Compositional variation during monogenetic volcano growth and its implications for magma supply to continental volcanic fields

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Abstract: Individual volcanoes of continental monogenetic volcanic fields are generally presumed to erupt single magma batches during brief eruptions. Nevertheless, in two unrelated volcanic fields (the Waipiata volcanic field, New Zealand, and the Miocene–Pliocene volcanic field in western Hungary), we have identified pronounced and systematic compositional differences among products of individual volcanoes. We infer that this indicates a two-stage process of magma supply for these volcanoes. Each volcano records: (1) intrusion of a basanitic parent magma to lower- to mid-crustal levels and its subsequent fractionation to form a tephritic residual melt; (2) subsequent transection of this reservoir by a second batch of basanitic melt, with tephrite rising to the surface at the head of the propagating basanite dyke. Eruption at the surface then yields initial tephrite, typically erupted as pyroclasts, followed by eruption and shallow intrusion of basanite from deeper in the dyke. By analogy with similar tephrite–basanite eruptions along rift zones of intraplate ocean-island volcanoes, we infer that fractionation to tephrite would have required decades to centuries. We conclude that the two studied continental monogenetic volcanic fields demonstrate a consistent history of early magma injections that fail to reach the surface, followed by capture and partial eruption of their evolved residues in the course of separate and significantly later injections of basanite that extend to the surface and erupt. This systematic behaviour probably reflects the difficulty of bringing small volumes of dense, primitive magma to the surface from mantle source regions. Ascent through continental crust is aided by the presence in the dyke head of buoyant tephrite captured during transection of the earlier-emplaced melt bodies.

Keywords: Otago, Pannonian Basin, magmas, composition, volcanism.

Monogenetic volcanoes are small and occur as scoria cones, tuff cones and rings, and maars; they form from single, typically brief eruptions (Walker 1993). Monogenetic volcanoes form in two distinct settings: (1) as isolated fields of volcanoes on continental lithosphere, ranging from thinned lithosphere (<30 km) resulting from stretching and extension (e.g. Ethiopia (Barberi & Varet 1970; Ebinger et al. 1993) and the Basin and Range province (Brandon & Goles 1995)) to normal or thick lithosphere (e.g. the San Francisco field (Conway et al. 1998) and Hopi Buttes (White 1991)); (2) as ‘parasitic’ vents along the rift zones or flanks of large polygenetic central volcanoes (e.g. Tolbachik (Doubik & Hill 1999), La Palma (Klügel et al. 1999) and Hawaii (Moore 1992)).

Some single eruptions forming monogenetic volcanoes atop large central volcanoes are known to have produced petrologically varied magmas (Klügel 1997, 1998; Klügel et al. 1999, 2000) that reflect the presence of magma reservoirs within the large volcano. Such variation has not been noted in single small-volume monogenetic volcanoes typical of continental fields, which are thought to lack stable magma storage zones. These volcanoes are formed by more or less direct eruption of magma from the mantle, with each volcano resulting from successful propagation of a small batch of magma to the surface along a new pathway (Spera 1984; Hasenaka & Carmichael 1985, 1987; Connor et al. 2000). In this paper, we present evidence for similar, single-eruption, compositional variation in products of two widely separated and unrelated continental monogenetic volcanic fields, and suggest that the ‘plumbing systems’ and magma supply dynamics for such fields may be more nuanced than hitherto appreciated.

Waipiata and western Hungarian volcanic fields

The Waipiata volcanic field occupies an area of c. 5000 km² onland in southeastern New Zealand (Fig. 1) and continues offshore over a similar, but very poorly constrained, area. It formed between c. 16 and 12 Ma (Coombs et al. 1986), on continental crust of >30 km thickness (Koons et al. 1999) during a period of mild crustal extension (King 2000). In this study, remnants of 55 volcanoes of the Waipiata volcanic field were examined (Németh 2001), some 75% of which comprise glassy pyroclastic rocks intruded by dykes and sills, and/or overlain by lavas.

An intracontinental Miocene–Pliocene volcanic field in western Hungary developed between 7.56 and 2.3 Ma (Balogh et al. 1986) across an area half the size of the Waipiata volcanic field (Fig. 1). There are two distinct parts to the western Hungarian volcanic field (Fig. 1), and these developed together in a tectonic regime that varied during that time from transtensional to transpressional (Fodor 1995). Volcanoes of the western Hungarian volcanic field also consistently comprise basal glassy pyroclastic units overlain by lavas that cap buttes (Németh & Martin 1999).

The pyroclastic rocks of each of the studied parts of the western Hungarian volcanic field contain various proportions of country rock clasts (Fig. 2), and apparently represent vent-filling
assemblages and locally preserved well-bedded tuff ring deposits. Dykes and lavas have subplanar to highly irregular, locally peperitic (Martin & Németh 2000), contacts with pyroclastic rocks, suggesting intrusion soon after emplacement of the tuffs and tuff breccias while they were still unconsolidated. The pyroclastic rocks typically have aphyric or sparsely feldspar-phyric juvenile clasts (Fig. 2), whereas the slightly younger dykes and lavas are characterized by abundant pyroxene ± kaersutite phenocrysts. There are abundant deep-seated cumulate fragments, 1–15 cm in size, in the topmost beds of pyroclastic deposits at some of the volcanoes.

**Analytical methods and results**

Samples of pyroclastic rocks were examined in thin section, and those containing remnants of fresh, isotropic glass were analysed.

**Fig. 1.** Overview maps of the two studied volcanic fields. (a) Waipiata volcanic field in the South Island of New Zealand; (b) small-volume intracontinental volcanic fields in western Hungary. TC, ’The Crater’; Sz, Szigliget.

**Fig. 2.** Photomicrographs of representative volcanic glass shards from the studied volcanic fields. (a) ’The Crater’; (b) Szigliget. The moderately vesicular texture of the glass shards, and the paucity of microlites, should be noted. Scale bars represent 1 mm.
by electron microprobe to obtain glass compositions. The juvenile clasts themselves are glassy or palagonitic, with variably abundant feldspar and pyroxene microlites as well as occasionally some larger plagioclase phenocrysts of andesine composition (An 50%). Vesicularity estimated from thin section ranges from a few percent to perhaps up to 50%, with typical clasts of moderate vesicularity (<25%) (Fig. 2). Vesicles are small, generally circular to elliptical in section (Fig. 2), and separated by thick glass walls; such pyroclasts are generally interpreted to result from phreatomagmatic eruption processes (Heiken 1974; Fisher & Schmincke 1984; White & Houghton 2000).

Results of microprobe analyses of pyroclast glass were compared with existing whole-rock XRF analyses of dykes and lavas from the same volcanoes (Embey-Isztin 1993; Donnelly 1996; Figs 3 and 4, Table 1). Deposits of 'The Crater' typify features of single volcanoes in the Waipiata volcanic field (Németh 2000), and have pyroclastic rocks with less MgO, less FeO, and more K2O than dykes and lavas from the same vent (Fig. 4a and b; Table 1). CIPW norm calculations indicate that the pyroclast glasses are tephrite (regardless of Fe2O3 to FeO ratios chosen), and lavas are basanite (Table 1). A similar degree of compositional discrimination is illustrated by the TAS diagram (Fig. 3). Total alkali v. silica (TAS) diagram for volcanic glass shards and lava compositions are not distinct in this diagram.

![TAS diagram - Waipiata Volcanic Field](image)

**Fig. 3.** Total alkali v. silica (TAS) diagram for volcanic glass shards and lava flows from throughout the Waipiata field. Because TAS differences within single volcanoes are modest, and vary across different ranges, the fields for glass shard and lava compositions are not distinct in this diagram.

![Harker diagrams](image)

**Fig. 4.** Major element discrimination diagrams for volcanic glass shards and lava flows from individual volcanoes in the Waipiata volcanic field (WVF) and western Hungary. From the Waipiata volcanic field, data from a single volcanic remnant are presented (glass and lava from 'The Crater'). For comparison with other lava flow compositions, each diagram shows the data field for all Waipiata lava flows (lava - Waipiata field). From western Hungary, data from a similar vent remnant are shown (glass - Szigliget; lava - Szigliget). The outlined field represents all glass data from both the Waipiata field and western Hungarian fields. In (a), Na2O v. K2O and MgO v. K2O, FeO total and Al2O3 are plotted. (Note the separation of data representing volcanic glass shards v. lava flows, suggesting fractional crystallization with separation of olivine, minor clinopyroxene and magnetite.) In (b), representative Harker diagrams (SiO2 v. MgO, K2O, FeO, and Al2O3) are plotted, showing crystal fractionation trends between volcanic glass shards and lava flows. In each frame of (a) and (b), data from the La Palma eruption are also plotted to illustrate the similar fractionation trend for La Palma, the Waipiata volcanic field and western Hungary. (c) shows the effect on 'apparent' composition of using larger electron beam diameter (d; abscissa in μm) during electron microprobe measurements of glass shards. It should be noted that increasing beam diameter leads to lower measured values of MgO and FeO, thus yielding lower values of normative olivine in CIPW calculation. We used the smaller of the beam diameters, thus conservatively biasing glass measurements to less tephritic compositions.
are plausible fractionating phases to produce the tephrites.

Table 1. Composition of volcanic glass shards from 'The Crater', Waipiata volcanic field, compared with XRF data from associated lava flows (first two columns)

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<td>46.41</td>
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<td>2.47</td>
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<td>2.93</td>
<td>2.86</td>
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<td>13.2</td>
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<td>10.98</td>
<td>10.63</td>
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<td>11.7</td>
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<td>12.69</td>
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<td>0.08</td>
<td>0.16</td>
<td>0.29</td>
<td>0.22</td>
<td>0.19</td>
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<td>3.14</td>
<td>3.3</td>
<td>3.91</td>
<td>4.22</td>
<td>4.01</td>
<td>8.12</td>
<td>8.16</td>
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<td>8.33</td>
<td>8.38</td>
<td>9.64</td>
<td>9.24</td>
<td>9.37</td>
<td>8.12</td>
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<td>4.49</td>
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<td>5.03</td>
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<td>2.51</td>
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<td>1.83</td>
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<td>7.51</td>
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<td>99.38</td>
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<td>4.06</td>
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<tr>
<td>Total CaO</td>
<td>8.24</td>
<td>8.68</td>
<td>8.82</td>
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<td>9.5</td>
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<td>2.19</td>
<td>1.83</td>
<td>1.58</td>
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<tr>
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<td>7.56</td>
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<td>7.9</td>
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<td>6.76</td>
<td>7.29</td>
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<td>0.42</td>
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<td>0.45</td>
<td>0.44</td>
<td>0.57</td>
<td>0.65</td>
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<tr>
<td>Total ol</td>
<td>4.6</td>
<td>3.53</td>
<td>2.62</td>
<td>1.77</td>
<td>3.78</td>
<td>2.49</td>
<td>16.97</td>
<td>21.64</td>
</tr>
<tr>
<td>Total or</td>
<td>13.58</td>
<td>15.45</td>
<td>14.55</td>
<td>12.24</td>
<td>11.46</td>
<td>12.94</td>
<td>10.81</td>
<td>9.34</td>
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<tr>
<td>Total ab</td>
<td>19.7</td>
<td>20.31</td>
<td>18.14</td>
<td>18.49</td>
<td>20.75</td>
<td>18.32</td>
<td>16.67</td>
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<td>Total ne</td>
<td>13.45</td>
<td>10.43</td>
<td>15.11</td>
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<td>47.81</td>
<td>42.96</td>
<td>44.7</td>
<td>43.08</td>
<td>39.45</td>
<td>34.96</td>
</tr>
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</table>

Analyses were performed by electron microprobe (JEOL 8600 Superprobe at the Geology Department, Otago University), using 15 kV acceleration voltage, 10–20 μm electron beam diameter on polished thin sections and OXIDE9 standard. First set of data represents raw chemical composition; second set represents data normalized to 100%. CIPW norms were calculated for 0.3 Fe2O3/FeO ratios. Mg-number, magnesium number; ol, normative olivine; or, normative orthoclase; ab, normative albite; ne, normative nepheline; an, normative anorthite; D.I., differentiation index. The total values varied between 94 and 99% on measured volcanic glass shards from lapilli tuffs and tuffs. This variation seems only to manifest in the SiO2 content of the measured glass shard indicating SiO2 loss of the glass shard. However the deeper reason of such effect needs further investigation. For the comparison of various data sets a uniform normalization has been applied on each glass shard data. Glass shard data over 97% of total values is generally considered a very good measurement in microprobe studies and perhaps a 100% normalization does not give significantly new results in calculation of CIPW norms.

Discussion

The eruption of both basanite and tephrite during single eruptions of a continental monogenetic volcanic field is unexpected, because each volcano and eruption occupies a new site, each volcano is too short lived to develop its own magma chamber in which differentiation might take place, and the time necessary for differentiation of a basanite parent to tephrite far exceeds the duration of an eruption or of magma transport from source to surface (Table 2).

As indicated by Table 2, differentiation of basanite parent magma to tephrite is, however, commonplace in polyphase alkali volcanoes. In the Eifel volcanic field, the Rothenberg volcano, which had an original edifice volume of some 0.05 km3 (Houghton & Schmincke 1989) records a number of eruptions that tapped progressively a zoned magma chamber developed at upper-mantle and/or mid-crustal levels (30–20 km; Schmincke 1977a, 1977b; Duda & Schmincke 1978; Schmincke et al. 1983). Such repeatedly tapped, zoned, magma columns are believed to form over hundreds (to thousands?) of years (Hawkesworth et al. 2000) from a mafic parent magma. In contrast, individual eruptions playing a part in the construction of Rothenberg volcano probably had durations of days to months on the basis of its sedimentary record (Houghton & Schmincke 1986; Houghton & Schmincke 1989).

In 1949, both basanite and tephrite were ejected during a single, 5 week long eruption that formed monogenetic cones and lava flows on the volcanic island of La Palma, Canary Islands (Klügel et al. 1999; White & Schmincke 1999). In this case, the tephrite is inferred to have formed from a basanite parent magma that was injected into the island volcano's deep rift zone in the
Table 2. Summary comparison of the time scales of magma rise speed (time), eruption duration, and magma differentiation time, with notes on the calculation methods and locations

<table>
<thead>
<tr>
<th>Time scales</th>
<th>Notes</th>
<th>Reference</th>
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</thead>
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<tr>
<td><strong>Magma rise speed and/or time</strong></td>
<td></td>
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<tr>
<td>Few hours to 4 days from lower crust to the surface</td>
<td></td>
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<tr>
<td>0.1–10 m s$^{-1}$ from source</td>
<td>Basis of calculation</td>
<td>Klügel 1998</td>
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<td>36 h from mantle to Moho (0.1 m s$^{-1}$) and 1.5 h from Moho to surface (5 m s$^{-1}$)</td>
<td>Xenolith settling velocity (Stoke’s law) applied to varying fluid behaviour</td>
<td>Sparks et al. 1977</td>
</tr>
<tr>
<td>0.1 m s$^{-1}$ from mantle to Moho then 10 m s$^{-1}$ from Moho to surface</td>
<td>Nögrád–Gömör volcanic field, Hungary alkali basalt hosted xenoliths; fluid inclusion study</td>
<td>Szabó &amp; Bodnár 1996</td>
</tr>
<tr>
<td><strong>Eruption duration</strong></td>
<td></td>
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</tr>
<tr>
<td>c. 1300 days (14 November 1963–1967) with distinct active periods lasting for days from various vent sites</td>
<td>Location of eruption and its type</td>
<td>Thorarinsson 1967</td>
</tr>
<tr>
<td>10–20 h (1–2 January 1996)</td>
<td></td>
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<tr>
<td>10 days (30 March 1977–09 April 1977), 147 h duration for small-volume lava extrusion</td>
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<tr>
<td>3 days (1965)</td>
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<tr>
<td>100 days (1955) with a more active period in the beginning lasting for days, then activity changed to fumarole steam</td>
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<td>38 days (1949)</td>
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<td></td>
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<tr>
<td><strong>Magma differentiation time</strong></td>
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<tr>
<td>Basalt through andesite to dacite, 1–4 ka</td>
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<tr>
<td>Basalt to rhyolites, 5–6 ka</td>
<td></td>
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<tr>
<td>Basanite to phonolite via 50% crystal fractionation, 10 ka</td>
<td>Tenerife, Canary Islands; U–Th–Ra isotope series</td>
<td>Hawkesworth et al. 2000</td>
</tr>
<tr>
<td>Phonolite to more evolved phonolite via 50% crystal fractionation, a few hundred years</td>
<td>Tenerife, Canary Islands; U–Th–Ra isotope series</td>
<td>Hawkesworth et al. 2000</td>
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<tr>
<td>Hawaii to mugearite, &lt;200 years</td>
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<td></td>
</tr>
<tr>
<td>Basanite to phonolite, 100 ka</td>
<td></td>
<td></td>
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<tr>
<td>Alkali basalt to trachyte, 90 ka</td>
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<tr>
<td>Basanite to tephrite, phonotephrite, &gt;13 years (small, shallow batches)</td>
<td>Mt Etna, Italy; U–Th–Ra isotope series</td>
<td>Condomines et al. 1995</td>
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<td>Basanite to tephrite in mantle, a century or more</td>
<td>La Palma, Canary Islands; historic account (13 years)</td>
<td>Bourdon et al. 1994</td>
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<td>Basanite to phonolite, &lt;150 ka</td>
<td>Tephrites not petrologically derived from historically erupted magmas</td>
<td>Klügel et al. 2000</td>
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</table>

upper mantle (200–350 MPa, c. 15 km, Moho at ocean-island setting) no later than 1936, the time of the most recent preceding eruption (Klügel et al. 2000); this eruption also emplaced some magma higher into the volcanic edifice. After at least 13 years of differentiation (probably more) at depth to produce tephrite, a new injection of basanite transected the deep reservoir, following to the surface tephrite magma that collected additional, phonotephrite magma, from small high-level reservoirs en route (Klügel et al. 2000).

A key feature of tephrite–basanite successions, then, is that they reflect evolution of a basanite parent magma over time. When basanite and tephrite are erupted together, as at La Palma in 1949, eruption of magmas from different batches, with different crystal fractionation histories, is inferred (Klügel et al. 2000).

In the Waipiata and western Hungarian volcanic fields, basanite and tephrite occur together in volcanoes that were neither large nor the western Hungarian field.

In the second scenario, throughout the area of the Waipiata and western Hungarian volcanic fields, magma was injected to form small (kilometre-scale) mid-crustal magma bodies, then
injected again from the same or newly formed adjacent source areas. When evolved magma bodies were encountered by later injections, the additional buoyancy provided by the entrained tephritic melts would have favoured propagation of these dykes to the surface. The degassing and expulsion of volatile phases upon mixing of two different magmas (the stalled and the newly intruded) would also have facilitated the propagation of dykes (Rubin 1995), as would the increased hydrostatic pressure developed in the crustal reservoir when encountered by newly intruding basanite dyke(s). In this scenario, basanite magma would rarely reach the surface unless an evolved, tephritic reservoir was encountered at mid-crustal depths, although exceptionally large batches of basanite might extend to the surface without a boost from tephrite buoyancy and/or increased hydrostatic pressure as a result of melt mixing. Diachronous eruptions, as indicated by existing dates, are more easily accommodated in this scenario. It also bears a strong physical resemblance to the model for the 1949 La Palma eruption, with the main distinction being that storage is not localized within the rift zones of a large volcanic system.

**Conclusion**

Continental monogenetic volcanic fields are subject to the same physical constraints as other volcanic systems. Dense mantle-derived magmas are prone to ponding near their levels of neutral buoyancy, at depths of 25–30 km, at the upper-mantle–continental crust boundary and/or in rheological and density contrast zones between the brittle–ductile transition at mid-crustal levels (Ryan 1987; Walker 1989; Lister 1991; Lister & Kerr 1991; Watanabe *et al.* 1999). Eruption of such magmas in small volumes requires substantial injected volumes of which only a small proportion reaches the surface, and/or specific stress conditions within the transected lithosphere (Watanabe *et al.* 1999). We have identified mechanisms that may help bring small volumes of magma to the surface, and suggest that where these mechanisms operate there should be a systematic presence of early erupted evolved rocks. These are commonly present as pyroclastic deposits rather than lava because their early arrival favours interaction with groundwater to produce phreatomagmatic eruptions, and/or because they have higher volatile contents. We are unable to assess the universality of this behaviour, because pyroclastic deposits have not been sampling targets for most petrological investigations. We find, however, similar compositional bimodality among early pyroclastic and subsequent effusive products associated with two widely spaced and unrelated volcanic fields, each of which is a typical intracontinental, monogenetic field, and each of which was at the time of volcanism exposed to only weak stresses related to nearby transcurrent plate boundaries. We conclude that similar compositional bimodality among eruptive products of intracontinental volcanoes in volcanic fields may be the rule, rather than the exception.

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