What lies beneath: Deciphering magma chamber dynamics at Ngauruhoe volcano

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ABSTRACT

Mt. Ngauruhoe is among the youngest active volcanoes in the Taupo Volcanic Zone, but its eruption history and magmatic evolution may be just as complicated as its older, more silicic neighbors. Whole-rock chemical data, xenolith content, and isotope data can be used to determine progressive changes in composition with time. The results show that Ngauruhoe has no consistent trend of magmatic evolution, even over periods as short as 100 years. Instead, a combination of processes including magma mixing, crustal assimilation, mafic recharge, and fractional crystallization play a role in the evolution of Ngauruhoe magmas. The prominence of each of these magmatic processes over time, determines the evolution of Ngauruhoe's plumbing system. It appears Ngauruhoe's plumbing system is becoming increasingly complicated with the recent development of many small, interconnected magma chambers.

INTRODUCTION

Mt. Ngauruhoe is located in the Taupo Volcanic Zone (TVZ) of New Zealand, a volcanic arc forming the southern extension of the Tonga-Kermadec arc into the continental crust of New Zealand (Graham et al.1987). The TVZ is characterized by rhyolitic volcanism in its center and andesitic volcanism to its southern and northern extremities. Mt. Ngauruhoe lies in the southern portion of the TVZ, in the Tongariro volcanic complex where it is the youngest of nine andesite cones built over the complex's 275 ka history.

In its 2500-year history, Ngauruhoe has displayed a variety of eruption styles including effusive, strombolian, vulcanian, and sub-plinian eruptions. Pre-historic eruption types are evidenced by the lava, pyroclastic, and block-and-ash flows that form the cone. In recent years the cone has erupted frequently, with major historic eruptions occurring in 1870, 1949, 1954-55, and 1973-75. Due to the frequent and unpredictable nature of its eruptions, Mt. Ngauruhoe presents a challenge to volcanic hazard modelers (Hobden et al. 2002).

A volcano's eruption style is typically influenced predominantly by magma composition. Magma composition can impact the temperature, viscosity, yield strength, and pre-eruptive volatile content of the magma. It directly depends on the magma source, magma mixing, the degree of fractional crystallization, and the amount of crustal assimilation (Hobden et al. 2002). However, Mt. Ngauruhoe has been erupting with varying eruption styles and seemingly unsystematic changes in magma composition.

Numerous geochemical and petrological studies have been conducted at the volcano to determine the reason for Ngauruhoe lava's chemical variations. A study by Price et al. of nearby Ruapehu volcano notes that short term (~1000 yrs) chemical variation may be due to the complex plumbing system characteristic of andesite volcanoes. Hobden et al., thoroughly examines the magmatic evolution of the Tongariro complex determining the evolution of the volcano's plumbing system over its 275 ka life-span. Here I expand upon Hobden's study by examining Ngauruhoe's evolution in greater detail. Xenoliths, which are found within most Ngauruhoe flows, and bulk lava chemical compositions are used to interpret the cone's irregular compositional pattern and to develop a history of the volcano's complex plumbing system.

METHODS

Fieldwork and collection of samples in the Mangatepopo Valley, on the north to northwest side of Mt. Ngauruhoe, were conducted in February 2010. According to Hobden et al. (2002) this succession of flows is characteristic of the evolution of the cone. Flows in the valley were mapped and given relative ages. Relative ages were assigned to flows based upon the law of superposition where clear relationships could be discerned. When clear age relationships did not exist, ogive structures and the amount of vegetation on flows were used to discern ages. Additionally, outcrops of the 1.85-ka Taupo Pumice were utilized as a time marker. If evidence for age relationships was not sufficient, flows were given the same relative age. Finally, age relationships were compared with those given to the flows by Hobden et al. (2002).

Samples were collected from three historic flows, 12 prehistoric flows, and one historic pyroclastic flow. All samples were selected to represent each flow's characteristic texture and phenocryst content.

In the lab, I examined each sample and recorded its mineralogy and textures. Thin-sections were prepared for each sample. Each thin section was examined for its mineralogical content and texture. Based upon a literature review, I noted the concentration of xenoliths and lithic fragments present in each of the thin sections. Xenoliths and lithic fragments provide evidence for crustal assimilation. The samples were also prepared for X-Ray Fluorescence (XRF) to gain whole-rock major and trace element analyses. Supplementary data, including $^{87}Sr/^{86}Sr$

ratios, was obtained from Hobden et al. (2002). After a review of previous geochemical studies (Price et al. 2004, Hobden et al. 1999, Hobden et al. 2002, Hobden 1997, Graham and Hackett 1987, Davidson et al. 2004, Snelling 2003, Graham et al. 1988), I developed numerous variation diagrams from the XRF and isotope data. Major elements SiO_2 and MgO, trace element Cerium (Ce), and $^{87}Sr/^{86}Sr$ ratios were used to determine fractional crystallization, magma source, and crustal assimilation patterns.

In order to assess evolutionary trends from the data, I split the samples into 5 groups. For this study, Hobden's group classifications were utilized. Her classifications are based primarily on age, but location and geochemistry of the flow were also taken into consideration (Hobden 1997). With the geochemical data and group classifications I was able to develop a likely magmatic evolutionary history for Mt. Ngauruhoe volcano.

RESULTS

Group 1 consists of the oldest flow samples. These flows are located primarily on the north-northwest side of the cone in the Mangatepopo Valley and were found beneath the 1.85 ka Taupo Ignimbrite. Group 1 samples have the lowest weight percent SiO_2 (54.02-55.51) and the lowest $^{87}Sr/^{86}Sr$ value (0.704532). Their MgO weight percents lie between 3.86 and 4.7.

Group 2 lavas are the next oldest set of flows with some flows older than the Taupo ignimbrite and some younger. Like Group 1 lavas, they are also located in the Mangatepopo Valley. However, these lavas have a slightly higher SiO_2 wt % (54.51-57.94) and $^{87}Sr/^{86}Sr$ value (0.704766). MgO wt % is approximately the same (3.73-4.82).

Group 3 lavas are located only on the southern face of the cone, which is outside my fieldwork area. Therefore, data from Hobden et al. (1997) was utilized. This group demonstrates the lowest weight percent MgO (2.17-3.24) and a high but tightly constrained SiO_2 wt % (58.03-58.30). $^{87}Sr/^{86}Sr$ value (0.705268) shows a large increase from group 1 and 2 lavas.

Group 4 lavas are again located primarily on the southern face of Ngauruhoe so data from Hobden et al. (1997) was utilized. These lavas flows are among the most silicic (57.30-58.62 wt % SiO_2) but are also the most magnesium rich (4.43-5.41 wt% MgO. Its $^{87}Sr/^{86}Sr$ value (0.70472) is lower than group 3 lavas.

Group 5 lavas return to the northern slope of the cone and many continue into the Mangatepopo valley. These represent the most recent flows, occurring over the last 140 years. Group 5 flows show an array of SiO_2 values (54.74-56.94 wt%) and the widest range of MgO (3.85-5.47 wt%). $^{87}Sr/^{86}Sr$ ratios range from 0.705339-0.706165. Large increases in $^{87}Sr/^{86}Sr$ ratios occur within this group with the ratio increasing by almost 0.0007 between 1974-1975. Numerous xenoliths are found within the 1975 flow and a high density of lithic fragments can be seen in the 1954 flow.

DISCUSSION

Magmatic Evolution of Ngauruhoe Volcano

It is clear from the geochemical data that the magmatic evolution of Mt. Ngauruhoe Volcano does not follow a trend that could be caused by a single process. All eruptions produced basaltic andesite lava, but show interesting variations in composition. On an MgO versus SiO_2 variation diagram (Figure 1A), no clear evolutionary pattern is recognizable. Closed system fractional crystallization typically creates a smooth, linear trend of decreasing MgO with increasing SiO_2 (Hobden et al. 1999, Davidson et al. 2004). However, the 5 groups appear to plot randomly. This trend indicates that other processes (ie. magma mixing, crustal assimilation, and mafic recharge), in addition to fractional crystallization, play a role in the evolution of Ngauruhoe magmas.

Isotopic compositions of the lavas further explicate the processes responsible for these variations. Radiogenic isotope compositions reflect the magma source or contamination from the crust, but are not influenced by closed system processes (Hobden et al. 1999, Snelling 2003, Graham and Hackett 1987, Price et al. 2004). Variations in $^{87}Sr/^{86}Sr$ do not reflect fractionation trends but a new magma source or crustal assimilation. Xenoliths help constrain these results because their presence typically indicates crustal contamination (Steiner 1958, Graham and Hackett 1987, Graham et al. 1988, Hobden et al. 2002, Hobden 1997, Price et al. 2004). Finally, studies have shown that light rare earth elements including Ce, tend to increase with SiO_2 due to fractionation processes. A decrease in Ce with SiO_2 could be an indication of magma mixing (Hobden et al. 1997).

Utilizing this information in combination with the MgO-SiO_2 variation diagram a clearer evolutionary picture can be developed. Group 1 lava compositions can be explained primarily by fractional crystallization processes. However, one flow revealed unusually high MgO content demonstrable of a mafic recharge event.

Fractional crystallization processes followed by magma recharge and mixing can explain the geochemical variations between Group 1 and Group 2 magmas. As seen in Figure 1A, many of the Group 2 lavas follow a linear trend of decreasing MgO and increasing SiO_2 extending from the Group 1 lavas. This indicates the influence of fractional crystallization. However, there is no clear pattern in the Ce data (Figure 1B), which indicates another process is at work.

Furthermore, many of the Group 2 lavas have much higher MgO and SiO_2 wt % values. This, in combination with the slight increase in the $^{87}Sr/^{86}Sr$ ratio can be explained by a magma mixing event.

Group 3 lavas have a distinct geochemical signal relative to the other groups. The lavas have a much lower MgO wt % and a large change in the $^{87}Sr/^{86}Sr$ ratio compared to Group 2 lavas of 0.0005. These differences can only be explained by a new and isotopically distinct magma source. Crustal assimilation may have also played a significant role in the production of this magma type.

The transition from Group 3 to Group 4 lavas marks an increase to the highest silica content of all groups as well as a very high MgO content. Since the lavas are unexpectedly magnesium rich relative to silica, magma mixing processes were important in Group 4 development. In addition, radiogenic Sr ratios drop to approximately the Group 2 level. These compositional changes reflect a return to the old magma source, active during Group 1 and 2.

Finally, Group 5 lavas show a dramatic jump in $^{87}Sr/^{86}Sr$ value compared to Group 4 lavas, with a difference of approximately 0.0009. This indicates either a new magma source or large amounts of crustal contamination. Since the radiogenic isotope populations of the flows vary over short time scales, crustal contamination is the most likely candidate. Furthermore, numerous xenoliths are found within the flows. According to Steiner (1958), these xenoliths originate from a quartzo-feldspathic gneiss because many exhibit relict banding, lineation, and lensoid structures. Since the basement rock beneath Ngauruhoe is a gneiss this is a good indication for shallow crust contamination (Graham and Hackett 1987, Graham et al. 1988). Another important characteristic of Group 5 lavas is the wide range in MgO and SiO_2 content.

The varied compositional nature and degree of crustal contamination suggest that Group 5 magmas are the result of numerous small magma batches held in several shallow, unconnected reservoirs.

From the geochemical data and inferred magmatic processes, an evolution of the plumbing system beneath Mt. Ngauruhoe (Figure 2) was created. Group 1 magmas represent andesite melts created in the lower crust in a single storage reservoir. Over time, the magma chamber develops numerous independent storage reservoirs at shallower and shallower levels in the crust. The increasingly complicated nature of the plumbing system with time could be part of the explanation for the volcano's recent array of eruption styles.

Group 5: A closer look

Over the past 140 years, Ngauruhoe has erupted 4 times in 1870, 1949, 1954, and 1975. Like the volcano's prehistoric flows, the historic flows show no clear evolutionary trend. The historic eruptions too seem to plot arbitrarily on an MgO versus SiO_2 variation diagram (Figure 3A). Even on a time scale as short as 140 years, numerous petrogenetic processes appear to affect the volcano's magmatic evolution. Since historic eruptions have been observed, we have much more information concerning these events. In particular, absolute ages of the flows make their analysis increasingly accurate.

The geochemical variations between the 1870 and 1949 flows can be explained by fractional crystallization and small amounts of crustal assimilation. Fractional crystallization appears to play the main role as MgO decreases with increasing SiO_2 while Ce demonstrates a slight increase. However, $^{87}Sr/^{86}Sr$ varies significantly with an increase of almost 0.0004 indicating some crustal assimilation. Between the 1949 and 1954 eruptions MgO weight percent increases relative to SiO_2 while Ce weight percent decreases. This indicates mafic recharge and mixing processes. The 1974 and 1975 lavas demonstrate radically different MgO, SiO_2, and $^{87}Sr/^{86}Sr$ values. It appears the 1954 magma fractionated to the 1974 flow composition, but large amounts of crustal contaminant entered the magma body prior to the 1975 eruption. Though the $^{87}Sr/^{86}Sr$ value from 1974 to 1975 increased by almost 0.0007, one year is not enough time for an isotopically distinct mantle source to reach the surface. Andesite migration velocity is estimated at 5m/year (Hobden et al. 1997). Therefore, the change in radiogenic Sr is likely due to increasing amounts of crustal assimilation. In addition, the 1975 flow has a much higher density of xenoliths. These gneissic xenoliths are convincing evidence for crustal contamination at shallow levels (Graham and Hackett 1987).

CONCLUSION

By examining the geochemical data, I found that Ngauruhoe volcano has no consistent trend of magmatic evolution. Instead numerous processes, including fractional crystallization, magma mixing, crustal assimilation, and mafic recharge, all play a role in the development of magma batches. Due to the vast array of processes and the compositions they produce, the plumbing system at Ngauruhoe volcano is fairly complex. The volcano's history includes many, small magma batches that travel through several small, independent magma chambers. Furthermore, the most recent flows demonstrate the most geochemical variation. This suggests that the cone's plumbing system is becoming increasingly complicated.

Beyond its application to Ngauruhoe volcano's magmatic evolution, this study contributes to the greater understanding of andesite volcanos in the TVZ. In combination with studies by Price et al. (2004) and Hobden et al. (2002), andesite volcano magma chamber processes and evolution can be deciphered. Though Ngauruhoe is far younger than the volcanoes, Ruapehu and Taranaki, analyzed by Price et al. (2004) it appears to be evolving in the same manner. Ruapehu's and Taranaki's plumbing systems have also become increasingly complex with time. Like Ngauruhoe, they began with andesite melts produced in the lower crust by melting, fractionation, and assimilation and eventually evolved a complex system of storage reservoirs from which distinct magma batches evolve separately. Currently, Ruapehu and Taranaki appear to be following a common trend in the TVZ for andesite volcanoes to evolve into rhyolite volcanoes due to increasing amounts of crustal assimilation (Price et al. 2004). Due to Ngauruhoe's short life span, these patterns cannot yet be accounted for. However, its similar evolutionary trend to Ruapehu and Taranaki support the volcano's potential to follow this long-term trend as well.

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FIGURE CAPTIONS

Figure Captions:

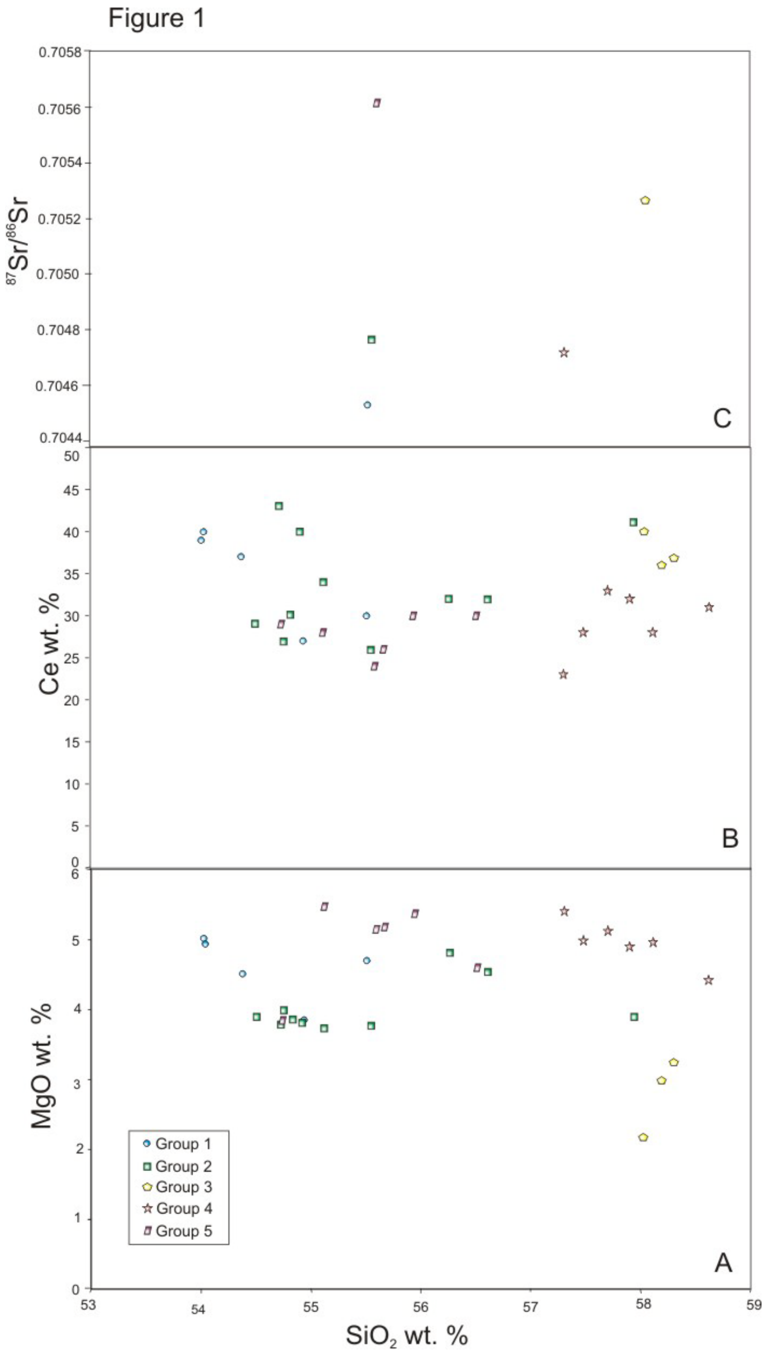

Figure 1. SiO2 wt. % versus MgO wt. % (A), Ce wt. % (B), and 87Sr/86Sr (C). All flows are represented and classified according to their groups.

Figure 2

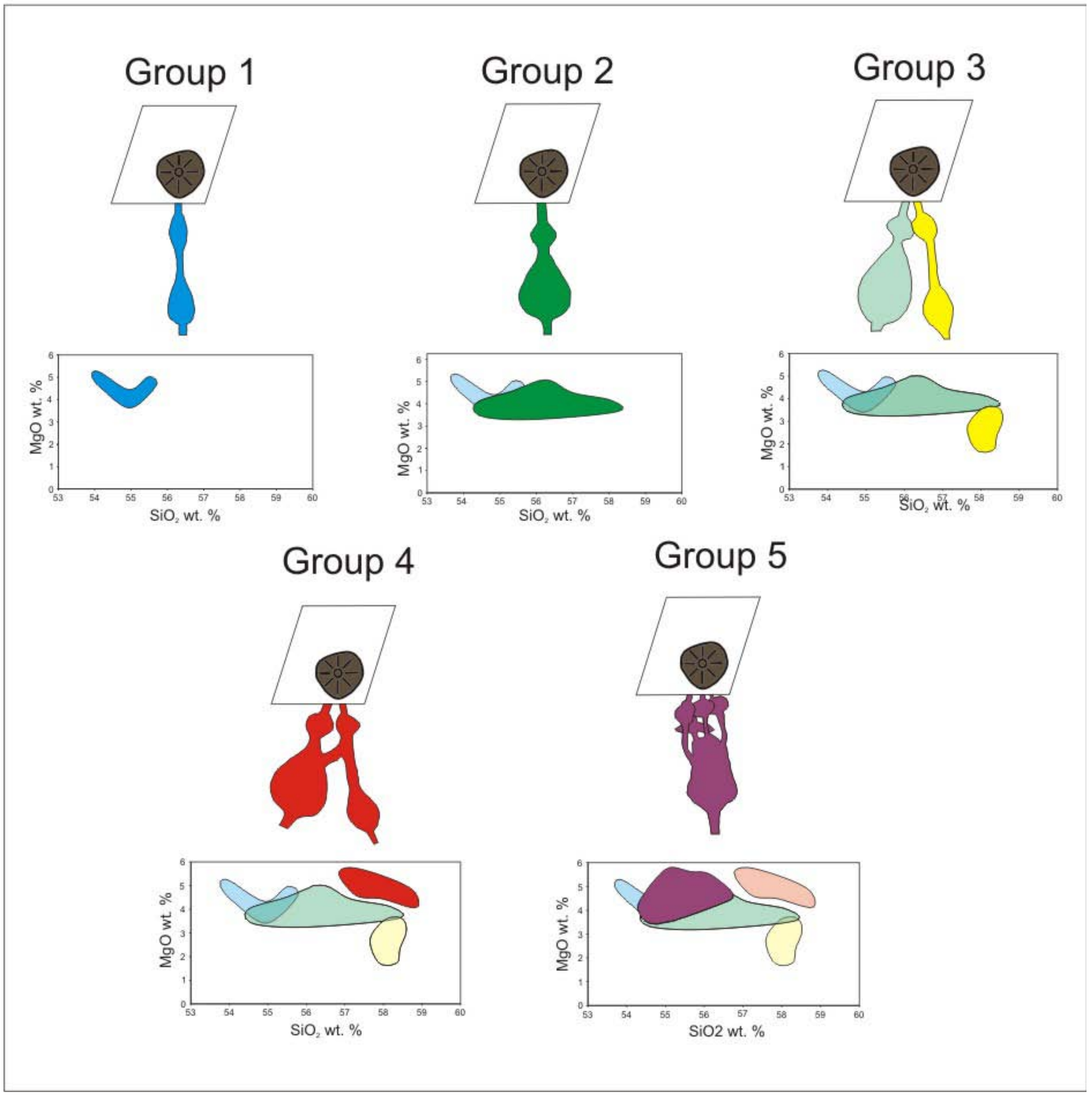

Figure 2. Schematic diagrams of Ngauruhoe's magma chamber evolution through time. Each group represents a segment of time when lavas produced are of similar geochemistry and location on the cone. Group 1 magmas represent andesite melts created in the lower crust in a single storage reservoir. Over time, the magma chamber develops numerous independent storage reservoirs at shallower and shallower levels in the crust. The increasingly complicated nature of the plumbing system with time could be part of the explanation for the volcano's recent array of eruption styles.

Figure 3

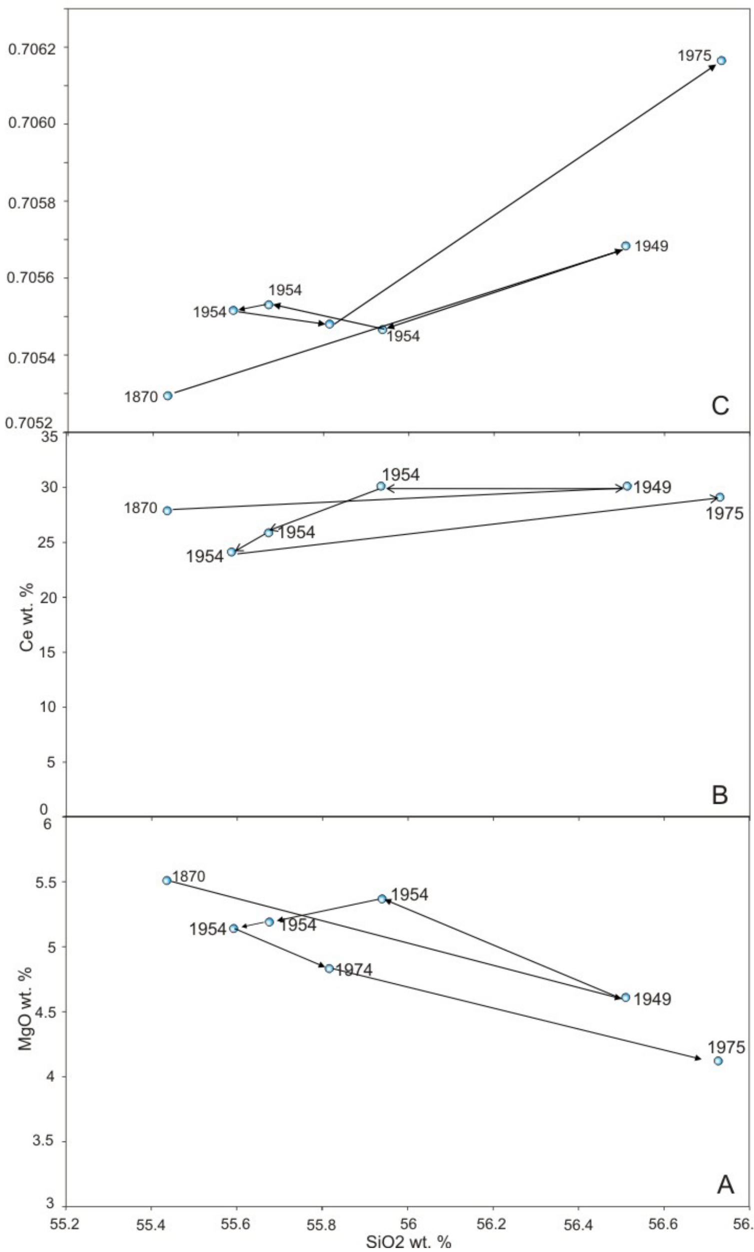

Figure 3. SiO2 wt. % versus MgO wt. % (A), Ce wt. % (B), and 87Sr/86Sr (C) for all historic lava flows. The arrows represent geochemical progression over time.