doi: 10.1046/j.1365-3121.2003.00491.x

Mesozoic high-Ba–Sr granitoids from North China: geochemical characteristics and geological implications

Qing Qian,[1] Sun-Lin Chung,[2] Tung-Yi Lee[3] and Da-Jen Wen[2]

[1]*Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, People's Republic of China;* [2]*Department of Geosciences, National Taiwan University, 245 Choushan Road, Taipei, People's Republic of China;* [3]*Department of Earth Sciences, National Taiwan Normal University, Taipei, People's Republic of China*

ABSTRACT

Mesozoic magmatism occurred extensively in the North China block (NCB) and the Dabie–Sulu orogen (DSO) post-dating the North–South China collision, resulting in abundant intrusive and volcanic rocks ranging from basic to acidic compositions. The intermediate-acidic intrusive rocks can be grouped into two types, namely high-Ba–Sr granitoids and low-Ba–Sr granitoids that both have distinct geochemical characteristics. The high-Ba–Sr granitoids are similar in most of the incompatible trace element systematics to the associated basic rocks, which probably originated from melting of subcontinental lithospheric mantle, indicating significant mantle contributions to them. Geochemical similarities are observed between the basic rocks from the NCB and DSO, implying a regional-scale magma-generating mechanism and that mantle enrichment beneath the DSO was independent from the Triassic deep continental subduction in the region. We therefore interpret that the Mesozoic magmatism resulted from delamination of the ancient lithospheric mantle beneath the eastern part of North China.

Terra Nova, 15, 272–278, 2003

Introduction

Granitic rocks have been classified into different types by various criteria, including field geology, major and trace element geochemistry, mineralogy, assumed origin and tectonic environment (Frost *et al*., 2001, and references therein). Among these types, three are particularly abundant, namely the I-type, S-type (Chappell and White, 1974) and A-type (White, 1979). Generally, the traditional I-, S- and A-type granites possess low Ba and Sr concentrations (hence, denominated together as low-Ba–Sr granitoids). However, Tarney and Jones (1994) identified an additional type that, named high-Ba–Sr granitoids, exhibits many trace-element characteristics distinct from the low-Ba–Sr granitoids. The high-Ba–Sr granitoids are marked by high Ba and Sr, low Y and heavy rare earth elements (HREE), lack of apparent negative Eu anomaly and depletion of Nb in spidergrams.

The North China block (NCB), underlain by the Sino-Korean craton, was relatively stable from the Mesoproterozoic to Late Palaeozoic. It was amalgamated with the Siberian block to the north in the Late Palaeozoic along the central Asian orogenic belt (Sengör *et al*., 1993), and collided with the South China block (SCB) to the south during the Triassic (Li *et al*., 2000) along the Qinling–Dabie–Sulu orogenic belt. The latter resulted in deep (> 200 km) subduction of the SCB beneath the NCB along the Dabie–Sulu orogen (DSO) (Ye *et al*., 2000). Following the continental collision, a series of geological events (the Yanshanian movements) occurred in the eastern part of North China, of which the most prominent are: (1) replacement of a cold, thick (> 180 km) and refractory lithospheric keel (Archaean in age, Gao *et al*., 2002) beneath the NCB by relatively hot, thin (~ 80 km) and fertile mantle (Griffin *et al*., 1998; Menzies and Xu, 1998; Fan *et al*., 2000); and (2) widespread occurrence of magmatism (mainly 165–100 Ma in age) in the eastern part of the NCB and the DSO (Fig. 1) (Wang *et al*., 1996; Chen *et al*., 1997; Ma *et al*., 1998; Fan *et al*., 2001). Replacement of the lithospheric mantle probably occurred from Jurassic to Late Cretaceous (Xu, 2001), largely contemporaneous with the magmatism. Hence the Yanshanian magmatism may be an important manifestation of mantle evolution beneath the NCB.

However, there is still controversy about the geochemistry and petrogenesis of the Yanshanian igneous rocks. Wang *et al*. (1996) proposed that these rocks are dominantly shoshonitic and subordinately high-K calc-alkaline in character, forming a 'shoshonite province', while Xu *et al*. (1999) argued that they are mainly high-K calc-alkaline and subordinately alkaline, with minor shoshonitic series. Zhang *et al*. (2001a,b) interpreted most of them as adakites derived by high-pressure melting of lower continental crust (garnet-in and plagioclase-out). Based on a compilation of 192 analyses from the literature (Appendix), plotted in Figs 2–4, we show that the intermediate to acidic rocks from the NCB and DSO comprise dominantly high-Ba–Sr granitoids and subordinately low-Ba–Sr granitoids. This identification leads to some geological implications that markedly differ from the previous views.

Geochemical characteristics of the Yanshanian magmatism

The Yanshanian igneous rocks from the NCB and DSO show a wide range of composition, with SiO_2 varying continuously from ~46.5–77.5 wt% (Fig. 2a). In the SiO_2 vs. K_2O diagram (Fig. 2b), the rocks plot dominantly in high-K calc-alkaline field, and subordinately in shoshonitic and rarely in medium-K calc-alkaline fields, showing an overall potassic character.

Correspondence: Dr Qing Qian, Institute of Geology and Geophysics, Chinese Academy of Sciences, PO Box 9825, Beijing 100029, China. Tel.: 86 10 62007825; fax: 86 10 62010846; e-mail: qianqing@mail.igcas.ac.cn

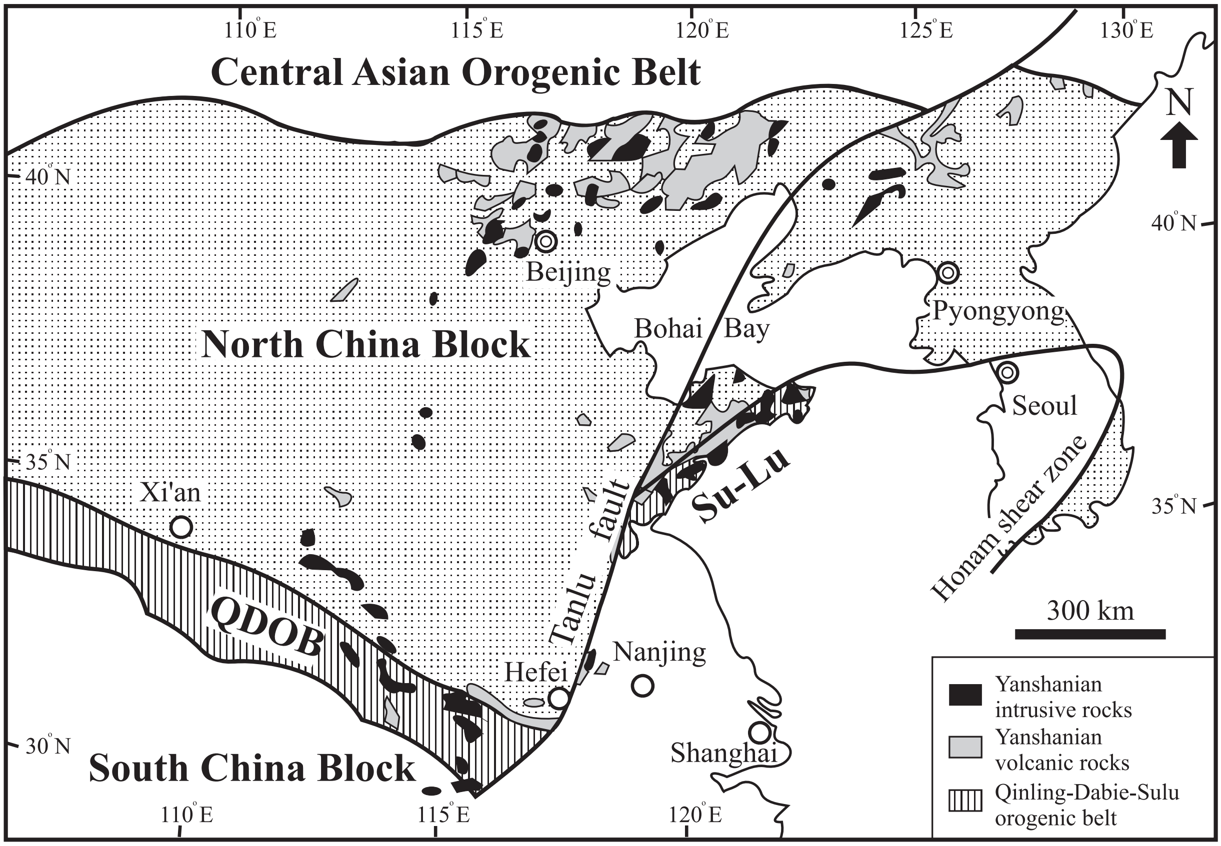

Fig. 1 Sketch map of the distribution of the Yanshanian igneous rocks from North China and the Dabie–Sulu orogenic belt (modified after Chung, 1999).

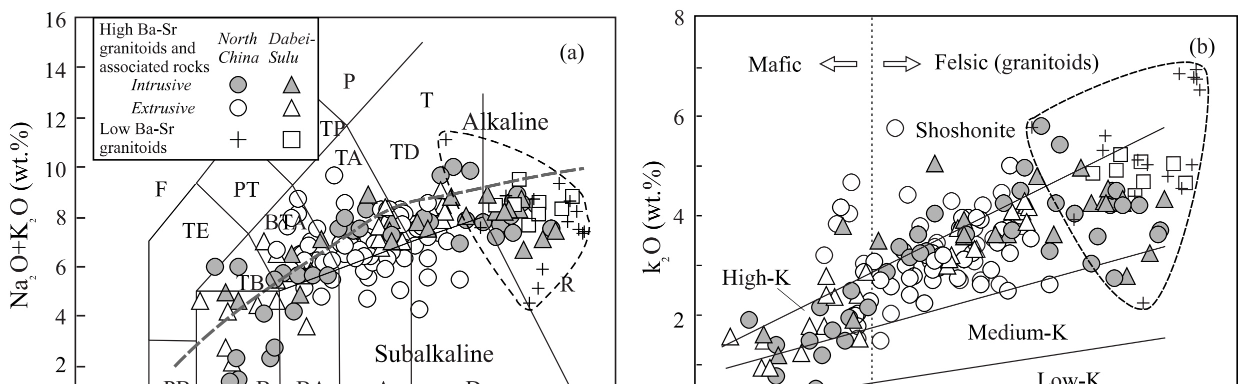

Fig. 2 Geochemical classification diagrams for Mesozoic igneous rocks from the North China Block (NCB) and Dabie–Sulu orogen (DSO). (a) $Na_2O + K_2O$ vs. SiO_2 diagram. Key to abbreviations: PB, picrobasalt; B, basalt; BA, basaltic andesite; A, andesite; D, dacite; R, rhyolite; TB, trachybasalt; BTA, basaltic trachyandesite; TA, trachyandesite; TD, trachydacite; T, trachyte; TE, tephrite; PT, phonotephrite; TP, tephriphonolite; P, phonolite; F, foidite. (b) K_2O vs. SiO_2 diagram. Note that rocks with SiO_2 < 55 wt% and > 55 wt% are classified as mafic and felsic (granitoids if intrusive), respectively. Dashed line delineates the areas of the low-Ba–Sr granitoids. Data from the NCB are from Qin (1995), Chen *et al*. (1997), Xu *et al*. (1999), Qiu *et al*. (2000) and Guo *et al*. (2001). Data from the DSO are from Ma *et al*. (1998), Jahn *et al*. (1999) and Fan *et al*. (2001).

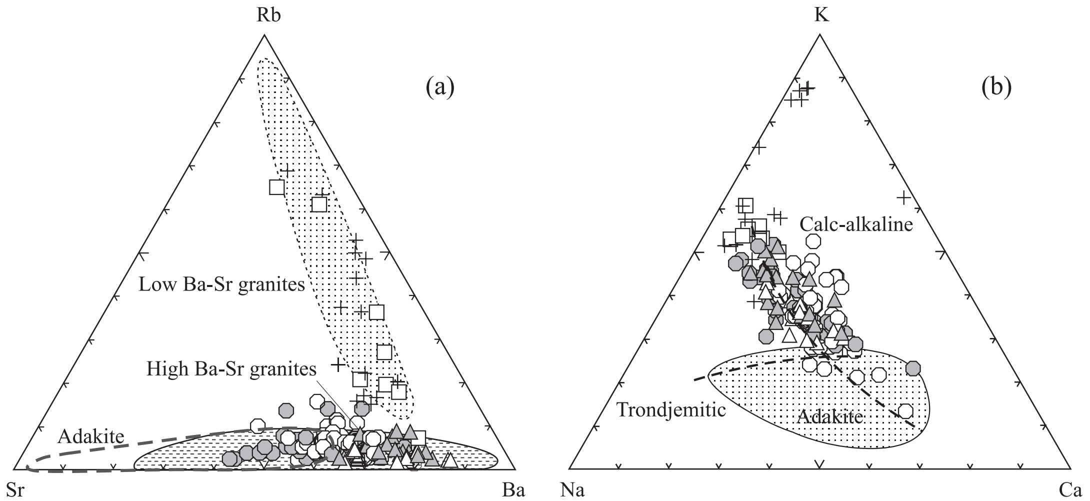

Fig. 3 (a) Sr–Rb–Ba plot (after Tarney and Jones, 1994), and (b) Na–K–Ca plot for Yanshanian intermediate-acidic rocks from the North China Block (NCB) and Dabie–Sulu orogen (DSO). Sample symbols are the same as that in Fig. 2. Fields of high-Ba–Sr and low-Ba–Sr granitoids are based on data from Fowler and Henney (1996) and Fowler *et al.* (2001). Fields of adakite are based on data from Kay (1978), Defant *et al.* (1991a,b), Sajona *et al.* (1993, 1994), Morris (1995), Stern and Kilian (1996) and Yogodzinski *et al.* (1994, 1995).

Rocks with SiO_2 > 55 wt% and < 55 wt% are termed felsic and mafic, respectively.

Based on Sr and Ba abundances, the granitoids can be divided into two types, namely, the high-Ba–Sr granitoids and low-Ba–Sr granitoids. The former generally have Sr > 300 p.p.m. and Ba > 500 p.p.m., and the latter have Sr < 300 p.p.m. and Ba < 500 p.p.m. This criterion applies well for most of the samples, except a few samples with low Sr (< 300 p.p.m.) but high Ba (up to 1470 p.p.m.) concentrations (grouped as low-Ba–Sr granitoids). In Tarney and Jones' (1994) Sr–Rb–Ba plot (Fig. 3a), the two types show apparently different trends, similar to the Scottish Caledonian granitoids. In addition, the high-Ba–Sr granitoids have high light rare earth elements (LREEs), low Y (4–30 p.p.m.) and heavy rare earth elements (HREEs), and depleted Nb (but not Eu) in spidergrams (Fig. 4a,b). Consequently, they have high Sr/Y (16–170) (Fig. 4d) and La/Yb (10–115) ratios. The low-Ba–Sr granitoids are also depleted in Nb, but in contrast strongly depleted in Ba, Sr and Eu (Fig. 4a,b) and have lower Sr/Y (1.8–21) (Fig. 4d) and La/Yb (6–56) ratios. It is notable that the high-Ba–Sr granitoids have incompatible element patterns similar to that of the associated mafic rocks (which is also true of many orogenic rocks worldwide, Tarney and Jones, 1994), but are relatively lower in most of the moderate to slight incompatible elements (Fig. 4a,b).

The two types of granitoids also show differences in major element compositions. The high-Ba–Sr granitoids have a relatively more mafic member and thus wider range of SiO_2 (55.5–74.8 wt%), coupled with higher Al_2O_3 (11.5–18.4 wt%, mostly > 14.0 wt%) and P_2O_5 (0.02–0.89 wt%, mostly > 0.20 wt%) contents, and lower K_2O/Na_2O (0.6–1.6). Corresponding values for the low-Ba–Sr granitoids are: 66.0–77.5 wt%, 11.5–16.8 wt% (mostly < 14.0 wt%), 0.02–0.25 wt% (mostly < 0.20 wt%) and 0.8–9.4, respectively.

The high-Ba–Sr granitoids from the NCB have a wide range in εNd(T) (T) (− 3.8 to − 20.2) but have a restricted range of initial $^{87}Sr/^{86}Sr$ ratios (0.7051– 0.7068). Those from the DSO are more uniform in εNd(T) (− 15.2 to − 21.4), with relatively higher initial $^{87}Sr/^{86}Sr$ ratios (0.7058–0.7096). Moreover, isotope compositions of the high-Ba–Sr granitoids are largely identical with those of the associated mafic rocks in each region (Fig. 4c). Nd-depleted mantle model ages (T_{DM}) of the high-Ba–Sr granitoids and mafic rocks mostly range between 1.50 and 2.20 Ga in both regions (Appendix). Limited Sr–Nd isotope data available for the low-Ba–Sr granitoids are heterogeneous, with initial $^{87}Sr/^{86}Sr$ and εNd(T) values of 0.7043–0.7317 and − 9.4 to − 13.0, and 0.7086–0.7149 and − 14.0 to − 20.5 for samples from the NCB and DSO, respectively (Appendix).

Magma source and petrogenesis of high-Ba–Sr granitoids

Two competing hypotheses have been proposed for the genesis of high-Ba–Sr granitoids. One is by Tarney and Jones (1994) who explored partial melting of three possible precursor magma sources: (1) subducted ocean islands or plateaus, (2) hydrous mafic underplates in the lower crust and (3) the lower continental lithosphere enriched by carbonatitic melts. The other is by Fowler and Henney (1996) and Fowler *et al.* (2001) who advocated the Scottish Caledonian granitoids as products of crystal fractionation from associated shoshonitic mafic magmas that originated from an enriched mantle lithosphere. In the latter, it is considered that crystallization of highly REE-conserved accessory minerals such as apatite and titanite play a crucial role in decreasing the abundances of REE, P and Ti through differentiation.

In North China, the Badaling complex (located ~40 km north of

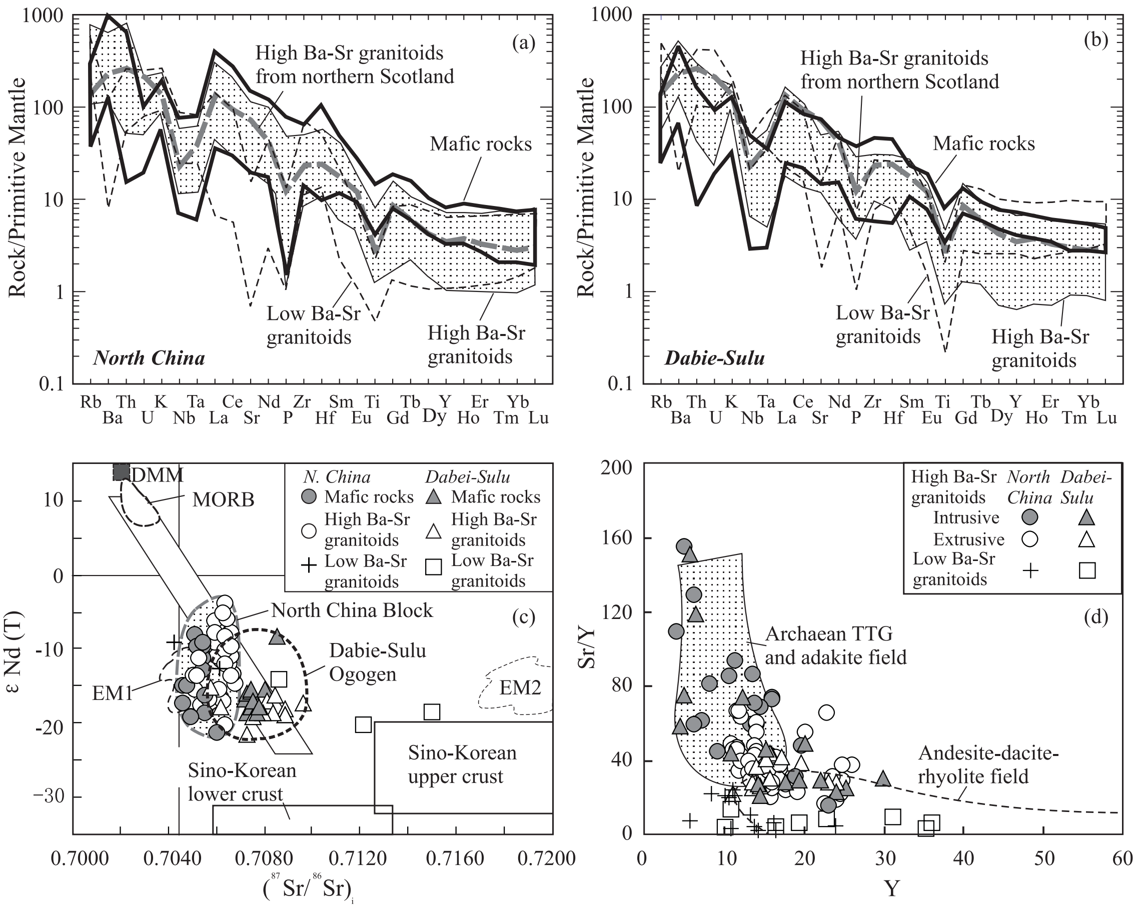

Fig. 4 (a,b) Primitive mantle-normalized multi-element distribution diagrams for Yanshanian igneous rocks from the North China Block (NCB) and Dabie–Sulu orogen (DSO), respectively. Normalizing data are after Sun and McDonough (1989). High-Ba–Sr granitoids from the Scottish Caledonian Orogen (Fowler *et al.*, 2001) are shown for comparison. (c) Initial $^{87}Sr/^{86}Sr$ vs. εNd(T) plot. Fields of Sino-Korean lower and upper crust are after Jahn *et al.* (1999). (d) Y vs. Sr/Y plot for Yanshanian igneous rocks from the NCB and DSO. Fields of Archaean TTG (trondhjemite, tonalite and granodiorite) and adakites, and arc andesite–dacite–rhyolite are after Martin (1999).

Beijing) serves as a good case example that comprises a whole series of magmas from mafic to intermediate and acidic compositions to study the magma source and petrogenesis of high-Ba–Sr granitoids. Major and trace element and Sr–Nd isotope data of the mafic rocks and high-Ba–Sr granitoids suggest that the Badaling high-Ba–Sr granitoids were generated by differentiation of the associated mafic magmas derived from an enriched subcontinental lithospheric mantle, with substantial crustal contamination (Qian *et al.*, 2002). Similarly, Li *et al.* (2002) postulated that Jurassic basaltic rocks from western Liaoning in the NCB originated from an enriched lithospheric mantle, and the accompanied andesitic and dacitic rocks (also high in Ba and Sr) represent differentiated products from the basaltic magmas through a combined assimilation and fractional crystallization (AFC) process. Ma *et al.* (1998) proposed a similar interpretation for coeval mafic rocks and high Ba–Sr granitoids (mainly Group II of Ma *et al.*'s classification) from the northern Dabie Mountains. Given the fact that high-Ba–Sr granitoids from both the NCB and the DSO exhibit incompatible elemental characteristics and Sr–Nd isotope compositions almost indistinguishable from those of the associated mafic rocks (Fig. 4a–c), we argue that the high-Ba–Sr granitoids contain a significant mantle component. Similarities in the multi-element distribution patterns between the high-Ba–Sr granitoids and the associated mafic rocks have been observed in Scottish Caledonides and many other orogens worldwide (Tarney and Jones, 1994), interpreted to indicate large mantle contributions to the generation of high-Ba–Sr granitoids (Tarney and Jones, 1994; Fowler *et al.*, 2001). Enrichment of the lithospheric mantle beneath the NCB may have been caused by interactions with small-volume melts from the lithosphere, asthenosphere or recycled crustal materials (Menzies, 1990). A similarly enriched old mantle lithosphere may also exist beneath the DSO (Fan *et al.*, 2001). In contrast, the low-Ba–Sr granitoids were possibly derived from melting of the lower–middle continental crust (Qian *et al.*, 2002).

Geological implications

Tarney and Jones (1994) pointed out that high-Ba–Sr granitoids dominate in the Archaean, and also occur extensively as plutons and volcanics in many Late Cretaceous and Tertiary orogenic belts worldwide. Our observations from North China lead to identification of an important high-Ba–Sr granitoid province of Mesozoic age. The high-Ba–Sr granitoids and their extrusive associates from the NCB and DSO show elemental characteristics (e.g. high Sr, Ba and LREE, low Y and HREE, elevated La/Yb and Sr/Y ratios, and lack of negative Eu anomaly) that are typical of adakites and Archaean TTG (trondhjemite, tonalite and granodiorite) suites (Martin, 1986; Drummond and Defant, 1990; Martin, 1999, and references therein). Therefore, they have been envisaged by some workers as adakites derived from lower crustal melting under high pressure with eclogite residue (Zhang *et al.*, 2001a,b; Defant *et al.*, 2002). Zhang *et al.* (2001a) further argued that the continental crust of the NCB was > 50 km thick during the Mesozoic so that there was an 'East China Plateau' comparable in height to the present Tibet. However, we note that these high-Ba–Sr granitoids are different from adakites by possessing higher K_2O/Na_2O (0.65–1.1), more variable Al_2O_3 (11.5–19.5 wt%) and much more enriched Sr and Nd isotopes. Furthermore, they delineate a calc-alkaline trend, rather than showing the trondhjemitic affinities of adakites in the Na–K–Ca plot (Fig. 3b), and are associated with Nb-depleted potassic mafic rocks (Ma *et al.*, 1998; Chen *et al.*, 2002; Li *et al.*, 2002; Qian *et al.*, 2002), in contrast to adakites that are occasionally associated with Nb-enriched basalts (Aguillón-Robles *et al.*, 2001, and references therein). The adakite-like geochemical features of the high-Ba–Sr granitoids can be explained as reflecting the enriched mantle source signatures, followed by differentiation of highly REE-conserved accessory phases (Li *et al.*, 2002; Qian *et al.*, 2002), similar to the case reported in the Scottish Caledonides (Fowler and Henney, 1996; Fowler *et al.*, 2001). Hence we argue that the adakite-like elemental characteristics of the high-Ba–Sr granitoids do not witness high-pressure melting of the lower crust.

Post-collisional interactions of the subducted crust (i.e. part of the SCB) with the asthenosphere (Jahn *et al.*, 1999) or the North China mantle lithosphere (Li *et al.*, 1998; Fan *et al.*, 2001) have been envisaged to explain some of the arc-type geochemical characteristics (e.g. enriched LILE, depleted Nb, and enriched Sr and Nd isotopes) of the mafic rocks from the DSO. These scenarios, however, could not apply further northward to account for the widespread occurrence of contemporaneous magmatism with similar elemental and isotopic characteristics (Fig. 4a–c) in the northern part of the NCB (Fig. 1). Taking the occurrence of Ordovician kimberlites into account, the suggested presence of an ancient (Griffin *et al.*, 1998; O'Reilly *et al.*, 2001) and enriched (Xu, 2001) mantle source in the NCB is considered vital, and consistent with the Nd T_{DM} data (Appendix) dominated by Palaeo- to Meso-proterozoic ages. Such a tempero-spatial association and petrochemical similarities of the Yanshanian magmas from the NCB and DSO indicate that mantle source enrichment beneath the DSO does not require continental subduction, but does require a larger-scale mechanism for the magma generation in the regions.

Basalt- and kimberlite-borne mantle xenoliths and geophysical data have consistently documented that delamination of *c*. 80–140 km of Archaean lithospheric mantle took place beneath the NCB during the Mesozoic (Griffin *et al.*, 1998; Menzies and Xu, 1998; Xu, 2001), coeval with the Yanshanian magmatism. The identification of the high-Ba–Sr granitoids provides further information that links the magmatism and the mantle evolution. Considering the significant contribution of the lithospheric mantle to the high-Ba–Sr granitoids and making reference to other continental collision zones where removal of the lower part of thickened lithospheric mantle has been widely accepted for causing post-collisional magmatism (Platt and England, 1994), we invoke delamination of the ancient Sino-Korean cratonic mantle lithosphere and upward movement of hotter asthenosphere to account for the post-collisional magmatism in the NCB and DSO. The geotherm thus raised may have triggered partial melting of veined peridotite (Foley, 1992) within the remnant lithospheric mantle to form potassic mafic magmas, some of which later differentiated into the high-Ba–Sr granitoids. The resultant extension and basin formation lasted into the Cenozoic and, after a substantial amount of lithospheric thinning was achieved, led to a new episode of magmatism consisting exclusively of intraplate basalts (Chung, 1999) resulting from decompression melting of the ascended asthenosphere. Furthermore, detailed studies, in particular precise dating of the Yanshanian magmatism, are required to unravel the complete scenario of tectonic evolution from stable craton to extension in North China.

Concluding remarks

The geochemical data presented here suggest that in the NCB and DSO the intermediate-acidic rocks of the Yanshanian post-collisional magmatism consist dominantly of high-Ba–Sr granitoids and subordinately of low-Ba–Sr granitoids. The geochemical and Sr–Nd isotope characteristics of the high-Ba–Sr granitoids are similar to those of the associated mafic lavas, suggesting significant contributions from the enriched lithospheric mantle to this type of granitoid. Geochemical similarities of the Yanshanian magmatism from the NCB and DSO require a regional-scale magma-generating mechanism that we ascribe to delamination of the Sino-Korean cratonic lithospheric mantle.

Supplementary material

The following supplementary material is available from http://www.blackwellpublishing.com/products/journals/suppmat/ter/ter491/ter491sm.htm

Appendix

Compiled data of Yanshanian igneous rocks from the North China Block (NCB) and Dabie–Sulu Orogen (DSO).

Acknowledgments

Comments from two anonymous reviewers that led to significant improvement of this paper are highly appreciated. This study has been supported by Major State Basic Research Development Program (G1999075502) and National Natural Science Foundation (No. 40002006) of China.

References

Aguillón-Robles, A., Caimus, T., Benort, M., Bellon, H., Maury, R.C., Cotton, J., Bourgois, J. and Michaud, F., 2001. Late Miocene adakites and Nb-enriched basalts from Vizcaino Peninsula, Mexico: indicators of East Pacific Rise subduction below southern Baja California? *Geology*, **29**, 531–534.

Chappell, B.W. and White, A.J.R., 1974. Two contrasting granite types. *Pacific Geol.*, **8**, 173–174.

Chen, Y.X., Chen, W.J. and Zhou, X.H., 1997. *Geochronology, Geochemistry and Tectonic Settings of Mesozoic Volcanic Rocks in Western Liaoning and Its Adjacent Regions*. Seismologic Press, Beijing (in Chinese with English abstract).

Chen, B., Jahn, B.M. and Wei, C.J., 2002. Petrogenesis of Mesozoic granitoids in the Dabie UHP complex, Central China: trace element and Nd–Sr isotope evidence. *Lithos*, **60**, 67–88.

Chung, S.L., 1999. Trace element and isotope characteristics of Cenozoic basalts around the Tanlu Fault with implications for the Eastern Plate Boundary between North and South China. *J. Geol.*, **107**, 301–312.

Defant, M.J., Clark, L.F., Stewart, R.H., Drummond, M.S., De Boer, J.Z., Maury, R.C., Bellon, H., Jackson, T.E. and Restrepo, J.F., 1991a. Andesite and dacite genesis via contrasting processes: the geology and geochemistry of EI Valle Volcano, Panama. *Contrib. Miner. Petrol.*, **106**, 309–324.

Defant, M.J., Richerson, P.M., De Boer, J.Z., Stewart, R.H., Maury, R.C., Bellon, H., Drummond, M.S., Feigenson, M.D. and Jackson, T.E., 1991b. Dacite genesis via both slab melting and differentiation: petrogenesis of La Yeguada volcanic complex, Panama. *J. Petrol.*, **32**, 1101–1142.

Defant, M.J., Xu, J.F., Kepezhinskas, P., Wang, Q., Zhang, Q. and Xiao, L., 2002. Adakites: some variations on a theme. *Acta Petrol. Sinica*, **18**, 129–142.

Drummond, M.S. and Defant, M.J., 1990. A model for trondhjemite–tonalite–dacite genesis and crustal growth via slab melting: Archean to modern comparisons. *J. Geophys. Res.*, **95**, 21503–21521.

Fan, W.M., Guo, F., Wang, Y.J., Lin, G. and Zhang, M., 2001. Post-orogenic bimodal volcanism along the Sulu Orogenic Belt in eastern China. *Phys. Chem. Earth (a)*, **26**, 733–746.

Fan, W.M., Zhang, H.F., Baker, J., Jarvis, K.E., Mason, P.R.D. and Menzies, M.A., 2000. On and off the North China craton: where is the Archaean keel? *J. Petrol.*, **41**, 933–950.

Foley, S., 1992. Vein-plus-wall-rock melting mechanisms in the lithosphere and the origin of potassic alkaline magmas. *Lithos*, **28**, 435–453.

Fowler, M.B. and Henney, P.J., 1996. Mixed Caledonian appinite magmas: implications for lamprophyre fractionation and high Ba–Sr granite genesis. *Contrib. Miner. Petrol.*, **126**, 199–215.

Fowler, M.B., Henney, P.J., Darbyshire, D.P.F. and Greenwood, P.B., 2001. Petrogenesis of high Ba–Sr granites: the Rogart pluton, Sutherland. *J. Geol. Soc. London*, **158**, 521–534.

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J. and Frost, C.D., 2001. A geochemical classification for granitic rocks. *J. Petrol.*, **42**, 2033–2048.

Gao, S., Rudnick, R.L., Carlson, R.W., McDonough, W.F. and Liu, Y.S., 2002. Re–Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton. *Earth Planet. Sci. Lett.*, **198**, 307–322.

Griffin, W.L., Zhang, A.D., O'Reilly, S.Y. and Ryan, C.G., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton. In: *Mantle Dynamics and Plate Interactions in East Asia* (M. F. J. Flower, S. L. Chung, C. H. Lo and T. Y. Lee, eds), pp. 107–126. American Geophysical Union Geodynamics Series 27. American Geophysical Union, Washington.

Guo, F., Fan, W.M., Wang, Y.J. and Lin, G., 2001. Late Mesozoic mafic intrusive complexes in North China Block: constraints on the nature of subcontinental lithospheric mantle. *Phys. Chem. Earth (a)*, **26**, 759–771.

Jahn, B.M., Wu, F.Y., Lo, C.H. and Tsai, C.H., 1999. Crust–mantle interaction induced by deep subduction of the continental crust: geochemical and Sr–Nd isotopic evidence from post-collisional mafic–ultramafic intrusions of the northern Dabie complex, central China. *Chem. Geol.*, **157**, 119–146.

Kay, R.W., 1978. Aleutian magnesian andesites: melts from subduction Pacific ocean crust. *J. Vol. Geotherm. Res.*, **4**, 117–132.

Li, S., Jagoutz, E., Chen, Y.Z. and Li, Q.L., 2000. Sm–Nd and Rb–Sr isotopic chronology and cooling history of ultrahigh pressure metamorphic rocks and their country rocks at Shuanghe in the Dabie Mountains, Central China. *Geochim. Cosmochim. Acta*, **64**, 1077–1093.

Li, W.P., Li, X.H., Lu, F.X., Zhou, Y.Q. and Zhang, D.G., 2002. Geological characteristics and its setting for volcanic rocks of early Cretaceous Yixian Formation in western Liaoning province, eastern China. *Acta Petrol. Sinica*, **18**, 193–204 (in Chinese with English abstract).

Li, S., Nie, Y.H., Hart, S.R. and Zheng. S.G., 1998. Upper mantle–deep subducted continental crust interaction: (II) Sr and Nd isotopic constraints on the syn-collisional mafic to ultramafic intrusions in the northern Dabieshan, eastern China. *Science in China (Series D)*, **28**, 18–22.

Ma, C., Li, Z., Ehlers, C., Yang, K. and Wang, R., 1998. A post-collisional magmatic plumbing system: Mesozoic granitoid plutons from the Dabieshan high-pressure and ultrahigh-pressure metamorphic zone, east-central China. *Lithos*, **45**, 431–456.

Martin, H., 1986. Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas. *Geology*, **14**, 753–756.

Martin, H., 1999. Adakite magmas: modern analogues of Archean granitoids. *Lithos*, **46**, 411–429.

Menzies, M.A., 1990. Archaean, Proterozoic, and Phanerozoic lithospheres. In: *Continental Mantle* (M. A. Menzies, ed.), pp. 67–86. Clarendon Press, Oxford.

Menzies, M.A. and Xu, Y.G., 1998. Geodynamics of the North China craton. In: *Mantle Dynamics and Plate Interactions in East Asia* (M. F. J. Flower, S. L. Chung, C. H. Lo and T. Y. Lee, eds), pp. 155–165. American Geophysical Union Geodynamics Series 27. American Geophysical Union.

Morris, P.A., 1995. Slab melting as an explanation of Quaternary volcanism and aseismicity in southwest Japan. *Geology*, **23**, 395–398.

O'Reilly, S.Y., Griffin, W.L., Djomani, Y.H.P. and Morgan, P., 2001. Are lithospheres forever? Tracking changes in subcontinental lithospheric mantle through time. *GSA Today*, **11**, 4–9.

Platt, J.P. and England, P.C., 1994. Convective removal of lithosphere beneath mountain belts: thermal and mechanical consequences. *Am. J. Sci.*, **294**, 307–336.

Qian, Q., Chung, S.L., Lee, T.Y. and Wen, D.J., 2002. Geochemical characteristics and petrogenesis of the Badaling high Ba–Sr granitoids: a comparison of igneous rocks from North China and the Dabie–Sulu Orogen. *Acta Petrol. Sinica*, **18**, 275–292 (in Chinese with English Abstract).

Qin, D.J., 1995. *Yanshanian magma activity and mineralization in Lingqiu-Laiyuan Area*. Doctoral Dissertation, Beijing University (in Chinese with English abstract).

Qiu, J.S., Lo, C.H., McInnes, B.I.A. and Zhou, J.C., 2000. Potash-rich magmatism and associated gold–copper mineralization in the Yishu deep fault zone and its vicinity, eastern China. *Resource Geol.*, **50**, 269–280.

Sajona, F.G., Bellon, H., Maury, R.C., Pubellier, M., Cotton, J. and Rangin, C., 1994. Magmatic response to abrupt changes in geodynamic settings: Pliocene–Quaternary calc-alkaline and Nb-enriched lavas from Mindanao (Philippines). *Tectonophysics*, **237**, 47–72.

Sajona, F.G., Maury, R.C., Bellon, H., Cotton, J., Defant, M.J. and Pubellier, M., 1993. Initiation of subduction and the generation of slab melts in western and eastern Mindano, Philippines. *Geology*, **21**, 1007–1010.

Sengör, A.M., Natal'In, B.A. and Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature*, **364**, 299–307.

Stern, C.R. and Kilian, R., 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austral Volcanic Zone. *Contrib. Mineral. Petrol.*, **123**, 263–281.

Sun, S.-S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: *Magmatism in the Ocean Basins* (A. D. Saunders and M. J. Norry, eds). *Geol. Soc. [London] Spec. Publ.*, **42**, 313–345.

Tarney, J. and Jones, C.E., 1994. Trace element geochemistry of orogenic igneous rocks and crustal growth models. *J. Geol. Soc. London*, **151**, 855–868.

Wang, D.Z., Ren, Q.J., Qiu, J.S., Chen, K.R., Xu, Z.W. and Zen, J.H., 1996. Characteristics of volcanic rocks in the shoshonite province, eastern China, and their metallogenesis. *Acta Geol. Sinica*, **70**, 23–34 (in Chinese with English Abstract).

White, A.J.R., 1979. Sources of granite magmas. *Geol. Soc. Am., Abstracts with Programs*, **11**, 539.

Xu, Y.G., 2001. Thermo-tectonic destruction of the Archaean lithospheric keel beneath the Sino-Korean craton in China: evidence, timing and mechanism. *Phys. Chem. Earth (a)*, **26**, 747–757.

Xu, B.L., Yan, G.H. and Xu, Z.B., 1999. Geochemistry and genetic implication of three series of Yanshanian granite in northern Hebei Province. *Acta Petrol. Sinica*, **15**, 208–216 (in Chinese with English abstract).

Ye, K., Cong, B.L. and Ye, D.N., 2000. The possible subduction of continental material to depths greater than 200 km. *Nature*, **407**, 734–736.

Yogodzinski, G.M., Kay, R.W., Bolynets, O.N., Koloskov, A.V. and Kay, S.M., 1995. Magnesian andesite in the western Aleutian Komandorsky region: implications for slab melting and processes in the mantle wedge. *Geol. Soc. Am. Bull.*, **107**, 505–519.

Yogodzinski, G.M., Volynets, O.N., Koloskov, A.V., Seliverstov, N.I. and Matvenkov, V.V., 1994. Magnesian andesites and the subduction component in a strongly calc-alkaline series at Piip Volcano, far western Aleutians. *J. Petrol.*, **35**, 163–204.

Zhang, Q., Qian, Q., Wang, E.Q., Wang, Y., Zhao, T.P., Hao, J. and Guo, G.J., 2001a. An East China plateau in mid-late Yanshanian period: implication from adakites. *Chinese J. Geol.*, **36**, 248–255 (in Chinese with English abstract).

Zhang, Q., Wang, Y. and Wang, Y.L., 2001b. Preliminary study on the components of the lower crust in east China Plateau during Yanshanian Period: constraints on Sr and Nd isotopic compositions of adakite-like rocks. *Acta Petrol. Sinica*, **17**, 505–513 (in Chinese with English abstract).

Received 18 July 2002; revised version accepted 30 April 2003

