Revealing emplacement dynamics of a simple flood basalt eruption unit using systematic compositional heterogeneities

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Intra-lava geochemical variations resulting from subtle changes in magma composition are used here to provide insights into the spatial-temporal development of large basalt lava flow fields. Recognition that flood basalt lavas are emplaced by inflation processes, akin to modern pāhoehoe lava, provides a spatial and temporal framework, both vertically at single locations and laterally between locations, to examine lava flow emplacement and lava flow field development. Assuming the lava inflation model, we combine detailed field mapping with analysis of compositional profiles across a single flow field to determine the internal spatio-temporal development of the Palouse Falls flow field – a lava produced by an individual Columbia River flood basalt eruption.

Geochemical analyses of samples from constituent lobes of the Palouse Falls lava field demonstrate that systematic compositional whole-rock variations can be traced throughout the flow field from the area of the vent to distal limits. Chemical heterogeneity within individual lava lobes (and outcrops) show an increase from lava crusts to cores, e.g., MgO = 3.24 to 4.23 wt%, Fe_2O_3 = 14.71 to 16.05 wt%, Cr = 29 to 52 ppm, and TiO_2 = 2.83 to 3.14 wt%. This is accompanied by a decrease in incompatible elements, e.g., Y = 46.1 to 43.4 ppm, Zr = 207 to 172 ppm, and V = 397 to 367 ppm. Systematic compositional variations from the source to distal areas are observed through constituent lobes of the Palouse Falls flow field. However, compositional heterogeneity in any one lobe appears less variable in the middle of the flow field, as compared to more proximal and distal margins. Excursions from the general progressive trend from vent to distal limits are also observed and may reflect lateral spread of the flow field during emplacement, resulting in the juxtaposition of lobes of different composition.

Transport of magma through connected sheet lobe cores, acting as internal flow pathways to reach the flow front, is interpreted as the method of lava transport. Additionally, it can explain the general paucity of lava tubes within flood basalt provinces. In general, flow field development by a network of lava lobes may account for the occurrence of compositionally similar glasses noted at the proximal and distal ends of some flood basalt lavas.

Keywords: Compositional heterogeneity, flood basalts, lava emplacement, lava inflation model.

INTRODUCTION

Continental flood basalts record some of the largest volcanic eruptions on Earth and require the accumulation of large volumes of eruptible magma. Typically, these volcanic provinces are constructed of extensive (~ $10^4 – 10^5$ km^2) pāhoehoe lava flow fields (Self et al., 1997; Bondre et al., 2004; Bryan et al., 2010). The mechanisms of lava flow field development have important implications for understanding timing and durations of volcanism (Self, et al., 1997, 1998) as well as any resultant climatic or environmental impact from these voluminous basaltic provinces (e.g., Thordarson and Self, 1996; Chenet et al., 2008; Self et al., 2015). However, absolute timescales and periodicity of individual eruptions are presently beyond the precision of dating methods (Barry et al., 2010). Broad, province-scale characterisation of flood basalt flow fields requires detailed correlations of lava physical features and parameters, e.g., lobes, lava transport pathways across individual eruptive units, as well as diagnostic geochemical signatures of multiple lavas through the province succession, to identify individual eruptive units and constrain flow emplacement processes (e.g. Vye-Brown et al., 2013a).

Voluminous lava flow fields in flood basalt provinces show many physical characteristics similar to smaller, historical lava flows and pāhoehoe (Hon et al. 1994; Self et al., 1997). Structural and morphological evidence for an inflation mechanism of emplacement includes compound lavas with thick crusts, massive cores, and internal vesicular layering (Hon et al., 1994; Self et al., 1998; Thordarson and Self 1998; Bondre et al., 2004). Such evidence results from the endogenous growth of each lava lobe and would have enabled the propagation of lava through insulated pathways to new lobes at an advancing flow front. By this mechanism, lavas inflate and therefore thicken as cooling accompanies progressive emplacement of magma between brittle upper and lower crusts (Hon et al., 1994; Self et al., 1996, 1998). Later-emplaced lava within a lobe forms the massive, central zone, or core, which commonly cools to display columnar jointing. Several additional lines of evidence supporting emplacement of the majority of lobes in a flood basalt flow field by inflation include: anisotropy of magnetic susceptibility (AMS; Canon-Tapia and Coe, 2002); quantitative fluid dynamic and thermal constraints (Keszthelyi and Self, 1998); and within-lava geochemical variations (e.g., Philpotts, 1998; Maclennan et al., 2003; Reidel, 1998, 2005; Passmore et al., 2012; Vye-Brown et al. 2013b). These features have been applied to quantitatively assess the emplacement style of some extensive flood basalt and historical lava flows to reveal that variations in lava character can be related to the spatio-temporal development of a lava flow. In particular, compositional variation in magma output during an eruption should be systematically recorded vertically and laterally within a flow field due to the nature of inflation as an emplacement mechanism. Here, we explore the potential insights gained from examining compositional variations within the products of a single, large volume basalt eruption.

An inherent problem in associating observed geochemical variations to an eruption sequence in flood basalt lavas has been the lack of a single, suitably well-defined eruption unit or flow field. Only a few studies have attempted this (e.g. Martin, 1989; 1991; Vye, 2009). The difficulty lies in unambiguously identifying the constituent lobes of a single flow field within an apparently monotonous succession of similar-looking basalt lavas. To resolve this, a well-established stratigraphy is needed, and a program of detailed mapping and logging. Having physically identified a traceable single flow field over a wide area, principles of the inflation model can be applied to investigate its chronological development (Vye-Brown et al., 2013a). The relative temporal relationship within individual lobes can be extrapolated from single lobes to an entire flow field. For example, in general, more distal lobes are likely to be emplaced later than proximal lobes, and the cores of lobes may be synchronously linked by a molten core. However, this does not take account of potential complexities caused by anastomosing lava flows that may result in more distal lobes forming prior to proximal ones (Vye-Brown et al., 2013a). The model thus relates chronologic development within a lobe to the emplacement of adjacent lobes. Therefore, physical characterization of a flow field offers the opportunity to further investigate intra-lava geochemical variation and relate any geochemical signature to emplacement of the flow field as a tool for investigations elsewhere. Here we compare the relatively simple, well-constrained physical emplacement sequence of the Palouse Falls flow field of the Wanapum Basalt in the Columbia River Basalt Group (CRBG), with compositional heterogeneity recorded in its constituent lobes.

Palouse Falls flow field

The Basalt of Palouse Falls (hereafter Palouse Falls) is here termed a simple flow field, typically consisting of just one lobe at each observed location, consistent with previous use of the term "simple" lava (Walker, 1972). The Palouse Falls is the oldest lava field of the Frenchman Springs Member (Beeson et al., 1985). The stratigraphic position of the Palouse Falls makes it relatively easy to identify in the field; in many locations it marks the first lava of the Wanapum Basalt following a significant hiatus commonly marked by a widespread saprolite horizon (temporally equivalent to the Vantage interbeds). In some proximal locations the Palouse Falls overlies petrographically distinct Eckler Mountain lavas. The Palouse Falls is one of the smallest-volume flow fields of the CRBG, at only 233 km^3 (Martin et al., 2013), and is calculated to have been emplaced over a minimum of 19.3 years (Vye-Brown et al., 2013a). It is typically sparsely phyric (<10%) with small, tabular and equant plagioclase phenocrysts up to 5mm long. The flow field was traced along near-continuous exposure over ~ 30 km along the banks of the Snake River from the presumed vent area near Palouse Falls (approximate position based on the lack of more eastern-lying exposures, S.P. Reidel, pers. comm., 2009), to Lower Monumental Dam (N46^{o}39.828' W118^{o}13.377'). Individual lobes vary in size from 58 m thick in the proximal area to just 2 m thick at the southern margin of the flow field (Fig. 1). There, the flow field consists of two overlying lobes and is only 4 m thick in total. Lobes studied in borehole cores from the distal reaches of the flow field, in the Pasco Basin (~ 70 to ~ 85 km from the presumed vent area), are up to 50 m thick. Significant thinning of the flow field occurs with increasing distance from vent, apart from within the Pasco Basin fill. Here, ponding of lava likely occurred in the topographic depression of the Pasco Basin. Upper crusts of the sheet lobes typically exhibit abundant vesicular horizons and multiple megavesicle horizons (dome-shaped voids with flat floors and arched to dome-shaped roofs, with dimensions ranging from several to tens of centimeters; floored by moderately vesicular to nonvesicular glassy segregated material; Thordarson and Self, 1998). Lobe cores are typically separated from the upper crust by a zone of horizontal jointing. Cores are well-jointed with either a radial, or hackly jointed section in the centre. Chatter marks occur on some of the thick columns (> 80 cm diameter). Individual sheet lobes within the Palouse Falls flow field range from < 1 to ~ 4 km long, and on average cover an area of ~ 4-5 km^2. The total areal extent of the Palouse Falls is 10,495 km^2 (Martin et al., 2013), implying that there may be around 2100-2620 constituent lobes as this flow field is largely a single layer. Here, we characterise, in detail, seven of the constituent lobes to indicate a minimum range of physical and compositional variations between lobes.

METHODOLOGY

Six vertical sections representing seven different sheet lobes were logged and sampled, of which five sections occur along a near continuous outcrop, from a source-proximal position to the distal reaches of the Palouse Falls flow field (Fig. 1). One additional lobe was logged from borehole core records from the Pasco Basin but was not sampled (grey log in Fig. 1). Samples were taken at intervals within each vertical section, representing a single lobe. The intervals typically range up to 10 m according to the physical features that characterise each locality (Fig. 2). High-intensity sampling was conducted within one lobe to ensure no bias was introduced by the sampling interval (PF_4, Fig. 1). The physical lava features (Fig. 2) are summarised on compositional plots so that compositional variations can be considered relative to structures resulting from the inflation process.

The average sample size collected was 500g and altered rock was avoided. Samples were split to remove weathered or joint faces and powdered in an agate mill. Sample sizes of at least 300g were used to produce a homogeneous powder representative of the whole-rock sample. The quenched, glass-rich Palouse Fall samples are finely crystalline in nature, which further minimise sample heterogeneities, ensuring analytical reproducibility.

Major and trace element analyses are presented for 62 samples from the seven outcrop sections (Figs 1 and 4, plus supplementary data). Major and trace element analyses were conducted on whole-rock powders, following the XRF technique at the Open University as described by Potts et al. (1984). Both major and trace element analyses were carried out using an ARL 8420+ dual goniometer wavelength dispersive XRF spectrometer. The heterogeneity index (HI) is applied to quantify the significance of compositional heterogeneity within each sample suite (Table 1, Rhodes, 1982; Rubin et al., 2001). Precision and accuracy were calculated by repeat runs of USGS standards BHVO-1 and WS-E, as well as study samples DCy5 and FSc7 (Table 2). Furthermore, a suite of samples were analysed at the Washington State University labs to enable cross-laboratory comparisons between samples for the CRBG results from the Open University and those reported in the literature (Table 3). Correlation coefficients for this comparison are a good fit at $R^2 = 0.9991$ for all the major and trace elements used in this study.

RESULTS

Chemostratigraphic subdivisions of the CRBG at formation and group levels are well established (Hooper, 2000). Plots of TiO_2 versus P_2O_5 emphasise the principal differences between the CRBG formations such as the 'Ti gap' separating the Wanapum Basalt from older formations (Seims et al., 1974; Fig. 3). Whilst further plots including SiO_2/K_2O, Zr/Sr, SiO_2/P_2O_5 and Cr/TiO_2 have been used to subdivide some formations to the level of individual flow fields, it is acknowledged that eruption units of the Wanapum Basalt are difficult to subdivide on this basis (Hooper, 2000; Martin et al. 2013). Compositional variability greater than analytical error may be problematic for stratigraphic correlations across the CRBG based on chemistry alone. The results of this study reveal that the composition of the Palouse Falls lava lies at the lower end of the compositional range for the Wanapum Basalt for TiO_2 and P_2O_5 with values approaching the "Ti gap" separating the Grande Ronde and Wanapum Basalts (Fig. 3).

Palouse Falls intra-lobe variation

Intra-lobe compositional variations within a single flow field can be assessed by analysing suites of samples taken at varying heights within lobes of that field. Alongside detailed logging, any compositional variation can be compared to the physical structure of the lobe. Intra-lobe geochemical variation can occur vertically (e.g., Fig. 4) but also laterally across the constituent lobes of the flow field. Tie-lines between sample points have been used to more-readily illustrate the results for vertical intra-lobe variation and to identify core and crustal zone divisions between logged sections. However, these plots are not a reflection of the absolute compositional variability, and the plots may have a more step-like appearance at zone boundaries if the sampling frequency was greater. Segregation features within the Palouse Falls were not sampled as part of this study. This was to avoid known localised perturbations to bulk composition (Goff, 1996; Hartley and Thordarson, 2010).

Vertical geochemical variations

Generally, within individual lobes there are distinct variations in some oxides and compatible elements. Some of the concentrations increase from lava crusts towards the cores, e.g., MgO = 3.24 to 4.23 wt%, Fe_2O_3 = 14.71 to 16.05 wt%, Cr = 29 to 52 ppm, and TiO_2 = 2.83 to 3.14 wt%. Where this occurs, there is similarly a decrease in incompatible elements, e.g., Y = 46.1 to 43.4 ppm, Zr = 207 to 172 ppm, and V = 397 to 367 ppm. Variation in some elements (e.g., Cu, Ni, Th, Pb, and Ga) within individual lobes is rarely reconcilable outside analytical error.

Within these data it is assumed that the most vent-proximal section is within a sheet lobe exposed in the lower Winn Lake Canyon (PF_1; Fig. 1). Relative to other sampled lobes, the Winn Lake Canyon section displays a highly variable composition (Fig. 4). Sequential decreases in some incompatible elements and oxides occur from the lobe crust toward the core (e.g., TiO_2, Al_2O_3, and V). This is accompanied by increases in some compatible elements (e.g., Fe_2O_3, Sr, Cr, and MnO). It is apparent that the upper crust to core boundary, and the lower contact of a finely jointed area of the lobe core, correlate with changes in the compositional profile. Overall, there appears to be a shift from slightly more evolved upper and lower crusts to a less-evolved lobe core.

The second section away from the assumed vent area is a sheet lobe exposed along the Snake River (PF_2; Fig. 1). This lobe reveals fewer oscillations in the compositional profile than PF2 (Fig. 5). This may be the result of larger sampling intervals; only one sample was acquired from the lobe core in this section as the core is massive, lacking the finely jointed zone so clearly displayed in PF_1. However, despite the low sampling frequency, there is a similar apparent progressive decrease and increase from crust to core in the incompatible and compatible elements, respectively, as in section PF_1. In some elements the section reveals limited variation outside of 98% certainty for analytical error (supplementary data). PF_2 is the first occurrence in the Palouse Falls flow field where many of the samples are within analytical error of each other. This is reflected in the calculated heterogeneity index (HI; Table 1).

The next sampled lobe, 22km away from the assumed vent area, is PF_3 (Figs. 1 and 2) that shows a transition in composition between the lobe core and a finely vertically-jointed zone. Inflections in chemical composition into this zone are similar to the middle of the lobe core in PF_2, although no finely vertically-jointed horizon was noted in PF_2 (Fig. 5). Compared to the finely jointed zone, samples either side differ from it, although they are compositionally similar to one another for many elements. The signature of the upper crust suggests a progressive increase in compatible elements (e.g., V, Sr, MgO, Na_2O) toward the lobe core with either gradational or stepped decreases in incompatible elements.

The next section is 30km away from the assumed vent area, near Lower Monumental Dam (PF_4; Fig. 1). Here, samples were collected at ~ 2 metre intervals to reduce the possibility of any bias imposed on the compositional profiles by sample preference (Fig. 7). The resulting compositional profiles give the most detailed characterisation of intra-lobe variation in this study. Clear positive and negative inflections in incompatible and compatible elements, respectively (with few exceptions), are present at the crust to lobe core boundary and at the finely jointed zone noted in the middle of the lobe core. The lowermost contact of the lobe was not exposed, although the upper part of the lower crust was accessible. Omission of the lowermost sample(s) is reflected in the restricted compositional range of the lower crust by comparison with other lobes in the Palouse Falls flow field (e.g., PF_2; Fig. 5).

The furthest outcrop exposure from the assumed vent area is the Ginkgo Dyke area (PF_5; Fig. 1), ~ 40-50 km from source. The chemical profiles of this lobe (supplementary data) are similar to those from Snake River profile PF_2 (Fig. 5). Whilst care is taken not to over-interpret profiles with fewer sampling points, variations with height within this lobe bear similarities to PF_2, such as systematic enrichment/depletion of elements and oxides (e.g. SiO_2, MgO, CaO, Zr) rather than the stepped compositional variation seen in the intervening lobes.

The final section sampled in the distal reaches of the Palouse Falls flow field is borehole DC8 from the Pasco Basin (PF_7; Fig. 1). A distinct contrast emerges when comparing this logged section with the exposed sections along the Snake River (PF_1-5). Other than the principal core to crust divisions, few of the physical characteristics identified in outcrop are observable within the borehole lobe. However, the lobe sampled within the borehole is confirmed to belong to the Palouse Falls flow field as it overlies the Vantage interbeds, does not display any of the petrographically distinct features of the Eckler Moutain Basalt, and is overlain by the plagioclase-phyric Ginkgo flow field. Progressive increases in the abundance of oxides and some trace elements (e.g. MgO, CaO, Sr and Cr) occur with height from the basal core to the upper crust in conjunction with progressive decreases in the abundance of Zr, P_2O_5, Y and V (supplementary data).

Inter-lobe compositional variations in the Palouse Falls flow field

If we compare the analytical results from lobes of the entire flow field, using each sampled lobe as a single locality, the range of values in proximal lobes is greater than in distal lobes, e.g. MgO ranges up to 0.75 wt% with reduced variation in the middle of the field (Fig. 5). Compositional heterogeneity between adjacent lobes and across the flow field reveals progressive variations with distance from the vent. Average values for samples from: a) within lava cores; b) within lava crusts, and c) relative to the total range of sample values for the whole flow field demonstrate similar patterns in the mean compositional ranges. There are decreases in compatible elements (e.g. Cr = 52 to 32 ppm) and indices of fractionation (Mg number = 35.8 to 31.8) as well as increases in incompatible elements (e.g. TiO_2 = 2.87 to 3.12 wt%) with increasing distance from the assumed vent area (Fig. 6).

Small-scale variations

Lateral geochemical variations

In addition to vertical compositional variation, there is also the potential for lateral local compositional variations within a lobe, as shown from a sampling suite from the Sand Hollow flow field, outcropping on the State Highway 26, N46°46.821’ W118°05.603’ (Fig. 7). Three horizons were sampled on either side of the core to upper crust transition zone with three samples taken at one metre intervals laterally at each horizon. The results show variation outside of analytical error for some elements. This suggests significant compositional variation exists within the same laterally continuous horizon and may also exist within individual samples. However, in this case, the mean average analysis at each horizon is generally distinct from the sample ranges vertically.

Vertical small-scale geochemical variations

Small-scale sampling suites, consisting of closely-spaced samples, offer an opportunity to investigate the degree and source of variation. Further, it is important to assess the scale at which heterogeneity correlates with emplacement features. Compositional profiles from high-resolution sampling at 20 cm intervals in vesicle-rich to vesicle-poor bands within the complex upper crust of a lobe from the Grande Ronde Basalt at Lyons Ferry Marina (N46°35.174’ W118°13.345’) show similar characteristics to whole intra-lobe profiles (compare Figures 4 and 8). Degassed vesicular bands have slightly less evolved compositions than the overlying non-vesicular bands within the upper crust, e.g. MgO = 4.95 wt% in vesicular band 1 as compared to 4.60 wt% in non-vesicular band 1. This suggests that the process(es) responsible for the heterogeneity occurs at various scales. Similar small-scale sample investigations at 10 cm intervals from the lower crust into the core of a lobe from the Sand Hollow flow field (within the Wanapum Basalt, at N46°40.032’ W118°13.380’) reveal a range of compositions as extensive as those observed in the entire lobe (Fig. 9). The degree of heterogeneity in this small zone is outside analytical error for most elements but the high-resolution sampling does not provide a greater insight to the cause of such variable compositions.

DISCUSSION

Origin of compositional variability

On all scales the major and trace element compositional variations in the Palouse Falls flow field lobes appear to be coupled to intra-lava volcanological features. Such heterogeneity in lavas in other provinces has been attributed to either random variation (Lindstrom and Haskin, 1981), or a variety of causative processes including crystal accumulation (Philpotts et al., 1999; Philpotts and Philpotts, 2005; Passmore et al. 2012), surface mixing and thermal erosion during emplacement of the lava (Reidel and Fecht, 1987; Reidel, 2005; Hooper, 2007), and weathering (Wimpenny et al., 2007). There is no evidence for crystal accumulation within the Palouse Falls flow field due to the uniformly fine-grained, quench-cooled texture of the basalt. Lobe growth by either surface mixing or thermal erosion of disparate flows is also precluded as features found on lobe margins and surfaces, such as glassy selvages and pāhoehoe ropes, support emplacement of the lava as a single cooling unit. The effects of weathering may result in compositional profiles in a vertical section through a basalt lava, where weathering intensity decreases with depth from the surface and/or is amplified in highly vesicular zones. Such variability would be preferentially seen within mobile elements, e.g. Ca, Mg, Na, Ba and lacking in relatively immobile elements, e.g. Ti, Nb, Zr (e.g. Nesbitt and Wilson, 1992) but no such patterns are seen within the CRBG results here. We propose that the semi-systematic variation in the lobe profiles is a result of magmatic heterogeneity (Rubin et al., 2001) rather than any post-emission processes.

Mass balance calculations were run using PETROLOG software (Danyushevsky, 2001) to assess the extent to which the compositions observed can be explained by magmatic processes. The calculations assume a volatile content of ~0.3 wt% H_2O, which is in agreement with values for Columbia River Basalt magmas (Thordarson and Self, 1996; Hartley and Thordarson, 2010) and olivine-plagioclase-clinopyroxene phases for the fractionation assemblage. The first run calculations used the least evolved composition with the highest MgO% for the Palouse Falls flow field. With such parameters, the most evolved sample compositions can be attained within 5 % fractional crystallisation. A second run used an average composition for the Imnaha Basalts, which are suggested to represent the most plume-like composition of the CRBG (e.g. Hooper, 2000). Application of the model, using parameters identical to those used in the first run, reveals that between 34 and 46% fractional crystallization of an Imnaha magma produces the Palouse Falls compositions. With either of these run outcomes there is scatter in the composition of the samples from the flow field results relative to the model results, suggesting that processes other than simple fractional crystallisation are involved in generating the compositional profiles. However, identification of responsible process(es) is difficult to resolve within the compositional range. Results from osmium isotopes within another eruptive unit in the CRBG, the Sand Hollow flow field, support variable degrees of crustal contamination of magma erupted to form a single flood basalt flow (Vye-Brown et al., 2013b).

Intra-lobe compositional variations appear to be coupled to physical, emplacement-related features both within individual lobes and with distance from source across the flow field. Thus, intra-lobe variations record pre-emission magmatic compositional differences. Consideration of the features inherent to inflated sheet lobes such as vesicle-rich horizons and massive cores suggest that systematic variations from more evolved lobe crusts to less evolved lobe cores as well as more evolved compositions at the distal edges of the flow reflect the presence of discretely different, compositionally distinct magmas that were available at the same time. The currently available data does not allow us to distinguish between the existence of more than one distinct magma type or a compositional gradational spectrum within a single magmatic body. However, we can identify that the eruption of the Palouse Falls magma must have occurred from either a stratified, periodically replenished, magma chamber or a network of separate chambers deepening towards more primitive compositions with time, sequentially tapped during the ongoing eruption. We now consider how this magmatic compositional variability can be used as a tool to map out the emplacement of large flow fields.

Implications for emplacement models

The physical similarity between voluminous flood basalts and modern active and historical basaltic lavas results from the emplacement style (Self et al., 1996; Ho and Cashman, 1997; Keszthelyi and Self, 1998; Thordarson and Self, 1998; Waichel et al., 2006; Passey and Bell, 2007). The variation in volume by several orders of magnitude between lava flows, such as those on Hawaii or Iceland, and continental flood basalts has given rise to speculation on whether emplacement models for small volume lavas (< 1 km^3) can be applied as analogues for large volume lavas (up to 6000 km^3, Reidel and Fecht, 1987). However, the similarities in morphologies, surface features, and internal zonation of pāhoehoe sheet lobes and inflated pāhoehoe sheet lobes in Hawaii (Hon et al., 1994; Self et al., 1996) has led to an increasing recognition of pāhoehoe inflation as an important process in emplacement of flood basalts. Whilst we may consider, on this basis, that the vertical growth of a lobe in any one location is understood, the degree of connectivity between lava lobes remains poorly constrained, along with other questions of how intra-lobe lava flow pathways facilitate the formation and growth of new lobes, and what connective pathways may look like over time.

Compositional evidence for flow field development

The results presented here record systematic compositional variation both vertically and horizontally within a large volume flood basalt pāhoehoe flow field. Decreases in compatible element abundance with enrichment in incompatible elements from the crusts to the cores of individual lobes appears to be fairly consistent throughout the flow field. In some localities there is limited compositional variation within a lobe (e.g., PF_2). Here, the composition of the lava that was initially emplaced varies little (within analytical error) from subsequent magma that injected into, and inflated, the lobe. As well as the vertical changes in chemistry, there is also a lateral correlation between lobes, with slightly less evolved crust compositions found at greater distances from vent. This supports the field evidence for sequential emplacement of lobes from the vent to the distal reaches of the flow field, accompanied by a shift in magma composition. The evidence corroborates the intra-lobe temporal relationship of less-evolved melts emplaced later in the eruption, represented in the lobe cores.

The distribution of compositional variations within the Palouse Falls flow field supports laminar lava flow emplacement through a connected network of lobe cores. Such a pattern corroborates lobe cores forming from the last emplaced lava within each profile. Furthermore, it is likely that the most distal lobe core is emplaced before all the more proximal lobes have become stagnant (with an infill of molten magma) and crystallised. This is significant, as the observed near constant lobe core thicknesses are a result of the mechanism of emplacement (Vye-Brown et al., 2013a) and the cores of proximal lobes are interpreted to act as feeders for more distal lobes.

Lava transport methods

The transport of magma to the propagating front of the flow field through lobe cores could be sheet-like, through lava tubes, or through a preferential series of pathways within connected lobe cores. There is a notable absence of lava tubes within the Palouse Falls flow field and within flood basalt provinces generally (e.g., Kauahikaua et al., 1998; Bondre et al., 2004). Radiating joints within the elliptical masses of lava (e.g., Rosalia flow field in the Dalles area of the Columbia River province, N45°41.911’ W121°23.693’) have been proposed to be similar to lava tubes observed in flow fields on Hawaii (Waters, 1960; Greeley, 1971; Greeley et al., 1998; Halliday, 2002). Laboratory studies and field data indicating that lava tube development results from an increase in frictional resistance to lava flow as the distance between cooled crusts is reduced due to advance of the solidification fronts. According to the documented evolution of tubes on Kilauea volcano, Hawaii, (Zablocki, 1978; Hon et al., 1994), the resulting decrease in cross-sectional area increases the lava flow velocity, and lava crust growth is retarded due to the influx of hot lava. This produces well-developed tubes on timescales suggested to be within 2-4 weeks of sheet lobe formation (Hon et al., 1994). The rapid transport of lava through tubes, or sheet lobe cores acting as internal flow pathways, may account for the occurrence of compositionally similar glasses at the proximal and distal ends of some CRBG flow units (Swanson et al., 1975; Mangan et al., 1986). However, tubes may be misidentified elongate or channel-confined lobes as such features are present but scarce in flood basalt provinces. Propagation of lava through connected sheet lobes remains a preferred method for flow field development (e.g. Self et al., 1997, 1998; Thordarson and Self, 1998; Keszthelyi et al., 2006).

In detail, flow field formation must be highly complex. However, during the emplacement of the last distal lobe there must be at least one active proximal near-vent lobe and a series of linked lobes all the way through the flow field in order to transfer the same-composition magma through the lobe cores and into the most distal sheet lobe core. Thus, based on our inflation model, preferential pathways of lava flow through lobe cores may be expected to have similar chemistry. Progressive variations in composition from the source to distal areas would be observed through the constituent lobes of the flow field over time. Excursions from this general trend may reflect lateral spread of the flow field in addition to longitudinal development. This would result in adjacent lobes within a flow field exhibiting differing compositional variations, which is observed in the Palouse Falls flow field.

Developments of the inflation model

Our results show that there are significant variations in the character of the compositional profile of any single vertical section through a lobe. Such variability may be further affected by: 1) the very outermost few centimeters of the upper and lower crusts often not being sufficiently well preserved to provide samples for analysis; and 2) the possibility that the upper crust may not be the compositional mirror of the lower crust due to inhibited development of the lower crust during lobe emplacement and thickening (see Keszthelyi and Self, 1998). The latter feature may also be affected by rafting of cooled sections of the upper crust on magma flowing within the core. Furthermore, variation in the lower crust may be affected by variations in the flow dynamics at the base of the lava core including either thermal or mechanical erosion; turbulence caused by topographic variations in the substrate; and shear deformation of crystal lattice caused by flow of overlying lava. Whilst thermal erosion may be theoretically possible, it appears that such a physical process is both unsupported by field observation and unlikely within this province (Greeley et al., 1998; Kerr, 2001). Evidence for variations in the stress regime within inflated lobes is provided by AMS studies, which identify variable shear rates and isolate late-stage shearing at the lava core-crust boundary (Canon-Tapia and Coe, 2002). Shear deformation within the lower crustal zone would complicate the simplistic model of laminar flow associated with the pāhoehoe inflation model but may enable some propagation of magma towards an advancing flow front once a crystal lattice has formed.

Implications for magmatism

Investigation of the origin of compositional variations in flood basalts and other magmatic and volcanic bodies may provide new insight to the assembly and extraction of large bodies of eruptible magma. Heterogeneities in ignimbrites are common, including the Fish Canyon Tuff, USA (Bachmann and Bergantz, 2008), Bishop Tuff, USA (Hildreth and Wilson, 2007), Valley of Ten Thousand Smokes, Alaska (Fierstein and Wilson, 2005) and Zaragoza, Mexico (Carrasco-Nunez and Branney, 2005). In all of these examples the heterogeneity has been interpreted as spatial and temporal variability, preserved in the deposits through the mechanism of emplacement, resulting from complex mixing and withdrawal from a density-stratified magma chamber. However, long-term heterogeneities may be induced by: mixing, assimilation, internal phase changes and decompression (Bachmann and Bergantz, 2008). Whilst basalt magmatic systems may not preserve heterogeneity to the same extent as more evolved magmas, the same range of processes generating compositional heterogeneity are otherwise applicable. The active processes and the timescales over which such processes occur (i.e., the length of repose periods between eruptions) may influence the degree of compositional heterogeneity within a single flow field. Long eruption durations (calculated to be a minimum of 19.3 years for the Palouse Falls flow field, Vye-Brown et al., 2013a) may also increase the possibility of extracting compositionally different magmas during the lifetime of an eruption.

In comparison to this study on lava, compositional variability in sills (Latypov, 2003) has previously been interpreted as resulting from: style and duration of emplacement (Gibb and Henderson, 1996; Gibb and Henderson, 2006); assimilation and contamination of melt with wallrock (DePaolo, 1981); and magmatic heterogeneities preserved as a function of emplacement (Richardson, 1979). However, sub-horizontally emplaced sills have many similarities with thick lava lobes or sheet lobes; the outer portions of each body are emplaced first with relatively younger magma emplaced into the centre, creating an age profile younging from the outer margins to the middle. The differences between flood basalt lavas and sills come from the different cooling rates and style – whilst flood basalt sequences have an asymmetric cooling profile displayed in a thick upper crust and thin lower crust, sills are more likely to have a symmetrical cooling profile as both the upper and lower contacts have a similar thermal regime with the surrounding country rocks. However, detailed studies on the timing and style of emplacement of flood basalt lavas may offer useful insights to the understanding of sill emplacement.

CONCLUSIONS

Systematic geochemical compositional variation within the Palouse Falls lava provides supporting evidence for the emplacement of individual lobes by pāhoehoe-type inflation. The composition of the Palouse Falls is variable both with height within individual lobes and between lobes, typically with more evolved lobe crusts enriched in incompatible elements and less evolved mafic cores. The range of composition across the flow field questions the validity of chemostratigraphic methods to identify flow fields within flood basalt provinces unless there is a large sample suite. Metre-scale sampling and compositional analysis within single flow fields offers a significant advance in the understanding of emplacement mechanisms that are not revealed by lower resolution datasets. Intra-lobe compositional variations appear to be coupled to physical, emplacement-related features both within individual lobes and between different lobes, with distance from source. Such compositional variation is a result of magmatic heterogeneity from the point of eruption and these data provide a record of sequential development of the magmatic system over time.

Compositional variations from the source to distal areas are observed through the constituent lobes of the Palouse Falls flow field. Excursions from the general progressive trend may reflect lateral spread of the flow field during emplacement, in addition to longitudinal development. This would result in lobes of differing composition being juxtaposed against each other within a flow field, which is what we observe in the case of the Palouse Falls flow field. Transport of magma through sheet lobe cores, which act as internal flow pathways, may account for the occurrence of compositionally similar glasses noted at the proximal and distal ends of some CRBG flow units. Propagation of magma through a series of linked sheet lobes remains a preferred method of transport of lava during flow field development. Lateral variability through the Palouse Falls flow field reflects the subsurface presence of discretely different magmas that were available at the same time. Compositional variability could be the result of an eruption that sequentially taps either a stratified periodically replenished magma chamber or a network of separate chambers deepening toward more primitive compositions with time. If sufficient compositional variability exists then compositional mapping may enable identification of flow pathways and temporal development within a lava flow field.

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Figure Captions

Figure 1 Logs of sections measured and sampled through lava sheet lobes within the Palouse Falls flow field. Section designations are in bold; names of under- and overlying lavas in capitals. Log of borehole DH4 (PF_6) shown in grey was not sampled but provides further physical information on the extent of the flow field. Insets: Map of extent of Columbia River flood basalt province and detail of the Palouse Falls flow field, after Martin et al. (2013), showing position of continental suture boundary (thick black line; after Mohl and Thiessen, 1995) and principal feeder dykes (dashed lines; Wolff et al., 2008); sample localities for each section shown on small inset, including those of non-Palouse Falls lavas shown in Figs. 7-9. Map projection for all coordinates WGS 84.

Figure 2 Example of structural (or zonal) variations recognised within a lobe from Palouse Falls flow field (section PF_3; Fig. 1) used to illustrate intra-lobe geochemical plots and to enable correlation between logs of each lobe. Dark grey band within core denotes a finely jointed zone, whereas pale grey bands in upper crust indicate vesicle-rich layers.

Figure 3 Plot of TiO_2 and P_2O_5 for CRBG samples from Hooper (2000), showing the "Ti gap" of Seims et al. (1974) that separates the lower formations from the Wanapum Basalt, and the distribution of all samples from the Palouse Falls from this study within the established chemostratigraphy. Data from samples of Eckler Mountain Basalt, that lies between the Palouse Falls and Grande Ronde Basalts in some locations, is not shown as these basalts contain < 2 wt% TiO_2.

Figure 4 Compilation diagram of major oxides (wt %) and trace element (ppm) variations within Winn Lake Canyon lobe (section PF_1; Fig. 1). Dark grey band within core denotes a finely jointed zone, whereas pale grey bands in upper crust indicate vesicle-rich layers.

Figure 5 SiO_2, MgO, TiO_2 wt%, Y and Zr ppm variation plotted with height within each sampled lobe of the Palouse Falls flow field from the vent proximal site in the east to the distal reaches of the flow field in the Pasco Basin to the west. Closed circles indicate samples within the upper or basal crust of each lobe. Open circles indicate samples from each lobe core. Dashed lines represent the boundaries between the zones of the lower crusts, cores, and upper crusts.

Figure 6 Mean average values for Y, TiO_2, Cr and Mg number are plotted against distance from the vent area for the Palouse Falls flow field. The values are calculated for samples within either the lobe core (open circles) or the upper and basal crusts (closed circles) for each locality. The bars indicates the total spread of raw data for each log in the flow field.

Figure 7 Lateral compositional variation in SiO_2, Fe_2O_3, TiO_2 and MgO (wt %), Sr and Zr (ppm) within three horizons from a Wanapum flow exposed on in road cuttings on State Highway 26 (N46^{o}46.821’ W118^{o}05.603’).

Figure 8 Sample positions and results of a high-resolution sampling suite within and between vesicular bands of the upper crust of a Grande Ronde flow field at Lyons Ferry Marina (N46^{o}35.174’ W118^{o}13.345’). Grey bands show the position of vesicle-rich bands. Photo shows the outcrop shown in the log as indicated.

Figure 9 Results of a high-resolution sampling suite through the basal crust into the core (sample 06_318) of the Sand Hollow flow field at Palouse Falls Rapids (SH_8, N46^{o}40.032’ W118^{o}13.380’). Solid bars indicate the average of samples throughout the lobe at this locality, the average of the crustal samples and the lobe core samples within this lobe.

Table 1 Mean average results for all samples within each lobe of the Palouse Falls flow field, standard deviation about the sample means within each lobe and standard deviation of the analytical precision calculated from reproducibility analyses of WS-E for major oxides and BHVO_1 for trace elements, used to calculate the Heterogeneity Index (HI) value for each lobe. The HI is defined as $HI = \frac{\sum (S_i)/(P_i)}{n}$ where S_i is the standard deviation (2σ) about the mean, P_i is the analytical precision for element i, and n is the number of elements used in the calculation. Heterogeneity index values of ≤ 1 indicate that no compositional heterogeneity can be identified outside analytical variance.

Table 2 Collated results for standard deviation and standard error from repeat analyses of international standards BHVO-1 and WS-E, and study samples DCy5 and FSc7. The residual value is the difference between each measurement and the mean value for the dataset. These values are squared and added together for each element in turn to produce ‘S’. Standard Deviation is calculated from $StdDev = \sqrt{S/N}$ where N is the number of analyses conducted. Standard Error is calculated from $E = \frac{1}{\sqrt{N}} StdDev$

Table 3 Analytical results of a cross-laboratory comparison between XRF analyses conducted at the Open University with analyses of the same sample split at Washington State University.

Supplementary data

Figure A Compilation diagram of major oxides (wt %) and trace element (ppm) variations within the N Snake middle (PF_2) lobe of the Palouse Falls flow field. Pale grey bands in the upper crust indicate vesicle-rich layers.

Figure B Compilation diagram of major oxides (wt %) and trace element (ppm) variations within the N Snake middle-distal (PF_3) lobe of the Palouse Falls flow field. The dark grey band within the core denotes a finely jointed zone, whereas the pale grey bands in the upper crust indicate vesicle-rich layers.

Figure C Compilation diagram of major oxides (wt %) and trace element (ppm) variations within the Lower Monumental Dam (PF_4) lobe of the Palouse Falls flow field. The dark grey band within the core denotes a finely jointed zone, whereas the pale grey bands in the upper crust indicate vesicle-rich layers.

Figure D Compilation diagram of major oxides (wt %) and trace element (ppm) variations within the W of Ginkgo Dyke (PF_5) lobe of the Palouse Falls flow field. Grey bands indicate vesicle-rich layers.

Figure E Compilation diagram of major oxides (wt %) and trace element (ppm) variations within the DC8 borehole core (PF_7) lobe of the Palouse Falls flow field. Grey bands indicate areas of vesicle-rich banding in contrast with vesicle-poor portions of the lobe.

Table Major and trace element results of samples from the Palouse Falls flow field. Grey areas indicate samples that lie within the core of a lobe whilst clear areas indicate samples from the upper and lower crusts.