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Petrogenesis of high – $Mg^{\#}$ Cenozoic volcanic rocks of southern Qiangtang area, Tibetan Plateau: geochemical and Sr – Nd isotopic evidence

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Abstract: The Nadingcuo volcanic rock suite is the most voluminous Cenozoic volcanic suite in the southern Qiangtang area of the northern Tibetan Plateau. These high-K calc-alkaline volcanic rocks were formed between 36 and 34 Ma, characterized by high $Mg^{\#}$ values, high concentrations of TiO_2 and P_2O_5, $^{87}Sr/^{86}Sr$ ratios of 0.704682-0.706 112, and εNd(t) values of −1.2 to 1.6. There is a lack of reasonable explanations for sourcing and origin of magmas that formed the rocks with high $Mg^{\#}$ values and TiO_2 and P_2O_5 enrichments, which makes the previous research results still controversial. This study reviews the geochemical characteristics of Nadingcuo volcanic rocks and the data we have newly found in our fieldwork. We give some new interpretation to the magmatic evolution of the basaltic magmas in the discussed area dominated by fractional crystallization. The geochemistry of trachyandesite and trachyte units in the studied area is indicative of formation from mantle-derived magmas that mixed with crustal materials. The high values of $Mg^{\#}$ and TiO_2 and P_2O_5 enrichment in these units are evident to show the mixing between mantle-derived magmas with ~30-40 wt.% rhyolitic melt or assimilation of a similar amount of felsic rocks. The geochemistry of basaltic rocks in the area also suggests that the Nadingcuo basalts may have been derived from an ocean island basalt (OIB)-type source that contained and was mixed with ancient mantle wedge derived material, indicating that a 36-34 Ma asthenospheric upwelling event in the Qiangtang area may relate to the northward subduction of Indian lithospheric mantle and the southward subduction of Asian lithospheric mantle. This upwelling of asthenospheric material was centered in the southern Qiangtang area between 36 and 34 Ma, while the northward movement of the Indian Craton caused this upwelling mantle flow to continuously migrate northward, resulting in the current centering of this upwelling in the Hoh Xil-Kunlun region.

Key words: Tibetan Plateau; southern Qiangtang area; high-$Mg^{\#}$ volcanic rocks; Sr-Nd isotopic composition

1 Introduction

The Tibetan Plateau is generally considered to have formed during the India-Asia collisional orogeny, and thus provides a natural laboratory for the study of continental geodynamics. Cenozoic volcanic rocks are widely distributed in northern Tibet, recording the tectonic evolution of this area, displaying important

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petrological constraints on uplift mechanisms and geodynamic models for the Tibetan Plateau.

A significant amount of researches have been undertaken on Paleogene volcanic rocks in the Qiangtang area of northern Tibet (Deng *et al.*, 1998; Chi *et al.*, 1999, 2006; Ding *et al.* 2007; Lai *et al.*, 2007, 2013; Wang *et al.*, 2008a; Liu *et al.* 2008; Liu *et al.*, 2009; Wang *et al.*, 2010; Chen *et al.*, 2013). Paleogene high-K calc-alkaline volcanic rocks in the northern Qiangtang region crop out in the Duogecuoren, Wulanwnla Lake, Chibuzhangcuo, and other areas, whereas the Paleogene high-K calc-alkaline volcanic activity in the southern Qiangtang area formed volcanic units in and around the Nadingcuo area. Paleogene volcanic rocks in northern Qiangtang are dominated by high-K calc-alkaline latites, trachytes, quartz trachytes, andesites, dacites, and rhyolites, the majority of which erupted during the middle Eocene (46–38 Ma). These latites and trachytes have high $Mg^{\#}$ values, high Sr concentrations and low Y concentrations, suggesting the magmas that formed these units as a result of either (1) partial melting of subducted crustal material (Wang *et al.*, 2008a; Lai *et al.*, 2013), or (2) partial melting of delaminated lower continental crustal material (Chen *et al.*, 2013).

The Nadingcuo volcanic rocks exposed in the Sêngdo area are the most voluminous Cenozoic volcanic unit in this area, which cover all of the main rock types in the southern Qiangtang, including high-K calc-alkaline volcanics dominated by trachybasalt, olivine basaltic trachyandesite, pyroxene latite, and trachyte units. All of these high-K calc-alkaline volcanic rocks formed during the late Eocene (between 35.03 ± 0.54 and 34.24 ± 0.78 Ma). And the latite and trachyte units in this area have high $Mg^{\#}$ values, geochemically similar to adakites in that they have high Sr and low Y concentrations (Liu *et al.*, 2009; Wang *et al.*, 2010). They coexist with basaltic rocks with similarly high Sr and low Y concentrations. That also have elevated TiO_2 and P_2O_5 concentrations. This makes distinction with contemporaneous rocks in the northern Qiangtang area.

This study is supplemented by some new data about whole-rock major, trace element and Sr-Nd isotopic compositions. It also reviews the geological and geochemical characteristics of the volcanics in the Nadingcuo area as well as its adjacent areas, focusing on the magmatic processes that caused the formation of these high-$Mg^{\#}$ and TiO_2- and P_2O_5-enriched basalts, latites, and trachytes. The comparison between these volcanics and Eocene high-K calc-alkaline volcanic rocks in the northern Qiangtang and Duogecuoren areas shows new geochemical constraints for the nature of the source and the processes involved in the formation of the Eocene volcanic rocks in the southern Qiangtang.

2 Geological setting and petrology

On a regional scale, the Tibetan Plateau is composed of a tectonic collage of continental terranes or blocks. From north to south, the plateau is dominated by the E-W-trending Songpan-Ganzi, Qiangtang, Lhasa, and Himalayan terranes. These collages are separated by the Jinsha, Bangong, and Indus-Yalu sutures, representing fragments of the Paleotethys, Midtethys, and Neotethys oceans, respectively (Yin & Harrison, 2000). The exposed Cenozoic volcanic rocks in the southern Qiangtang area are bounded by the Jinshajiang suture in the north and the Bangong-Nujiang suture in the south (Fig. 1A), whereas Cenozoic volcanic rocks in the Duogecuoren-Zhentouya area of the northern Qiangtang region crop out to the east of Bamaoqiongzong. Cenozoic volcanic rocks in the southern Qiangtang area predominantly crop out within and to the west of the Nadingcuo area. These volcanics consist of sodic-alkali basalts in the Lagala (59 Ma) (Ding *et al.*, 2003) and Bangdacuo (44 Ma) areas (Deng *et al.*, 1998), 36–34 Ma high-K calc-alkaline volcanics in the Nadingcuo (Fig. 1B), Zougouyouchacuo, and Ejumaima areas (Chi *et al.*, 1999; Liu *et al.*, 2003; Ding *et al.*, 2007), and 30–24 Ma peralkaline potassic-ultrapotassic volcanics in the Yulinshan and Gemucuo areas (Chi *et al.*, 1999,

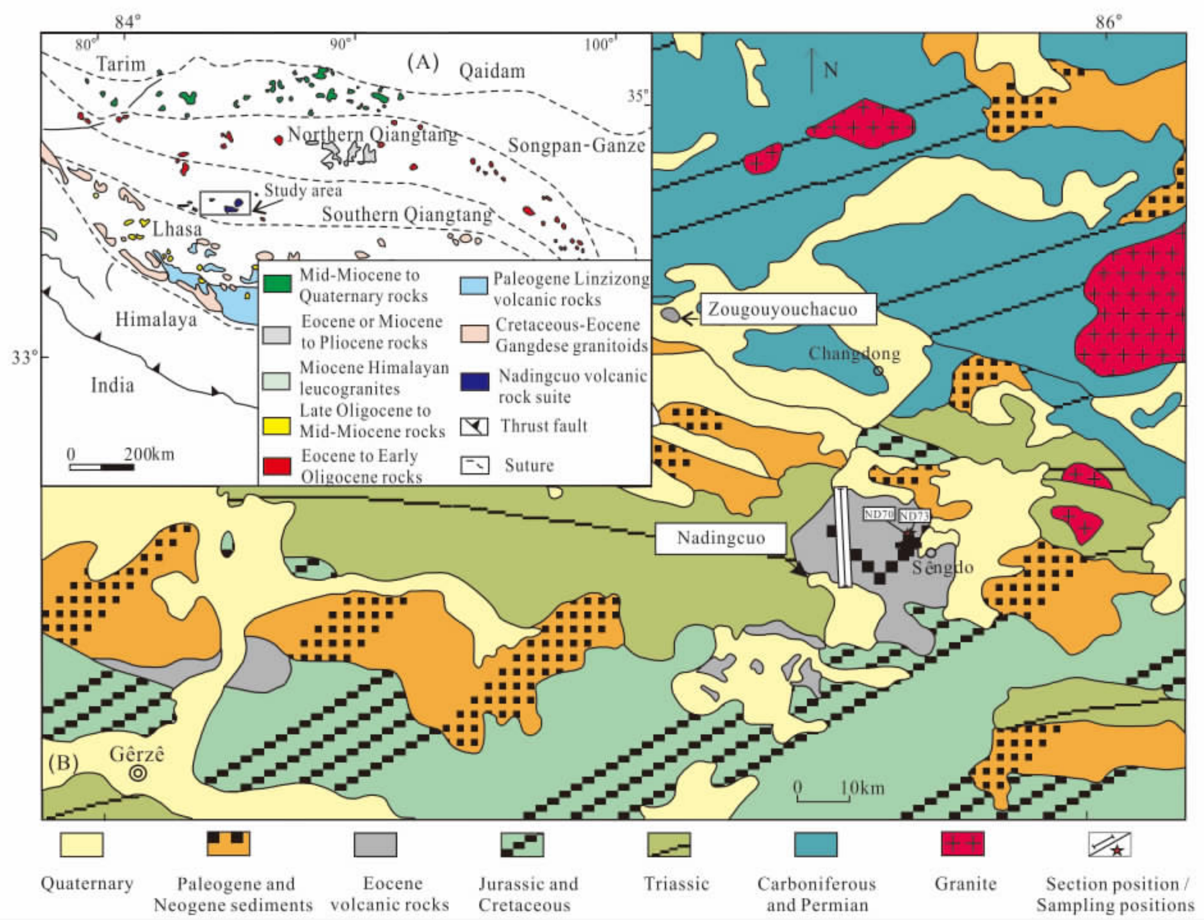

Fig. 1 (A) Map of Tibetan Plateau showing major blocks and temporal-spatial distribution of Cenozoic volcanic rocks; (B) Simplified geological map of Nadingcuo volcanic rocks in Qiangtang area (after Wang *et al.*, 2008a; Ding *et al.*, 2007; Pan *et al.*, 2004; Yin & Harrison, 2000; Ding *et al.*, 2007; Liu *et al.*,2009; Wang *et al.*, 2010)

2006; Liu *et al.*, 2003).

The Nadingcuo volcanic rocks exposed in the Sêngdo area represent the most voluminous Cenozoic volcanic unit in the southern Qiangtang area. These rocks are generally medium-sized lava sheets and multiple lava mounds. They are distributed over an area of about 700 km^2 from north to south of the Nadingcuo area. These volcanic rocks lie unconformably on top of Upper Triassic or upper Carboniferous-Lower Permian carbonates or turbidites. The lower lava sheets in the unit are black basalts cropping out to the southwest of Nadingcuo, whereas the upper lava sheets form the main part of the Nadingcuo volcanics, consisted of gray trachybasalts, olivine basaltic trachyandesites, trachyandesites, and trachytes. A few small and isolated volcanic remnant mounds are sporadically distributed in the west of the main lava sheets and are formed of latites and trachytes.

3 Genesis of the Nadingcuo magmas

3.1 Magmatic discrimination

This review of the geochemistry of the Nadingcuo volcanic rocks is based on the data presented in this study (Table 1) combined with analyses given by Ding *et al.*(2007); Liu *et al.*, (2009), and Wang *et al.* (2010).

The Nadingcuo trachybasalts contain olivine phenocrysts, and trachyandesites in the study area contain olivine and clinopyroxene phenocrysts, consistent with the lower Fe, Mg and Ca concentrations in the tachyandesites compared with the trachybasalts. In comparison, trachytes in the study area contain euhedral sanidine, clinopyroxene, and dark-rimmed amphibole phenocrysts that were formed during fractionation at depth. Basalts in the study area have Sr concentrations of ~1000 ppm, and olivine-, and clinopyroxene-bearing basaltic latites have the highest Sr concentrations of any volcanics in the study area. The lower Sr concentrations in the trachyandesites are connected to the fractionation of plagioclase and sanidine. These variations in phenocrysts and concentrations are indicative of the fractional-crystallization-dominated evolution of the magmas that formed these rocks.

Table 1 Sr-Nd isotopic compositions of Nadingcuo volcanic rocks

Sample No.	Rb /ppm	Sr /ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ	$(^{87}Sr/^{86}Sr)_i$	Sm /ppm	Nd /ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	$(^{143}Nd/^{144}Nd)_i$	$\varepsilon_{Nd}(t)$	T_{DM} Ma	$f_{Sm/Nd}$	T_{DM2} Ma
ND056-2	117	1867	0.1820	0.705214	13	0.70512	10.71	68.13	0.0951	0.512622	12	0.512600	0.1	681	-0.52	836
ND060	21	1340	0.0454	0.705183	13	0.70516	9.67	59.13	0.0989	0.512652	9	0.512629	0.7	664	-0.50	790
ND060-2	23	1381	0.0491	0.705188	8	0.70516	9.85	60.30	0.0987	0.512645	10	0.512622	0.6	672	-0.50	801
ND062	55	1142	0.1401	0.705836	10	0.70577	7.45	48.98	0.0919	0.512657	12	0.512636	0.8	620	-0.53	779
ND070	70	1039	0.1946	0.705436	11	0.70534	7.58	49.87	0.0918	0.512621	21	0.512599	0.1	665	-0.53	837
ND073	80	952	0.2418	0.705474	13	0.70535	7.89	52.97	0.0900	0.512619	11	0.512598	0.1	657	-0.54	839

$(^{87}Sr/^{86}Sr)_i = (^{87}Sr/^{86}Sr)_s - (^{87}Rb/^{86}Sr)_s(e^{\lambda Rbt} - 1)$; $\varepsilon_{Nd}(t) = [^{143}Nd/^{144}Nd)_s(t)/(^{143}Nd/^{144}Nd)_{CHUR}(t) - 1] \times 10^4$; $f_{Sm/Nd} = (^{147}Sm/^{144}Nd)_s/(^{147}Sm/^{144}Nd)_{CHUR} - 1$; $T_{DM} = 1/\lambda_{Sm} \times \ln\{[^{143}Nd/^{144}Nd)_s - (^{143}Nd/^{144}Nd)_{DM}] / [^{147}Sm/^{144}Nd)_s - (^{147}Sm/^{144}Nd)_{DM}] + 1\}$; $T_{DM2} = 1/\lambda_{Sm} \times \ln a$, $a = \{(^{143}Nd/^{144}Nd)_s - (^{143}Nd/^{144}Nd)_{DM} - [^{147}Sm/1^{44}Nd) s - (^{147}Sm/Nd)_c](e^{\lambda Smt} - 1)\} / [^{147}Sm/^{144}Nd)_c - (^{147}Sm/^{144}Nd)_{DM} + 1$; $\lambda_{Rb} = 1.43 \times 10^{-11}$ $year^{-1}$; $\lambda_{Sm} = 6.540 \times 10^{-12}$ $year^{-1}$.

Variations in highly compatible and highly incompatible elements are an important indicator of whether fractional crystallization or variation in the degree of partial melting is the main control over the composition of a magma. The Nadingcuo volcanic rocks within the southern Qiangtang area have Th concentrations that increase slightly, compared with sharp decreases in Cr concentration, a relationship that is typical for magmas undergoing fractional crystallization.

3.2 High $Mg^{\#}$ latite-trachyte: a product of magma mixing and assimilation contamination

The early magmatic evolution of the Nadingcuo trachybasalts was dominated by olivine and clinopyroxene fractionation, which resulted in the much lower $Mg^{\#}$ values of the fractionated magma. Only fractional crystallization can be used to explain the high $Mg^{\#}$ values of the Nadingcuo latite-trachyte units, with these latites and trachytes having other characteristics similar to high $Mg^{\#}$ adakites, such as high Sr and low Y concentrations. Two main models have been proposed for the genesis of the high-$Mg^{\#}$, high-Sr, and low-Y latites-trachytes in the study area, as discussed in the introduction of this paper. Both melting of subducted oceanic crustal and delaminated eclogitic crustal material and subsequent interaction with the surrounding mantle peridotite. High-$Mg^{\#}$ adakites can also be formed as the result of basaltic magmas' mixing with felsic magmas (Stern & Kilian, 1996; Rapp *et al.*, 1999; Wang *et al.*, 2008b). And both high-$Mg^{\#}$ and -Sr, and low-Y basaltic magmas' mixing with felsic magma will potentially form high-$Mg^{\#}$ adakites.

Experimental studies indicate that intermediate-acid melts formed by the partial melting of mafic rocks have $Mg^{\#}$ values of 40-10 (Fig. 2). In addition, adakitic melts are associated with rutile-bearing residual eclogites, characterized by low TiO_2 concentrations (Xiong *et al.*, 2005). In contrast to TiO_2-deficient adakitic melts, the latites and trachytes from the upper section of the Nadingcuo volcanics and the TiO_2- and P_2O_5-enriched basalts in the lower part of these volcanics have distinctly fractionated REE concentrations. The Nadingcuo trachybasalts also have higher Mg# values and TiO_2 and P_2O_5 concentrations, compared with the latites-trachytes, and also have high Sr and low Y concentrations. These units are also associated connected to each other, indicating that the high-Mg#, high-Sr, and low-Y latites and trachytes in the study area were most probably formed as a result of the mixing of felsic and basaltic magmas. In addition, LREE and HREE concentrations decrease during the transition from basalt to trachyte. This phenomenon is not consistent with the fact that LREE concentrations should increase with a decrease in the degree of partial melting of a mafic eclogitic source. It also contrasts with the fact that REE concentrations should increase in a melt during fractional crystallization. The REE concentrations of Cenozoic rhyolites in northern Tibet are generally lower than those of the Nadingcuo basalts, indicating that mixing of the magmas that formed these two units should have led to a decrease in REE concentrations. This decrease, along with the increase in the amount of rhyolite that was added to the mixed magma, suggests that is the process that formed the Nadingcuo volcanic rocks.

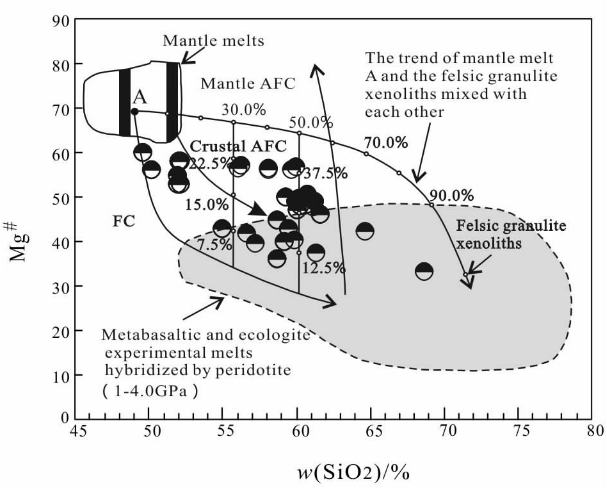

Fig. 2 Mg# versus SiO_2 (wt.%) diagram (after Stern & Kilian, 1996; Rapp *et al.*, 1999; Lai, 2013)

The Sr-Nd isotopic composition of the Nadingcuo volcanic rocks gives evidence for mixing between magmas and crustal materials. And the characteristics of the high Mg# latite-trachyte also impose constraints on the composition of the crustal material that these magmas assimilated with. The volcanic sample is used as a reference point with the most depleted Sr-Nd isotopic composition, while the average values of Cenozoic volcanic rocks of the Qiangtang terrane as a crustal end-member are taken as a reference for geochemical and isotopic composition of felsic granulite xenoliths. The calculations concerned show that a mixing ratio that indicates a maximum of 45 wt.% of assimilation of felsic rocks or melts by the magmas that formed the trachytic rocks in the region (Fig. 3), with the results close to those (< 38 wt.%) derived from the modeling of SiO_2 concentrations and Mg# values.

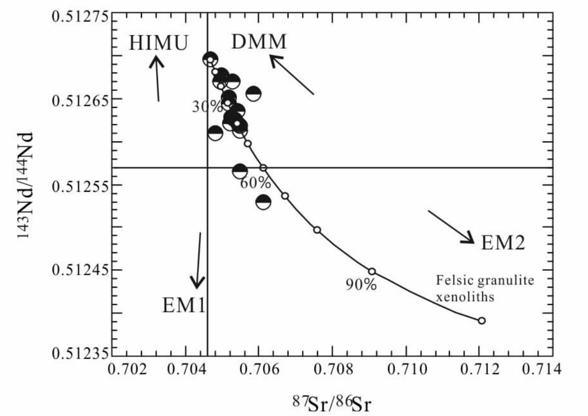

Fig. 3 Diagram of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ (after Madureira, 2011)

It should be noted that modeling with different felsic end-member compositions changes the mixing ratios, yielding results as low as 10 wt.%. For example, Sr-Nd isotopic modeling using the average composition of the Miocene Hoh Xil rhyolites yields a mixing ratio of trachytic magma with rhyolitic melts or felsic rocks of no more than 30 wt.%. However, the same mixture calculated using SiO_2 and Mg# variations yields a ratio of no greater than 35 wt.%.

Modeling with a dacite or more basic composition as the average composition of crustal material mixed with the basaltic magma did not yield results consistent with the high Mg# values and Sr-Nd isotopic compositions of the latites and trachytes in the study area.

While with modeling using the Sr-Nd isotopic composition of a dacite as a crustal end-member resulting in a mixing ratio of 55 wt.%, although a mixing ratio of 70 wt.% was required to generate a high $Mg^{\#}$ trachyte.

This indicates that the larger the amount of basic material within the crust, the greater the difference in mixing ratios between the two methods of calculation used during this study.

Therefore, the Nadingcuo basaltic magmas are known to have mixed with around 30 wt.%-40 wt.% of rhyolite melt or to have selectively assimilated the same amount of felsic rocks when undergoing fractional crystallization. This reasonably explains the continuous variations between the Nadingcuo basalt and latite-trachyte compositions, such as the continuous decrease in REE concentrations with no change in REE patterns between the latites and trachytes and the basalts. The fact is that the latites and trachytes have high $Mg^{\#}$ values but low Cr and Ni concentrations, and that there are variations in isotopic compositions between these units.

3.3 Nature of source region

The Nadingcuo basalts have low La/Nb, Ba/Nb, and Rb/Nb ratios, elevated TiO_2 and P_2O_5 concentrations, and $^{87}Sr/^{86}Sr$ ratios that are similar to asthenospheric mantle-derived OIB-type Miocene alkaline volcanic rocks in the Gansu Lixian area (Fig. 4A, B). However, the Nadingcuo volcanic rocks are distinctly different from both Andean calc-alkaline volcanic rocks and intracontinental subduction or delaminated lower-crust-associated high-K calc-alkaline and shoshonitic volcanic rocks of the Duogecuoren region of the northern Qiangtang area. The Duogecuoren volcanic rocks are characterized by high La/Nb, Ba/Nb, Rb/Nb, and $^{87}Sr/^{86}Sr$ ratios (Fig. 4C, D), although the Nadingcuo basalts are slightly depleted in Nb, Ta, and Ti relative to the other LILEs, potentially indicative of contributions from lithospheric mantle material or an ancient mantle wedge. Previous researches indicate that the Bangong-Nujiang suture in the south of Nadingcuo volcanic rocks recorded the closure of an ocean basin associated with bilateral subduction during the Early Cretaceous (132-110 Ma). Using Rb/Sr and $^{87}Sr/^{86}Sr$ ratios of Andean calc-alkaline basalts to calculate $^{87}Sr/^{86}Sr$ ratios for the Nadingcuo basalts rather than the modern subduction mantle wedge ratios yields an average $^{87}Sr/^{86}Sr$ ratio of 0.704 761-0.705 134 at 36 Ma using a formation age of 110 Ma for both the basalts and the ancient mantle wedge. These data are similar to the composition of the most basic basalts in the Nadingcuo area. In addition, as shown in Fig. 14A-B, the Nadingcuo basaltic rocks have La/Nb, Ba/Nb, Rb/Nb, and $^{87}Sr/^{86}Sr$ values that are similar to an intermediate composition between those in OIB-type Miocene alkaline volcanic rocks in the Gansu Lixian area and the composition of the Early Cretaceous ancient mantle wedge.

Moreover, this suggests that the source region for these basalts is closer in composition to the source region of OIB-type Miocene alkaline volcanic rocks in the Gansu Lixian area than to the mantle wedge material, suggesting that the Nadingcuo basalts may have been derived from an OIB-type source that included asthenospheric material mixed with ancient mantle wedge components, giving further evidence of the melting of upwelling asthenospheric mantle material during the generation of these magmas.

4 Tectonic implications

Replumaz *et al* (2010a) suggested that seismic tomography data for the study area provide evidence for the presence of an elongated, continuous, NW-SE-trending anomaly at depths between 1 100 and 1 600 km below the zone where India collided with Asia (14°N-16°N; shown as TH for Tethys in Fig. 5; this anomaly is thought to record the location of late Mesozoic oceanic subduction. In addition, the IN anomaly located beneath India (26°N-28°N) at depths of about 450-900 km (Fig. 5) is thought to represent a slab of subducted Indian continental material that underwent slab breakoff at 25 Ma.

The Nadingcuo basalts offer evidence for the upwelling of deep asthenospheric materials within the source region of the magmas that formed these units, indicating that the asthenospheric upwelling center in the northern Qiangtang-Hoh Xil area was present beneath southern Qiangtang at 35 Ma (Fig. 6). In addition, this upwelling of deep asthenospheric material caused diapiric melting along an unsubstantial tectonic belt. This melting also involved lithospheric mantle components that were softened by heating, resulting in partial melting and the forming of the southern Qiangtang 36–34 Ma high-K calc-alkaline basaltic magmas. Contemporaneous magma chambers also formed during a magmatic underplating event beneath the lower crust.

Finally, the Nadingcuo basaltic magmas mixed with rhyolitic melts or assimilated the same amount of felsic rocks while undergoing fractional crystallization to form high-$Mg^{\#}$ latites and trachytes from the original, more primitive basaltic magma.

5 Conclusions

(1) The Paleogene Nadingcuo high-K calc-alkaline volcanic rocks include basalts, basaltic latites, latites, and trachytes, all of which have high $Mg^{\#}$ values, are enriched in TiO_2 and P_2O_5, have low La/Nb, Ba/Nb, and Rb/Nb ratios, and have $^{87}Sr/^{86}Sr$ values of 0.704 682–0.706 112, and $\varepsilon Nd(t)$ values of −1.6 to 1.2.

(2) Units from Basaltic to trachytic within the Nadingcuo volcanic rocks were formed as a result of assimilation and fractional crystallization. They have $Mg^{\#}$ values and HREE concentrations that decrease in the progression from basalt to latite and trachyte units

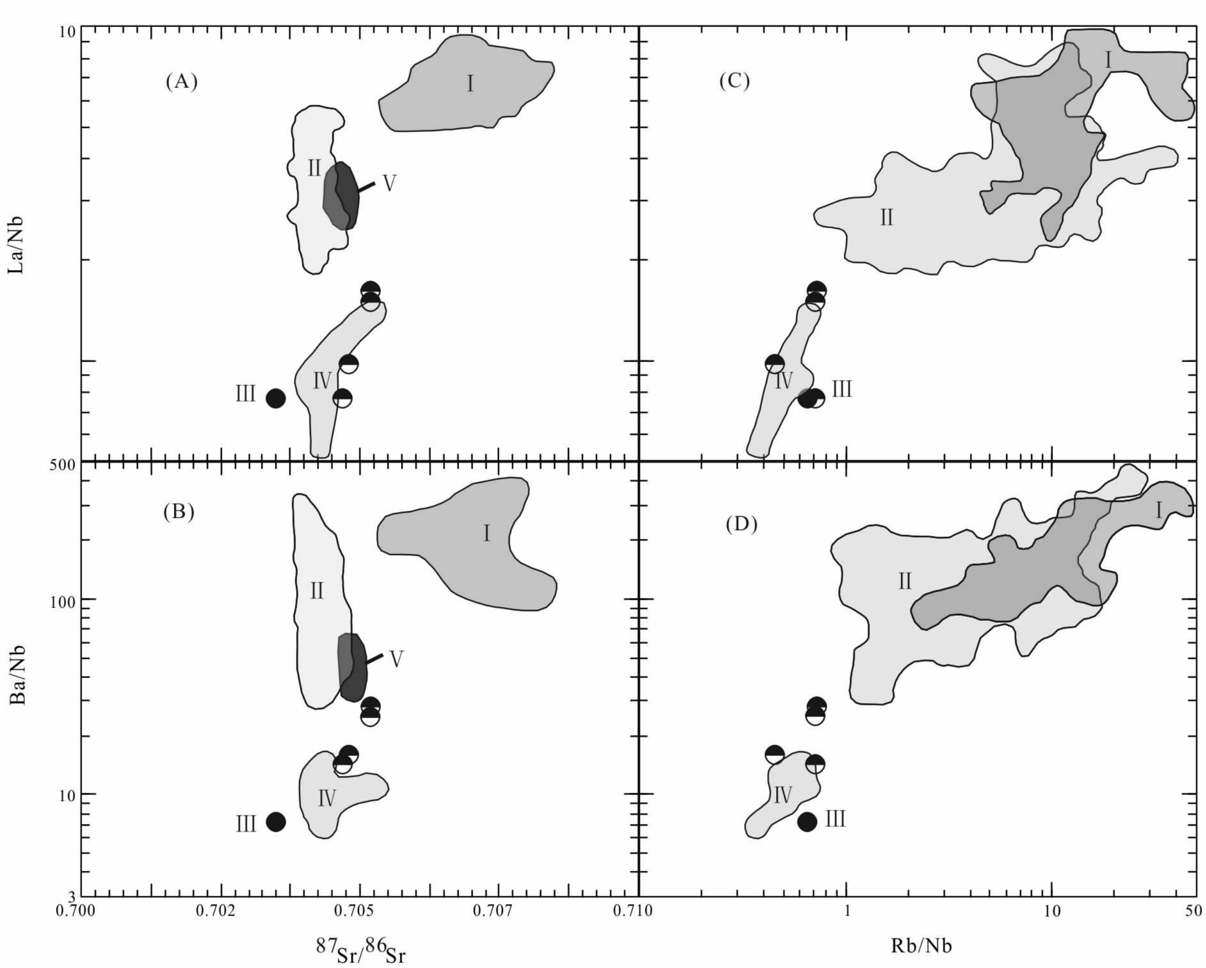

Fig. 4 **$^{87}Sr/^{86}Sr$ versus La/Nb(A), Ba/Nb(B), Rb/Nb versus La/Nb(C) and Ba/Nb(D) for Cenozoic volcanic rocks within Nadingcuo volcanic rocks.**

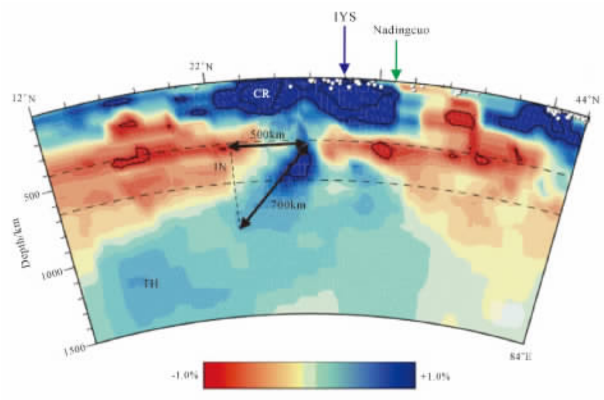

Fig. 5 Tomographic cross-sections perpendicular to collision front with distinct anomalies from south to north (after Replumaz *et al.*, 2010a, 2010b) .

as a result of mixing of basaltic magmas with 35-40 wt.% rhyolitic melt or assimilation of the same amount of felsic rocks.

(3) The primary magma for the Nadingcuo volcanic rocks was derived from an OIB-type source that mixed with ancient mantle wedge source components, indicating that during 36–34 Ma, the southern Qiangtang area was located in a center of upwelling of asthenospheric material. The ongoing northward-directed low-angle movement of the Indian Craton into this area forced the region of upwelling mantle flow to continuously migrate northward, with this upwelling center now underlying the Hoh Xil-Kunlun area.

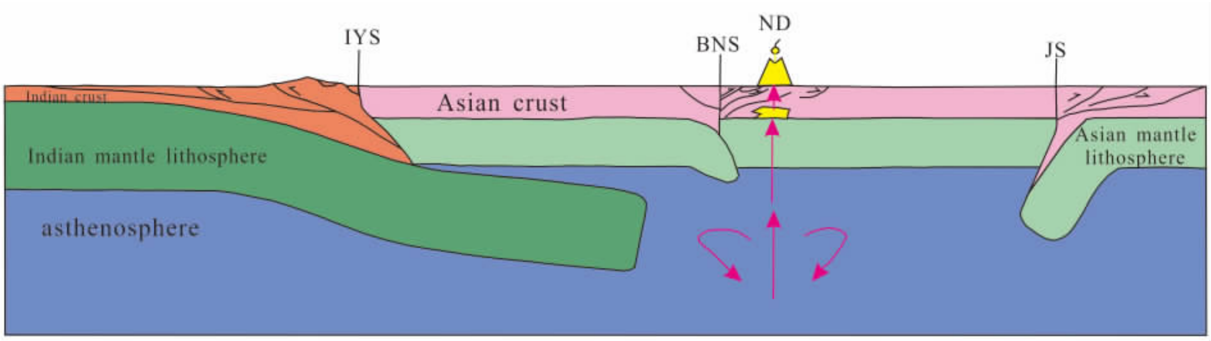

Fig. 6 Schematic lithosphere-scale cross section of Tibet during Eocene and a suggested model to produce Nadingcuo volcanic rocks

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References

Chen J L, Wu J B, Xu J F, *et al.* 2013. Geochemistry of Eocene high-Mg# adakitic rocks in the northern Qiangtang terrane, central Tibet: Implication for early uplift of the plateau. *Geological Society of America Bulletin*, **125**(11/12) : 1800-1819.

Chi X G, Dong C Y, Liu J F, *et al.* 2006. High Mg# and Low Mg# potassic-ultrapotassic volcanic rocks and their source nature on the Tibetan Plateau. *Acta Petrologica Sinica*, **22** (3) : 595-602. (in Chinese with English abstract) .

Chi X G, Li C, Jin W, *et al.* 1999. Spatial temporal evolution of cenozoic volcanism and uplifting in North Tibet. *Geological Review*, **45**(Suppl.) : 978-986. (in Chinese with English abstract) .

Deng W M. 1998. Cenozoic intraplate volcanic rocks in the northern Qinghai Xizang Plateau. Beijing: Geological Publishing House, 1-168. (in Chinese)

Ding L, Kapp P, Zhong D, *et al.* 2003. Cenozoic volcanism in Tibet: evidence for a transition from oceanic to continental subduction. *Journal of Petrology*, **44**(10) : 1833-1865.

Ding L, Kapp P, Yue Y, *et al.* 2007. Postcollisional calc-alkaline laves and xenoliths from the southern Qiangtang terrane, central Tibet. *Earth Planetary Science Letters*, **254**: 28-38.

Lai S C, Qin J F, Li Y F. 2007. Partial Melting of Thickened Tibetan Crust: geochemical evidence from cenozoic adakitic volcanic rocks. *International Geology Review*, **49** (4) : 357-373.

Lai S C, and Qin J F. 2013. Adakitic rocks derived from the partial melting of subducted continental crust: evidence from the Eocene volcanic rocks in the northern Qiangtang block. *Gondwana Research*, **23**(2): 812-824.

Liu S, Hu R Z, Feng C X, *et* al. 2003. Cenozoic adakite-type volcanic rocks in Qiangtang , Tibet and its significance. *Acts Geologica Sinica: English Edition*, **77**(2): 187-193.

Liu S, Hu R Z, Feng C X, *et al.* 2008. Cenozoic high Sr/Y volcanic rocks in the Qiangtang terrane, northern Tibet: geochemical and isotopic evidence for the origin of delaminated lower continental melts. *Geological Magazine*, **145** (4): 463-474.

Liu J F, Chi X G, Zhao X Y, *et al.* 2009. Chronology, geochemistry and tectonic significances of the Cenozoic Zougouyouchacuo and Nadingcuo volcanic rocks in northern Tibetan Plateau. *Acta Petrologica Sinica*, **25**(12): 3259-3274.

Madureira P, Mata J, Mattielli N, *et al.* 2011. Mantle source heterogeneity, magma generation and magmatic evolution at Terceira Island (Azores archipelago): constraints from elemental and isotopic (Sr, Nd, Hf and Pb) data. *Lithos*, **126**: 402-418.

Pan G T, Ding J, Yao DS, 2004. The geological map of the Qinghai-Xizang (Tibet) Plateau and adjacent areas (1:1500000). Chengdu: Chengdu Cartographic Publishing House, (In Chinese)

Rapp R P, Shimizu N, Norman M D, *et al.* 1999. Reaction between slab-derived melt and peridotite in the mantle wedge: experimental constraints at 3.8 GPa. *Chemical Geology*, **160**: 335-356.

Replumaz A, Negredo A M, Villasenor A, *et al.* 2010a. Indian continental subduction and slab break-off during Tertiary collision. *Terra Nova*, **22**: 290-296.

Replumaz A, Negredo A M, Guillot S, *et al.* 2010b. Multiple episodes of continental subduction during India/Asia convergence: insight from seismic tomography and tectonic reconstruction. *Tectonophysics*, **483**: 125-134.

Stern C R, Kilian R. 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Austral Volcanic Zone. *Contributions to Mineralogy and Petrology*, **123**: 263-281.

Wang B D, Chen J L, Xu J F, *et al.* 2010. Chronology and Geochemistry of the Nadingcuo Volcanic Rocks in the Southern Qiangtang Region of the Tibetan Plateau: partial melting of Remnant Ocean Crust along the Bangong-Nujiang Suture. *Acta Geologica Sinica: English Edition*, **84**: 1461-1473.

Wang Q, Wyman D A, Xu J F, *et al.* 2008a. Eocene melting of subducting continental crust and early uplifting of central Tibet: Evidence from central-western Qiangtang high-K calc-alkaline andesites, dacites and rhyolites. *Earth and Planetary Science Letters*, **272**(1/2): 158-171.

Wang Q, Wyman A, Xu J F, *et al.* 2008b. Triassic Nb-enriched basalts, magnesian andesites, and adakites of the Qiangtang terrane (Central Tibet): evidence or metasomatism by slab-derived melts in the mantle wedge. *Contributions to Mineralogy and Petrology* , **155**(4): 473-490.

Xiong X L, Adam J, Green T H. 2005. Rutile stability and rutile/melt HFSE partitioning during partial melting of hydrous basalt: implications for TTG genesis. *Chemical Geology*, **218**(3/4): 339-359.

Yin A, Harrison T M. 2000. Geologic evolution of the Himalayan-Tibetan orogen. *Annual Review of Earth and Planetary Science*, **28**: 211-280.