Important crustal growth in the Phanerozoic: Isotopic evidence of granitoids from east-central Asia

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The growth of the continental crust is generally believed to have been essentially completed in the Precambrian, and the amount of juvenile crust produced in the Phanerozoic is considered insignificant. Such idea of negligible growth in the Phanerozoic is now challenged by the revelation of very large volume of juvenile crust produced in the period of 500 to 100 Ma in several orogenic belts. While appreciable volumes of juvenile terranes in North America (Canadian Cordillera, Sierra Nevada and Peninsular Range, Appalachians) have been documented based on Nd isotopic data, the mass of new crust formed in the East-Central Asian Orogenic Belt (ECAOB), eastern part of the Altaid Tectonic Collage, appears to be much greater than the above terranes combined. New and published Nd-Sr isotope data indicate that the Phanerozoic granitoids from the southern belt of the ECAOB (Xinjiang-West Mongolia-Inner Mongolia-NE China) as well as from Mongolia and Transbaikalia were generated from sources dominated by a depleted mantle component. These granitoids represent a significant growth of juvenile crust in the Phanerozoic.

Although most plutons in this huge orogenic belt belong to the calc-alkaline series, the ECAOB is also characterized by the emplacement of voluminous A-type granites. The origin of these rocks is probably multiple and is still widely debated. However, the isotopic data (Sr-Nd-O) and trace element abundance patterns of A-type granites from the ECAOB clearly indicate their mantle origin.

The evolution of the ECAOB and the entire Altaid Collage is most likely related to successive accretion of arc complexes. However, the emplacement of a large volume of post-tectonic A-type granites requires another mechanism—probably through a series of processes including underplating of massive basaltic magma, partial melting of these basic rocks to produce granitic liquids, followed by extensive fractional crystallization. The proportion of juvenile to recycled, as well as that of arc-related to plume-generated, continental crust remains to be evaluated by more systematic dating and isotope tracer studies.

1. Introduction

The terrestrial continental crust is a unique feature among the planets in the solar system. Its formation and evolution is undoubtedly one of the most important subjects of research and debate in earth science. Two major hypotheses have been proposed to explain the evolution of the continental crust. The first proposes that the present mass of the crust was formed very early in the earth history and has been recycled through the mantle in steadily decreasing fashion such that new additions are balanced by losses, resulting in a steady state system (Armstrong 1968, 1981, 1991). The second proposes that the crust grew throughout geological time, with a rapid growth rate in early (Reymer and Schubert 1984, 1986) or in late Archean (Taylor and McLennan 1985, 1995), followed by a diminished rate afterwards. Other hypotheses suggest rates of crustal growth in between the two extremes. Whether or not the continental

mass has been added in an episodic or continuous fashion (Moorbath 1978; Stein and Hofmann 1994) is another issue of debate. In all cases, the amounts of new continental material or juvenile crust formed in the Phanerozoic, and especially in the last 250 Ma, have been considered to be very minor or insignificant. However, this scenario has undergone revision in the last decade through studies of the Canadian Cordillera (Samson *et al* 1989) and east-central Asia.

In east-central Asia, very large volumes of granitic rocks of late Paleozoic to Mesozoic ages were emplaced in the East Central Asian Orogenic Belt (ECAOB), bounded by the Siberian and Sino-Korean cratons (figure 1). The ECAOB and orogenic belts to the west
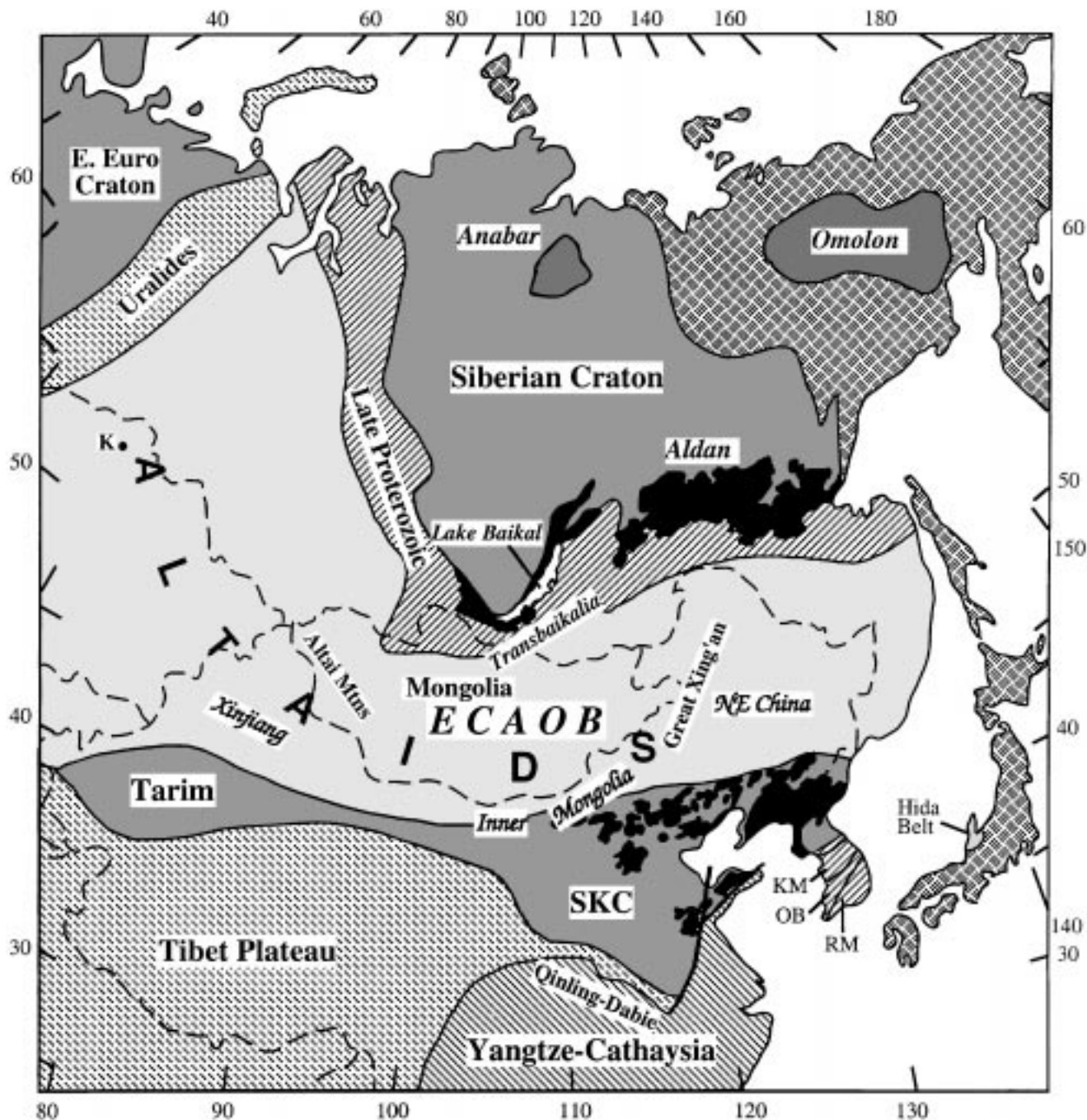

Figure 1. Simplified tectonic divisions of Asia. The East Central Asian Orogenic Belt (ECAOB), equivalent to the eastern part of the Altaid Tectonic Collage (Sengör *et al* 1993), is situated between two major Precambrian cratons: Siberian in the north and Sino-Korean (SKC)-Tarim in the south. Black areas are exposed Archean to early Proterozoic rocks. Crossed pattern on the right-hand side including Japan represents Pacific fold belts. The Hida Belt of Japan may belong tectonically to the ECAOB. **Abbreviations:** K = Kokchetav (in northern Kazakhstan); KM = Kyonggi Massif, OB = Ogchon Belt, RM = Ryongnam Massif (all in Korea).

of it and up to the Ural Mountains have been collectively called Altaid Tectonic Collage (Sengör *et al* 1993; Sengör and Natal'in 1996). The Altaid Collage is different from the classical collisional orogens, such as the Alpine, Himalayan, Hercynian and Caledonian belts. According to Sengör and his collaborators (Sengör *et al* 1993; Sengör and Natal'in 1996), it was formed by accretion of arc complexes produced in subduction zones, and is characterized by the emplacement of immense volumes of granitic magmas and the general absence of nappe complexes imbricating older continental crust. However, the statement on the general absence of nappe complexes has been challenged by subsequent works, particularly in Kazakhstan (e.g., Gruschka *et al* 1997).

In the ECAOB, two gigantic belts of alkaline syenites and granites may be recognized: (**1**) a northern belt from northern Mongolia to Transbaikalia, and (**2**) a southern belt from Xinjiang (western China) through southern Mongolia to NE China (Manchuria). According to recent publications, more than 350 distinct granitic plutons are exposed in northern Mongolia and Transbaikalia and occupy a total area $\geq 500,000 \, \mathrm{km}^2$ (Zanvilevich *et al* 1995; Wickham *et al* 1995, 1996). In NE China, several hundred granitic bodies have been identified and constitute an area of $\approx 100,000 \, \mathrm{km}^2$. Numerous granitic bodies also occur in northern Xinjiang and western Mongolia (Altai Mountains). Undoubtedly, this orogenic belt contains the most voluminous young granitic intrusions in the world. However, the precise time of the emplacement and origin of these granitoids, as well as their geodynamic significance in the context of Phanerozoic continental evolution are still poorly known and remain among the most pressing questions of crustal evolution to be answered.

These granitoids and related rocks of the ECAOB have been poorly studied and received little attention in the western geological literature until recently (Sengör *et al* 1993; Zanvilevich *et al* 1995; Sengör and Natal'in 1996; Wickham *et al* 1995, 1996; Kovalenko *et al* 1996; Hong *et al* 1995, 1996; Han *et al* 1997). Published results and our unpublished geochemical and Sr-Nd isotope data on granites from the southern belt (Northern Xinjiang, Inner Mongolia and NE China) and from Mongolia to Transbaikalia indicate that most of the magmatic activities took place in the last 300 Ma, and that the rocks were formed from ''juvenile'' materials with significant amounts of upper mantle component.

In addition to the Nd isotopic evidence, oxygen isotope analyses of alteration-resistant titanites from 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 ($\approx 450 \, \mathrm{Ma}$) to $+1.5‰$ in the youngest suite ($\approx 220 \, \mathrm{Ma}$). This corresponds to a decrease in whole-rock $\delta^{18}O$ from $+11‰$ to $+6‰$. It appears that whereas the older magmas 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-forming events were taking place in east-central Asia in the late Phanerozoic.

The purposes of this paper are:

- to document the juvenile nature of the Phanerozoic granitoids from the ECAOB based on the existing and our unpublished Nd-Sr isotopic data, and
- to discuss the general implications on the global Phanerozoic crustal growth.

We advocate that the granitic rocks of the ECAOB represent the most significant mass transfer from the mantle to the continental crust in the Phanerozoic.

2. Brief account of lithological characters and emplacement periods of granites

According to Kovalenko *et al* (1995), igneous activities in Mongolia and Transbaikalia continued throughout the entire Phanerozoic without any significant interruption. Most ages of magmatic rocks have been estimated by paleontological data and other stratigraphic means, only a small proportion has been determined by radiochronometric methods.

Since the early Paleozoic, numerous granitic rocks have been emplaced; they include

- the calc-alkaline series (tonalite-granodiorite-granite) of Caledonian ages in northern Mongolia and Transbaikalia (e.g., Angara-Vitim batholith, Litvinovsky *et al* 1992);
- 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;
- the Hercynian (late Carboniferous to Permian) alkaline series in southern Mongolia to NE China and in northern Mongolia to Transbaikalia; Permian granitoids of the calc-alkaline series, represented by the vast Hangay batholith ($\approx 100,000 \, \mathrm{km}^2$) in Mongolia; and
- the early Mesozoic ($\approx 200 \, \mathrm{Ma}$) granites of the calc-alkaline series and S-type granites in the Mongol-Okhotsk belt, plus the alkaline to peralkaline series in Transbaikalia.

Thus, the ECAOB is characterized by the occurrence of voluminous K-rich granitoids which include alkaline and peralkaline granites, syenogranites, syenites and minor granodiorites. Quartz and perthitic feldspar are predominant phases, accompanied by small amounts of plagioclase, mafic and other accessory minerals. Alkaline mafic minerals, such as arfvedsonite, riebeckite and aegirine-augite, are only found

in late alkaline granites and syenites. Many plutons contain abundant miarolitic cavities and igneous layering formed by biotite-rich bands. Mafic enclaves are generally rare; but in Transbaikalia (Zanvilevich *et al* 1995; Wickham *et al* 1995, 1996) significant amounts of mafic rocks occur as enclaves and synplutonic dykes in granitoids of various ages.

The ages of granites roughly decrease from north to south within the ECAOB. In Transbaikalia and northern Mongolia, five main stages of K-rich magmatic activity have been distinguished (Zanvilevich *et al* 1995; Wickham *et al* 1995, 1996): (**1**) Ordovician-Silurian (≈ 450 Ma, U-Pb), (**2**) Devonian (≈ 375 Ma), (**3**) Early Permian (≈ 280 Ma), (**4**) Late Permian (≈ 250 Ma), and (**5**) Triassic (≈ 220 Ma). In northern Xinjiang, granites of high-K to medium-K series appear to dominate; most of these were emplaced intruded in the period of 400-200 Ma (Hu *et al* 2000a, b). However, A-type granites, exposed mainly along the Ulungur River, were intruded at about 300 Ma (Rb-Sr ages, Wang *et al* 1994; Han *et al* 1997). A-type granites in central inner Mongolia were emplaced slightly later at ca. 280 Ma (whole-rock Rb-Sr, Hong *et al* 1995). In both northern Xinjiang and Inner Mongolia, in addition to A-type granites, granitoids of early Paleozoic to Mesozoic ages also occur. Further east to NE China the existing age data indicate three intrusive episodes for K-rich granitoids (Fang, 1992; Wu and Jahn, unpublished results): (**1**) late Permian (270-250 Ma), (**2**) late Triassic-early Jurassic (220-180 Ma), and (**3**) middle Jurassic (170-150 Ma). Thus, there is an apparent younging trend of granitic intrusions from the west to the east along the ECAOB.

In addition to the apparent regional age variation, two trends are also observed:

- a regular decrease in size for younger plutons, and
- 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, with the younging of plutons.

That is, the younger plutons tend to be more alkaline in nature. 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; Kononova *et al* 1996). However, we note that in the southern belt (Xinjiang-Inner Mongolia-NE China) such an increase of alkalinity of granitoids with the decrease of intrusive ages is not as clearly documented as in Transbaikalia (Hong *et al* 1996).

3. Nd-Sr-O isotopic data for granitoids of the ECAOB

Precise age data are vital to estimate the production rate of juvenile crust. However, within such voluminous granitoids in the ECAOB, only a few per cent of them have been reliably dated. Most of the intrusive ages reported in the literature are based on geological correlations or other non-radiochronometric means (Litvinovsky, personal comm.; see also Kovalenko *et al* 1995).

The age information and Nd-Sr isotopic data used in this paper come from two sources:

- unpublished results obtained in Rennes (on granites of NE China and inner Mongolia), and
- results published in international journals, some of which were obtained in Rennes (Kovalenko *et al* 1992; Zhao 1993; Hong *et al* 1995; Chen *et al* 1995; Zhou *et al* 1995; Arakawa and Shimura 1995; Han *et al* 1997).

We have included here the granitoids of the Hida Belt of Japan, which has been considered as part of the Asian continent prior to the opening of the Japan Sea (Hirooka *et al* 1983; Mizutani and Hattori 1983; Cluzel 1991).

All unpublished data are presented graphically and the analytical values will be reported elsewhere (Wu *et al* 2000). Figure 2 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 ECAOB. High $^{87}Rb/^{86}Sr$ ratios (up to 100) are indicative of A-type and highly differentiated I-type granitoids. Note that the I_{Sr} values were individually calculated by subtracting the radiogenic components from the measured $^{87}Sr/^{86}Sr$ ratios; they may bear large uncertainties for high Rb/Sr rocks, and not uncommonly yield unreasonably low ratios of less than 0.700 (figure 2). 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 isochron age, all related by the equation:

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

Take, for example, three cogenetic 300 Ma granites with $^{87}Rb/^{86}Sr$ ratios of 1, 10, and 100. If a 2% error is assigned for their $^{87}Rb/^{86}Sr$ ratios, then they would have uncertainties for the calculated initial $^{87}Sr/^{86}Sr$ ratios of ± 0.000085, ± 0.00085, and ± 0.0085, respectively. Thus, assuming the initial $^{87}Sr/^{86}Sr$ ratio for them to be 0.705, a calculated I_{Sr} for the third granite as low as 0.6965 is possible, though completely meaningless. We note that a single unreasonably low I_{Sr} of 0.698 was reported for a granite of relatively low Rb/Sr ratio ($^{87}Rb/^{86}Sr \approx 1.2$) from western Mongolia (Kovalenko *et al* 1992). This is likely to be due to post-magmatic Rb/Sr open system behavior or some analytical problem. Nevertheless, most I_{Sr} values for low Rb/Sr rocks seem to show a restricted range of I_{Sr} values from 0.702 to 0.707 (figure 2), which is rather low for most granitic rocks formed in Phanerozoic orogenic belts. The data suggest that contribution of
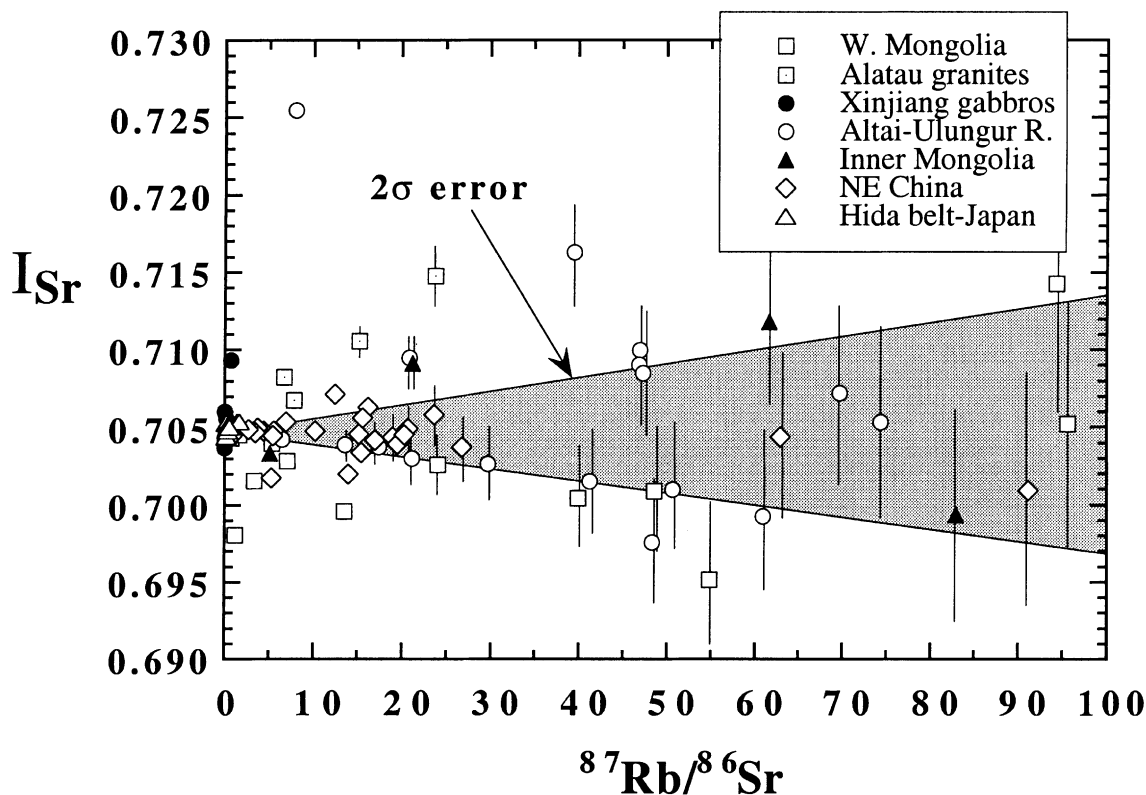
Figure 2. Initial $^{87}Sr/^{86}Sr$ (=I_{Sr}) vs $^{87}Rb/^{86}Sr$ plot for Phanerozoic granitoids from the ECAOB. Data of Xinjiang gabbros (Chen *et al* 1995) are also shown for comparison. The more reliable I_{Sr} values for rocks with Rb/Sr ratios less than 20 are found between 0.702 and 0.707, a range considered as relatively low for Phanerozoic granitic rocks. I_{Sr} values calculated from rocks with high to very high Rb/Sr ratios are too imprecise to have any useful petrogenetic meanings. Grey area indicates the propagation of error size induced by 2% Rb/Sr uncertainty in I_{Sr} values.

ancient crustal material in the petrogenesis of these granitic rocks was limited.

Relative to Sr, Nd isotopic data can provide a much clearer constraint to the origin of granitic rocks. Many Altaid granites are characterized by positive $\varepsilon_{Nd}(T)$ values (figure 3). The ranges for individual terrains are: $+6.7$ to $+5.1$ for 21 A-type granites of Xinjiang (Zhao 1993; Han *et al* 1997), $+5.4$ to $+3.0$ for 4 A-type granites of Inner Mongolia (Jahn, unpublished), and $+2.8$ to $+1.2$ for 25 highly differentiated I-type granites from NE China (Wu *et al* 2000). In addition, a variety of granitic rocks from northern Xinjiang indicate a range of $\varepsilon_{Nd}(T)$ values from as high as $+7$ for alkali granites from the Ulungur River area to as low as -5 for biotite granites from other localities (Zhao 1993). Kovalenko *et al* (1992) obtained a range of $\varepsilon_{Nd}(T)$ values from $+7.7$ to $+3.0$ for 17 granitic rocks (age ≈ 378 Ma) from the Altai Mountains of western Mongolia. Additional data for granites of the Alatau Mountains and for gabbros of west Tianshan in western Xinjiang are shown for comparison in figure 3. Note that many of the granitic rocks have the same $\varepsilon_{Nd}(T)$ values as the mantle-derived gabbroic rocks. These data thus provide strong evidence for depleted material as the major source of magmatism in the southern belt of the ECAOB. The same

conclusion was also reached from Pb isotopic studies on K-feldspars of granitoids from the western Junggar region in Xinjiang (Kwon *et al* 1989; Jin and Zhang 1993).

These isotopic data are in strong contrast to those for most Phanerozoic granites occurring in the classical collisional orogens. The latter were mainly produced by remelting of older continental crust and are characterized by negative $\varepsilon_{Nd}(T)$ and high I_{Sr} values, as exemplified by the Hercynian granites of south Brittany and the Massif Central in France, and the Manaslu leucogranites of the Himalayas (figure 4). So far, we are not aware of any coupled Nd-Sr isotopic data published for granites of Transbaikalia. However, the Triassic Kharitonovo pluton of Transbaikalia (alkaline and peralkaline rocks, $T \approx 240$–220 Ma) is characterized by low initial $^{87}Sr/^{86}Sr$ ratios of about 0.704 (Zanvilevich *et al* 1995). This pluton has a range of "primary" magmatic whole-rock $\delta^{18}O$ values of $+6.5$ to $+4.5‰$, deduced from alteration-resistant titanite $\delta^{18}O$ data (ca. $+3$ to $+0.5‰$), which is consistent with derivation from upper mantle rocks (Wickham *et al* 1995, 1996).

Sm-Nd fractionation during magma genesis may change model ages to some extent, depending on the partition coefficient of Sm/Nd of the fractionated
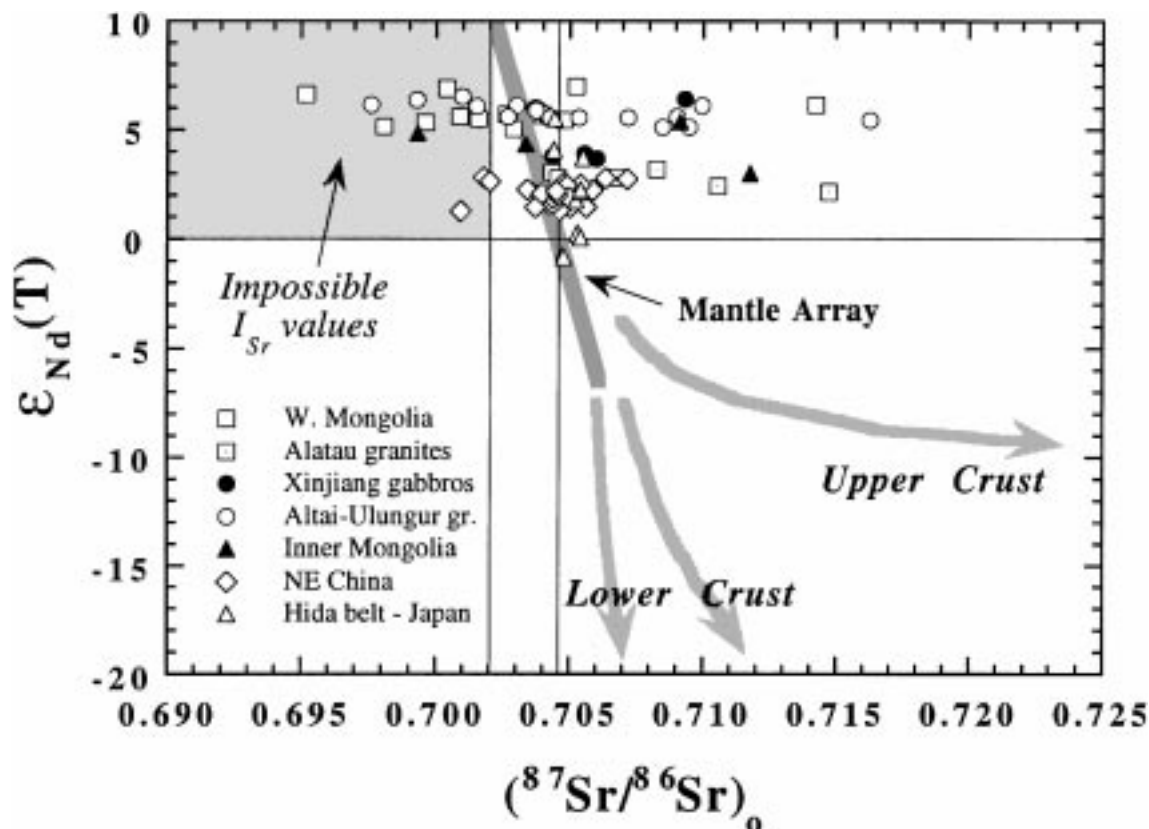
Figure 3. Plot of $\varepsilon_{Nd}(T)$ vs initial $^{87}Sr/^{86}Sr$ isotopic ratios for Phanerozoic granitoids from the ECAOB. Data for Tianshan gabbros of Xinjiang are also shown for comparison. The calculated $(^{87}Sr/^{86}Sr)_o$ or I_{Sr} values have a wide range, which is due partly to the large uncertainty inherent in rocks of high Rb/Sr ratios and partly to open system in low Sr alkaline granites. However, the restricted and positive $\varepsilon_{Nd}(T)$ values are indicative of the juvenile characteristics and formation of new continental crust.

phases. Rocks with high $f_{Sm/Nd}$ ratios (e.g., -0.2 to 0, or positive values) are often observed in A-type granites produced through fractional crystallisation; they often produce aberrant and meaningless T_{DM} ages. Similarly, some of the very low Sm/Nd ratios or highly negative $f_{Sm/Nd}$ values (-0.6 to -0.7) as shown in figure 5 could also reflect a fractionation effect. However, the young and small range of T_{DM} ages, covering a large variation of $f_{Sm/Nd}$ values (figure 5), cannot be only due to REE fractionation. The overall scenario is convincing evidence for a significant mantle contribution in the genesis of these granites.

Abundant Nd isotopic data have been published by Kovalenko *et al* (1992, 1996) for Phanerozoic granitic rocks from the central to northern belts of the ECAOB (Mongolia and Transbaikalia). Using the Nd model age (T_{DM}) approach, Kovalenko *et al* (1996) delineated three isotope provinces (Caledonian, Hercynian, and pre-Riphean) which coincide with three tectonic zones of corresponding ages. In each province the model ages are limited in a narrow range, regardless of the emplacement age of the granites. We re-summarize their Nd isotopic data in figures 6–8. Without exception, Phanerozoic granites emplaced into Caledonian and Hercynian tectonic

zones have positive $\varepsilon_{Nd}(T)$ values, suggesting their juvenile characteristics; whereas those intruded into the pre-Riphean basement show variable $\varepsilon_{Nd}(T)$ from positive to negative values, hence indicating variable proportions of old Precambrian crust mixed with the mantle peridotite in their source (figure 6). Note that some late Neoproterozoic to early Paleozoic granites (600–500 Ma) have $\varepsilon_{Nd}(T)$ values as high as $+10$, indicating their derivation from an almost pure depleted mantle component.

Figure 7 illustrates that the majority of the rocks emplaced in the Caledonian and Hercynian belts have Sm-Nd model ages (T_{DM}) younger than 1000 Ma, whereas those intruded in the Precambrian terranes have an older range from ca. 800 to 2500 Ma. If the rocks with high $f_{Sm/Nd}$ values (≥ -0.2, shown in the grey region of figure 8) are excluded, then all granitoids from Mongolia and Transbaikalia would have T_{DM} limited to 1500 Ma (figure 8). Nevertheless, granites intruded in the Pre-Riphean basement generally have lower $\varepsilon_{Nd}(T)$ values and higher T_{DM} than those intruded in the Caledonian and Hercynian belts. This is consistent with the nature of the crustal contaminant (older), but not necessarily a greater proportion of crust/mantle mixing.
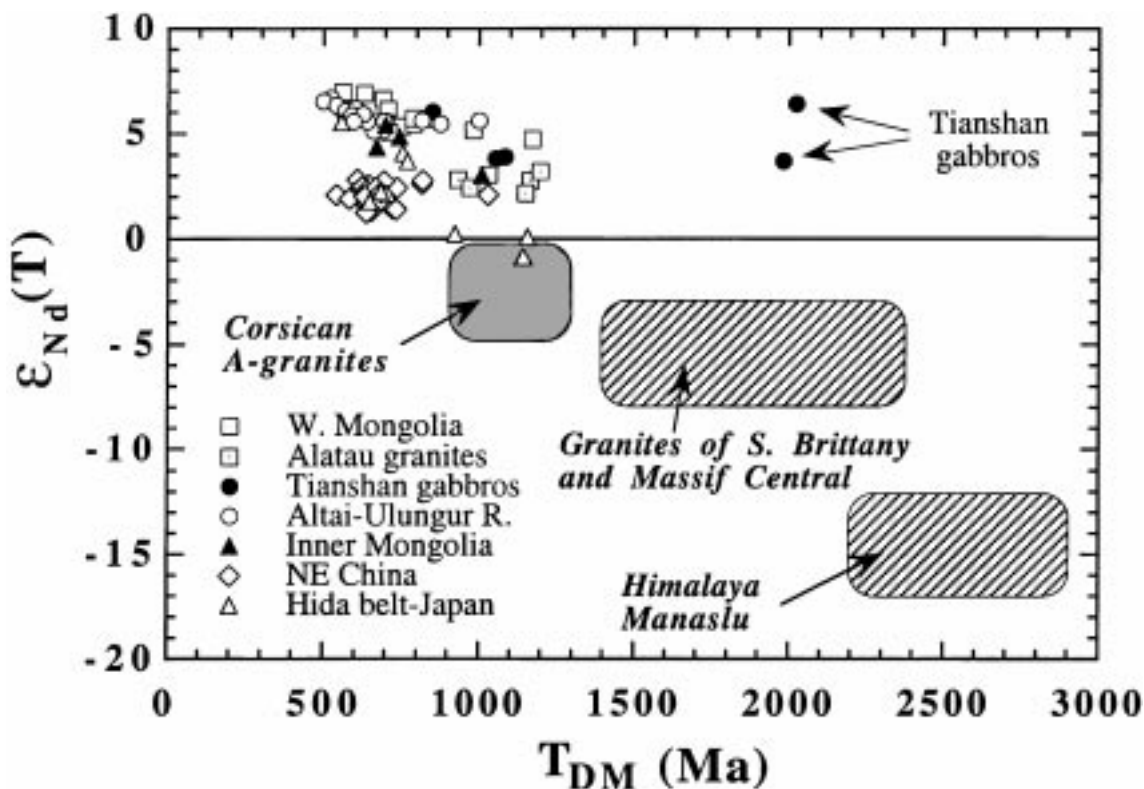
Figure 4. $\varepsilon_{Nd}(T)$ vs T_{DM} plot for Phanerozoic granitoids from the ECAOB. Data for Tianshan gabbros of Xinjiang are shown for comparison. The model ages are young, ranging from 500 to 1200 Ma, and are in strong contrast with those of the majority of Phanerozoic granitic rocks in the world. The young T_{DM} of the Altaid granites suggest their derivation from depleted mantle-dominated source rocks. **Data sources:** Corsican A-type granites (Poitrasson *et al* 1995); granites of S. Brittany (Bernard-Griffiths *et al* 1985); granites of Massif Central (Downes *et al* 1997); leucogranites of Himalaya—Manaslu (Vidal *et al* 1984); Tianshan gabbros (Chen *et al* 1995).
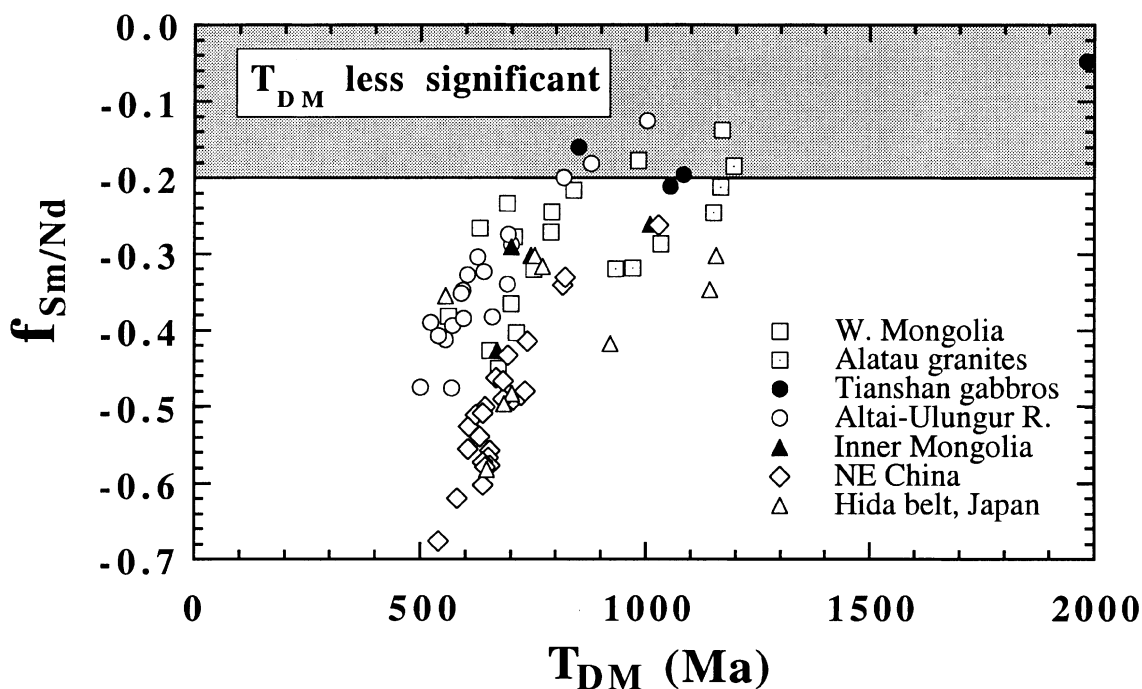

Figure 5. $f_{Sm/Nd}$ vs T_{DM} plot for Phanerozoic granitoids from the ECAOB. Data for Tianshan gabbros are shown for comparison. T_{DM} for rocks with $f_{Sm/Nd}$ values higher than -0.2 (or $^{147}Sm/^{144}Nd$ ratio of 0.157) may produce large uncertainty in model age calculation, hence they are less significant and excluded from discussion. Despite the large range of $f_{Sm/Nd}$ values, the calculated model ages are "young" in comparison with most Phanerozoic granitic rocks (ca. 1.5 to 2.0 Ga).
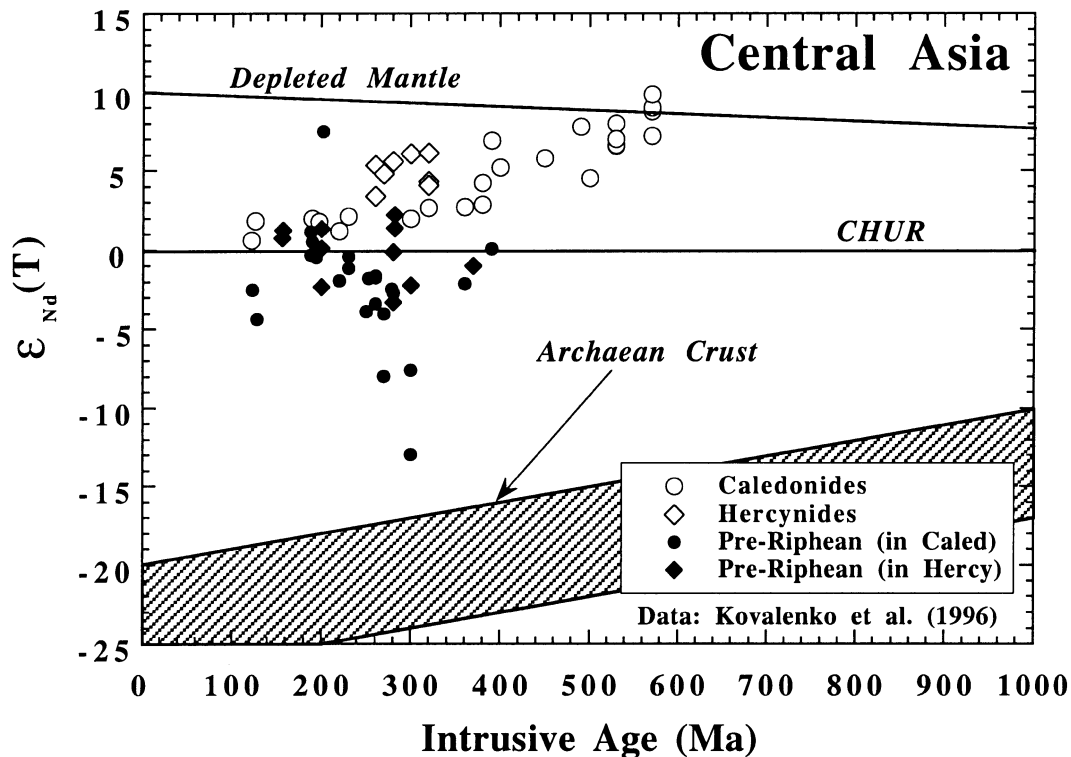
Figure 6. $\varepsilon_{Nd}(T)$ vs intrusive age plot for Phanerozoic granitoids from Mongolia and Transbaikalia (data from Kovalenko *et al* 1996). Granites intruded in Caledonian and Hercynian belts (open symbols) are characterized by positive $\varepsilon_{Nd}(T)$ values, whereas those intruded in pre-Riphean basement "enclaves" within Caledonian and Hercynian belts (black symbols) have both positive and negative $\varepsilon_{Nd}(T)$ values.
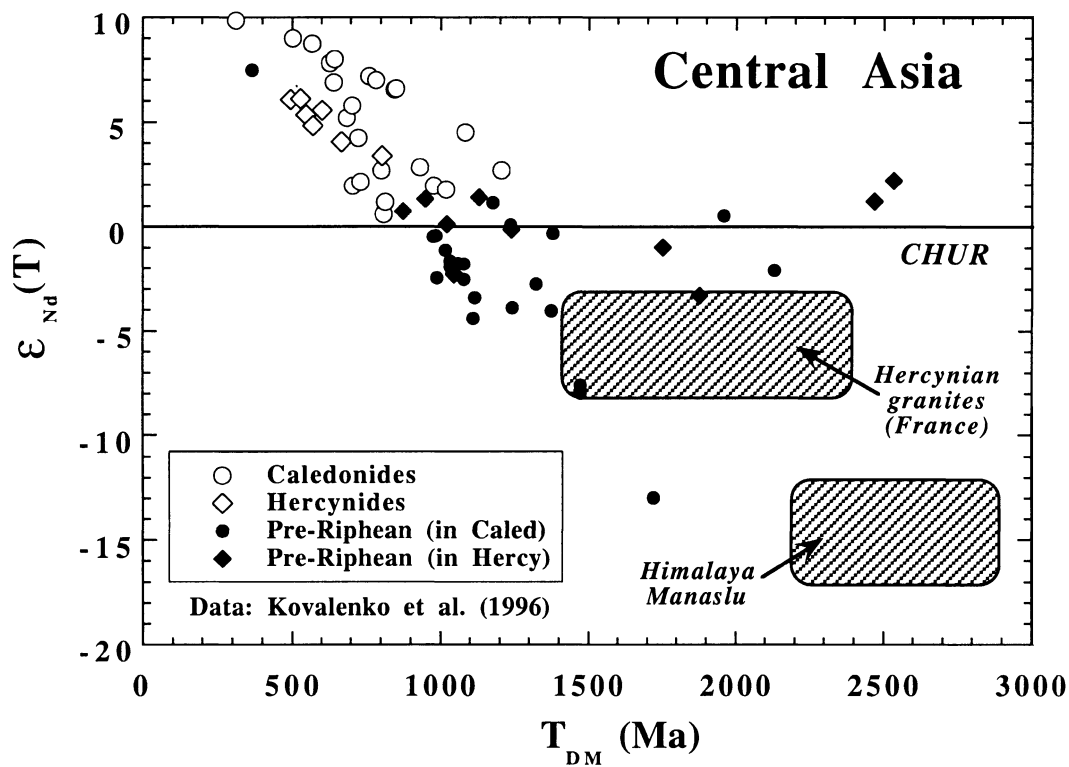

Figure 7. $\varepsilon_{Nd}(T)$ vs T_{DM} plot for Phanerozoic granitoids from Mongolia and Transbaikalia (data from Kovalenko *et al* 1996). Model ages (T_{DM}) are young (300 to 1200 Ma) for those intruded in Caledonian and Hercynian belts, which are similar to Phanerozoic granitic rocks from the southern belt of the ECAOB. T_{DM} are generally older (800–2500 Ma) for those intruded in pre-Riphean basement, suggesting more involvement of Precambrian crustal material in their petrogeneses.
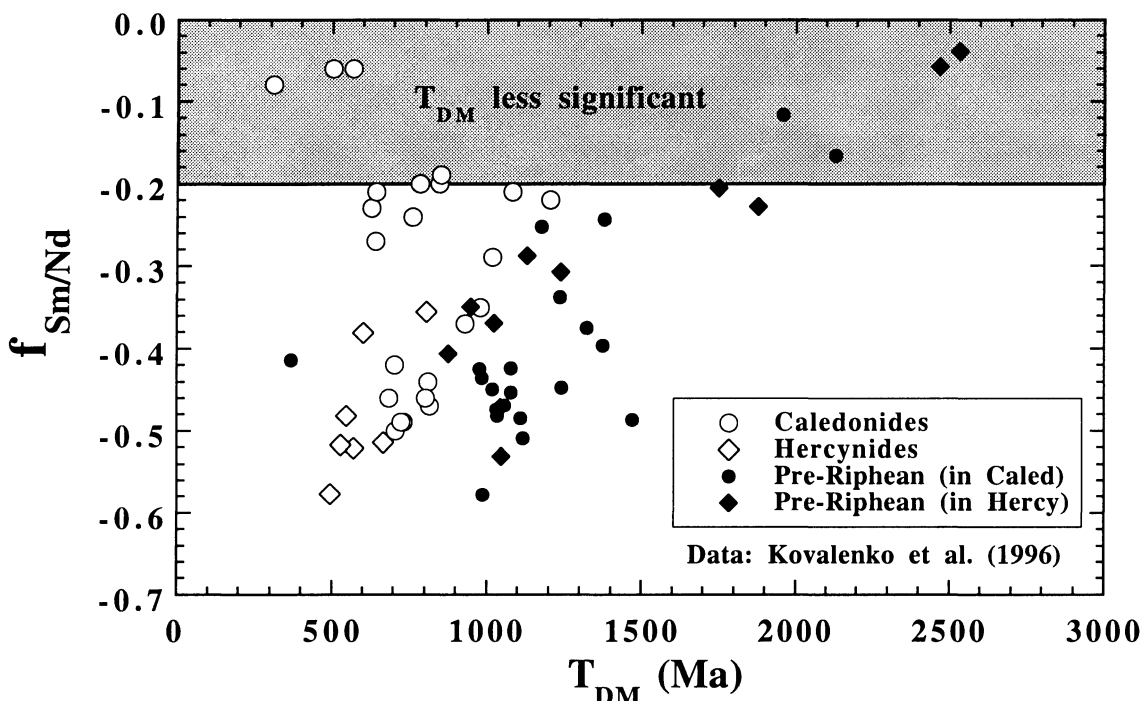
Figure 8. $f_{Sm/Nd}$ vs T_{DM} plot for Phanerozoic granitoids from Mongolia and Transbaikalia (data from Kovalenko *et al* 1996). The data in the grey zone are excluded from discussion. The calculated model ages are still "young" in comparison with most Phanerozoic granitic rocks (ca. 1.5 to 2.0 Ga).

4. Discussion

4.A *Genesis of the Phanerozoic crust*

Until now, the best documented examples of Phanerozoic juvenile granitic rocks are those from the Mesozoic Sierra Nevada and Peninsular Range batholiths in the western U.S. (DePaolo 1981), the Canadian Cordillera (Samson *et al* 1989; Samson and Patchett 1991), and the Appalachians (Whalen *et al* 1996; Samson 1998). While a significant mantle contribution to the generation of the Altaid granitoids is indicated by the Nd isotopic evidence, the precise mechanisms for the growth and evolution of the Phanerozoic continental crust remain debatable. Several pertinent questions include:

(**1**) Could subduction processes (Sengör *et al* 1993) alone be responsible for formation of the juvenile crust?

(**2**) Could the granites in this region have been formed by partial melting of a "young" mafic lower crust which was underplated during post-thickening extensional collapse, as envisioned for the Hercynides in the Massif Central (Costa and Rey 1995)?

(**3**) Was intraplate magmatism a significant process of continental growth, particularly during the Phanerozoic?

(**4**) Did the underplated mantle melts (basaltic liquids) interfinger with pre-existing granulites of various compositions, much like the model given by Wickham *et al* (1996), which together were

then melted to produce granite, with the residue sinking back into the mantle by processes like delamination?

(**5**) Is the Phanerozoic a major period of continental growth? If so, would that significantly alter the commonly accepted scenario of the growth of continental crust?

Because crustal growth curves were also determined in part from the Sm-Nd model age approach, erroneous conclusions may be reached if the material did not come from the depleted mantle, or important Sm/Nd fractionation occurred during melting and magma differentiation processes (Arndt and Goldstein 1987; Jahn *et al* 1990). Besides, what was the relative role of lithospheric and asthenospheric mantle as the dominant "mantle component" (Whalen *et al* 1996)?

In any case, the striking feature for the granites in the ECAOB is their relatively high $\varepsilon_{Nd}(T)$ values and low T_{DM} model ages (and probably, low I_{Sr} ratios). Windley (1993, 1995) distinguishes two types of orogens:

- collisional orogens, formed by the collision of two or more large continental blocks (e.g., Himalayas, Alps, Grenville, etc.), and
- accretionary orogens, formed by the growth and amalgamation of island arcs, intervening accretionary prisms, etc. (e.g., Altaids, North American Cordillera, Andes, Birimian, Nubian-Arabian, etc.).

A depleted isotopic character is unusual for granitic rocks of collisional orogens worldwide, except a few

as exemplified by the Newfoundland Appalachians (Whalen *et al* 1996), but are more commonly observed for those in accretionary orogens. High $\varepsilon_{Nd}(T)$ values could reflect a direct contribution of mantle in subduction zones (DePaolo 1981; Farmer and DePaolo 1983). However, abundant A-type granites are post-orogenic and appear to have no direct connection with subduction processes. Thus, it appears that subduction processes alone could not have been responsible for the formation of all the juvenile crust (Question 1).

4.B *Implication for the origin of alkaline and peralkaline granitoids*

Although many plutons and batholiths of the ECAOB belong to the calc-alkaline series and have differentiated I-type characteristics, the emplacement of voluminous granites of the alkaline and peralkaline series (A/NK $\leq$ 1 and A/CNK $\leq$ 1, with A,C,N,K = molecular proportion of Al_2O_3, CaO, Na_2O and K_2O, respectively) is remarkable. Of these rocks, many are post-orogenic A-type granites (A/CNK $\leq$ 1). The origin of A-type granites is still much debated, and it appears that no single petrogenetic model is applicable for all cases (Whalen *et al* 1987; Eby 1992). Mechanisms involving melting of crustal sources are favored from trace element geochemistry (Collins *et al* 1982; Creaser *et al* 1991; Anderson and Morrison 1992; Turner *et al* 1992; Cocherie *et al* 1994; Poitrasson *et al* 1995; Landenberger and Collins 1996), whereas mantle sources are often advocated from isotopic constraints (Javoy and Weiss 1987; Foland and Allen 1991; Turner *et al* 1992; Whalen *et al* 1996; Han *et al* 1997). However, this is not universally true, as many A-type granites are known to have a crustal isotopic signature
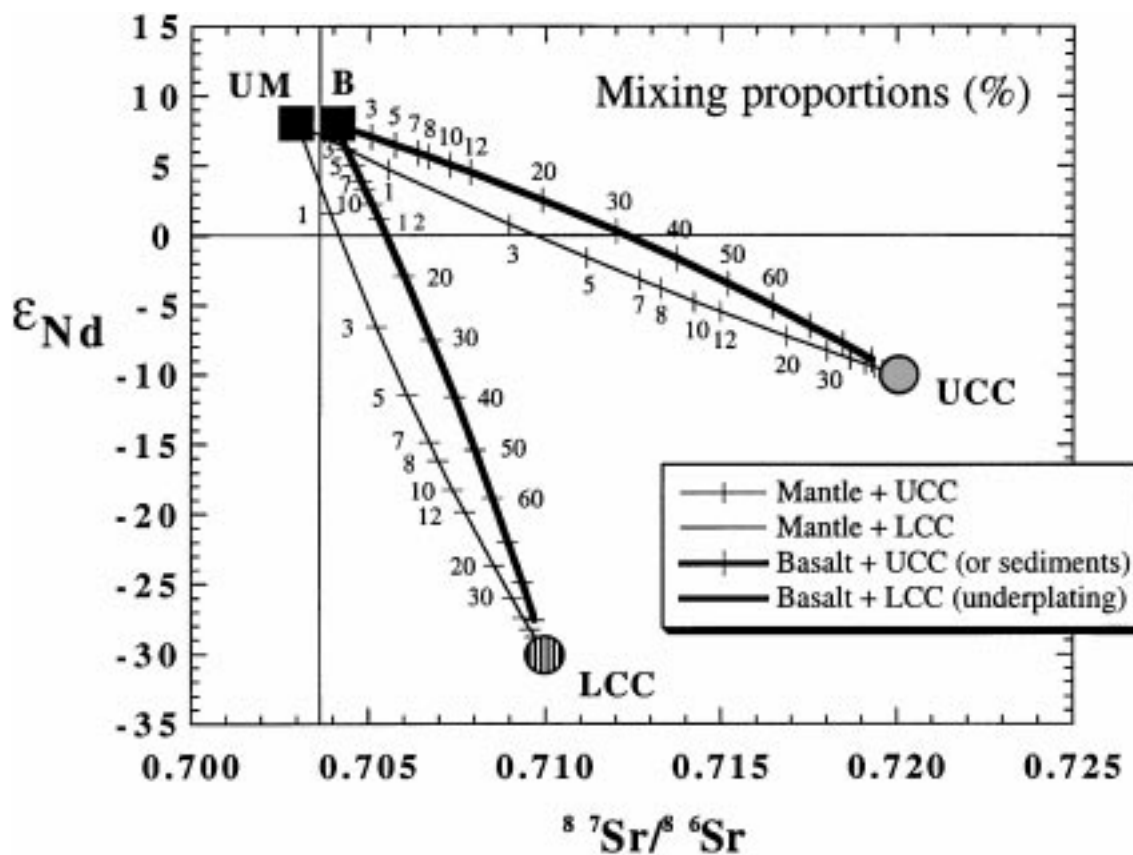

Figure 9. ε_{Nd} vs $^{87}Sr/^{86}Sr$ isotopic ratio plot showing mixing proportions between two end-members: (1) depleted mantle or juvenile components (UM = upper mantle peridotite; or B = basalt) and (2) crustal components (LCC = lower continental crust; or UCC = upper continental crust). The parameters used are:

	UM	Basalt	UCC	LCC
$^{87}Sr/^{86}Sr$	0.703	0.704	0.720	0.710
[Sr] ppm	20	150	350	300
ε_{Nd}	+8	+8	−10	−30
[Sm] ppm	0.42	3.5	5.2	4.8
[Nd] ppm	1.2	15	26	24
Sr/Nd	16.7	10	13.5	2.5

Sr and Nd concentrations of the UCC from Taylor and McLennan (1985), and those of the LCC from Rudnick and Fountain (1995).

(Charoy and Raimbault 1994; Darbyshire and Sewell 1997). In most cases, rocks of mantle derivation have also been contaminated by crustal material to some extent. Models involving mixing of mantle-derived magmas and crustal components (assimilated crustal rocks or crust-derived magmas), followed by fractional crystallisation are becoming increasingly popular.

A detailed discussion of petrogenetic models for the Altaid granites is beyond the scope of this paper, but it can be found in several related works (Hong *et al* 1995; Han *et al* 1997; Wu *et al* 2000). The available trace element and Nd-Sr isotopic compositions of the A-type (Xinjiang and Inner Mongolia) and differentiated I-type granites (NE China) indicate the mixing model as the most probable process and the dominance of mantle component over crustal material (e.g., Kovalenko *et al* 1996). A simple mixing calculation using different end-members is shown in figure 9. Two depleted juvenile components are used—mantle peridotite (UM) and basaltic rock (B). Because many I_{Sr} values have large uncertainties, we estimate the mixing proportions by using Nd isotopic compositions only. In all cases, granites with positive $\varepsilon_{Nd}(T)$ values would represent at least 70% juvenile component if upper continental crust (UCC) is the crustal end-member, and $\geq 85\%$ if lower continental crust (LCC) is considered. For the granites from the ECAOB, the majority of the southern belt (figures 4, 5) and those emplaced in the Caledonian and Hercynian zones in Mongolia and Transbaikalia (figures 6, 7) would be 100 to 80% juvenile. This implies extensive mantle differentiation and rapid crustal growth during the Phanerozoic. However, those emplaced in the Pre-Riphean zones have variable mixing proportions, from roughly 15 to 50% juvenile component (using Curve B-LCC, figure 9). It appears that the production of a huge amount of alkaline to peralkaline granites was initiated by extensive basalt underplating and accompanied by large-scale crustal extension (Questions 2 and 4, section 4.A). Consequently, intraplate magmatism was probably a significant process of continental growth in the Phanerozoic (Questions 3 and 5).

4.C *Tectonic model of Altaid collage by Sengör et al (1993)*

Sengör *et al* (1993) published an important and stimulating paper on the evolution of the Altaid tectonic collage. It provides an excellent forum for further research. According to this and a subsequent article (Sengör and Natal'in 1996), the Altaids (including the ECAOB and the region westwards to the Urals) provide a spectacular example of continental enlargement in the Phanerozoic, and their tectonic evolution involves accretion of arc complexes. The above authors have estimated that about 5.3 million km^2 of material accreted to Asia, half of which

may be of juvenile origin. Here we point out a few problems with this general model:

(**1**) The idea of using "magmatic front" as a new kind of structural marker in the reconstruction of the tectonic evolution is very creative, but the validity of this approach hinges on reliable age data for all individual granitic plutons. At present, this is far from the reality, and the number of plutons with precise age determination is very small in comparison with the total number of granitic plutons in the ECAOB. We cite here an example of granitoids in NE China. These rocks were assigned Hercynian or late Paleozoic ages (see published geologic maps), but, more recently, they have been found to be Indosinian ($\approx 200\,Ma$) based on some preliminary Rb-Sr and K-Ar dating results. However, our whole-rock and mineral Rb-Sr and Ar-Ar analyses for three of these "Indosinian" plutons show that they were intruded separately during a time interval of 165 to 140 Ma (Wu, Jahn and Lo, unpublished). The above example of incorrect age assignment by geological correlations is not an isolated case in the ECAOB. Until more precise age data are obtained, the tectonic model based on the magmatic front concept must inevitably involve large uncertainties.

(**2**) The model of Sengör *et al* (1993) suggests that the orogenic belts forming the Altaid collage have evolved dominantly along a single subduction zone, in front of a migratory island arc, called the Kipchak arc. In other words, the entire process of arc accretion is achieved by back-stepping of a single subduction zone. Such a process appears to be oversimplistic, particularly with regard to the presence of ancient crustal blocks within the vast ECAOB (see point 3 below). It is questionable, therefore, whether the separately identifiable and seemingly independent arc complexes must be regarded as disrupted and displaced fragments of a single Kipchak arc.

(**3**) The model stresses the paucity of ancient gneiss terrains that represent ancient continental fragments. Although our Nd isotopic data indicate a very significant mantle input for the generation of the Altaid granitoids, the data of Kovalenko *et al* (1996) for Mongolia and Transbaikalia and those for Xinjiang-inner Mongolia-NE China (see also Zhao 1993; Hu *et al* 2000a, b) also suggest the presence of older crustal rocks in the ECAOB. Even the young model ages (T_{DM}) of 500–1000 Ma are still considerably older than the intrusive ages, suggesting the presence of older crust in the granite petrogenesis. The significant negative Nb anomalies in geochemical spidergrams observed in the A-type granites of Xinjiang (Han *et al* 1997) and inner Mongolia (Hong *et al* 1995) and in the I-type granites of NE China (Wu *et al* 2000) are in perfect agreement with the idea that old crustal rocks were involved in the granite petrogenesis. Consequently, the presence of older crustal blocks,

in addition to island arc complexes, is not insignificant in the Altaid collage.

(**4**) The importance of A-type granites appears to be downplayed in the model of Sengör *et al* (1993), which indicates that high-K granites were only generated widely in the Permian through anatectic magmatism. The high-K granites (A-type) of the Ulungur River, northern Xinjiang, were emplaced in the Carboniferous (≈ 300 Ma) and were generated by melting of sources dominated by mantle components (Han *et al* 1997; figures 3 and 4). The ''anatectic'' origin of high-K granites (Sengör *et al* 1993) is in contradiction with the isotopic data. By contrast, Coleman (1989) suggested that all A-type granites are generated by underplating of basaltic magmas in the lower crust, followed by partial melting of a mixed lower crustal assemblage. It is speculated that the voluminous post-orogenic A-type granites emplaced (mainly?) during the late Paleozoic could be related to a mantle plume, which supplied the necessary mantle material for the ultimate granite geneses and the necessary thermal energy for lithospheric extension.

4.D *Comparison between the granitoids of the Altaids and Cathaysia*

Cathaysia in the Yangtze Craton (figure 1) is a major Phanerozoic orogenic belt in SE China. Like the ECAOB, it is also characterized by voluminous Phanerozoic granitoids with rich mineralisations. Thus, a brief comparison of their isotopic signatures with those of the ECAOB appears interesting for the understanding of their respective crustal development. Cathaysia has been considered as the easternmost part of the Tethyside orogen (Hsu *et al* 1990;

Sengör *et al* 1993). Cathaysia and the ECAOB are situated to the south and north of the Sino-Korean craton, respectively, and they exhibit very contrasting tectonic styles and crustal evolutions. The principal characteristics and differences between the Altaid and Cathaysia orogens are summarized in table 1. A-type granites also occur in Cathaysia (Xu *et al* 1992), but their Nd isotopic signatures are generally ''crustal'' (Martin *et al* 1994; Charoy and Raimbault 1994; Darbyshire and Sewell 1997). Most granitic rocks in SE China were produced by remelting of Proterozoic crustal sources; only very few granitic bodies in coastal Fujian and Taiwan have witnessed a greater contribution of the depleted mantle component in their magma genesis (Jahn *et al* 1976, 1986, 1990; Huang *et al* 1986; Lan *et al* 1995; Gilder *et al* 1996; Chen and Jahn 1998).

Figure 10 summarizes the Nd isotopic features of Phanerozoic granites from the Cathaysia orogenic belt and the Yangtze craton in comparison with those from the southern belt of the ECAOB. The isotopic distinction is very clear, suggesting that the Altaid granitoids represent an immense juvenile crustal addition, whereas Cathaysian granitoids are mainly reworked ancient crust, implying little net crustal growth.

5. Conclusions

- The vast orogenic belt (ECAOB) that welded together the Siberian and Sino-Korean cratons is characterized by voluminous granitic rocks of Paleozoic to Mesozoic ages. New Sr-Nd isotopic data and published isotopic and geochemical results show that abundant granitic rocks from the southern belt

Table 1. Comparison of crustal evolution between the ECAOB and SE China.

	East-Central Asia (Altaid)	SE China (Cathaysia)
Type of orogen	**Altaid (accretionary*)**	**Tethyside (collisional*)**
Characteristics	Immense Phanerozoic granitic intrusions	Immense Phanerozoic granitic intrusions
Period of intrusion	550 to 150 (possibly 120) Ma $\Delta T \approx 400$ Ma	400 (?) to 80 Ma $\Delta T \approx 300$ Ma
Total volume	≈ 5.3 M sq. km** ($\approx 11\%$ of total Asia)	not estimated
Granitic type	mainly I- and A-types Alkaline and peralkaline granites dominate	mainly S-type (I, A, M subordinate) CA granites dominate
Crustal type	mainly juvenile	mainly reworked
$e_{Nd}(T)$	$+7$ to $+1$	-2 to -17
Tectonics	Assembly of numerous arc complexes; intruded by vast granitic plutons and covered in places by their volcanic equivalent. Plume activities?	Assembly of ancient continental blocks; vast granitic plutons formed by remelting of old basement rocks
Structure	Nappe complexes absent**; suture zones broad**	Nappe complexes common suture zones narrow and elongate
Basement rocks	Precambrian basement rocks rare**	Proterozoic basement dominates

Note: *Terminology of Windley (1993, 1995).
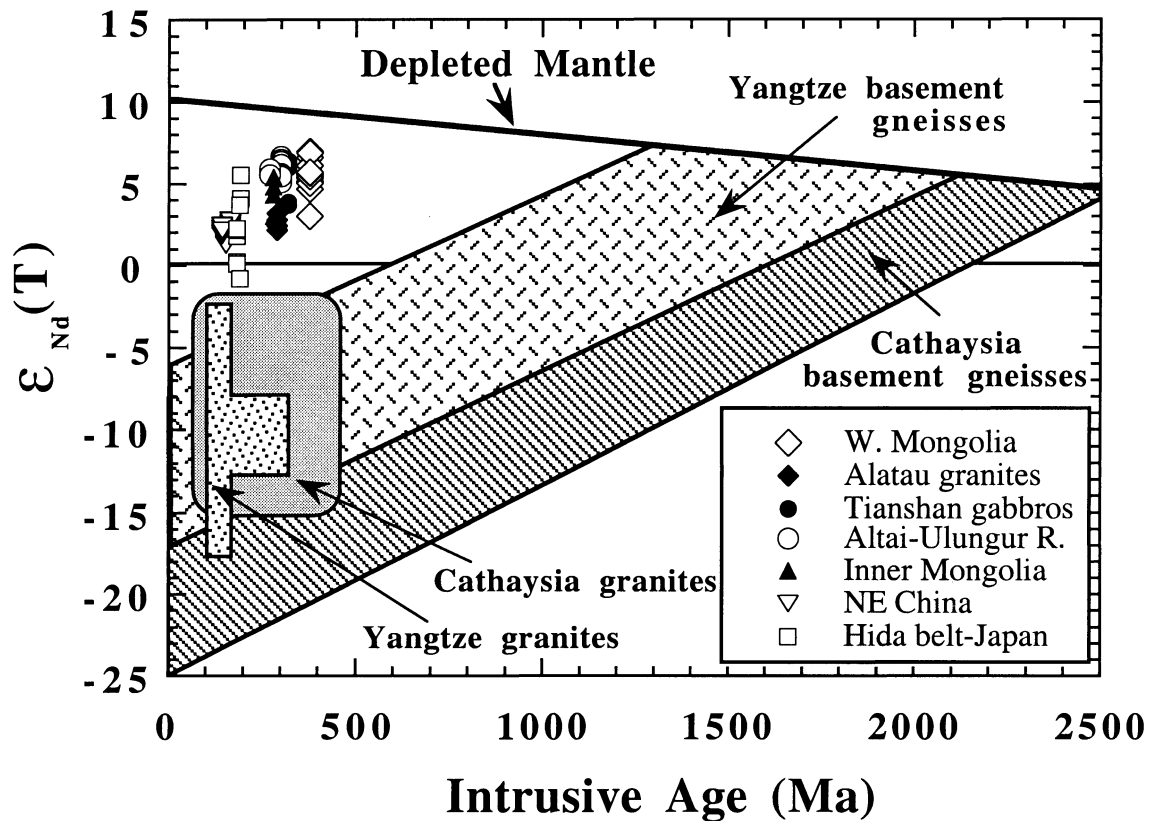**According to Sengör *et al* (1993); controversial.

Figure 10. Comparison of granitic rocks from the Altaids (ECAOB) and Yangtze-Cathaysia in SE China. The granitoids from both orogenic belts were emplaced during approximately the same period (ca. 400 to 100 Ma) but were generated from very different source rocks as shown by the contrasting $\varepsilon_{Nd}(T)$ values. The Yangtze-Cathaysia granites were mainly formed by remelting of Precambrian basement rocks with little contribution from the upper mantle, except for the Cretaceous granitic rocks of coastal Fujian and Taiwan. Data for Cathaysia are from the compilation of Chen and Jahn (1998).

Table 2. Phanerozoic juvenile crustal growth.

Arc magmatism (Reymer and Schubert 1984)	
(**Canadian Cordillera and Altaid Collage**	
excluded)	$\approx 1.1\,\mathrm{km^3/a}$
Canadian Cordillera	
($\Delta T = 350\,\mathrm{Ma}; \approx 1\,\text{million}\,\mathrm{km^2}$)	
(Samson *et al* 1989)	$\approx 0.15\,\mathrm{km^3/a}$
Altaid Collage ($\Delta T = 400\,\mathrm{Ma}; \approx 2\,\text{million}\,\mathrm{km^2}$)	
(Sengör *et al* 1993)	$\approx 0.30\,\mathrm{km^3/a}$
Total Phanerozoic growth rate	$\approx 1.55\,\mathrm{km^3/a}$
For comparison:	
Birimian terranes ($\approx 2.1\,\mathrm{Ga}; \Delta T = 120\,\mathrm{Ma}$)	
Outcrop = W. Africa (0.9 million $\mathrm{km^2}$)	
+ Guyana (0.3 million $\mathrm{km^2}$)	
+ possible extension ≈ 3 million $\mathrm{km^2}$ (total)	
Growth rate (Boher *et al* 1992)	$\approx 1.6\,\mathrm{km^3/a}$
	(overestimated?)
Arabian-Nubian Shield ($\Delta T \approx 300\,\mathrm{Ma};\ 900\text{-}600\,\mathrm{Ma}$)	
Growth rate	$\approx 0.15\,\mathrm{km^3/a}$
(similar to that of the Canadian Cordillera)	

of the ECAOB (Xinjiang-western Mongolian-inner Mongolia-NE China) possess un-ambiguous isotopic characteristics for juvenile crust ($I_{Sr} \approx 0.702$ to 0.707; $\varepsilon_{Nd}(T) = +7$ to $+1$). This is also true for Phanerozoic granitoids from Mongolia and Trans-

baikalia. Oxygen isotopic data for granitic rocks from Transbaikalia also support a significant mantle input, particularly for those emplaced during the Permian or later (Wickham *et al* 1995, 1996). Consequently, the ECAOB represents probably the most important mass transfer from the mantle to the continental crust in Phanerozoic times.

- The origin of A-type granites has long been controversial, and A-type granites seem to have multiple origins. Most of the post-orogenic A-type granites from the ECAOB are demonstratably of predominantly mantle origin based on their Nd-Sr isotopic data. The mantle origin involves a two-stage process, with a basaltic rock or magma as the immediate protolith of the A-type granite through partial melting or fractional crystallisation, respectively.

- The tectonic evolution of the ECAOB (or Altaid Collage) is most probably related to the accretion of arc complexes and the emplacement of juvenile crust as suggested by Sengör *et al* (1993). This idea is generally compatible with the available Sr-Nd-O isotopic data. However, the emplacement of voluminous post-orogenic A-type granites requires an additional process, probably involving basalt underplating from mantle plume partial melting and followed by extensive fractional crystallisation. If

the volume of the basaltic protoliths is considered, the juvenile material of the Altaid Collage separated from the upper mantle would be much greater than the total mass of the granitoids presently observed. It appears that intraplate magmatism involving plume melting, basalt underplating, differentiation or remelting of a basaltic source, is an important process of continental growth in the Phanerozoic.

- For the entire Altaid Collage, Sengör *et al* (1993) estimated that during the 400 Ma of crustal evolution, a total area of about two million km^2 of juvenile crust was added to Asia. This is translated into a growth rate of about 0.3 km^3/a. Combining this with the growth rate of the Canadian Cordillera (about 0.15 km^3/a, Samson *et al* 1989; Samson and Patchett 1991), the combined would be at least 50% higher than the global growth rate of ca. 1.1 km^3/a 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 ECAOB, may considerably change our views of continental growth.

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