I. N. Bindeman · J. C. Bailey

A model of reverse differentiation at Dikii Greben' Volcano, Kamchatka: progressive basic magma vesiculation in a silicic magma chamber

Received: 4 September 1993 / Accepted: 9 March 1994

Abstract Dikii Greben' Volcano is the largest modern volcano with silicic rocks in the Kurile-Kamchatka island arc. It consists of many domes and lava flows of rhyodacite, dacite and andesite which were erupted in a reverse differentiation sequence. Non-equilibrium phenocryst assemblages (quartz + Mg-rich olivine, An-rich + An-poor plagioclase etc.), abundance of chilled mafic pillows in the dacites and andesites, and linear variations of rock compositions in binary plots are considered as mineralogical, textural and geochemical evidence for mixing. Mafic pillows in volcanics have a lower density (because of high porosity) and contain the same non-equilibrium phenocryst assemblages as the host rocks. Their groundmass contains skeletal microlites of plagioclase and amphibole proving that the groundmass as well as the pillows themselves formed from a water-rich basaltic magma at depth. They are considered as supercooled, vesiculated floating drops of a hot hybrid layer in the magma chamber which formed after refilling. The lower density of the inclusions allows them to float in the host magma and to concentrate at the top of the chamber prior to eruption. Magma mingling was effected by mechanical disintegration of the inclusions in the host magma during eruption. The rhyodacitic and basic end-members of the mixing series cannot be linked by low-P fractionation though high-P, amphibole-rich fractionation is not excluded.

Introduction

There are many described examples of the contemporary association and eruption of a wide variety of magma types in volcanic and plutonic environments (Yoder 1973; Sakuyama 1979; Nixon 1988; Blundy and Sparks 1992) which involve mixing between highly contrasting magmas. Mixing between low-viscosity basic magmas demonstrated in experimental models is considered the usual result of periodic refilling of an evolving magma chamber by new pulses of parental melt (Campbell and Turner 1985; Turner and Campbell 1986). In contrast, fast convective mixing between fluids with large contrasts in viscosity and temperature, e.g. silicic and basic magmas, is practically impossible (Yoder 1973; Turner and Campbell 1986). Petrological studies of some plutons have clearly shown that both basic and silicic magma coexisted in the chamber without extensive mixing throughout much of their evolution (Wiebe 1988, 1993; Litvinovsky et al. 1993).

It is becoming apparent that the most plausible mechanism for mixing magmas with gross differences in composition and temperature is forced convection during eruption (Kouchi and Sunagawa 1985; Koyaguchi and Blake 1989). The calculated short residence time for phenocrysts (Nixon 1988) implies that mixing of different magmas took place shortly before or more likely during the course of eruption. Sakuyama and Koyaguchi (1984) estimated the time necessary for magma mixing as hours/days based on the transportation time for mantle xenoliths. In such time periods, mixing between strongly contrasting magmas is largely incomplete. As the difference in composition and temperature increases, large scale inhomogeneity of compositions and textures appears and sometimes extends to the whole range of compositions between the mixing end-members. For example, quenched mafic inclusions and banded structures in intermediate and silicic rocks are considered to be the result of supercooling and
non-mixing of two thermally constrasting magmas during basic magma refilling of silicic reservoirs (Yoder 1973; Eichelberger 1980). These inhomogeneities along with the mineral zoning pattern record information about the mixing end-members and can be used to estimate the volume proportion of refilling, mixing ratio and mixing history. It should be stressed here that the mixing ratio does not simply reflect the proportions of the two mixing magmas since the mixing history also includes the additional mechanism of basic magma concentration near the chamber roof prior to eruption.

This article is devoted to the petrological study of the active Dikii Greben' Volcano, Kamchatka, which provides an example of large scale mixing between rhyodacitic and basaltic magma which took place in the last 2000–1500 years.

Geology and magmatic evolution of the volcano

The Dikii Greben' (Wild Ridge) Volcano is an active volcano located in south Kamchatka (Fig 1). It is the largest modern volcano with silicic volcanic rocks in the whole Kurile-Kamchatka island arc. The volume of the volcanics exceeds 15 km$^3$, and these are spread over a territory of about 40 km$^2$ (Ogorodov et al. 1978). At the present time it is a complex volcanic edifice consisting of a number of extrusive domes and lava flows, accompanied by small amounts of pyroclastic breccias. The main centre of eruption is the highest point of the volcano - Mount Nepriyatnaya (Unpleasant) – which is a partly broken extrusive dome. Large rock falls from Mount Nepriyatnaya occur annually and suggest that the dome may still have been growing until recent times.

The geology and general petrographic features of the volcano are given by Piip (1947), Svyatlovsky (1975), Ogorodov et al. (1978) and Ogorodov (1980).

The Dikii Greben' Volcano series is composed of phenocryst-bearing calc-alkaline rhyodacites (5 km$^3$), dacites (8 km$^3$) and andesites (2 km$^3$). Dacites and andesites, in contrast to rhyodacites, contain mafic pillows (magmatic inclusions) of basaltic and basaltic andesite composition which form a separate mode on the histogram of SiO$_2$ contents (Fig. 2).

The $^{14}$C and tephrochronological age determinations on the volcano reveal the history of eruptions. According to Ogorodov (1980), the basement of the volcano, which is composed of rhyodacitic pumices, has an age of 8000 years. These pumices, which belong to the Kuril'skoye Lake centre and are distinguished from the Dikii Greben' lavas by different K/Na ratios, are not considered further. Some tephrochronologically dated pyroclastic eruptions, also rhyodacitic, took place 5000 and 2000–1500 years ago (Ponomareva, in press). Field observations and tephrochronological data allow us to propose the following sketch of the magmatic evolution. The oldest rocks - rhyodacites lacking magmatic inclusions and forming approximately 30 vol.% of all volcanics - were formed from 8000 until 2000–1500 years ago. They constitute 75–80% of the volcanic history. Dacites and andesites, which form the largest part of the volcanics, were erupted during the last 2000–1500 years and thus take up less than 25–20% of the volcano's history. The magmatic evolution is characterized by reverse differentiation and intensification during the last 2000–1500 years.

Analytical techniques

Minerals were analysed at Moscow State University using an energy dispersive procedure on a CamScan electron microscope with a Link AN1100 microprobe analyser. Major elements in rock samples were obtained by XRF analysis of glass discs at the Chemistry Laboratory of Saratov State University (Table 8) and the Geological Survey of Greenland in Copenhagen (Table 9), supplemented by atomic absorption (Na, Mg) and wet chemical techniques [FeO, H$_2$O$^+$, (loss on ignition) LOI]. Most traces were obtained by XRF analysis...