Variations in whole rock and mineral composition of the Lower Steens Basalt, SE Oregon

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Abstract

The Steens Basalt (~16.7 Ma) of SE Oregon is the oldest member of the Columbia River Flood Basalt (CRB) event. The Steens flows were fed by dikes near Steens Mountain, and originally covered ~50,000 km³. At Steens Mountain, 100-250 flows are stacked in over 900 m of near vertical exposure. Flows range from aphyric to extremely plagioclase phyric, and compound flows are abundant. The Steens Basalt is dominantly basalt (48-52 wt.% SiO_2), unlike the rest of the CRB, which are dominantly basaltic andesite in composition.

The Steens Basalt is subdivided into Upper and Lower units by previous workers, based on compositional distinctions. The lower flows are more mafic, tholeiitic and incompatible trace element poor, whereas the upper flows are less magnesian, mildly alkalic, and generally more enriched in incompatible trace elements. These changes up section are analogous to the cryptic layering typical of layered mafic intrusions.

New mineral chemistry on the Lower Steens Basalt reveals cryptic variations in olivine, clinopyroxene and plagioclase compositions, signaling temporal changes in magmatic conditions. A stratigraphically low and relatively less magnesian flow has homogeneous olivine (cores and rims Fo_{76-78}), suggesting a well-equilibrated magma reservoir. Olivine of <Fo_{80} is unlikely to be in equilibrium with mantle; thus the liquid from which these olivines fractionated was differentiated to some degree. Above it, a more magnesian flow has diverse olivine signaling recharge, mixing and incomplete equilibration; cores are Fo_{85-75}, and rims are as low as Fo_{63}. Clinopyroxene Mg# and anorthite content are highest from this sample (Mg# 67-77, An_{68-98}), but samples above and below this height exhibit excursions to lower ranges (Mg# 60-73, An_{66-88}). The majority of olivine grains are normally zoned with respect to MgO, but many of the grains are remarkably homogeneous from core to rim. Reverse zoning is generally restricted to minor elements in both olivine (Ni) and clinopyroxene (Cr), but is particularly notable in the flows with the most homogeneous forsterite content. The chemostratigraphic record from the Lower Steens Basalt records development of a large crustal mafic magma system in which periods of recharge and mixing with resident magma alternate with periods of differentiation in well-mixed reservoirs.

Geology of the Steens

The Steens Basalt is roughly coeval with the Imnaha flows of the Columbia River Basalt (Fig. 1). Steens lavas erupted within no more than 300,000 years of the 16.73 Ma Steens magnetic reversal (Mankinen et al. 1985; Jarboe et al. 2008; 2010; 2011; Fig. 1B).

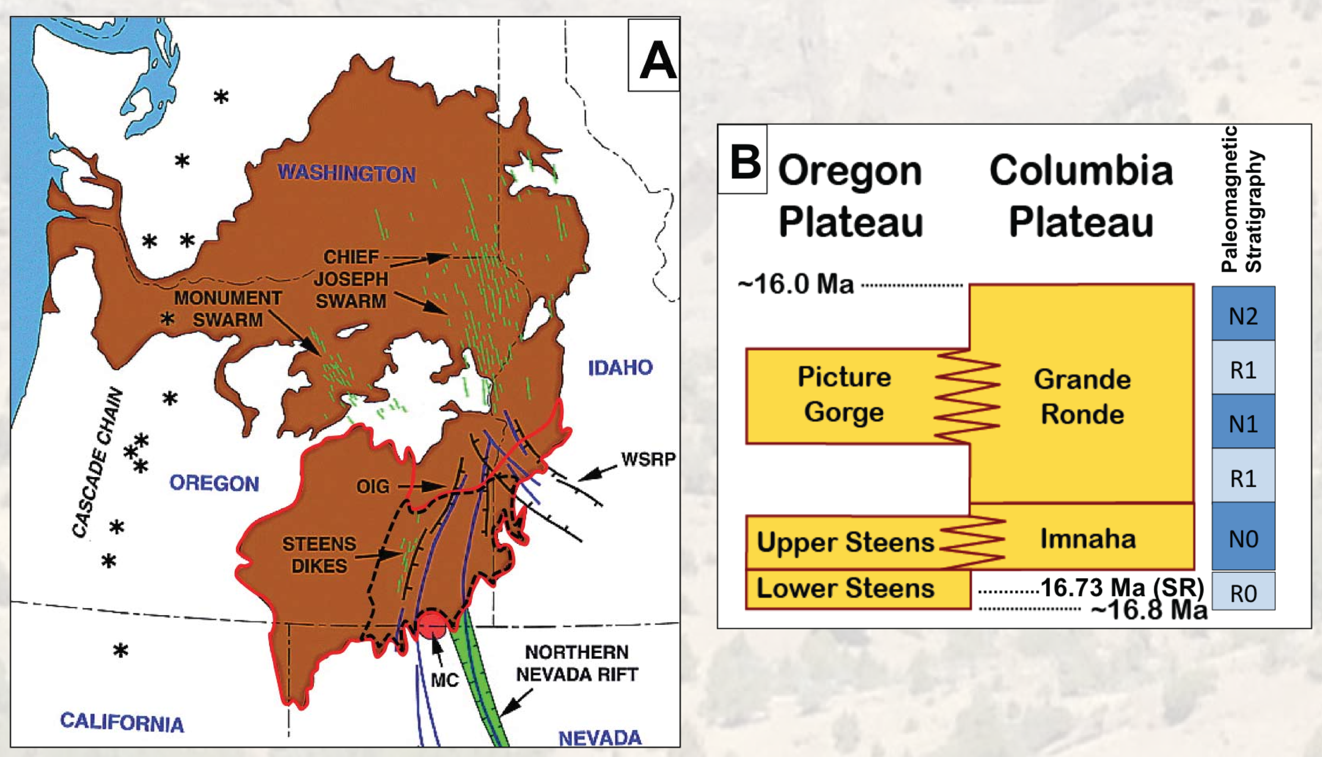


Figure 1. (A) - Map of the CRB. Red line is approximate areal extent of Lower Steens; dashed black line is Upper Steens. Normal fault near green Steens dikes is Steens Mountain. MC, McDermitt caldera; OIG, OR-ID graben; WSRP, Western Snake River Plain. Modified from Camp & Ross (2004) and Camp & Hanan (2008). (B) – Schematic regional stratigraphy for the CRB. Paleomagnetic stratigraphy and Steens Reversal (SR) from Jarboe et al. (2008; 2010). Modified from Camp & Hanan (2008) and Wolff & Ramos (2013).

A Rich Record of Open System Processes

The Steens Basalt crops out in a spectacular, km-thick sequence of ~200 thin (generally <10 m) compound and single lava flows that were fed by NNE-striking dikes (Fig. 1A and 2).

Figure 2. Photo of Steens Mountain as viewed from a saddle near the headwaters of Indian Creek (looking due north). Approximately 700 m of nearly vertically stacked lava flows are visible. On the far left, a NE trending dike is evident.

Whole Rock Chemistry

Stratigraphic Variations

The Steens Basalt is divided into Upper and Lower sections based on chemostratigraphic distinctions: the flows transition from more mafic and tholeiitic (Lower Steens) to more silica rich and mildly alkalic (Upper Steens) with increasing stratigraphic height (Fig. 3).

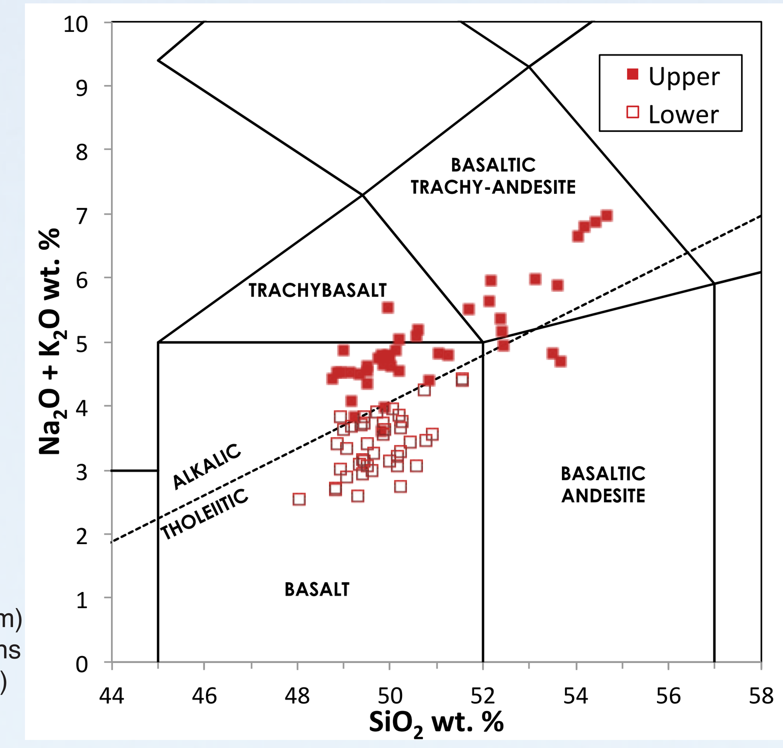


Figure 3. Total alkalis versus silica diagram for the Steens Basalt. Lower Steens (from base of section through ~400 m) filled red squares, Upper Steens (above 400 m to top of section) open red squares.

Changes up section are evident in other major and trace elements, as well as whole rock and mineral isotope compositions (Fig 4).

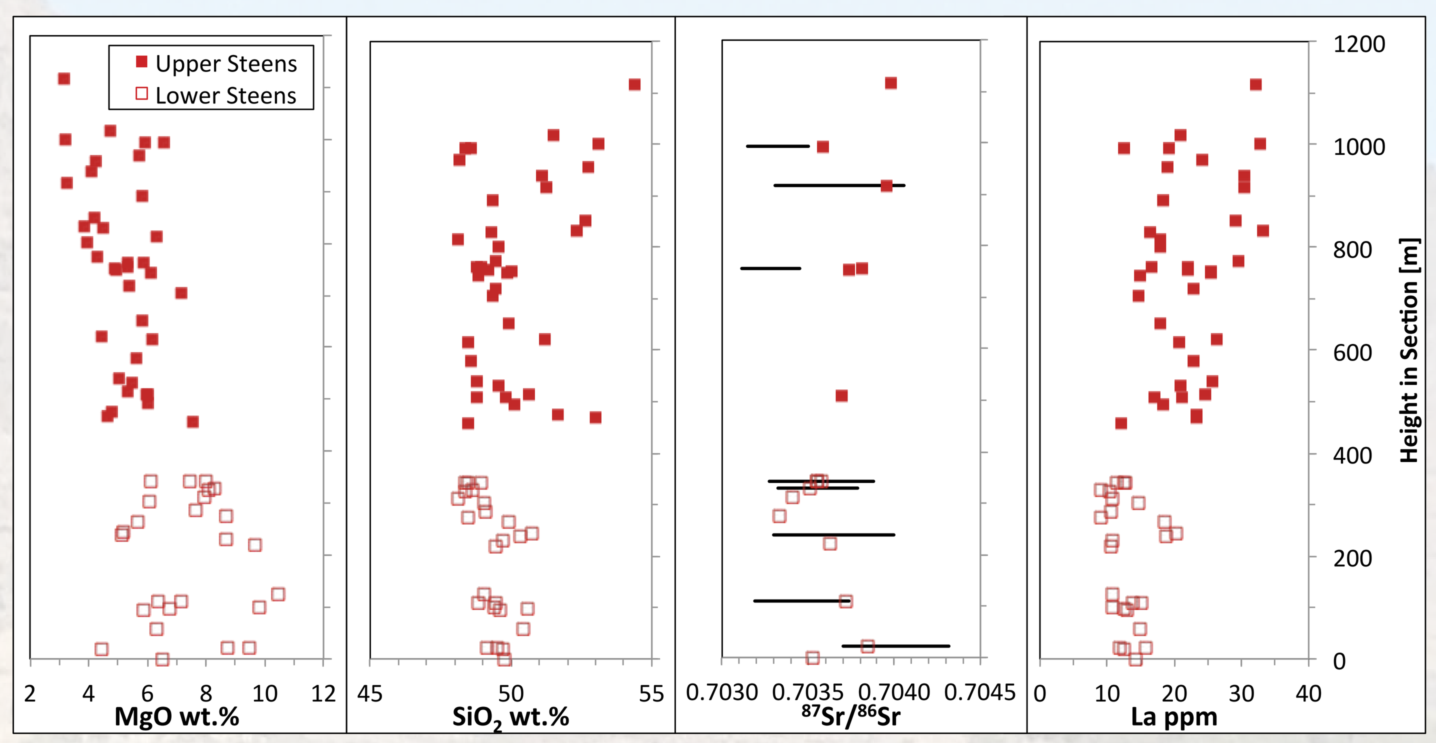


Figure 4. Major, trace element and isotopic compositions from the Steens Basalt as correlated with stratigraphic position at Steens Mountain (Johnson et al. 1998; Wolff & Ramos 2013; Ramos et al. 2013). Sr isotopic compositions for whole rock are plotted as symbols, black lines (through or near the symbols) indicate corresponding range of plagioclase $^{87}Sr/^{86}Sr$.

Petrography

Steens lava textures range from aphyric to extremely plagioclase phyric. Modal olivine ranges up to 15% in some flows; phenocrystic pyroxene is rare. Coarsely plagioclase phyric flows (Fig. 5) are typically interbedded with sparsely phyric olivine basalts. Flows contain up to 40% plagioclase, with megaphenocrysts ranging from 1-4 cm.

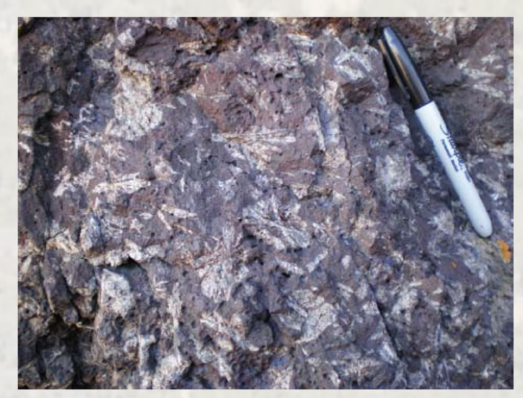
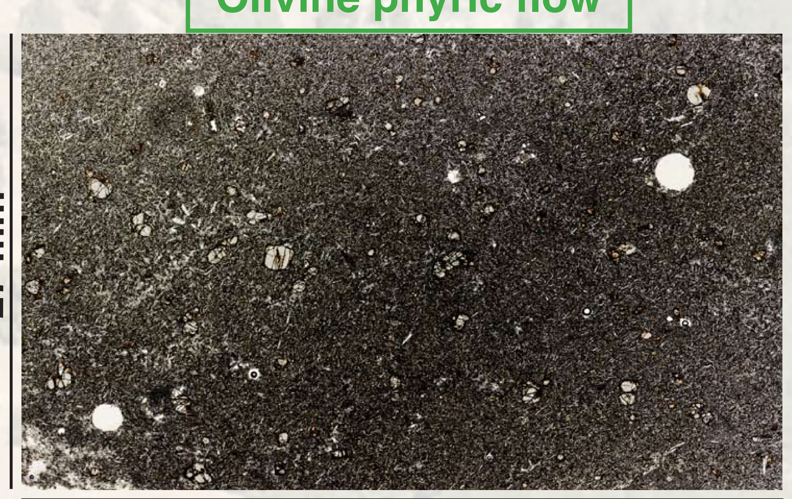


Figure 5. Coarsely plagioclase phyric flow in outcrop.

Photomicrographs of common flow textures

Olivine phyric flow



27 mm

46 mm

Olivine and plag phyric flow

Plag megacrystic flow

Mineral Chemistry

Stratigraphic Variations

Olivine microprobe analyses appear to record temporal variations in magmatic conditions. A stratigraphically low flow has homogeneous olivine (cores and rims Fo_{80-82}), suggesting a well-equilibrated magma reservoir. Above it, a flow with similar MgO content has diverse olivine signaling recharge, mixing and incomplete equilibration; cores are Fo_{85-75}, and rims are as low as Fo_{63} (Fig. 6).

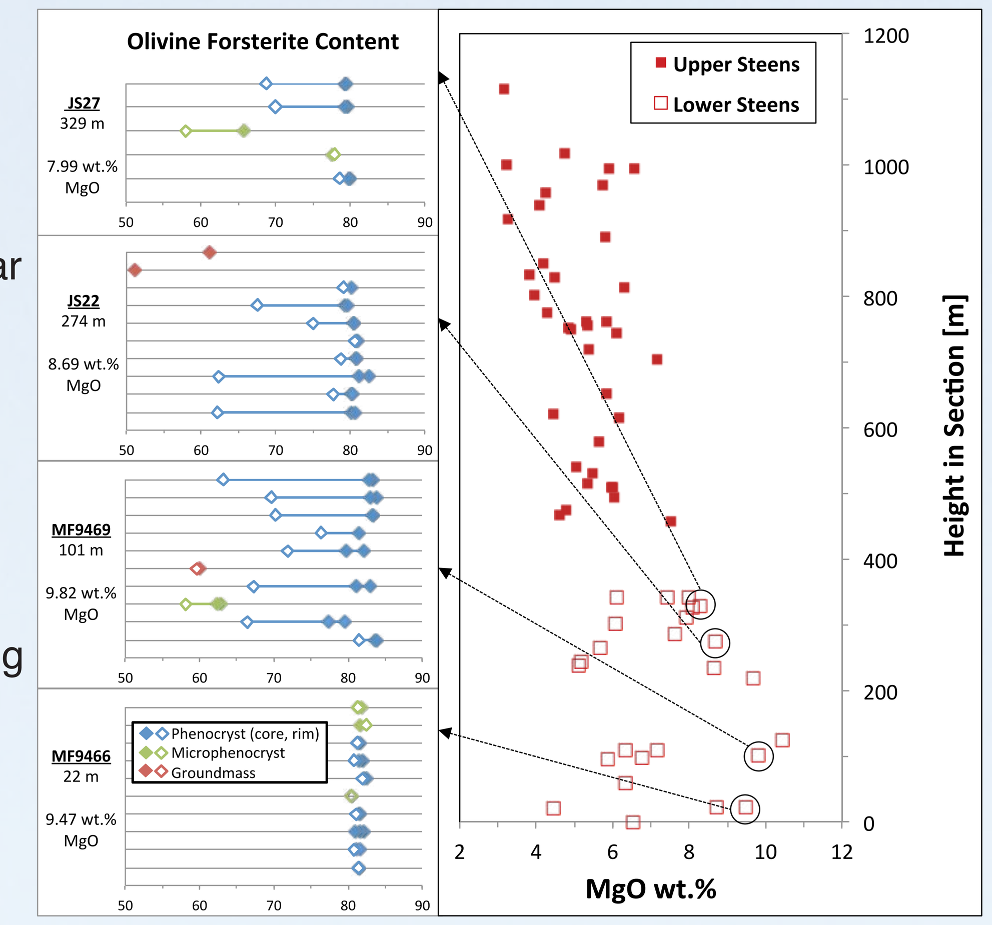
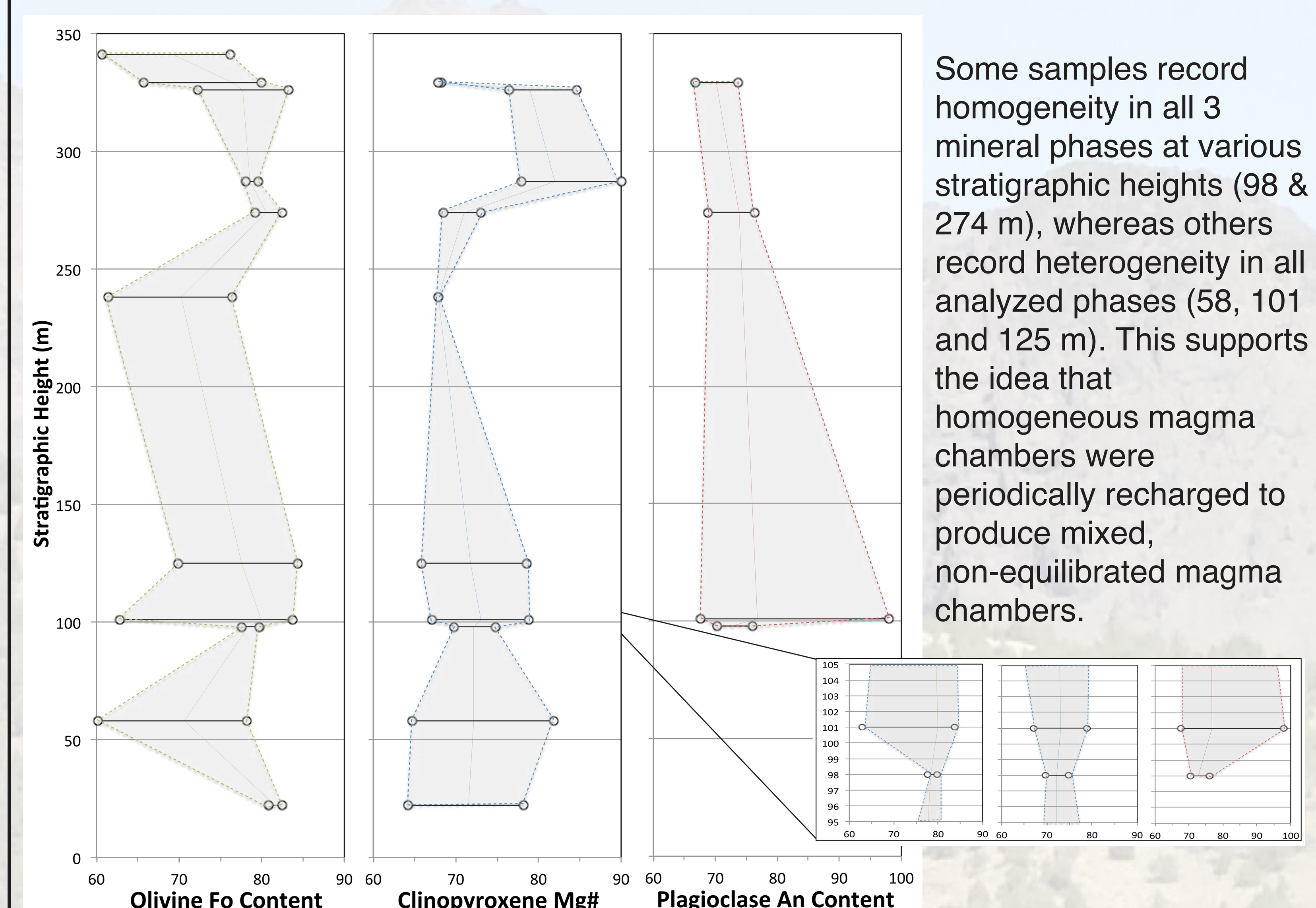


Figure 6. Olivine Fo content from the Lower Steens and whole rock MgO compositions from the Steens Basalt as correlated with stratigraphic position at Steens Mountain (new data this study; Johnson et al. 1998; Wolff & Ramos 2013; Ramos et al. 2013). Samples analyzed for olivine compositions are circled in the MgO panel with arrows to the corresponding olivine panels.

Magma Recharge and Equilibration



Some samples record homogeneity in all 3 mineral phases at various stratigraphic heights (98 & 274 m), whereas others record heterogeneity in all analyzed phases (58, 101 and 125 m). This supports the idea that homogeneous magma chambers were periodically recharged to produce mixed, non-equilibrated magma chambers.

Figure 7. Olivine, clinopyroxene and plagioclase mineral chemistry with stratigraphic height. Plagioclase data from 4 samples, olivine and cpx from 12 and 10 samples respectively. Solid colored lines are average core values from each sample, circles represent max and min values from each sample. Inset shows region between 95 and 105 m to clearly demonstrate variation up section.

Future Work

1. Additional petrography and mineral chemistry to fully characterize all textures and phases in samples from the entire Lower Steens section.
2. Whole rock and isotopic analyses on newly acquired samples.
3. Assessment of geochemical and mineralogical data in the context of how the Steens lavas differentiated as they traversed through the crust.
4. Modeling with widely used petrological models (DePaolo AFC, MELTS, EC-RAFC, etc.) and the new Magma Chamber Simulator (MCS) to fully describe the pre-eruptive magma conditions, as well as the range and combination of processes that served to differentiate the flows (recharge, fractionation, assimilation, and combinations thereof).

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