The role of subduction channel mélanges and convergent subduction systems in the petrogenesis of post-collisional K-rich mafic magmatism in NW Tibet

Zhengfu Guo a,⁎, Marjorie Wilson b, Lihong Zhang a, Maoliang Zhang a, Zhihui Cheng a, Jiaqi Liu a

a Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China
b School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

A R T I C L E   I N F O

Article history:
Received 27 June 2013
Accepted 16 March 2014
Available online 29 March 2014

Keywords:
Potassic-rich magmatic rocks
Subduction channel
Enriched asthenospheric mantle source
Plateau uplift
Northwest Tibet

A B S T R A C T

Post-collisional potassium-rich mafic magmatism occurred in the northwestern part of the Tibetan Plateau, close to the western syntaxis of the Himalayan orogen, from 8.3 Ma to the present. This magmatism is associated with a tectonic setting influenced by opposing N and S dipping subduction systems formed during the collision of India and Asia. It postdates continent–continent collision and has been linked to the onset of near vertical subduction of Indian continental lithosphere at ~8 Ma. The magmatic rocks have relatively high MgO (4.02–9.04 wt.%), SiO2 (46.15–57.49 wt.%), K2O (3.26–7.23 wt.%), Ba (1071–3210 ppm), Th (8.2–85.2 ppm), and Pb (18.6–54.8 ppm) contents, and relatively low Al2O3 (12.74–15.78 wt.%), Sr–Nd–Pb isotopic compositions range from: (87Sr/86Sr)i (0.7072–0.7131), (143Nd/144Nd)i (0.511953–0.512528) and (206Pb/204Pb)i (18.67–19.08). Chondrite-normalized rare earth element (REE) patterns are characterized by light REE (LREE) enrichment, flat heavy REE (HREE) patterns and slightly negative Eu anomalies in some of the magmatic rocks. Primitive mantle-normalized incompatible element patterns display strong enrichments in large ion lithophile elements (LILE) relative to high field strength elements (HFSE) and distinct negative Ta–Nb–Ti anomalies. The major and trace element and Sr–Pb isotope characteristics of the most primitive mafic igneous rocks are interpreted in terms of a mantle source region dominated by subduction channel-derived mélangé material derived from both the Indian and Asian subduction systems. This mélangé material was underplated below the lithosphere of the Songpan-Ganzi terrane of NW Tibet, probably within the past 25 Ma. Partial melting of the underplated mélangé was induced by adiabatic decompression linked to the onset of near vertical subduction of the Indian slab at ~8 Ma.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Post-collisional potassic magmatism has occurred within the Tibetan Plateau over an extended period from 50 to 8 Ma (e.g. Arnaud et al., 1992; Chen et al., 2010; Chung et al., 2005; Deng, 1998; Ding et al., 2003; Guo et al., 2006, 2013; Roger et al., 2000; Turner et al., 1993, 1996; Wang et al., 2010; Williams et al., 2004; Zhao et al., 2009). Understanding the petrogenesis of this magmatism may provide important constraints on the history and mechanism of Plateau uplift (e.g. Arnaud et al., 1992; Chung et al., 2005; Cooper et al., 2002; Deng, 1998; Ding et al., 2003, 2007; Guo et al., 2006; Mo et al., 2006; Pearce and Mei, 1988; Roger et al., 2000; Turner et al., 1993, 1996; Wang et al., 2008, 2010, 2012; Williams et al., 2004; Zhang et al., 2008). Uplift of the Tibetan Plateau has been linked to a decrease in atmospheric CO2 concentrations over the past ~40 Myr and to global cooling in Cenozoic times (Dupont-Nivet et al., 2007; Garzione, 2008; Raymo and Ruddiman, 1992).

Potassic magmatic rocks with ages ranging from 8 to 0 Ma (including the only active volcano, Ashi) are mainly limited to the northwestern part of the Plateau, to the east of the western syntaxis of the India-Eurasia collision zone (Fig. 1), which is thought to be one of the most active areas of continental lithospheric subduction and intermediate-depth seismicity in the world (e.g. Negredo et al., 2007). Although there have been previous studies of these post-collisional magmatic rocks (e.g., Arnaud et al., 1992; Cooper et al., 2002; Guo et al., 2006; Turner et al., 1993, 1996; Williams et al., 2004; Zhang et al., 2008), their petrogenesis is still poorly understood. Compared with studies of the post-collisional magmatism in other areas of the Plateau, there is relatively little published geochemical data for the K-rich rocks in northwestern Tibet, because of their inaccessibility and high altitude (more than 4500 m on average). Moreover, most of the previously studied samples were of evolved magmatic rocks, the parental magmas of which have undergone combined crustal contamination and fractional crystallization (AFC; Guo et al., 2006), making it difficult to constrain the nature of their mantle source. The lack of detailed field, petrological
and geochemical data for primitive mafic K-rich volcanic rocks has thus far precluded further constraints on the characteristics of their mantle source region, petrogenesis and geodynamic setting.

This study focuses on a region of post-collisional K-rich mafic magmatism in NW Tibet located between a zone of northward subducting Indian continental lithosphere and southward subducting Asian lithosphere for which the geodynamic setting, though complex, is well constrained by geological and geophysical data (Fig. 2). We report bulk-rock major and trace element and Sr–Nd–Pb isotope data which, combined with previously published geochemical and geophysical data, allow us to develop a robust petrogenetic model for post-collisional magmatism located between converging continental subduction systems.

2. Geological setting

The Tibetan Plateau is a collage of four east–west-trending allochthonous terranes: the Tarim, Songpan-Ganzi, Qiangtang and Lhasa terranes from north to south (Fig. 1a). The post-collisional K-rich mafic magmatic rocks which are the focus of this study are located in the western parts of the Tarim and Songpan-Ganzi terranes in the northwestern Tibetan Plateau, close to the western syntaxis of the India-Eurasia collision zone (Fig. 1). Previous studies (e.g. Negredo et al., 2007) have suggested that the Indian plate continued its northward motion subsequent to India-Asia collision at ~55 Ma (Fig. 2a, b); following inferred slab break-off at ~44–48 Ma Indian continental lithosphere then began to subduct steeply beneath the northwestern part of the Tibetan Plateau from ~8 Ma (Fig. 2c). Geological and geophysical studies (Burtman and Molnar, 1993; Negredo et al., 2007; Searle et al., 2011; Zhao et al., 2010, 2011) indicate a relatively shallow-dipping (~45°) southward subduction of Asian continental lithosphere beneath NW Tibet since ~25 Ma (Fig. 2b, c). The post-collisional K-rich mafic magmatic rocks studied here are thus located between a zone of northward subducting Indian continental lithosphere and southward subducting Asian lithosphere (Fig. 2c).

The age of the magmatism ranges from 8.3 Ma to A.D. 1951 (Supplementary Data Table A.1 and Fig. 3). The magmatic activity is the youngest and highest in the Tibetan Plateau; most of the volcanic fields are located above 4500 m on average (Guo et al., 2006; Liu, 1999). Nine K-rich volcanic fields, including the Ashikule volcanic field in which the only known active volcano Ashi is located (Supplementary Data Table A.1 and Fig. 1), form the basis of this study. They include lava flows, cinder cones, scoria cones, plugs and dykes. Ashi last erupted in A.D. 1951 and has a well-preserved cinder cone and very fresh lava flows (Guo et al., 2006; Liu, 1999). Magmatism is closely associated with a series of strike-slip faults (Fig. 1). Exposures of volcanic rocks range from less than 1 km² to 360 km². The Dahongliutan and Kangxiwa volcanic fields have the smallest exposed areas of 1–2 km², whereas the Quanshuigou and Heishibei volcanic fields have the largest exposed areas of 220–360 km². Lava flow thicknesses vary from ~100 m in the Quanshuigou volcanic field to less than 20 m in the Kangxiwa volcanic field. We have sub-divided the volcanic fields into three sub-groups based upon their geochemical characteristics and petrography (Fig. 1): (1) a southern sub-group (including the Tianshuihai, Quanshuigou, Keliya and Heishibei volcanic fields), (2) a central sub-group (including

![Fig. 1.](image-url)
the Ashikule, Qitaidaban and Dahongliutan volcanic fields), and (3) a northern sub-group (including the Kangxiwa and Pulu volcanic fields).

3. Petrography

The studied samples are from small volume dykes, cinder cones, plugs and lava flows (Table 1). They have porphyritic textures with phenocrysts (Fig. 4) of clinopyroxene, phlogopite, amphibole, plagioclase, and rare olivine; the groundmass includes phlogopite, clinopyroxene, olivine, sanidine, plagioclase, biotite, amphibole, apatite, Fe–Ti oxides, zircon and glass (Table 1). Phenocrysts are up to 0.2 mm–4 mm in size. All of the analyzed samples are petrographically fresh and show no evidence of significant hydrothermal alteration or weathering.

4. Analytical methods

4.1. Whole rock major and trace element analyses

Samples 4–5 kg in weight were cut into several thin slices. Fresh slices were cleaned three times using deionized water, dried, and then
crushed in an agate mortar in preparation for whole-rock major element, trace element and Sr–Nd–Pb isotope analysis.

Whole-rock major element contents (wt%) were determined on fused glass disks by X-ray fluorescence (XRF) using an XRF-1500 sequential spectrometer (SHIMADZU, Japan) at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing (IGGCAS). Sample powders (0.6 g) were fused with Li2B4O7 (6 g) in a TR-1000S automatic bead fusion furnace (SHIMADZU, Japan) at 1100 °C for 10 min. Loss on ignition (LOI) was determined by ignition of 2 g whole-rock powder at 1100 °C for 10 h. The analytical precision was better than 2% relative. The detailed analytical procedures follow those reported by Guo et al. (2006). Representative analytical data for the most primitive samples (SiO2 < 50 wt%; MgO > 6 wt%) are presented in Table 2; the complete data is provided in Supplementary Data Table A2.

Rare earth element (REE) and trace element contents were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at IGGCAS. Whole-rock powders (60 mg) were spiked with mixed isotope tracers (87Sr/86Sr for Rb–Sr isotope analyses and 143Nd/144Nd for Sm–Nd isotope analyses), then dissolved with a mixed acid (HF:HClO4 = 3:1) in Teflon capsules for 7 days at room temperature. Rb and Sr and rare earth element (REE) fractions were separated in solution using AG50W × 8 (H+) cationic exchange resin columns. Sm and Nd fractions were evaporated and dissolved in 2% HNO3 to give solutions for analysis by mass spectrometry. The mass fractionation corrections for Sr and Nd isotopic ratios were based on 86Sr/88Sr = 0.1194 and 146Nd/144Nd = 0.7219, respectively. The international standard NBS987 gave 87Sr/86Sr = 0.710254 ± 16 (n = 8, 2 sigma) (the recommended value is 0.710240) and international standard NBS607 gave 86Sr/88Sr = 0.119753 ± 27 (n = 12) (the recommended value is 0.119426). The whole procedure blank is less than 2 × 10−11 g for Rb–Sr isotopic analysis and 5 × 10−11 g for Sm–Nd isotopic analysis. Analytical errors for Sr and Nd isotopic ratios are given as 2 sigma (2σ) in Table 3. The 87Rb/86Sr and 147Sm/144Nd ratios were calculated using the Rb, Sr, Sm and Nd concentrations obtained by ICP-MS. The initial 87Sr/86Sr and 143Nd/144Nd ratios were calculated using the average ages of the samples based on 40Ar/39Ar, K–Ar dating and other analytical methods (Supplementary Data Table A1).

For whole-rock Pb isotope measurements, in order to minimize contamination from the atmosphere during the crushing process, 100 mesh powders of samples were used. 150 mg whole-rock powder was weighed and dissolved in Teflon capsules using concentrated HF at 120 °C for 7 days. Pb was separated from the silicate matrix and purified using ACI × 8 anionic ion-exchange columns with dilute HBr as eluant. The whole procedure blank is less than 1 ng. During the period of analysis repeat analyses of the international standard NBS981 yielded 206Pb/204Pb = 0.463399 ± 0.000055 (n = 6, 2 sigma) (the certified value is 0.463485). 207Pb/204Pb = 0.710255 ± 0.000001 (n = 6) (the certified value is 0.710279). The whole procedure blank is less than 1 ng. During the period of analysis the most representative sample pairs of NBS981 have shown error of 0.000001 (0.01%). The whole procedure blank is less than 1 ng.

5. Results

All of the post-collisional K-rich mafic magmatic rocks studied have relatively high MgO (4.02–9.04 wt %) contents, Mg-numbers (0.56–
from 1 to 2. Their compositions in an Na2O+K2O+SiO2 class of magma show that the studied samples plot in the
agram lie almost totally within the trachybasalt
eralies and positive anomalies in the large ion lithophile elements (LILE)
Table 1
<table>
<thead>
<tr>
<th>Field no.</th>
<th>Sample no.</th>
<th>Field name</th>
<th>Faces</th>
<th>Mg-no.</th>
<th>Phenocrysts</th>
<th>Groundmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CT09</td>
<td>Tianshuai</td>
<td>Lava flow</td>
<td>0.65</td>
<td>Cpx + Pl + Bi + Fe–Ti</td>
<td>Pl + Sani + Bi + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>1 CT12</td>
<td>Tianshuai</td>
<td>Lava flow</td>
<td>0.65</td>
<td>Pl + Ol + Cpx</td>
<td>Cpx + Sani + Bi + Pl</td>
<td></td>
</tr>
<tr>
<td>1 CT17</td>
<td>Tianshuai</td>
<td>Lava flow</td>
<td>0.64</td>
<td>Pl + Cpx + Pl</td>
<td>Sani + Bi + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>1 CT05</td>
<td>Tianshuai</td>
<td>Lava flow</td>
<td>0.67</td>
<td>Cpx + Pl + Ol</td>
<td>Cpx + Sani + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>1 CT23</td>
<td>Tianshuai</td>
<td>Dyke</td>
<td>0.66</td>
<td>Pl + Phl + Cpx</td>
<td>Pl + Sani + Bi + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>2 QS12</td>
<td>Quanshuigou</td>
<td>Lava flow</td>
<td>0.60</td>
<td>Pl + Cpx + Phl</td>
<td>Pl + Cpx + Sani + Ol + Ap + Pl</td>
<td></td>
</tr>
<tr>
<td>2 QS27</td>
<td>Quanshuigou</td>
<td>Lava flow</td>
<td>0.60</td>
<td>Ol + Cpx + Phl</td>
<td>Pl + Cpx + Sani + Bi + G</td>
<td></td>
</tr>
<tr>
<td>2 QS19</td>
<td>Quanshuigou</td>
<td>Lava flow</td>
<td>0.59</td>
<td>Pl + Cpx + Phl</td>
<td>Cpx + Sani + Pl + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>2 QS23</td>
<td>Quanshuigou</td>
<td>Lava flow</td>
<td>0.63</td>
<td>Ol + Cpx + Pl + Ap</td>
<td>Cpx + Sani + Pl + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>2 QS18</td>
<td>Quanshuigou</td>
<td>Lava flow</td>
<td>0.63</td>
<td>Ol + Cpx + Pl + Bi</td>
<td>Cpx + Sani + Pl + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>2 QS24</td>
<td>Quanshuigou</td>
<td>Lava flow</td>
<td>0.64</td>
<td>Ol + Cpx + Phl</td>
<td>Pl + Cpx + Sani + Ol + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>3 KY03</td>
<td>Keliya</td>
<td>Plug</td>
<td>0.65</td>
<td>Cpx + Ol + Pl + Bi</td>
<td>Cpx + Am + Pl</td>
<td></td>
</tr>
<tr>
<td>3 KY02</td>
<td>Keliya</td>
<td>Dyke</td>
<td>0.60</td>
<td>Sani + Pl + Bi + Am</td>
<td>Pl + Cpx + Sani + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>3 KY06</td>
<td>Keliya</td>
<td>Dyke</td>
<td>0.64</td>
<td>Cpx + Pl + Bi</td>
<td>Pl + Bi + Sani + Ap + Qz</td>
<td></td>
</tr>
<tr>
<td>3 KY01</td>
<td>Keliya</td>
<td>Plug</td>
<td>0.65</td>
<td>Cpx + Pl + Bi + Am</td>
<td>Pl + Sani + Am + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>4 HS041</td>
<td>Heishibi</td>
<td>Lava flow</td>
<td>0.59</td>
<td>Cpx + Pl + Ol + Am</td>
<td>Cpx + Pl + Sani + Ol + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>4 HS046</td>
<td>Heishibi</td>
<td>Lava flow</td>
<td>0.56</td>
<td>Cpx + Pl + Am</td>
<td>Pl + Sani + Am + Tit + G</td>
<td></td>
</tr>
<tr>
<td>4 HS047</td>
<td>Heishibi</td>
<td>Lava flow</td>
<td>0.57</td>
<td>Cpx + Pl + Ol + Am</td>
<td>Cpx + Pl + Sani + Bi + Ap</td>
<td></td>
</tr>
<tr>
<td>4 HS028</td>
<td>Heishibi</td>
<td>Lava flow</td>
<td>0.61</td>
<td>Cpx + Pl + Sani + Fe–Ti</td>
<td>Cpx + Pl + Sani + Am + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>5 AH607</td>
<td>Ashikule</td>
<td>Lava flow</td>
<td>0.63</td>
<td>Cpx + Pl</td>
<td>Cpx + Pl + Sani + Bi + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>5 AH605</td>
<td>Ashikule</td>
<td>Lava flow</td>
<td>0.65</td>
<td>Cpx + Pl + Sani + Fe–Ti</td>
<td>Pl + Sani + Bi + Am + G</td>
<td></td>
</tr>
<tr>
<td>5 AH609</td>
<td>Ashikule</td>
<td>Plug</td>
<td>0.64</td>
<td>Pl + Bi + Sani + Fe–Ti</td>
<td>Cpx + Pl + Sani + Am</td>
<td></td>
</tr>
<tr>
<td>5 AH602</td>
<td>Ashikule</td>
<td>Lava flow</td>
<td>0.68</td>
<td>Cpx + Pl + Phl + Ol</td>
<td>Cpx + Pl + Sani + Ap + G</td>
<td></td>
</tr>
<tr>
<td>5 AH618</td>
<td>Ashikule</td>
<td>Lava flow</td>
<td>0.68</td>
<td>Cpx + Pl + Ol + Am</td>
<td>Pl + Sani + Bi + Am + Qz + G</td>
<td></td>
</tr>
<tr>
<td>5 AH615</td>
<td>Ashikule</td>
<td>Lava flow</td>
<td>0.68</td>
<td>Cpx + Pl + Phl</td>
<td>Cpx + Pl + Sani + Fe–Ti + Bi + G</td>
<td></td>
</tr>
<tr>
<td>7 YS74</td>
<td>Dahongliutan</td>
<td>Lava flow</td>
<td>0.63</td>
<td>Cpx + Pl + Sani + Bi</td>
<td>Cpx + Pl + Am + Bi + Sani + Ap + G</td>
<td></td>
</tr>
<tr>
<td>7 YS78</td>
<td>Dahongliutan</td>
<td>Lava flow</td>
<td>0.66</td>
<td>Cpx + Pl + Ol + Bi</td>
<td>Pl + Sani + Ol + Cpx + Am + Bi + Zr + G</td>
<td></td>
</tr>
<tr>
<td>7 YS50</td>
<td>Dahongliutan</td>
<td>Lava flow</td>
<td>0.63</td>
<td>Pl + Sani + Am + Ol</td>
<td>Pl + Sani + Cpx + Am + Bi + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>7 YS79</td>
<td>Dahongliutan</td>
<td>Lava flow</td>
<td>0.62</td>
<td>Cpx + Pl + Ol + Am + Fe–Ti</td>
<td>Cpx + Pl + Sani + Am + Bi + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>7 YS07</td>
<td>Dahongliutan</td>
<td>Lava flow</td>
<td>0.62</td>
<td>Cpx + Pl + Am + Ol + Bi</td>
<td>Cpx + Ol + Pl + Bi + Am + G</td>
<td></td>
</tr>
<tr>
<td>8 KX04</td>
<td>Kangxiwa</td>
<td>Lava flow</td>
<td>0.71</td>
<td>Cpx + Pl + Bi + Fe–Ti</td>
<td>Cpx + Pl + Sani + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>8 KX51</td>
<td>Kangxiwa</td>
<td>Lava flow</td>
<td>0.69</td>
<td>Cpx + Pl + Ol + Am</td>
<td>Cpx + Pl + Ap + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>8 KX49</td>
<td>Kangxiwa</td>
<td>Lava flow</td>
<td>0.70</td>
<td>Cpx + Pl + Ol + Am</td>
<td>Cpx + Pl + Ap + Fe–Ti + G</td>
<td></td>
</tr>
<tr>
<td>8 KX02</td>
<td>Kangxiwa</td>
<td>Lava flow</td>
<td>0.70</td>
<td>Cpx + Pl + Ol</td>
<td>Cpx + Pl + Ap + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>8 PL51</td>
<td>Pulu</td>
<td>Lava flow</td>
<td>0.68</td>
<td>Ol + Cpx + Pl + Cpx</td>
<td>Pl + Sani + Cpx + Bi</td>
<td></td>
</tr>
<tr>
<td>9 PL61</td>
<td>Pulu</td>
<td>Lava flow</td>
<td>0.68</td>
<td>Ol + Cpx + Pl</td>
<td>Pl + Sani + Cpx + Bi</td>
<td></td>
</tr>
<tr>
<td>9 PL3</td>
<td>Pulu</td>
<td>Lava flow</td>
<td>0.56</td>
<td>Ol + Cpx + Pl + Bi</td>
<td>Pl + Sani + Bi + Fe–Ti</td>
<td></td>
</tr>
<tr>
<td>9 PL18</td>
<td>Pulu</td>
<td>Lava flow</td>
<td>0.59</td>
<td>Ol + Cpx + Pl</td>
<td>Pl + Cpx + Bi</td>
<td></td>
</tr>
<tr>
<td>9 PL52</td>
<td>Pulu</td>
<td>Lava flow</td>
<td>0.59</td>
<td>Ol + Cpx + Pl + Fe–Ti</td>
<td>Cpx + Pl + Cpx + Fe–Ti + G</td>
<td></td>
</tr>
</tbody>
</table>
| 9 PL43    | Pulu       | Lava flow  | 0.59  | Ol + Cpx + Pl + LREE (La, Ce) are higher in the central subgroup than those in the northern and southern subgroups (Fig. 7). Th contents decrease from the southern subgroup through the central subgroup to the northern subgroup. REE patterns are steeper in the central subgroup than those in the northern and southern subgroups (Fig. 6). The average value of La/Yb is 82.8, 76.2, 55.8 in the central, northern and southern subgroups, respectively (Supplementary Data Table A.2; Table 2). Ba/Th increases and Th/Nd decreases from the southern through the central to the northern subgroup (Fig. 8).

The NW Tibetan post-collisional magmatic rocks have high (87Sr/86Sr) (0.7072–0.7131) and low (143Nd/144Nd) (0.511593–0.512582) relative to Bulk Silicate Earth (BSE) values, and high (265Th/238Pu) (15.57–15.95) and (208pb/232Th) (38.66–39.58) at relatively constant (206Pb/204Pb), (18.67–19.08) with respect to the Northern Hemisphere Reference Line (NHRL) (Tables 3 and 4; Fig. 9). (87Sr/86Sr) varies considerably in the southern subgroup but is relatively constant in the northern subgroup (Figs. 6b and 9). The Sr–Nd isotope compositions (Fig. 9) plot within a triangular field bounded by the isotopic compositions of depleted MORB-source mantle (DMM), Indian continental basement [proxied by the isotopic composition of the Higher Himalayan Crystalline Series; see Pan et al. (2004) and Richards et al. (2005)] and references therein for a more detailed discussion] and Asian continental basement [proxied by the isotopic composition of deep-drill-core metamorphic rock samples from the basement of the central Tarim Basin to
the north of the Tibetan Plateau (Fig. 1); see Jiang et al. (2004), Zhang et al. (2004), Guo et al. (2005b) and Zhang et al. (2009) and references therein for a more detailed discussion.

6. Discussion

The post-collisional K-rich magmatism of the Tibetan Plateau has been considered to be important in constraining the uplift history of the Plateau (e.g. Arnaud et al., 1992; Chen et al., 2010; Chung et al., 2005; Ding et al., 2007; Guo et al., 2006; Pearce and Mei, 1988; Roger et al., 2000; Turner et al., 1993, 1996; Wang et al., 2012; Williams et al., 2001, 2004). The major and trace element contents and Sr–Nd–Pb isotope compositions of the most primitive mafic rocks provide important insights on nature of their mantle source, and the geodynamic setting, whilst their ages can constrain the timing of Plateau uplift.

6.1. Age trend of the K-rich magmatism in NW Tibet

To constrain the age relationships of the potassium-rich magmatism in NW Tibet (Fig. 1), we have compiled all the available geochronological data from the published literature (Supplementary Data Table A.1). Several different methods (e.g. $^{40}$Ar/$^{39}$Ar, K–Ar, Zircon U–Pb) have been used to date the magmatic rocks. We have checked the data quality and compared the ages from the different methods to constrain the age ranges of the magmatic rocks. These data indicate that age of the magmatism ranges from 8 Ma to the present day; the history of volcanism appears to be longer in the central subgroup volcanic fields than those in the southern and northern sub groups (Fig. 3). The unique active volcano in the Plateau, Ashi, is located within the central subgroup (Fig. 1).

6.2. Nature of the mantle source region of the K-rich magmas

The post-collisional K-rich mafic magmatic rocks are characterized by significant enrichment in LILE and LREE relative to HFSE and HREE, with strongly negative Nb–Ta–Ti anomalies and positive Pb anomalies in primitive mantle – normalized incompatible trace element patterns (Fig. 7), consistent with an origin as subduction-related magmas (e.g. Gill, 1981; Pearce and Parkinson, 1993). Their Sr–Nd–Pb isotope compositions fall within a field enclosed by depleted MORB-source mantle (Workman and Hart, 2005), Indian continental basement and Asian continental basement (Fig. 9), suggesting that their source region contains both India- and Asia-derived continental crustal components. Evidence for opposing northward subduction of the Indian slab (e.g. Li, 2008; Zhao et al., 2010) and southward subduction of Asian lithosphere beneath NW Tibet (e.g. Negredo et al., 2007; Zhao et al., 2011) supports this inference.

Marschall and Schumacher (2012) proposed a physical process by which components from a subducting slab and overlying mantle wedge can be transported into the mantle source of subduction-related magmas. This involves formation of a mélangé zone within a subduction channel on the top surface of the slab in which hydrated mantle rocks are mixed with material derived from the subducting slab, including trench sediments (cf., Gerya et al., 2002; Guillot et al., 2009). The trace-element characteristics of exhumed metamorphic mélangé rocks are similar to those of subduction-related magmas (Marschall and Schumacher, 2012), with the distinctive enrichment in LILE and significant depletion in HFSE (e.g. Nb, Ta and Ti), suggesting that deeply subducted mélangé components may provide an important source component for arc magmas. We have developed this model for the NW Tibetan post-collisional tectonic setting (Fig. 2), proposing the
### Table 2

Major and trace element analyses of the representative potassium-rich magmatic rocks in NW Tibet.

| Field no.: 2222255555 | Sample no.: QS27 QS19 QS23 QS18 QS24 AH607 AH605 AH609 AH602 | Field name: Quanshuigou Quanshuigou Quanshuigou Quanshuigou Quanshuigou Ashikule Ashikule Ashikule Ashikule | Age (Ma): 5.23 5.23 5.23 5.23 5.23 1.07 1.07 1.07 1.07 | SiO₂ 48.80 49.66 47.97 48.75 49.62 47.90 46.15 48.12 47.11 | TiO₂ 1.50 1.40 1.58 1.67 1.72 1.90 2.39 1.93 2.51 | Al₂O₃ 13.88 13.27 14.61 14.75 14.95 13.91 13.78 14.24 14.10 | Fe₂O₃* 10.86 10.77 10.33 10.45 10.09 10.79 11.43 9.61 9.99 | MnO 0.12 0.13 0.12 0.13 0.12 0.16 0.16 0.14 0.14 | MgO 6.49 6.23 7.09 7.33 7.16 7.31 8.52 6.85 8.46 | CaO 9.84 9.58 9.10 8.75 8.38 9.21 8.28 10.21 8.68 | Na₂O 3.38 3.21 3.30 3.48 3.03 3.53 3.49 3.26 3.32 | K₂O 3.86 4.30 4.54 3.72 3.80 4.35 4.74 4.45 4.41 | P₂O₅ 1.26 1.44 1.26 0.99 1.12 1.03 1.06 1.19 1.25 | LOI 1.01 1.34 0.76 0.59 1.32 0.82 1.57 0.68 0.66 | Mg-no. 0.60 0.59 0.63 0.65 0.59 0.63 0.65 0.64 0.68 | La 113.7 104.3 101.4 92.5 71.8 137.7 97.3 95.8 116.2 |
| Field no.: 558889 | Sample no.: AH618 AH615 KX44 KX51 KX80 KX49 KX62 PL61 | Field name: Ashikule Ashikule Kangxiwa Kangxiwa Kangxiwa Kangxiwa Kangxiwa Pulu | Age (Ma): 1.07 1.07 1.07 1.07 1.07 1.07 1.07 1.07 | SiO₂ 46.73 47.40 48.75 48.62 49.47 48.52 48.55 49.52 | TiO₂ 2.38 2.17 1.90 1.54 1.48 1.86 1.91 1.83 | Al₂O₃ 13.85 14.55 12.76 13.55 13.71 12.79 12.74 13.43 | Fe₂O₃* 10.23 10.37 9.12 9.30 9.00 9.15 9.23 9.50 | MnO 0.16 0.17 0.15 0.12 0.13 0.14 0.15 0.11 | MgO 6.78 6.04 5.83 8.25 8.29 8.77 8.83 8.10 | CaO 9.86 7.27 8.08 8.91 9.32 8.56 8.52 8.51 8.51 | Na₂O 3.76 3.44 2.89 3.64 2.49 2.90 3.48 3.17 | K₂O 4.74 4.52 5.71 4.68 4.86 5.77 5.31 4.89 | P₂O₅ 0.96 1.06 1.80 1.39 1.26 1.54 1.28 0.94 | LOI 1.79 2.05 0.74 1.46 1.13 0.71 0.86 1.08 | Mg-no. 0.68 0.68 0.70 0.69 0.69 0.70 0.70 0.68 | La 105.9 101.6 117.8 132.3 131.8 115.3 136.2 172.8 | Ce 192.6 204.2 251.3 246.1 247.2 248.6 281.5 342.6 | Pr 21.3 23.7 30.7 29 31.5 31.4 34.9 35.7 | Nd 7.83 9.23 12.25 9.54 11.47 125.3 121.6 109.5 | Sm 12.3 15.1 28.1 19.6 21.8 29.3 23.8 20.2 | Eu 2.89 4.04 6.53 4.02 5.81 6.46 4.83 5.13 | Gd 9.02 12.68 17.2 7.31 15.26 17.11 12.29 14.66 |
involved in isotopically distinct Indian and Asian mélangé components in the petrogenesis of the K-rich magmas.

Enrichment of the source of subduction-related magmas has traditionally been attributed to migration of aqueous fluids and/or melts derived from the subducted slab into the mantle wedge (e.g., Elburg et al., 2002; Gill, 1981; Guo et al., 2013; Hawkesworth et al., 1997; Johnson and Plank, 1999; Pearce, 1983). Compositional distinctions have been identified between subduction-related magmatic rocks whose sources have been modified by subduction-related fluids and those that have been enriched by slab-derived melts (e.g., Class et al., 2000; Guo et al., 2013; Hawkesworth et al., 1997; Johnson and Plank, 1999; Tatsunami et al., 1986; Woodhead et al., 2001). Slab-derived fluids, which carry little REE and HFSE, can introduce significant amounts of LILE (e.g., K, Rb, Cs, Sr, Ba, U, Pb) from the subducting slab to the source region in the mantle wedge, whilst slab-derived melts are characterized by high Th and LREE concentrations. On the basis of the above discussion, the northward changes in REE and LILE (Figs. 6–8) of the K-rich rocks could be simply explained by influx of Indian slab-derived melts and Asian slab-derived fluids to the mantle source of the magmas in the southern and northern subgroups, respectively. Recent studies (e.g., Prelević et al., 2013; Tommasini et al., 2011) have, however, suggested that Th (and Sm) enrichments in K-rich magmatic rocks could be linked to the presence of subducted blueschist-facies melange components in their mantle source. Zoisite/epidote and lawsonite in blueschists are thought to be major repositories of Sr, Pb, U, Th, and LREE (Brunsmann et al., 2000; Feineman et al., 2007; Frei et al., 2004; Hickmott et al., 1992; Spandler et al., 2003; Tommasini et al., 2011; Usui et al., 2006) because of their high partition coefficients for these elements. Partial melting of well-mixed blueschist-facies mélangé rocks within the mantle wedge could thus result in Th enrichment of subduction-related magmas.

The potassic magmatic rocks from NW Tibet studied here have variable Th and Sm enrichments with respect to La (Fig. 8c). They define two near linear trends in a ($^{87}\text{Sr}/^{86}\text{Sr}$) vs Ba/Th diagram (Fig. 8b); one trend lies between a depleted mantle source component and an inferred Asian mélangé component with high Ba/Th and the other between the same depleted mantle and an inferred Indian mélangé component with low Ba/Th. The variation of ($^{87}\text{Sr}/^{86}\text{Sr}$) vs Ba/Th thus suggests that the mantle source of the Tibetan potassic magmas consist of three end-members: (1) a depleted MORB-source mantle (cf., Workman and Hart, 2005), (2) an Asian mélange component which has ($^{87}\text{Sr}/^{86}\text{Sr}$), of ~0.708 and (3) an Indian mélange component with ($^{87}\text{Sr}/^{86}\text{Sr}$) > 0.713 and Ba/Th similar to Indian continental basement. This suggests that the Indian and Asian subducted mélanges provide important source components for the K-rich magmas in the southern and northern subgroups, respectively (Fig. 8b).

### 6.3 A petrogenetic model for the K-rich magmatic rocks in NW Tibet

The most primitive post-collisional K-rich mafic magmatic rocks which form the basis of this study have high MgO contents, Mg-numbers and Ni concentrations (Table 2; Supplementary Data Table A2), indicating that they are partial melting products of the upper mantle. Their ages (8.3 Ma–present) reflect an important tectono-magmatic event which induced partial melting of the upper mantle beneath NW Tibet. This event can be linked to the onset of near vertical subduction of Indian continental lithosphere at ~8 Ma (e.g., Negredo et al., 2007; Zhao et al., 2010, 2011). Marschall and Schumacher (2012) provide an elegant physico-chemical conceptual framework for subduction zones that involves subduction channel mélangés in the recycling of trench sediments into the source of subduction-related magmas. We have adapted this model for the NW Tibetan geodynamic setting of converging subduction systems and propose a two-stage petrogenetic model for the post-collisional K-rich magmatism. The first stage involves formation of mélanges in the Asian and Indian subduction channels at the slab–mantle interface.
as a consequence of the southward subduction of Asian continental lithosphere since 25 Ma (Fig. 2b), and northward flat slab subduction of Indian lithosphere from 55 Ma to 8 Ma (Fig. 2a), followed by steep subduction of the Indian slab since 8 Ma (Fig. 2c) (Li, 2008; Negredo et al., 2007; Zhao et al., 2010). The Asian mélange component does not appear to introduce radiogenic 87Sr/86Sr (Fig. 9) but does have low 143Nd/144Nd, reflecting the isotopic composition of the trench sediments derived from the Asian continent. The incorporation of the Indian mélange component into the source of the potassic magmas may postdate the addition of the Asian mélange component, linked to the onset of steep subduction of the Indian slab since 8 Ma.

The mantle-normalized incompatible trace element pattern of average mélange rocks reported by Marschall and Schumacher (2012) is similar to those of the K-rich mélange in NW Tibet, characterized by enrichment in LILE and significant depletion in Nb, Ta and Ti (Fig. 7f). The compositions of mélange rocks (Marschall and Schumacher, 2012) are also consistent with those of the K-rich volcanic rocks in a Ce/Pb vs Nb/La diagram (Fig. 8d). These similarities support the role of mélange components in the petrogenesis of the K-rich magmas.

The second stage of the model involves the diapiric transportation of buoyant, low-density, enriched mélange domains into the shallow mantle, effectively underplating the base of the Tibetan lithosphere (Fig. 2). The absence of K-rich magmatism in NW Tibet during the period 25–8 Ma suggests that the mantle was too cool for melting of the underplated mélange at this stage (Fig. 2b). However, Asian mélange underplating could have caused uplift of the northwestern Tibetan Plateau during this period. We have no way of knowing when underplating of Indian mélange material beneath the Songpan-Ganzi terrane commenced; our suggestion in Fig. 2(c) is that it may have occurred slightly later. The onset of magma generation at ~8 Ma clearly requires the plating of Indian mélange material beneath NW Tibet since 8 Ma.

Field no. refers to number of volcanic field in Fig. 1. Chondritic uniform reservoir (CHUR) at the present day (87Rb/86Sr)CHUR = 0.0847 (McCulloch and Black, 1984); (87Sr/86Sr)i = 0.7045 (DePaolo, 1988); (143Nd/144Nd)i = 0.512536 (Goldstein et al., 1984) was used for the calculations. λ87Rb = 1.42 × 10–11 year–1 (Steiger and Jager, 1977); λ143Nd = 6.54 × 10–12 year–1 (Lugmair and Marti, 1978). Both εNd(i) and εNd(i) were obtained by using the average ages in the volcanic fields (Supplementary Data Table A1).

<table>
<thead>
<tr>
<th>Field no.</th>
<th>Sample no.</th>
<th>Field name</th>
<th>87Sr/86Sr</th>
<th>87Sr/86Sr ± 2σ</th>
<th>143Nd/144Nd</th>
<th>143Nd/144Nd ± 2σ</th>
<th>εNd(i)</th>
<th>εNd(i) ± 2σ</th>
<th>εNd(i)</th>
<th>εNd(i) ± 2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CT09</td>
<td>Tianshuihai</td>
<td>0.2184</td>
<td>0.708158</td>
<td>52.01</td>
<td>0.0830</td>
<td>0.51235 ± 7</td>
<td>0.51232 ± 7</td>
<td>5.84</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CT12</td>
<td>Tianshuihai</td>
<td>0.1719</td>
<td>0.711850</td>
<td>104.42</td>
<td>0.1110</td>
<td>0.51224 ± 6</td>
<td>0.51223 ± 6</td>
<td>7.69</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>CT17</td>
<td>Tianshuihai</td>
<td>0.2245</td>
<td>0.70817</td>
<td>52.29</td>
<td>0.1129</td>
<td>0.51230 ± 9</td>
<td>0.51230 ± 9</td>
<td>6.44</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CT05</td>
<td>Tianshuihai</td>
<td>0.2275</td>
<td>0.707945</td>
<td>48.99</td>
<td>0.1076</td>
<td>0.512218 ± 8</td>
<td>0.512214 ± 8</td>
<td>8.13</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>QS27</td>
<td>Quanshuigou</td>
<td>0.1909</td>
<td>0.708514</td>
<td>56.11</td>
<td>0.1228</td>
<td>0.51231 ± 7</td>
<td>0.51232 ± 7</td>
<td>5.74</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>QS19</td>
<td>Quanshuigou</td>
<td>0.2241</td>
<td>0.712826</td>
<td>118.28</td>
<td>0.1436</td>
<td>0.512167 ± 10</td>
<td>0.512162 ± 10</td>
<td>9.15</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>QS23</td>
<td>Quanshuigou</td>
<td>0.2010</td>
<td>0.711348</td>
<td>122.63</td>
<td>0.1120</td>
<td>0.512328 ± 8</td>
<td>0.512324 ± 8</td>
<td>5.99</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>QS24</td>
<td>Quanshuigou</td>
<td>0.2179</td>
<td>0.706743</td>
<td>72.97</td>
<td>0.1188</td>
<td>0.512236 ± 7</td>
<td>0.512232 ± 7</td>
<td>7.79</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Sr and Nd isotope compositions of the post-collisional potassium-rich magmatic rocks in NW Tibet.
provided the critical trigger for melting of the underplated mélanges (Fig. 2c). Steep subduction of the Indian slab beneath NW Tibet has been attributed to a sharp change in the convergence angle between India and Asia since 8 Ma (Lee and Lawver, 1995).

6.4. Generic application of the model to other areas of the Alpine–Himalayan orogeny

Prelević et al. (2013) have recently proposed a similar mélangé model to explain the source of post-collisional potassic magmatism throughout the Alpine–Himalayan orogenic belt. The mélangé is considered to contain a mixture of fore-arc depleted harzburgite and terrigenous trench sediments. They propose that such material becomes accreted beneath the lithosphere of the upper plate during continental collision.

Similar REE patterns to those of the potassic rocks of NW Tibet have been reported for potassic rocks within the Mediterranean area from SE Spain (Conticelli et al., 2009; Nelson, 1992; Prelević et al., 2008, 2010, 2013) and central Italy (Boari et al., 2009; Owen, 2008; Perini et al., 2004; Prelević et al., 2010, 2013). These geochemical similarities strongly support a similar petrogenesis.

7. Conclusions

Based on the major and trace element and Sr–Nd–Pb isotopic compositions of post-collisional potassic magmatic rocks in NW Tibet, combined with geochronological data from the literature, we propose a two-stage model to explain their petrogenesis. The enriched source of the magmas is considered to comprise a mixture of subduction channel mélangé material derived from opposing Indian and Asian subduction systems; this material became underplated beneath the continental lithosphere of the Songpan-Ganzi terrane of NW Tibet. The Indian and Asian mélanges carry the distinctive geochemical and isotopic signature of subducted terrigenous trench sediments, derived from the respective Indian and Asian continental basements, mixed with hydrated mantle material from the local mantle wedges. Partial melting of the underplated mélangé may have been triggered by asthenospheric upwelling linked to the onset of steep subduction of the Indian slab at ~8 Ma.
Acknowledgments

This study was supported by a grant from special project of Chinese Academy of Sciences (XDB03010600), grants from the National Natural Science Foundation of China (NSFC) (No: 41020124002 and 41130314) and by a joint project between the Royal Society of London and NSFC. We are grateful to Drs X. Chen and W. Guo for their help.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2014.03.020.

References


Conticelli, S., Avanzinelli, R., Poli, G., Brachia, E., Giordano, G., 2013. Shift from lamproite-like to leucitic rocks: Sr–Nd–Pb isotope data from the Monte Cimino volcanic complex vs. the Vicostratovolcano, Central Italy. Chemical Geology 353, 246–266.


Fig. 5. (a) K2O + Na2O (wt %) vs SiO2 (wt %) variations in the K-rich igneous rocks of NW Tibet. All data plotted have been recalculated to 100 wt.% on a volatile-free basis (Supplementary Data Table A.2). Classification boundaries are from Le Bas et al. (1986) and Le Maitre et al. (1989). Filled and open symbols represent, respectively, data from this study and the published data of Arnaud et al. (1992), Turner et al. (1993, 1996), Ding (1998), Liu et al. (2003), Williams et al. (2004), Wang et al. (2005), Guo et al. (2006), Zhang et al. (2008), Li (2008), Wang and Zhang (2011) and Yang (2011). Rock types shown by letters are as follows. S2: basaltic trachydacite; S3: trachydacite; U1: tephrite; U2: phonotephrite; U3: tephriphonolite. Large filled symbols represent the compositions of the most primitive maﬁc volcanic rocks (i.e. MgO > 6 wt.%) highlighted in this study. (b) K2O (wt %) vs SiO2 (wt %) diagram for the same samples plotted in (a). The dividing lines show the classiﬁcation boundaries from Rickwood (1989) and Le Maitre et al. (2002). Data sources and symbols are as in (a).
Fig. 6. Chondrite-normalized rare earth element patterns; normalization factors are from Sun and McDonough (1989). The dashed lines denote the range of previously published data for the post-collisional K-rich magmatic rocks in NW Tibet (Arnaud et al., 1992; Deng, 1998; Guo et al., 2006; Li, 2008; Liu et al., 2003; Turner et al., 1993, 1996; Wang and Zhang, 2011; Wang et al., 2005; Williams et al., 2004; Yang, 2011; Zhang et al., 2008). Data sources are as in Fig. 5(a).
Fig. 7. Primitive mantle-normalized trace element patterns; normalization factors are from Sun and McDonough (1989). The dashed lines denote the range of previously published data for the post-collisional K-rich magmatic rocks in NW Tibet (Arnaud et al., 1992; Deng, 1998; Guo et al., 2006; Li, 2008; Liu et al., 2003; Turner et al., 1993, 1996; Wang and Zhang, 2011; Wang et al., 2005; Williams et al., 2004; Yang, 2011; Zhang et al., 2008). Data for the average composition of subduction channel mélangé rocks in panel (f) are from Marschall and Schumacher (2012). Data sources are as in Fig. 5(a).


Fig. 8. (a) Ba/Th vs Th/Nd. (b) (87Sr/86Sr)i vs Ba/Th. (c) Th/La vs Sm/La. (d) Ce/Pb vs Nb/La. All data plotted as filled symbols are from Supplementary Data Table A.2 and Table 3. The red star represents the composition of MORB-source mantle (Sun and McDonough, 1989) in (b). The red circle filled with yellow represents the average composition of mélange rocks (Marschall and Schumacher, 2012) in (d). Symbols are as in Fig. 5(a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 9. (a) \(^{143}\text{Nd}/^{144}\text{Nd}\) vs \(^{87}\text{Sr}/^{86}\text{Sr}\). (b) \(^{87}\text{Sr}/^{86}\text{Sr}\) vs \(^{206}\text{Pb}/^{204}\text{Pb}\). (c) \(^{143}\text{Nd}/^{144}\text{Nd}\) vs \(^{206}\text{Pb}/^{204}\text{Pb}\). (d) \(^{207}\text{Pb}/^{204}\text{Pb}\) vs \(^{206}\text{Pb}/^{204}\text{Pb}\). (e) \(^{208}\text{Pb}/^{204}\text{Pb}\) vs \(^{206}\text{Pb}/^{204}\text{Pb}\). The Sr–Nd–Pb isotope data for samples from this study are from Tables 3 and Table 4. Symbols are as in Fig. 5(a). Arrows point towards the composition of depleted MORB-source mantle (DMM) (Workman and Hart, 2005), Indian continental basement (Ahmad et al., 2000; Guo and Wilson, 2012; Inger and Harris, 1993; Richards et al., 2005) and Asian basement (Guo et al., 2005b; Jiang et al., 2004; Zhang et al., 2004; Zhang et al., 2009). The large black square, large blue circle, and large yellow-filled red triangle represent the compositions of depleted MORB-source mantle (DMM), Indian basement and Asian basement, respectively. The NHRL (Northern Hemisphere Reference Line) is shown for reference in (d) and (e) (Hart, 1984). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)


