.* 2001, 2004). The model ages are interpretable only when f_{Sm-Nd} values fall in the range of −0.4 ± 0.2. Consequently, from Figures 6c and 6d, the granites from NE China and Inner Mongolia have young model ages ranging from 500 to 1200 Ma, except for a few plutons emplaced within the domain of the Jiamusi Massif. This is clearly distinguished from most of the European Caledonian and Hercynian granites, and even more clearly from the leucogranites of the Himalayas.

Junggar Basin. The geology of northern Xinjiang in NW China may be conveniently divided into five 'terranes' (from north to south): Altai, East and West Junggar, and East and West Tianshan (Fig. 2). A summary of the geological and isotopic characteristics of these terranes was given by Hu *et al.* (2000). The Junggar Basin is covered by Cenozoic desert sands and thick continental basin sediments ($\geq$10 km) as old as the Permian. Drilling records indicate little deformation within the basin, suggesting stable configuration of the basement at least since the Permian (Coleman 1989). The nature of the Junggar basement has been much debated; some consider that the basin represents a microcontinent with Precambrian basement (Wu 1987), whereas others regard it as trapped Palaeozoic oceanic crust of various origins (Feng *et al.* 1989; Hsü 1989; Coleman, 1989; Carroll *et al.* 1990). Surrounding the Junggar Basin, numerous ophiolites are exposed in the East and West Junggar terranes, as well as in its southern margin. These terranes can be appropriately referred to as 'island-arc assemblages', and no rocks of Precambrian age have been documented. Coleman (1989) considered these terranes as oceanic arc assemblages, and compared them with those in the present western Pacific.

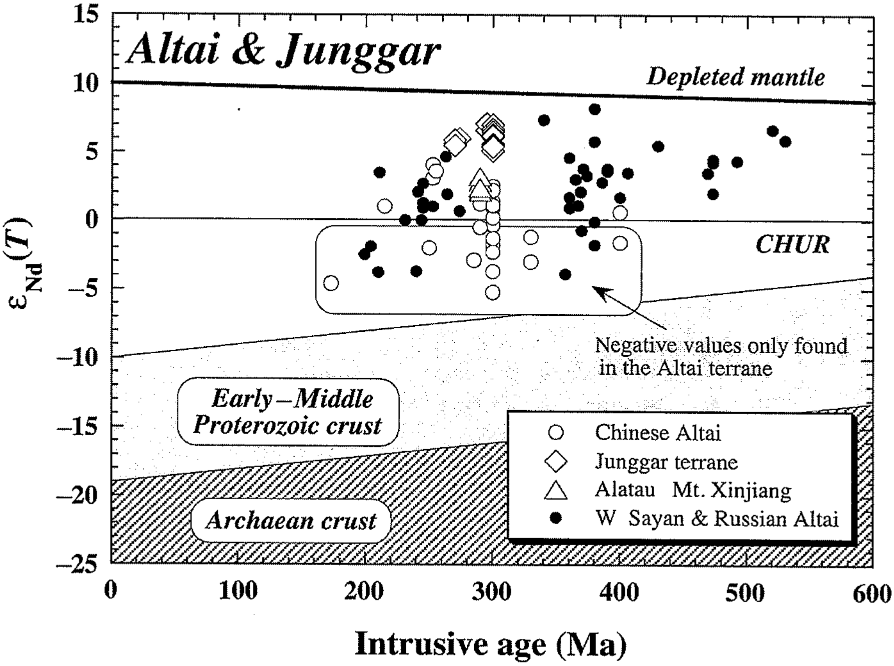
A variety of Phanerozoic granitoids occur throughout northern Xinjiang. The results of isotopic investigations are summarized in Figure 7. As for the case of NE China, the majority of granitoids have positive $\varepsilon_{Nd}(T)$ values which suggest the dominance of the mantle component in the generation of these rocks. This is particularly true for the granitoids from the E and W Junggar terranes (Fig. 7a; Zhao 1993; Han *et al.* 1997; Chen & Jahn 2004). Based on trace-element and Sr–Nd isotopic study, Chen and Jahn (2004) concluded that the basement is mostly likely underlain by Early to Middle Palaeozoic arc and oceanic crust assemblage that was trapped during the Late Palaeozoic tectonic consolidation of Central Asia. This is consistent with the very young model ages ranging from 400 to 1000 Ma (400 to 600 Ma in a two-stage model) for the Junggar granites (Fig. 7b).

Composite terranes of the Altai Mountains. The western Sayan and Gorny Altai in southern Siberia are considered to have formed during the complex evolution of the Palaeo-Asian Ocean (Sengör *et al.* 1993; Buslov *et al.* 2001; Dobretsov *et al.* 2004). The region is an Early Palaeozoic accretionary complex and island-arc system. It has been demonstrated to have large-scale strike-slip faults (up to several thousand kilometres) caused by subduction and collision of seamounts and island arcs (Buslov *et al.* 2001). Vendian to Lower Cambrian ophiolite, HP/LT schists, Cambro-Ordovician turbidites, etc. are intruded by Ordovician and Devonian granitoids, and unconformably overlain by Silurian sediments, Devonian volcanics and non-marine clastics. The region was further intruded by post-orogenic Permian to Jurassic A-type granites (Vladimirov *et al.* 1997). Kruk *et al.* (2001) analysed 44 granitoid samples of Cambrian to Jurassic ages and the results are shown in Figure 7. The majority of the granitoids (35 out of 44) possess positive $\varepsilon_{Nd}(T)$ values, hence juvenile nature. Six samples with negative $\varepsilon_{Nd}(T)$ values (from -1.8 to -3.9) come from the 'Altai-Mongolian terrane', a contiguous part of the Chinese Altai. This obviously reflects the effect of Precambrian crust in the granitoid petrogenesis.

Similarly, the granitoids emplaced in the Chinese Altai composite terrane show a wide range of isotopic compositions and model ages (Fig. 7a, b). A tight relationship between the isotopic compositions of granitoids and the nature of their basement rocks can be established. An extensive Sm–Nd isotope study by Hu *et al.* (2000) reveals that the basement rocks of Altai and Tianshan were largely produced in the Proterozoic, but that of Junggar seem to represent very young accreted terrane with little Precambrian history (Chen & Jahn 2004). The parallel manifestation of isotopic compositions and model ages between basement rocks and intrusive granites argue for the significant role of crustal 'contamination' in the genesis of the Phanerozoic granitoids. An implication is that the presence of old Precambrian microcontinents is significant in the accretionary history of Central Asia.

East-central Kazakhstan. Heinhorst *et al.* (2000) undertook a comprehensive study of mineralization in association with a variety of magmatic rocks in east-central Kazakhstan. Although the types of mineralization (Au, Cu, rare-metal, or REE) may be related to a particular magmatic suite or a lithological variety, most granitic rocks have positive $\varepsilon_{Nd}(T)$ values irrespective of their compositions, here represented by SiO_2 contents (Fig. 8a; Heinhorst *et al.* 2000). The granitoids were intruded in several episodes: 450 and 300 Ma for magmatic suites with gold mineralization, about 300 Ma for granitoids with rare-metal mineralization, and *c.*250 Ma for A-type granites with REE mineralization. There is a slight tendency for an increase of $\varepsilon_{Nd}(T)$ with younger ages of the rocks (Fig. 8b). Single-stage model ages for all cases are between 400 and 1500 Ma.

The above data for the southern belt of the CAOB–from Kazakhstan, northern Xinjiang, Inner Mongolia to NE China, covering a distance



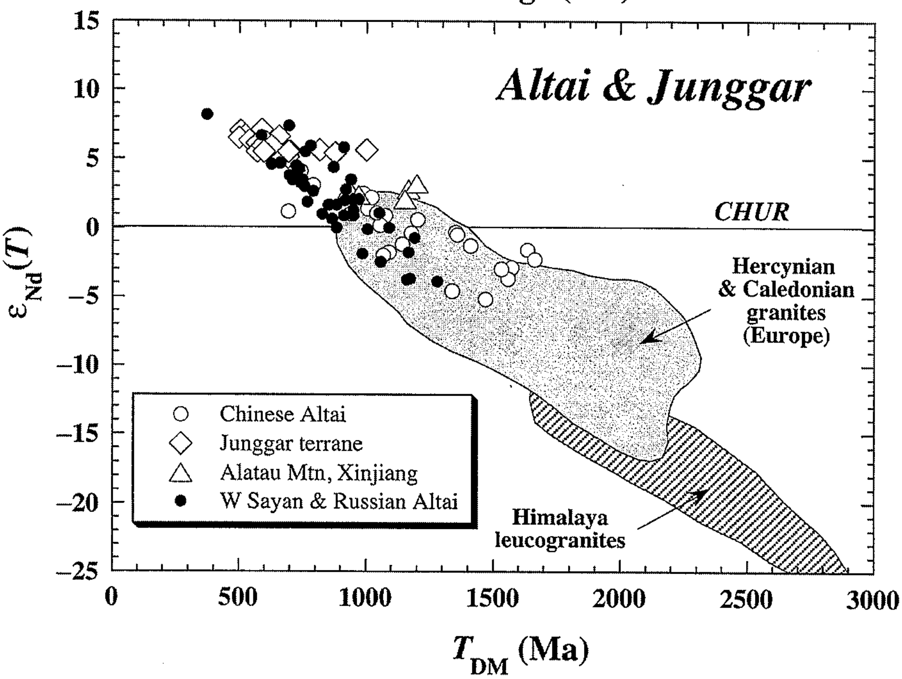
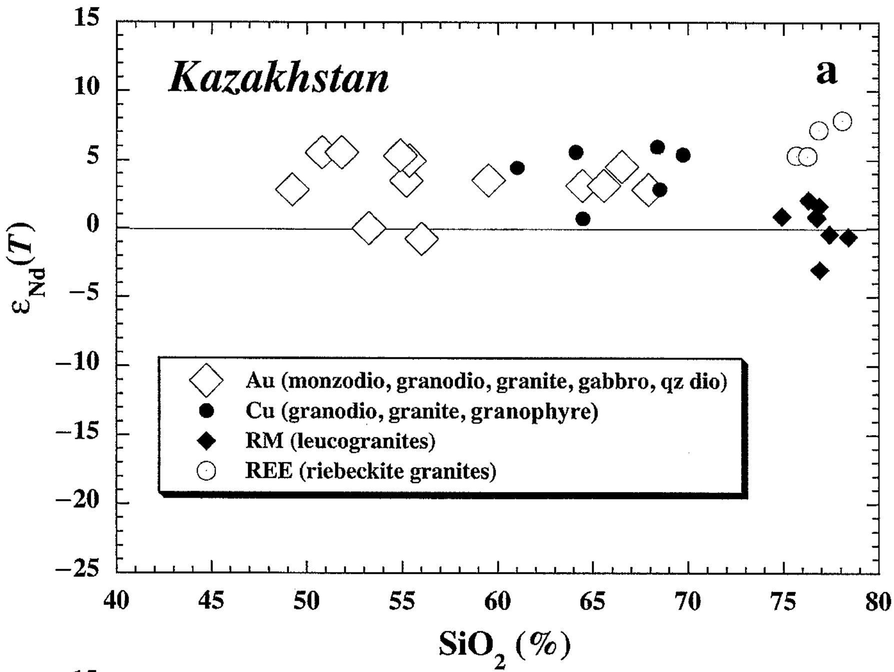


Fig. 7. Isotope diagrams for granitoids from the Altai Mountians (Chinese and Russian) and Junggar terrane. (**a**) $\varepsilon_{Nd}(T)$ v. intrusive ages, (**b**) $\varepsilon_{Nd}(T)$ v. T_{DM} plot. Data sources: **Chinese Altai**: Zhao (1993), Junggar: Han *et al.* (1997), Chen and Jahn (2002), **Alatau**: Zhou *et al.* (1995), **Western Sayan and Gorny Altai**: Kruk *et al.* (2001).



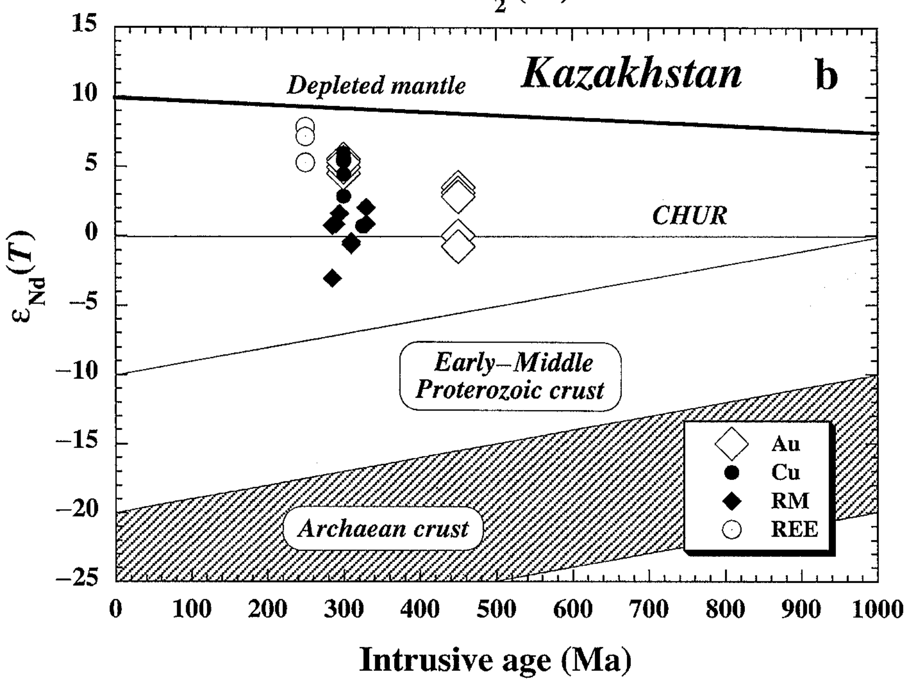


Fig. 8. Isotope diagrams for granitoids from east-central Kazakhstan. (**a**) $\varepsilon_{Nd}(T)$ v. SiO_2, and (**b**) $\varepsilon_{Nd}(T)$ v. intrusive ages. Data source: Heinhorst *et al.* (2000).

of nearly 5000 km, indicate that most of the granitoids, despite their highly differentiated nature and sometimes strong hydrothermal alteration leading to important mineralizations, possess a clear signature of high proportions of the mantle component in their petrogeneses.

Central Mongolia to Transbaikalia. The Nd–Sr isotopic compositions of granitoids from the northern belt of central Mongolia to Transbaikalia have been extensively studied by Kovalenko *et al.* (1992, 1996, 2004). These authors delineated four isotope provinces ('Precambrian', 'Caledonian', 'Hercynian', and 'Indosinian'), which coincide with three tectonic zones of corresponding ages for the northern belt of the CAOB, and with one (Indosinian) in Inner Mongolia and NE China (Kovalenko *et al.* 2004). Presented in Figure 9a, b, c are the published data of Kovalenko *et al.* (1996) and the recently acquired Nd isotopic data for granitoids from three regions:

(1) the Baydrag and Hangay terranes of west-central Mongolia (Kozakov *et al.* 1997; Jahn *et al.* 2004);
(2) northern Mongolia (Jahn, unpublished); and
(3) Transbaikalia (the Bryansky and Tsagan–Khurtei complexes; Litvinovsky *et al.* 2002*b*).

The Transbaikalian and northern Mongolian samples roughly correspond with the 'Barguzin' belt and 'Caledonides' of Kovalenko *et al.* (2004). The Baydrag terrane is the only Precambrian microcontinent containing granulitic and amphibolitic gneisses of Archaean ages. The Barguzin Belt and the Hangay–Hentey Basin are known to be 'composite' terranes comprising Proterozoic and Phanerozoic formations.

The Hangay–Hentey Basin occupies a large area in central to north-central Mongolia. The basin is filled with Cambrian to Carboniferous sediments, mainly of shallow-marine origin, and volcanics. It is intruded by impressive amounts of Early Palaeozoic to Mesozoic granitoids. The granitoid belt extends to Transbaikalia and further to the Sea of Okhotsk. The tectonic significance of the basin is controversial. Zorin (1999) and Parfenov *et al.* (1999) considered the basin as an accretionary wedge, whereas Sengör and Natal'in (1996), following Zonenshain *et al.* (1990), took it as part of the Mongol–Okhotsk oceanic gulf. Alternatively, it has also been suggested to be a back-arc basin formed within an Andean type margin produced by northward subduction of the South Mongolian oceanic plate (Gordienko, 1987), or as a post-orogenic successor basin formed on the Early Palaeozoic basement of northern Mongolia (Ruzhentser & Mossakovsky 1996). Note that although the Mongol–Okhotsk ocean basin has been frequently hypothesized in tectonic models, its closure history and location of suture zone have never been clearly defined (Badarch *et al.* 2002). Based on Nd isotopic data, Kovalenko *et al.* (1996, 2004) suggested that the southern Hangay Basin is underlain by Precambrian rocks.

As shown in Figure 9a, b, c, Phanerozoic granites emplaced into 'Caledonian' and 'Hercynian' provinces have positive $\varepsilon_{Nd}(T)$ values, suggesting their juvenile characteristics, whereas those intruded into the Baydrag and the composite terranes (Barguzin and Hangay–Hentay) show $\varepsilon_{Nd}(T)$ values from positive to negative, indicating variable but always minor contributions of Precambrian crust in the generation of the granitic rocks. Note that some Late Neoproterozoic to Early Palaeozoic granites (600–500 Ma) have $\varepsilon_{Nd}(T)$ values as high as +10 (Fig. 9b), suggesting their derivation from an almost pure depleted mantle component (=100% basaltic source).

In addition to the Nd isotopic evidence, oxygen isotope analyses of alteration-resistant titanites from anorogenic granites of Transbaikalia (Wickham *et al.* 1995, 1996) show a progressive decrease in $\delta^{18}O$ of titanite (sphene) from +6.5‰ in the earliest suite (*c.*450 Ma) to +1.5‰ in the youngest suite (*c.*220 Ma). This corresponds with a decrease in whole-rock $\delta^{18}O$ from +11‰ to +6‰. It appears that whereas the older granitoids with higher $\delta^{18}O$ values may have a crustal heritage, the younger magmas, particularly the A-type granites, became increasingly mantle-like in terms of their oxygen isotopic composition. This suggests that a series of important crust growth events was taking place in Central Asia in the Late Phanerozoic.

Discussion

Genesis of the Phanerozoic crust in the CAOB

Windley (1993, 1995) distinguishes two types of orogens:

(1) collisional orogens, formed by collision and amalgamation of two or more large continental blocks (e.g. Himalayas, Alps, Grenville, etc.), and
(2) accretionary orogens, formed by accretion of island-arc complexes and intervening accretionary prisms, etc. (e.g. CAOB, North American Cordillera, Andes, Birimian, Nubian–Arabian, etc.).

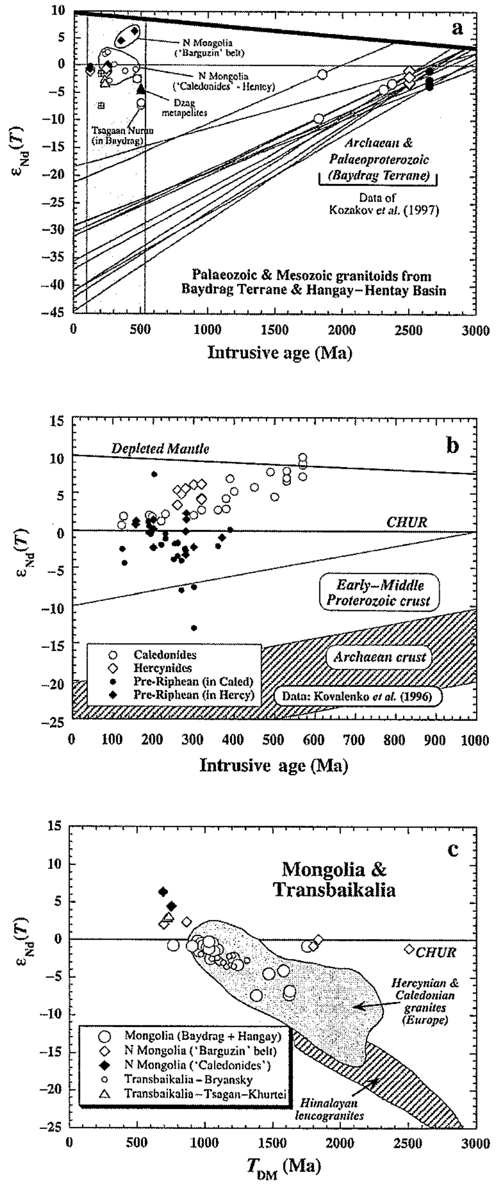


Fig. 9. Isotope diagrams for granitoids from Mongolia and Transbaikalia. (**a**) ε_{Nd} (T) v. intrusive ages for granitoids of west-central Mongolia (data: Jahn *et al.* 2004; Kozakov *et al.* 1997); (**b**) $\varepsilon_{Nd}(T)$ v. intrusive ages for granitoids of Mongolia and Transbaikalia (data: Kovalenko *et al.* 1996). Granites intruded in 'Caledonian and Hercynian' belts (open symbols) are characterized by positive ε_{Nd} (T) values, whereas those intruded in pre-Riphean basement (black symbols) have both positive and negative $\varepsilon_{Nd}(T)$ values. (**c**) ε_{Nd} (T) v. T_{DM} plot for west-central Mongolia and Transbaikalia (data: Jahn *et al.* 2004).

The CAOB is a prime example for accretionary tectonics. The Central Asian orogenic system evolved during a span of about 400–450 Ma since the Vendian. Documented field data clearly indicate that many lithological assemblages represent products of oceanic and subduction-related processes (Sengör *et al.* 1993; Kovalenko *et al.* 1995; Sengör and Natal in 1996; Badarch *et al.* 2002). The lithology includes ophiolite suites, ocean island and seamount fragments, fore-arc/back-arc basin assemblages, and accretionary complexes. These rocks are evidently of mantle derivation, at least for most of them. If the CAOB is entirely accreted from such lithological assemblages, then its juvenile character is easily justified without conformation from isotopic studies. However, the voluminous distribution of granitoids in the CAOB requires further explanation.

Granitoids are the most representative 'continental component'. They probe the lower part of the continental crust. Reputedly, they also have the most diverse and controversial origins. Since the CAOB contains Precambrian microcontinental fragments, probably derived from Gondwana (Zonenshain *et al.* 1990; Buslov *et al.* 2001) as well as from Laurasia (Berzin and Dobretsov 1994), determination of their juvenile v. recycled nature is important for understanding the growth rate of the continental crust and the geodynamic evolution of the orogen. This can only be achieved through using radiogenic isotope tracer techniques. The most striking feature of the granitoids from Central Asia is their dominantly positive $\varepsilon_{Nd}(T)$ values, low I_{Sr} ratios and young T_{DM} model ages (Kovalenko *et al.* 1996, 2004; Jahn *et al.* 2000*a*, *b*, 2004; Chen *et al.* 2000; Wu *et al.* 2000, 2002, 2003*a*, *b*; Chen & Jahn 2004). That is, much of the crust in the CAOB was made up of 'young' mantle-derived material. Such a conclusion is essentially identical to that reached by Sengör *et al.* (1993) on the basis of their geological and tectonic analyses. The ultimate message is clear: the formation of a large composite continent, like Asia, involves not only amalgamation of broken-up supercontinental fragments (e.g. the Angara and Sino-Korean cratons), but also massive addition of juvenile material from the upper mantle.

Two mechanisms may be envisaged for the growth of the continental crust (e.g. Rudnick 1995):

(1) Lateral growth: melting of mantle-wedge or subducted oceanic crust in convergent plate margins where the most active crust–mantle interaction takes place. In this case, magmas are formed mainly by melting of mantle-wedge peridotites that have been metasomatized by fluids/melts

released from subducted oceanic crust, or, occasionally, by direct melting of subducted basaltic crust when the subducted slab is hot. These magmas, mainly basaltic to andesitic, make up the bulk of the arc complexes, and accretion of arc complexes, including fore-arc/back-arc sediments, contributes to the 'lateral growth' process.

(2) Vertical growth: overplating of volcanic rocks and underplating of mantle-derived basaltic magmas near or at the crust–mantle interface within pre-existing continental blocks or accreted arc complexes. Subsequent differentiation and melting of the lower crustal mixed lithologies triggered by hot underplated basaltic magmas contributes to the formation of new crust. This is the 'vertical growth' process.

Both processes have probably played equally important roles in the making of the CAOB throughout the Phanerozoic. The lateral growth process appears indisputable in the concept of the plate tectonics, and Sengör *et al.* (1993) even used 'magmatic front' as a new tool to delineate the tectonic evolution of the Altaid Collage. The vertical process may be controversial, but it could be the most viable process to explain the impressive belts of post-collisional peralkaline and A-type granitoids in Central Asia. The idea expressed herein is illustrated in Figure 10.

Formation of 'syn-orogenic' granitoids of arcs and accreted arcs

Granitic rocks are commonly abundant in continental arcs, but are generally trivial in oceanic island arcs. Such a contrast is likely to be due to the different nature of the crust overlying the zones of melt generation (Fig. 10a). However, the CAOB is essentially accreted from oceanic arcs and ancient microcontinental mass; the latter is limited in number and size. But, why has there been such a widespread felsic (granitic and rhyolitic) magmatism since the early Palaeozoic?

The granitoids of the CAOB may be considered to fall into two broad categories:

(1) Those formed during the building of an arc (Fig. 10a), following the accretion of arc complexes, and possibly in the arc–microcontinent collision (Fig. 10b); these will be collectively called as 'syn-orogenic' granitoids. This would correspond roughly with the 'early granitoids' of Litvinovsky and Zanvilevich (1998), and the lithology includes the tonalite–granodiorite–granite, tonalite–plagiogranite, and quartz monzonite–granite series.

(2) Those formed after the accretion of arc complexes and during the post-accretion extensional or rifting tectonic phase (Figs 10c, d). These are understood as 'post-accretionary' and correspond with the often used term of 'post-collisional' granitoids in the literature.

Accretion of arc complexes, especially if subparallel and along-margin transport of the arc terrane is involved (e.g. Patchett and Chase 2002), is likely to result in 'soft collision', which lacks the dynamics to form significant thrust belts or nappes. Thus, the use of terms like 'syncollisional' or 'post-collisional' may be somewhat misleading for the case of Central Asia. In Transbaikalia and Mongolia, the post-accretionary granitoids are represented by quartz syenite–granite, monzonite–syenite–granite, syenite-granite, and alkaline to peralkaline granite series (Litvinovsky and Zanvilevich, 1998). In general, the abundance of synorogenic granitoids in the CAOB is overshadowed by that of post-accretionary granitoids. However, the precise proportion remains to be determined.

For the generation of granitoids in individual arcs, the process is known in the subduction zones to involve melting of the mantle wedge followed by magmatic differentiation, or direct melting of the warm subducted slab, forming tonalite–trondhjemite–granodiorite (TTG) or adakite magmas (Fig. 10a). Arc complexes also comprise rocks of sedimentary origin, including clastic and calcareous sediments. The subsequent accretion of arc complexes might not induce melting without further heat supplies. A good example is that the modern arc–continent collision of Taiwan (at an oblique angle) does not produce significant magmatism. To engender large volumes of granitic magmas, accreted arc complexes might have been underplated by basaltic magma which was buoyantly blocked at the lower crust (Fig. 10c). Basaltic underplating provides the necessary heat source for melting, and also materially participates in felsic magma generation (Fig. 10d). How the basaltic liquids are generated in the first place is quite debatable, but the parallel evolution of chemical composition between the granitoids and contemporaneous basaltic rocks (Litvinovsky and Zanvilevich, 1998) observed in Transbaikalia provides the best evidence for the participation of basaltic magma in the generation of granitoids (Fig. 11).

To achieve a high-temperature melting, as suggested from melt inclusion studies for some granites (Litvinovsky *et al.* 2002*a*, *b*), crust overthickening may be another viable process

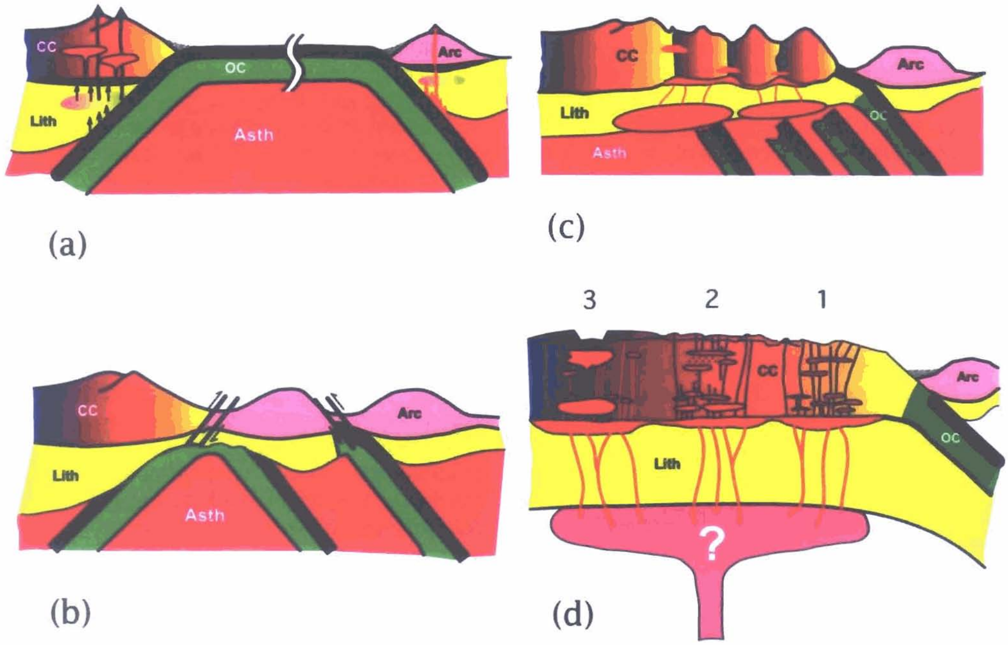


Fig. 10. Schematic diagrams showing the growth of continental crust by lateral and vertical accretion. (**a**) Generation of arc magmas in a continental arc (left side) via partial melting of a mantle wedge, followed by a series of processes (basaltic underplating, assimilation of lower crust, melting of mixed lithologies, magma differentiation), leading to formation of arc granitoids. Subduction of a young and hot oceanic lithosphere may produce TTG (tonalite–trondhjemite–granodiorite) or adakitic magmas in an intra-oceanic arc setting (right side). (**b**) Accretion of island arcs to the continental margin. New arcs are formed by back-stepping of subduction zone. They are then accreted again to the continental margin. Together they enlarge the mass and size of the continental crust by lateral accretion processes. (**c**) Generation of granitic magmas in accreted arc complexes. Basaltic underplating provides heat and material (=mantle component) for the magma generation. Initial basaltic magma could be produced by partial melting of mantle peridotites at the lithosphere/asthenosphere interface after delamination of the oceanic lithosphere. (**d**) Intracrustal melting for the generation of post-orogenic granitoids. This is achieved by a combination of processes, including crustal and lithospheric extension, melting of mantle plume, underplating of basaltic magma at the base of the crust, partial melting of 'young' crust and magmatic differentiation.

in addition to basalt underplating. This process is considered very likely in continent–continent collisional orogens, like the Himalayas, but it is rather ambiguous or may be unfavourable for an accretionary orogen like the CAOB. However, if accreted arc complexes contain sufficient water-saturated sediments, then melting could be promoted by the added water.

In conclusion, the synorogenic granitoids were probably generated in two stages: first during the building of individual arcs via subduction zone magmatism, and then conversion of arc complexes plus underplated basaltic liquids within accreted arc complexes. Melting of accreted arc complexes may be further promoted by water-saturated sediments. Finally, the syn-orogenic granitoids dominate the felsic magmatism of the early Palaeozoic ($\geq$300 Ma) when arc complexes were being built.

Origin of post-accretional granitoids–via vertical growth

Although many plutons and batholiths of the CAOB have the calc-alkaline characteristics typical of subduction zone magmatism, the emplacement of voluminous granites of the alkaline and peralkaline series deserves attention. Petrogenetically, these rocks are akin to the A-type granites, which are generally known to form in post-collisional extensional (rifting) environments. In the CAOB, two gigantic belts of alkaline granites are recognized:

(1) the northern belt from northern Mongolia to Transbaikalia, and
(2) the southern belt from the Gorny Altai through southern Mongolia, Inner Mongolia to the Great Xing'an and Zhangguanggcai Ranges in NE China.

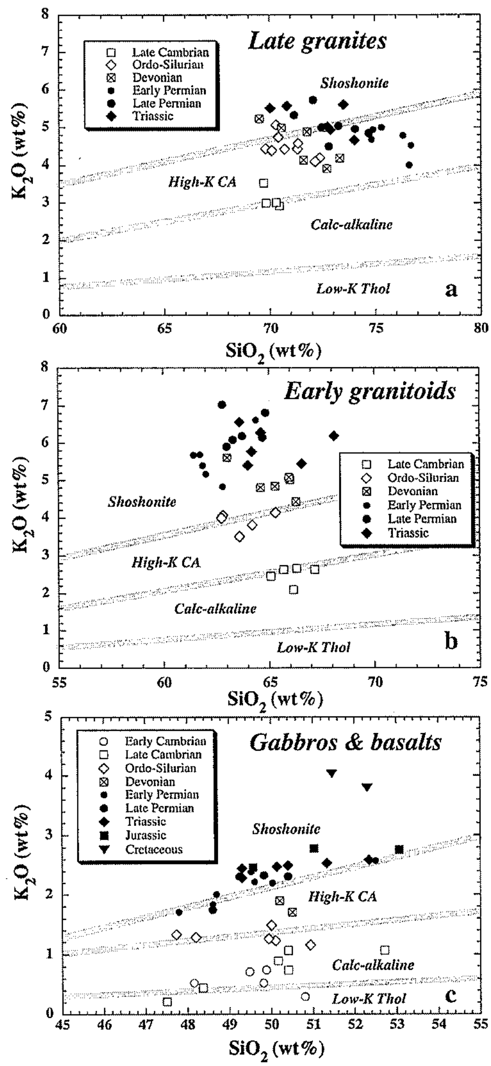


Fig. 11. Chemical evolution of basic and granitic rocks from the Mongolian–Transbaikalian belt, as represented by the K_2O v. SiO_2 plots (data from Litvinovsky and Zanvilevich, 1998). Increase of K_2O as rocks become younger is clearly indicated for late granites ('post-collisional'), early granites (synorogenic) and gabbros/basalts. This suggests that the ultimate mantle source is increasingly enriched in alkali elements through time. The parallel evolution between basic and granitic rocks further implies that basaltic magmas have materially participated in the genesis of granitoid rocks. The boundary lines are taken from Le Maitre *et al.* (1989) and Rickwood (1989).

The northern belt is probably the largest province of peralkaline granitoids, which extends over 2000 km with a width of 200–300 km, and occupy a total area of $\geq$500 000 km^2 (Kovalenko *et al.* 1995; Zanvilevich *et al.* 1995). It comprises more than 350 massifs of peralkaline granitoids and a number of bimodal volcanic rocks of the basalt–trachyrhyolite–comendite series. The largest Bryansky pluton has a dimension of about 1500 km^2, emplaced at *c.*280 Ma, and is composed of a syenite-to-granite series (Yarmolyuk *et al.* 2001; Litvinovsky *et al.* 2002*a*, *b*). The entire belt was developed in several stages from Devonian to Cretaceous, with the main pulses of peralkaline granitic plutons and their volcanic analogues during the Permian and Triassic.

The southern belt is equally impressive in the length of distribution, but the total volume appears less important in comparison with the northern belt. In the Gorny Altai (Russia), A-type granitoids were emplaced at two stages: Permo-Triassic (250 Ma) and Triassic–Jurassic (200 Ma), in probably the largest Permo-Triassic rift system in Asia (Vladimirov *et al.* 1997). In the Junggar terrane of northern Xinjiang and in Inner Mongolia, A-type granites were formed at 300–280 Ma (Hong *et al.* 1995; Han *et al.* 1997; Zhao *et al.* 2000; Chen & Jahn 2004). In NE China, several hundred granitic bodies have been identified and constitute an area of *c.*100 000 km^2. A-type granites are mainly distributed in the Great Xing'an and Zhangguangcai Ranges, but they were emplaced in three episodes (Jahn *et al.* 2001; Wu *et al.* 2002):

(1) Permian (300–280 Ma);
(2) Late Triassic to Early Jurassic (210–180 Ma), and Cretaceous (*c.*120 Ma).

It appears that throughout the entire southern belt, post-accretionary A-type granites were emplaced in the Late Palaeozoic, Early Jurassic and Cretaceous.

All these rocks possess positive to slightly negative $\varepsilon_{Nd}(T)$ values (+7 to −4) and young model ages (T_{DM}) of 500–1300 Ma, which are summarized in Figure 12 (Kruk *et al.* 1998; Jahn *et al.* 2001; Chen & Jahn 2004; Wu *et al.* 2002; Litvinovsky *et al.* 2002*a*, *b*; Jahn, unpublished). This advocates that the source of post-accretionary granitoids in the CAOB is dominated by the mantle-derived component, rather than recycled ancient crust, as has been documented for some occurrences in SE China (e.g. Charoy & Raimbault 1994; Darbyshire & Sewell 1997). In most cases, rocks of mantle derivation have also been contaminated by crustal material. Models involving mixing of mantle-derived magmas and crustal components (assimilated crustal rocks or crust-derived

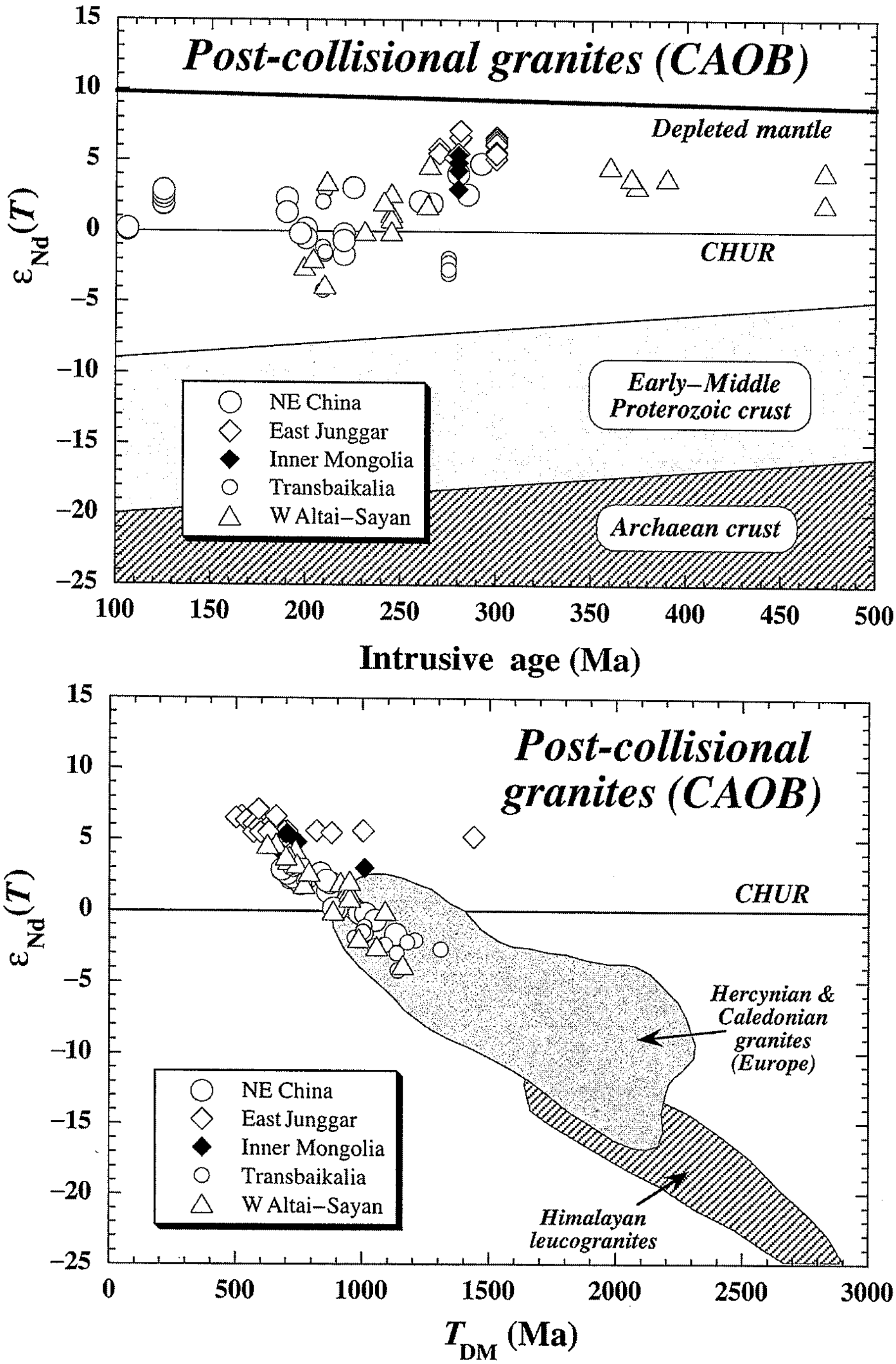


Fig. 12. Isotope diagrams for A-type granitoids from Central Asia. (**a**) ε_{Nd} (T) v. intrusive ages, and (**b**) $\varepsilon_{Nd}(T)$ v. T_{DM} plot. Data source: **NE China**: Wu *et al.* (2002), **eastern Junggar**: Chen and Jahn (2002), **Inner Mongolia**: Jahn (unpubl.), **Transbaikalia**: Jahn (unpubl.), Yarmolyuk *et al.* (2001), western Sayan–Gorny Altai: Kruk *et al.* (2001).

magmas), followed by fractional crystallization, are most acceptable.

The production of a huge amount of alkaline to peralkaline granites was very likely initiated by large-scale crustal extension and accompanied basalt underplating. This has been suggested to be connected with mantle plume activities. A Siberian superplume has been proposed for the Northern Mongolia–Transbaikalia Belt (Yarmolyuk *et al.* 2001; Kovalenko *et al.* 2004). The geological manifestations of a superplume are not expected to have a sharp chronology, particularly when intrusive events are concerned. A sharp chronology can only be observed in basaltic volcanism related to large plume head melting, such as the 65 Ma Deccan Traps (Courtillot *et al.* 1986), the 184 Ma Karoo Traps (Encarnacion *et al.* 1996; Duncan *et al.* 1997), or the 250 Ma Siberian Traps (Renne and Basu 1991; Campbell *et al.* 1992; Renne *et al.* 1995). Magmatic differentiation and cooling of magmatic bodies in plutonic conditions would retard the radiochronometers to different degrees for intrusive rocks. Consequently, intrusive rocks of different ages, up to several tens of millions of years, could be related to the same superplume activity. The hypothesized Siberian superplume could be responsible for the Siberian Trap, as well as all the post-collisional granitic intrusions in the period from 250 to 200 Ma. Note that the magmatism of a superplume need not be spatially contiguous; it would take place where the lithosphere is thin, favouring decompressional melting. Yarmolyuk *et al.* (2001) observed that the intraplate magmatism (peralkaline granites and bimodal basalt–comendite) was centred around the Hangay batholith in Mongolia in the Permian. The centre was then shifted eastward to the Hentay batholith and Transbaikalia in the Triassic. To these authors, this suggests a westward displacement of 800 km for the CAOB relative to a mantle plume.

Stein and Goldstein (1996) argued that the present-day arc magmatism is commonly associated with oceanic plateaux, hence suggesting that generation of large amounts of continental lithosphere (crust and mantle) over short periods is probably associated with plume head magmatism. They further advanced this idea for the formation of the Arabian–Nubian Shield, which was considered to build up initially from an oceanic plateau as a result of melting of a plume head. Upon reaching a convergent margin, the thick oceanic plateau resisted subduction, and plate convergence took place on its own margins, generating calc-alkaline magmas. Later transition from calc-alkaline to alkaline magmatism would mark the end of plate convergence. They considered that alkaline magmatism was associated with melting of enriched lithospheric mantle, and that the transformation from plume head to continental lithosphere has been an important process of crustal growth.

The manifestation of oceanic plateaux in the CAOB remains to be identified. The Permian and Cretaceous A-type granites in NE China seem to be better explained by a delamination model, in which the lithospheric delamination was followed by upwelling and partial melting of the asthenosphere (Wu *et al.* 2002). While the lateral growth mechanism via accretion of arc complexes undeniably played an important part in the making of the CAOB, the vertical growth through intraplate magmatism has probably contributed even more significantly to the formation of the gigantic orogenic belt and the enlargement of the Asian continent. Certainly, a prerequisite of such enlargement is the presence of crustal extension. If not, the underplated mafic rocks could be nullified by likely delamination. In the case of the CAOB, rifting reached its climactic phase during the Permian and Triassic (e.g. Kovalenko *et al.* 2004).

Estimate of the proportions of juvenile crust, and its implications

The proportions of juvenile crust in any given area in the CAOB must be evaluated from detailed knowledge about the distribution of lithological types, of which the granitoids must be further estimated using the isotope tracer technique. This is not an easy task. However, for individual granitoid bodies, this can be done reasonably well using a simplistic two-component mixing calculation. Assuming a fixed depleted mantle ($\varepsilon_{Nd} = +8$) and variable crustal end-members, the result of calculation is shown in Figure 13. The proportion of the mantle component (or percentage of juvenile crust) for positive $\varepsilon_{Nd}(T)$ granites varies from 60 to 100%, depending on the compositions of the assumed crustal end-members. We take the Nd isotopic composition of the Jiamusi Massif for NE China ($\varepsilon_{Nd} = -12$), the Baidarik Block for Central Mongolia (-30, Fig. 9), the basement gneisses for Altai (-15; Hu *et al.* 2000), Junggar (-4), and the Kazak basement is assumed to be the same as the Altai gneisses. For the Mongolian granitoids with $\varepsilon_{Nd}(T)$ values of -5 or higher, the proportion of juvenile crust is 80% or higher. Kovalenko *et al.* (2004) made an extensive compilation of Nd isotope data, and showed that basaltic rocks of Permian and younger in

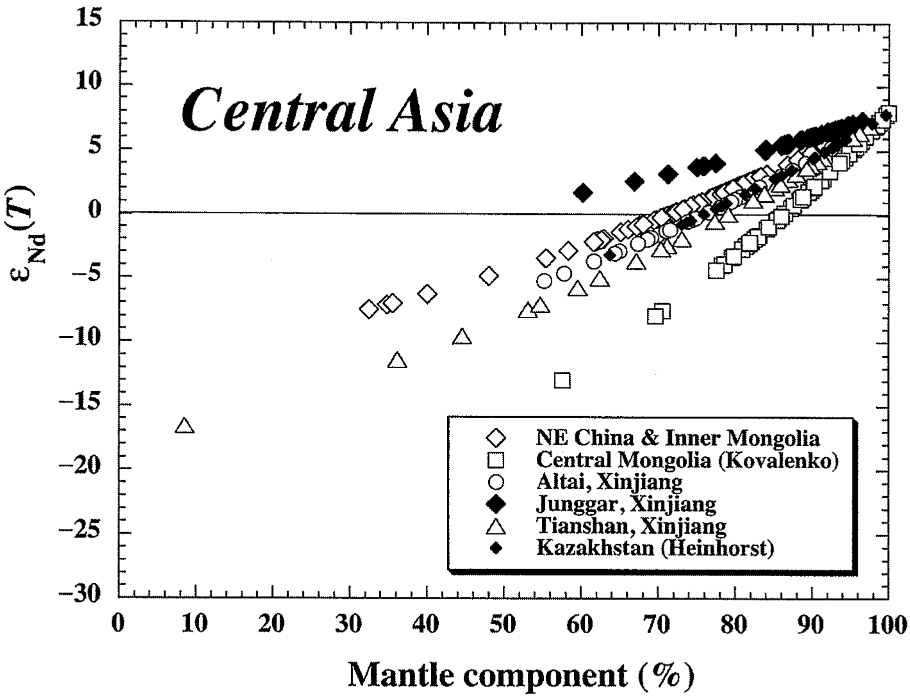


Fig. 13. Estimate of proportions of the mantle or juvenile component in the generation of Central Asian granitoids. The equation used is:

$$X^{m} = (\varepsilon^{c} - \varepsilon^{r})Nd_{c}/[\varepsilon^{r}(Nd_{m} - Nd_{c}) - (\varepsilon^{m}Nd_{m} - \varepsilon^{c}Nd_{c})]$$

where X^{m} = % mantle component (represented by basalt). ε^{c}, ε^{r}, ε^{m} = Nd isotope compositions of the crustal component, rock measured, and mantle component, respectively. Nd_c, Nd_m = Nd concentrations in the crustal and mantle components, respectively. Parameters used: $\varepsilon^{m} = +8$, $\varepsilon^{c} = -12$ (NE China), -30 (Central Mongolia), -15 (Altai and Kazakhstan), -4 (Junggar), -18 (Tianshan). Nd_m = 15 ppm, Nd_c = 25 ppm.

Mongolia and Transbaikalia are characterized by rather low $\varepsilon_{Nd}(T)$ values ($\leq +3$). Interpretation of the low values could be multiple without added constraints. However, trace-element abundances of mafic rocks and granitoids from Transbaikalia (e.g. Litvinovsky *et al.* 2002*a*, *b*) strongly suggest that their ultimate mantle sources were enriched. If a lower $\varepsilon_{Nd}(T)$ value is used for the mantle component in the mixing calculation, then the proportion of the mantle component would be further enhanced.

In any case, the general scenario in Central Asia as shown in Figure 13 implies extensive mantle differentiation and rapid crustal growth during the Phanerozoic. However, a significant proportion of recycled crust is also 'isotopically' visible in the granitoids emplaced in the Jiamusi Massif, Altai and Tianshan composite terranes, and Pre-Riphean zones of Mongolia as exemplified by the present study.

Conclusions

These are as follows:

(1) The Central Asian Orogenic Belt (CAOB) that welded together the Siberian and Sino-Korean cratons is characterized by very abundant granitic rocks of Palaeozoic to Mesozoic ages. The Nd–Sr isotopic data show that most of these granitic rocks are very juvenile. Considering the immense geographical coverage, the CAOB represents undoubtedly the most important site of crustal growth in the Phanerozoic.

(2) The tectonic evolution of the CAOB is mainly related to accretion of arc complexes, as suggested by Sengör *et al.* (1993). This idea is generally supported by the available Sr–Nd–O isotopic data (Wickham *et al.* 1995, 1996 for oxygen isotopes). However, the granites with negative $\varepsilon_{Nd}(T)$ values require the existence of old Precambrian blocks; thus, accretion of old terranes is confirmed.

(3) Conversion of arc assemblages into granitoids (=intracrustal differentiation) was most likely triggered by underplating of basaltic magma, which provided not only the heat source but also the added juvenile material. The process involved mixing of underplated magma and lower crustal rocks, and melting of the mixed sources, and was followed by fractional crystallization.

(4) The origin of A-type granites has long been controversial, but most post-accretionary A-type granites from the CAOB are demonstrably of mantle origin (*sensu lato*). The generation of voluminous Late Permian to Cretaceous alkaline and peralkaline granites could be related to the Siberian superplume and to the lithospheric delamination. In this connection, intraplate magmatism was an important process – in addition to the lateral accretion of arc complexes – of crustal growth in the Phanerozoic.

(5) The rate of apparent crustal growth for the entire period of the Phanerozoic may be estimated, but the growth rate at any given time interval of 50–100 Ma is not possible, due to the paucity of reliable age data for many granites. For the entire Altaid Collage, Sengör *et al.* (1993) estimated that during the 350 Ma of crustal evolution, a total area of about 2.5 million km^2 of juvenile crust was added to Asia. This is translated into a growth rate of about 0.3 km^3/year. Combining this with that of the Canadian Cordillera (about 0.15–0.23 km^3/year, Samson *et al.* 1989; Samson and Patchett, 1991) and western United States (DePaolo *et al.* 1991), the new rate would be at least 50% higher than the global growth rate of *c.*1.1 km^3/year, deduced from arc magmatism by Reymer and Schubert (1984, 1986). Consequently, the recent 'discovery' of juvenile crust in several Phanerozoic orogenic belts, in particular the CAOB, may considerably change our views on the growth rate of the continental crust.

I have benefited from close collaboration with many of my colleagues in Rennes (R. Capdevila), in China (Fuyuan Wu, Bin Chen and Aiqin Hu), and elsewhere (B. Litvinovsky, A. Zanvilevich, S. Wilde) during the last five years since the launch of the IGCP-420 project: *Crustal Growth in the Phanerozoic: Evidence from East-Central Asia.* I have also learned a great deal about the geology of northern Xinjiang, west-central Mongolia, the Gorny Altai in southern Siberia and NE China, during the past field workshops. Unesco's support of this project is highly appreciated. The constructive comments of R. Capdevila, B. Litvinovsky, Shen-su Sun, Fuyuan Wu, Bin Chen, V. I. Kovalenko, W. Collins and an anonymous reviewer have significantly improved the final version. The financial assistance of the Croucher Advanced Studies Institutes made it possible for me to deliver this lecture at the University of Hong Kong. This is a contribution to *IGCP-420: Crustal Growth in the Phanerozoic: Evidence from East-Central Asia.* The National Science Council of Taiwan provided financial support for the final preparation of this article.

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