**Mg, Sr and O isotope geochemistry of syenites from northwest Xinjiang, China:
tracing carbonate recycling during Tethyan oceanic subduction**

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Abstract

Magnesium isotopic compositions of igneous rocks could be potentially used to trace recycling of supracrustal materials. High- $\delta^{26}\text{Mg}$ granitoids have been previously reported and explained to reflect the involvement of surface weathered materials in their sources. Low- $\delta^{26}\text{Mg}$ granitoids, however, have not been reported. In this study, we report high-precision Mg isotopic analyses of Cenozoic alkaline syenites and syenogranites from the Kuzigan and Zankan plutons, northwest Xinjiang, China. The Kuzigan syenites were originated from the mantle metasomatized by recycled supracrustal materials, and the syenogranites are differentiated products of the syenites. Both syenites and syenogranites have $\delta^{26}\text{Mg}$ values (-0.46 to -0.26‰ and -0.41 to -0.17‰, respectively) significantly lighter than the mantle ($-0.25 \pm 0.07\text{‰}$, 2SD). No correlation of $\delta^{26}\text{Mg}$ with either SiO_2 or MgO is observed, indicating limited Mg isotope fractionation during alkaline magmatic differentiation. The low $\delta^{26}\text{Mg}$ of the syenites and syenogranites thus reflect a light Mg isotopic source. This, combined with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70814 to 0.71105) and negative correlation between $\delta^{26}\text{Mg}$ and $\delta^{18}\text{O}$, suggests that the magma source contains recycled marine carbonates. Modeling of the Mg-O-Sr isotopic data indicates that the recycled carbonate is mainly limestone with minor dolostone, suggesting that the metasomatism occurred at depths shallower than 60 to 120 km. Given that the plutons are located at the India-Eurasia collision zone, the carbonate recycling was most likely derived from the subducted Tethyan oceanic crust during the Mesozoic-Cenozoic. Our study suggests that the combined Mg, O and Sr isotopic studies are powerful for tracing recycled carbonates and identifying their species in mantle sources.

Keywords: Magnesium isotopes; Syenites; Magmatic differentiation; Carbonate recycling; Tibetan and Pamir plateau

1. Introduction

Warm global climate at Cretaceous-early Cenozoic era was attributed to a high $p\text{CO}_2$ level possibly maintained by subduction of Tethyan oceanic crust with pelagic carbonate and subsequent release of CO_2 from arc volcanism (Kent and Muttoni, 2008). However, according to the carbon budget in subduction zones, the expelled carbon from arc volcanism is much less than that subducted, implying that a mass of undissolved carbonate is subducted to the deep mantle (Kerrick and Connolly, 2001). Tracing the recycled carbonates and evaluating their proportions in the mantle becomes an important issue (e.g., Li, 2015).

Recent studies show that Mg isotopic compositions of igneous rocks could be used to trace the recycling of supracrustal materials in the magma source (Shen et al., 2009; Li et al., 2010; Yang et al., 2012; Huang et al., 2015; Wang et al., 2016). Compared with the upper mantle ($\delta^{26}\text{Mg} = -0.25 \pm 0.07\text{‰}$, 2SD; Teng et al., 2010), clastic sedimentary rocks ($\delta^{26}\text{Mg}$ of -1.64 to $+0.92\text{‰}$; Li et al., 2010; Huang et al., 2013) and carbonates ($\delta^{26}\text{Mg}$ of -5.60 to -0.66‰ ; Beinlich et al., 2014; Saenger and Wang, 2014), on average, have heavy and light Mg isotopic compositions, respectively. Therefore, Mg isotopes are an effective tool in distinguishing recycled clastic sediments and carbonates, given that Mg isotopes are not significantly fractionated during high temperature magmatic processes. Especially, stability of carbonate species (calcite, dolomite and magnesite) in the mantle via subduction depends on the P-T conditions (Dasgupta and Hirschmann, 2010). Thus, constraining the species of recycled carbonates has a crucial implication for understanding the depth of the recycled carbonates. However, the species of recycled carbonate is difficult to identify by using Mg isotopes alone because all carbonate minerals (e.g., calcite, dolomite and magnesite) have light Mg isotopic composition (Beinlich et al., 2014; Saenger and Wang, 2014). Nevertheless, carbonate minerals have significantly different Mg and Sr contents but similar O contents, then mixing of calcite, dolomite and magnesite with the mantle will generate different curves in the plots of Mg versus O and Sr isotopes. Thus, a combination of Mg, Sr and O isotopes may be an effective approach to identify the species of carbonates and to explore their potential application in tracing deep carbon recycling.

80 The Pamir syntaxis belongs to the westernmost part of the Himalayan-Tibetan orogen,
81 formed by the Tethyan oceanic subduction and the India-Eurasia collision during Paleozoic to
82 Cenozoic. Cenozoic post-collisional potassic and ultrapotassic igneous rocks are widely
83 distributed in the middle Pamir (Hacker et al., 2005; Ke et al., 2006, 2008; Jiang et al., 2012).
84 Previous studies proposed that these potassic and ultrapotassic rocks in Pamir originated from the
85 enriched mantle source related to the subducted India continent (Pan, 2000; Jiang et al., 2012).
86 Contemporaneous ultrapotassic magmatic rocks in Tibet were also generally proposed to be the
87 products of partial melting of the enriched mantle (Turner et al., 1996; Miller et al., 1999;
88 Nomade et al., 2004; Williams et al., 2004; Chung et al., 2005; Zhao et al., 2009; Jiang et al.,
89 2012; Wang B. D. et al., 2014). Therefore, if huge amounts of carbonates were carried into the
90 deep mantle by subduction of the Tethyan oceanic slabs, the chemical properties of mantle
91 beneath the Tibetan plateau would have been modified by recycled carbonates and then may
92 imprint the signature on mantle-derived igneous rocks, a hypothesis which can be examined using
93 Mg-O-Sr isotopes as discussed above.

94 In this study, we report Mg, O and Sr isotopic data for ultrapotassic alkaline syenites and
95 evolved syenogranites from two Cenozoic plutons (Kuzigan and Zankan) in the Pamir syntaxis,
96 northwestern Xinjiang, China. The aim of this study is to (i) investigate the behavior of Mg
97 isotopes during alkaline magmatic differentiation which is not addressed yet, and the origin of the
98 low $\delta^{26}\text{Mg}$ syenites and syenogranites, (ii) evaluate the imprint of carbonate recycling in the
99 mantle beneath the Pamir plateau during the subduction of the Tethyan oceanic slabs, and (iii)
100 explore a way using Mg-O-Sr isotopes to identify recycled carbonate species.

101 2. Geological setting and samples

102 The Pamir syntaxis, located in the western Himalayan-Tibetan orogen, is composed of
103 several distinctive terranes and suture zones that accreted to the southern margin of Asia during
104 the late Paleozoic–Mesozoic closure of the Paleo-Tethys Ocean and the Mesozoic-Cenozoic
105 closure of the Neo-Tethys Ocean (Burtman and Molnar, 1993; Schwab et al., 2004). The Pamir
106 area is divided into the northern, central and southern zone based on the Paleozoic and Mesozoic

107 sutures (Burtman and Molnar, 1993). To the south, the Indus suture and Shyok suture were the
108 marks of the final India-Eurasia collision in Cenozoic (Bouilhol et al., 2013).

109 Cenozoic igneous rocks were widely distributed in the central and southern Pamir (Ducea et
110 al., 2003; Hacker et al., 2005). The Kuzigan alkaline pluton, paralleling the Karakorum fault, is
111 one of this Cenozoic magmatic belt (Fig. 1a). It is bounded by a Miocene granite pluton
112 (Karibasheng) (Fig. 1a) to the northeast and gneissic granites of unknown age to the southwest
113 (Fig. 1b). The Kuzigan pluton is made up of alkaline syenites, syenitoids and syenogranites, with
114 medium- to coarse-grained aegirine-augite syenites and syenogranites as their representative rocks.
115 The different lithologies have gradual contacts without clear boundaries, indicating a synchronous
116 magmatic activity. SHRIMP U-Pb zircon ages of syenites and syenogranites confirm that they
117 belong to the same magmatic episode at ca. 11Ma (Ke et al., 2006, 2008; Jiang et al., 2012). The
118 Zankan syenitic pluton is another intrusive body of the Cenozoic magmatism belt to the southeast
119 along the Karakorum fault (Fig. 1a). Kuzigan and Zankan plutons were considered to be the
120 products of the synchronous magmatic activity and tectonic process in the Pamir syntaxis based
121 on the same age (ca. 11Ma; Pan, 2000), rock type and geochemical feature (Pan, 2000).

122 Syenites and syenogranites from the Kuzigan pluton share the same mineral assemblage of
123 potassium feldspar, oligoclase, quartz, aegirine-augite, minor biotite and rare hornblende. Mineral
124 modes, however, are different, e.g. aegirine-augite are enriched in syenites (6-20% in volume) but
125 depleted in syenogranites (less than 2% in volume). In addition, syenites and syenogranites have
126 similar Sr, Nd and Pb isotopic compositions (see Table 1 for Sr isotopes, and Ke et al., 2006 and
127 Jiang et al., 2012 for Nd-Pb isotopes). Hence, the same spatial and temporal distribution, the
128 similar mineral assemblage and Sr-Nd-Pb isotopic compositions suggest that syenites and
129 syenogranites from the Kuzigan pluton were from the same source (Pan, 2000; Ke et al., 2006;
130 Jiang et al., 2012). Syenites from the Zankan pluton are medium-grained aegirine-augite syenites
131 with similar texture and mineral assemblage as syenites from the Kuzigan pluton. The gneissic
132 biotite granites from the wall rock are poorly studied, which are composed of potassium feldspar,
133 oligoclase, quartz and minor biotite.

134 Previous studies suggested that the Kuzigan pluton were derived from the hybridized

135 lithospheric mantle and could not be produced by partial melting of the thickened lower crust or
136 subducted slab based on the following arguments (Jiang et al., 2012): (1) Melts derived by partial
137 melting of thickened lower crust or of subducted slab would show the adakitic affinity, which,
138 however, are not observed in the Kuzigan pluton, (2) the Kuzigan pluton has much higher Ba
139 (2200-9100 ppm) and Sr (840-3100 ppm, most > 1100 ppm) contents than those of the common
140 granites, suggesting that the source of Kuzigan pluton is more enriched in Ba and Sr than the source
141 of common granites, and (3) high Ba/Sr (10-34) and low Rb/Sr (0.08-0.26) ratios suggest a
142 metasomatized mantle source with the presence of both phlogopite and amphibole.

143 Twelve syenites and nine syenogranites were collected along a geological section from the
144 Kuzigan pluton. Two syenites samples from the Zankan pluton for comparison and two gneissic
145 granites from the wall rock are selected. All samples collected in this study are fresh without
146 secondary alteration.

147 **3. Analytical methods**

148 **3.1 Major elements**

149 Major elements were determined by a Prodigy inductively coupled plasma-optical emission
150 spectroscopy (ICP-OES) using standard methods at the China University of Geosciences, Beijing
151 (CUGB). Loss on ignition (LOI) was determined gravimetrically after heating the samples at
152 1000°C for half hour. The analytical uncertainties were better than 1% after repeated
153 measurements of rock reference standards AGV-2 and GBW07103.

154 **3.2 Oxygen and strontium isotopes**

155 Oxygen isotopes were analyzed using a *Finnigan MAT-251EM* mass spectrometer at the Key
156 Laboratory for Isotope Geology, Ministry of Land and Resources. Oxygen isotopes were
157 processed by the BrF_5 method described by Clayton and Mayeda (1963) and then converted into
158 CO_2 by reacting with graphite rod at 700°C. Analytical reproducibility in this study is $\pm 0.2\%$
159 (2SD). The oxygen isotopic data are reported by δ values relative to Vienna SMOW (Standard

160 Mean Ocean Water).

161 Strontium isotopes were analyzed by using a *Neptune Plus* MC-ICP-MS at the Isotope
162 Geochemistry Laboratory of the China University of Geosciences, Beijing. Strontium isotope
163 fractionation is corrected to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Data are corrected for ^{87}Rb interference by the
164 measured ^{85}Rb abundance. A 200 ppb Sr solution typically produced 5.0 V for ^{88}Sr and 0.004 V
165 for ^{85}Rb signal (with a $10^{11}\Omega$ resistor for the Faraday cups) with $^{85}\text{Rb}/^{88}\text{Sr}$ less than 8×10^{-4} .
166 Correction of the interference of ^{87}Rb breaks down only when $^{85}\text{Rb}/^{88}\text{Sr}$ is $> 1 \times 10^{-3}$. Therefore,
167 separation of Sr from Rb was efficient and $^{87}\text{Sr}/^{86}\text{Sr}$ of samples are reliable in this study. NBS987
168 measured during the course of this study yields $^{87}\text{Sr}/^{86}\text{Sr} = 0.710262 \pm 16$ (2SD, $n = 7$). The
169 BHVO-2 gives a value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.703458 \pm 10$ (2SD). The total blank for Sr isotope analysis
170 is less than 1.0 ng.

171 3.3 Magnesium isotopes

172 Magnesium isotopes were analyzed using a *Nu Plasma* MC-ICP-MS at the Isotope
173 Laboratory of the University of Arkansas (UA), USA, and a *Neptune Plus* MC-ICP-MS at the
174 Isotope Geochemistry Laboratory of the China University of Geosciences, Beijing. The
175 experiment parameters applied in the two laboratories at UA and CUGB are shown in [Tables 2](#).
176 [All geostandards and three samples that were measured in both of the labs yield consistent results](#)
177 [within quoted errors \(Tables 3 and 4\).](#)

178 3.3.1 Analytical method at UA

179 The analytical method in UA has been previously reported (e.g. [Yang et al., 2009](#); [Li et al.,](#)
180 [2010](#); [Teng and Yang, 2014](#); [Teng et al., 2015a](#)). Briefly, the whole rock powder (200 mesh) was
181 dissolved in a 3:1 mixture of concentrated HF:HNO₃, then a concentrated HCl:HNO₃ mixture (3:1)
182 and re-dissolved by concentrated HNO₃. The chemical separation of Mg was achieved using ion
183 exchange resin AG50W-X8 (Bio-Rad 200-400 mesh) following the procedure described by [Teng](#)
184 [et al. \(2007\)](#). The same column procedure was repeated two times with the whole procedure blank

less than 10 ng. The long-term external precision was $\pm 0.06\text{‰}$ for $\delta^{25}\text{Mg}$ and $\pm 0.07\text{‰}$ for $\delta^{26}\text{Mg}$ (2SD) (Teng et al., 2010, 2015a, b).

3.3.2 Analytical method at the CUGB

The chemical procedure used in CUGB is the same as that in UA. The recovery of Mg is up to 99.5% ~99.9% and whole procedure blank is less than 10 ng as well. Mg isotope analysis, however, was conducted using a *Neptune* MC-ICP-MS (Table 2). The detailed instrument parameters at the CUGB have been previously reported by Liu et al. (2014) and He et al. (2015). Hence, we report the parts relevant to Mg isotope analysis in details below.

All samples and standards were introduced to the Ar plasma in 3% HNO_3 using a Scott double pass quartz glass spray chamber and a low-flow 50 $\mu\text{L}/\text{min}$ PFA self-aspiration micro nebulizer, with help of a Cetac ASX-110 autosampler. The sample introduction system was washed with 3% HNO_3 for two minutes after each measurement to avoid cross-contamination. Mg isotopes were determined in a low-mass resolution mode under wet plasma conditions. The isobaric interferences, such as $^{12}\text{C}^{12}\text{C}^+$, $^{12}\text{C}^{14}\text{N}^+$, $^{23}\text{NaH}^+$ and $^{25}\text{MgH}^+$ have been checked at the low resolution mode. They are unresolvable by signal peaks of 3% HNO_3 (the blank solution) and thus could be negligible. ^{24}Mg , ^{25}Mg and ^{26}Mg ion beams are simultaneously collected in L3, C, and H3 Faraday cups. Each measurement consists of a 3 s idle time and 30 cycles of 4.19 or 8.39 s integration time. About 400 ppb Mg concentration typically produced 4.5~8 V ^{24}Mg signal (with a $10^{11}\Omega$ resistor for the Faraday cups) (Table 2). The Mg isotope ratios are reported related to the Dead Sea metal Mg standard (DSM3) using the expression:

$$\delta^x\text{Mg} (\text{‰}) = [({}^x\text{Mg}/{}^{24}\text{Mg})_{\text{sample}} / ({}^x\text{Mg}/{}^{24}\text{Mg})_{\text{DSM3}} - 1] \times 1000, \text{ where } x = 25 \text{ or } 26.$$

The sample-standard sequence for each sample was repeated 4 or 6 times to get a better reproducibility and accuracy. The internal precision, calculated by 4 or 6 times duplicate measurement within an analytical session, is generally better than $\pm 0.10\text{‰}$ (2SD). During a typical analytical session, the in-house standard GSB Mg with known values (an ultrapure single elemental standard solution from China Iron & Steel Research Institute) and at least one rock reference standard (e.g. BHVO-2, BCR-2, AGV-2) were analyzed with unknown samples to check long-term reproducibility of the method.

The long-term external precision (2SD) is $\pm 0.06\text{‰}$ for $\delta^{26}\text{Mg}$ and $\pm 0.05\text{‰}$ for $\delta^{25}\text{Mg}$, based

on the following analyses since June 2012 (Fig. 2): (1) Mg isotope analyses of pure Mg solutions without column chemistry (GSB Mg: $\delta^{26}\text{Mg} = -2.04 \pm 0.04\text{‰}$, $\delta^{25}\text{Mg} = -1.05 \pm 0.03\text{‰}$, $n = 58$), (2) analyses of reference materials from USGS processed through column chemistry twice, yielding $\delta^{26}\text{Mg} = -0.25 \pm 0.06\text{‰}$ and $\delta^{25}\text{Mg} = -0.13 \pm 0.04\text{‰}$ for BHVO-2 ($n = 48$), $\delta^{26}\text{Mg} = -0.19 \pm 0.05\text{‰}$ and $\delta^{25}\text{Mg} = -0.10 \pm 0.03\text{‰}$ for BCR-2 ($n = 19$), $\delta^{26}\text{Mg} = -0.17 \pm 0.05\text{‰}$ and $\delta^{25}\text{Mg} = -0.08 \pm 0.03\text{‰}$ for AGV-2 ($n = 13$) (Table 3, Fig. 2). $\delta^{26}\text{Mg}$ values of BCR-2 are identical to the literature data within the analytical uncertainty (e.g., Huang et al., 2011). $\delta^{26}\text{Mg}$ values of AGV-2 obtained in this study are identical to the data reported by An et al. (2014), but slightly heavier than that reported by Lee et al. (2014). $\delta^{26}\text{Mg}$ values of BHVO-2, PCC-1, DST-1 and seawater analyzed in CUGB are well consistent with the recommended values within uncertainty (Teng et al., 2015a) (Table 3).

4. Results

4.1 Major element compositions

The major element compositions of syenites and syenogranites from the Kuzigan and Zankan plutons are reported in Table 1. Chemical compositions are extensively variable in the Kuzigan pluton, with SiO_2 ranging from 51.60 to 74.81 wt.% and MgO varying from 0.10 to 5.54 wt.%. Sample 018R4 with the lowest SiO_2 content (51.60 wt.%) is classified as syenite based on the mineral assemblage (60% potassium feldspar, 3% oligoclase, 22% aegirine-augite, 10% biotite and 5% melanite). The Kuzigan and Zankan plutons are characterized by high K_2O contents (3.74 to 11.74 wt.%). In particular, the syenites are highly enriched in K_2O with $\text{K}_2\text{O}/\text{Na}_2\text{O}$ mostly >2 , showing affinities with shoshonitic and ultrapotassic igneous rocks in Tibet (Jiang et al., 2012; Zhao et al., 2009; Liu et al., 2014).

4.2 Oxygen and strontium isotopic compositions

Oxygen and strontium isotopic data are reported in Table 1. Samples from the Kuzigan pluton have high $\delta^{18}\text{O}$ values from 8.6 to 11.6‰ with an average of 10.2‰. $\delta^{18}\text{O}$ values of the

240 syenite (8.6 to 10.4‰) are slightly lighter than those of the syenogranites (10.0 to 11.6‰).
241 Syenites from the Zankan pluton also display heavy O isotopic compositions (10.1 and 11.1‰),
242 slightly heavier than those of the Kuzigan pluton. The wall rock, gneissic granites, is the lightest
243 among samples analyzed in this study ($\delta^{18}\text{O} = 8.5\text{‰}$).

244 The syenites and syenogranites have relatively constant Sr isotopic ratios over the wide SiO_2
245 range. In detail, the syenites show a larger range of $^{87}\text{Sr}/^{88}\text{Sr}$ ratios (0.708143 to 0.711045) than that
246 of syenogranites (0.709368 to 0.710284). Two syenites from the Zankan pluton have similar Sr
247 isotopic ratios as those from the Kuzigan pluton (Table 1).

248 4.3 Magnesium isotopic compositions

249 Magnesium isotopic data of syenites and syenogranites are presented in Table 4. In a $\delta^{25}\text{Mg}$
250 versus $\delta^{26}\text{Mg}$ plot, samples and reference materials together yield a slope of 0.513. Several
251 samples analyzed at UA were also analyzed at CUGB for comparison. The results from the two
252 labs are well consistent within analytical uncertainty (Table 4). Therefore, the Mg isotope data
253 obtained from the two labs are comparable.

254 Magnesium isotopic compositions of syenites and syenogranites from the Kuzigan pluton
255 vary from -0.40 to -0.26‰ with an average of $-0.35 \pm 0.08\text{‰}$ and from -0.40 to -0.17‰ with an
256 average of $-0.32 \pm 0.14\text{‰}$, respectively. This is in contrast to the heavy $\delta^{26}\text{Mg}$ in I- and A-type
257 granitoids (Shen et al. 2009; Li et al., 2010), and the mantle-like Mg isotopic compositions in
258 I-type granites (Liu et al., 2010) (Fig. 3). Despite overlapping, $\delta^{26}\text{Mg}$ values of the syenogranites
259 are on average slightly heavier than those of the syenites (Fig. 3). Two syenites from the Zankan
260 pluton have slightly lighter Mg isotopic compositions (-0.37 and -0.46‰) than those from the
261 Kuzigan region (Table 4). The wall rocks, gneissic granites, have mantle-like $\delta^{26}\text{Mg}$ values of
262 -0.26‰ and -0.27‰ (Table 4).

263 5. Discussion

264 The light Mg isotopic compositions in the syenites and syenogranites from the Kuzigan and
265 Zankan plutons may result from magmatic differentiation, assimilation of wall rocks during
266 ascent, kinetic isotopic fractionation (thermal and chemical diffusion), or source heterogeneity. In

267 this section, we first explore the possible mechanisms responsible for the light Mg isotopic
268 signatures. Then we discuss the carbonate recycling during subduction of Tethyan oceanic crust
269 based on the observations from Mg-O-Sr isotope geochemistry of these alkaline rocks.

270 **5.1 The lack of Mg isotope fractionation during alkaline magmatic differentiation**

271 Equilibrium Mg isotope fractionation is limited during crystal–melt differentiation of
272 komatiitic, basaltic and granitic magmas, consistent with the undetectable Mg isotopic differences
273 among common silicate minerals (olivine, pyroxene, hornblende and biotite) (Handler et al., 2009;
274 Yang et al., 2009; Young et al., 2009; Dauphas et al., 2010; Liu et al., 2010, 2011; Pogge von
275 Strandmann et al., 2011; Xiao et al., 2013; Hu et al., 2015). To date, the behavior of Mg isotope
276 fractionation during magmatic differentiation in the alkaline syenitic system is unclear.

277 The primary magma of the Kuzigan alkaline pluton had undergone fractional crystallization
278 evolving from syenites to syenogranites as illustrated in the Hacker diagrams (Fig. 4). Fractional
279 crystallization of aegirine-augite would enrich the melt in Al_2O_3 , K_2O , and Na_2O and deplete the
280 melt in MgO , FeO (total FeO) and CaO from syenites to syenogranites based on the chemical
281 composition of aegirine-augites. The SiO_2 is negatively correlated with MgO , CaO , and total FeO
282 and is positively correlated with $\text{Na}_2\text{O}+\text{K}_2\text{O}$ in the syenite series (Fig. 4), indicating the fractional
283 crystallization of aegirine-augites from the original syenitic magma. This is supported by the
284 gradually decreased contents of aegirine-augites in the Kuzigan pluton from syenites to
285 syenogranites. However, there is no clear relationship between Mg isotopic compositions and the
286 indicators of fractional crystallization of aegirine-augites, e.g., MgO , CaO , and total FeO (Fig. 5).
287 Although fractional crystallization of aegirine-augites seems to shift the evolved syenogranites
288 towards slightly heavier $\delta^{26}\text{Mg}$ values with an average of -0.32‰ , the Mg isotopic difference
289 between syenites and syenogranites falls within the analytical uncertainty (Fig. 5). Therefore, the
290 effect of crystal-melt fractionation on Mg isotopic compositions in alkaline syenitic system from
291 the Kuzigan pluton is insignificant, consistent with the previous studies on I- and A-type granite
292 systems (Shen et al., 2009; Li et al., 2010; Liu et al., 2010).

293 5.2 Origin of low $\delta^{26}\text{Mg}$ and high $\delta^{18}\text{O}$ in syenites and syenogranites.

294 Given the limited Mg isotope fractionation during alkaline magmatic differentiation, other
295 processes that could potentially produce low- $\delta^{26}\text{Mg}$ signatures include: (1) assimilation by wall
296 rocks, (2) thermal and chemical diffusion within the magma chamber and/or around the contact
297 boundaries (Richter et al., 2008, 2009; Teng et al., 2008, 2011; Huang et al., 2009; Lundstrom,
298 2009), and/ or (3) heterogeneous source involved by low- $\delta^{26}\text{Mg}$ materials (Yang et al., 2012; Huang
299 et al., 2015).

300 Extensive assimilation by wall rocks with light Mg and heavy O isotopic compositions may
301 lower $\delta^{26}\text{Mg}$ and increase $\delta^{18}\text{O}$ values of the syenites and syenogranites. However, xenoliths of wall
302 rocks have not been found yet even along the contact zones, indicating a lack of strong assimilation.
303 The wall rocks, gneissic granites, have heavier Mg isotopic compositions (-0.26‰ and -0.27‰) and
304 lighter O isotopic compositions (8.5‰) than the syenites and syenogranites, excluding the
305 possibility that the light $\delta^{26}\text{Mg}$ and heavy $\delta^{18}\text{O}$ in the syenites and syenogranites were caused by
306 wall rock assimilation. In addition, the lack of any major shift in Mg isotopic compositions along
307 the sample profile precludes extensive assimilation of wall rocks during magma ascent,
308 differentiation and emplacement (Fig. 6).

309 Chemical and thermal diffusion could produce large Mg isotope variation under a chemical or
310 temperature gradient (Richter et al., 2008, 2009; Huang et al., 2009; Teng et al., 2011). For a
311 magmatic body, the contact boundary is a place where the temperature and chemical gradients are
312 most likely maintained. If diffusion was responsible for the observed Mg isotope variation, then the
313 $\delta^{26}\text{Mg}$ values are expected to correlate with the distance to the contact boundary. However, the
314 low- $\delta^{26}\text{Mg}$ samples are not only distributed along the boundaries, but also occur over the whole ~9
315 km long geological section cross the Kuzigan pluton (Fig. 6). Furthermore, the negative correlation
316 between Mg and O isotopes is difficult to explain by thermal diffusion (Fig. 7). During thermal
317 diffusion, heavy isotopes always tend to be enriched at the cold end relative to light isotopes,
318 resulting in two different stable isotopic systems that correlate positively with each other (Richter et
319 al., 2008, 2009; Huang et al., 2009; Teng et al., 2011). Therefore, the negative correlation between

320 $\delta^{26}\text{Mg}$ and $\delta^{18}\text{O}$ rules out chemical or thermal diffusion as the cause of the low $\delta^{26}\text{Mg}$ in the
321 Kuzigan syenites and syenogranites.

322 The most likely mechanism for the low- $\delta^{26}\text{Mg}$ in the Kuzigan syenites and syenogranites is
323 source heterogeneity, as shown by the O isotopic data. Syenites and syenogranites from the Kuzigan
324 and Zankan plutons have heavy O isotopic compositions compared with the normal mantle ($\delta^{18}\text{O} =$
325 5.5‰ ; [Hoefs, 2009](#)). Magmatic differentiation could increase $\delta^{18}\text{O}$ of syenogranites because quartz
326 is the most ^{18}O -rich mineral compared to feldspar and clinopyroxene ([Hoefs, 2009](#)). Nonetheless,
327 the heavy O isotopic compositions of syenites should not be affected by magmatic differentiation
328 and thus reflect either crustal contamination or source heterogeneity. Crustal contamination would
329 increase $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ as well as SiO_2 and Sr contents, and lead to positive correlations
330 between $\delta^{18}\text{O}$ and SiO_2 and between $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr, which are not observed here. Therefore, the
331 high $\delta^{18}\text{O}$ values of these syenites must inherit from their mantle source that had been affected by
332 sedimentary or metasedimentary protoliths. The negative correlation between $\delta^{26}\text{Mg}$ and $\delta^{18}\text{O}$
333 strongly suggests that carbonates are the most likely component in their mantle source based on
334 their extremely light Mg and heavy O isotopic compositions ([Fig. 7](#)). The sedimentary signature is
335 also reflected in the high $^{87}\text{Sr}/^{86}\text{Sr}$ ([Table 1](#)) and extreme LILE enrichment (e.g., Ba and Sr) ([Ke et](#)
336 [al., 2006](#); [Jiang et al., 2012](#)).

337 **5.3 Species of recycled carbonate and mantle source depth**

338 Stability of subducted carbonate species in the mantle strongly depends on the P-T
339 conditions. Dolomite could dissociate into aragonite + magnesite under high P-T conditions (e.g.,
340 at $T = 700^\circ\text{C}$, $P > 5.3\text{--}6.0\text{ GPa}$) ([Sato and Katsura, 2001](#)). Calcite is unstable in the presence of
341 enstatite and will transform to dolomite + diopside assemblage under conditions of $P = 2.3\text{ GPa}$, T
342 $= 1000^\circ\text{C}$ ([Kushiro et al., 1975](#)). Therefore, constraining the species of recycled carbonates has an
343 implication for understanding the mantle source depth. However, to date, how to identify the
344 species of recycled carbonate is poorly known.

345 Calcite and dolomite have similar Mg, O and Sr isotopic compositions, but the latter has
346 heavy Mg isotopic composition and higher Mg and lower Sr contents. Thus, mixing of calcite and

347 dolomite with the depleted mantle will generate curves with different curvatures in the plots of
348 Mg versus O and Sr isotopes, which could be a potential tool for distinguishing dolomite from
349 calcite recycled into the mantle via subduction.

350 To identify and constrain the species of carbonates involved in the formation of the syenites
351 from the Kuzigan and Zankan plutons, we modeled their Mg, O and Sr isotopic compositions (Table
352 5, Fig. 8, 9). In order to eliminate the effect of siliceous-clastic component, the relatively pure
353 dolostones and limestones from Cretaceous strata in Tibet are selected as end members based on
354 their SiO₂, CaO and MgO contents (Chen and Dong, 1982; Zong et al., 1982; Li et al., 2008).
355 Recent studies found that $\delta^{26}\text{Mg}$ of calcite-rich carbonates varies greatly through carbonate-silicates
356 interaction during subduction due to their low MgO contents, while the dolomite carbonates tend to
357 keep their original $\delta^{26}\text{Mg}$ signature (Wang et al., 2014). Therefore, Mg isotopic compositions of
358 ultrahigh pressure metamorphic (UHPM) calcitic and dolomitic marbles in subduction zone rather
359 than sedimentary carbonates are used for modeling calculation (Wang et al., 2014).

360 The Mg-O isotope modeling shows that mixing of a small amount of dolostone with the
361 depleted mantle (DMM) could significantly lower the $\delta^{26}\text{Mg}$ values and increase the $\delta^{18}\text{O}$ values.
362 However, dolostone alone makes the slope of the mixing line too sharp to fit the Mg and O
363 isotopic compositions of syenites. Involvement of the Indian sediments (clastic sediments) or
364 limestone could overlap the observed $\delta^{26}\text{Mg}$ variation (Fig. 8, 9). However, unrealistically large
365 amount of the Indian sediments (from 74% to 90% relative to dolostone) is required in order to fit
366 the data by mixing dolostone, Indian sediments and DMM (Fig. 8a). This amount of Indian
367 sediments is contradictory to the modeling result based on Mg and Sr isotopic compositions in Fig.
368 8b, in which a maximum 30% of Indian sediments is needed.

369 If the recycled carbonates contain both dolostone and limestone, then the limestone must be
370 a major component (65% to 90%) to fit the Mg and O isotopic data (Fig. 9a). However,
371 involvement of carbonates (limestone + dolostone) alone could not account for Sr isotopic
372 compositions of the samples (Fig. 9b). Hence, the clastic sediments (e.g., Indian sediments) with
373 heavy Mg isotopic composition and high $^{87}\text{Sr}/^{86}\text{Sr}$ are required. These clastic sediments were
374 probably carried into the mantle source by subducted India continent during the India-Eurasia

375 collision. The Mg-Sr isotope modeling shows that all samples lie along mixing lines between the
376 DMM and a mixture of dolostone (18-34%), limestone (60-67%) and Indian sediment (6-15%)
377 (Fig. 9b). A mixture with similar proportions of dolostone, limestone and clastic sediments also
378 explains the co-variation of Mg and O isotopes (Fig. 9c). Therefore, the variations of Mg, O and
379 Sr isotopic compositions can be best explained by mixing dolostone, limestone and clastic
380 sediments in the magma source region of the Kuzigan and Zankan plutons.

381 The contamination by both limestone and dolostone indicates that the hybridized depth in the
382 mantle is shallow, because stability of deeply recycled carbonates strongly depends on their depth
383 in the mantle (Kushiro et al., 1975; Sato and Katsura, 2001; Dasgupta and Hirschmann, 2010).
384 Therefore, the mantle source of the syenites and syenogranites in Kuzigan and Zankan areas had
385 been hybridized at a depth shallower than 60 to 120 km, consistent with a previous study that
386 suggested a < 70 to 100 km metasomatized mantle source inferred from the metasomatic volatile
387 phase relation (phlogopite and amphibole) (Jiang et al., 2012).

388 **5.4 Implication for carbonate recycling during subduction of the Tethyan oceanic slabs**

389 Pamir syntaxis is a complex subduction accretion system formed by northward subduction of
390 the Tethyan ocean to Asia during Paleozoic to early Cenozoic. Particularly, huge amounts of
391 carbonates were transported into the deep mantle along with the subduction and closure of the
392 Neo-Tethys ocean. According to the carbon budget, a part of carbon was released to the surface
393 by volcanic emission of CO₂, which was suggested to be responsible for the global warming
394 during Cretaceous to early Cenozoic (Kerrick and Connolly, 2001; Kent and Muttoni, 2008).
395 Another part of carbon was stored in carbonate minerals and recycled into the deep mantle. In this
396 case, the recycling carbonates would be recorded in mantle-derived post-collisional magmatic
397 rocks distributed in Tibet-Pamir region.

398 Ultrapotassic and potassic samples from the Kuzigan alkaline complex reveal that carbonates
399 were involved into the upper mantle source based on their low $\delta^{26}\text{Mg}$ isotopic compositions. Such
400 a signature has also been observed in the Zankan syenites to the south in the Pamir region.
401 Coincidentally, the Oligocene-Miocene (24 to 10 Ma) ultrapotassic volcanic rocks from the

central and southern Lhasa subterranean also present exhibit the similar low $\delta^{26}\text{Mg}$ values, implying the carbonate contamination in the mantle underneath the Tibet plateau (Liu et al., 2015). It is reasonable to speculate that recycled carbonate might be broadly existent in the mantle sources of the Cenozoic potassic and ultrapotassic igneous rocks widely distributed in the Tibetan-Pamir Plateau. More studies are needed to constrain the spatial-temporal scale of carbonate metasomatism in the upper mantle underneath the Tibetan Plateau.

6. Conclusion

We report the Mg, O and Sr isotopic compositions for the syenites and evolved syenogranites from the Kuzigan and Zankan plutons of the Pamir syntaxis in NW Xinjiang, China. The main conclusions are:

1. The alkaline syenites and syenogranites from the Kuzigan and Zankan regions have light Mg isotopic compositions with $\delta^{26}\text{Mg}$ varying from -0.46 to -0.17‰. Syenites and syenogranites have similar Mg isotopic compositions, indicating limited Mg isotope fractionation during alkaline magma fractional crystallization.
2. The syenites display a negative correlation between Mg and O isotopic compositions, which suggest the involvement of recycled sedimentary carbonates in their mantle source.
3. The combined Mg-O-Sr isotopic data could be used to identify species of recycled carbonates and thus constrain the metasomatized depth.
4. In view of the tectonic setting of the Pamir syntaxis, the recycling of carbonate was likely related to subduction of the Tethyan oceanic slab during Mesozoic-Cenozoic.

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620

Table 1 Bulk-rock compositions, O and Sr isotopic compositions of syenites and syenogranites from the Kuzigan and Zankan plutons

Sample	SiO ₂	FeO	MgO	CaO	Na ₂ O	K ₂ O	LOI	δ ¹⁸ O	⁸⁷ Sr/ ⁸⁶ Sr
Kuzigan syenites									
017E ^{a, b}	55.41	6.03	2.49	9.29	2.30	7.97	0.43		0.708143
017Q3	58.10	5.80	3.41	9.24	2.80	6.69	0.33	9.3	0.709822
017U1	61.32	3.82	2.36	6.07	3.24	6.76	0.49		0.709923
018B1 ^b	62.81	3.49	2.28	6.55	3.28	7.06	1.14	9.6	0.709895
018L ^b	63.32	3.57	0.40	4.50	5.55	6.39	0.58	8.6	0.709752
018P	56.30	5.72	2.36	6.71	2.61	7.33	0.80		0.709164
018R2	55.20	6.43	3.71	10.06	2.56	5.43	2.12		0.710032
018R4	51.60	6.31	4.64	12.13	1.25	6.45	0.60		0.710098
019A2 ^b	65.81	2.78	0.60	3.22	4.30	7.17	1.00	10.4	
019H ^b	54.18	4.70	5.54	14.31	0.58	6.71	0.53		0.709960
019J ^{a, b}	58.38	4.48	4.18	7.91	2.33	7.98	0.38	9.4	0.711045
019L1	61.49	2.01	1.95	5.18	0.96	11.74	0.33		0.710426
Kuzigan syenogranites									
018A	74.60	1.03	0.10	0.96	4.27	5.82	0.76	10.0	0.710284
018E ^b	74.16	1.02	0.24	1.34	4.02	4.92	0.58	11.6	0.709402
018M ^b	74.81	0.81	0.17	1.42	5.11	3.74	0.55	11.3	0.709582
018O ^{a, b}	73.75	1.86	0.23	1.19	3.88	5.57	0.57	11.2	0.709368
018S	72.49	1.51	0.25	1.61	3.36	6.33	0.38	10.5	0.710027
018U ^b	71.72	1.77	0.39	1.91	3.76	5.58	0.37	10.2	0.709914
019A3	66.62	2.10	0.43	2.41	4.27	6.57	0.61		0.709916
019E	67.43	2.46	0.53	3.02	4.13	6.60	0.65	10.9	0.709883
019I ^b	66.35	2.46	0.47	2.98	4.72	6.87	0.52	11.2	0.709914
Zankan syenites									
024A	64.68	2.60	0.35	3.05	4.25	8.24	0.67	10.1	0.709910
024B	57.05	6.44	1.84	10.14	3.59	6.70	0.75	11.1	0.710254
Wall rocks									
017E2 ^b	72.57	1.38	0.47	1.70	4.00	4.72	0.68		
017I	71.60	1.41	0.48	1.73	4.01	5.02	0.79	8.50	

622 ^a Sr isotopic compositions are from [Ke et al. \(2006\)](#).

623 ^b SiO₂, FeO (total FeO), MgO, CaO, Na₂O, K₂O and LOI (loss in ignition) contents are from [Ke et al. \(2006\)](#).

Table 2 Instrumental operating parameters at UA and CUGB

Lab	UA	CUGB
Instrument	<i>Nu Plasma</i> MC-ICP-MS	<i>Neptune Plus</i> MC-ICP-MS
Spray chamber	quartz cyclonic spray chamber	Scott double pass quartz glass spray chamber
Nebulizer	100 μ l/minute glass concentric self-aspiration nebulizer	50 μ l/minute PFA self-aspiration micro nebulizer
Autosampler	SC-2 from ESI	Cetac ASX-110
Interface cones	Nickel	Nickel
Faraday cups	L4, Ax and H5	L3, C, H3
Instrument resolution	Low resolution mode	Low resolution mode
Typical ^{24}Mg sensitivity	2.5 to 4.5 V/100 ppb	4.5 to 8 V/400 ppb
Analytical section	4 blocks and 40 cycles for each block	4 or 6 blocks and 30 cycles for each block
Background ^{24}Mg signal	$< 10^{-4}$ V	$< 2 \times 10^{-4}$ V
Blank ^a	< 10 ng	< 10 ng
In-run precision ^b	$\pm 0.02\text{‰}$ (2SD)	$\pm 0.02\text{‰}$ (2SD)
Internal precision ^c	$< 0.1\text{‰}$ (2SD)	$< 0.1\text{‰}$ (2SD)
External precision	0.07‰ (2SD) for $\delta^{26}\text{Mg}$	0.06‰ (2SD) for $\delta^{26}\text{Mg}$

The parameters of UA are from [Yang et al. \(2009\)](#), [Teng et al. \(2010\)](#), [Teng and Yang \(2014\)](#).

^a Blank is the whole-procedure blank through dissolution, column processing and measurement.

^b In-run precision is the precision on $^{26}\text{Mg}/^{24}\text{Mg}$ ratio for a single measurement of one block.

^c Internal precision is the precision on $^{26}\text{Mg}/^{24}\text{Mg}$ ratio based on ≥ 4 repeat runs of the same sample solution

Table 3 Mg isotopic compositions of synthetic solutions and reference materials measured at UA and CUGB

Lab	Lab ID	$\square \delta^{26}\text{Mg}$	2SD	$\square \delta^{25}\text{Mg}$	2SD	n ^c	N ^d
UA	KH Olivine	-0.27	0.08	-0.15	0.05	4	
	KH Olivine	-0.31	0.06	-0.15	0.05	4	
	KH Olivine	-0.27	0.06	-0.17	0.06	4	
	IL-Granite	0.02	0.08	0.01	0.05	4	
	IL-Granite	-0.04	0.07	-0.02	0.05	4	
	IL-Granite	-0.03	0.07	-0.01	0.06	4	
	IL-Granite	-0.07	0.05	-0.03	0.01	4	
	IL-Chondrite	-0.07	0.07	-0.03	0.04	4	
	IL-Mg-1	-0.08	0.07	-0.01	0.04	4	
	IL-Clinopyroxene	-0.02	0.04	-0.02	0.05	4	
	BHVO-2 ^a	-0.20	0.07	-0.10	0.04		7
	Seawater ^a	-0.83	0.09	-0.43	0.06		
	PCC-1 ^a	-0.23	0.06	-0.10	0.01		3
	DST-1 ^a	-0.30	0.01	-0.13	0.01	4	5
CUGB	GSB Mg ^b	-1.05	0.03	-2.04	0.04	4	58
	BHVO-2	-0.25	0.06	-0.13	0.04	4	48
	BCR-2	-0.19	0.05	-0.10	0.03	4	19
	AGV-2	-0.17	0.05	-0.08	0.03	4	13
	Seawater	-0.83	0.02	-0.42	0.03	4	2
	PCC-1	-0.25	0.04	-0.13	0.02	4	2
	DST-1	-0.32	0.04	-0.16	0.04	4	2

IL-Granite: Mg:Fe:Al:Ca:Na:K:Ti:Ni = 1:5:30:5:10:20:0.1:0.1.

IL-Chondrite: Mg:Fe:Ca:Ni:Al:Na:K:Ti = 1:3:0.2:0.2:0.2:0.1:0.1:0.1.

IL-Mg-1: Mg:Fe:Al:Ca:Na:K:Ti = 1:1:1:1:1:1:0.1.

IL-Clinopyroxene: Mg:Fe:Ca:Al = 1:0.5:2:0.1.

^a Recommended values in [Teng et al. \(2015a\)](#).

^b GSB Mg is an ultrapure single elemental standard solution from China Iron & Steel Research Institute.

^c n is the times of sample analyzing during an analytical session.

^d N is the times to repeat sample dissolution, column chemistry and instrumental analysis.

Table 4 Mg isotopic compositions of syenites and syenogranites from the Kuzigan and Zankan plutons

Lab	Samples	$\delta^{26}\text{Mg}$	2SD	$\delta^{25}\text{Mg}$	2SD
Kuzigan syenites					
CUGB	017E	-0.39	0.07	-0.17	0.05
UA	017Q3	-0.31	0.08	-0.20	0.05
CUGB	017U1	-0.38	0.09	-0.18	0.04
UA	018B1	-0.33	0.07	-0.15	0.05
UA	018L	-0.33	0.09	-0.15	0.05
	Replicate ^a	-0.26	0.05	-0.14	0.04
	Duplicate ^b	-0.26	0.07	-0.13	0.06
CUGB	018P	-0.37	0.02	-0.20	0.07
CUGB	018R2	-0.30	0.09	-0.17	0.05
CUGB	018R4	-0.39	0.06	-0.20	0.02
UA	019A2	-0.32	0.05	-0.17	0.05
	Replicate	-0.37	0.07	-0.19	0.05
UA	019H	-0.39	0.08	-0.20	0.05
UA	019J	-0.31	0.07	-0.14	0.05
UA	019L1	-0.40	0.09	-0.21	0.05
	Replicate	-0.38	0.05	-0.20	0.04
Kuzigan syenogranites					
UA	018A	-0.18	0.05	-0.10	0.05
	Replicate	-0.17	0.05	-0.08	0.04
CUGB	Replicate	-0.20	0.08	-0.09	0.08
UA	018E	-0.38	0.07	-0.20	0.06
UA	018M	-0.41	0.09	-0.21	0.05
CUGB	Replicate	-0.39	0.05	-0.20	0.04
UA	018O	-0.37	0.09	-0.15	0.05
	Replicate	-0.28	0.05	-0.14	0.04
	Duplicate	-0.30	0.07	-0.16	0.06
UA	018S	-0.34	0.08	-0.17	0.05
UA	018U	-0.33	0.05	-0.18	0.04
CUGB	Replicate	-0.32	0.05	-0.17	0.04
CUGB	019A3	-0.39	0.02	-0.19	0.03
UA	019E	-0.21	0.07	-0.11	0.06
UA	019I	-0.31	0.07	-0.15	0.05
Zankan syenites					
CUGB	024A	-0.37	0.07	-0.18	0.05
CUGB	024B	-0.46	0.07	-0.20	0.05
Wall rocks, gneissic granites					
UA	017E2	-0.26	0.07	-0.13	0.05
UA	017I	-0.27	0.05	-0.15	0.04

626 ^a Replicate: repeated sample dissolution, column chemistry and instrumental

627 analysis.

628 ^b Duplicate: repeated measurement of Mg isotopic ratios on the same solutions.

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Table 5 Magnesium, oxygen and strontium isotopic compositions and MgO, Sr contents of end members for mixing modeling

End member	$\delta^{26}\text{Mg}$	$\delta^{18}\text{O}$	$^{87}\text{Sr}/^{86}\text{Sr}$	MgO (wt.%)	Sr (ppm)
DMM	-0.25	5.5	0.7025	38	7.7
Dolostone	-2.17	22.0	0.7080	23	222
Limestone	-0.66	22.0	0.7080	0.5	340
Indian sediments	-0.05	17.0	0.8000	2.3	88

DMM is the depleted mantle. The $\delta^{18}\text{O}$ and $\delta^{26}\text{Mg}$ ($-0.25 \pm 0.07\text{‰}$) values of DMM are from [Hoefs \(2009\)](#) and [Teng et al. \(2010\)](#), respectively. Other data of the DMM are taken from [Workman and Hart \(2005\)](#).

Dolostone is the Cretaceous dolostones of Cuoqin basin, Qinhai-Tibet Plateau ([Li et al., 2008](#)). In order to avoid the post-diagenetic effect on Sr isotopic composition of the dolostone, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Cretaceous sea water in the south Tibet (0.708; [Huang et al., 2004](#)) is used to represent that of the dolostones. $\delta^{26}\text{Mg}$ value of dolostone is an average Mg isotopic composition of ultrahigh pressure metamorphic (UHPM) dolomitic marbles from [Wang et al. \(2014\)](#). Other data of the dolostone are taken from [Li et al. \(2008\)](#).

Limestone is the Cretaceous pure biogenic limestones of Nyanang-Gamba, Tibet. The $\delta^{18}\text{O}$ value of Gamba limestones is from [Li et al. \(2005\)](#). $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Cretaceous sea water in the south Tibet (0.708; [Huang et al., 2004](#)) is used to represent that of the limestones. MgO content is from [Chen and Dong \(1982\)](#). The Sr concentration is from [Zong et al. \(1982\)](#). The $\delta^{26}\text{Mg}$ value is the average of Mg isotopic compositions of UHPM calcitic marbles from [Wang et al. \(2014\)](#).

Indian sediment is clastic sediments from the Lesser, High and Tethyan Himalayan sediments from the Sutlej Valley ([Richards et al., 2005](#)). MgO content, Sr concentration and $^{87}\text{Sr}/^{86}\text{Sr}$ ratio are from [Richards et al. \(2005\)](#) and [Bouilhol et al. \(2013\)](#). $\delta^{18}\text{O}$ values of clastic sediments span a large range and we select $\delta^{18}\text{O} = 17\text{‰}$ as its average for modeling. The $\delta^{26}\text{Mg}$ value is the Mg isotopic composition of sediments from [Li et al. \(2010\)](#).

Figure captions

Fig. 1 Simplified geological map of the eastern Pamir and sample section. (a) geological map modified from Jiang et al. (2012), emphasizing Cenozoic igneous rocks. Inset shows location of Pamir region within the India-Eurasia collision zone. (b) section map of the Kuzigan alkaline pluton, emphasizing the rock types, contact relationships, and sampling locations.

Fig. 2 Magnesium isotopic compositions of BHVO-2, BCR-2, AGV-2 and GSB Mg (an ultrapure single elemental standard solution from China Iron & Steel Research Institute) since 06/2012. The black horizontal line represents the average $\delta^{26}\text{Mg}$. Error bars represent 2SD uncertainties. Data are reported in Table 3.

Fig. 3 Magnesium isotopic compositions of granitoids rocks in literatures and the Kuzigan and Zankan plutons in this study. Mg isotopic data for A-type and I-type granitoids are from published literatures (Shen et al. 2009; Li et al. 2010; Liu et al. 2010). The grey bar is $\delta^{26}\text{Mg}$ value of the Earth ($-0.25 \pm 0.07\text{‰}$; Teng et al., 2010).

Fig. 4 Plots of SiO_2 contents versus MgO, total FeO, CaO and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ contents. The data source is from Table 1.

Fig. 5 Plots of $\delta^{26}\text{Mg}$ versus SiO_2 , MgO, Total FeO and CaO contents. The dashed line represents $\delta^{26}\text{Mg}$ value of the Earth (-0.25‰ ; Teng et al., 2010). Data are reported in Tables 1 and 4.

Fig. 6 Relationship of $\delta^{26}\text{Mg}$ values and sample spatial distribution. The dashed line represents $\delta^{26}\text{Mg}$ value of the Earth (-0.25‰ ; Teng et al., 2010). The gray strips are contact boundaries based on the sample section (Fig. 1b).

Fig. 7 Plot of $\delta^{26}\text{Mg}$ versus $\delta^{18}\text{O}$ of syenites and syenogranites from the Kuzigan and Zankan alkaline intrusions. Data are from Tables 1 and 4.

Fig. 8 (a) Mg-O isotopes modeling for mixing of the depleted mantle (DMM), dolostone and the Indian sediment. (b) Mg-Sr isotopes modeling for mixing of the

DMM, dolostone and the Indian sediment. The label on each curve is proportions of dolostone:Indian sediment. Parameters and data source are listed in [Tables 1, 4 and 5](#). Points on mixing curves are at 10% intervals.

Fig. 9 (a) Mg-O isotopes modeling for mixing of the DMM, dolostone and limestone. (b) Mg-Sr isotopes modeling for mixing of the DMM, dolostone, limestone, and the Indian sediment. (C) Mg-O isotopes modeling for mixing of the DMM, dolostone, limestone and Indian sediment. Parameters and data source are listed in [Tables 1, 4 and 5](#). Points on mixing curves are at 10% intervals. The label on each curve is proportions of dolostone:limestone and dolostone:limestone:Indian sediment, respectively. Mixing calculations illustrate different sedimentary rocks recycled and then hybridized the upper mantle in the Pamir region.

Figure

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9