Geochemical constraints on petrogenic processes on Venus

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Abstract. Abundances of three incompatible elements (K, U, Th) have been determined by robotic spacecraft in five surface materials on Venus. We present these data normalized to terrestrial normal mid-ocean ridge basalt (NMORB) derived from the depleted mantle. Relative to NMORB, all of the Venus materials studied are enriched in all of these elements. The moderately enriched (Venera 9 and 10, Vega 1 and 2) basaltic rocks are similar to one another in the sense of their enrichment trends ($U_N > K_N$) but differ from the highly enriched Venera 8 material, where the trend is $K_N > U_N$. This difference implies that the enrichment pattern for the basaltic materials is not controlled by crystallization of an NMORB-like magma or by contamination of such a magma by highly enriched Venera 8 material within the crust, and the Venera 8 material cannot have evolved from the magma of any of the basaltic rocks. Our calculations show the K-U-Th pattern for any of the Venus rocks analyzed was not controlled by batch partial melting of primitive mantle. The Venera 8 material could be produced as a partial melt from eclogitic tholeiite, but none of the basaltic materials could be because the sense of their $U_N > K_N$ trends is opposite to the enrichment trends in calculated models ($K_N > U_N$). The Venus basalts differ from fresh terrestrial rocks (NMORBs and oceanic island-arc volcanics) in having nearly constant K/U ratios, while terrestrial rocks have nearly constant Th/U ratios. This may suggest an unusual composition of mantle source(s) of the Venus basalts and/or unusual fractionation process(es) on that planet.

1. Introduction

Venus has an important geochemical difference from Earth. On Earth's surface the interelement ratios found in pristine igneous rocks are greatly changed by secondary weathering processes in which the elements are selectively dissolved and transported. In contrast it is clear that on the surface of Venus, where liquid transport does not occur, secondary processes should not fractionate the elements significantly. Venus surface material may look like sediments or loose soil, but the processes that comminuted the surface material seem not to have disturbed major element abundances or U and Th concentrations relative to their values in pristine igneous rocks [*Florensky et al.*, 1977; *Nikolayeva*, 1990; *Zolotov and Volkov*, 1992; *Basilevsky et al.*, 1992]. This circumstance facilitates petrogenic studies of Venus rocks, partly compensating for the scarcity of chemical measurements on that planet.

Petrogenic processes on Venus have been broadly discussed by *Hess and Head* [1990], *Barsukov* [1992], and *Kargel et al.* [1993]. These studies are based largely on the major-element compositions of Venus rocks [*Surkov*, 1990], and they conclude that magmatic and volcanic activity on Venus should, in general, be very similar to that on Earth. The other geochemical data available for Venus rocks relate to the large-ion-lithophile (LIL) elements potassium, uranium, and thorium [*Surkov* [1990]; data summarized by *Surkov* [1997]]. LIL elements are well known to be incompatible with respect to the normal mantle minerals [*Basaltic Volcanism Study Project*, 1981; *Gill and Condomines*, 1992; *Green*, 1994]. There is no obvious reason to argue against

incompatible behavior of the LIL elements on Venus. During melting, any of these elements goes preferentially into the melt, to a degree that may vary depending on petrogenetic variables. It has long been known that LIL element contents in rocks are more variable than major-element abundances, so they are more informative about petrogenesis. As known, incompatible element concentration ratios in terrestrial basalts have been used in the same way isotopic ratios are to characterize mantle magma sources.

In the present paper we discuss petrogenetic processes in Venus in the light of constraints imposed by incompatible-LIL-element ratios. To derive these constraints, we first summarize the LIL data in a relevant form, then we compare the implications of this summary to the predictions that result from some end-member petrogenetic models. We will show that none of these earlier petrogenetic models for the formation of Venus basalts, which have been characterized as normal tholeiites [*Surkov et al.*, 1976, 1987; *Barsukov*, 1992; *Kargel et al.*, 1993], satisfy the geochemical constraints.

2. In Situ Measurements of LIL-Element Abundances on the Venus Surface

The incompatible elements K, U, and Th are natural long-lived radioactive elements that emit gamma rays when they decay. Exploiting this property, five Soviet landers (Venera 8, 9, and 10 and Vega 1 and 2) made scintillation gamma ray spectrometric (GRS) analyses of K, U, and Th abundances in the surface rocks on Venus. These measurements have been described in detail in Russian and English journal papers [*Vinogradov et al.*, 1973a,b; *Surkov*, 1977; *Surkov et al.*, 1973, 1976, 1986a,b, 1987] and summarized in three books [*Surkov*, 1985; *Surkov*, 1990, 1997]. We briefly review these data from a geochemical rather than a technical perspective.

Table 1. K, U, and Th Contents of Venus Rocks, Measured by Gamma Ray Spectrometers on Landers Venera 8, 9, and 10 and Vega1 and 2

	K, wt. %	U, ppm	Th, ppm
Venera 8	4.0±1.2	2.2±0.7	6.5±0.2
Venera 9	0.47±0.08	0.60±0.16	3.65±0.42
Venera 10	0.30±0.16	0.46±0.26	0.70±0.34
Vega 1	0.45+0.22	0.64±0.47	1.5±1.2
Vega 2	0.40±0.20	0.68±0.38	2.0±1.0

After *Surkov* [1990, 1997].

The gamma ray spectrometers began to operate during descent of the landers through the lower atmosphere and continued to operate as long as the landers remained functional on the surface of Venus. The spectra taken before landing provided information on the background gamma radiation. The main contributors to background were gamma ray sources in the instruments inside the landers, and cosmic-ray-induced short-lived radionuclides (mostly ^{24}Na) in the lander structure. After subtracting the background spectra from total on-surface spectra measured, the corrected spectra consisted of gamma radiation emitted by the rock under the lander. The source area of surface material was a circle 4.0-4.5 m in diameter, which was estimated to contribute about 90% of the gamma radiation received by the detector [*Surkov*, 1990, 1997].

For each lander site, all the spectra obtained were energy-scaled and resolution-equalized to provide an integrated spectrum for the local rock. GRS-measured K, U, and Th abundances in the Venus rocks were compared with a library of spectra of terrestrial reference rocks with known K, U, and Th contents. These terrestrial rock reference spectra had been measured on natural outcrops of igneous rocks using a spare copy of the flight spectrometer, in some cases mounted inside a spare lander. Corrections were made to offset two effects: the greater scattering and absorption of gamma radiation by the denser atmosphere of Venus than that of Earth and, where necessary, scattering/absorption of the lander materials on Venus. Statistical errors associated with element determinations were slightly higher on Venus than in the measurements made on terrestrial outcrops, as a result of different conditions such as higher temperature and pressure, which were exhaustively modeled in the instrument calibration [*Surkov*, 1990, 1997]. The directions of interelement trends appear to be less sensitive to error than absolute values of concentrations or elemental ratio (section 3), as is the case in terrestrial GRS analyses.

Data on K, U, and Th concentrations deduced from lander gamma ray spectra are presented in Table 1 for the surface material at five landing sites on Venus.

3. Presentation of Geochemical Data in a Form Relevant to Petrogenic Considerations

Differences in the behavior of incompatible elements in melt-solid systems are particularly striking when normalized abundances of the elements are compared [e.g., *Pearce*, 1983]. The standard normalizing factor in terrestrial petrogenetic studies is the composition of normal mid-ocean ridge basalt (NMORB). NMORB is derived from mantle material depleted in incompatible elements relative to putative primitive (primordial) mantle (the bulk silicate sphere of Earth, assumed to be fertile undifferentiated chondrite-like material); the formation of the depleted mantle is attributed to silicate melt extraction from

primitive mantle, both for Earth [e.g., *Saunders et al.*, 1988; *Sun and McDonough*, 1989] and for Venus [e.g., *Hess and Head*, 1990; *Head et al.*, 1994]. K, U, and Th abundances in the Venus mantle reservoirs, including the depleted mantle, are unknown and not necessarily the same as they are in the earth.

It is commonly assumed that the bulk silicate portion of Venus is similar to the bulk silicate component of Earth in K abundance [e.g., *Kargel et al.*, 1993; *Namiki and Solomon*, 1995] and/or in Th and U abundances [*Namiki and Solomon*, 1996]. However, the bulk mantle composition of Earth (to say nothing of Venus) is not really known, and values assumed are strongly model-dependent [e.g., *Hart and Zindler*, 1986]. (Even the bulk composition of the lower crust of earth is not known with certainty; see, for example, *Taylor and McLennan* [1985]). In order not to build a model based on other models, we use a different approach. The surface of Venus is dominated by volcanic units, probably basaltic in composition [e.g., *Head et al.*, 1992]. Since during melting incompatible elements go from the mantle source preferentially into erupted melts, the mantle source residue is depleted in these elements; thus Venus must have a mantle depleted in incompatible elements. The bulk compositions of this depleted mantle and melts from it are unknown. We will assume basaltic melts derived from the more or less depleted mantle of Venus are similar to NMORB in K, U, and Th abundances, and test the geochemical consequences of four end-member petrogenetic scenarios.

In terrestrial petrogenic studies, "spider" diagrams are used to compare trace element abundances in rocks to those in NMORB. Figure 1 is a spider diagram that summarizes abundances of K, U, and Th in the rocks analyzed on Venus [*Vinogradov et al.*, 1973a,b; *Surkov et al.*, 1976, 1987] relative to average fresh NMORB [*Nikolaeva*, 1995a,b]. Analytical uncertainties for the measurements, which are not shown in Figure 1a, appear in Figure 1b. Also included in Figure 1a are the K values for three Venus rocks (Venera 13 and 14, Vega 2') that were measured by the X-ray fluorescence instrument.

Three important properties of the geochemical pattern in Figure 1 are as follows:

1. All five rocks in which K, U, and Th were measured are enriched relative to NMORB in all of these incompatible elements. This suggests they are enriched in the other LIL elements as well.

2. The Venera 8 and probably the Venera 13 materials are highly enriched in LIL elements. The Venera 9 and 10 and the Vega 1 and 2 rocks are moderately enriched.

3. All of the moderately enriched rocks, which have been interpreted as tholeiitic basalts [*Surkov et al.*, 1976, 1987; *Barsukov*, 1992; *Kargel et al.*, 1993], are similar to one another, but they differ from the highly enriched rock in being more enriched in normalized U than K ($U_N > K_N$).

It may appear that the measured values of element contents are not precise enough (Figure 1b) to reach this conclusion. However, to reverse the sense of the trend to $K_N > U_N$ would require increasing K by ~2s and decreasing U by ~2s, with probability about $0.05 \times 0.05 \sim 0.0025$. Thus the $U_N > K_N$ sense of the trend is on firmer ground than the absolute abundances reported. The direction of the trend is important to section 4.

As far as we know, data on the K, U, and Th contents of Venus rocks have not been displayed as a spider diagram, though this tool is widely used in terrestrial petrogenic studies. This new look at old data (Figure 1) raises the new question of why all of the Venus basalts in which K, U, and Th have been measured are enriched in incompatible elements relative to NMORB of Earth.
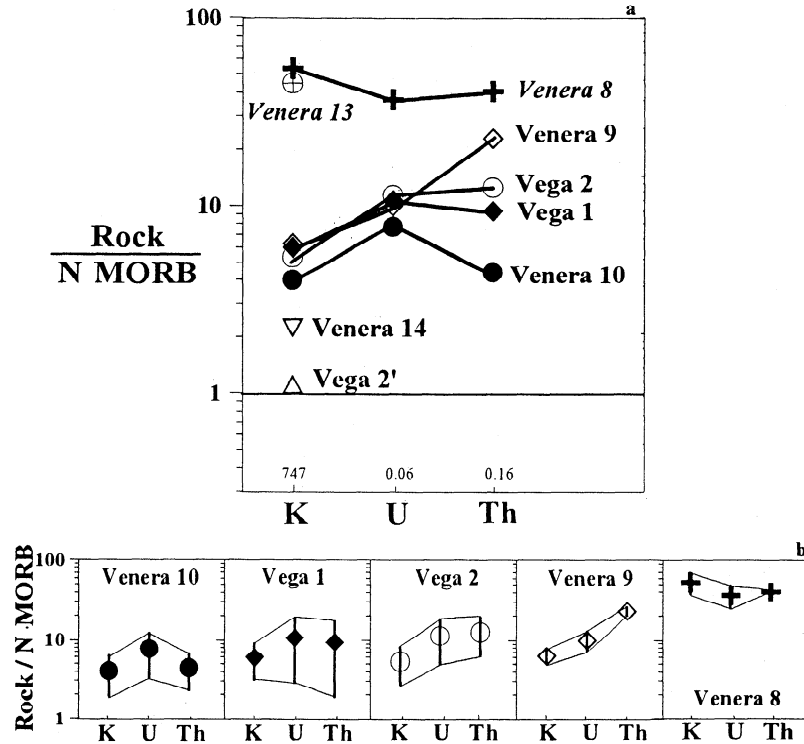
Figure 1. K, U, and Th abundances normalized to average fresh NMORB [*Nikolaeva*, 1995a,b] for the Venus rocks measured by GRS at the Venera 8, 9, and 10 and the Vega 1 and 2 landing sites [*Vinogradov et al.*, 1973a,b; *Surkov et al.*, 1976, 1987] and by XRF at the Venera 13 and 14 and the Vega 2 landing sites (see *Barsukov* [1992] for a data summary). The rock measured by XRF at the Vega 2 site is labeled Vega 2'. In Figure 1a interelement trends are shown by solid lines for K, U, and Th, omitting analytical errors. Normalizing values of the elements, in ppm, appear at the bottom of the box. Figure 1b shows analytical error bars (solid lines, 2s standard deviations) and error corridors (thin lines). Error values for the Venera 8 rock are from *Surkov et al.* [1976].

4. End-Member Petrogenetic Processes in the Light of Geochemical Constraints

The geochemical enrichment pattern in Figure 1 was produced by petrogenic processes. Below we attempt to understand how the petrology of Venus is constrained by the three observations just made about the pattern of Figure 1. We consider the behavior of K, U, and Th in a simple example of each of the following major end-member processes: (1) intracrustal contamination of magma by LIL-element-enriched crustal material during ascent of the magma to the surface, (2) intracrustal fractional crystallization of the magma, (3) partial melting in the magma source, and (4) recycling of material enriched in LIL elements by fractionation on the surface, back into the magma source.

4.1. Crustal Contamination

Assume that magmas of the moderately enriched basalts were derived from a depleted mantle, as NMORB is, and then were contaminated by highly enriched (e.g., Venera 8) material within the crust. In this case the contaminated magma would inherit the K-U and U-Th relations of the highly enriched material. The sense of the trends in Figure 1a show, however, that the Venera 8 rock is relatively richer in K than in U ($K_N > U_N$), while all then basaltic rocks have $U_N > K_N$. This means the enrichment of these basalts in LIL elements did not result from crustal contamination
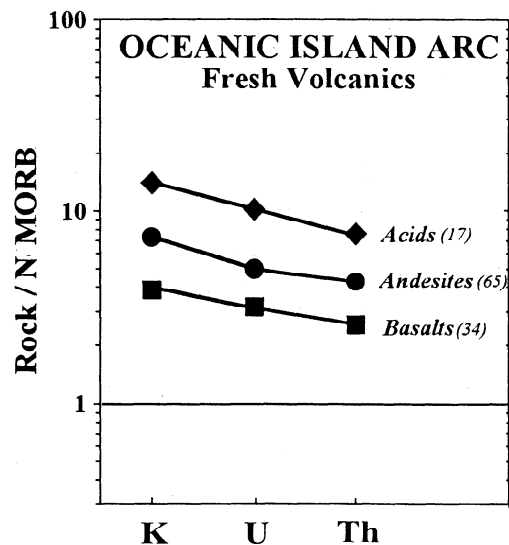

Figure 2. K, U, and Th abundances normalized to average fresh NMORB [*Nikolaeva*, 1995a,b] for average fresh oceanic island-arc basalts, andesites, and acid rocks (dacites and rhyolites) on Earth [*Nikolaeva*, 1997]. Numbers of samples averaged are shown in parentheses. See Figure 1 for normalizing values in ppm.
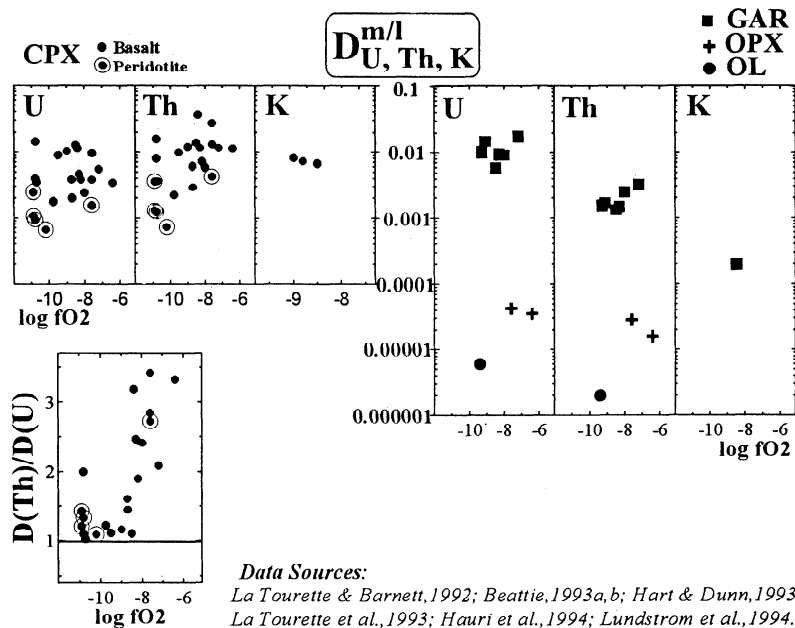
Figure 3. Summary of published experimental data (see data source list) on partition coefficients, $D_{K,U,Th}{}^{m/l}$, for clinopyroxene (CPX), orthopyroxene (OPX), olivine (OL), and garnet (GAR); and ratios of Th/U partition coefficients [D(Th)/D(U)] for CPX, plotted against oxygen fugacity. Data are from equilibrium experiments in the basalt-peridotite system, under anhydrous conditions at pressures of 1-36 kbar and temperatures about 1200°-1600°C.

of their magmas, at least not by material similar to Venera 8 rock. The possibility remains that the enriched character of these basaltic materials results from LIL-enriched source region(s).

4.2. Intracrustal Fractional Crystallization of Magma

Fractional crystallization during ascent through the crust is known to increase concentrations of K, U, and Th, but it has little effect on the shape of the K-U-Th pattern [*Pearce*, 1983; *Gill and Condomines*, 1992]. The geochemical patterns in Figure 2 illustrate this. Here compositional data are shown for a set of 116 samples of unaltered oceanic island-arc (OIA) volcanic rocks from the OIA data base, chosen on the basis of chemical/petrographic criteria of freshness [*Nikolaeva*, 1997]. Andesites and more evolved rocks in oceanic island-arc settings are known to be intracrustal derivatives of parental basaltic magma [*Gill*, 1981; *Kay and Kay*, 1986; *Ellam and Hawkesworth*, 1988; *Hawkesworth et al.*, 1991, 1993 and references therein]. Figure 2 shows that during intracrustal evolution of magma the K-U-Th patterns of evolved rocks approximately preserve the K-U-Th pattern of the parental basaltic magma. This would mean the highly enriched Venera 8 ($K_N>U_N$) material cannot be derived from magma of any of the moderately enriched rocks ($U_N>K_N$), and these basalts, in turn, cannot be derived from NMORB-like parental magma, by intracrustal fractional crystallization.

4.3. Partial Melting of the Magma Source

To model the K-U-Th pattern of magma relative to its source material, we calculated the partitioning of K, U, and Th between minerals and melt. Partitioning of element i between a mineral and liquid is expressed by the partition coefficient $D_i{}^{m/l}$, which is the ratio (concentration of element i in mineral m) /

(concentration of element i in liquid l). Experimental data on K, U, and Th partition coefficients from the literature are shown in Figure 3 as a function of f_{O2} for clinopyroxene (CPX), orthopyroxene (OPX), olivine (OL), and garnet (GAR), in equilibrium with basalt-peridotite melts under anhydrous conditions at pressures of 1 to 36 kbar and temperatures of 1200° -1600°C [*LaTourette and Burnett*, 1992; *Beattie*, 1993a,b; *Hart and Dunn*, 1993; *LaTourette et al.*, 1993; *Hauri et al.*, 1994; *Lundstrom et al.*, 1994]. All three LIL elements have $D_{LIL}{}^{m/l} \ll 1$, meaning they are strongly incompatible relative to these minerals and partition preferentially into the melt. The K, U, and Th partition coefficients for CPX and GAR are 2 to 3 orders of magnitude higher than those for OPX and OL. Therefore the partitioning of K, U, and Th in CPX- and/or GAR-bearing rocks will be dominated by the effects of these minerals. The partition coefficients of K for OPX and OL have not been measured accurately, being extremely low ($\ll 10^{-4}$) (see summary in the work by *Green* [1994]). The values of these coefficients were assumed to be zero in the following calculations. The partition coefficients for Th and U have been shown to depend to some extent on melt and mineral compositions and possibly on temperature, but not on pressure [*Beattie*, 1993a]. $D_{Th}{}^{CPX-l}$ and $D_U{}^{CPX-l}$ are found to be correlated [*La Tourette and Burnett*, 1992]: The $D_{Th}{}^{CPX-l}/D_U{}^{CPX-l}$ ratio increases with decreasing f_{O2}, though its value is >1 in all cases (Figure 3). This ratio has been considered to be more reliable and robust than either partition coefficient separately [*La Tourette and Burnett*, 1992]. For our calculations we used $D_U{}^{CPX-l}$ and $D_{Th}{}^{CPX-l}$ values for oxidizing and reducing conditions based on $(D_{Th}/D_U)^{CPX-l} = 3.4$ and 1.1, respectively [*La Tourette and Burnett*, 1992; *Hauri et al.*, 1994]. For mantle peridotite melting models we used the $D_{U,Th}{}^{CPX-l}$ values recommended by *Beattie* [1993a]. The adopted values of partition coefficients for K, U, and Th are listed in Table 2.

Table 2. Values of K, U, and Th Partition Coefficients Adopted for Calculations

	D_U	D_{Th}	D_K	D_{Th}/D_U	Source
CPX/basaltic melt:					
Oxidizing conditions	0.0038	0.013	0.007	3.4	*La Tourette and Burnett* [1992], *Hart and Dunn* [1993]
Reducing conditions	0.0127	0.014	0.007	1.1	*Hart and Dunn* [1993], *Hauri et al.* [1994]
CPX/peridotitic melt	0.00094	0.00125	0.007	1.3	*Beattie* [1993a], *Hart and Dunn* [1993], *Hauri et al.* [1994]
OPX/peridotitic melt	0.000036	0.000016	0	0.4	*Beattie* [1993a]
OL/peridotitic melt	0.000006	0.000002	0	0.3	*Beattie* [1993a]
GAR/basaltic or peridotitic melt	0.00588	0.00137	0.0002	0.2	*Haui et al.* [1994]

Calculations of partitioning during partial melting were made using the mass balance equation:

$$C_i^l/C_i^0 = 1 / (F + D_i^{s/l} - F D_i^{s/l}),$$

where C_i^l is the concentration of element i in the partial melt, C_i^0 the initial concentration of element i in the source, F the degree of melting (weight fraction), and $D_i^{s/l}$ the bulk solid-liquid partition coefficient

$$D_i^{s/l} = \Sigma f_m D_i^{m/l}$$

Here f_m is the weight fraction of mineral m in the source under consideration. We calculated the C_i^l/C_i^0 ratio, where i is either K, U, or Th, as a measure of the enrichment of element i in the melt relative to the source rock. The calculations assumed equilibrium or batch melting and considered the source mineralogy and degree of melting to be variables.

We start with the model for partial melting of primitive mantle discussed as a possible source of the basalts that cover the vast plains of Venus [*Hess and Head*, 1990; *Head et al.*, 1994]. The K-U-Th enrichment pattern for the Venus rocks relative to putative primitive mantle peridotite, estimated by *Hofmann* [1988] for Earth, is shown at the right in Figure 4. The K-U-Th pattern does not change significantly when normalized to

other published estimates of the primitive mantle composition [e.g., *Sun and McDonough*, 1989]. The effect of source mineralogy on calculated K, U, and Th enrichment patterns for partial melts relative to mantle lherzolites is shown in Figure 4, left. Comparison between the left and the right patterns in Figure 4 shows that the pattern of any of the measured Venus rocks is quite different in shape from the pattern of any of the melts produced by reasonable degrees of partial melting of lherzolites having a plausible range of compositions. This means that none of the patterns of K-U-Th fractionation for Venus rocks studied were controlled by batch melting of the primitive mantle.

Another source material that has been proposed for Venus rocks is tholeiitic basalt in the eclogite facies [*Hess and Head*, 1990; *Head and Hess*, 1996; *Herzog and Hess*, 1996]. Figure 5 (left) shows calculated K, U, and Th enrichment patterns for partial melts relative to a source tholeiitic eclogite containing 50% CPX and 50% GAR, in oxidizing and reducing environments. Also shown in Figure 5 (left) is the pattern for oceanic island-arc adakites, which are subduction-related andesites that have been recognized as natural partial melts from tholeiitic eclogite [*Kay*, 1978; *Sun*, 1980; *Defant and Drummond*, 1990; *Hawkesworth et al.*, 1991; *Yogodzinsky et al.*, 1995; *Morris*, 1995]. Based on the K-U-Th pattern alone, when adakites are compared with calculated patterns for tholeiitic eclogite-derived partial melts, we are led to conclude that the
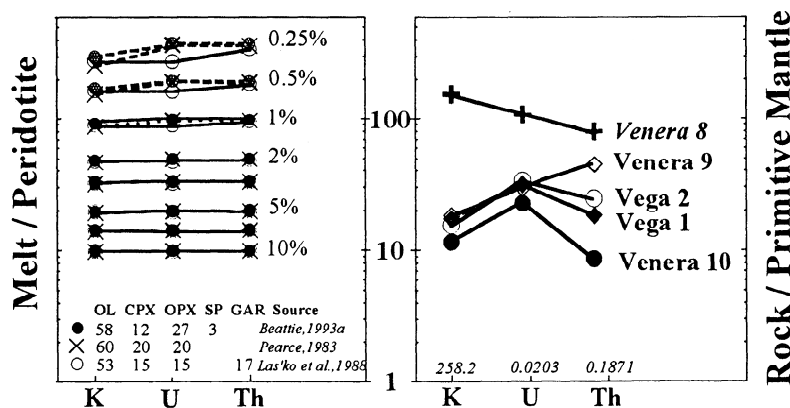

Figure 4. Comparison between calculated K-U-Th enrichment patterns for peridotite-derived partial melts relative to the peridotite source (left) and enrichment patterns for K, U, and Th abundances in Venus rocks normalized to primitive mantle peridotite of the composition estimated by *Hofmann* [1988] (right). At left, calculated enrichment patterns are shown for different degree of partial melting (entered as percents) and for three peridotite mineralogies ranging from spinel (SP) lherzolite to garnet lherzolite (norms at bottom of the box). Patterns for unrealistically low degrees of partial melting are drawn in gray. Numbers at right bottom are normalizing values in ppm. Partition coefficients used are from Table 2. Sources of data for Venus rocks are shown in Figure 1.
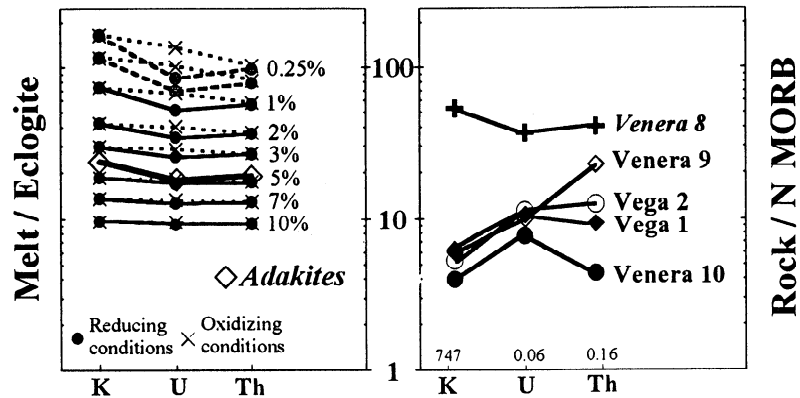
Figure 5. Comparison between calculated K-U-Th enrichment patterns for eclogite-derived partial melts relative to the tholeiitic eclogite (50% CPX, 50% GAR) source (left) and enrichment patterns for K, U, and Th abundances in Venus rocks normalized to average fresh NMORB tholeiite [after Nikolaeva, 1995a,b] (right). At left, calculated enrichment patterns are shown for different degrees of partial melting (entered as percents) for oxidizing and reducing environments. Patterns for unrealistically low degrees of partial melting are drawn in gray. Also shown at left is the observed pattern of K, U, and Th abundances in partial melts from tholeiitic eclogite, in the form of Aleutian island-arc adakites. An average for six samples [Kay, 1977, 1978; Sun, 1980; Yogodzinsky et al., 1995] is shown, normalized to average fresh NMORB tholeiite [after Nikolaeva, 1995a,b]. Numbers at right bottom are normalizing values in ppm. Partition coefficients used are from Table 2. Sources of data for Venus rocks are shown in Figure 1.

adakites are 3-5% partial melts of tholeiitic eclogite. The same values of the degree of melting were gotten by Yogodzinsky et al. [1995] from models involving 13 other trace elements. This agreement of results suggests that the three incompatible elements K, U, and Th, alone, establish a valid geochemical signature for at least this petrogenic process.

The K-U-Th enrichment pattern for Venus rocks relative to average fresh NMORB tholeiite [after Nikolaeva, 1995a,b] is shown in Figure 5, right. The average N-MORB composition used is based on a set of 67 samples selected from the NMORB database that were judged to be unaltered on the basis of chemical/petrographic criteria of freshness [Nikolaeva, 1995a,b].
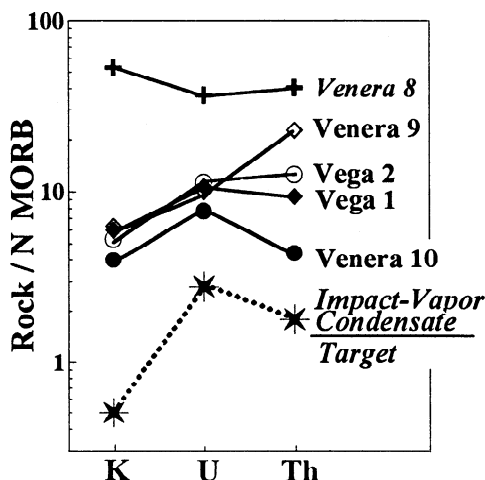

Figure 6. K, U, and Th abundances normalized to average fresh NMORB [Nikolaeva, 1995a,b] for Venus rocks, and the K-U-Th enrichment pattern in impact-vapor condensate after impact evaporation of granite target material using a light-gas gun [Yakovlev et al., 1992]. Sources of data for Venus rocks are shown in Figure 1.

(Eight additional fresh samples from Bach et al. [1996] have subsequently been added to the set, but this has not significantly changed the average K, U, and Th concentrations.) The pattern does not change significantly when normalized to the average NMORB of Hofmann [1988] or Sun and McDonough [1989].

Comparison between the left and the right patterns in Figure 5 shows that Venera 8 material is similar to 1-2% partial melts from eclogite in both the enrichment level and the shape of the pattern. This suggests that the Venera 8 material may have been derived from eclogite having the composition of NMORB-like tholeiite. But the same cannot be the case for the moderately enriched basaltic rocks on Venus. There is disagreement in both the sense of the trend ($U_N > K_N$ in the Venus rocks, $K_N > U_N$ in the calculated models) and in the lower levels of enrichment on Venus. We conclude that the moderately enriched basaltic rocks of Venus could not be derived from NMORB-like tholeiitic eclogite.

The K-U-Th pattern for partial melts could be influenced by volatile components such as H_2O and CO_2. However, an attempt to allow for the role of volatiles in Venus petrogenesis would raise more questions than it answered because the abundances of volatile species in the Venus interior are poorly constrained (see Hess and Head [1990] for a summary), and necessary data on (low-density fluid)/melt, fluid/mineral partition coefficients, particularly for accessory minerals and for a range of fluid compositions, are among the suggestions for future work made by Green [1994] in his recent review.

4.4. Recycling of Material Fractionated on the Surface Back into the Mantle

On Venus, unlike Earth, there is no geological evidence for effective exogenic chemical fractionation processes such as water transport [Florensky, 1977; Zolotov and Volkov, 1992; Basilevsky et al., 1992]. Basalt that resided on the surface of Venus would be recycled with approximately the same composition it had when it erupted. However, the absence of water migration on
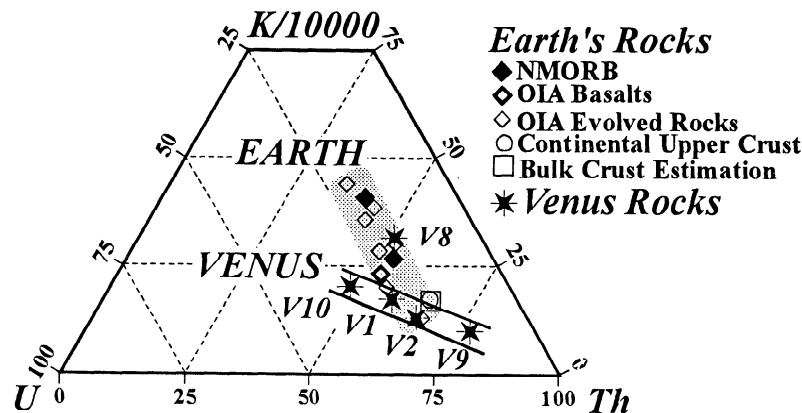
Figure 7. Ternary diagram showing the difference in interelemental variation of K, U, and Th in terrestrial and Venus rocks. Terrestrial rocks are represented by an average of fresh NMORBs [*Nikolaeva*, 1995a,b], an average of fresh oceanic island-arc (OIA) basalts and evolved rocks [*Nikolaeva*, 1997], the average composition of continental upper crust [*Taylor and McLennan*, 1985], and the estimated bulk crustal composition [*McLennan and Taylor*, 1996]. V8, V9, V10, and V1, V2 are Venera 8, Venera 9, Venera 10, and Vega 1, Vega 2 respectively. Note that terrestrial rocks form a field with nearly constant Th/U ratios (shaded area). The Venera 8 material lies in this field. In contrast, Venus basaltic rocks (V9, V2, V1, and V10) define a band with nearly constant K/U ratios (area between two solid lines). Sources of data for Venus rocks are shown in Figure 1.

Venus might make more important the chemical effects of another exogenic process, namely, impact-induced fractionation. The most impressive example of this process is the result of one, unique experiment of *Yakovlev et al.* [1992]. In this experiment, impact-vapor condensate was found to be enriched in U relative to K (Figure 6). If condensate of this type could be separated and mixed with the magma... But, as the Germans say: Ein Versuch, kein Versuch (one occurrence is no occurrence). This prohibits further consideration of the topic.

5. Conclusions

Consideration of the constraints placed by their contents of K, U, and Th suggests that the Venus basalts that have been studied could not have crystallized from NMORB-like magma, nor from magma of that type that had been contaminated by highly enriched Venera 8 material within the crust. Venera 8 material could not be evolved from the magma of any of these basaltic rocks. Neither the highly enriched Venera 8 material nor the moderately enriched basaltic rocks could be produced by batch melting of hypothetical primitive mantle. The Venera 8 material may have been produced by a low degree of partial melting of NMORB-like tholeiitic eclogite, but none of the Venus basaltic rocks were. Thus none of the standard petrogenetic processes considered satisfies the constraints imposed by K, U, and Th data on the moderately enriched basaltic rocks of Venus (from the Venera 9 and 10 and the Vega 1 and 2 sites), though these basaltic materials have been referred to earlier as normal tholeiites in composition [*Surkov et al.*, 1976, 1987; *Barsukov*, 1992; *Kargel et al.*, 1993].

The difference in K-U-Th patterns between Venus basaltic rocks studied and terrestrial rocks (fresh NMORBs and oceanic island-arc volcanics) is summarized in the triangular diagram of Figure 7. The terrestrial rocks form a broadband-like field with nearly constant Th/U ratios (shaded area in Figure 7). The Venera 8 material lies in this field. Venus basaltic rocks, on the other hand, occupy a band of nearly constant K/U ratios (the area

between two solid lines in Fig. 7). This is a surprising difference. It appears to suggest either an unusual composition of the mantle source(s) of the basalts, or unusual fractionation process(es) on Venus, or both. Before exploring those avenues, however, it would seem profitable first to search for K-U-Th analogs of the Venus rocks, all of which are enriched in incompatible elements, among the LIL-element-enriched rocks of Earth, both oceanic and continental. This will require a continued program of K-U-Th systematization of terrestrial igneous rocks for planetologic comparisons. The K-U-Th systematics of terrestrial oceanic hot-spot-related enriched rocks appears to be a particularly fruitful area to study.

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