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# Origin of arc-like continental basalts: Implications for deep-Earth fluid cycling and tectonic discrimination

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ABSTRACT

Continental basalts generally display enrichment of fluid-mobile elements and depletion of high-field-strength elements, similar to those that evolved in the subduction environment, but different from oceanic basalts. Based on the continental flood basalt database for six large igneous provinces, together with rift-related basalt data from the Basin and Range Province, this study aimed to test the validity of geochemical tectonic discrimination diagrams in distinguishing arc-like intra-continental basalts from arc basalts and to further investigate the role of deep-Earth water cycling in producing arc-like signatures in large-scale intra-continental basalts. Our evaluation shows that arc-like intra-continental basalts can be distinguished from arc basalts by integrating the following factors: (1) the FeO, MgO, and $Al_2O_3$ concentrations of the primary melt; (2) Ti—V, Zr—Zr/Y, Zr—Ti, and Ti/V—Zr/Sm—Sr/Nd discrimination diagrams; (3) the coexistence of arc-like and OIB-like subtype basalts within the same province; (4) primitive mantle-normalized trace element distribution patterns. The similarity of enrichment in fluid-mobile elements (Ba, Rb, Sr, U, and K) between arc-like and true arc basalts suggests the importance of water flux melting in producing arc-like signatures in continental basalts. Experimentally determined liquid lines of descent (LLD) imply high magma water concentrations for continental flood basalts (CFBs) and the Basin and Range basalts. Furthermore, estimates based on the $Al_2O_3$–LLD method indicates 4.0–5.0 wt% pre-eruptive magma $H_2O$ concentration for CFBs and the Basin and Range basalts. The tight relationships between $H_2O$/Ce and Ba/La, Ba/Nb and Rb/Nb based on global arc basalt data were further used to estimate the primary $H_2O$ concentrations. With the exception of the Emeishan CFBs (mainly containing 4.0–5.6 wt% $H_2O$), all other CFBs investigated have similar estimated primary $H_2O$ contents, with values ranging from 1.0 to 2.0 wt%. The estimated primary $H_2O$ content of the Basin and Range basalts is extremely high and up to 10.0 wt%. Thus, this study demonstrates that water flux melting played an important role in the generation of many intra-continental igneous provinces. This new finding was further employed to investigate the tectonic setting of 320–270 Ma basalts in Inner Mongolia, North China. Most basalts from three key rock units (i.e. Amushan, Benbatu, and Dashizhai formations) from the Central Asian Orogenic belt are classified as non-arc types. The estimated magma $H_2O$ concentrations suggest a strong link between $H_2O$ content and arc-like geochemical signatures. Together with established geological evidence, we proposed that these 320–270 Ma basaltic rocks were most likely produced in a post-orogenic extensional environment facilitated by subducted slab-driven deep-Earth fluid cycling. We propose a mantle transition zone water-filtering model that links deep-Earth fluid cycling, large-scale intra-continental basaltic magmatism, and supercontinent cycles into a self-organized system.


## 1. Introduction

Continental basalts generally show a spectrum of elemental and isotopic compositions that range well beyond those observed in oceanic basalts. Compared with the smooth primitive mantle-normalized trace element distribution patterns (Hofmann, 1997; Sun and McDonough, 1989), the majority of continental basalts have complex trace element distribution patterns with pronounced negative and positive anomalies (Ivanov and Litasov, 2013; Jourdan et al., 2007; Puffer, 2001; Wang et al., 2008, 2009, 2014; Xia, 2014). The most intrinsic feature of continental basalts, especially those from large igneous provinces (LIPs), are the negative anomalies of the high-field-strength elements (HFSEs: Nb, Ta, Ti, Zr, and Hf), similar to island arc basalts. Such features will be called arc-like signatures hereafter (they are similar to the low-Ti continental basalts in the literature). Previous studies have demonstrated that continental flood basalts (CFBs), the most volumetrically abundant basalts found in intra-continental areas, plot within an arc tectonic setting in various discrimination diagrams (Duncan, 1987; Xia, 2014).

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This implies that the use of these diagrams, which are empirically derived, may lead to incorrectly characterizing tectonic setting (Duncan, 1987). Therefore, systemic investigation of how to discriminate arc-like continental flood basalts from island arc basalts is crucial for determining the tectonic setting of ancient continental basalts.

The chemistry of basalt is dependent on the composition of its source reservoir, the melting conditions (pressure, temperature, hydrous, or anhydrous) and subsequent effects, including partial melting, melt migration and accumulation, and various assimilation and fractionation crystallization (AFC) processes that it may have undergone on its way to the surface (Duncan, 1987). Only when some, or all, of these are unique to a particular tectonic environment can basalt composition be used as a diagnostic indicator of tectonic setting. Thus, the question of how arc-like trace element distribution patterns are generated becomes crucial to discriminating arc-like continental basalts from true arc basalts generated in a subduction system.

One point of general agreement is that the arc-like geochemical signatures of basaltic rocks indicate direct or indirect contributions from water (including other fluid phases) released from subducted slabs (Hawkesworth et al., 1995; Ivanov and Litasov, 2013; Ivanov et al., 2008; Jourdan et al., 2007; Merle et al., 2014; Murphy and Dostal, 2007; Puffer, 2001; Sprung et al., 2007; Ulmer, 2001; Wang et al., 2008, 2009, 2014, 2015; Wilson et al., 1995). Detailed geochemical analyses and petrogenetic studies suggest hydrated, long-term isolated mantle reservoirs account for both the arc-like chemical signature and enriched radiogenic isotope characteristics of arc-like continental basalts (Hawkesworth et al., 1995; Ivanov and Litasov, 2013; Ivanov et al., 2008; Jourdan et al., 2007; Merle et al., 2014; Wang et al., 2008, 2009, 2014). However, the question of how and where (asthenosphere or lithosphere) fluid was released from subducted slabs to influence or control the generation of arc-like signatures is still unclear.

Attribution of arc-like geochemical signatures to sub-continental lithospheric mantle (SCLM) modified by paleo-subduction is a conventional interpretation (Hawkesworth et al., 1995; Murphy and Dostal, 2007; Sprung et al., 2007; Wang et al., 2008, 2009, 2014; Wilson et al., 1995). However, discovery of abundant hydrous phases (Pearson et al., 2014; Schmandt et al., 2014) and evidence for high water content in nominally anhydrous minerals (Fukao et al., 2009; Smyth et al., 2003), together with numerical modeling (Bercovici and Karato, 2003; Faccenda et al., 2012; Maruyama and Okamoto, 2007) and geophysical investigations (Fukao et al., 2009; Huang et al., 2005), show that at high rates of subduction, significant amounts of water can subduct as deep as the mantle transition zone (MTZ). Thus, the arc-like signatures may be linked to deep-Earth fluid cycling down to the MTZ (Ivanov and Litasov, 2013; Ivanov et al., 2008). However, arc-like geochemical signatures of continental basalts can also be simply attributed to contamination of asthenospheric mantle-derived melts by lithospheric components (Xia, 2014). Thus, the origin of arc-like geochemical signatures in intra-continental basalts remains unclear.

Using available geochemical datasets of global continental flood basalts (Fig. 1a, b, and c), together with rift basalt examples from the Basin and Rang Province (Greater Basin) (GEOROC: http://georoc.mpch-mainz.gwdg.de/georoc/), we attempt to decipher the similarities and differences between island arc basalts and arc-like continental basalts, and to examine which of the most cited geochemical diagrams are successful in discriminating arc-like intra-continental basalts from true island arc basalts.

Utilizing our new findings, we have applied them to a controversial area, in this case the Central Asian Orogenic Belt (CAOB; Fig. 1d), in order to test their veracity.

## 2. Database and methods

The data used in this study were obtained from the GEOROC database (access date: December 13, 2014). The continental basalts included in this study are from the Siberian, Central Atlantic, Karoo, Deccan, Emeishan, and Columbia River (Yellowstone) LIPs and the Basin and Range basalts (Greater Basin) as an example of typical post-orogenic extension-related basalts. Owing to their importance in characterizing water contribution in mantle melting, and in fractionation of light ion lithophile elements (LILEs, such as Ba, Sr, Rb, U, and Th) relative to HFSEs (such as Nb, Ta, Zr, Hf, and Ti), typical arc basalts are also examined. They include the well-studied intra-oceanic arcs (Izu-Bonin, Tonga, and Kermadec arcs) and other arcs that were emplaced within older continental materials or thick sequences of sediments (Andes and Luzon arcs). The data for these five arcs were also obtained from the GEOROC database. The average arc basalt data for global continental and oceanic arcs and 12 individual arcs (Kermadec, Marianas, Tonga, Aleutian, Andes, Central American, Greater Antilles, Luzon, Kamchatka, and Cascades arcs) from Kelemen et al. (2007) are also included in order to estimate the composition of primary arc basaltic melts on a global scale. Finally, for comparison, the estimated primary arc basaltic melts from the Marianas arc (Tamura et al., 2011, 2014) and the average of primary or nearly primary average arc basaltic melt compositions from the Japan, Cascades, Mexico, Indonesia, Izu-Bonin, and Aleutians arcs from Grove et al. (2012) are also included.

There is always the issue of quality when using large compiled databases. The data quality depends on the analytical methods and the reputation of the various laboratories for maintaining high standards. In this study, we have not made any attempt to discriminate between "good" and "bad" data, since it is virtually impossible to quantify this. In some cases, where outliers are orders of magnitude different from the bulk of the data, we have ignored these by excluding them from the plots.

We have applied three steps in selecting the sample data. Firstly, the major element data set only includes samples with $SiO_2$ ranging from 43 wt% to 56 wt% and LOI values ≤5 wt% (or total summations ranging from 95 wt% to 102%, if LOI values are not available). Secondly, highly evolved samples with MgO ≤8 wt% are excluded in reconstructing the primary major element melt compositions from the data set. Thirdly, bivariate plots of Zr against selected trace elements were used for evaluating the mobility of such elements during alteration (Polat et al., 2002; Wang et al., 2008, 2010). Samples plotting off the main trend (defined by 80–90% of the data) are also excluded in the discussion involving fluid-mobile elements (Ba, Sr, Rb, U, Th, and K).

The primary major melt compositions were estimated by adding equilibrium olivine to selected starting material at 1% increments until the resulting basaltic magma was in equilibrium with $Fo_{91}$. The prerequisite of this method is to determine starting materials that only underwent olivine fractionation. However, fractionation of both clinopyroxene and plagioclase can modify FeO compositions of primary melts (Langmuir et al., 1992; Wang et al., 2012, 2014) and would cause an over- or underestimation of primary MgO contents (Langmuir et al., 1992; Wang et al., 2012). As magmas crystallize at depth, their major and trace element compositions evolve along lines determined by their phase equilibria. These are the so-called liquid lines of descent (LLDs). Fractional crystallization of plagioclase would significantly deplete $Al_2O_3$, whereas both olivine and clinopyroxene fractionation will increase $Al_2O_3$. Clinopyroxene fractionation would also quickly deplete CaO contents, but both olivine and plagioclase increase CaO contents. Thus, plagioclase and clinopyroxene together in the fractional mineral assemblage would change the slope of the $Al_2O_3$—MgO and CaO—MgO liquid lines of descent. This implies that the turning points on $Al_2O_3$—MgO and CaO—MgO liquid lines of descent can be used to determine the appearance of these two minerals in the fractional mineral assemblage. As shown in Fig. 2, $Al_2O_3$ contents correlate negatively with MgO at MgO = 3.5–4.0 wt% (Columbia River), 5 wt% (Karoo), 6 wt% (Siberia), 6–6.5 wt% (Basin and Range), and 8.0 wt% (CAMP) and then quickly decrease (become positively) or become flat with decreasing MgO. $Al_2O_3$ contents of basalts from the Emeishan (Fig. 2c) and Deccan (Fig. 2d) LIPs continuously correlate negatively with MgO without inflection on the $Al_2O_3$—MgO liquid lines of descent. This indicates