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Massive granitoid generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic

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The Central Asian Orogenic Belt (CAOB), also known as the Altaid Tectonic Collage, is characterized by vast distribution of Paleozoic and Mesozoic granitic intrusions as well as basaltic to rhyolitic volcanics. The granitoids have a wide range of compositions and roughly show a temporal evolution from calc-alkaline, alkaline to peralkaline series. The emplacement times for most granitic plutons fall between 500 to 120 Ma, but only a small proportion of plutons have been precisely dated. In this paper we document the available Nd isotopic data to advocate that massive juvenile continental crust was generated during the Phanerozoic in Central Asia.

Most Phanerozoic granitoids of Central Asia are characterized by low initial Sr isotopic ratios, positive $\epsilon_{Nd}(T)$ values and young Sm-Nd model ages (T_{DM}) of 300 to 1200 Ma. This is in strong contrast with the coeval granitoids emplaced in some "classic" orogenic belts, such as, the European Caledonides and Hercynides, Cathaysia of SE China and South Korea. The isotope data indicate their "juvenile" character and suggest their derivation from source rocks or magmas separated shortly from the upper mantle. Granitoids with negative $\epsilon_{Nd}(T)$ values also exist, but they occur in the environs of Precambrian blocks and their isotope compositions reflect contamination of the older crust in the magma generation processes.

The evolution of the CAOB is undoubtedly related to accretion of young arc complexes and old terranes (microcontinents). However, the emplacement of large volumes of post-tectonic granites requires another mechanism—probably through a series of processes including underplating of massive basaltic magma, intercalation of basaltic magma with lower crustal granulites, partial melting of the mixed lithologic assemblages leading to generation of granitic liquids, followed by extensive fractional crystallization. The proportions of the juvenile or mantle component for most granitoids of Central Asia are estimated to vary

from 70 to 100%. The recent "discovery" of juvenile crust in many Phanerozoic orogenic belts elsewhere, together with the CAOB, may considerably change our views of the continental growth.

Introduction

The problem of the growth and evolution of the continental crust has always been an important subject of research in earth sciences. The continental crust is distinguished from the oceanic crust by its more evolved and differentiated nature. It consists mainly of rocks of granitoid compositions (sedimentary rocks and gneisses included), accompanied by subordinate amounts of mafic and ultramafic rocks. The continental crust on earth is a unique feature within the entire solar system and the formation of abundant granitoids is undoubtedly related to the presence of water and its interaction with the silicate earth.

The issue of the rate and nature of continental growth has not yet been resolved satisfactorily. On one hand, continents are known to grow by lateral accretion of arc complexes in active continental margins and by vertical underplating of mantle-derived magma, which may be followed by a series of complex processes leading to production of granitoid rocks. On the other hand, continents are progressively destroyed through chemical and physical erosion from the surface, delamination of the lower crust from the bottom (or A-type subduction), and even direct subduction to mantle depths as evidenced from ultrahigh-pressure metamorphic terranes. Thus, much of the continental mass has gone through recycling in a perpetually dynamic earth since its earliest formation in the early Archean (or Hadean). The real debate on continental growth must be focussed on the net growth—the balance between the quantity of crustal material separated from the mantle and the volume of the continent destroyed and recycled back into the mantle. The steady state or no-growth model advocated by Armstrong since 1968 (Armstrong, 1968, 1981, 1991) incorporates the dynamic processes of crustal growth and destruction, and it has stood the test of geochemical mass balance and isotopic arguments. However, the same geochemical and isotopic data have also been used to argue for a net growth of the continents by other authors (e.g., Moorbath, 1978; Taylor and McLennan, 1985, 1995; Stein and Hofmann, 1994). In order to avoid any ambiguity in this paper, the term "continental growth" means production of continental material through a series of mantle-crust differentiation processes. It involves only processes of addition but not destruction or recycling.

Despite the contrasting net-growth models, it is widely agreed that the production of the continental crust was essentially completed in the Precambrian, especially prior to 2.5 Ga. The amount of new crust formed in the Phanerozoic has been considered minor or

Figure 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. Black areas are exposed Archean to early Proterozoic rocks. Dark grey pattern on the right-hand side including Japanese islands represents Pacific fold-belts. The Hida Belt of Japan may belong tectonically to the CAOB. Abbreviations: K = Kokchetav (in northern Kazakhstan); KM = Kyonggi Massif, OB = Ogcheon Belt, RM = Ryongnam Massif (all in Korea).

insignificant. This was earlier supported by Nd isotope studies of the granitoids from several intensely studied classic orogenic belts, such as the Caledonides, Hercynides, the Yangtze-Cathaysia of SE China, and the Himalayas. However, recent isotope investigations in western North American Cordilleras (DePaolo, 1981; Samson et al., 1989, 1995; Samson and Patchett, 1991; Whalen et al., 1996) and the Lachlan and New England Foldbelts of eastern Australia (McCulloch and Chappel, 1982; Hensel et al., 1985; Eberz et al., 1990; Collins, 1996, 1998) have revealed that a substantial proportion of the Phanerozoic crust is juvenile.

Central Asia is immense in size and its geology is poorly known outside of the former USSR and China. It is rich in mineral resources, which have been subject of numerous studies in the last forty years. In a synthesis of geologic data obtained in the former USSR and China, Sengör et al. (1993) hypothesized that nearly half of the gigantic Central Asian Orogenic Belt (which they termed the Altaid Tectonic Collage) was derived from the mantle by arc accretion. If this is true, the growth of the continental crust in the Phanerozoic would be much more significant than we have previously estimated from classic orogenic belts. That is, the Phanerozoic crust is no longer composed essentially of reworked Precambrian crust.

The purposes of this paper are: (1) to demonstrate the dominantly juvenile nature of the Phanerozoic granitoids from the CAOB using Sm-Nd isotopic data, and (2) to discuss the general implications on the global Phanerozoic crustal growth. We underline that the granitic rocks of the CAOB represent the most significant mass transfer from the mantle to the continental crust in the Phanerozoic.

Lithological characters and emplacement periods of granites

In Central Asia, very large volumes of granitic rocks of late Paleozoic to Mesozoic ages were emplaced during the formation of the Central Asian Orogenic Belt (CAOB). The CAOB, bounded by the Siberian and North China cratons (Figure 1), represents a complex evolution of Phanerozoic orogenic belts (Tang, 1990; Dobretsov et al., 1995) and it has also been termed Altaid Tectonic Collage (Sengör et al., 1993). According to Sengör, the Altai was formed by successive accretion of arc complexes, accompanied by emplacement of immense volumes of granitic magmas. "Altaid Collage" may be better known to the western reader, but "CAOB" has been used for the past thirty years of research by the Russian and Chinese geologists, we therefore chose to use the latter simply to respect the tradition.

In this orogenic zone two gigantic belts of alkaline syenites and granites may be recognized: (1) a northern belt from central-northern Mongolia to Transbaikalia, and (2) a southern belt from Kazakhstan, Xinjiang, through southern Mongolia, Inner Mongolia to NE China (Figure 1). More than 350 distinct granitic plutons are exposed in northern Mongolia and Transbaikalia and occupy a total area 500,000 km² (Zanvilevich et al., 1995; Wickham et al., 1995, 1996). The available age data show five main stages of felsic magmatic activity in Transbaikalia (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). Our ongoing study indicates that the magmatism extends to 100 Ma.

According to Kovalenko et al. (1995), these plutons 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); (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 (100,000 km²) in west-central Mongolia; and (4) the early Mesozoic (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. The lithologic types are composed mainly of alkaline and peralkaline granites, syenogranites, syenites and minor granodiorites.

In east central Kazakhstan, important mineralisations (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., 1999). These rocks were intruded in several episodes from 450 to 250 Ma. Heinhorst et al. (2000) considered these rocks to be 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 Altai, massive post-collisional alkaline granite intrusions were emplaced in Permian to Jurassic times. These rocks have been dated at 250 to 200 Ma using zircon U-Pb and Rb-Sr isochron methods (Vladimirov et al., 1997).

In northern Xinjiang, granites of alkaline to calc-alkaline series appear to be dominant; most of these were emplaced in the period of 400–200 Ma but culminated around 300 Ma (Hu et al., 1999a,b). A-type granites of the Ulungur River in northern Xinjiang 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 ca. 280 Ma (whole-rock Rb-Sr, Hong et al., 1995). In NE China, several hundred granitic bodies have been identified and constitute an area of 100,000 km². The existing age data indicate four episodes of granitic intrusion (Fang, 1992; Jahn et al., 1999; Wu et al., 2000a): (1) late Permian (270–250 Ma), (2) late Triassic-early Jurassic (220–180 Ma), (3) middle Jurassic (170–150 Ma), and (4) Cretaceous (ca. 120 Ma). An apparent younging trend of granitic intrusions from the west to the east is observed within the southern part of the CAOB.

Nd isotopic data for Phanerozoic granitoids—a survey

Three principal types of diagrams will be presented: (a) initial Nd isotope composition $\epsilon_{Nd}(T)$ vs. intrusive ages; (b) $\epsilon_{Nd}(T)$ vs. depleted-mantle-based model age T_{DM} ; and (c) $f_{Sm/Nd}$ vs. T_{DM} . For model ages, we assume a linear Nd isotope evolution for the depleted mantle $\epsilon_{Nd} = 0$ at 4.56 Ga to +10 at the present, but the choice of 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 lie on (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 (for more detailed discussion, see Jahn et al., 1990). Many peralkaline granitoids of Central Asia show highly fractionated REE patterns, sometimes with the tetrad effect (Masuda et al., 1987; Masuda and Akagi, 1990; Bau,

1996; Jahn et al., 1999) leading to enhanced Sm/Nd ratios and negative model ages. In this case, single-stage model ages are evidently not reasonable. 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. If this model is adopted, we shall observe that most granitoid data would form a linear array in the $\epsilon_{Nd}(T)$ vs. T_{DM} plots. Fortunately, this ambiguous problem can be partially "corrected" if the degree of Sm/Nd fractionation, expressed as $f_{Sm/Nd}$ value, is limited to the range of -0.2 to -0.6, as shown later in Figure 4.

In the following, we first present isotope diagrams for the classic Phanerozoic orogenic belts in western Europe and in SE China and Korea, then demonstrate the contrasting isotopic features for the central Asian granitoids.

Classic Phanerozoic orogenic belts

(a) European Caledonides and Hercynides

In Figure 2 we summarize the available isotope data for the granitoids from the European Hercynides and Caledonides. The data of young Himalayan granites (ca. 20 Ma) are also shown for comparison, but their $\epsilon_{Nd}(T)$ values are not adjusted to a Palaeozoic age and their T_{DM} were calculated using a two-stage model because most of them have $f_{Sm/Nd}$ higher than -0.2 (Figure 2b). We note that almost all of the Hercynian (450 data points) and Caledonian granitoids (80) and all Himalayan leucogranites (29) are characterized by negative $\epsilon_{Nd}(T)$ values (Figure 2a). This suggests that the granitoids were mainly generated from sources containing large proportions of recycled Precambrian crust. Most of the Hercynian granitoids with near-zero $\epsilon_{Nd}(T)$ values are the post-tectonic A-type granites from Corsica (Poirasson et al., 1995). These rocks also have high Sm/Nd ratios, leading to very high T_{DM} , up to 3800 Ma (Figure 2b), but their mantle component is significantly higher than the rest as argued from the Nd isotope data. Figure 2b 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 to 2000 Ma. Note also that the Hercynian and Caledonian data sets cannot be distinguished as a whole.

(b) SE China and S. Korea

Cathaysia in the Yangtze Craton (Figure 1) is a major Phanerozoic orogenic belt in Asia. Like the CAOB, it is also characterized by voluminous Phanerozoic granitoids with rich mineralisations. Thus, a brief comparison of their isotopic signatures with those of the CAOB appears interesting 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 Sino-Korean craton, respectively, and they exhibit very contrasting tectonic styles and crustal evolutions. Their principal characteristics and differences 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 Cathaysia 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., 1995b; Gilder et al., 1996; Chen and Jahn, 1998).

The Phanerozoic granitoids of SE China (Yangtze craton, Cathaysia and Taiwan) also show negative $\epsilon_{Nd}(T)$ values except a few cases (Figures 3a,b,c). Some Mesozoic granites from Dabieshan show the lowest $\epsilon_{Nd}(T)$ from -15 to -25, suggesting their derivation from a protolith of Archean to early Proterozoic age (Figure 3a). In the $\epsilon_{Nd}(T)$ vs. initial $^{87}Sr/^{86}Sr$ diagram, the data indicate the dominance of both upper and lower crust in the generation of granitic liquids. The mantle component is subordinate (Figure 3b). Single-stage model ages range from 1,000 to 2,500 Ma for the majority of the

Figure 2 Isotope diagrams for granitoids from European Hercynides and Caledonides, and the Himalayas. Note that T_{DM} for Himalayan leucogranites shown in (a) were calculated using a two-stage model because a large number of them have $f_{Sm/Nd} > -0.2$. Data sources : Caledonian Belt : Hamilton et al. (1980), Halliday (1984), Frost and O'Nions (1985), Dempsey et al. (1990), Skjerlie (1992); 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); Himalaya: Vidal et al. (1984), Deniel et al. (1987), Inger and Harris (1993), Gazis et al. (1998), Harrison et al. (1999).

granitoids (Figure 3c). However, Chen and Jahn (1998) showed that there is an oceanward younging of T_{DM} and increase of $\epsilon_{Nd}(T)$ within the entire SE China.

With respect to the granitoids of SE China, the average late Paleozoic to Cretaceous granitoids of South Korea are characterized by even lower $\epsilon_{Nd}(T)$ values (Figures 3d, e, f) but comparable T_{DM} model ages (Figure 3f). However, the basement gneisses and metasediments show very radiogenic initial Sr isotope ratios (up to 0.775) and very old Nd model ages (1,500–3,800 Ma). Furthermore, the Sr isotope data indicate that the granitoids had no direct genetic relationship with the metasediments or gneisses in the Ogcheon belt (Figure 3e).

Like in the European Caledonides and Hercynides, the granitoids of SE China and South Korea are dominated by the recycled continental crust. While the mantle component plays an important

part in the generation of some Cretaceous granitoids in the coastal region of SE China and Taiwan (Jahn et al., 1990; Lan et al., 1995b; Chen and Jahn, 1998), it is totally absent in S. Korea. The overall picture indicates that there is a significant difference in the crustal development between SE China and S. Korea.

Central Asian Orogenic Belt

(a) NE China & Inner Mongolia

In NE China, 350 granitic bodies were intruded (mainly during the Mesozoic) in the Da Hinggan (or Great Khinggan), Xiao Hinggan (Lesser Khinggan) and Zhangguangcai Mountains. Some of the granites were emplaced within the domain of the Jiamusi Massif, a Precambrian microcontinental block whose metamorphic age

Table 1 Comparison of crustal evolution between the CAO and Cathaysia of 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 120 Ma $\Delta T \approx 400$ Ma	400 (?) to 80 Ma $\Delta T \approx 300$ Ma
Total volume	≈ 5.3 M sq. km** ($\approx 11\%$ 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
$\epsilon_{Nd}(T)$	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 eqv. Plume activities?	Assembly of ancient continental blocks; vast granitic plutons formed by remelting of old basement rocks
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, 1996); ** According to Sengör et al. (1993)

Figure 3 Isotope diagrams for granitoids from SE China (a, b, & c) and S. 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), Lee et al. (1999).

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 subordinated A-type granites (Wu et al., 2000a). They are covered by extensive Mesozoic and Tertiary acid volcanic rocks. Petrographic examination of deep drilled cores revealed that the Songliao Basin in central NE China is underlain by vast granitic rocks (Wu, unpublished). This suggests that the true volume of granitic rocks is much greater than what is observed in the present geologic map. Until now the tectonic setting for the emplacement of such immense distribution of granitic rocks in NE China is not resolved. It appears to have a connection with continental rifting but no relation with subduction zone processes.

In Inner Mongolia, several periods of granitic intrusions took place from Devonian to Jurassic times. Our samples came from a Paleozoic 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 (SHRIMP

zircon age of 309 ± 8 Ma) and a Mesozoic collision-type granitic suite of mainly adamellite with subordinate granodiorite and leucogranite (Rb-Sr age of 230 ± 20 Ma; Chen et al., 2000).

The Nd-Sr isotope data including all derivative parameters (intrusive and model ages, $f_{\text{Sm}/\text{Nd}}$) for the Phanerozoic granitic rocks from NE China, Inner Mongolia and the Hida belt of Japan are presented in Figure 4. In contrast to the European or SE China granites, the majority of the analyzed samples have positive $\epsilon_{\text{Nd}}(\text{T})$ values, indicating their relatively juvenile character. Note that most of the samples with negative $\epsilon_{\text{Nd}}(\text{T})$ values came from within the domain of the Precambrian Jiamusi Massif. 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 data from Xinjiang (see next section) and from the CAOB's northern belt of Mongolia-Transbaikalia (Kovalenko et al., 1996). This lowering of $\epsilon_{\text{Nd}}(\text{T})$ values of granitic intrusions was most probably effected by contamination of old crustal rocks.

Figure 4 Isotope diagrams for granitoids from Kazakhstan, northern Xinjiang, NE China and Inner Mongolia. Data sources: NE China: Wu et al. (2000a, 2000b) and Jahn et al. (1999); Inner Mongolia: Jahn, unpublished; Hida belt: Arakawa and Shimura (1995) and Arakawa et al. (2000); Xinjiang: Zhao et al. (1993), Zhou et al. (1995), Jahn (unpublished); Kazakhstan: Heinhorst et al. (1999).

Figures 4b and 4c show that they have a wide range of single-stage model ages. Aberrant model ages (negative or > 4,000 Ma) are produced due to strong Sm/Nd fractionation through crystallisation and magma-hydrothermal interaction leading to the tetrad effect of REE distribution (Masuda et al., 1987; Masuda and Akagi, 1990; Bau, 1996; Irber, 1999; Jahn et al., 1999). We therefore consider model ages interpretable only when $f_{\text{Sm/Nd}}$ values are -0.4 ± 0.2 . Consequently, the granites of NE China and Inner Mongolia have young model ages ranging from 500 to 1200 Ma except a few plutons emplaced in the Jiamusi Massif (Figures 4b and 4c). This is clearly distinguished from the granites of classic orogenic belts described above, and even more from the leucogranites of the Himalayas.

(b) Northern Xinjiang-Altai and Junggar

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 (Hu et al., 2000a). A brief summary of geological characteristics of these terranes was given by Hu et al. (2000a). The Altai terrane is a composite terrane consisting of Proterozoic gneiss complexes and Phanerozoic sedimentary cover and intrusions. The Junggar Basin is covered by Cenozoic desert and thick continental basin sediments (10 km) as old as 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 considered that the basin represents a microcontinent of Precambrian basement, whereas others regarded it as a trapped Paleozoic oceanic crust of various origins (Feng et al., 1989). 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 ages have been documented. Coleman (1989) considered these terranes as

Figure 5 Isotope diagrams for granitoids from Mongolia and Transbaikalia. Data sources: Kovalenko et al. (1996). Granites intruded in "Caledonian and Hercynian" belts (open symbols) are characterized by positive $\epsilon_{Nd}(T)$ values, whereas those intruded in pre-Riphean basement (black symbols) have both positive and negative $\epsilon_{Nd}(T)$ values.

oceanic arc assemblages and compared them with those in the present western Pacific.

A variety of Phanerozoic granitoids occur throughout northern Xinjiang. As for the case of NE China, the majority of granitoids have positive $\epsilon_{Nd}(T)$ values (Figures 4d, e, f) which suggest very large proportions of the mantle component in the generation of these rocks. This is particularly true for the granitoids from the Junggar terranes (Zhao, 1993; Han et al., 1997) and Alatau Mtns (Zhou et al., 1995). On the other hand, granitoids emplaced in the Altai composite terrane tend to show a wider range of isotopic compositions (Figure 4d). Granites of negative $\epsilon_{Nd}(T)$ values are most probably generated from a mixed source or due to contamination by Proterozoic gneisses during magma differentiation and emplacement.

Figures 4e and 4f show that the Junggar granites have very young model ages ranging from 300 to 1,000 Ma, whereas the granites from the Altai have more variable T_{DM} from 700 to 1,700 Ma. A tight relationship between the isotopic compositions of granitoids and the nature of their basement rocks can be established. Hu et al. (2000a) concluded from their Sm-Nd isotope data 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. 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. A tectonic implica-

tion is that the presence of old Precambrian microcontinents is important in the accretionary history in Central Asia.

(c) East central Kazakhstan

Heinhorst et al. (2000) undertook a comprehensive study of mineralisation in association with a variety of magmatic rocks in east-central Kazakhstan. Although the types of mineralisation (Au, Cu, rare-metal, or REE) may be related to a particular magmatic suite or a lithological variety, most granitic rocks have positive $\epsilon_{Nd}(T)$ values (Figures 4d and 4e) irrespective of their compositions or rock types (Heinhorst et al., 2000). The granitoids were intruded in several episodes: 450 and 300 Ma for magmatic suites with gold mineralisation, about 300 Ma for granitoids of rare-metal mineralisation, and ca. 250 Ma for A-type granites of REE mineralisation. Single stage model ages for all cases are between 400 to 1,400 Ma (Figure 4f).

(d) Northern belt of the CAOB—Mongolia to Transbaikalia

Kovalenko et al. (1996) delineated three isotope provinces ("Caledonian", "Hercynian", and pre-Riphean) which coincide with three tectonic zones of corresponding ages for the northern belt of the CAOB. We re-summarize their Nd isotopic data in Figure 5. Without exception, Phanerozoic granites emplaced into "Caledonian" and "Hercynian" tectonic zones have positive $\epsilon_{Nd}(T)$ values, suggesting their juvenile characteristics; whereas those intruded into the pre-Riphean basement show variable $\epsilon_{Nd}(T)$ from positive to negative values, indicating variable contributions of old Precambrian crust in the generation of granitic rocks (Figure 5a). Note that some late Neoproterozoic to early Paleozoic granites (600–500 Ma) have $\epsilon_{Nd}(T)$ values as high as +10, indicating their derivation from an almost pure depleted mantle component.

Figure 5b illustrates that the majority of the rocks emplaced in the Caledonian and Hercynian belts have Sm-Nd model ages younger than 1000 Ma, whereas those intruded in the Precambrian terranes have older T_{DM} from ca. 900 to 2500 Ma. If the rocks with fSm/Nd outside of the range -0.4 ± 0.2 are excluded, then all granitoids would have T_{DM} limited to 1500 Ma.

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 (450 Ma) to +1.5‰ in the youngest suite (220 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 Central Asia in the late Phanerozoic.

Discussion

Genesis of the Phanerozoic crust

The above data for the southern belt of the CAOB—from Kazakhstan, northern Xinjiang, Inner Mongolia to NE China, covering a distance of nearly 5000 km, indicate that most of the granitoids, despite of their highly differentiated nature and sometimes strong hydrothermal alteration leading to important mineralisations, possess a clear signature of high proportion of the mantle component in their petrogeneses. They are considered relatively juvenile and their massive intrusions suggest a significant addition of juvenile continental crust during the Phanerozoic. Likewise, the granitoids of the northern belt from central Mongolia to Transbaikalia have been extensively studied by Kovalenko and his associates, and a similar conclusion has been reached.

With regard to the massive generation of Phanerozoic juvenile crust, the best documented examples until now are those from the

Figure 6 Estimate of proportions of the mantle or juvenile component in the generation of Central Asian granitoids. The equation used is :

$$X^m = (\epsilon^c - \epsilon^r) Nd_c / [\epsilon^c (Nd_m - Nd_c) - (\epsilon^m Nd_m - \epsilon^c Nd_c)],$$
 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: $\epsilon^m = +8$; $\epsilon^c = -12$ (NE China), -30 (Central Mongolia), -15 (Altai and Kazakhstan), -4 (Junggar); $Nd_m = 15$ ppm; $Nd_c = 25$ ppm.

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), the Appalachians (Whalen et al., 1996; Samson et al., 1995) and eastern Australia (McCulloch and Chappel, 1982; Hensel et al., 1985; Eberz et al., 1990; Collins, 1996, 1998). While a significant mantle contribution to the generation of the CAOB granitoids is indicated by the Nd isotopic evidence, the precise mechanisms for the growth and evolution of the Phanerozoic continental crust remain debatable. Sengör et al., (1993) suggested that subduction processes alone to be responsible for formation of the juvenile crust. Windley (1993, 1995) distinguishes two types of orogens: (1) collisional orogens, formed by the collision of two or more large continental blocks (e.g., Himalayas, Alps, Grenville, etc.), and (2) accretionary orogens, formed by the growth and amalgamation of island arcs, intervening accretionary prisms, etc. (e.g., Altids, North American Cordillera, Andes, Birimian, Nubian-Arabian, etc.). A depleted mantle isotopic character is unusual for granitic rocks of collisional orogens worldwide, but are more commonly observed for those in accretionary orogens. High $\epsilon_{Nd}(T)$ values could reflect a direct contribution of mantle in subduction zones, but they could equally have no connection with subduction as well, as evidenced from the abundant A-type granites which are post-orogenic and not generated in subduction zones. Thus, subduction processes alone could not have been responsible for the formation of all the juvenile crust in the CAOB.

Implication for the origin of alkaline and peralkaline granitoids

Although many plutons and batholiths of the CAOB 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 1 and A/CNK 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 1), whose origin 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 (e.g., Collins et al., 1982; Creaser et al., 1991; 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; Whalen et al., 1996; Han et al., 1997). However, this is not universally true, as many A-type granites are also known to have a crustal isotopic signature (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. 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. Consequently, intraplate magmatism was probably a significant process of continental growth in the Phanerozoic.

Estimate of the proportions of juvenile crust

The Phanerozoic era appears to be a period of significant continental growth. A detailed discussion of petrogenetic models for individual CAOB granites is beyond the scope of this paper, but it can be found in several related works (e.g., Litvinovsky et al., 1992; Kovalenko et al., 1995; Zandvilevich et al., 1995; Hong et al., 1995; Han et al., 1997; Litvinovsky and Zandvilevich, 1998; Wu et al., 2000a). The available trace element and Nd-Sr isotopic data of A-type granites from Xinjiang and Inner Mongolia, and differentiated I-type granites from NE China indicate that the mixing model is the most probable process and the dominance of mantle component over crustal material. A mixing calculation using a fixed depleted mantle ($\epsilon_{Nd} = +8$) and variable crustal end-members suggest that the proportion of the mantle component (or % juvenile crust) for positive $\epsilon_{Nd}(T)$ granites varies from 60 to 100% (Figure 6) depending on the compositions of the assumed crustal end-members, which are taken from the Jiamusi Massif for NE China ($\epsilon_{Nd} = -12$, Jahn, unpublished), the Baidarik Block for Central Mongolia (-30 , Kozakov et al., 1997), the basement gneisses for Altai (-15), and Junggar (-4), and the Kazak basement assumed to be the same as the Altai gneisses. This implies extensive mantle differentiation and rapid juvenile crustal addition during the Phanerozoic. However, significant proportions of recycled crust are visible in the granitoids emplaced in the Jiamusi Massif and Altai composite terranes, and Pre-Riphean zones in Mongolia and Transbaikalia.

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/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 new rate would be at least 50% higher than the global growth rate of ca. 1.1 km^3/a deduced from arc magmatism only 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 of the continental growth.

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