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Magmatic diversity on Venus: Constraints from terrestrial analog crystallization experiments

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ABSTRACT

Igneous diversity is common on terrestrial planets and has been experimentally investigated for the Earth and Mars, but only suggested for Venus. Since Venus and Earth are sister planets and have similar bulk chemistry, experiments on terrestrial basalts can place constraints on the formation of the Venera and Vega basalts. Furthermore, experimental results can suggest the types of magmas that should be present on Venus if processes of differentiation similar to those taking place within the Earth are occurring on Venus, as suggested by the Venera and Vega analyses. The interpretation of the Venera 13 analysis as an alkali basalt suggests deep partial melting of a carbonated source region; while the identification of Venera 14 and Vega 2 as tholeiites suggest relatively shallow melting of a hydrous lherzolitic or peridotite source region. The residual liquids produced by differentiation of a Venus tholeiite, based on experiments on analog compositions, range from rhyolites to phonolites, depending on pressure of crystallization and bulk water content. Results from these crystallization experiments on tholeiitic terrestrial compositions can constrain the type and quality of data needed from future missions to determine the petrologic history of surface igneous rocks.

1. Introduction

Extensive work has been done exploring the petrologic origin of the rocks analyzed from the Venera and Vega missions (see Fegley, 2003; Treiman, 2007 for a full summary). This work has shown that Venus and Earth have similar K/Th, U/Th, and K/U ratios (e.g., Basilevsky et al., 1992; Kargel et al., 1993; Fegley, 2003; Treiman, 2007) and in general this suggests a Venus mantle with major element chemistry similar to the terrestrial mantle (e.g., Hess and Head, 1990; Kargel et al., 1993; Treiman, 2007). However, the data from the Venera and Vega landers have large error bars compared with terrestrial geochemical analyses, thereby making direct implications from this data challenging (e.g., Kargel et al., 1993; Grimm and Hess, 1997; Treiman, 2007). Here I rely on crystallization experiments on terrestrial tholeiitic compositions in order to make predictions about the types of magmas that could be on Venus and the types of chemical analysis future missions will need to provide in order to constrain the igneous diversity of the Venus surface.

Seven Russian missions provided chemical analyses of rocks on the surface of Venus. Venera 13, 14, and Vega 2 provided the only major element bulk chemistry of these rocks (Surkov et al., 1984, 1986); while the other missions provided a subset of elemental analyses (e.g., Kargel et al., 1993; Fegley, 2003; Treiman, 2007). For this paper, I focus on the Venera 13, 14 and Vega 2 analyses because they are the most complete analyses (Table 1). The Venera 13 analysis is consistent with that of an alkali basalt, either a leucite or lamprophyre, while the Venera 14 and Vega 2 analyses are similar to those of olivine tholeiites from mid-ocean ridges (e.g. Basilevsky et al., 1992; Kargel et al., 1993; Fegley, 2003). The interpretation of the Venera 13 analysis as an alkali basalt suggests deep partial melting of an anhydrous, carbonated source region; while the Venera 14 and Vega 2 tholeiites suggest relatively shallow melting of a lherzolitic or peridotite source region (Hess and Head, 1990; Kargel et al., 1993; Dasgupta et al., 2007). Carbonate-rich volcanism, and therefore a carbonated mantle, has also been suggested based on lava flow morphology and thermochemical calculations (Kargel et al., 1994; Treiman, 1995). However, Venus basalts (both Venera and Vega analyses) have super chondritic Ti/Al ratios (Treiman, 2007) and are enriched in incompatible elements compared with the incompatible element levels of mid-ocean ridge basalts (Nikolaeva and Ariskin, 1999) suggesting a similarity to terrestrial ocean island alkalic basalts rather than mid-ocean ridge basalts (Treiman, 2007). Further, recent analyses from the Galileo mission have provided evidence for the presence of felsic rocks in the Venusian highlands (Hashimoto et al., 2008), implying that, similar to the Earth, the crust of Venus may contain not only basaltic rocks (such as those analyzed by Venera and Vega), but evolved magmas as well (Bonin, 2012). Petrologic modeling of the basaltic rocks from Venera and Vega has shown that crystallization of a Venus

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Table 1
Venera 13 and 14 and Vega 2 chemical analyses (in wt%) shown to 1 decimal place and with 2 sigma errors (reproduced from Treiman, 2007).

	Venera 13	2σ	Venera 14	2σ	Vega 2	2σ
SiO_2	45.1	6.0	48.7	7.2	45.6	6.4
TiO_2	1.6	0.9	1.3	0.8	0.2	0.2
Al_2O_3	15.8	6.0	17.9	5.2	16.0	3.6
FeO	9.3	4.4	8.8	3.6	7.7	2.2
MnO	0.2	0.2	0.2	0.2	0.1	0.2
MgO	11.4	12.4	8.1	6.6	11.5	7.4
CaO	7.1	2.0	10.3	2.4	7.5	1.4
Na_2O	n.d.		n.d.		n.d.	
K_2O	4.0	1.2	0.2	0.1	0.1	0.2
SO_3	1.6	2.0	0.4	0.6	0.9	1.2
P_2O_5	n.d.		n.d.		n.d.	
Sum	96.1		95.8		89.6	

n.d. – no data.

basalt at shallow crustal levels can produce phonolitic and rhyolitic/granitic compositions (Shellnutt, 2013). This is consistent with a Venusian crust that is more diverse in composition than seen at the Venera and Vega landing sites, and which may have as much diversity in igneous rocks as seen on Earth.

The data from the Venera and Vega landers have large error bars compared with terrestrial geochemical analyses and do not provide mineralogy of the target rock, thereby drawing direct conclusions from this data is challenging (e.g., Kargel et al., 1993; Grimm and Hess, 1997; Treiman, 2007). In order to make predictions about the types of magmas that could be on Venus, I will rely on crystallization experiments on terrestrial tholeiitic compositions. Extensive crystallization experiments have been conducted on terrestrial olivine tholeiites at varying pressures, temperatures, and water contents in order to understand the residual liquids produced by igneous differentiation (e.g., Green, 1970; Spulber and Rutherford, 1983; Filiberto and Nekvasil, 2003; Nekvasil et al., 2004; Whitaker et al., 2007, 2008). Such diversity has also been experimentally investigated for the martian crust using basalt crystallization experiments (e.g., Minitti and Rutherford, 2000; Whitaker et al., 2005; Nekvasil et al., 2007; Filiberto, 2008; McCubbin et al., 2008; Rapp et al., 2013). If similar processes of magma ponding and differentiation have occurred on Venus, then compositions similar to terrestrial igneous suites would be expected. Therefore, by comparing these experimental results and natural terrestrial suites with the data from Venera and Vega, we can constrain the types of igneous rocks that could be present on Venus, as well as the quality and type of data needed from future missions to distinguish the different suites.

2. Experiments on terrestrial tholeiitic basalts

Crystallization experiments have been conducted from 0 to 27 kb pressure and varying water contents to explore the compositions of rocks that can be produced by igneous differentiation from terrestrial tholeiitic basalt compositions (e.g., Green, 1970; Spulber and Rutherford, 1983; Filiberto and Nekvasil, 2003; Nekvasil et al., 2004; Whitaker et al., 2007, 2008). Igneous differentiation occurs when a magma ponds at a certain depth, cools and crystallizes. The residual liquids then separate from the crystallized minerals and erupt on the surface. The residual liquids produced by differentiation in these experiments range from rhyolites to phonolites, depending on pressure of crystallization and bulk water content of the magma. Table 2 summarizes the experimental conditions (pressure, water content) needed to produce each terrestrial rock suite and Fig. 1 shows the compositional diversity that can be produced.

2.1. Low pressure

Crystallization of a tholeiitic magma at low pressure (<2 kb; <10 km depth) follows the thoeliitic trend and produces residual liquids that range from olivine tholeiites, ferrobasalts, and icelandites, through rhyolites (Spulber and Rutherford, 1983; Horn, 2004; Whitaker et al., 2007). The experimental liquid line of descent is characterized by an initial iron, titanium, and phosphorous-enrichment, caused by early crystallization of forsteritic olivine, followed by an increase in silica, associated with depletions in iron and titanium, driven by Fe–Ti oxide crystallization (Spulber and Rutherford, 1983; Horn, 2004; Whitaker et al., 2007). Potassium increases incompatibly, while sodium is buffered by plagioclase crystallization (Spulber and Rutherford, 1983; Nekvasil et al., 2000; Horn, 2004; Whitaker et al., 2007). Alkali elements increase with crystallization, but the total alkali content never rises above the Irvine and Baragar (1971) subalkalic–alkalic boundary (Fig. 1). Terrestrial examples of this suite of rocks are from Volcano Alcedo, Galapagos and Thingmuli, Iceland (Fig. 2) and are only found at ocean islands (Carmichael, 1964; Geist et al., 1994, 1995).

2.2. Upper mantle/lower crust

Ponding at the base of the crust/upper mantle (assuming average crustal thickness of 20–40 km Grimm and Hess, 1997. See Table 2 for calculation) can produce three different classes of igneous rocks, depending on pressure and volatile content: (a) potassic

Table 2
Experimental conditions (pressure and dissolved water content in the magma) of magma ponding and crystallization to produce terrestrial igneous suites (Green, 1970; Spulber and Rutherford, 1983; Filiberto and Nekvasil, 2003; Nekvasil et al., 2004; Whitaker et al., 2007, 2008). Examples of each terrestrial igneous suite are included, and are possible analogs to Venus igneous suites (Carmichael, 1964; Abbott, 1969; Leeman et al., 1976; Stout and Nicholls, 1977; Feigenson et al., 1983; Stolz, 1985; Lanphere and Frey, 1987; Spengler and Garcia, 1988; Le Roex et al., 1990; Frey et al., 1991; Geist et al., 1994, 1995; Stout et al., 1994; Kar, 1998). Color coding and references the same as Figs. 1 and 2. Depth (km) is calculated assuming 10 kbar (1 GPa) being equivalent to 36 km depth and crustal thickness of 20–40 km, with a preferred crustal thickness of 30 km (Grimm and Hess, 1997).

Fractionation Pressure		Depth (km)	Volatile Content	Trend	Terrestrial Analog
Surface	0-2kb	0-10		Tholeiitic Trend	Galapagos Thingmuli
Base of the crust/Upper mantle	5-11kb	20-40	<0.3wt% water	Potassic Alkalic Series	Snake River Plain
	9-11kb	30-40	>0.3wt% water	Sodic Alkalic Series	Nandewar Ascension Island
	12-16kb	45-60	>0.3wt% water	Silica-undersaturated	Hawaii
Mantle	18-27kb	65-100	~0.2 wt% water	Phonolitic Series	Tristan de Cunha