Invited Review Article

Interpreting chemical compositions of small scale basaltic systems: A review

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ABSTRACT

Small scale basaltic magmatic systems occur in all of the major tectonic environments of planet Earth and are characteristically expressed at the Earth's surface as fields of small monogenetic cones. The chemical compositions of the materials that make up these cones reflect processes of magma generation and differentiation that occur in their plumbing system. The volumes of magmas involved are very small and significantly their compositional ranges reveal remarkably complex processes which are overwhelmed or homogenized in larger scale systems. Commonly, compositions are basaltic, alkalic and enriched in light rare earth elements and large ion lithophile elements, although the spectrum extends from highly enriched nephelinites to subalkalic and tholeiitic basalts. Isotopic analyses of rocks from volcanic fields almost always display compositions which can only be explained by the interaction of two or more mantle sources. Ultimately their basaltic magmas originate by small scale melting of mantle sources. Compositional variety is testament to melting processes at different depths, a range of melting proportions, a heterogeneous source and fractionation, magma mixing and assimilation within the plumbing system that brings magmas to the surface. The fact that such a variety of compositions is preserved in a single field shows that isolation of individual melting events and their ascent is an important and possibly defining feature of monogenetic volcanism, as well as the window their chemical behavior provides into the complex process of melt generation and extraction in the Earth's upper mantle.

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Contents

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1. Introduction

At a fundamental level volcanoes are the expression of magmatic systems that are a process whereby the internal energy of planet Earth is transferred to the surface. The paradigm of plate tectonics recognizes this link between internal processes and their role in the evolution of the planet's surficial architecture. Plate tectonic theory has also driven an understanding of magmatic systems as identifiably different entities linked to distinct events in the evolutionary history of the Earth. This has led to a compartmentalization of the way magmatic systems are understood that is rooted in concepts of their relationship to plate boundaries, hence the ideas of divergent plate, convergent plate and intraplate igneous associations.

The chemical composition of volcanic rocks has become a primary tool in the study of the origin and evolution of magmatic systems. Distinctive geochemical signatures are linked to particular tectonic settings, and variations within suites of spatially and temporally linked rocks provide the basis for their interpretation in terms of petrogenetic processes. Increasingly, stratigraphically constrained sampling of volcanic deposit sequences has provided the clue to unravelling the fine details of their petrogenetic evolution; recent developments have been in the recognition of systematic chemical differences within volcanic sequences and their interpretation in terms of the processes that create and modify magmas in their passage from source to surface (e.g. Brenna et al., 2010; McGee et al., 2012; Price et al., 2012; Reiners, 2002; Smith et al., 2008). While this is of undoubted academic interest it also carries the practical corollary that knowledge of the way magmas are produced and particularly the rate with which they rise to the Earth's surface is a vital input to volcanic risk scenarios.

Small-scale basaltic volcanic systems are the most widespread form of magmatic system on Earth (Cañón-Tapia and Walker, 2004) although they are also the smallest in terms of magma volume. They characteristically occur as fields of small volcanoes found in a variety of different tectonic settings including intraplate, extensional and subduction-related environments (Cañón-Tapia, 2016). Individual volcanoes in these fields typically form during a time-constrained series of eruptions and represent a distinct batch of magma (e.g. Németh and Kereszturi, 2015). The duration of eruptions building such volcanoes may be months, (e.g. Mirador 1979 April–May, Southern Chile Lopez-Escobar and Moreno, 1981, Izu (Yamamoto et al., 1991), Ukinrek (Kienle et al., 1980)) or years (e.g. Paricutin February 1943–February 1953, Mexico, Erlund et al., 2010).

The last two decades have seen a renewed interest in small scale basaltic volcanism in terms of volcanology, geochemistry, structural and tectonic controls as well as hazard and risk studies. The associated volcanoes have also attracted increased interest because significant aspects of their chemical compositions provide insights into the behaviour of their mantle sources. Their most significant chemical characteristics are the remarkable compositional variations observed between individual eruptive centres and within sequences that represent very small magma volumes and the interpretation that the compositions of magmas erupted at the Earth's surface represent processes that generate magmas within the upper mantle. With the advancement of analytical techniques there has been a shift in the past few decades from studies combining classical volcanology, petrology and chemistry (e.g. major element analyses and norm calculations of the Springerville

volcanics, USA (Condit et al., 1989), and the volcanological and petrographic study of the Laacher See tephra by Woerner and Schmincke (1984)) to studies involving techniques such as the measurement of uranium series (U-series) isotopes (e.g. U-Th-Ra isotopic analyses in the Newer Volcanic Province, Australia (Demidjuk et al., 2007)) and the Auckland Volcanic Field (McGee et al., 2011, 2013) and in-situ techniques such as the measurement of melt inclusions (e.g. the Chaîne des Puys volcanic field, France (Jannot et al., 2005) and the Higashi-Izu volcanic Field, Japan (Nichols et al., 2012). These have revealed complexities in magmatic systems which help constrain the parameters and melting processes relating to the source region beneath volcanic fields.

1.1. The monogenetic concept, and the scope of this review

In volcanological terms the idea of monogenetic behaviour is one of a temporally limited cone building eruption sequence (e.g. Németh and Kereszturi, 2015); many small scale volcano fields are made up of individual cones that fit this description. Geochemically, the term monogenetic is most useful to refer to a batch of magma which is generated by a single continuous process. However, the increasing numbers of detailed studies of such systems in recent years has shown that melting processes can range from simple melting of a homogeneous source to more complicated melting of a multi-component source (c.f. McGee et al., 2012). Specifically, volcanoes that are the product of distinct magma batches are not geochemically monogenetic although they may be described as monogenetic from a volcanological perspective (e.g Udo Volcano, Brenna et al., 2010). Although we agree that the term monogenetic can be applied to small scale basaltic systems, recognising that for both volcanological and geochemical applications there is a poorly defined transition to polygenetic medium and large scale magmatic systems, in this review we prefer the term 'small-scale basaltic system'.

Small-scale basaltic systems are characteristically expressed at the Earth's surface as volcano fields consisting of clusters of scattered and mostly small (<2 km^2 magma volume) volcanoes that are fundamentally basaltic. Individual volcanoes in volcano fields show characteristic compositional ranges which equate to batches of magma (c.f. Francis and Oppenheimer, 2004) within the general compositional framework of the field as a whole. In many cases the erupted basalts show geochemical characteristics that suggest that they have not been significantly modified by processes of fractionation and assimilation during their journey through the crust and therefore they represent approximations of primary melts of their mantle source. Such magmas reflect the processes of melting and extraction from their sources, the compositional signatures of which are overprinted in larger - more complex - systems where compositions range from basaltic to intermediate and felsic (e.g. trachybasalt, benmoreite, trachyte, phonolite) and provide evidence for greater compositional modification during transit through the crust.

These generalities aid in the focussing of this review. Although there are examples of submarine small volume eruptive centres (such as those that extend southwards from the mainland in the Higashi-Izu volcanic field, Japan e.g. Hasebe et al., 2001; Nichols et al., 2012) we focus on terrestrial examples as they are by far the most abundantly studied, and thus provide a more robust underpinning for a review. Although we refer to examples from subduction, extensional and intraplate tectonic settings we focus the discussion mainly on rock compositions from

intraplate environments. Magmas which ascend in intraplate contexts represent snap-shots of the process of mantle melting and are unbiased by tectonic processes and context-specific characteristics, such as the influx of fluid mobile elements from slab fluids and sediments.

Although the compositions that are erupted in small volcanic systems generally do not reflect large-scale crustal processing, the presence of truly primitive basalts (i.e. those that are completely unmodified from their starting compositions from the onset of melting to eruption at the surface) is extremely rare. In this review we discuss volcano fields where the majority of the compositions are in the basalt range. However, we include more differentiated compositions with specific source signatures, such as the phono-tephrites of Wudalianchi which contain up to 8 wt.% MgO (e.g. Hsu and Chen, 1998), and fields which show evolution of compositions towards more felsic rock types that are due to crustal processes (such as in the Trans Mexican Volcanic Belt where compositions range from basalt to andesite e.g. Wallace and Carmichael, 1999; Siebe et al., 2004). Although the latter are clearly not 'primitive' basalts, they are not part of long-term established, stratovolcanoes and we include them in our discussion of the compositional characteristics of small scale basalt systems because they reflect the behaviour of small volume melt batches in their respective environments.

Table 1 summarises the main characteristics of representative examples of volcanic fields worldwide. The fields listed were chosen based on the amount and range of data available (e.g. whole rock major and trace element contents, isotopic data), so as to best represent each tectonic environment and each continent. In general, data compilations from whole-field studies are used, although some examples from individual volcanoes are discussed where data are available for a complete volcanic sequence (e.g. Paricutin, Cebriá et al., 2011; Motukorea, McGee et al., 2012; examples from the Newer Volcanic Province of Southern Australia). Although each volcanic field has its own individual character, source composition or crustal structure (such as the existence of polygenetic centres preceding monogenetic centres at Higashi-Izu (Hasebe et al., 2001), the presence of flood basalts beneath the monogenetic centres in Yemen (Baker et al., 1997), or the highly potassic basalts at Wudalianchi (e.g. Zou et al., 2003)), this review seeks to summarise the general characteristics of small-scale basaltic magmatic systems and their products, and identify future research directions where knowledge is currently sparse or lacking.

2. The chemical characteristics of small scale basaltic magmatic systems

Fundamental to an understanding of the geochemical behaviour of small-scale basaltic systems is the concept of a compositionally discrete magma batch. However, although some small scale basaltic cones are demonstrably the product of a single magma batch there are also abundant examples of cones built by interaction of compositionally distinct magma batches or by sequential eruption of magma batches.

2.1. The compositional spectrum

Although the compositions of volcanoes in volcano fields are dominantly basaltic there is wide variation within this spectrum from strongly silica-undersaturated nephelinites through basanites and alkali basalts to sub-alkaline transitional and tholeiitic basalts (Fig. 1). Magmas with relatively high MgO contents and magnesium numbers ($Mg\# = [\frac{MgO}{mol.}/(\frac{MgO}{mol.} + \frac{FeO}{mol.})] \times 100]$ appropriate to equilibration with mantle source mineralogy (Mg# ~65–70) encompass a range from nephelinite to tholeiite. Magmas with lower MgO and higher alkalies and other incompatible elements represent either evolution from primary mantle-derived compositions or expressions of unique mantle lithologies, and describe a wider compositional range from undersaturated to over-saturated compositions that remain within the basaltic spectrum (<53 wt.% SiO_2).

The geochemical character of a volcano field is in part related to its specific tectonic setting including intraplate (e.g. Eastern Australia, northern New Zealand), extensional (e.g. central Europe, Arabia) and subduction associated (e.g. Mexico, Japan) settings. Important underlying factors for the development of such volcanic systems are small magma volumes, episodic eruption of discrete magma batches and a crustal environment that allows the passage and escape of small magma volumes through the crust.

Although the observed compositions of volcanoes in each of intraplate, extensional and subduction related tectonic environments overlap, there are some distinct trends as illustrated in Fig. 1 where data from each tectonic setting are shown. In intraplate and extensional tectonic settings compositions are more commonly undersaturated to strongly undersaturated in terms of silica compared with those in subduction-related settings where compositions tend toward silica oversaturation.

There is a greater abundance of high MgO compositions in volcano fields generally compared with the central volcanoes of subduction-related arcs and with oceanic ridges/rifts, and arc-related rocks show a greater abundance of more evolved compositions (MgO 3–5 wt.% compared to 8–10 wt.% in volcanic fields (Fig. 2). Oceanic rifts display a similar pattern of more abundant lower MgO compositions, but shifted to slightly higher values than those for arcs (5–7 wt.% MgO). This difference points to the more significant role of shallow (crustal) processes in rifts and arcs. A similar pattern is also shown in the data from volcano fields with those in subduction settings showing a greater abundance of more differentiated compositions. Volcano fields in extensional environments however, display a similar pattern to purely intraplate fields (a peak at 9–10 wt.% MgO). This relative lack of differentiated compositions is also seen in SiO_2 abundance, although there is much less spread in the global data. However, it can be clearly seen that the pattern in SiO_2 content for volcanic fields is shifted to lower values, with a peak at 46–48 wt.% SiO_2 compared to 52–54 wt.% for arcs and 49–51 wt.% for ridges.

The relative abundance of alkalic compositions such as nephelinites and basanites has been noted in several studies from volcanic fields in extensional and intraplate settings (e.g. the Auckland Volcanic Field (AVF), Newer Volcanic Province (NVP), Jeju, Zuni-Bandera and Arabia, see Table 1). A notable characteristic is that compositions in these settings often display a negative trend on a total alkali-silica plot (Fig. 1). This characteristic is often accompanied by high MgO contents suggesting that the negative correlation is a source-related rather than differentiation-related feature. When plotted according to tectonic setting it can be seen that this characteristic is more pronounced in intraplate fields. The compositional trends in subduction-related fields and some extensional fields are more commonly towards higher silica and higher alkali content.

A highly significant observation of small scale basaltic volcanic systems is that there is a strong correlation between the volume of individual magma batches (individual volcanoes) and their chemical composition (McGee et al., 2015). The importance of this observation is that it links the behaviour of the mantle source directly with its surface manifestation as a volcano field. In general the smallest volume magma batches have compositions at the low SiO_2 highly alkaline end of the compositional spectrum. Larger volumes trend toward less alkaline more silica saturated compositions, thus in total, the compositional spectrum nephelinite-basanite-alkali basalt-tholeiite is defined. A related pattern is that larger volume systems trend toward chemical patterns that are interpreted as due to processes in more complex shallow plumbing systems whereas smaller volumes show chemical complexity which is linked to their mantle source componentry and behaviour. By its nature, this important correlation is best demonstrated in relatively young volcano fields because volumes become increasingly difficult to estimate as erosion degrades primary volcanic land forms.

Table 1
Worldwide monogenetic fields from different tectonic settings.

Volcanic field (VF)	No. centres and size of area (km^2)	Active since (Ma)	Most recent activity	*Lava chemistry	Source features and petrogenesis	Fractional crystallisation and/or crustal contamination	[a]Degree of melting	**Data references used in this work
Intraplate								
Auckland Volcanic Field (AVF), New Zealand	50 over 360 km^2	0.26 Ma	Rangitoto: c. 500 yrs. BP	Nephelinitic to alkalic basalt, rare subalkalic basalt	3 sources: garnet asthenospheric mantle, carbonated veins, spinel metasomatised lithospheric mantle	Near source fractional crystallisation in some centres, none in others	0.75–5%	Needham et al. (2011), McGee et al. (2012, 2013), and Smith et al. (2008)
South Auckland Volcanic Field (SAVF), New Zealand	100 over 300 km^2	1.59	0.51 Ma	Transitional to tholeiitic (low alkalis), and basanites (high alkalis)	2 groups which are thought to have different sources (garnet and spinel bearing, with some influence of a HIMU or EMII component)	Ol + Cpx fractional crystallisation.	<8% and <12% for the two groups	Briggs et al. (1994), Cook et al. (2005), and Rafferty and Heming (1979)
Northland fields, New Zealand	Unknown no. centres over 2500 km^2	2.3 Ma	1300 yrs. BP	Alkalic basalt, some subduction chemical traits. Rare intermediate and rhyolitic compositions (not shown in Fig. 1)	Area of previous subduction (seen in a negative Nb anomaly).		5–20%	Huang et al. (2000) and Smith et al. (1993)
Jeju Island, Korea	360 over 700 km^2	Late Pliocene	1002 and 1005 CE	Alkalic basalts and trachybasalts	Distinct magma batches from garnet and spinel bearing mantle	Ol + Cpx + − Spinel fractional crystallisation.	<10%	Brenna et al. (2010, 2012) and Tatsumi et al. (2005)
Newer Volcanic Province (NVP), Australia	400 over 15,000 km^2	Earliest 4.5 Ma	5000 yrs. BP, near Mt. Gambier	Basanite-hawaiite, plus a major subalkalic component	Deep and shallow mantle sources invoked	Limited fractional crystallisation	2–5%	Boyce et al. (2014), Demidjuk et al. (2007), Jordan et al. (2015), Van Otterloo et al. (2014), and Vogel and Keays (1997))
Wudalianchi Volcanic Field, NE China	14 over 800 km^2	Quaternary	Laoheishan & Huoshaoshan 1720 CE	Potassic phonotephrites to tephri-phonlites	Mantle source thought to be phlogopite-bearing garnet peridotite. Late Tertiary lithospheric extension produced slow decompression melting, which may be related to recent subduction of the Pacific plate		5–7%	Hsu and Chen (1998), Zou et al. (2003), and Zou et al. (2008) (Data from the 2 most recent eruptions only reported in this review)
Extension								
Harrat Ash Shaam, Jordan	Unknown no. centres over 11,400 km^2	Miocene (c. 14 Ma)	17th Century	Alkali basalts to basanites	Polybaric melting of a heterogeneous source (spinel and garnet bearing)	Limited fractional crystallisation	2–5% mixing with <1% deeper melts	Shaw et al. (2003)
Cima Volcanic Field, California, USA	70 over 150 km^2	3 principal periods of activity 7.55–6.47 Ma, 5.12–3.27 Ma and 1.14–0.015 Ma	c. 10,000 yrs. BP	Alkali olivine basalts and basanites to basaltic trachy-andesites	Polygenetic character of some of the cones. 3 groups of basalts (age and composition), group 1 thought to be from LREE enriched Pacific MORB in a slab gap, and groups 2 and 3 either smaller degrees of melting or subcontinental lithospheric mantle		Smaller for groups 2 and 3 than group 1	Farmer et al. (1995)

Zuni Bandera Volcanic Field, New Mexico, USA	>7 over c. 150 km²	1.5 Ma	1000 CE	Alkalic to tholeiitic basalts and basanites	Polybaric melting: a mixture of alkalic melts from garnet mantle, and tholeiitic melts from spinel mantle	Fractional crystallization of Ol + −Cpx + −spinel in the tholeiitic magmas, little in the alkalic magmas	Mixing of <1% and 3–10% melts	Menzies et al. (1991) and Peters et al. (2008))
Southwest (SW) Nevada Volcanic Field, USA	17 over apporx. 500 km²	5 Ma	77 ka, Lathrop Wells	Alkalic basalts to Trachybasalts	Separate and independent magma batches. Lathrop Wells: increasing silica saturation with time	Some deep fractional crystallisation of Ol − +amphibole.	Thought to be small and variable	Valentine and Perry (2007)
Big Pine Volcanic Field, California, USA	24 over 500 km²	1.2 Ma	Unknown (active until 0.032 Ma)	Basanites, to alkalic and subalkalic basalts and trachybasalts	Coupled melting and mixing of two distinct sources	Limited fractional crystallisation. Variation in single centres is equal to that of the entire field	'Small'	Blondes et al. (2008)
Siebengebirge, Germany (Part of the Central European Volcanic Province (CEVP))	Unknown no. of centers ver 1500 km²	28 Ma	Unknown (active until 6 Ma)	Basanite to rare alkali basalt and trachytes	Melting of spinel peridotite containing residual amphibole	Fractional crystallisation of Ol + Cpx + oxides + amph + plag in the alkalic and more evolved rocks. Assimilation of lower crust is suggested	'Small'	Jung et al. (2012)
Westerwald and Vogelsberg, Germany (Part of the CEVP)	Unknown no. centers over 800 km²	32-21 Ma and 19-9 Ma	Unknown	Basaltic, with some trachytic to phonolitic compositions	Melting of garnet peridotite (Westerwald) and at the garnet-spinel boundary with residual amphibole (Vogelsberg)	Significant alteration by crustal contamination and fractional crystallisation	Westerwald 4–7% Vogelsberg 3–10%	Haase et al. (2004)
West and East Eifel Volcanic Fields, Germany	240 over 600 km²	0.7 Ma – 10,000 yrs. BP	Ulmener Maar (c. 11,000 yrs. BP)	Dominant foiditic potassic basalts, some nephelinites and basanites in the west Eifel field	Although rift related the field is thought to lie above a mantle plume	The Laacher See tephra was the largest eruption (>6km³), and was modelled as erupting from a shallow zoned magma column	Lowest in the nephelinites and highest in the basanites	Shaw et al. (2003), Schmincke (2007), and Woerner and Schmincke (1984)

Subduction

Michoacán-Guanajuato Volcanic Field, Mexico (part of the Trans Mexican Volcanic Belt (TMVB))	1000 over 40,000 km²	Pleistocene	Parícutin (1943–1952)	Calc-alkaline andesites and basalts, some alkali and transitional		Affected by fractional crystallisation and assimilation (the latter documented in Parícutin)	Not given	Hasenaka and Carmichael (1987) and Luhr and Carmichael (1985) (Jorullo volcano); Cebriá et al. (2011) (Parícutin volcano)
Sierra del Chichinautzen Volcanic Field, Mexico (part of the TMVB)	220 over 2500 km²	Quaternary	1825BP (Chichinautzen group)	Calcalkaline andesites and basalts	Hydrous melting of heterogeneous (enriched/depleted) mantle	Polybaric fractional crystallisation with or without assimilation	3–8% for the smaller cones	Agustín-Flores et al. (2011), Siebe et al. (2004) and Wallace and Carmichael (1999)
Higashi-Izu Volcanic Field, Japan	70 centers over 350 km² on land, 50 over 700 km² including submarine cones	Monogenetic from 0.15 Ma	Teishi Kaikyu (submarine) 1989	High aluminium basalts to basaltic andesite	Thought to be from a similar source, at similar degrees of partial melting	Intra-volcano geochemical diversity seen in melt inclusions due to crystallisation history. Evolution of magmas by crustal contamination.	Not given	Hamuro (1985) and Nichols et al. (2012)
Pali Aike (PA) and Camasu Aike (CA), Chile/Argentina border	470 over 4500 km² (PA), unknown no. over 200 km² (CA)	3.8 Ma-recent (PA), 2.9–2.5 Ma (CA)	Unknown	Alkali basalt, trachybasalt to basanite (PA + CA), some basaltic andesites (CA)	Backarc setting. Thought to be generated in a slab window. Intraplate OIB with HIMU-like signature, melting of a garnet lherzolite source (PA and CA)	CA has primitive and more evolved compositions, the latter due to polybaric fractional crystallisation	PA: 1–2.7% CA: Similar to PA	Choo et al. (2012) (PA), D'Orazio et al. (2000) (PA), D'Orazio et al. (2005) (CA)
Carrán-Los Venados (CLV), Chile	65 over 160 km²	Holocene	1979 CE (Mirador)	Calc-alkaline to tholeiitic basalt to basaltic andesite	A similar (spinel lherzolite) source is invoked for all centres	Some effects of fractional crystallisation of olivine and oxides.	4–10%	Bucchi et al. (2015)

[a] Degrees of melting depend on models and parameters chosen by the authors of the cited references.
[b] Lava chemistry is based on data plotted in the total alkali silica (TAS) scheme of Le Maitre (2002), note that individual references may classify rock compositions differently based on the TAS scheme used in the publication.
[c] Figures in this work use data from references in bold.
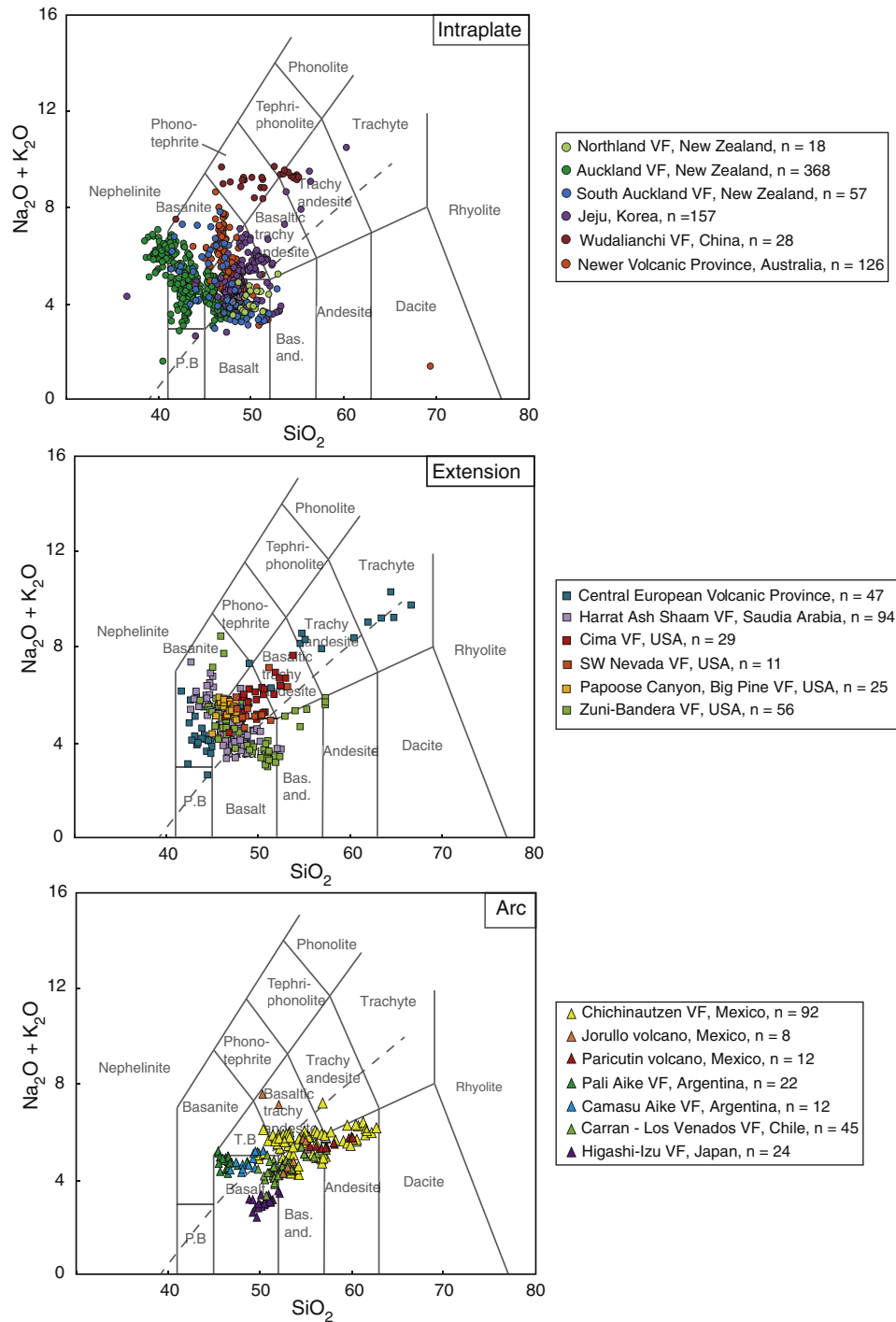
Fig. 1. Total alkali-silica plot after Le Maitre (2002). The dashed line is the alkaline-subalkaline division from Irvine and Baragar (1971). Volcanic fields (VF) are plotted by their dominant tectonic setting, all data sources are listed in Table 1.

2.2. Compositional variation within a magma batch

The compositional characteristics of basaltic magmas generated by partial melting within the upper mantle reflect the physical and chemical environment of their source. Potentially, magmas may rise unmodified from their source but crystallization differentiation together with conduit assimilation modifies the composition of these primary magmas. The extent to which primary magmas become compositionally modified is related to the rate of magma rise and to the tectonic setting, and the extent of melting which is in turn related to the volume of magma produced.

No volcanic field produces basalt which can be said to be truly primitive; therefore differentiation has occurred to some degree in all cases. In the case of intraplate fields such as the AVF and the NVP – which contain the most 'primitive' compositions (MgO 8–14 wt.%) – small amounts of fractionation of olivine with or without clinopyroxene can explain some inter-and intra-volcano trends. Smith et al. (2008) suggested that because small scale basaltic eruptions are generally fueled by rapidly ascending melts which do not form magma chambers, some trends may be explained by deep seated crystallization of mineral phases which are not represented as a phenocryst component in the erupted magma. This has also been suggested as an
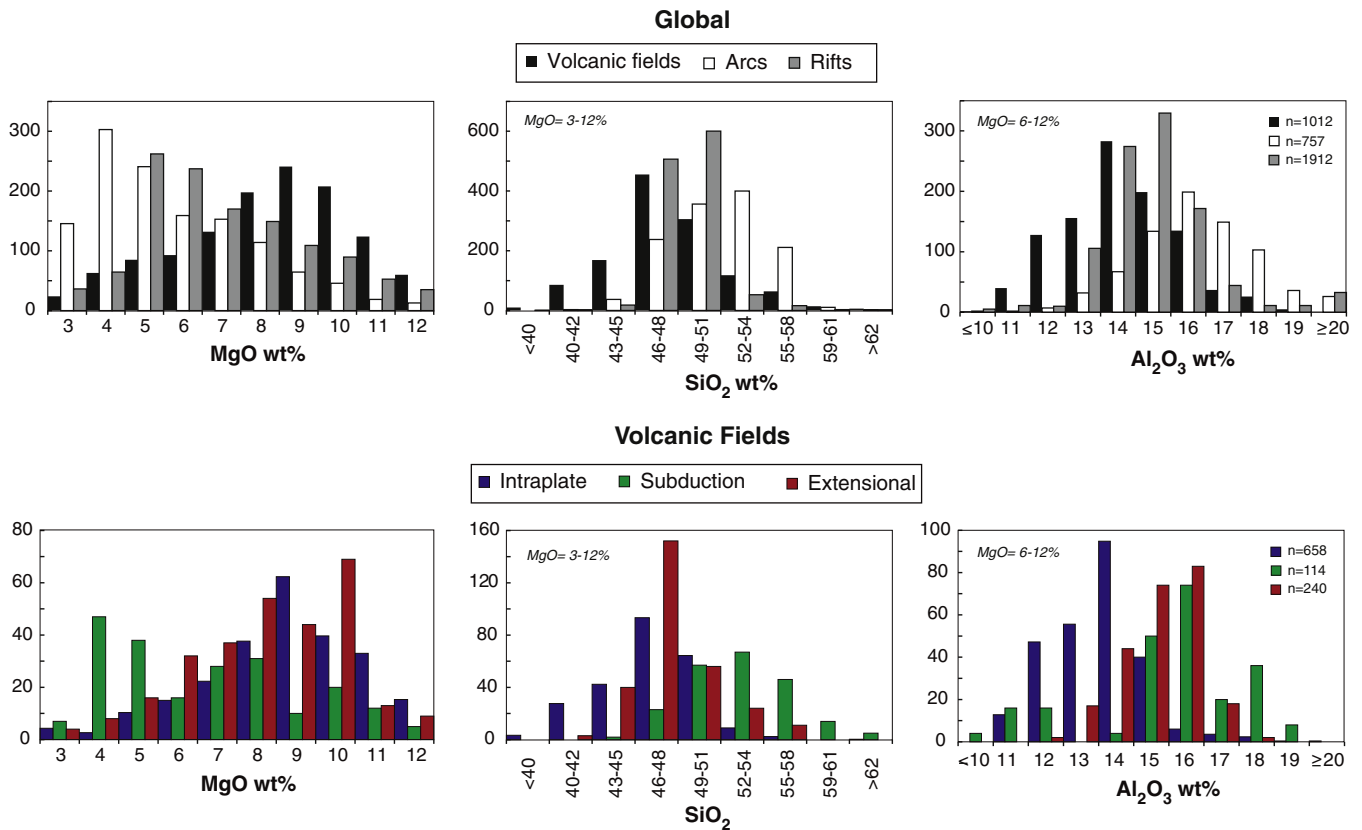
Global

Volcanic Fields

Fig. 2. Histograms of global data for volcanic fields, arcs and rifts (upper panel) and volcanic fields in intraplate, subduction and extensional settings (lower panel), for MgO, SiO$_2$ and Al$_2$O$_3$. The Y axis in each figure is the number of samples in each bin, note that numbers of samples in each histogram are normalized to similar n = x for each figure. Data sources for volcanic fields (n = 1228) are the same as those for Fig. 1, listed in Table 1 by tectonic setting. Arc and rift data are from the Georoc database; arc data (n = 1676) are from the Kermadecs, Lesser Antilles and Andes, and rift data (n = 2653) are from the Galapagos, North Sea, Ninety-East and Iceland ridges. All Georoc data was filtered by data for volcanic whole rock analyses only, and for samples for which major element data were available, and MgO between 3 and 12 wt.% inclusive. Note that samples between 6 and 12 wt.% MgO are reported for Al$_2$O$_3$ so as to avoid the effects of differentiation.

explanation for some of the trends at Lake Purrumbete, NVP (Jordan et al., 2015).

A relatively newly recognised feature in small-scale basaltic volcanoes is the systematic evolution in the composition of magma through the course of an eruption. Detailed sampling through the stratigraphy in volcanic sequences has revealed compositional variations that reflect deep seated fractionation processes acting on magma bodies close to their source (e.g. Blondes et al., 2008; Reiners, 2002; Smith et al., 2008). In these examples, magma erupted early in a sequence is typically relatively evolved in terms of chemical composition (lower MgO, higher total alkalis and higher incompatible element abundances) compared with magma erupted toward the end of an eruption sequence. The studies of Reiners (1998, 2002) demonstrated a model of 'reactive melt transport' to explain this phenomena in small volume magma batches whereby magmas ascending through the mantle become enriched due to reaction with wall-rock, which becomes progressively depleted over time and thus leads to the eruption of magmas more similar to the original input composition over the course of the eruption. In other cones there are compositional trends indicating two or more discrete magma batches (e.g. Boyce et al., 2014; Brenna et al., 2010) in a mingling relationship. There is also evidence that some 'monogenetic' cones have produced eruptions of compositionally distinct magma in temporally discrete episodes separated by years or decades (e.g. Needham et al., 2011; Linnell et al., 2016). Clearly there exists a spectrum of cases between a simple single compositional trend and complex cones. Magmatic systems in which the plumbing system is reused over significant time periods will show thermal evolution and ultimately geochemical evolution which may be reflected in more evolved

lithologies, dominance of shallower level processes, and the evolution of volcano fields to central cone complexes (e.g. Jeju, Brenna et al., 2012).

2.3. The compositional effect of fractionation and assimilation

Trends of increasing alkali content negatively correlated with SiO$_2$ at low silica content (<~46–48 wt.% SiO$_2$) which are mainly seen in intraplate settings together with trends of increasing alkali content positively correlated with SiO$_2$ at higher silica content which are seen in all tectonic settings (Figs. 1 and 2) are explained by differentiation processes with or without assimilation. Analyses of rocks from Cima and Camasu Aike volcanic fields for example have differentiation trends within the alkalic field ranging from basalt to basaltic trachyandesite which are explained by fractional crystallization (c. 20% in the case of Cima) of the main basaltic mineral phases olivine ± clinopyroxene ± plagioclase ± oxides (Farmer et al., 1995 and D'Orazio et al., 2005 respectively). More extensive trends such as that from basanite to trachyte in the Central European Volcanic Province (CEVP) are attributed to fractional crystallization with extensive lower crustal contamination (Haase et al., 2004; Jung et al., 2005), whilst the compositions generally remain within the alkalic field. Compositions in subduction related settings range from basalt to andesite, and tend not to extend to extreme alkalic compositions as in extensional settings, suggestive of more 'normal' evolution as one may expect in a crustal magma reservoir (e.g. Morgado et al., 2015). Positive trends in the Higashi-Izu volcanic field are explained by contamination of the parental basalt with granitic crust rather than fractional crystallisation (Hamuro, 1985),

which may explain the limited range in total alkalis-silica compared to, for example, the compositional ranges in the Mexican fields (Fig. 1). Parícutin volcano in the Michoacan-Guanajuato volcanic field of Mexico has long been used as an example of how combined fractional crystallization and assimilation can explain evolution from basalt to basaltic andesite in volcanic systems (Cebriá et al., 2011; Erlund et al., 2010; Luhr and Carmichael, 1985) however this model has been recently challenged in a melt inclusion study by Rowe et al. (2011) who suggest that contamination occurred before crystallization, and that at least two magma sources must have been involved.

3. The source of magma

Individual small volcanoes making up volcanic fields are primarily basaltic in composition and as such their origin lies in the mantle. The often near-primitive nature of the products of small-scale basaltic volcanoes facilitates an understanding of the nature of their mantle source as the melts reaching the surface experience little modification on their ascent unlike systems where magmas are more evolved (through, for example, long-term residence in magma chambers). Observation of basalts ranging from these near-primitive compositions to more evolved compositions also produced in monogenetic systems allows an investigation of the parameters involved in the melting process, as well as how the melts are extracted from their mantle sources and modified on their way to the surface.

3.1. Homogeneous and heterogeneous sources

A significant outcome of recent studies is the acknowledgement that the mantle source regions beneath volcanic fields are almost never homogeneous or simple; this is reflected in the use of such words as 'polycyclic' (e.g. Bradshaw and Smith, 1994), 'polybaric' (e.g. D'Orazio et al., 2005; Peters et al., 2008) and 'polymagmatic' (e.g. Brenna et al., 2010; Van Otterloo et al., 2014) in studies of basaltic volcanic fields, and the recent publication of articles challenging or supporting the term 'monogenetic' through the appraisal of what this term means from various perspectives (Cañón-Tapia, 2016; Cashman and Biggs, 2014; Németh and Kereszturi, 2015; Valentine and Gregg, 2008). From a geochemical perspective, it has now been widely shown that very few volcanoes involve the melting of only one petrographically and compositionally discrete source.

The involvement of more than one source is seen in the trace element ratios and isotopic ratios of rocks from volcanic fields, although careful analysis of differentiation processes is clearly important so as not to confuse source effects with the effects of crustal contamination (e.g. the Westerwald region of the CEVP, Haase et al., 2004). Radiogenic isotopes are critical in the study of mantle sources because of their sensitivity to components such as highly enriched or old mantle sources, sediments or fluids. For example, Pb isotopic ratios clearly show the heterogeneity of the mantle sources involved in most of the volcanic fields plotted in Fig. 3 with some fields of data displaying a linear array (such as the NVP, Carrán-Los Venados (CLV) and Pali Aike, Fig. 3A), whilst others show a clear triangular pattern (Fig. 3B) such as the AVF, Yemen, Jeju and Arabia. Each 'point' of the triangle is interpreted as a distinct component, with the compositions lying between these points representing mixtures. Typical findings from in-depth studies investigating mantle sources are that asthenosphere-lithosphere interaction is common, as is the involvement of enriched, physically discrete components. Commonly, one or more of these discrete components are envisaged as being metasomatised, carbonated and/or containing hydrous minerals.

3.2. Asthenosphere-lithosphere interaction

Geochemical studies of basalts in volcanic fields often describe interaction of melts generated in the asthenosphere with those
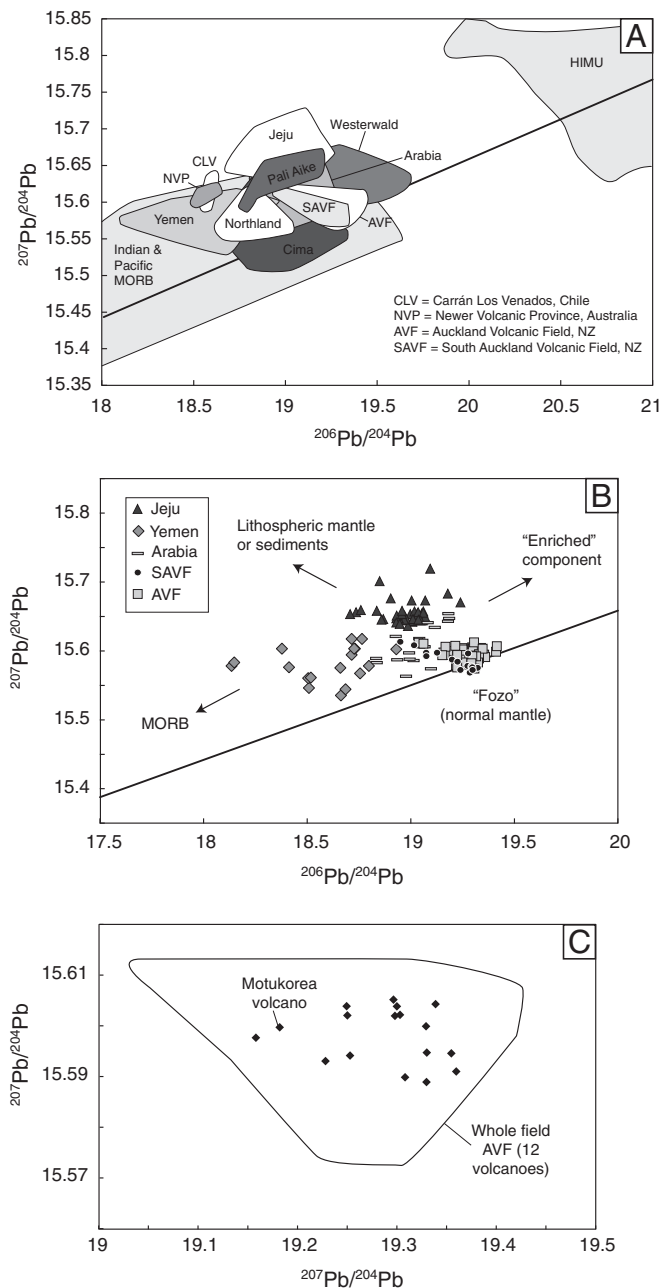

Fig. 3. Pb isotopic compositions for rocks in volcanic fields for which these data have been obtained (see Table 1 for data sources). HIMU and Indian and Pacific Mid Ocean Ridge Basalt (MORB) data fields are from a data compilation by Stracke et al. (2005). B. Pb isotopic data for rocks in selected volcanic fields which illustrate well that their compositions are the result of mixing of heterogeneous mantle. "Fozo" refers to the 'focal zone' mantle composition of e.g. Stracke et al. (2005). Volcanic field abbreviations in legend are as in A. C. The example of Motukorea volcano from the Auckland Volcanic Field shows how rocks from a single sequence can display heterogeneity which is seen on the scale of the whole field (data from McGee et al., 2012, 2013).

generated in the lithosphere. In this context the terms asthenosphere and lithosphere refer to mantle lithofacies that are either garnet bearing or spinel bearing which carry implication for the depths involved; in either case small scale melts carry a distinctive geochemical signature.

The concept of asthenospheric and lithospheric sources helps to explain the spread in isotopic ratios and the mixing trends often observed in data sets from volcanic fields. Typically, hypothetical end member compositions are used, although sometimes individual

volcano compositions cover the extremes of trends and can be used directly. Such a model, and the fact that it is now so commonly used, suggests that the idea of rapidly ascending melt batches from a single melting event is probably simplistic as there is obviously melt/residue interaction throughout the melting column/zone. This suggests that extraction of melts starts deep and proceeds upwards, however, the timing or sequence of mixing appears to be dependent on the particular tectonic regime. In the case of the Harrat Ash Shaam volcanic field in Jordan, lithospheric extension primarily creates melting in the lithospheric mantle and very small degree melts of the underlying garnet asthenosphere are incorporated secondarily (Shaw et al., 2003), whilst in the intraplate AVF, melting begins in the asthenosphere, and with larger degrees of melting incorporates melts from the shallower lithospheric mantle (McGee et al., 2013).

Commonly, one or other of the asthenospheric or lithospheric sources are envisaged as having a distinct 'flavour' to explain a particular compositional characteristic, or spectrum of characteristics. An example of this is that the lithospheric component is often modelled as being metasomatised, to explain why some rock compositions have higher concentrations of light rare earth elements (LREEs) within the same volcanic field (e.g. Mt. Gambier, NVP, Australia, Van Otterloo et al., 2014; Zuni-Bandera volcanic field, USA, Menzies et al., 1991; Peters et al., 2008; Southern Cascades, USA, Strong and Wolff, 2003, South Auckland Volcanic Field (SAVF), New Zealand, Cook et al., 2005). A further example of this is the North Island of New Zealand, where subduction migrated from the north to its present position as the Taupo Volcanic Zone during the Late Cenozoic, but left vestiges of subduction characteristics in the lithospheric mantle which can be seen in the composition of rocks from volcanic fields from Northland down to the SAVF (Cook et al., 2005; Huang et al., 2000; McGee et al., 2013). Wass and Rogers (1980) suggested that metasomatism is in fact necessary as the means by which continental intraplate volcanism could initiate, by lowering the solidus sufficiently to allow small degrees of melting to occur.

3.3. Enriched components

Many studies invoke the involvement of discrete components, often in the form of veins, of more exotic compositions such as eclogite or pyroxenite, and/or of carbonated, hydrated or recycled composition. The melting and subsequent incorporation into melts of such components are cited as the cause of high LREE or large ion lithophile element (LILE) contents such as Sr and Ba, especially in nephelinites (e.g. McGee et al., 2012; Van Otterloo et al., 2014), as well as isotopic trends towards the "High-μ" (HIMU) or "Enriched Mantle" (EM) fields. These discrete components provide the 'missing piece' in studies of volcanic fields which require a third constituent to explain the full spectrum of compositions observed (e.g. Fig. 3B).

The inclusion of discrete, enriched components is often connected to the tectonic history of a region, for example the incorporation of old, pyroxenitic oceanic crust with a HIMU signature mixing with fertile asthenosphere in the case of the Lunar Crater volcanic field, Nevada, (Rasoazanamparany et al., 2015), and the evidence for HIMU-like 'fossil' veins at the base of the lithosphere suggested by Sprung et al. (2007) as originating from a Cretaceous plume beneath New Zealand. In other tectonic settings, the current tectonic context contributes signatures, such as in the Hocheifel where EM and HIMU compositions are thought to come from mantle 'plumelets' beneath the active rift (Jung et al., 2006). The identification of these components as of eclogitic, peridotitic or pyroxenitic mineralogy requires the careful use of compositional data (for example, CaO/Al_2O_3, MnO, SiO_2 e.g. Timm et al., 2009, and diagnostic HFSE ratios such as Zr/Hf (Fig. 4A) where element mobility in fluids is likely to be low and partition coefficients are similar thus source heterogeneity is more clearly demonstrated) and may be important in terms of the initiation of melting as compositions with modally less olivine and
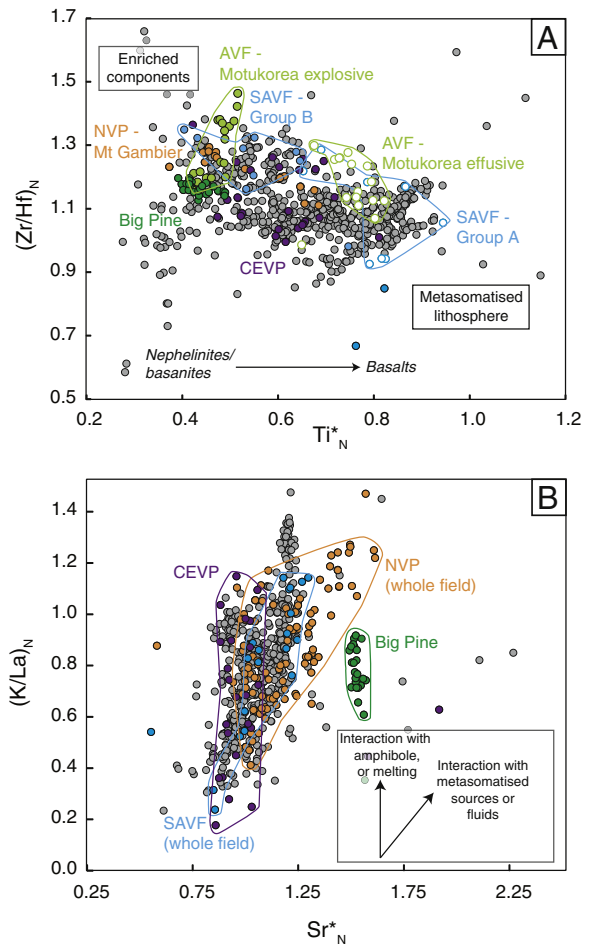

Fig. 4. Primitive mantle normalized high field strength and large-ion lithophile element ratios vs. element anomalies for all volcano fields in Table 1 for samples of MgO > 6 wt.%. A $(Zr/Hf)_N$ vs. Ti^*_N (calculated as $Ti_N/(Hf_N \times Sm_N)$ showing examples from the literature which involve mixing of an 'enriched' component melt and 'metasomatised lithosphere'. NVP (Newer Volcanic Province) Mt. Gambier data are from Van Otterloo et al. (2014), SAVF (South Auckland Volcanic Field) groups A and B are from Cook et al. (2005) and AVF (Auckland Volcanic Field) Motukorea data are from McGee et al. (2012). All other data references are as in Table 1. Many fields and individual centers show a spread of data suggesting mixing of sources whilst others (such as Big Pine) show little variation. B. $(K/La)_N$ vs. Sr^*_N (calculated as $Sr_N/(Pr_N \times Nd_N)$. Vertical arrays suggest less interaction with fluid metasomatised sources (which would be expected to be elevated in mobile Sr and K), and a greater influence of amphibole, or melting processes (because of the incompatibility of La). The lack of variation in Sr^*_N in the Big Pine data is further evidence that it does not involve a metasomatised source. Data are normalized to the primitive mantle values of Sun and McDonough (1989).

more pyroxene have lower solidi (e.g. Hirschmann and Stolper, 1996; Prytulak and Elliott, 2009).

The melting of lithospheric hydrous veins containing metasomatic amphibole is suggested by Pilet et al. (2008, 2011) as a key factor in the genesis of alkaline basalts in oceanic and continental settings. Such hydrous mineral phases (typically amphibole, but sometimes phlogopite) can be reflected in volcanic field basalts by particular chemical characteristics such as negative K anomalies leading to elevated $(K/La)_N$ ratios (Fig. 4B) and bowed shapes in rare earth element (REE) plots, a feature which is notably present in the CEVP (e.g. Siebengebirge, Jung et al., 2012; Hocheifel; Jung et al., 2006, Rhön, Jung et al., 2005; Eger rift, Brandl et al., 2015; Haase and Renno, 2008), along with other volcanic fields such as in Syria (Ma et al., 2011) and Turkey (Ersoy et al., 2012) where amphibole has been modelled as a constituent of the melting region.

Carbonated lithologies are also suggested as important components, and can be a reason for the abundance of silica-undersaturated

compositions in volcanic fields when associated with other key trace element signatures such as low Ti/Eu and K/La (e.g. McGee et al., 2015; Scott et al., 2014). However, silica under-saturation has also been attributed to the involvement of melts of volatile-poor eclogite (e.g. Kogiso and Hirschmann, 2006; Kogiso et al., 2003), and additionally, involvement of enriched components is not unique to the generation of magmas supplying volcanic fields, as evidenced by numerous studies of larger basaltic intraplate – often plume-related – volcanic systems such as the Azores (e.g. Beier et al., 2007; Millet et al., 2008; Prytulak et al., 2014; Widom et al., 1997), Canary Islands (e.g. Lundstrom et al., 2003; Sigmarsson et al., 1998) and Hawaii (e.g. Herzberg, 2006; Lassiter and Hauri, 1998; Sisson et al., 2009).

3.4. The spatial scale of heterogeneity in magma sources

Detailed studies of individual eruptive events within volcanic fields reveal that mantle source heterogeneity exists on a very small spatial scale. These variations exist on both vertical and horizontal scales, as evidenced by distinctive chemical signatures correlating with pressure indicators such as fractionation corrected major element oxides (Al$_2$O$_3$, CaO, SiO$_2$ c.f. Hirose and Kushiro, 1993), or middle-REE/heavy-REE (MREE/HREE) ratios. Detailed chemical analysis of stratigraphic sequences reveals the role which discrete components play in the petrogenesis of a small eruptive centre. Motukorea Volcano in the AVF is an example of a small volume basaltic volcano in which magmas erupted early are modelled as very small degree melts of an enriched component and these are followed without temporal break by magmas produced by melting of ambient garnet-bearing peridotite; these components can distinguished by their Pb-isotopic signature which mimics that of the whole volcanic field (Fig. 3C) (McGee et al., 2012). Heterogeneity on the scale of 500 m or less was also recently found in the Lunar Crater volcanic field by Rasoazanamparany et al. (2015) in a similarly detailed stratigraphic study of a single monogenetic eruption. This is significant, as there are few examples in larger magmatic systems where such heterogeneity can be seen except in exceptional circumstances such as the glacial unloading-related melting of distinct mantle sources in Iceland (Sims et al., 2013).

The case of subduction related volcanic fields is more complicated because the mantle source is influenced by the chemical composition of fluids which come from the slab, and the depth at which this occurs. However, small eruptive centers in subduction settings show the heterogeneity of these fluids and the small scale on which they are found as described in studies from closely-spaced monogenetic centers in Southern Chile (Hickey-Vargas et al., 2002) and the Cascades (Borg et al., 1997; Strong and Wolff, 2003). Thus far, the majority of studies of volcanic fields which show multiple source components are from intraplate and extensional settings perhaps because the more extensive differentiation processes which occur in subduction related volcanic fields overprint such detail.

4. The mantle source

4.1. Depth and extent of melting

In most studies of small-scale basaltic systems, magmas are modelled as melts originating in garnet bearing asthenosphere and this is a defining feature of their petrogenesis. A major indicator of this feature is the generally steep trend displayed on chondrite-normalised REE profiles in samples compared to basalts in other more complex tectonic settings (Fig. 5). Additionally the lower Al$_2$O$_3$ concentrations displayed by analyses from volcanic fields compared with those from arcs (Fig. 2) at high MgO contents is evidence for a deeper origin for such melts because it has been shown experimentally that increasingly higher pressures decrease whole rock Al$_2$O$_3$ contents in mafic material (e.g. Baker and Stolper, 1994; Hirose and Kushiro, 1998; Kogiso et al., 2003).
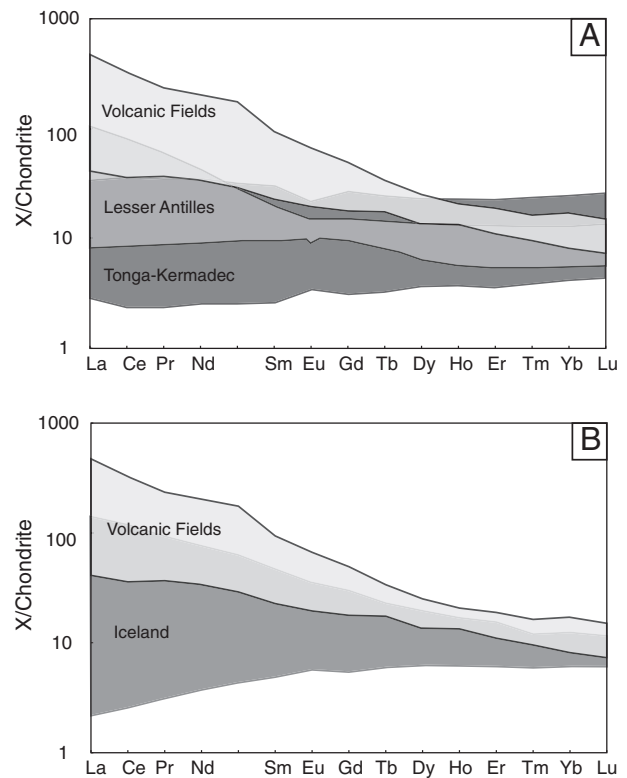

Fig. 5. Chondrite normalized rare earth element (REE) plot for all volcanic fields in Table 1 for which samples have been analyzed for REE with MgO >6 wt.% and A. selected arc data (Lesser Antilles and Tonga-Kermadec data from Davidson et al., 2013) and B. rift data represented by a Georoc compilation of Iceland data (samples >6 wt.% MgO). Volcanic field data clearly show a steeper trend and higher light-REE concentrations compared to arcs and rifts. Data are normalized to the chondrite values of Sun and McDonough (1989).

Mantle source composition and the proportion of modal garnet or spinel is generally modelled quantitatively by the use of MREE/HREE ratios in basalts from volcanic fields. Data for 11 volcanic fields for which trace element data exist are plotted in Fig. 5 (using samples with MgO 6–12 wt.%). Ocean rifts and subduction-related arcs display notably lower Tb/Yb compared to the volcanic field dataset and this is interpreted as a lesser influence from residual garnet which is further supported by the generally higher Al$_2$O$_3$ contents at high MgO displayed by subduction related volcanic fields compared to those from intraplate or extensional settings (Fig. 2) indicating melt generation at lower pressures. The positive trend displayed in the volcanic field data is likely due to the mixing of deep and shallow (i.e. asthenospheric and lithospheric) melts, as discussed above. Even compositions of some extensional volcanic fields with the general characteristics of being produced from mainly spinel peridotite or lherzolite have been modelled as requiring the input of small quantities of low degree garnet peridotite melts (e.g. Arabia and Yemen, Baker et al., 1997; Shaw et al., 2003). It must be noted, however, that melting in the presence of metasomatic hydrous minerals (such as amphibole) or the crystallization of metasomatic clinopyroxene may affect MREE/HREE ratios leading to poor estimates of depth and degree of melting. Careful scrutiny of trace element characteristics that are diagnostic of the presence of amphibole or clinopyroxene (e.g. Dy/Dy*, Davidson et al., 2013) and isotopic ratios to identify the effects of metasomatism is encouraged in future studies of small volume basalts.

The effect of garnet in the source region is also seen in the abundance of Th-excesses in studies where U-series isotopes have been obtained (Fig. 7). As Th is more incompatible than U in garnet when melting occurs the melt becomes enriched in Th over U if this mineral is present (e.g. Elliott, 1997). Small-scale volcanoes from subduction settings fall
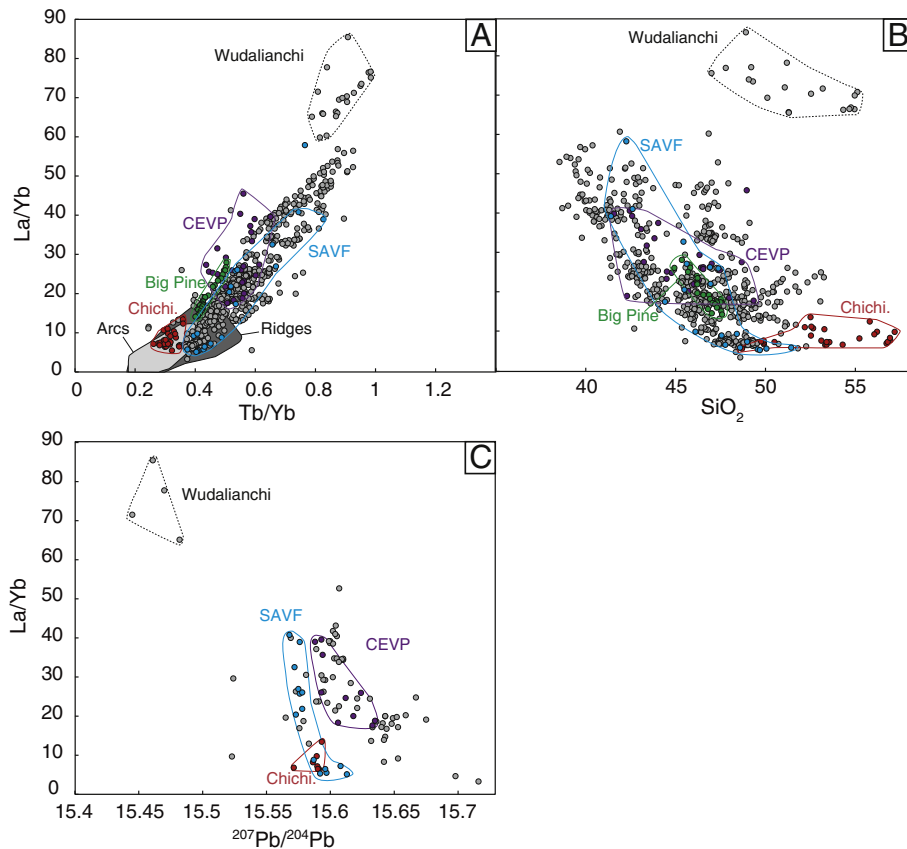
Fig. 6. Correlations with La/Yb for volcanic fields. Only data of between 6 and 12 wt.% MgO inclusive are plotted. Volcanic field data sources are from Table 1, and in all figures Wudalianchi data are indicated as they have a unique chemical composition (see text). In all figures, an example from an intraplate setting (the South Auckland Volcanic Field, "SAVF"), a subduction related setting (Chichinautzen, Mexico, "Chichi.") and two examples from extensional settings (Big Pine, California and the Central European Volcanic Province, "CEVP") are shown, although note Pb isotopic analyses are not available for Big Pine samples. A. La/Yb vs. Tb/Yb data display a positive trend indicating a correlation between smaller degrees of melting and greater depth/higher abundance of residual garnet in the mantle source. Rifts and arcs are as for Fig. 1 with the exception of data from the Andes arc. B. A negative correlation is observed in the global dataset between La/Yb and SiO2 suggesting that smaller degrees of melting produced silica undersaturated compositions. C. A broad negative trend is observed between La/Yb and ²⁰⁷Pb/²⁰⁴Pb, which is especially notable within individual fields, as shown in the CEVP and SAVF. The Chichinautzen volcanic field displays little correlation in A-C, and plots closer to arc-tpye La/Yb vs. Tb/Yb, see text for discussion.

partially in the U-excess field in Fig. 7 due to the presence of fluids from the slab in which mobile U is a major constituent, although there is evidence that magmas produced in subduction-related volcanic fields have shallower origins, as they do not display such high Tb/Yb ratios. For example, data from the Chichinautzen volcanic field plot close to that of arcs in La/Yb vs. Tb/Yb plots and in a cluster rather than a positive correlation (Fig. 6), suggesting that the magmas are not formed by mixing of deep and shallow melts. However, the MREE/HREE ratio can also be influenced by the mineralogy and starting composition of the source, for example, Wudalianchi compositions are highly elevated in trace element content and isotopic composition (Fig. 6) and this is thought to be due to an unusual mantle source, metasomatised by K₂O-rich fluids (Hsu and Chen, 1998; Kuritani et al., 2011, 2013) potentially containing phlogopite (Zhang et al., 1995; Zou et al., 2003). Equally, such ratios can be shifted lower if the mantle source is depleted, such as in the Pali Aike volcanic field in Southern Argentina (Choo et al., 2012; D'Orazio et al., 2000).

Whilst the literature is unanimous that volcanic field basalts are produced by small degrees of melting (see Table 1) this can vary within the field itself. Strong and Wolff (2003) in their detailed study of the cones in the Southern Cascades, showed that variable degrees of melting were implicated in melt generation, and observed a correlation between this and the quantity of fluid mobile elements. Different groups of basalts in the Cima volcanic field are also thought to originate from different degrees of melting of the mantle source, although another possible explanation is contemporaneous melting of a different source (Farmer et al.,

1995). A similar model is suggested for the Zuni-Bandera volcanic field (Peters et al., 2008), and the Pali Aike volcanic field (D'Orazio et al., 2000) demonstrating that a complex interplay between distinct mantle components and melting dynamics is common in studies of volcanic fields.

4.2. Correlations between melting dynamics and chemical composition

Notable correlations exist between indices of partial melting (e.g. La/Yb), indices of garnet/spinel i.e. depth (e.g. MREE/HREE ratios), silica, LILE concentrations and radiogenic isotopes (Fig. 6B and C); specifically, silica undersaturated, LILE enriched and isotopically enriched compositions are correlated with smaller degrees of partial melting at greater depths. This indicates that enriched components in the deeper mantle – often in the form of veins or small, discontinuous bodies – which give rise to generally alkalic, low silica, higher incompatible element compositions are preferentially tapped at small degrees of melting (c.f. McGee et al., 2015; Shaw et al., 2003; Sprung et al., 2007). The correlation is marked in intraplate and extension related volcanic fields, but is yet to be observed in subduction related fields. A few studies of individual eruptions have focused on this correlation, and observed that the enriched component is often detected at the very beginning of the eruption (Blondes et al., 2008; Ma et al., 2011; McGee et al., 2012), suggesting that it may have an important role to play in the initiation of the melting event (c.f. Wass and Rogers, 1980).

4.3. Why and how are small-volume melting events generated?

There are obvious tectonic reasons in most settings which explain the process of melting, such as the input of fluids to subduction related fields and the presence of decompression melting beneath actively rifting areas; these have been well-documented and discussed (e.g. Cañón-Tapia, 2016; Németh, 2010; Németh and Kereszturi, 2015; Valentine and Hirano, 2010). The local or regional stress field and tectonic setting are important factors in the genesis and form of some volcanic fields (e.g. Le Corvec et al., 2013) and may govern whether polygenetic or monogenetic systems occur (Bucchi et al., 2015; Takada, 1994). The evolution of some volcanic fields has been linked to tectonic plate movement, such as in the San Francisco volcanic field (Arizona) (Tanaka et al., 1986), and in northern New Zealand where both subduction and intraplate geochemical signatures are seen in the Northland basalts (Huang et al., 2000); the position of the volcanic arc in Mexico is thought to express a shift from polygenetic to monogenetic volcanism from north to south (Connor, 1987). Volcanism in intraplate settings is harder to explain: delamination of the lithosphere causing sporadic and dispersed upwelling over millions of years has been suggested as an explanation for the distribution and age range of volcanic fields in New Zealand (Hoernle et al., 2006). Lithospheric structure has been invoked as the cause of small volume magmatism in some other volcano fields, such as the edge-driven convection model of Demidjuk et al. (2007) for the Newer Volcanic Province. A similar idea is invoked for the Zuni-Bandera volcanic field of New Mexico, where changes in lithospheric thickness beneath the field are linked to changes in melting processes (Peters et al., 2008).

Although some volcano fields are found in purely subduction-related, extensional or intraplate settings worldwide (Connor and Conway, 2000; Petrone et al., 2003) others are found in extensional settings near to active arcs such as in the Cascades of the western USA (e.g. Leeman et al., 2005), or in intraplate settings which are gently rifting due to the occurrence of plume-like upwellings, such as in the Central European Volcanic Province (CEVP) (e.g. Haase and Renno, 2008). Volcanic fields can also be found in association with large stratovolcanoes as in southern Chile (e.g. Bucchi et al., 2015; Cembrano and Lara, 2009; López-Escobar et al., 1995) and Mexico (e.g. Schaaf et al., 2005; Siebe et al., 2004), suggesting complex melting regimes and plumbing systems beneath these areas.

Of geochemical interest is the enigma of how small volume volcanic fields develop in areas where there is no obvious cause of melting (i.e. truly intraplate, non-plume related fields such as the AVF, New Zealand, or the NVP, Southern Australia). It has been suggested that in such settings, eruptions are frequently paired (Németh et al., 2003; Strong and Wolff, 2003), and that the second event in each pair is always larger (e.g. Brenna et al., 2010; Needham et al., 2011), identifying the first as a 'pathfinder'. However, this does not solve the problem of how the first, smaller eruption is generated.

5. Timescale information from geochemical data

5.1. Timescales in the source

Surprisingly few U-series studies of volcano fields exist despite the fact that the fields which are accessible and more extensively studied are generally Holocene, and therefore within the measureable five half-lives of U—Th at least ($t_{1/2}$ ^{230}Th: 76,000 years, e.g. Peate and Hawkesworth, 2005) and generally lack extensive differentiation processes making them ideal for such studies. Some aspects of U-series studies simply provide more evidence for parameters deduced from other isotopic or elemental indices (such as degrees of melting, and whether melting is in the presence of fluids or residual garnet). The data in Fig. 7 almost all plot in the field of Th-excess related to the prevalence of melts generated in the garnet-stability zone, except for the Pinacate volcanic field (Mexico, Asmerom and Edwards, 1995) and
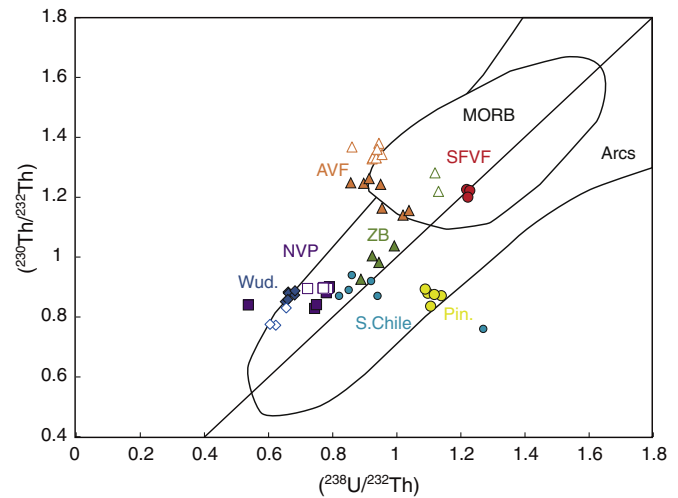

Fig. 7. Published U—Th isotopic data for volcanic fields worldwide. MORB and arc data fields are from Lundstrom et al. (2003). Wudalianchi (Wud.) data are from Zou et al. (2003), Newer Volcanic Province (NVP) data are from Demidjuk et al. (2007), Southern Chile (S. Chile) data are from Hickey-Vargas et al. (2002), Zuni Bandera (ZB) data are from Peters et al. (2008), Auckland Volcanic Field (AVF) data are from McGee et al. (2013), and Pinacate (Pin.) and San Francisco Volcanic Field (SFVF) data are from Asmerom and Edwards (1995). Filled and unfilled symbols in the same colour denote individual centres within fields, although note that each Southern Chile data point is from a distinct small eruptive centre. See text for discussion.

Pucón small eruptive centres (Southern Chile, Hickey-Vargas et al., 2002), which lie completely and partially in the field of U-excess, respectively, and the San Francisco Volcanic Field (Asmerom and Edwards, 1995) which lies on the equiline. Variations exist within individual data sets, which can be attributed to differences in depth and degree of melting (e.g. AVF, McGee et al., 2013) and Zuni-Bandera alkalic vs. tholeiitic compositions (Peters et al., 2008), and source region compositions (e.g. also AVF, Wudalianchi, Zou et al., 2003) and Southern Chile (Hickey-Vargas et al., 2002)).

The main power of the U-series chain is its time-related information, as the half-lives within the decay chain are on the order of the timescales of magmatic processes (e.g. Lundstrom, 2003). The use of timescale-related data can range from the more obvious observations, such as whether or not disequilibrium is observed (e.g. if ^{226}Ra disequilibrium is observed, this must have occurred within 5 half-lives of Ra, i.e. 1600 yrs. × 5 = 8000 yrs., as shown in Turner et al. (2001)), to more complex melting and upwelling models or deduction of mantle porosity and melt transport.

Upwelling rates in small scale basaltic systems have been modeled using U—Th isotopes for the Mt. Shank and Mt. Gambier volcanoes of the NVP, Australia (1.5 cm/yr, (Demidjuk et al., 2007), Rangitoto volcano in the AVF, New Zealand (0.1–1.5 cm/yr, (McGee et al., 2011) and the two most recent eruptions of the Wudalianchi volcanic field, NE China (<1.6 cm/yr, Zou et al., 2003). All modelled upwelling rates are similar and low, as is expected for intraplate regions. Thus far, studies of volcanic fields from subduction and extensional settings have not included this data, but it is assumed that the upwelling rates would be greater. Protactinium (Pa) isotope studies would be particularly useful in subduction related volcanic fields as ^{231}Pa is not fractionated by fluid input, rather partial melting degree, ingrowth and mantle porosity (Turner et al., 2006). McGee et al. (2015) additionally modelled the melting rates required to produce the measured (^{230}Th/^{232}Th) ratio for five eruptive events in the AVF, and found a strong correlation with eruptive volume, suggesting that larger eruptions are related to the extent of melting in the deep asthenosphere.

Studies using Ra isotopes could be vital in modelling the scale of mantle porosity and thus the rates and style of melt transport in small

volcanic systems. When porosity is low, higher ^{226}Ra-excesses can be generated due to diffusive interaction between the melt and surrounding matrix (e.g. Lundstrom, 2000); because these excesses are introduced at the beginning of the melting event and the half-life of ^{226}Ra is only 1600 years; the longer the melting column the more likely that the initial excess will start to decay and the measured ratio will be lower (e.g. Turner et al., 2000). McGee et al. (2011) analysed the (^{226}Ra/^{230}Th) ratios of samples from eruptions of Rangitoto volcano (c. 550 yrs. BP) — the only volcano in the AVF known to have erupted twice, alkalic then subalkalic basalts (Needham et al., 2011). The initial, alkalic basalts display higher ^{230}Th-excess but lower ^{226}Ra-excess than the subsequent, subalkalic basalt. This was modelled as two isolated melting events whose melts ascended via a high speed, deep channelized conduit and shallower, slower, diffusive porous flow respectively, which additionally provides support for the 'pathfinder' theory of melt ascent.

5.2. Timescales of melting

One of the classic tools for estimating the speed of magma ascent uses the size of mantle xenoliths found within basalts to calculate the rate at which a basaltic magma must have been moving in order to carry the xenolith (e.g. Sparks et al., 1977). Although several volcanic fields are known to contain mantle xenoliths (e.g. the Older and Newer Volcanic Provinces of Australia, Price et al., 2014; Van Otterloo et al., 2014 and the Cima volcanic field, Farmer et al., 1995), very few studies have utilized this approach. Jankovics et al. (2013) used this method to calculate minimum settling rates of xenoliths of 0.1–0.41 m/s, corresponding to minimum ascent rates, for basalts in the Bakony-Balaton Highland Volcanic Field, western Pannonian Basin, Hungary. Additionally, Jankovics et al. (2013) used Ca profiles in olivine xenocrysts within basaltic bombs to calculate ascent rates, and achieved crystal residence times on the order of days, suggesting fast magma ascent rates (from 60 km depth) of 0.19 m/s. Rapid ascent rates - on the scale of hours from similar depths - have also been modelled using water diffusion profiles in olivines from xenoliths in the Pali Aike volcanic field, Chile (Demouchy et al., 2006).

Combined volcanological-chemical studies of individual eruptions or whole volcanic fields where the relative timing can be deduced are useful for defining the timescale on which melting processes occur, such as the involvement and exhaustion of source components, and changes in melting regime over time. An important observation is that studies that have catalogued significant changes in chemistry within individual eruption sequences (e.g. the Lunar Crater volcanic field, (Rasoazanamparany et al., 2015); the AVF, (McGee et al., 2013); Udo volcanic center, Jeju, (Brenna et al., 2010), and the Big Pine volcanic field, (Blondes et al., 2008)), and attribute these changes to the melting and interaction of different source components, varying degrees of melting, at varying depths, show that these processes occur on timescales short enough to be represented in very short-lived eruptions. McGee et al. (2012) showed that the time scale of a single eruption was sufficient for small amounts of discontinuous mantle components to be exhausted in the melted process. The exhaustion of small degree melts was also suggested by Reiners (2002) as a general model to explain the observation that many basaltic eruptions become increasingly more primitive, or more similar to their hypothesized parental magma composition, over time, as is seen in eruptions from the NVP (Lake Purrumbete, Jordan et al., 2015), Jeju (Udo, Brenna et al., 2010) and the AVF (Crater Hill, Smith et al., 2008).

Larger, longer-lived compositional changes have been noted in other settings. (Ma et al., 2011) noted that a general decrease in eruptive volume coupled with an increase in silica undersaturation in the Syrian Al Ghab-Homs volcanic field could be explained by an increase in the involvement of discrete veins from the late Miocene to the Quaternary, reflecting a decrease in the thermal anomaly and greater importance of lithospheric melts with time. A change over longer periods of time,

over a large area was also noted in monogenetic fields in NE China, where a decrease in the degree of melting through increasing (La/Ce)$_N$ ratios in primitive basalts is observed from the early Pleistocene to the Holocene (Hsu and Chen, 1998).

5.3. The geochemical longevity of 'monogenetic' events

The relative longevity of the Parícutin eruption (9 years e.g. Rowe et al., 2011) indicates the presence of a magma reservoir, consistent with the observed differentiation of its magmas. A similar story is suggested for nearby Jorullo volcano (e.g. Johnson et al., 2008), and indeed its compositions and deduced magma processes are quite different to those of its neighboring, far more primitive cone, La Pilita, which cannot be related to Jorullo by fractional crystallization or by smaller degrees of melting, and thus must represent a completely distinct, melting event (Luhr and Carmichael, 1985). Whether a small volume basaltic cone is the result of an older 'monogenetic' eruption or the beginning of a more complex composite structure is a difficult question (c.f. McKnight and Williams, 1997) emphasized by Hasenaka and Carmichael (1987) who presented compositional evidence suggesting the presence of long-lived magma reservoirs in the Michoacan-Guanajuato volcanic field, Mexico.

6. Future research directions

In this paper we have reviewed current knowledge of the composition of small basaltic fields and have raised several important questions and areas for future study. It is significant that the melting processes that produce small-scale batches of basaltic magma commonly occur in tectonic environments that are not directly linked to plate boundary processes. A commonly invoked cause of melting is decompression melting in an upwelling mantle source. Although this model can explain low degrees of melting it does encounter difficulties in explaining the production of small magma batches on widely ranging time scales. A case in point is evidence for up to five compositionally distinct magma batches erupted in the AVF within an time period as brief as 100 years (Cassidy, 2006) contrasting with long term (millions of years) small-scale volcanism in Northland New Zealand (Smith et al., 1993). We emphasize the importance of enriched components in the genesis of small melting anomalies, however, the actual mechanism of melting in many cases is unknown. A combination of geophysical and geochemical studies would be a useful avenue of future study.

An important uncertainty regarding the source of magmas is the effect that metasomatism has on trace element variability in peridotite lithologies. Metasomatism can cause the formation of mineral phases such as phlogopite and amphibole whose partition coefficients differ greatly from those of anhydrous minerals. This is clearly seen in the highly REE-enriched nature of basalts from fields known to be from complex source regions (e.g. Wudalianchi, Fig. 5). Studies of mantle xenoliths within basalts in volcanic fields will be useful in defining the effect of such metasomatism and where it occurs (c.f. Scott et al., 2014; Price et al., 2014).

'Preferential' preservation of small scale compositional features because of the small magma volumes involved is an idea which has been suggested in recent studies of volcanic fields (e.g. Rasoazanamparany et al., 2015; Shaw et al., 2003; McGee et al., 2012), and we suggest that the extent to which magmatic processes (such as degrees of melting, and proportion of mixing of components) are reflected in the geochemistry is related to the volume of individual magma batches (c.f. McGee et al., 2015). As systems become larger less complexity is preserved and the discrete signatures of different processes become homogenized (Brandl et al., 2015; Siebe et al., 2004). This begs the question of whether OIBs are just simply larger versions of individual volcanoes in volcanic fields, and whether a sustained magma source is the only difference between OIB volcanoes and the multiple cones of volcano fields. Further work on the evolution of volcanic fields (in terms of their physical volcanology

and compositional characteristics) over their lifetimes would be a useful avenue of further study.

Timescales of melting processes on the scale of fields and of individual eruptions are areas of investigation which are becoming more common with the use of time-sensitive tools such as the uranium series disequilibrium chain. At the time of writing, element diffusion studies in individual crystals have not been applied to small scale basaltic systems, however this is a logical direction in order to investigate source to surface speeds, and to test the hypothesis that magmas in small scale magmatic systems ascend rapidly with little interaction with the crust. Combining physical volcanological observations with compositional studies of complete volcanic sequences also provides timescale information within a relative chronology, and more can be made of this exclusive feature of small-scale volcanism, where outcrops are accessible.

Our compilation of references and data for small volume volcanic fields shows that those in subduction related tectonic settings are under-represented in geochemical studies. The use of melt inclusions due to the paucity of un-differentiated compositions, such as in the studies of the Higashi-Izu volcanic field magma genesis (Nichols et al., 2012) and Paricutin primary magmas (Rowe et al., 2011) would be a useful addition to the global dataset, especially in the seeking of common processes in small melt volume generation.

7. Summary and conclusions

Several important concepts underlie an understanding of the role of small scale basaltic magmatic systems in the wider framework of an evolving Planet Earth. A key to understanding the environment of magma generation lies in the chemical composition of the materials erupted in a temporally discrete episode to form an individual volcanic cone.

In this review of the geochemical behaviour of monogenetic magmatic systems we have identified the key aspects of the geochemistry of small basaltic systems as:

1. Small basaltic volcanoes can be described in terms of the eruption of a batch of magma that rises as a discrete body and is erupted within a confined time period. Magma batches may represent a single melting event but commonly they are shown to represent melts of more than one source component or mixtures of distinct melt batches, and a range of processes can occur within a single eruption (for example, mixing of sources, crystallisation of different minerals, variation in degrees of partial melting).
2. The primary magmas observed in small scale basaltic systems range from strongly silica-undersaturated nephelinites through basanites and alkali basalts to silica saturated and oversaturated transitional and tholeiitic basalts.
3. Source regions beneath volcanic fields are never homogeneous, and often more than two mantle components are involved in the genesis of a magma batch. Isotopic studies used in conjunction with more traditional geochemical modelling techniques have proven extremely useful in elucidating the details of an entire magmatic system.
4. Most studies invoke small (sometimes <1%) degrees of partial melting of the source or sources.
5. Tectonic setting (modern and ancient) can play a large part in the form and chemistry of a volcanic field.
6. There is a strong correlation between magma volume and degree of silica saturation in primary magmas. Small magma batch volumes are characteristically more silica undersaturated compared with the larger volume transitional and tholeiitic compositions.

Despite the small volumes involved in individual magma batches, volcano fields are the most widespread form of volcanism on Earth. Because their small size requires rapid ascent rates if the magmas are to reach the Earth's surface, the composition of the basalts in volcano fields carry the signature of the deep seated processes that give rise to them. We suggest that an important characteristic of small-scale basaltic eruptions is that they show geochemical evidence for the isolation and preservation of magmatic processes, whether the melting event is composed of one magma batch or many. Tectonic setting is clearly a significant factor in the extent of differentiation of basalts in volcanic fields, but we suggest that this is not a defining factor rather that the isolation of the melting event and its subsequent evolution defines whether a field of individual, generally geochemically unique cones develops instead of a centralized system.

Acknowledgments

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60

L.E. McGee, I.E.M. Smith / Journal of Volcanology and Geothermal Research 325 (2016) 45–60

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