Petrogenesis of the Wa'awa'a trachyte, Hualalai volcano, Hawaii

Caroline Seaman
Department of Geology, Colorado College, 14 E. Cache La Poudre St.,
Colorado Springs, CO 80903-3294
Faculty sponsor: Bruce Loeffler, Colorado College

INTRODUCTION

Trachyte has traditionally been grouped as an end member in the alkalic basalt series which includes basalt, hawaiite, mugearite, benmoreite, and trachyte. All of these rock types are observed in the Hawaiian Islands. However, on intraplate ocean islands in general, trachyte and basalt are usually the most abundant members of the series and some volcanoes have only trachyte and basalt (Philpotts, 1990) The scarcity of intermediate rocks in this series is called the Daly Gap after Reginald Daly who first remarked on the phenomenon.

Theories to explain the Daly gap include disequilibrium crystallization, unmixing of magmas, fluid behaviors related to density and viscosity, and partial melting. Hualalai volcano on the Island of Hawaii, which has alkalic basalt and one large trachyte flow on its surface, but no known intermediate lavas, is a good place to test these theories. Equilibrium fractional crystallization is also a possible process in the formation of the trachyte on Hualalai.

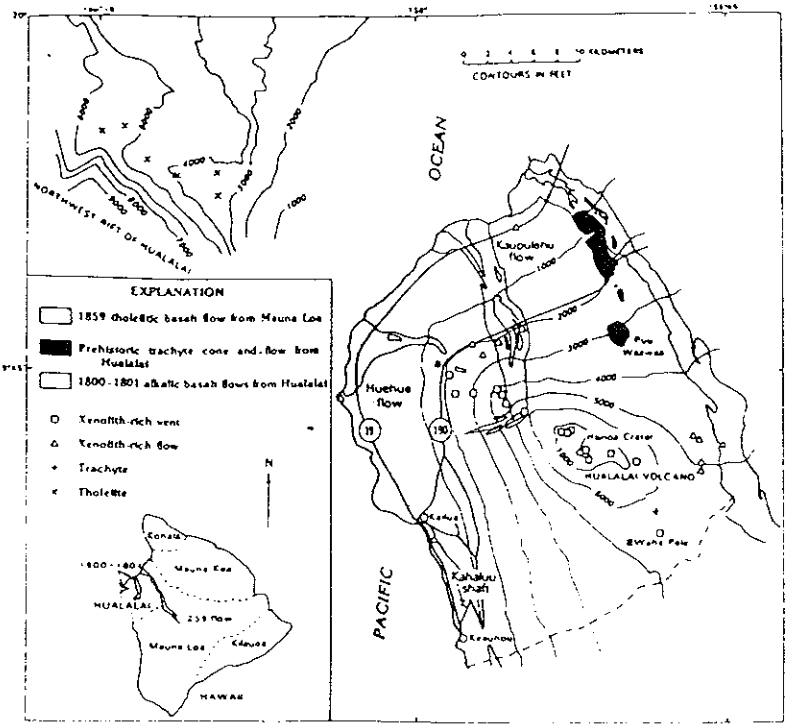

Figure 1. Geologic map of Hawaii showing location of Hualalai and Pu'u Wa'awa'a. (Moore et al., 1987)

REGIONAL GEOLOGY

The Hawaiian Islands. Study of Hawaiian volcanoes has revealed that compositional variations and changes in volume of erupted lavas over time follow patterns that have been observed in most Hawaiian volcanoes. Clague (1987) outlines four stages of Hawaiian volcanic evolution. The first stage is the pre-shield alkalic stage in which small volumes of alkalic basalt and basanite are erupted under water. Toward the end of this stage, alkalic basalt becomes transitional to tholeiitic basalt as the volcano moves into the main shield building stage. In this stage, large volumes of tholeiitic lava build the volcanic edifice above the surface of the ocean. The third stage is a post-shield alkalic stage. Eruption volume decreases and lava composition changes to alkalic basalt. During this stage, occasional ankaramite, hawaiite, mugearite, benmoreite, and trachyte also erupt. The last stage is a rejuvenated alkalic stage and is not present in all volcanoes. Alkalic lavas of this stage are strongly undersaturated and include basalt, basanite, nephelinite, and melilite.

Hualalai Volcano. Hualalai is located on the west side of the Island of Hawaii on the flank of Mauna Loa (Figure 1). Hualalai's surface is covered by alkalic basalts, rare basalt transitional to hawaiite and one large trachyte flow. The basalts range in age from approximately 13 ka to the present. The oldest flow that crops out is the trachyte flow which has been dated at 106±6 ka. The extreme thickness of the trachyte flow (100 meters) has prevented it from being covered by more recent basalt flows.

Tholeiitic lavas have been discovered at depth in drill cores, and Clague (1987) estimates the end of tholeiitic volcanism at 120 ka. Since the transition to the post-shield alkalic stage, distribution of lavas has been bimodal, with abundant basalt and less voluminous trachyte and no known intermediates. Hualalai is presently in the post-shield alkalic stage of volcanic evolution and has erupted in historic times.

There is some evidence to suggest that Hualalai has a significant amount of trachyte beneath the basaltic surface layer. A water well at Huehue Ranch reveals a trachyte unit that has been covered by subsequent basalt flows. Trachyte also appears as blocks in a tuff at Waha Pele vent and as small xenoliths and cinder at other vents (Clague, 1987).

Geophysical evidence also supports the theory that there may be a large volume of trachyte on Hualalai. There is an aeromagnetic low over the summit and rift zones of Hualalai which is not present on any of the other Hawaiian volcanoes. This low indicates that the material below the basalts on the surface has a very low magnetic field, a characteristic consistent with the behavior of lower-iron trachyte. Low gravity (250 Ga) over the summit and rift zones also supports the possibility that trachyte is present, indicating that a lower density material lies beneath the surface (Moore et al., 1987).

METHODS

A geologic map of Hualalai Volcano compiled by Richard B. Moore and David A. Clague was used for reference in sampling the trachyte flow. Prominent points on the flow are named. Pu'u Wa'awa'a is the cinder cone at the vent where the flow originated. Pu'u Huluhulu is a kipuka, or an island of trachyte that has been surrounded on all sides by later basalt flows. Pu'u Anahulu is a long high hill that is the main body of the flow.

83 samples were collected at Pu'u Wa'awa'a, Pu'u Anahulu, and Pu'u Huluhulu. Samples include pumice, obsidian, trachytic lava and basaltic lava. Trachyte samples were collected from both proximal and distal ends of the flow and at different depths within the flow. Of these 83 samples, 30 representative samples were selected for more detailed petrographic and geochemical analysis.

Thin section blanks were cut at the Colorado College and sent to Wagner Petrographic for thin section preparation. Sections were analyzed at the Colorado College Geology Department.

30 samples were pulverized and fused, and major, minor, and selected trace element concentrations were determined by x-ray fluorescence at the Colorado College. Trace and rare element concentrations were found by INAA for 10 representative samples at Oregon State University.

In addition to the one alkalic basalt sample collected from Hualalai, alkalic basalt analyses reported by Moore and others (1987) are used in major and incompatible element diagrams to model petrogenic processes in the formation of the trachyte. Trace element abundances in Hawaiian basalts vary from volcano to volcano, but remain relatively constant in individual volcanoes over time. Though the alkalic basalts used in these models are younger than the trachyte, they are probably similar to alkalic basalts that were being produced at the time the trachyte erupted.

GEOCHEMISTRY

In a Na_2O+K_2O versus SiO_2 discrimination diagram, samples identified in the field as trachyte plot in the center of the trachyte field with little variation among samples. SiO_2 weight % ranges from 61.68 to 63.00. The alkalic basalts show a slightly wider range in composition, with SiO_2 weight % between 45 and 48. However, a marked lack of intermediate compositions is apparent between 48% and 61.68% SiO_2. In Harker variation diagrams, K_2O, Na_2O, MnO, and Al_2O_3 all plot higher with higher SiO_2 content and CaO, MgO, TiO_2, and P_2O_5 all decrease with decreasing SiO_2. Again, basalt samples cluster together, as do the trachyte samples, and there are no intermediates.

Spider plots of incompatible elements and Rare Earth Element (REE) diagrams normalized to continental crust and ocean island basalt proved to be good matches for trachyte compositions (figure 2). Relative to these standards, the trachyte is depleted in Ba, Sr, and Cr which could have been removed by fractionation of potassium feldspar, plagioclase and clinopyroxene respectively. REE plots show a slight depletion in Eu which can be accounted for by the fractionation of plagioclase. A strong correlation of high Sr to low SiO_2 and vice versa on bivariate plots indicates that plagioclase has either fractionated out of the trachyte or that plagioclase was left behind during partial melting. The lack of correlation of Ba with SiO_2 suggests that there has not been significant removal of potassium feldspar from the trachyte.

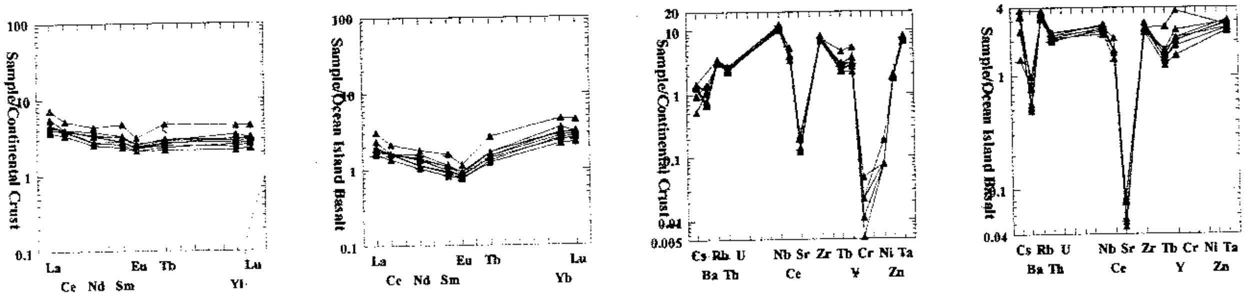

Figure 2. Rare earth element and spider plots showing trachyte samples normalized to continental crust and ocean island basalt. Note: scale for REE plots is a 0.1-100 logarithmic scale and spider diagrams have smaller log scales.

Bivariate plots also reveal trace element depletions in the trachyte that could have either been left behind during partial melting or removed by crystal fractionation. A plot of V versus SiO_2 shows V on the order of 400 ppm for basalts while the trachyte samples have about 10 to 40 ppm V, suggesting lesser amounts of magnetite in the trachyte. Ni has a nearly linear relationship to MgO. The trachytes have only accessory olivine and have low Ni and MgO. Basalts with a lot of modal olivine plot with higher Ni and MgO. Sc, Cr and MgO are also less abundant in the trachyte, indicating a lack of clinopyroxene, while the basalts have high Sc, Cr and MgO and also have more clinopyroxene. The lack of certain phases in the trachyte compared to the basalts could support either partial melting or fractional crystallization processes.

High field strength elements such as Ta, Nb, Th, Zr, Hf, Tb, and Yb are extremely incompatible and do not form phases of their own, even at very large degrees of fractional crystallization. The ratio of one high field strength element to another should be the same as the mantle source from which it was derived. La/Nb, Th/Ta, La/Ta and La/Yb ratios were plotted against SiO_2. On plots of La/Ta and La/Yb all trachyte samples cluster close together and the ratio of high field strength elements in the basalt is 10 to 13 and trachyte samples range from 8 to 14. The La/Nb ratio for basalt is 0.8 compared to a range of 0.5-0.9 for trachyte. However, since La is in all of these plots, it is important not to give too much weight to these graphs without considering the results of other elements. Trachyte samples also cluster very closely on the Th/Ta plot with ratios from 1.12 to 1.28 while the ratio for the basalt sample is 1.00. These ratios remain constant for most plots, suggesting that the mantle source for the basalts and trachytes is similar in composition.

DISCUSSION

Philpotts (1990) outlined the theories which are still being evaluated to explain the Daly Gap. "Non-ideal behavior in the liquids" could have a number of effects on the composition of the magma. Cooling liquids may have a very rapid rate of compositional change which would be reflected in dramatic changes in the slope of the liquidus. A rapid rate of compositional change upon cooling would favor the production of the end members. Little or no cooling before eruption would result in basalt, whereas any cooling, even small degrees, would produce trachyte. "Sufficiently non-ideal behavior" could even result in liquid immiscibility. Differences in the density and viscosity of the members of the series may favor the eruption of the end members. Though denser, basalt would have sufficiently low viscosity to flow to the surface, and trachyte, though viscous, has low enough density that buoyancy helps it to erupt. Supposedly the intermediate compositions remain below the surface because they are both too dense and too viscous to make it to the upper levels of the crust. It is also possible that trachyte is not a product of fractionation of a basalt, but represents a very small degree of partial melt from the mantle. Though many explanations have been suggested to explain this bimodal distribution, none are sufficiently convincing to settle the question definitively.

If any of these processes are factors in the formation of the Wa'awa'a trachyte, evidence should be observed in geochemical and petrographic analysis. If a rapid rate of compositional change excluded intermediate members of the series, disequilibrium textures should be observed in thin sections of the trachyte. In fact, no such textures are present. The trachyte is aphyric, no zoning of minerals is apparent, and there are no reaction rims around any minerals. If density and viscosity factors played a part in the distribution of lavas in the alkalic series, evidence of intermediate bodies at depth should be present. Though trachyte xenoliths appear in several basalt flows on Hualalai, no intermediate composition xenoliths are present. Drill cores have never revealed any evidence of intermediate compositions below the surface. Although the lack of evidence of intermediate rocks at depth does not support the density/viscosity theory, it also does not exclude it as a possibility.

In the absence of evidence to support the disequlibrium fractionation theory and the density/viscosity model, the two explanations remaining to be evaluated are partial melting and fractional crystallization models. The trachyte could have formed as a very small degree of partial melting of the mantle or possibly of an alkalic basalt. The other possibility is that a basaltic melt underwent a large degree of fractional crystallization.

Allegre and Minster (1978) developed a number of trace element plots that can be used to test igneous processes. More examples of these plots and their applications are described by Geist and others (1986). The most useful of these plots follows the formula H/M versus H, where H is a hygromagmatophile, or, to use Geist's terminology, highly incompatible element. M is a magmatophile or moderately incompatible element. In theory, fractional crystallization should not change the ratio of the elements while partial melting would. Allegre and Minster (1978) suggest using Ta, Th, La, or Ce for the H element and Zr, Hf, and the heavy REE as M.

When this method of testing igneous processes was applied to the trachyte, the pairs La/Sm, Ce/Tb, Th/Tb, Ta/Tb, Ta/Lu, Ce/Sm, and La/Tb all indicated partial melting (figure 3). However plots of other pairs, such as Ta/Zr, La/Yb, Th/Lu, Ta/Yb, Ce/Hf, Th/Yb, La/Zr, and Th/Hf, seem to indicate a fractional crystallization trend, while others give inconclusive results.

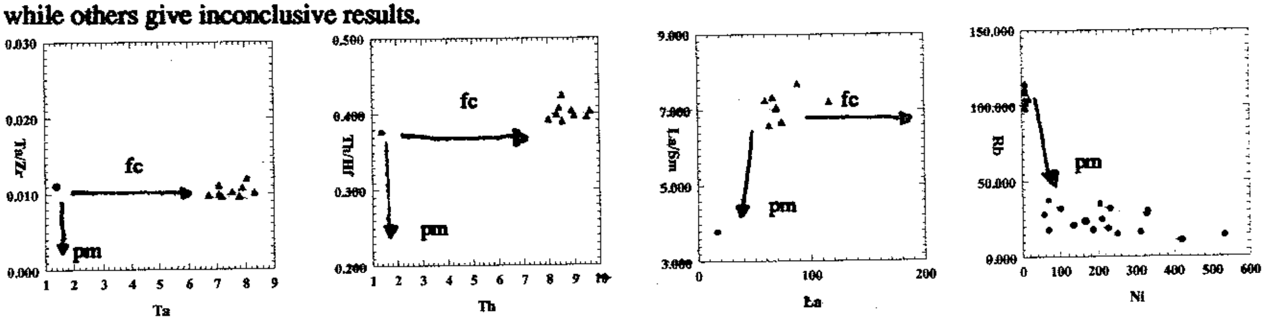

Figure 3. H/M versus M and Ni versus Rb plots showing igneous process interpretation. Circles represent basalt samples and triangles represent trachytes. Pm and fc labels and arrows indicate igneous process trends. In the Ni vs. Rb plot at far right, a fractional crystallization path would be directed horizontally left from the trachyte cluster on the y-axis.

Geist and others (1986) use a plot of Ni versus Rb to determine fractionation processes. Fractional crystallization would remove Ni from the melt as olivine crystals formed, yet Rb, being incompatible, would be only slightly enriched. However, if olivine is left behind during partial melting, Ni concentrations will remain constant and Rb will change. The trend in figure 3 indicates partial melting.

Trace element analysis seems rather ambiguous. Some H/M versus H plots suggest fractional crystallization has occurred while others support partial melting. Excel spreadsheets written by Diane Smith of Trinity University were used to model igneous processes. Trace element abundances are entered into an Excel spreadsheet that had distribution coefficients for each element. An alkalic basalt from Hualalai was used as a starting point. The program is only set up to model fractional crystallization up to 80%, however, trace element abundances for 80% crystallization were approaching those found in the trachyte. Clague (1987) estimated 85-90% crystallization of a basaltic melt to produce the trachyte, and trace element abundances for the trachyte at this level of fractionation are a good match.

The estimated volume of the flow is 5.5 km^3 which is the single largest eruptive event on the island of Hawaii. 85-90% crystallization would require a volume of 37-55 km^3 of parental magma (Clague, 1987). The magma chamber under Kilaeua was mapped at 3 km diameter and 3 km deep (Wilson, 1989). If Kilaeua can be used as a model for Hualalai, a magma chamber of these dimensions could have held the fractionating magma.

REFERENCES

Allegre, C.J. and J.F. Minster, 1978, Quantitative models of trace element behavior in magmatic processes: Earth and Planetary Science Letters, v. 38, p. 1-25.

Clague, David A., 1987, Hawaiian xenolith populations, magma supply rates, and development of magma chambers: Bulletin of Volcanology,v. 49, p. 577-587.

Philpotts, Anthony R., 1990, Principles of igneous and metamorphic petrology: Prentice Hall, New Jersey.

Geist, Dennis J., Alexander R. McBirney, and Robert A. Duncan, 1986, Geology and petrogenesis of lavas from San Cristobal Island, Galapagos Archipeligo: Geologic Society of America Bulletin, v. 97, p. 555-566.

Moore, Richard B., David A. Clague, Meyer Rubin, and Wendy A. Bohrson, 1987, Hualalai Volcano, Hawaii. A preliminary summary of geologic, petrologic and geophysical data: USGS Professional Paper 1350, p. 571-585.

Wilson, Marjorie, 1989, Igneous Petrogenesis: Chapman and Hall, London, p. 254.