1
2 Carboniferous bimodal volcanic rocks in the Eastern
3 Tianshan, NW China: Evidence for arc rifting
4
5
6

7 Yunying Zhang^{a,b}, Chao Yuan^{a,*}, Xiaoping Long^c, Min Sun^d, Zongying
8 Huang^{a,b}, Long Du^{a,b}, Xinyu Wang^{a,b}
9
10
11

12 ^aState Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry,
13 Chinese Academy of Sciences, Guangzhou 510640, China

14 ^bUniversity of Chinese Academy of Sciences, Beijing 10069, China

15 ^cState Key Laboratory of Continental Dynamics, Department of Geology, Northwest
16 University, Northern Taibai Str. 229, Xi'an 710069, China

17 ^dDepartment of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong
18 Kong, China
19
20
21

22 * Corresponding author. Tel.: +86 20 85290708; fax: +86 20 85290130.

23 *E-mail address:* yuanchao@gig.ac.cn (C. Yuan).

Abstract:

Detailed geochronological, geochemical and Sr–Nd isotopic data are presented for late Paleozoic volcanic rocks in the Dashitou area from the Eastern Tianshan, NW China, aiming to constrain their petrogenesis and tectonic implications. The Dashitou volcanic rocks show a bimodal distribution in composition, with dominant rhyolite and subordinate basalt. LA–ICPMS zircon U–Pb age indicates that the volcanic rocks were erupted at 330 ± 3 Ma. The basaltic rocks are medium-K calc-alkaline, enriched in light rare earth element (LREE) and large ion lithophile element (LILE; Ba and U), and depleted in high field strength element (HFSE; Nb, Ta and Ti). These features, together with their depleted isotopic signature (initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7035$ to 0.7039 , $\epsilon_{\text{Nd}}(t) = 6.8$ to 7.1), suggest that they were likely derived from a depleted mantle source metasomatized by subduction-related fluids. The rhyolitic rocks are high-K calc-alkaline, and exhibit characteristics of A₂-type granite, with typical enrichment in alkalis, Zr and Nb, and depletion in Sr, P and Ti. They are characterized by positive $\epsilon_{\text{Nd}}(t)$ values (6.2 – 6.5) with young Nd model ages (0.57 – 0.58 Ga). Results of MELTS modeling imply that they were unlikely produced by fractional crystallization of coeval basaltic rocks. Instead, they were probably generated by partial melting of juvenile basaltic crust as a result of magma underplating. The geochemical and Sr–Nd isotopic characteristics, coupled with regional geology, indicate that the formation of the Dashitou bimodal volcanic rocks involves an extensional regime associated with a subduction-related environment. The rifting of the Dananhu–Harlik arc in response to the retreat of the subducting Northern Tianshan oceanic lithosphere may account for

the Dashitou bimodal volcanic rocks.

Keywords: Bimodal volcanic rocks; A-type rhyolite; Arc rifting; Eastern Tianshan;
Central Asian Orogenic Belt

1. Introduction

Bimodal volcanic suites lacking intermediate compositions are common in extensional settings linked to intraplate, post-collisional or back-arc rifting tectonic regimes (Hildreth et al., 1991; Pin and Paquette, 1997; Shinjo and Kato, 2000; Li et al., 2002a), and can provide important information regarding the crust–mantle interaction processes and the tectonic evolution of orogenic belts. It is unambiguous that basaltic magmas are mantle-derived, whereas the derivation of felsic magmas is a matter of considerable debate. Of all these various bimodal rock associations, that of A-type rhyolite with tholeiitic basalt is quite enigmatic. Several different processes have been proposed to account for the felsic magmas with A-type affinity, namely, fractional crystallization of coeval basaltic magmas with or without crustal contamination (Pin and Paquette, 1997; Peccerillo et al., 2003; Aydin et al., 2014), partial melting of pre-existing crustal rocks (Maria and Hermes, 2001; Li et al., 2002a; Tamura and Tatsumi, 2002) and mixing of mantle-derived basaltic with crust-derived felsic magmas (Mingram et al., 2000; Zhang et al., 2008).

The Tianshan belt occupies the southernmost part of the Central Asian Orogenic Belt (CAOB) and extends from west to east for over 2500 km through Uzbekistan,

Kyrgyzstan and Kazakhstan to northern Xinjiang in China (Fig. 1a; Windley et al., 1990; Sengör et al., 1993; Xiao et al., 2008). Voluminous late Paleozoic volcanic rocks with bimodal distribution occur in the east segment of the Tianshan belt (e.g., Shu et al., 2011). However, the cause of these volcanic rocks remains controversial, and proposed schemes include continental rift (Che et al., 1996; Xia et al., 2004, 2008), island arc (Xiao et al., 2004; Wang et al., 2007; Chen et al., 2013; Hou et al., 2014) and post-collisional settings (Yuan et al., 2010; Chen et al., 2011). In addition, the genetic relationship between basaltic and felsic volcanic rocks is ambiguous, which hinders the understanding of their petrogenesis and associated geodynamic processes. Furthermore, many porphyry Cu deposits (e.g., Tuwu and Yandong) developed during the Carboniferous in the Tianshan belt (Han et al., 2006; Zhang et al., 2006; Shen et al., 2014).

In this contribution, we report new zircon U–Pb ages, whole rock geochemical and Sr–Nd isotopic data for the Carboniferous bimodal volcanic rocks in the Dashitou area from the Eastern Tianshan, in order to (1) investigate their petrogenesis and genetic relationships, and (2) constrain the geodynamic processes in the Eastern Tianshan.

2. Geological background

The Chinese Tianshan is located between the Junggar plate to the north and the Tarim Block to the south, and was formed by progressive accretion of various terranes such as island arcs, ophiolitic mélanges, accretionary wedges, and possibly oceanic

plateaus and microcontinents during the Paleozoic (Fig. 1b; Xiao et al., 2004; Kröner et al., 2007; Windley et al., 2007; Zhang et al., 2015a). Geographically, it can be divided into the Western and Eastern Tianshan by the Urumqi–Korla road (Fig. 1b). This study focuses mainly on the Eastern Tianshan, which can be tectonically divisible into three subunits (from south to north): the Southern, Central and Northern Tianshan belts, separated by Kawabulake and Aqikuduke faults, respectively (Fig. 1c; Xiao et al., 2004, 2013). The Southern Tianshan resulted from collision between the Tarim Block and the Central Tianshan, and is dominated by Paleozoic ophiolitic mélanges and clastic rocks (e.g., turbidites, cherts and volcanoclastic rocks) and high-pressure metamorphic rocks (e.g., eclogite and blueschist) (Gao et al., 1998; Xiao et al., 2004). The Central Tianshan microcontinent is underlain by Proterozoic metamorphic basement consisting mainly of silimanite–biotite–quartz schists, granitic gneisses, granulites, amphibolites, migmatites and marbles (Hu et al., 2006; Chen et al., 2009; Shi et al., 2010), and is overlain by Paleozoic arc volcanic and volcanoclastic rocks (e.g., Zhu et al., 2009). Furthermore, voluminous Paleozoic subduction-related granitoids intruded into the Proterozoic basement (e.g., Li, 2004; Sun et al., 2006).

The Northern Tianshan represents a composite orogen, and is composed mainly of three subunits, namely from south to north the Yamansu arc, the Kanggurtag suture and the Dananhu–Harlik arc (Fig. 1c, Xiao et al., 2004, 2013; Wang et al., 2014). The Yamansu arc predominantly comprises Carboniferous arc-related volcanic rocks, including basalts, andesites and minor rhyolites interbedded with fine-grained clastic

sediments (Zhang et al., 2013; Hou et al., 2014). The Kanggurtag suture represents a 5 to 24 km wide and ~600 km long accretionary complex, which can be subdivided into two major tectonic assemblages: Devonian to Carboniferous meta-basaltic lavas, volcanoclastic rocks, deep-sea turbidites, sandstones and limestones in the southern part, and ophiolitic slices in the northern part (Yang et al., 1996; Xiao et al., 2004). Ophiolitic slices are composed mainly of serpentized ultramafic rocks, gabbros and meta-basalts in the Kanggurtag area, and have been considered to be late Cambrian in age, based on a SHRIMP zircon age of 494 ± 10 Ma for gabbros from this ophiolite (Li et al., 2008). In addition, geochemical data suggest that the Kanggurtag ophiolite formed in a supra-subduction zone (SSZ) setting (Li et al., 2008). Late-stage intensive deformation on the Kanggurtag accretionary complex has structurally repeated the thickness of the turbidite, and foliation has replaced original bedding (Xiao et al., 2004). The Dananhu–Harlik arc system has been considered as an Ordovician to Carboniferous island arc accompanied by prolonged arc magmatism (Xiao et al., 2004). The Ordovician to Silurian Huangcaopo group is dominated by marine clastics and tuffs with minor limestones and basalts (Ma, 1999), while the Devonian Kalatag, Dananhu and Tousuquan formations consist mainly of arc-related basaltic to felsic volcanic and volcanoclastic rocks and subordinate tuffaceous siltstones and sandstones (Tang et al., 2006). Carboniferous strata are widespread in the Dananhu–Harlik arc and dominated by calc-alkaline volcanic rocks including basalts, basaltic andesites and rhyolites, with minor sandstones and limestones (Shen et al., 2014). The Permian sedimentary sequences unconformably overlie the Carboniferous strata, and comprise

terrestrial sandstones and siliceous mudstone intercalated with basalts, andesites and rhyolites (Yuan et al., 2010). In addition, porphyry copper deposits spatially associated with plagiogranite porphyries including the Tuwu, Yandong, Linglong and Chihu ore districts are located on the southern margin of the Dananhu arc (Han et al., 2006) (Fig. 1c).

3. Petrology and sampling

The Dashitou volcanic rocks are situated to the west of the Dashitou town in the Bogda mountains, which crops out along the northern edge of the Turpan–Hami basin and is considered to be an intra-arc basin (Fig. 1c; Xiao et al., 2004; Chen et al., 2013). This region comprises mainly of Lower Carboniferous Qijiaojing Formation (C1q), and Upper Carboniferous Qijiagou Formation (C2qj) and Liushugou Formation (C2l). The Qijiaojing Formation is dominated by interbedded purple ignimbrite, rhyolite and green–black basalt, with minor tuffaceous sandstone and shale (Gu et al., 2010). The Liushugou Formation predominantly contains bimodal volcanic rocks, including basalt, basaltic andesite and rhyolite (Gao et al., 2014). In contrast, the Qijiagou Formation is composed mainly of purple sandstone, conglomerate and bioclastic limestone, with minor green tuff and basalt (Zhao et al., 2014).

The Dashitou volcanic rocks, sampled from the Liushugou Formation, are dominated by rhyolite with subordinate basalt, and commence with basaltic lava and culminate with rhyolite porphyry, suggesting a bimodal volcanic sequence (Wang et al., 2007; Gao et al., 2013). Wang et al. (2007) reported a Rb–Sr isochron age of

306.7 ± 2.3 Ma for a rhyolite sample from the Dashitou volcanics. In this study, Eight basaltic and six rhyolitic rocks were chosen for analyses. The basalts are dark grey, massive and fine-grained (Fig. 3a), and mainly composed of clinopyroxene, plagioclase and Fe–Ti oxides. The plagioclase grains are subhedral and lath-shaped (Fig. 3b). The rhyolitic samples are purple and show a porphyritic texture with phenocryst of K-feldspar (5–10 vol.%). The groundmass comprises K-feldspar (~35 vol.%), quartz (20–25 vol.%) and plagioclase (25–35 vol.%), with minor titanite, apatite and zircon (Fig. 3c, d).

4. Analytical methods

4.1. Zircon U–Pb dating

Zircons were separated from a rhyolitic sample (ET4QJ22) using conventional heavy liquid and magnetic separation techniques. Representative zircon grains were handpicked under a binocular microscope, and then were mounted in an epoxy resin disk and polished to about half of their thickness for analysis. In order to reveal the morphology and internal structure of zircons, cathodoluminescence (CL) images were obtained by using a JEOL JXA–8100 Electron Probe Microanalyzer with a Mono CL3 CL System, at State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (SKLIG GIG CAS).

Zircon U–Pb dating was conducted by using an Agilent 7500 inductively coupled plasma mass spectrometry (ICP–MS) coupled with a COMPex PRO 102 ArF-Excimer laser ($\lambda=193$ nm), at the School of Resources and Environmental Engineering, Hefei

University of Technology, China. Detailed descriptions of the instrumentation and analytical procedure can be found in Yan et al. (2015). Zircon 91500 and NIST610 were used as external calibration standards for zircon U–Pb isotope and trace element analyses, respectively. Zircon isotope ratios and trace elements were calculated using the program ICPMSDataCal 7.2. Concordia diagrams and weighted mean calculations were carried out using the Isoplot 3.0 program (Ludwig, 2003).

4.2. Major and trace elements

The whole-rock major and trace elements were determined at SKLIG GIG CAS. Major element compositions were measured using X-ray fluorescence spectrometry (Rigaku RIX 2000) on fused glass disks following analytical procedures described by X.H. Li et al. (2006) and analytical precision for major elements was between 1 and 5%. Trace elements analyses were carried out using a Perkin–Elmer Sciex ELAN 6000 ICP–MS, and the analytical procedures are referred to Li et al. (2002b) and analytical precision was generally better than 5%. Powdered samples (~40 mg) were digested with mixed HNO₃ and HF acid in steel–bomb coated Teflon beakers for two days in order to ensure complete dissolution of refractory minerals. USGS rocks standards (W-2, BCR-2, BHVO-2 and AGV-2) and the Chinese national rock standards (GSD-9, GSR-1, GSR-2 and GSR-3) were used to calibrate elemental concentrations of the measured samples.

4.3. Sr–Nd isotope analyses

Sr and Nd isotopic analyses were undertaken by using a Micromass Isoprobe multi-collector mass spectrometer (MC-ICP-MS) at SKLIG GIG CAS, following the procedures described by X.H. Li et al. (2006). Measured $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$ and $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, respectively. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the NBS987 standard and $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the Shin Etsu JNdi-1 standards measured during this study were 0.710238 ± 7 (2σ) and 0.512105 ± 5 (2σ), respectively.

5. Analytical results

The results of LA-ICPMS zircon U-Pb isotope analyses for Dashitou rhyolite sample ET4QJ22 are given in Appendix 1, and whole-rock major and trace element and Sr-Nd isotopic data are listed in Tables 1–2.

5.1. Geochronology

Zircons from this sample are mostly transparent and stubby to prismatic, with well-developed oscillatory zoning, indicating an igneous origin. Size of the zircons ranges from 50 to 150 μm in length, with length/width ratios of 1:1 to 3:1 (Fig. 4). The analyzed zircons have variable Th (55–121 ppm) and U (154–204 ppm) contents, with Th/U ratios of 0.32 to 0.64, consistent with a magmatic origin. Fourteen analyses gave $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 327 ± 6 Ma to 334 ± 5 Ma (Appendix 1), and form a coherent group with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 330 ± 3 Ma (Fig. 4), which is considered to be the extrusive age of the Dashitou volcanic rocks.

222

223 5.2. Major and trace elements

224 The basalts have consistent geochemical compositions, with low SiO₂ (49.7–52.7
225 wt.%), MgO (3.91–4.63 wt.%) but relatively high Al₂O₃ (16.3–16.7 wt.%) and TiO₂
226 (1.70–1.89 wt.%) contents. They are relatively Na-enriched as indicated by high
227 Na₂O/K₂O (3.5–5.6) ratios, and metaluminous with low A/CNK [molar Al₂O₃/(K₂O +
228 Na₂O + CaO)] values ranging from 0.75 to 0.84 (Fig. 5d). The basalt samples are
229 classified as sub-alkaline and medium-K calc-alkaline rocks on SiO₂ versus total
230 alkali (K₂O + Na₂O) and K₂O diagrams, respectively (Fig. 5a, b). They possess low
231 Cr (1.8–2.9 ppm) and Ni (1.3–2.0 ppm) but relatively high Sr (589–799 ppm) and Ba
232 (270–529 ppm) contents. In addition, their Nb/Ta (14.3–14.9) and Nb/La (0.26–0.27)
233 ratios are significantly lower than those of the primitive mantle (Sun and McDonough,
234 1989). The basalt samples are characterized by moderate LREE enrichment [(La/Yb)_N
235 = 2.91–3.05; (Gd/Yb)_N = 1.62–1.67], with slightly positive Eu anomalies (Eu/Eu* =
236 1.04–1.07) (Fig. 6a). On the primitive mantle-normalized trace element diagram (Fig.
237 6b), the basalts show relative enrichment in large ion lithophile elements (LILE; e.g.,
238 Ba, U and Sr), and depletion in high field strength elements (HFSE; e.g., Nb and Ta).

239 The rhyolite samples are characterized by high SiO₂ (68.0–71.2 wt.%) but low
240 MgO (0.20–0.52 wt.%), TiO₂ (0.58–0.68 wt.%) and Fe₂O₃^T (2.31–3.36 wt.%) contents.
241 They have high total alkali (K₂O+Na₂O = 9.52–10.6 wt.%) contents and K₂O/Na₂O
242 (0.99–1.37) ratios, showing alkaline and high-K calc-alkaline characteristics, and are
243 weakly peraluminous with A/CNK values ranging from 1.01 to 1.05 (Fig. 5d). The

rhyolite samples contain high Zr (284–333 ppm), Hf (7.11–8.32 ppm), Y (32.9–48.4 ppm) and Ba (1043–1262 ppm) but relatively low Sr (111–133 ppm) concentrations. These rocks show enriched LREE patterns $[(\text{La}/\text{Yb})_{\text{N}} = 6.83\text{--}8.59; (\text{Gd}/\text{Yb})_{\text{N}} = 1.61\text{--}1.76]$, with slightly negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.84\text{--}0.92$) (Fig. 6c). They are also enriched in the LILE (e.g., Rb, Ba and U) relative to the HFSE and LREE, with remarkably negative Nb, Ta, Ti and Sr anomalies (Fig. 6d).

5.3. Sr–Nd isotopic compositions

The whole-rock initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\epsilon_{\text{Nd}}(t)$ values have been calculated at 330 Ma on the basis of the zircon U–Pb ages of this study (Fig. 7). The basalts with low $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (0.03–0.05) have uniform initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7035 to 0.7039) and $\epsilon_{\text{Nd}}(t)$ values (6.82 to 7.05). In contrast, the rhyolite samples have high $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (2.27–2.76) as a result of fractionation of plagioclase, which would lead to large uncertainty in the initial Sr isotope ratios. If so, the calculated initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7014 to 0.7022) of the rhyolite samples are not geologically meaningful (e.g., Wu et al., 2002). The $\epsilon_{\text{Nd}}(t)$ values (6.21 to 6.47) of the rhyolite samples are lightly lower than those of the basalt samples and the ~345 Ma Hongshankou rhyolitic rocks [$\epsilon_{\text{Nd}}(t) = 6.35$ to 8.53] reported by Chen et al. (2013).

6. Discussion

6.1. Geochronological framework

The Bogda mountain is one of the most important volcanic belts during the late

Paleozoic in the Eastern Tianshan. Previous geochronological and geochemical studies have revealed that three pluses of bimodal volcanism occurred in the Bogda mountains, including (1) the early Carboniferous (ca. 345 Ma) Heishankou bimodal volcanism (Chen et al., 2013), the late Carboniferous (ca. 315 Ma) Sepikou bimodal volcanism (Gao et al., 2013) and the early Permian (ca. 295 Ma) Qijiaojing bimodal volcanism (Chen et al., 2011). New LA–ICPMS zircon age of this study indicates that the Dashitou volcanic rocks were emplaced at the early Late Carboniferous (330 ± 3 Ma). Moreover, subordinate andesite in the Bogda mountains may represent fractional products of basaltic magmas (Gao et al., 2014). These dates suggest that the eruption of volcanic rocks in the Bogda mountains was of multi-stages and may be successive from early Carboniferous to early Permian.

6.2. Petrogenesis of basaltic rocks

The basaltic rocks have low SiO_2 (49.7–52.7 wt.%) contents and high Mg# (up to 50), indicating that a mantle component played a prominent role in their genesis (Rudnick and Gao, 2003). However, the Cr (1.82–2.90 ppm) and Ni (1.34–1.97 ppm) concentrations are remarkably lower than those of primary mantle-derived magmas (e.g., Cr = 300–500 ppm, Ni = 300–400 ppm; Frey et al., 1978), suggesting that their parental magmas experienced significant crystal fractionation. The negative correlations between MgO, CaO, $\text{CaO}/\text{Al}_2\text{O}_3$, $\text{Fe}_2\text{O}_3^{\text{T}}$ and SiO_2 are compatible with fractionation of pyroxene and olivine (Fig. 8). The constant correlation of Al_2O_3 with SiO_2 , together with the positive Eu and Sr anomalies (Fig. 6b), suggests insignificant

fractionation of plagioclase. Furthermore, amphibole fractionation for the basaltic rocks has occurred as suggested by positive correlation between Dy/Yb and Mg#, because amphibole preferentially incorporates Dy relative to Yb (e.g., Garrison and Davidson, 2003).

Mantle-derived magmas generally assimilate crustal materials during their ascent or their storage in a crustal magma chamber. Commonly, crustal materials are characterized by low $\epsilon_{\text{Nd}}(t)$, Nb/La and Nb/Th but high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Rudnick and Fountain, 1995), and thus crustal contamination will cause decreases in $\epsilon_{\text{Nd}}(t)$, Nb/La and Nb/Th but an increase in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. In fact, the basaltic rocks have relatively homogeneous Sr–Nd isotopic compositions (Fig. 7), and their Mg# vary negatively with $\epsilon_{\text{Nd}}(t)$ values but positively with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Fig. 9a, b), which are inconsistent with crustal contamination. Furthermore, the constant Nb/La (0.26–0.27) and Nb/Th (2.63–2.70) ratios irrespective of Mg# (Fig. 9c, d) also preclude the possibility of significant crustal contamination.

The Sr–Nd isotopic compositions of the basaltic rocks [$\epsilon_{\text{Nd}}(t) = 6.7\text{--}7.1$; initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7035\text{--}0.7039$] suggest that they were originated from a depleted mantle source. Their Nb/Ta (14.3–14.9), Nb/La (0.26–0.27), Ce/Pb (5.2–11.6) and Nb/Yb (~1.1) ratios are significantly lower than those of oceanic island basalt (OIB) (e.g., Hofmann, 1997), implying that they were unlikely derived from an OIB-like mantle source. This inference is further demonstrated in the Nb/Y–Zr/Y plot (Fig. 10a) that derivations of the basaltic rocks are different from any of the mantle plume domains (Condie et al., 2005). Actually, the enrichments of LILE relative to HFSE with

310 remarkable Nb–Ta anomalies are indicative of some characteristics of arc-related
311 magmatism, and reflect a depleted mantle source previously hybridized by fluids or
312 melts from a subducted slab (Pearce et al., 2005). On a Th/Yb versus Nb/Yb diagram
313 (Fig. 10b), all of the basaltic rocks plot above the MORB–OIB array, further
314 suggesting the involvement of a subduction-related component (Pearce, 2008). The
315 significant depletion in Hf and Ta relative to Sm and La, respectively, is a diagnostic
316 characteristic of fluid-related subduction metasomatism, as Sm and La are much more
317 soluble than Hf and Ta in aqueous fluids (Fig. 10c; La Flèche et al., 1998).

318 The basaltic rocks are characterized by flat chondrite-normalized HREE patterns
319 (Fig. 6a), indicating that they were likely derived from a spinel-facies mantle. This
320 interpretation is further manifested in the Gd/Yb–Dy/Yb modeling plot (Fig. 10d).
321 Garnet has a high partition coefficient for Yb relative to Gd and Dy, and thus partial
322 melting of a garnet lherzolite mantle will cause strong fractionation of Dy/Yb and
323 Gd/Yb (e.g., Johnson, 1994). In contrast, spinel has similar partition coefficients for
324 Yb, Gd and Dy, and Dy/Yb and Gd/Yb will be slightly fractionated during melting in
325 the spinel stability field (Green, 2006). In the case of the Dashitou basaltic rocks, they
326 possess low Dy/Yb and Gd/Yb ratios, which plot along the melting curve of spinel
327 peridotite (Fig. 10d), suggesting that partial melting took place at a relatively shallow
328 depth, dominantly within the spinel stability field.

329 Collectively, we suggest that the Dashitou basalts were likely derived from a
330 depleted spinel-facies mantle fluxed by slab-derived fluids, accompanied by extensive
331 crystal fractionation of olivine, pyroxene and amphibole, with insignificant crustal

contamination.

6.3. Petrogenesis of rhyolitic rocks

For the bimodal rock suite, the genesis of felsic rocks is a long-standing and an enigmatic petrogenetic issue (e.g., Bonnefoi et al., 1995). The Dashitou rhyolites are characterized by high contents of SiO₂, total alkali, Zr, Nb and Y, and low abundances in MgO, CaO, Ba, Sr, P and Ti, with negative Eu anomalies. The above characteristics suggest that the Dashitou rhyolites are akin to A-type granites, as demonstrated in the (Na₂O+K₂O)/CaO versus Zr + Nb + Ce + Y plot (Fig. 11a) (Whalen et al., 1987). Furthermore, they can be classified as A₂-type granites (Fig. 11b), based on their relatively low Nb/Y ratios (0.25–0.38) (Eby, 1992). Several different petrogenetic processes have been proposed to account for the generation of silicic rocks with A-type affinity, as stated in the introduction; here we evaluate the possible mechanisms in order to constrain the origin of the Dashitou rhyolite.

The lack of mafic microgranular enclaves in the rhyolitic rocks, coupled with the homogeneous Sr–Nd isotopic compositions (Fig. 7), suggests that magma mixing of mantle- with crust-derived melts is not a plausible mechanism. The rhyolite and basalt have identical Nd isotopic compositions, implying that they probably share a common mantle-derived parental magma. The generation of the rhyolite in the Bogda mountain has been explained by fractionation of the coeval basaltic magma (Chen et al., 2013). In order to test the fractionation hypothesis, we modeled the fractionation history of the basaltic rocks using MELTS (Ghiorso and Sack, 1995; Smith and Asimow, 2005),

under certain P–T– $f\text{O}_2$ conditions. We use water content of 1 wt.%, pressure of 3 kbar, $f\text{O}_2 = \text{NNO} + 1$ and a starting composition of sample ET4QJ10. Modeling results indicate that fractional crystallization does not generate major element compositions analogous to the rhyolites (Fig. 8). The Dashitou rhyolites have high $\epsilon_{\text{Nd}}(t)$ values (6.21–6.47) and young Nd model ages (0.57–0.58 Ga), which are indistinguishable from the Dashitou basaltic rocks and juvenile crust in the CAOBS, implying that they were probably generated by partial melting of a juvenile crustal source produced by underplating of depleted mantle-derived basaltic magmas. Geochemical diversity of crust-derived melts strongly depend on source compositions and variable melting conditions (e.g., Beard and Lofgren, 1991; Patiño Douce and Beard, 1995). The rhyolites have high Na_2O (4.46–5.15 wt.%) and K_2O (4.73–6.11 wt.%) contents (Fig. 11c, d), compositionally resembling the melts formed by partial melting of middle to high K basaltic rocks (Sisson et al., 2005), which suggests that the assumed underplated mafic magmas share a common parental magma with the Dashitou basaltic rocks.

6.4. Geodynamic implication: Rifting of the Dananhu–Harlik arc

Bimodal volcanic suites usually occur in extensional settings related to intraplate, post-collisional or back-arc rifting tectonic regimes (Pin and Paquette, 1997; Shinjo and Kato, 2000; Li et al., 2002a). Recently, Carboniferous–Permian volcanism in NW China has been recognized as a large igneous province related to a rift system (Che et al., 1996; Xia et al., 2004, 2008). However, the geochemical characteristics of the

Dashitou basalts are different from those of plume-derived basaltic magmas. For instance, their low LREE contents and flat chondrite-normalized REE patterns with negative Nb, Ta and Ti anomalies are in contrast to high LREE contents and strongly fractionated REE patterns without negative Nb, Ta and Ti anomalies shared by plume-derived magmatism. In addition, high temperature is a diagnostic feature discriminating plume-related A-type rhyolites from others (e.g., Yuan et al., 2010). The calculated zircon saturation temperatures ($T_{Zr} = 831\text{--}847\text{ }^{\circ}\text{C}$) following the method of Watson and Harrison, (1983), are remarkably lower than those of A-type granites ($T_{Zr} = 934\text{--}1053\text{ }^{\circ}\text{C}$) associated with the Emeishan plume (Xu et al., 2001) and relatively lower than those of A-type rhyolites ($T_{Zr} = 872\text{--}940\text{ }^{\circ}\text{C}$) related to the Tarim plume (Liu et al., 2014). Moreover, the volcanic rocks in the Bogda mountain erupted over a long period (345–295 Ma; Chen et al., 2011, 2013), which is inconsistent with the rapid eruption rates (over a few million years) for plume-derived magmatism (Campbell, 2005). Therefore, the origin of the Dashitou volcanic rocks may be independent of a mantle plume. In addition, the widespread Carboniferous arc-related volcanic rocks in the Bogda mountain indicate that a post-collisional setting seems unlikely to cause the generation of the Dashitou volcanic rocks.

Accumulating evidence suggests that the Carboniferous bimodal volcanic rocks in the Bogda mountain formed under an extensional regime related to a subduction zone (e.g., back-arc rifting) (Xiao et al., 2004; Chen et al., 2013; Zhao et al., 2014). Indeed, the Dashitou basalts exhibit both arc-like and within-plate basalt affinities, implying that they probably formed within a back-arc tectonic setting. Arc-related

basalts are generally characterized by high water and oxygen fugacity, which can be estimated using some trace element contents. For example, with the increase of oxygen fugacity, partition coefficients of Cr for clinopyroxene and orthopyroxene and that of Ni for olivine increase significantly, while V becomes more incompatible (Ehlers, et al., 1992; Lee et al., 2003; Mallmann and O'Neill, 2009). Therefore, the low Cr (1.8–2.9 ppm) and Ni (1.3–2.0 ppm) but relatively high V (256–284 ppm) contents of the Dashitou basalts reflecting that their parental magmas underwent extensive crystallization of pyroxene and olivine under conditions of high oxygen fugacity. Additionally, the Dashitou basalts display high Al_2O_3 contents and positive Sr and Eu anomalies (Fig. 6b), which could be attributed to hydrous and oxidized magmatic conditions (Drake, 1975; Grove et al., 2002). The Dashitou basalts have relatively high Th but low Ta contents, and plot in the field of calc-alkaline arc basalts on a Hf/3–Th–Ta discrimination diagram (Fig. 12a) (Wood, 1980). On the other hand, they have relatively high Zr contents (~100 ppm) and high Ti/V ratios (39–42), identical to the compositions of basalts formed in a within-plate setting (Fig. 12b, c). Moreover, the Dashitou rhyolites share some characteristics of A_2 -type granites (Fig. 11b), indicative of an extensional setting. Collectively, an extensional tectonism imposed on a subduction zone (e.g., back-arc rifting) could be the most likely process to cause the generation of the Dashishou bimodal volcanic rocks, as documented in the Okinawa Trough behind the Ryukyu arc–trench system (Shinjo and Kato, 2000).

It is, however, still controversial as regards to: how the Bogda back-arc basin is formed, and where the subduction zone is located. Some researchers have suggested

420 that the Harlik–Dananhu arc resulted from the southward subduction of the Junggar
421 ocean represented by the Kelameili ophiolite (Ma et al., 1997; Qin et al., 2002; Chen
422 et al., 2013), while others consider a northward subduction of the northern Tianshan
423 ocean represented by the Kanggurtag suture (Li, 2004; Zhao et al., 2014; Xiao et al.,
424 2015). More and more evidence suggest that the Kelameili ocean only experienced
425 northward subduction beneath the east Junggar, but not southward subduction beneath
426 the Harlik arc. Firstly, contrasting sedimentary sequences on different sides of the
427 Kelameili ophiolite indicate an active continental margin and a passive continental
428 margin for the east Junggar and the Harlik area, respectively. For instance, Devonian
429 to Carboniferous calc-alkaline andesitic–dacitic–rhyolitic volcanic rocks locate to the
430 north-side of this mélange, whereas Devonian to Carboniferous terrigenous clastics
431 (e.g., quartzite- and marble-bearing sandstone) exist to the south-side of this mélange
432 (Li, 2004; Li et al., 2009). Secondly, structural cross-sections along the Hongliugou
433 and Sujiquan areas indicate the south-verging thrusting, consistent with a northward
434 subduction of the Kelameili ocean (Li et al., 2009). Furthermore, seismic receiver
435 function analyses by H.O. Li et al. (2006) show that all deep convertor surfaces below
436 moho in this region tilt northwards, further suggesting a N-dipping subduction.
437 Thirdly, many geochronological and geochemical studies on granites and volcanics in
438 the Kelameili area indicate that the closure of the Kelameili ocean occurred before the
439 late Carboniferous (e.g., Wu et al., 2009; Huang et al., 2012; Tian et al., 2015). For
440 example, Huang et al. (2012) reported a zircon U–Pb age of 343 ± 5 Ma for a tuff
441 sample overlying the Kelameili ophiolite, indicating that the emplacement age of this

ophiolite earlier than late Carboniferous. Wu et al. (2009) obtained a zircon SHRIMP U–Pb age of 350 ± 6 Ma for mafic volcanics overlying the molasse deposits in the Kelameili area, suggesting that this region had entered a post-collisional setting before the end of early Carboniferous. Collectively, it is suggested that the Kelameili ocean had experienced a single northward subduction. Therefore, we speculate that the Harlik–Dananhu arc, together with the Bogda back-arc basin, was unlikely related to the Kelameili ocean. Instead, the northwards subduction of the Northern Tianshan oceanic crust was more likely responsible for the generation of the Dananhu–Harlik arc and the Bogda back-arc basin.

Regional investigation indicates that the Dananhu arc is dominated by Silurian to Carboniferous calc-alkaline volcanic rocks and granitoids, probably produced by N-dipping subduction of the Northern Tianshan oceanic lithosphere (Xiao et al., 2004). The presence of Carboniferous (334–324 Ma) slab-derived adakites and coeval Tuwu porphyry copper deposits in the Dananhu arc strongly suggests an arc-related setting (Han et al., 2006; Zhang et al., 2006; Xiao et al., 2015). In addition, the Re–Os isochron age of 322.7 ± 2.5 Ma for the molybdenite in the Tuwu ore district (Rui et al., 2002), implies that arc magmatism lasted at least until the early Late Carboniferous. Since the Carboniferous, bimodal volcanic rocks began to develop in the Bogda mountain (e.g., Shu et al., 2011; Chen et al., 2013), reflecting a regional extensional tectonism probably associated with the roll-back of the Northern Tianshan oceanic lithosphere. Indeed, the volcanic rocks in the Dananhu arc decrease in age from north to south, consistent with the southward retreat of the subduction zone beneath the

Dananhu arc giving rise to southward younging of the arc magmatism (Xiao et al., 2004). From north to south, the stratigraphy of the Dananhu–Harlik area can be divided into (1) the Harik remnant arc; (2) the Bogda back-arc basin; (3) the Dananhu fore-arc; and (4) the Kanggurtag suture, all of which constitute a volcanic system within the Northern Tianshan ocean. Thus, we speculate that the generation of the Dashitou bimodal volcanic rocks was likely related to the rifting of the Dananhu–Harlik arc triggered by the roll-back of the Northern Tianshan oceanic lithosphere (Fig. 13).

7. Conclusions

The Dashitou volcanic rocks are composed of basalts and rhyolites, exhibiting a bimodal distribution in composition. Zircon U–Pb age of 330 ± 3 Ma indicates that they were extruded during the early Late Carboniferous. Whole-rock geochemical and Sr–Nd isotopic compositions suggest that the parental magma of the Dashitou basalts was derived from a depleted mantle source hybridized by subduction-related fluids. In contrast, the rhyolites were probably generated by partial melting of juvenile basaltic crust. The generation of the Dashitou bimodal volcanic rocks was not related to a plume or post-collisional setting, but rather associated with the rifting of the Dananhu–Harlik arc caused by the retreat of subducting Northern Tianshan oceanic lithosphere.

Acknowledgements

We are grateful to Ms. Shengling Sun, Ying Liu and Guangqian Hu, and Mr. Xianglin Tu, Jinlong Ma and Le Zhang, for their help with the geochemical analyses. We are indebted to two anonymous reviewers, whose insightful and constructive reviews have greatly improved the paper. We thank M. Santosh and Guochun Zhao for their kind and careful editorial help. This work was financially supported by the National Basic Research Program of China (2014CB440801), the National Science Foundation of China (41273012, 41573025, 41273048, 41173005). This work is a contribution to the IGCP 592.

References

- Aydin, F., Schmitt, A.K., Siebel, W., Sönmez, M., Ersoy, Y., Lermi, A., Dirik, K., Duncan, R., 2014. Quaternary bimodal volcanism in the Niğde Volcanic Complex (Cappadocia, central Anatolia, Turkey): age, petrogenesis and geodynamic implications. *Contributions to Mineralogy Petrology* 168, 1–24.
- Beard, J.S., Lofgren, G.E., 1991. Dehydration melting and water-saturated melting of basaltic and andesitic greenstones and amphibolites at 1, 3, and 6, 9 kb. *Journal of Petrology* 32, 365–401.
- Bonnefoi, C.C., Provost, A., Albarède, F., 1995. The ‘Daly gap’ as a magmatic catastrophe. *Nature* 378, 270–272.
- Campbell, I.H., 2005. Large igneous provinces and the mantle plume hypothesis. *Elements* 1, 265–269.
- Che, Z.L., Liu, L., Liu, H.F., Luo, J.H., 1996. Review on the ancient Yili Rift, Xingjiang, China. *Acta Petrologica Sinica* 12, 478–490 (in Chinese with English abstract).
- Chen, X.J., Shu, L.S., Santosh, M., 2011. Late Paleozoic post-collisional magmatism in the Eastern Tianshan Belt, Northwest China: new insights from geochemistry, geochronology and petrology of bimodal volcanic rocks. *Lithos* 127, 581–598.

512 Chen, X.J., Shu, L.S., Santosh, M., Zhao, X.X., 2013. Island arc bimodal magmatism in the
513 Eastern Tianshan Belt, Northwest China: geochemistry, zircon U–Pb geochronology and
514 implications for the Paleozoic crustal evolution in Central Asia. *Lithos* 168–169, 48–66.

515 Chen, X.Y., Wang, Y.J., Sun, L.H., Fan, W.M., 2009. Zircon SHRIMP U–Pb dating of the granitic
516 gneisses from Bingdaban and Laerdundaban (Tianshan Orogen) and their geological
517 significances. *Geochimica* 38, 424–431 (in Chinese with English abstract).

518 Condie, K.C., 2005. High field strength element ratios in Archean basalts: a window to evolving
519 sources of mantle plumes? *Lithos* 79, 491–504.

520 Drake, M.J., 1975. The oxidation state of europium as an indicator of oxygen fugacity.
521 *Geochimica et Cosmochimica Acta* 39, 55–64.

522 Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic
523 implications. *Geology* 20, 641–644.

524 Ehlers, K., Grove, T.L., Sisson, T.W., Recca, S.I., Zervas, D.A., 1992. The effect of oxygen
525 fugacity on the partitioning of nickel and cobalt between olivine, silicate melt, and metal.
526 *Geochimica et Cosmochimica Acta* 56, 3733–3743.

527 Frey, F.A., Green, D.H., Roy, S.D., 1978. Integrated models of basalt petrogenesis: a study of
528 quartz tholeiites to olivine melilitites from South Eastern Australia utilizing geochemical and
529 experimental petrological data. *Journal of Petrology* 19, 463–513.

530 Frost, B.R., Frost, C.D., 2008. On charnockites. *Gondwana Research* 13, 30–44.

531 Gao, J., Li, M.S., Xiao, X.C., Tang, Y.Q., He, G.Q., 1998. Paleozoic tectonic evolution of the
532 Tianshan orogen, northwestern China. *Tectonophysics* 287, 213–231.

533 Gao, J.G., Li, W.Y., Zhou, Y., Liu, J.C., Fan, T.B., Lu, L., Zhou, R.H., 2013. Geochemistry,
534 zircon U–Pb ages and geological significance of the Liushugou Formation rhyolite in the
535 Sepikou region, eastern Bogda, Xinjiang. *Geology and Exploration* 49, 665–675 (in Chinese
536 with English abstract).

537 Gao, J.G., Li, W.Y., Liu, J.C., Gao, Y.X., Guo, X.C., Zhou, Y., Fan, T.B., 2014. Geochemistry,
538 zircon U–Pb age and Hf isotopes of Late Carboniferous rift volcanic in the Sepikou region,
539 eastern Bogda, Xinjiang. *Acta Petrologica Sinica* 30, 3539–3552 (in Chinese with English
540 abstract).

541 Garrison, J.M., Davidson, J.P., 2003. Dubious case for slab melting in the Northern volcanic zone

542 of the Andes. *Geology* 31, 565–568.

543 Ghiorso, M., Sack, R., 1995. Chemical mass transfer in magmatic processes IV. A revised and
 544 internally consistent thermodynamic model for the interpolation and extrapolation of
 545 liquid–solid equilibria in magmatic systems at elevated temperatures and pressures.
 546 *Contributions to Mineralogy and Petrology* 119, 197–212.

547 Green, N.L., 2006. Influence of slab thermal structure on basalt source regions and melting
 548 conditions: REE and HFSE constraints from the Garibaldi volcanic belt, northern Cascadia
 549 subduction system. *Lithos* 87, 23–49.

550 Grove, T.L., Parman, S.W., Bowring, S.A., Price, R.C., Baker, M.B., 2002. The role of H₂O-rich
 551 fluid component in the generation of primitive basaltic andesites and andesites from the Mt.
 552 Shasta region, N California. *Contributions to Mineralogy and Petrology* 142, 375–396.

553 Gu, L.X., Hu, S.X., Yu, C.S., Li, H.Y., Xiao, X.J., Yan, Z.F., 2000. Carboniferous volcanics in
 554 the Bogda orogenic belt of eastern Tianshan: their tectonic implications. *Acta Petrologica*
 555 *Sinica* 16, 305–316 (in Chinese with English abstract).

556 Han, C.M., Xiao, W.J., Zhao, G.C., Mao, J.W., Yang, J.M., Wang, Z.L., Yan, Z., Mao, Q.G., 2006.
 557 Geological characteristics and genesis of the Tuwu porphyry copper deposit, Hami, Xinjiang,
 558 Central Asia. *Ore Geology Reviews* 29, 77–94.

559 Hildreth, W., Halliday, A.N., Christiansen, R.L., 1991. Isotopic and chemical evidence concerning
 560 the genesis and contamination of basaltic and rhyolitic magma beneath the Yellowstone
 561 plateau volcanic field. *Journal of Petrology* 32, 63–138.

562 Hofmann, A.W., 1997. Mantle geochemistry: the message from oceanic volcanism. *Nature* 385,
 563 219–229.

564 Hou, T., Zhang, Z., Santosh, M., Zhu, J., Luo, W.J., 2014. Geochronology and geochemistry of
 565 submarine volcanic rocks in the Yamansu iron deposit, Eastern Tianshan Mountains, NW
 566 China: constraints on the metallogenesis. *Ore Geology Reviews* 56, 487–502.

567 Hu, A.Q., Wei, G.J., Deng, W.F., Zhang, J.B., Chen, L.L., 2006. 1.4 Ga SHRIMP U–Pb age for
 568 zircons of granodiorite and its geological significance from the Eastern segment of the
 569 Tianshan Mountains, Xinjiang, China. *Geochimica* 35, 333–345 (in Chinese with English
 570 abstract).

571 Huang, G., Niu, G.Z., Wang, X.L., Guo, J., Yu, F., 2012. Formation and emplacement age of

572 Karamaili ophiolite: LA-ICP-MS zircon U-Pb age evidence from the diabase and tuff in
573 eastern Junggar, Xinjiang. *Geological Bulletin of China* 31, 1267–1278 (in Chinese with
574 English abstract).

575 Jahn, B.M., Wu, F.Y., Chen, B., 2000. Massive granitoid generation in Central Asia: Nd isotope
576 evidence and implication for continental growth in the Phanerozoic. *Episodes* 23, 82–92.

577 Johnson, K.T.M., 1994. Experimental cpx/ and garnet/melt partitioning of REE and other trace
578 elements at high pressures; petrogenetic implications. *Mineralogy Magazine* 58, 454–455.

579 Kröner, A., Windley, B.F., Badarch, G., Tomurtogoo, O., Hegner, E., Jahn, B.M., Gruschka, S.,
580 Khain, E.V., Wingate, M.T.D., 2007. Accretionary growth and crust formation in the Central
581 Asian Orogenic Belt and comparison with the Arabian–Nubian shield. *Geological Society of
582 America Memoirs* 200, 181–209.

583 La Flèche, M.R., Camire, G., Jenner, G.A., 1998. Geochemistry of post-Acadian, Carboniferous
584 continental intraplate basalts from the Maritimes Basin, Magdalen islands, Quebec, Canada.
585 *Chemical Geology* 148, 115–136.

586 Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of
587 volcanic rocks based on the total alkali–silica diagram. *Journal of Petrology* 27, 745–750.

588 Lee, C.T.A, Brandon, A.D., Norman, M., 2003. Vanadium as a proxy for paleo-fO₂ during partial
589 melting: prospects, limitations and implications. *Geochimica et Cosmochimica Acta* 67,
590 3045–3064.

591 Li, H.O., Jiang, M., Wang, Y.J., Zhang, L.S., Yu, G.X., 2006. Image of Crust and Upper Mantle
592 Structure along the Array from Fuyun to Kuerle by P-to-S Converted Waves. *Acta
593 Geological Sinica* 80, 135–141 (in Chinese with English Abstract).

594 Li, J.Y., 2004. Late Neoproterozoic and Paleozoic tectonic framework and evolution of Eastern
595 Xinjiang, NW China. *Geological Review* 50, 304–322 (in Chinese with English Abstract).

596 Li, J.Y., Yang, T.N., Li, Y.P., Zhu, Z.X., 2009. Geological features of the Karamaili faulting belt,
597 eastern Junggar region, Xinjiang, China and its constraints on the reconstruction of Late
598 Paleozoic ocean-continental framework of the Central Asian region. *Geological Bulletin of
599 China* 28(12), 1817–1826 (in Chinese with English Abstract).

600 Li, W.Q., Ma, H.D., Wang, R., Wang, H., Xia, B., 2008. SHRIMP dating and Nd–Sr isotopic
601 Tracing of Kangguertage ophiolite in eastern Tianshan, Xinjiang. *Acta Petrologica Sinica* 24,

602 773–780 (in Chinese with English abstract).

603 Li, X.H., Li, Z.X., Zhou, H., Liu, Y., Kinny, P.D., 2002a. U–Pb zircon geochronology,
604 geochemistry and Nd isotopic study of Neoproterozoic bimodal volcanic rocks in the
605 Kangdian Rift of South China: implications for the initial rifting of Rodinia. *Precambrian*
606 *Research* 113, 135–154.

607 Li, X.H., Zhou, H., Chung, S.L., Lo, C.H., Wei, G., Liu, Y., Lee, C.Y., 2002b. Geochemical and
608 Sr–Nd isotopic characteristics of late Paleogene ultrapotassic magmatism in southEastern
609 Tibet. *International Geology Review* 44, 559–574.

610 Li, X.H., Li, Z.X., Wingate, M.T.D., Chung, S.L., Liu, Y., Lin, G.C., Li, W.X., 2006.
611 Geochemistry of the 755 Ma Mundine Well dyke swarm, northwestern Australia: part of a
612 Neoproterozoic mantle superplume beneath Rodinia? *Precambrian Research* 146, 1–15.

613 Liu, H.Q., Xu, Y.G., Tian, W., Zhong, Y.T., Mundil, R., Li, X.H., Yang, Y.H., Luo, Z.Y.,
614 Shang-Guan, S.M., 2014. Origin of two types of rhyolites in the Tarim Large Igneous
615 Province: consequences of incubation and melting of a mantle plume. *Lithos* 204, 59–72.

616 Ludwig, K.R., 2003. User's Manual for Isoplot/Ex version 3.00—A Geochronology Toolkit for
617 Microsoft Excel. Berkeley Geochronology Center Special Publication 4, 1–70.

618 Ma, J.C., 1999. Study on the Huangcaopo Group in the Eastern Junggar. *Journal of Mineralogy*
619 *and Petrology* 19, 52–55 (in Chinese with English abstract).

620 Ma, R.S., Shu, L.S., Sun, J.Q., 1997. Tectonic Evolution and Metallization in the Eastern Tianshan
621 Belt, China. Geological Publish House, Beijing. (202 pp., in Chinese with English abstract).

622 Mallmann, G., O'Neill, H.St.C., 2009. The crystal/melt partitioning of V during mantle melting as
623 a function of oxygen fugacity compared with some other elements (Al, P, Ca, Sc, Ti, Cr, Fe,
624 Ga, Y, Zr and Nb). *Journal of Petrology* 50, 1765–1794.

625 Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. *Geological Society of*
626 *America Bulletin* 101, 635–643.

627 Maria, A., Hermes, O.D., 2001. Volcanic rocks in the Narragansett Basin, southeastern New
628 England: petrology and significance to early basin formation. *American Journal of Science*
629 301, 285–312.

630 Mingram, B., Trumbull, R.B., Littman, S., 2000. A petrogenetic study of anorogenic felsic
631 magmatism in the Cretaceous Paresis ring complex, Namibia: evidence for mixing of crust

632 and mantle-derived components. *Lithos* 54, 1–22.

633 Patiño Douce, A.E., Beard, J.S., 1995. Dehydration-melting of biotite gneiss and quartz
634 amphibolite from 3 to 15 kbar. *Journal of Petrology* 36, 707–738.

635 Pearce, J.A., Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in
636 volcanic rocks. *Contributions to Mineralogy and Petrology* 69, 33–37.

637 Pearce, J.A., Stern, J.R., Bloomer, S.H., Fryer, P., 2005. Geochemical mapping of the Mariana
638 arc–basin system: implications for the nature and distribution of subduction components.
639 *Geochemistry Geophysics Geosystems* 6, Q07006. doi:10.1029/2004GC000895.

640 Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite
641 classification and the search for Archean oceanic crust. *Lithos* 100, 14–48.

642 Peccerillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the
643 Kastamonu area, northern Turkey. *Contributions to mineralogy and petrology* 58, 63–81.

644 Peccerillo, A., Barberio, M.R., Yirgu, G., Ayalew, D., Barbieri, M., Wu, T.W., 2003. Relationship
645 between mafic and peralkaline felsic magmatism in continental rift settings: a petrological,
646 geochemical and isotopic study of the Gedemsa Volcano, Central Ethiopian Rift. *Journal of*
647 *Petrology* 44, 2003–2032.

648 Pin, C., Paquette, J.L., 1997. A mantle-derived bimodal suite in the Hercynian belt: Nd isotope
649 and trace element evidence for a subduction-related rift origin of the late Devonian Brevenne
650 metavolcanics, Massif Central (France). *Contributions to mineralogy and petrology* 129,
651 222–238.

652 Qin, K.Z., Sun, S., Li, J.L., Fang, T.H., Wang, S.L., Liu, W., 2002. Paleozoic epithermal Au and
653 porphyry Cu deposits in North Xinjiang, China: epochs, features, tectonic linkage and
654 exploration significance. *Resource Geology* 52, 291–300.

655 Rapp, R.P., Watson, E.B., 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for
656 continental growth and crust–mantle recycling. *Journal of Petrology* 36, 891–931.

657 Rudnick, R.L., Fountain, D.M., 1995. Nature and composition of the continental crust: a lower
658 crustal perspective. *Reviews of Geophysics* 33, 267–309.

659 Rudnick, R.L., Gao, S., 2003. The composition of the continental crust. In: Rudnick, R.L. (Ed.),
660 *The Crust*. Elsevier–Pergamon, Oxford, pp. 1–64.

661 Rui, Z.Y., Goldfarb, R.J., Qiu, Y.M., Zhou, T.M., Chen, R.Y., Pirajno, F., Yun, G., 2002.

662 Paleozoic–early Mesozoic gold deposits of the Xinjiang Autonomous Region, northwestern
 663 China. *Mineralium Deposita* 37, 393–418.

664 Sengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and
 665 Paleozoic crustal growth in Asia. *Nature* 364, 299–307.

666 Shen, P., Pan, H.D., Zhou, T.F., Wang, J.B., 2014. Petrography, geochemistry and geochronology
 667 of the host porphyries and associated alteration at the Tuwu Cu deposit, NW China: a case for
 668 increased depositional efficiency by reaction with mafic hostrock? *Mineralium Deposita* 49,
 669 1–23.

670 Shervais, J.W., 1982. Ti–V plots and the petrogenesis of modern and ophiolitic lavas. *Earth*
 671 *Planetary Science Letter* 59, 101–118.

672 Shi, W.X., Liao, Q.A., Hu, Y.Q., Yang, Z.F., 2010. Characteristics of Mesoproterozoic granites
 673 and their geological significance from Middle Tianshan Block, East Tianshan District, NW
 674 China. *Geological Science and Technology Information* 29, 29–37 (in Chinese with English
 675 abstract).

676 Shinjo, R., Kato, Y., 2000. Geochemical constraints on the origin of bimodal magmatism at the
 677 Okinawa Trough, an incipient back-arc basin. *Lithos* 54, 117–137.

678 Shu, L.S., Wang, B., Zhu, W.B., Guo, Z.J., Charvet, J., Zhang, Y., 2011. Timing of initiation of
 679 extension in the Tianshan, based on structural, geochemical and geochronological analyses of
 680 bimodal volcanism and olistostrome in the Bogda Shan (NW China). *International Journal of*
 681 *Earth Sciences (Geol Rundsch)* 100, 1647–1663.

682 Sisson, T.W., Ratajeski, K., Hankins, W.B., Glazner, A.F., 2005. Voluminous granitic magmas
 683 from common basaltic sources. *Contributions to Mineralogy and Petrology* 148, 635–661.

684 Smith, P.M., Asimow, P.D., 2005. *Adiabat_1ph*: a new public front-end to the MELTS, pMELTS,
 685 and pHMELTS models. *Geochemistry, Geophysics, Geosystems* 6, Q02004.
 686 <http://dx.doi.org/10.1029/2004GC000816>

687 Sun, G.H., Li, J.Y., Wang, D.G., Gao, L.M., Song, A.J., 2006. Zircon SHRIMP U–Pb ages of
 688 granite and granodiorite at the south side of the Aqikkuduk fault, East Tianshan, Xinjiang,
 689 China, and its tectonic implications. *Geological Bulletin of China* 25, 945–952 (in Chinese
 690 with English Abstract).

691 Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts:

implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.),
Magmatism in the Ocean Basin. Geological Society Special Publication, vol. 42. Blackwell
Scientific Publications, pp. 313–346.

Tamura, Y., Tatsumi, Y., 2002. Remelting of an andesitic crust as a possible origin for rhyolitic
magma in oceanic arcs: an example from the Izu–Bonin arc. *Journal of Petrology* 43,
1029–1047.

Tang, G.J., Chung, S.L., Wang, Q., Wyman, D.A., Dan, W., Chen, H.Y., Zhao, Z.H., 2014.
Petrogenesis of a Late Carboniferous mafic dike–granitoid association in the western
Tianshan: response to the geodynamics of oceanic subduction. *Lithos* 202–203, 85–99.

Tang, J.H., Gu, L.X., Zheng, Y.C., Fang, T.H., Zhang, Z.Z., Gao, J.H., Wang, F.T., Wang, C.S.,
Zhang, G.H., 2006. Petrology, geochemistry and genesis of the Na-rich volcanic rocks of the
Kalatag area, eastern Tianshan. *Acta Petrologica Sinica* 22, 1150–1166 (in Chinese with
English abstract).

Tian, J., Liao, Q.A., Fan, G.M., Nie, X.M., Wang, F.M., 2015. The discovery and tectonic
implication of Early Carboniferous post-collisional I-type granites from the south of
Karamaili in eastern Junngar. *Acta Petrologica Sinica* 31, 1471–1484 (in Chinese with
English abstract).

Wang, B., Cluzel, D., Jahn, B.M., Shu, L.S., Chen, Y., Zhai, Y.H., Branquet, Y., Barbanson, L.,
Sizaret, S., 2014. Late Paleozoic pre- and syn-kinematic plutons of the Kangguer–Huangshan
shear zone; Inference on the tectonic evolution of the Eastern Chinese Tianshan. *American
Journal of Science* 314, 43–79.

Wang, Q., Wyman, D.A., Zhao, Z.H., Xu, J.F., Bai, Z.H., Xiong, X.L., Dai, T.M., Li, C.F., Chu,
Z.Y., 2007. Petrogenesis of Carboniferous adakites and Nb-enriched arc basalts in the Alataw
area, northern Tianshan Range (western China): implications for Phanerozoic crustal growth
in the Central Asia orogenic belt. *Chemical Geology* 236, 42–64.

Wang, Y.X., Gu, L.X., Zhang, Z.Z., Wu, C.Z., Li, H.M., Yang, J.D., 2007. Sr–Nd–Pb isotope
geochemistry of Rhyolite of the Late Carboniferous Dashitou group in eastern Tianshan. *Acta
Petrologica Sinica* 23, 1749–1755 (in Chinese with English abstract).

Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition
effects in a variety of crustal magma types. *Earth Planetary Science Letter* 64, 295–304.

722 Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics,
723 discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* 95, 407–419.

724 Windley, B.F., Allen, M.B., Zhang, C., Zhao, Z.Y., Wang, G.R., 1990. Paleozoic accretion and
725 Cenozoic reformation of the Chinese Tien Shan Range, Central Asia. *Geology* 18,
726 128–131.

727 Windley, B.F., Alexeiev, D., Xiao, W.J., Kröner, A., Badarch, G., 2007. Tectonic models for
728 accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society of London*
729 164, 31–47.

730 Wood, D.A., 1980. The application of a Th–Hf–Ta diagram to problems of tectonomagmatic
731 classification and to establishing the nature of crustal contamination of basaltic lavas of the
732 British Tertiary Volcanic Province. *Earth and Planetary Science Letters* 50, 11–30.

733 Wu, F.Y., Sun, D.Y., Li, H.M., Jahn, B.M., Wilde, S., 2002. A-type granites in northEastern China:
734 age and geochemical constraints on their petrogenesis. *Chemical Geology* 187, 143–173.

735 Wu, R.J., Zhang, Y.Y., Tan, J.Y., Guo, Z.J., 2009. The characteristics of different structure layers
736 and tectonic implications since late Paleozoic in Kalamaily Area, Xinjiang. *Earth Science*
737 *Frontiers* 16, 102–109 (in Chinese with English abstract).

738 Xia, L.Q., Xu, X.Y., Xia, Z.C., Li, X.M., Ma, Z.P., Wang, L.S., 2004. Petrogenesis of
739 Carboniferous rift-related volcanic rocks in the Tianshan, northwestern China. *Geological*
740 *Society of America Bulletin* 116, 419–433.

741 Xia, L.Q., Xia, Z.C., Xu, X.Y., Li, X.M., Ma, Z.P., 2008. Relative contributions of crust and
742 mantle to the generation of the Tianshan Carboniferous rift-related basic lavas, northwestern
743 China. *Journal of Asian Earth Sciences* 31, 357–378.

744 Xiao, B., Chen, H.Y., Hollings, P., Han, J.S., Wang, Y.F., Yang, J.T., Cai, K.D., 2015. Magmatic
745 evolution of the Tuwu–Yandong porphyry Cu belt, NW China: Constraints from
746 geochronology, geochemistry and Sr–Nd–Hf isotopes. *Gondwana Research*
747 <http://dx.doi.org/10.1016/j.gr.2015.09.003>.

748 Xiao, W.J., Zhang, L.C., Qin, K.Z., Sun, S., Li, J.L., 2004. Paleozoic accretionary and collisional
749 tectonics of the Eastern Tianshan (China): implications for the continental growth of Central
750 Asia. *American Journal of Science* 304, 370–395.

751 Xiao, W.J., Han, C.M., Yuan, C., Sun, M., Lin, S.F., Chen, H.L., Li, Z.L., Li, J.L., Sun, S., 2008.

752 Middle Cambrian to Permian subduction-related accretionary orogenesis of North Xinjiang,
753 NW China: implications for the tectonic evolution of Central Asia. *Journal of Asian Earth*
754 *Sciences* 32, 102–117.

755 Xiao, W.J., Windley, B.F., Allen, M.B., Han, C.M., 2013. Paleozoic multiple accretionary and
756 collisional tectonics of the Chinese Tianshan orogenic collage. *Gondwana Research* 23,
757 1316–1341.

758 Xu, Y.G., Chung, S.L., Jahn, B.M., Wu, G.Y., 2001. Petrologic and geochemical constraints on
759 the petrogenesis of Permian–Triassic Emeishan flood basalts in southwestern China. *Lithos*
760 58, 145–168.

761 Yan, J., Liu, J.M., Li, Q.Z., Xing, G.F., Liu, X.Q., Xie, J.C., Chu, X.Q., Chen, Z.H., 2015. In situ
762 zircon Hf–O isotopic analyses of late Mesozoic magmatic rocks in the Lower Yangtze River
763 Belt, central Eastern China: Implications for petrogenesis and geodynamic evolution. *Lithos*
764 277, 57–76.

765 Yang, X.K., Tao, H.X., Luo, G.C., Ji, J.S., 1996. Basic features of plate tectonics in Eastern
766 Tianshan of China. *Xinjiang Geology* 25, 1901–1915 (in Chinese with English abstract).

767 Yuan, C., Sun, M., Wilde, S., Xiao, W.J., Xu, Y.G., Long, X.P., Zhao, G.C., 2010. Post-collisional
768 plutons in the Balikun area, East Chinese Tianshan: evolving magmatism in response to
769 extension and slab break-off. *Lithos* 119, 269–288.

770 Zhang, D.Y., Zhou, T.F., Yuan, F., Fiorentini, M.L., Said, N., Lu, Y.J., Pirajno, F., 2013.
771 Geochemical and isotopic constraints on the genesis of the Jueluotage native copper
772 mineralized basalt, Eastern Tianshan, Northwest China. *Journal of Asian Earth Sciences* 73(8),
773 317–333.

774 Zhang, L.C., Xiao, W.J., Qin, K.Z., Zhang, Q., 2006. The adakite connection of the
775 Tuwu–Yandong copper porphyry belt, Eastern Tianshan, NW China: trace element and
776 Sr–Nd–Pb isotope geochemistry. *Mineralium Deposita* 41, 188–200.

777 Zhang, X.H., Zhang, H.F., Tang, Y.J., Wilde, S.A., Hu, Z.C., 2008. Geochemical of Permian
778 bimodal volcanic rocks from Central Inner Mongolia, North China: implication for tectonic
779 setting and Phanerozoic continental growth in Central Asia Orogenic Belt. *Chemical Geology*
780 249, 261–281.

781 Zhang, Y.Y., Sun, M., Yuan, C., Xu, Y.G., Long, X.P., Tomurhuu, D., Wang, C.Y., He, B., 2015a.

Magma mixing origin for high Ba–Sr granitic pluton in the Bayankhongor area, central Mongolia: Response to slab roll-back. *Journal of Asian Earth Sciences* 113, 353–368.

Zhang, Y.Y., Yuan, C., Sun, M., Long, X.P., Xia, X.P., Wang, X.Y., Huang, Z.Y., 2015b. Permian doleritic dikes in the Beishan Orogenic Belt, NW China: Asthenosphere–lithosphere interaction in response to slab break-off. *Lithos* 233, 174–192.

Zhao, T.Y., Xu, S.Q., Zhu, Z.X., Liu, X., Chen, C., 2014. Geological and Geochemical Features of Carboniferous Volcanic Rocks in Bogda–Harlik Mountains, Xinjiang and Their Tectonic Significances. *Geological Review* 60, 115–124 (in Chinese with English abstract).

Zhu, Y.F., Guo, X., Song, B., Zang, L.F., Gu, L.B., 2009. Petrology, Sr–Nd–Hf isotopic geochemistry and zircon chronology of the Late Palaeozoic volcanic rocks in the southwestern Tianshan Mountains, Xinjiang, NW China. *Journal of the Geological Society, London* 166, 1085–1099.

Figure captions:

Fig. 1. (a) Simplified tectonic map of the CAOBS (modified after Jahn et al., 2000). (b) Sketch map of northern Xinjiang (modified after Zhang et al., 2015b). (c) Tectonic map of the Eastern Tianshan (modified after Xiao et al., 2004).

Fig. 2. Tectonic map of the Bogda mountains (modified after Zhao et al., 2014). The U–Pb ages of 345 Ma for Qijiaoqing volcanics and 315 Ma for Sepikou volcanics are from Chen et al. (2013) and Gao et al. (2014), respectively.

Fig. 3. Photographs of outcrops and photomicrographs showing the geological and mineralogical characteristics of the Dashitou bimodal volcanic rocks: (a) and (b) for the basaltic rocks, (c) and (d) for the rhyolitic rocks.

807

808 Fig. 4. LA-ICPMS zircon U–Pb concordia diagram for rhyolitic rocks (sample
809 ET4QJ22).

810

811 Fig. 5. (a) Total alkali–silica (TAS) diagram (after Le Bas et al., 1986). (b) SiO_2 – K_2O
812 compositions of the Dashitou volcanic rocks (after Peccerillo and Tayler, 1976). (c)
813 $\text{FeO}^{\text{T}}/(\text{FeO}^{\text{T}} + \text{MgO})$ versus SiO_2 plot (after Frost and Frost, 2008). (d) A/NK versus
814 A/CNK diagram (after Maniar and Piccoli, 1989).

815

816 Fig. 6. (a) Chondrite-normalized REE patterns and (b) primitive mantle-normalized
817 multi-element diagrams. Normalizing values from Sun and McDonough (1989).

818

819 Fig. 7. $\varepsilon_{\text{Nd}}(t)$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram for the Dashitou volcanic rocks in the Eastern
820 Tianshan. Data for 345 Ma bimodal volcanic rocks are from Chen et al. (2013).

821

822 Fig. 8. Binary diagrams of major oxides vs. SiO_2 for the Dashitou volcanic rocks. The
823 green lines represent results of fractional crystallization using MELTS (Ghiorso and
824 Sack, 1995). Models assuming a starting composition of ET4QJ10, at water content of
825 1 wt.%, pressure of 3 kbar and $f\text{O}_2 = \text{NNO}+1$.

826

827 Fig. 9. Binary diagrams of isotope, element and elemental ratios of the Dashitou
828 volcanic rocks from the Eastern Tianshan.

829

830 Fig. 10. (a) Zr/Y vs. Nb/Y plot for the basaltic rocks (after Condie, 2005). (b) Th/Yb
831 vs. Nb/Yb diagram for the basaltic rocks (after Pearce, 2008). (c) Plot of $(\text{Hf/Sm})_N$ vs.
832 $(\text{Ta/La})_N$ for the basaltic rocks (after La Flèche et al., 1998). (d) Plot of Gd/Yb vs.
833 Dy/Yb for the basaltic rocks (after Tang et al., 2014)

834

835 Fig. 11. (a) $(\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$ vs. $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ diagram (after Whalen et al.,
836 1987); FG represents fractionated felsic granite; OGT represents unfractionated M-, I-
837 and S-type granite; (b) diagram discriminating anorogenic (A_1) and post-collisional
838 (A_2) granite (after Eby, 1992). (c) and (d) plots of SiO_2 vs. Na_2O and K_2O for the
839 rhyolitic rocks compared with experimental melts; Data sources of experimental melts
840 are from Beard and Lofgren, (1991) (amphibolite: 1, 3, 6, 9 kb; 800–1000 °C), Rapp
841 and Watson, (1995) (metabasalt; 8–32 kb; 1000–1125 °C), Patiño Douce and Beard
842 (1995), (quartz amphibolite and quartz gneiss; 3–15 kb; 850–930 °C) and Sisson et al.
843 (2005) (medium to high K basaltic rocks; 700 Mpa; 825–975 °C).

844

845 Fig. 12. Discrimination diagrams for the Dashitou basaltic rocks from the Eastern
846 Tianshan. (a) Plot of Hf/3–Th–Ta (after Wood, 1980). (b) diagram of Zr–Zr/Y (after
847 Pearce and Norry, 1979). (c) Plot of Ti/1000 vs. V; the fields of MORB, IAT, BABB
848 and OIB are from Shervais, (1982).

849

850 Fig. 13. A schematic diagram for the Carboniferous tectonic evolution of the Eastern

851 Tianshan. Northwards subduction of the Northern Tianshan oceanic lithosphere gave
852 rise to the Dananhu–Harlik arc. Arc rifting as a result of slab roll-back produced the
853 Dashitou bimodal volcanic rocks and the Tuwu porphyry copper deposit.
854

855

856

857

858

859

860

861

862

863

864

865

866

867

868

869

870

871

872

873

874

875

876

Carboniferous (345-330 Ma)

878
879

880 **Table 1** Major oxides (wt.%) and trace elements (ppm) abundances of the bimodal volcanic rocks
881 in the Dashitou area from the Eastern Tianshan, NW China.

Sample	Basalt								Rhyolite	
	ET4QJ10	ET4QJ11	ET4QJ12	ET4QJ13	ET4QJ14	ET4QJ15	ET4QJ16	ET4QJ18	ET4QJ23	ET4QJ24
Major oxides (wt.%)										
SiO ₂	49.7	51.9	52.0	49.8		52.7	50.9	51.2	68.0	69.0
TiO ₂	1.70	1.75	1.89	1.85		1.82	1.80	1.81	0.68	0.62
Al ₂ O ₃	16.5	16.6	16.7	16.5		16.3	16.3	16.4	15.7	15.0
Fe ₂ O ₃ ^T	10.8	10.8	10.4	11.2		10.3	12.3	12.4	3.33	2.85
MnO	0.20	0.18	0.20	0.22		0.23	0.20	0.20	0.09	0.14
MgO	4.56	3.99	4.45	4.63		4.16	4.01	3.91	0.25	0.34
CaO	8.40	8.46	7.43	7.94		7.14	7.98	7.54	0.77	0.77
Na ₂ O	3.71	3.63	3.27	3.71		3.66	3.73	3.67	5.15	4.54
K ₂ O	0.69	0.64	0.94	0.76		0.76	0.71	0.71	5.28	5.07
P ₂ O ₅	0.32	0.32	0.32	0.33		0.34	0.33	0.32	0.09	0.08
L.O.I	2.71	1.79	2.41	2.67		2.08	1.20	1.41	0.72	0.94
Total	99.3	100.0	99.9	99.7		99.6	99.4	99.6	100.0	99.3
Trace elements (ppm)										
Sc	31.5	31.3	31.9	32.6	32.4	32.0	32.5	30.7	6.85	7.54
V	275	256	260	273	263	265	284	269	25.3	22.5
Cr	2.38	2.90	2.27	1.82	2.21	2.20	2.35	2.24	6.13	3.77
Co	28.5	26.6	27.9	28.8	28.9	28.8	28.2	26.8	1.21	1.35
Ni	1.84	1.47	1.54	1.54	1.34	1.97	1.57	1.48	0.98	1.42
Cu	13.6	14.6	14.0	14.0	14.5	16.5	13.8	13.4	4.72	5.37
Zn	107	105	106	110	108	113	101	97.2	103	72.9
Ga	20.9	20.5	19.9	20.9	18.3	18.9	20.5	18.9	17.1	17.2
Ge	2.96	2.75	2.54	2.86	2.34	2.68	2.95	2.95	2.41	2.21
Rb	9.36	6.91	13.1	10.9	8.48	11.3	9.04	8.60	97.9	100
Sr	799	734	718	791	668	672	589	606	133	130
Y	26.0	25.5	25.8	26.8	26.1	26.5	27.2	25.2	34.8	38.8
Zr	95.7	94.3	95.6	98.9	99.6	99.1	98.3	93.3	333	327
Nb	2.87	2.80	2.84	2.99	3.00	3.00	2.98	2.85	12.9	12.7
Cs	0.18	0.17	0.25	0.23	0.23	0.26	0.21	0.22	1.96	4.43
Ba	350	270	436	391	366	529	341	350	1139	1236
La	11.0	10.5	10.7	11.2	11.3	11.5	11.2	10.6	40.5	39.2
Ce	27.4	26.0	26.6	27.7	28.2	28.4	27.8	26.3	94.8	92.8
Pr	4.08	3.96	4.00	4.17	4.27	4.27	4.17	3.92	12.0	11.8
Nd	19.8	19.3	19.5	20.2	20.6	20.5	20.5	19.0	47.9	46.8
Sm	5.30	5.13	5.20	5.43	5.48	5.41	5.48	5.11	9.56	9.43
Eu	1.83	1.80	1.84	1.91	1.89	1.87	1.88	1.79	2.48	2.48
Gd	5.23	5.12	5.15	5.39	5.41	5.43	5.40	5.05	8.05	8.02
Tb	0.87	0.85	0.86	0.90	0.89	0.90	0.92	0.85	1.22	1.24
Dy	5.21	5.07	5.13	5.40	5.31	5.35	5.43	5.07	6.93	7.25
Ho	1.07	1.05	1.06	1.10	1.10	1.11	1.11	1.04	1.40	1.50
Er	2.90	2.78	2.84	3.00	2.97	3.01	3.04	2.82	3.88	4.21
Tm	0.43	0.41	0.41	0.44	0.43	0.44	0.44	0.42	0.59	0.65
Yb	2.61	2.53	2.58	2.69	2.69	2.71	2.75	2.57	3.78	4.12
Lu	0.40	0.39	0.40	0.42	0.42	0.42	0.42	0.40	0.60	0.64
Hf	2.82	2.74	2.81	2.90	2.93	2.91	2.88	2.74	8.32	8.03
Ta	0.19	0.19	0.19	0.20	0.21	0.20	0.21	0.19	0.78	0.75
Pb	3.50	3.14	2.42	5.32	2.40	2.97	3.13	2.71	12.55	7.17
Th	1.09	1.05	1.07	1.13	1.13	1.14	1.10	1.08	7.79	7.64
U	0.57	0.47	0.53	0.55	0.43	0.49	0.42	0.41	2.77	2.63
Mg#	49.6	46.3	49.8	49.0		48.4	43.1	42.4	15.0	21.9

Mg#=100*Mg/(Mg+Fe²⁺), assuming Fe²⁺/Fe^{total}=0.85; LOI=loss of ignition; Fe₂O₃^T=total Fe oxides as Fe₂O₃.

Table 1 (Continued)

Sample	Rhyolite			
	ET4QJ25	ET4QJ26	ET4QJ27	ET4QJ28
SiO ₂	68.2	68.0	70.0	71.2
TiO ₂	0.64	0.60	0.63	0.58
Al ₂ O ₃	15.7	15.2	14.9	14.7
Fe ₂ O ₃ T	2.82	3.36	2.31	2.52
MnO	0.05	0.19	0.11	0.05
MgO	0.23	0.52	0.34	0.20
CaO	0.60	0.68	0.78	0.69
Na ₂ O	4.46	4.54	4.67	4.79
K ₂ O	6.11	5.29	5.10	4.73
P ₂ O ₅	0.07	0.07	0.04	0.07
L.O.I	0.89	1.14	0.91	0.63
Total	99.8	99.6	99.8	100.1
Sc	6.06	7.48	8.02	6.96
Ti	3755	3764	3848	3655
V	23.7	27.2	28.4	21.5
Cr	4.24	3.56	5.98	4.36
Mn	325	1492	812	318
Co	1.12	1.90	1.22	1.22
Ni	1.29	1.20	1.26	1.02
Cu	4.09	5.06	5.24	5.06
Zn	75.1	91.1	76.1	67.3
Ga	15.1	20.1	16.9	15.4
Ge	1.80	2.36	2.48	2.22
Rb	117	103	103	87.6
Sr	123	123	131	111
Y	48.4	33.1	34.4	32.9
Zr	284	313	324	292
Nb	12.3	12.5	12.6	11.5
Cs	3.03	1.93	2.38	1.75
Ba	1262	1253	1242	1043
La	40.2	43.9	43.5	42.0
Ce	79.4	95.5	95.0	92.3
Pr	9.75	11.6	12.2	11.5
Nd	38.1	45.4	47.5	45.2
Sm	7.34	9.07	9.36	8.90
Eu	2.26	2.39	2.41	2.38
Gd	7.48	7.74	7.85	7.45
Tb	1.16	1.18	1.20	1.13
Dy	7.11	6.81	7.01	6.37
Ho	1.58	1.36	1.42	1.29
Er	4.47	3.73	4.00	3.57
Tm	0.64	0.57	0.62	0.56
Yb	3.80	3.68	3.99	3.51
Lu	0.60	0.57	0.63	0.56
Hf	7.66	7.94	8.03	7.11
Ta	0.74	0.75	0.75	0.69
Pb	9.13	9.98	9.61	10.3
Th	7.25	7.66	7.57	6.94
U	2.15	3.07	2.74	2.77
Mg#	15.8	26.7	25.8	15.4

886
887

Table 2. Sm-Nd and Rb-Sr isotopic analytical results of the bimodal volcanic rocks in the Dashitou area from the Eastern Tianshan, NW China.

Sample	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	εNd(t)
ET4QJ10	9.36	799	0.0339	0.703742	0.000007	0.703582	5.30	19.8	0.1617	0.512906	0.000005	0.512556	6.70
ET4QJ11	6.91	734	0.0273	0.703673	0.000008	0.703545	5.13	19.3	0.1612	0.512918	0.000006	0.512570	6.97
ET4QJ15	11.3	672	0.0485	0.704091	0.000007	0.703863	5.41	20.5	0.1596	0.512907	0.000004	0.512563	6.82
ET4QJ16	9.04	589	0.0444	0.703750	0.000007	0.703542	5.48	20.5	0.1618	0.512924	0.000004	0.512574	7.05
ET4QJ25	117	123	2.7630	0.714424	0.000010	0.701446	7.34	38.1	0.1164	0.512783	0.000005	0.512531	6.21
ET4QJ26	103	123	2.4412	0.713437	0.000007	0.701970	9.07	45.4	0.1208	0.512806	0.000005	0.512545	6.47
ET4QJ27	103	131	2.2737	0.712881	0.000006	0.702202	9.36	47.5	0.1190	0.512796	0.000006	0.512539	6.37

Carboniferous (345-330 Ma)