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Association of Late Paleozoic Adakitic Rocks and Shoshonitic Volcanic Rocks in the Western Tianshan, China

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Abstract The late Paleozoic adakitic rocks are closely associated with the shoshonitic volcanic rocks in the western Tianshan Mountains, China, both spatially and temporally. The magmatic rocks were formed during the period from the middle to the late Permian with isotopic ages of 248–268 Ma. The $^{87}Sr/^{86}Sr$ initial ratios of the rocks are low in a narrow variation range (~0.7050). The $^{143}Nd/^{144}Nd$ initial ratios are high (~0.51240) with positive $\varepsilon_{Nd}(t)$ values (+1.28–+4.92). In the $\varepsilon_{Nd}(t)$–$(^{87}Sr/^{86}Sr)_i$ diagram they fall in the first quadrant. The association of the shoshonitic and adakitic rocks can be interpreted by a two-stage model: the shoshonitic volcanic rocks were formed through long-term fractional crystallization of underplated basaltic magma, while the following partial melting of the residual phases formed the adakitic rocks.

Key words: adakite, shoshonitic series rocks, uderplating, western Tianshan Mountains, China

1 Introduction

The late Paleozoic adakitic rocks (quartz albite porphyry, albite porphyry, dacite) are closely associated with the shoshonitic volcanic rocks in the western Tianshan Mountains both spatially and temporally (Zhao et al., 2000; Xiong et al., 2001). The shoshonitic volcanic rocks and adakitic rocks, which were first identified by Iddings in 1895 and Defant in 1990, respectively, have drawn more and more attention of geologists in the last 20 years because of their important significance in specific tectonic settings and related Au and Cu mineralization.

Adakite is a type of intermediate igneous rocks with unique geochemical characteristics such as high Na, Al and Sr contents, low Y, high Sr/Y ratios and strong depletion of HREE. Positive Sr and Eu anomalies are also obvious (Defant, 1990). Much more attentions have been paid to the study of adakite mostly because of its specific genetic mechanism (derived from partial melting of either subducted slab or underplated basaltic lower crust) and also its close association with large or superlarge porphyry Cu deposits (Defant, 1993, 2001; Thieblemont, 1997; Sajona, 1998; Zhang et al., 2001; Xiong et al., 2001; Mungall, 2002; Wang et al., 2002; Hou et al., 2003). The authors recognized the close association of shoshonitic volcanic rocks with adakitic rocks, such as quartz albite porphyry, albite porphyry and dacite, in the Awulale region of the western Tianshan Mountains, and further confirmed that they erupted or intruded in the Permian and might have contributed to the Cu mineralization in the region. A possible petrogenetic model is proposed for these rocks.

2 Regional Geology

In the Awulale Mountain region, all shoshonitic volcanic rocks and associated adakatic quartz albite porphyry, albite porphyry and dacite occurring in the south of Nilka County (Fig. 1) were formed from the middle to the late Permian.

The adakitic rocks are composed mainly of dacite of the Hamistan Group, upper Permian and quartz albite porphyry intruded in the Xiaoshansayi Group. The shoshonitic volcanic rocks occur in the underlying Taerdetao Group, lower Permian.

The $^{40}Ar/^{39}Ar$ plateau age of adakitic quartz albite porphyry is 268±5 Ma and isochron ages of $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ is 256±5 Ma (Zhao et al., 2003). The isochron age of Rb-Sr and K-Ar dating are 248±12 Ma (Li et al., 2001) and 254±5 Ma, respectively (Yao, 1990).

3 Petrology

3.1 Adakitic rocks

The adakitic rocks in the Awulale region include quartz albite porphyry and dacite. The phenocrysts of quartz albite porphyry include magaugite, albite and minor biotite; the matrix is of pilotaxtic texture and consists mainly of albite microcrystals, a small amount of quartz and alkaline feldspar. The phenocrysts of adakitic dacite are sodium-oligoclase and hornblende, and the matrix consists of albite, with a small amount of alkaline feldspar and shows pilotaxtic texture. Electronic probe analysis shows that the

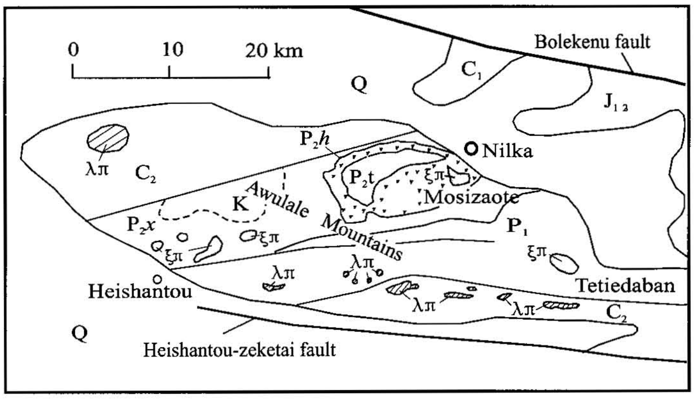

Fig. 1. Sketch geological map of Awulale shoshonitic volcanic rocks and associated adakitic rocks (modified from the 1:200,000 regional geological map).

Q – Quaternary, K – cretaceous, J_{1-2} – sandstone conglomerate, C_2 – volcanic sedimentary series, P_1 – volcanic sedimentary series, P_2x – Xiaoshansayi Group sandstone conglomerate, P_2h – Hamistan Group tuff, dacite, basalt, P_2t – Tiemulike Group pelitic siltstone, conglomerate, $\xi\pi$ – albite porphyry, $\lambda\pi$ – quartz albite porphyry

composition of feldspar in adakitic rocks is Ab 98.4–99.4, An 0.5–1.3, Or 0.1–0.3.

3.2 Shoshonitic volcanic rocks

The shoshonitic series volcanic rocks are composed of absarokite, shoshonite and minor banakite. Clinopyroxene, plagioclase, hornblende, magnetite and ilmenite are the main minerals in absarokite. The clinopyroxene consists of mainly augite and some diopside. Most of hornblendes were replaced by chlorites. The k-feldspar microcrystals exist in matrix is sanidine (Or 77.7, Ab 19.0, An 3.3). Anorthoclase microcrystals (Ab 64.2, An 7.3, Or 28.5) exist in apomicrocrystals. The minerals in absarokite exhibit micro-ophitic, diabasic and pyroxene synneusis textures.

The shoshonite consists mainly of olivine, augite, plagioclase, magnetite and minor biotite locally. The olivine phenocrysts were replaced by bowlingite as pseudomorph. Plagioclases were replaced by zoisites. The matrix is mostly devitrified microcrystals consisting of sanidine (Or 98.7, Ab 0.8, An 0.5), plagioclase and anorthoclase (Or 13.1, Ab 84.2, An 2.7). The minerals in shoshonite form microdiabasic, glass porphyritic and hyalocrystalline pilotaxitic textures.

The banakite and shoshonite have similar main minerals and textures. The only difference is that in the banakite the plagioclase has a composition of labradorite (An 56.3) and appears as albite Carlsbad twins; and the feldspar in matrix underwent albitization or zoisitization.

4 Geochemistry of Major and Trace Elements

4.1 Adakitic rocks

The adakitic rocks from the Awulale region are mainly intermediate acid in lithology (SiO_2 62–71%). They consist of dacite, quartz albite porphyry and albite porphyry and are characterized by high contents of Na_2O (4.40–6.98%) and Al_2O_3 (>15%) with high Na_2O/K_2O ratios (1.98–4.22). The contents of Sr are high (303–1633 ppm) while those of Y (4–7 ppm) and Yb (0.3–0.65 ppm) are very low. As a result, their Sr/Y ratios are very high (20–40). In the Sr/Y-Y diagram, these adakitic rocks are located in the adakite field, which is different from typical volcanic–arc andesite and dacite (Fig. 2)

The chondrite-normalized REE patterns of the adakitic rocks show obvious Eu positive anomalies (Eu/Eu*

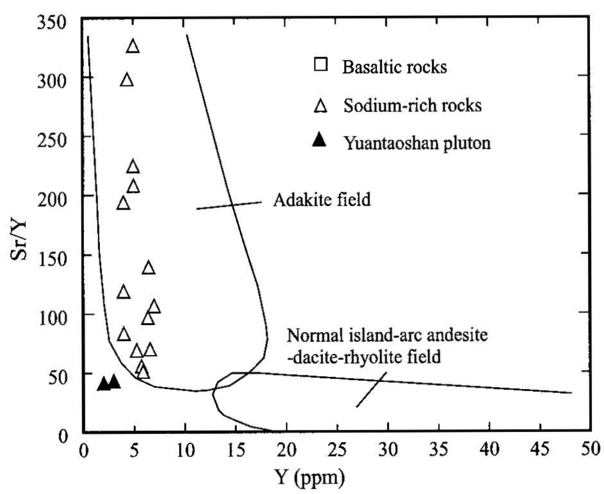

Fig. 2. The Sr/Y-Y diagram of adakitic rocks from the Awulale Mountain region.

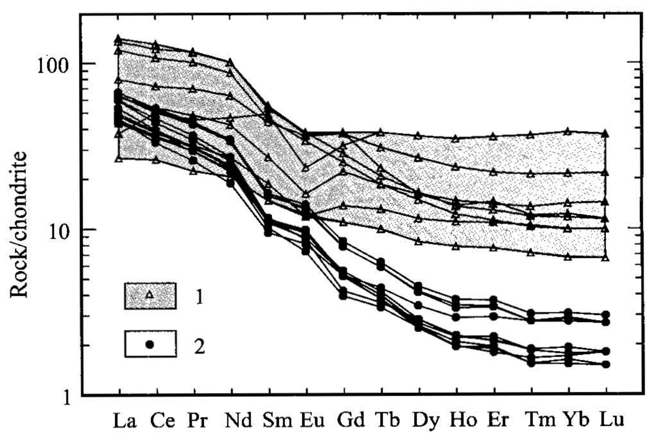

Fig. 3. Chondrite-normalized REE patterns of adakitic rocks and shoshonitic volcanic rocks from the Awulale Mountain region.

1. Shoshonitic volcanic rocks; 2. adakitic rocks.

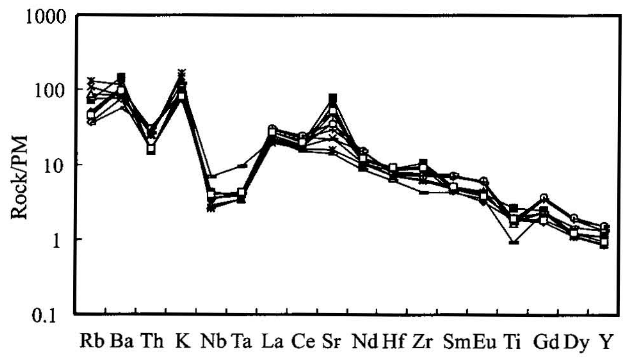

Fig. 4. Primitive mantle normalized trace element spidergram of adakitic rocks from te Awulale Mountain region.

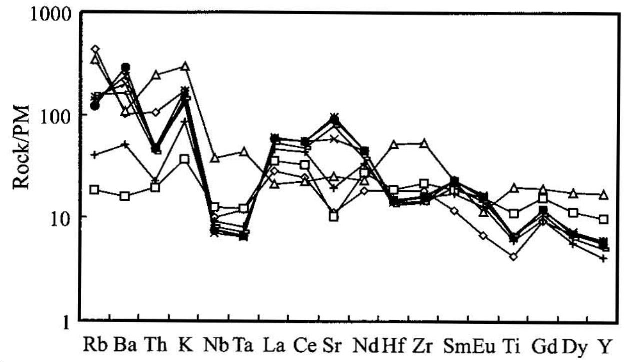

Fig. 5. Primitive mantle normalized spidergram for the shoshonitic volcanic rocks from the Awulale Mountain region.

1.06–1.27) and HREE depletion (Fig. 3). High field strength elements (HFSE) like Nb, Ta, U, Th and Ti are depleted and their primitive mantle normalized spidergram show an obvious positive anomaly of Sr (Fig. 4).

4.2 Shoshonitic volcanic rocks

The Awulale shoshonitic volcanic rocks are enriched in alkalis (Na_2O+K_2O >5%) and have high content of K_2O (as high as 8.12%), low content of TiO_2 (<1.6%), high and widely variable content of Al_2O_3 (13–19%), and high Fe_2O_3/FeO ratios (mostly>1). High contents of P, Rb, Sr, Ba and Th and negative anomalies of Nb, Ta and Ti can be seen in the primitive mantle normalized spidergram, which are typical for shoshonitic volcanic rocks (Fig. 5).

The total REE contents are highly variable (34–260 ppm) but lower than those of alkaline volcanic rocks in the study area. As shown by the chondrite-normalized REE patterns, the shoshonitic rocks are relatively enriched in LREE with weak or no Eu negative anomalies (Eu/Eu* 0.59–0.99, mostly 0.80) (Fig. 3).

5 Geochemistry of Sr and Nd Isotopes

5.1 Adakatic rocks

The initial ratios of $^{87}Sr/^{86}Sr$ are low with a narrow variation range (0.7051–0.7054). The initial ratios of $^{143}Nd/^{144}Nd$ are high (0.512384–0.512470) and the $\varepsilon_{Nd}(t)$ positive (+1.57– +3.26). In the $\varepsilon_{Nd}(t)$-($^{87}Sr/^{86}Sr)_i$ diagram adakitic rocks are distributed at the right of the mantle array falling in the first quadrant (Fig. 6).

5.2 Shoshonitic volcanic rocks

Sr and Nd isotopic compositions of the shoshonitic volcanic rocks and the adakitic rocks are very similar, i.e. low initial ratios of $^{87}Sr/^{86}Sr$ with a narrow variation randge (0.7054–0.7057, mostly 0.7050) and high initial ratios of $^{143}Nd/^{144}Nd$ (0.51232–0.51256) with positive ε_{Nd} (T) (+1.28– +4.92). In $\varepsilon_{Nd}(t)$–($^{87}Sr/^{86}Sr)_i$ diagram, the shoshonitic volcanic rocks fall in the same area as adakitic rocks. These characteristics are similar to those of potassic volcanic rocks in Vulture, Italy and Lesser Andiles in Grenada (Hawkesworth et al., 1979), and different from those of potassic rocks, which possess low initial ratios of $^{143}Nd/^{144}Nd$ and negative values of $\varepsilon_{Nd}(t)$ and fall in the fourth quadrant of the $\varepsilon_{Nd}(t)$–($^{87}Sr/^{86}Sr)_i$ diagram (Nelson, 1992) (Fig. 6).

6 Discussion

6.1 Tectonic settings

Most of adakitic rocks worldwide are located in island arcs and derived from partial melting of subducted slabs (O type) (Defant 1990, Martin et al., 1999) or the new underplated basaltic lower crust (C type) (Atherton et al., 1993; Martin et al., 1999; Xiong et al., 2001). The Awulale adakitic rocks were formed during the middle-late Permian. Based on the study of regional structure and paleontology, the collision of the plates took place in the western Tianshan Mountains in the early Carboniferous (Xiao et al., 1992; He et al., 1995). Therefore, the Awulale adakitic rocks were emplaced in the tectonic setting where the ocean was closed and entered a post-collision stage. The authors therefore hold that the Awulale adakitic magma was derived from the partial melting of the basaltic lower crust under a high-pressure and high-temperature condition. The shoshonitic volcanic rocks worldwide are commonly located in two tectonic settings, i.e., island arcs or active continental margins, and active zones such as continental rifting or deep-cutting faults. Based on the discrimination diagrams of Zr/Al_2O_3- TiO_2/Al_2O_3, Ce/P_2O_5-Zr/TiO_2 and 3Zr-50Nb-Ce/P_2O_5, the Awulale shoshonitic volcanic rocks were mainly formed in post-collision arc (PAP) and continental arc (CAP) settings (Zhao et al., 2000).

The characteristics mentioned above suggest that the Awulale adakitic rocks and shoshonitic volcanic rocks were generated in very similar tectonic settings, i.e., postcollisional active continental margins.

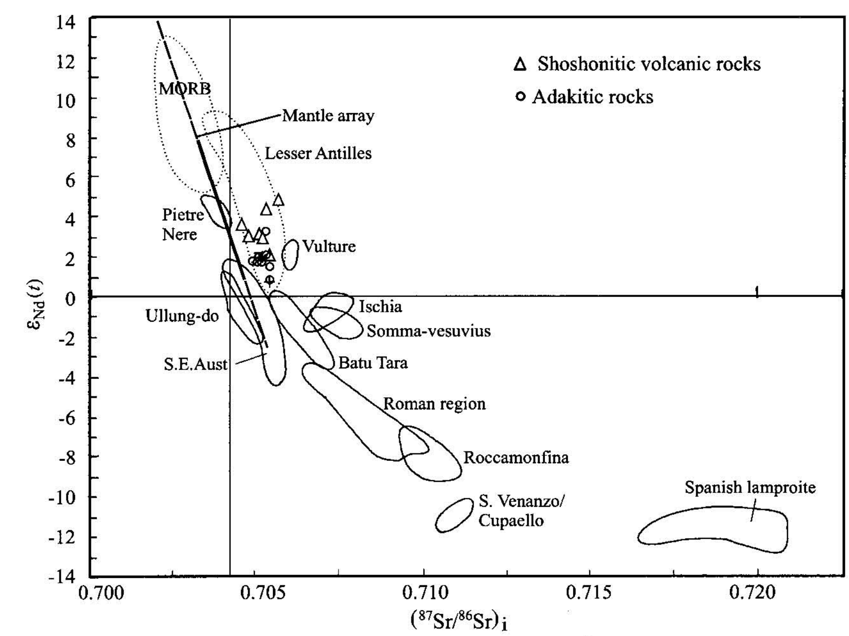

Fig. 6. The $\varepsilon_{Nd}(t)$–$(^{87}Sr/^{86}Sr)_i$ diagram of the shoshonitic volcanic rocks and adakitic rocks from Awulale Mountain.

6.2 Source materials

Adakitic rocks were commonly derived from partial melting of subducted slabs or from partial melting of new underplated basaltic rocks beneath the lower crust. The data of experimental petrology showed that the enrichment of potassium in shoshonitic magma could not be generated by partial melting of mantle rocks or crustal contamination. Based on the experiments, Meen (1987, 1990) suggested that long-term and high-degree (>85%) fractional crystallization of basaltic magma derived from partial melting of the upper mantle could generate shoshonitic magma (K_2O>6%) in a condition of thickened crust (>35 km) and high pressure (>1 GPa).

Weak depleted upper mantle rocks can be considered as the primitive source of the Awulale adakitic rocks and shoshonitic volcanic rocks based on the isotopic compositions of Sr and Nd (Fig. 6).

The contents of major elements are different between the Awulale adakitic rocks and shoshonitic volcanic rocks. The former are intermediate-acid in lithology and rich in Na, while the latter are basic to intermediate-basic and rich in K. These result in a continuous igneous series of basic → intermediate-basic → intermediate →intermediate-acid.

Obvious differences also exist in the REE compositions of the two associated rocks. The adakatic rocks are relatively rich in LREE with Eu positive anomaly. This is obviously different from the shoshonitic volcanic rocks, which are weakly enriched in LREE with weak or no Eu negative anomalies (Fig. 3). These features suggest that there was an evolutionary relation between the shoshonitic volcanic rocks and the adakitic rocks.

6.3 Petrogenetic model

Based on the similarity in tectonic setting, source material and geochemical evolutionary relationship between the Awulale shoshonitic volcanic rocks and the adakitic rocks, a model for their petrogenesis can be suggested as follows.

The basaltic magma derived from a low to middle degree of partial melting (<15%) of weakly depleted upper mantle could be taken as the primitive magma for the shoshonitic volcanic rocks and adakitic rocks. In conditions of thickened crust (>35 km) and high pressure (>1 GPa) (Meen, 1990), the basaltic magma in a magma chamber beneath the lower crust could generate shoshonitic magma through long-term and high-degree fractional crystallization and the coexisting residual phases are composed mainly of low-Ca pyroxene, plagioclase, augite and olivine.

Geophysical data indicate that the thickness of the crust in the western Tianshan Mountains ranges from 52 to 62 km (Li et al., 2001). These data also present the evidence for the existence of a crust-mantle mixed layer or complicate transitional zone composed of thin layers that are 2–3 km in thickness and have high and low velocities alternately (Peng et al., 2000; Zhao et al., 2001). These features suggest that the wide and strong underplating of basaltic magma took place near the crust-mantle boundary in the study area. In the western Tianshan Mountains and neighboring areas, widespread granitoids derived from crust-mantle differentiation and mantle-derived mafic igneous rocks are also the product of widespread underplating of basaltic magma during the late Paleozoic (Han 1999; Xiong et al., 2001).

After shoshonitic magma was extracted from basaltic magma, the residual phases (low-Ca pyroxene, plagioclase, augite and olivine) can remelt due to lithospheric extension and asthenospheric uplift to form adakitic magma with garnet, clinopyroxene±amphibole being the residual phases.

The petrogenetic process of the Awulale shoshonitic volcanic rocks and adakitic rocks can be summarized as a two-stage petrogenetic model: the shoshonitic volcanic rocks were formed in a stage of long-term fractional crystallization of basaltic magma followed by a stage of partial melting of residual phases coexisted with shoshonitic magma to form adakitic magma.

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