GEOCHEMISTRY OF THE VENERA 8 MATERIAL DEMONSTRATES THE PRESENCE OF CONTINENTAL CRUST ON VENUS*

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Abstract. In anticipation of MAGELLAN data on the Venera 8 and Venera 13 geologic-tectonic settings, I have restudied the possible terrestrial chemical counterparts of the materials at these landing sites on the basis of the most recent terrestrial geochemical data. My results indicate that the primitive mafic composition of the Venera 13 material is quite dissimilar to the inferred evolved intermediate composition of the Venera 8 material, suggesting the existence of continental crust on Venus.

Introduction

Whether continental crust exists on Venus or the Venusian crust contains only various types of basalt is still widely debated by both geologists and geochemists (for example, Masursky *et al.*, 1980; Phillips and Malin, 1983; Florensky and Nikolayeva, 1984, Sharpton and Head, 1985; Taylor and McLennan, 1985; Nikolayeva *et al.*, 1990). A controversial subject is the high concentrations of K, U, and Th measured at the Venera 8 landing site (Vinogradov *et al.*, 1973; Surkov *et al.*, 1976). Some students think this material chemically resembles the rocks typical of the continental crust of the Earth (Vinogradov *et al.*, 1973; Barsukov *et al.*, 1981; Florensky and Nikolayeva, 1984; Nikolayeva *et al.*, 1990). Others consider the Venera 8 material to be a potassic basalt similar to those analyzed by XRF (Barsukov *et al.*, 1982) at the Venera 13 landing site (Barsukov *et al.*, 1982; Taylor and McLennan, 1985; Surkov *et al.*, 1984, 1986). In anticipation of Magellan data on the Venera 8 and Venera 13 geologic-tectonic settings, I have restudied the possible terrestrial chemical counterparts of the materials at these landing sites on the basis of the most recent terrestrial geochemical data. My results indicate that the primitive mafic composition of the Venera 13 material is quite dissimilar to the inferred evolved intermediate composition of the Venera 8 material suggesting the existence of continental crust on Venus.

Seven compositional measurements have been made of the surface of Venus by XRF analysis (major oxide contents) and/or GS analysis (K, U, and Th contents). These were at the landing sites of Venera 8, 9, 10, 13, and 14, and Vega 1 and 2 (for a summary see Surkov *et al.*, 1986). Five of these sites have compositions that closely resemble the chemistry of terrestrial tholeiitic basalts (in both major oxides: data of Venera 14, Vega 2; and K, U, and Th: data of Venera 9, 10, Vega 1, 2),

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although the lithology of these materials (at least at the Venera 9, 10, 14 landing sites) is sedimentary (tuff, perhaps), as shown by the panoramic images (Basilevsky *et al.*, 1985). This means that venusian surface recycling, including high-temperature weathering, disturbs neither major element nor U and Th concentrations relative to their values in the initial rocks (in this case, tholeiitic basalts). (For a summary of this topic, see Basilevsky *et al.*, 1990). This means that the chemical compositions of Venusian surface materials can be discussed in terms of terrestrial igneous rock classifications.

In contrast to the five landing sites consisting of low-potassic tholeiitic materials, two high-potassic materials have been revealed at the landing sites of Venera 8 (Vinogradov *et al.*, 1973) and Venera 13 (Barsukov *et al.*, 1982). These are the subject of discussion in this paper.

Venera 13 Material

The major oxide composition measured by XRF at the landing site of Venera 13 is (in weight percents): SiO_2, 45.1±3.0); TiO_2, 1.59±0.45; Al_2O_3, 15.8±3.0; FeO(tot), 9.3±2.2; MnO, 0.2±0.1; MgO, 11.4±6.2; CaO, 7.1±0.96; K_2O, 4.0±0.63 (Barsukov *et al.*, 1982). This material has been interpreted to be similar to terrestrial high-potassic alkaline basalts or alkaline gabbros (which are indistinguishable on the basis of their bulk compositions) (Barsukov *et al.*, 1982). On the panorama images the analyzed material looks sedimentary, perhaps tuffaceous (Basilevsky *et al.*, 1985). Its high contents of K_2O and MgO and low silica content imply it is not highly evolved material (Barsukov *et al.*, 1982).

On Earth such a material occurs in various tectonic settings, both continental and oceanic; in particular, in arc shoshonitic associations (Barsukov *et al.*, 1982). An additional terrestrial example is given below.

Among the Quarternary volcanic rocks of the Sunda and Banda arcs (Indonesia), Wheller *et al.* (1987) found a group of low-SiO_2 high-MgO rocks which have turned out to be chemically similar to the Venera 13 material. In a conventional K_2O–SiO_2 diagram (Figure 1) the position of this mafic group is outlined by a thin dashed line. As one can see on the diagram the Venera 13 material falls just within this mafic field. Despite the fact that "volcanic rocks of the Sunda and Banda arcs range from tholeiitic through calc-alkaline and shohonitic to leucititic, the widest compositional span of mafic magmatism from an active arc setting" (Wheller *et al.*, 1987), solely the magmas of this mafic field have been interpreted by authors to be mantle-derived.

The importance of this for geologists studying Venus is as follows: In a terrestrial region characterized by complex tectonic relationships between continental and oceanic terraces, among the numerous volcanic rocks sampled only the members of this mafic field are believed on the basis of trace element data to represent primary, mantle-derived magmas (Wheller *et al.*, 1987). What kind of tectonic setting provides for the eruption of such a magma on Venus? This is my first geochemical question for the Magellan Geological Team.

Venera 8 Material

Except for K_2O content, there are no data on major oxide abundances in the Venera 8 material. The composition of this material has to be deduced from its measured K_2O, U, and Th contents. The accuracy of the first published values of the contents (Vinogradov *et al.*, 1973) has been re-evaluated by Surkov *et al.*, (1976) to take into account the difference between the venusian measurement environment (denser atmosphere) and terrestrial calibration test (less dense atmosphere). Since 1976 and until now these re-evaluated values are reproduced without changing by Surkov and his colleagues in all their publications (see, for example, Barsukov *et al.*, 1986). I have to believe these values to be still solid. These are: K_2O, 4.8±1.4 wt.%; U, 2.2±0.7 ppm; Th, 6.5±0.2 ppm (Surkov *et al.*, 1976).

As far as the measured K_2O content and the K_2O–SiO_2 diagram (Figure 1) are concerned the Venera 8 material could be either leucititic, like the Venera 13 material, or shohonitic, or high-K calc-alkaline. The K_2O content alone is not sufficient to define the nature of the material, though it constrains its alkalinity, in particular excluding affinity with calc-alkaline series.

U and Th are trace elements, and like K they are incompatible elements that are known to vary consistently with major element concentrations, which makes

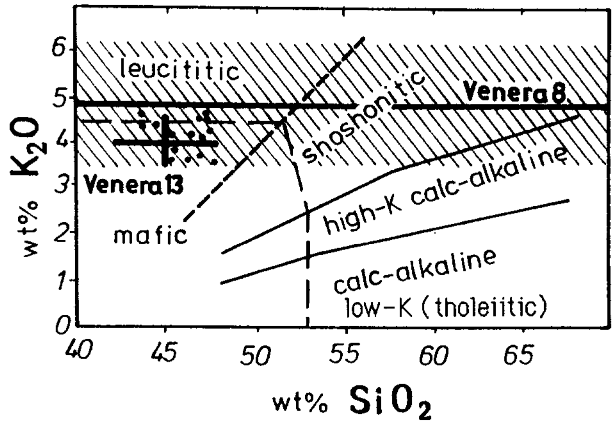

Fig. 1. A plot of K_2O vs. SiO_2 abundances in rock, showing positions of the Venera 13 and Venera 8 (Surkov *et al.*, 1984; Surkov *et al.*, 1976) materials. Peccerillo and Taylor's (1976) petrologic divisions are shown as solid lines. The boundary of leucititic (thick dashed line) and mafic (thin dashed line) fields are from Wheller *et al.* (1987). Points are the mafic Sunda-Banda arc volcanic rock compositions from Wheller *et al.* (1987).

them reliable indicators of igneous rock types (Vinogradov *et al.*, 1973). The general trend of K, U, and Th concentrations in normal terrestrial calc-alkaline rocks (after Haack, 1983) is illustrated in Figure 2.

However, to identify an unknown material on the basis of its K, U, and Th contents, a knowledge of the detailed K-U-Th systematics of terrestrial igneous rocks is necessary. But this knowledge does not exist, in part because of scarcity of published U and Th determinations; these have become routine in the most recent years only. This is why the analyzed Venera 8 material has been identified differently depending on the personal background of author. The compositional interpretations that have been put forward can be summarized roughly as follows:

(i) The Venera 8 material is silicic calc-alkaline, 'granite' (Vinogradov *et al.*, 1973).

(ii) It is intermediate subalkaline: 'shoshonite-like' (Barsukov *et al.*, 1982) or 'syenite (non-foidic)' (Barsukov *et al.*, 1981; Florensky and Nikolayeva, 1984; Surkov *et al.*, 1987).

(iii) It is intermediate alkaline, 'nepheline syenite' (Barsukov *et al.*, 1986).

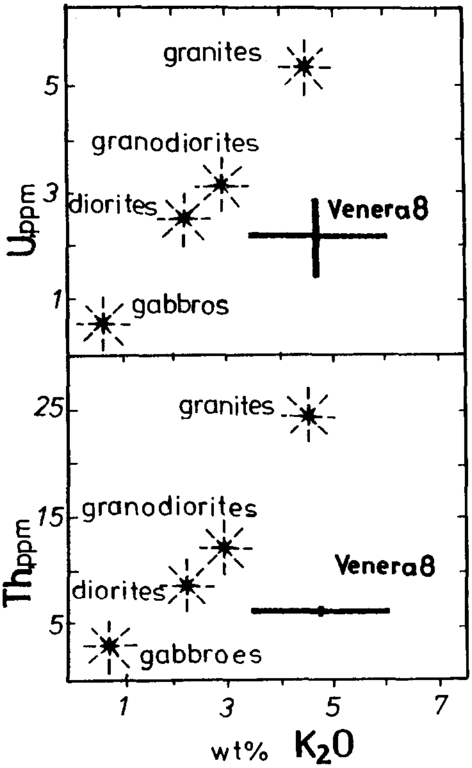

Fig. 2. K_2O-U-Th diagram, showing normal calc-alkaline rocks of the Earth (Haack, 1983) and the Venera 8 material (Surkov *et al.*, 1976).

(iv) It is mafic alkaline, like the Venera 13 material: 'alkaline basalt' (Taylor and McLennan, 1985) or 'alkaline gabbroid' (Surkov *et al.*, 1984, 1986).

Thus today the possibilities span almost the whole range of rock siliceousness, from mafic through intermediate to silicic, and of total alkalinity, from calc-alkaline through subalkaline to alkaline.

The most extreme proposals, (i) and (iv), can be readily rejected by using rough constraints. The K_2O-U-Th diagram (Figure 2) shows that the Venera 8 material contains all three incompatible elements in higher abundances than normal mafic rocks and in lower abundances than normal silicic rocks. The concentrations of these elements are closer to those of intermediate rocks. Also, the Venera 8 material in this diagram again falls off the calc-alkaline trend. The total alkali ($K_2O + Na_2O$) content of the material must be higher than the K_2O content, i.e. greater than about 3.5%, resulting in identification of the material as subalkaline or alkaline. Thus possibilities (ii) and (iii) survive for further consideration.

An additional constraint can be placed on possibility (ii), from U and Th data. The K_2O-SiO_2 diagram (Figure 1) makes it appear that the Venera 8 material could belong to the shoshonitic series. However the combined K_2O-U-Th data (Figure 3) show this material differs from typical arc shoshonitic associations (after Morrison's review, 1980) in having a higher Th content. Note that concentration of U changes from basalt to andesite by a factor about 3.5 in average, while those of Th, by a factor about 5 in average. This coupled with smaller uncertainty in Th content than those of U makes Th a better discriminant of petrological type, but only provided available U and K_2O constraining data.

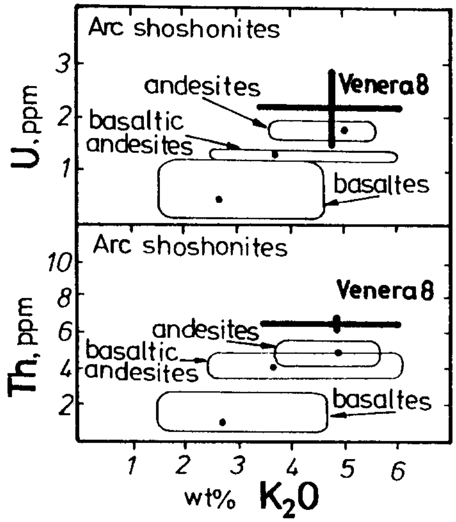

Fig. 3. K_2O-U-Th diagram, showing typical arc shoshonite associations of the Earth (Morrison, 1980) and the Venera 8 material as measured by Surkov *et al.* (1976). Points and envelopes indicate averages and ranges, respectively.

Further consideration of a possible terrestrial compositional counterpart of the Venera 8 material requires a search for specific samples similar to this material in K_2O, U and Th contents. Matching samples must satisfy three criteria.

First, only individual samples for which K_2O, U, and Th analyses have been published are considered. (Data averaged for more than one sample are not considered.)

Second, relative accuracy of the published U and Th analyses of the sample should be better than 5–10%. This limits the sources of data to the most recent works.

Finally, the sample should match Venera 8 material simultaneously in K_2O, U and Th contents, to within the published uncertainty limits (Surkov *et al.*, 1976).

Comparison of the Venera 8 data with approximatively a thousand published terrestrial analyses yielded seven samples which fully satisfy all the limiting conditions. The results are shown in K_2O-U-Th diagram (Figure 4). Brief descriptions of the seven samples are given in Table I; their total alkali-silica classifications are illustrated by Figure 5.

To test whether the selected samples form a particular compositional group or

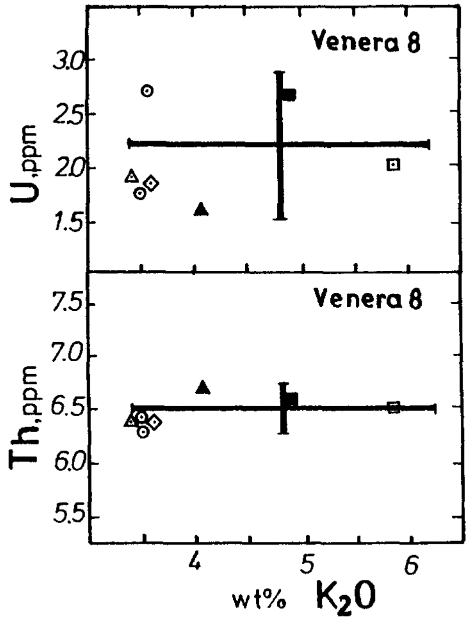

Fig. 4. K_2O-U-Th diagram, showing the terrestrial igneous rocks selected to be similar to Venera 8 material simultaneously in K_2O, U, and Th contents, as measured by Surkov *et al.* (1976). Symbols represent the following samples (as named by authors): filled square – melasyenite (Fowler, 1988); filled triangle – quartz monzonite (Anderson and Bender, 1989); open square – syenite (Bedard *et al.*, 1987); open triangle – quartz monzodiorite (Meen and Eggler, 1989); open diamond – granodiorite (Johnson *et al.*, 1989); open circles – andesites (Johnson and Lipman, 1989; Lipman, 1988). For details see Table I.

TABLE I

Whole-rock analyses and CIPW norms of the terrestrial igneous rocks found to be similar simultaneously in K_2O, U, and Th contents to Venera 8 material (as reported by Surkov *et al.*, 1976).

Setting	Scottish Highlands, Glen Dessary massif	Whipple Mtns, Bowman Wash pluton	Quebec, Megantic intrusive complex	Absaroka volcanic field, Montana, Independence stock	Latir volcanic field, New Mexico		
					Rio Hondo	Costa Caldera formation pluton	
Age	Caledonian	Proterozoic	Cretaceous	Cretaceous	Tertiary		
Authors sample name	Melasyenite	Quartz monzonite	Syenite	Quartz monzonite	Granodiorite	Andesite	Andesite
Authors sample number	GD 22	JP 44	ME 15	2011	J-101	79L-73	78L-187
wt%							
SiO_2	58,27	60,85	64,35	65,60	68,40	63,70	61,60
TiO_2	1,00	1,47	0,51	0,51	0,54	0,90	0,87
Al_2O_3	13,40	13,64	16,95	16,20	15,20	15,80	14,70
FeO(tot)	6,80	8,71	3,05	3,19	3,08	5,03	5,60
MnO	0,18	0,15	0,11	0,09	0,04	0,07	0,06
MgO	4,11	1,62	0,26	2,43	1,61	2,10	3,90
CaO	6,39	4,42	0,99	2,79	2,82	4,20	4,80
Na_2O	2,48	2,59	5,50	4,39	4,47	3,70	4,10
K_2O	4,90	4,05	5,86	3,39	3,62	3,50	3,60
P_2O_5	0,66		0,11	0,23	0,24	0,51	0,43
ppm							
U	2,70	1,60	2,0	1,88	1,80	1,80	2,70
Th	6,60	6,70	6,50	6,40	6,60	6,40	6,40
Source	Fowler, 1988	Anderson and Bender, 1989	Bedard *et al.*, 1987	Meen and Eggler, 1989	Johnson *et al.*, 1989	Johnson and Lipman, 1988	Lipman, 1988
CIPW norms, wt%							
Tot. feldspars	61,0	59,5	85,4	69,7	69,9	68,2	67,1
Orthoclase	29,0	25,0	34,6	20,0	21,4	20,7	21,3
Albite	21,0	21,9	46,5	37,1	37,8	31,3	34,7
Anorthite	11,0	13,6	4,3	12,5	10,7	16,2	11,1
Tot. pyroxenes	28,4	21,3	5,6	11,2	9,6	13,8	22,9

are members of a random set, SiO_2 variation diagrams were constructed (Figure 6). As can be seen, the selected samples are similar in K/U, Th/U, and FeO/(FeO+MgO) ratios, and reveal normal chemical trends of decreasing CaO and Na_2O and increasing Al_2O_3 as SiO_2 increases. This suggests the selected samples do form a discrete group of compositionally related members. Two of the samples (ME 15 and J-101) deviate from the trends in Figure 6, though they do not deviate from the common ratio ranges. These two samples, which lie at edges of the distribution in Figure 5, are considered to be possible, and the other five samples to be probable, compositional counterparts of the Venera 8 material. The probable major oxide composition range of the Venera 8 material, inferred from these terrestrial samples, is shown in Table II.

Common features of all the selected compositional counterparts of the Venera 8 material are intermediate levels of total alkali content, indicative of the subalkaline series; and intermediate levels of silica content, indicative of intermediate igneous rocks, as seen in a (K_2O+Na_2O)–SiO_2 diagram (Figure 5). The inferred probable compositional range of the Venera 8 material (Table II) is silica-saturated subalkaline, corresponding to the field of quartz monzonites-quartz syenites in Figure 5.

This evolved material is quite dissimilar to the primitive mafic material at the landing site of Venera 13, contrary to early suppositions of Surkov *et al.* (1984, 1986) and Taylor and McLennan (1985) based only on the similar potassium contents of these materials.

The inferred probable compositional range of the Venera 8 material much more

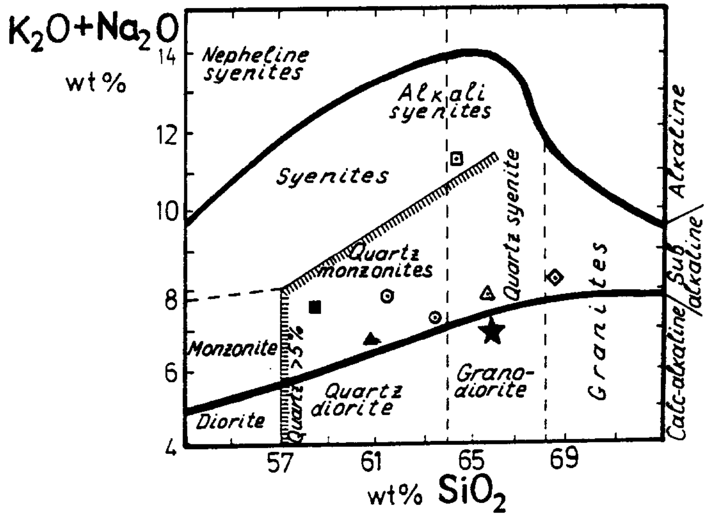

Fig. 5. Total alkalis vs. silica diagram, showing positions of the samples selected to be similar to the Venera 8 material simultaneously in K_2O, U, and Th contents as measured by Surkov *et al.* (1976). Symbols as in Fig. 4. Boundaries between petrologic families (dashed line) and calc-alkaline, subalkaline, and alkaline series (solid lines) are from Bogatikov *et al.* (1983) with simplification. Star indicates the average continental upper crust composition after Taylor and McLennan (1985).

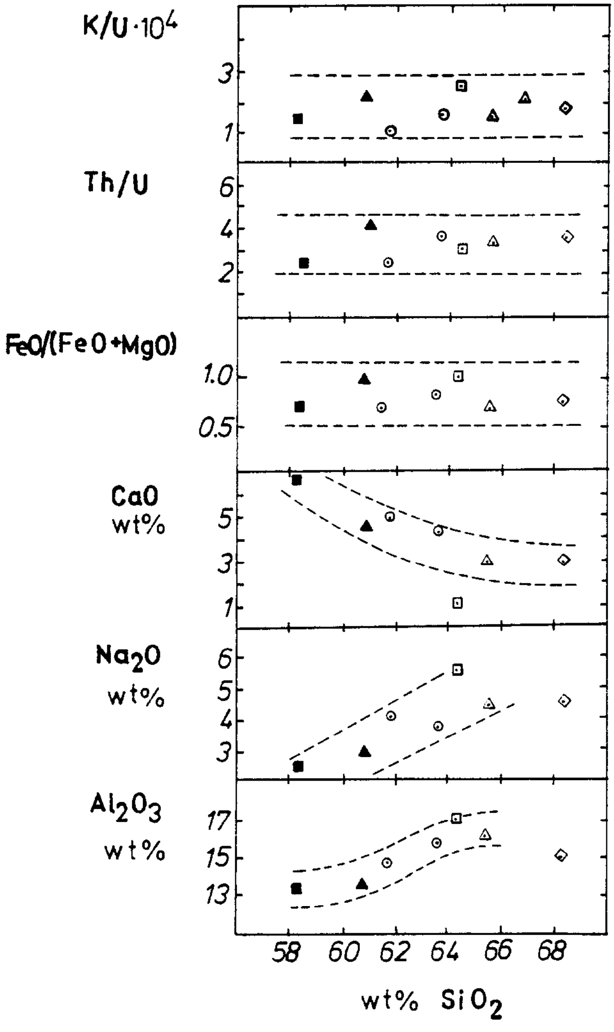

Fig. 6. SiO_2 variation diagrams for the samples selected to be similar to the Venera 8 material simultaneously in K_2O, U, and Th contents as measured by Surkov *et al.* (1976). Symbols are as in Fig. 4. Dashed lines indicate trends within the set of selected samples.

closely resembles the average composition of the terrestrial upper crust (shown by a star in Figure 5) which is described by most workers as corresponding to granodiorite (Taylor and McLennan, 1985). Both the probable Venera 8 compositional range and the terrestrial upper crust composition are near the boundary between the calc-alkaline and alkaline fields (Figure 5), though the former falls within the subalkaline series whereas the latter is calc-alkaline. This difference has been discussed by Florensky and Nikolayeva (1984), who attributed it to the different H_2O/CO_2 ratio on these planets.

TABLE II

Inferred probable composition of the Venera 8 material

	Probable range
wt%	
SiO_2	58,27–65,60
TiO_2	0,51–1,47
Al_2O_3	13,40–16,20
FeO_{tot}	3,19–6,80
MnO	0,06–0,18
MgO	1,62–4,11
CaO	2,79–6,39
Na_2O	2,48–4,39
K_2O	3,39–4,90
P_2O_5	0,23–0,66
ppm	
U	1,60–2,70
Th	6,40–6,70
CIPW norms, wt%	
Tot. feldspars	60–70
Orthoclase	20–29
Albite	21–37
Anortite	11–16
Tot. pyroxene	11–28

All seven terrestrial samples found to be similar to the Venera 8 material in K_2O, U, and Th contents (Table I) derive exclusively from continental regions of Earth. Petrogenesis of their magmas has been modeled by authors based on isotope and trace element geochemistry data, including U and Th. The magmas have been interpreted to have been significantly contamined by crustal material (Fowler, 1988; Bédard *et al.*, 1989), to have a crustal source (Anderson and Bender, 1989), to have been mixed with crustal-derived melt (Meen and Eggler, 1989), or to contain a large crustal component (Johnson and Lipman, 1988; Lipman, 1988).

TABLE III

Normative feldspar abundances in terra crust materials of Earth, Venus and Moon

	Earth[1]	Venus[2]	Moon[3]
Total Feldspars	67	60–70	69
Orthoclase	20	20–29	0,5
Albite	33	21–37	3,5
Anorthite	14	11–16	65
Total alkali feldspars	53	47–57	4

[1] Based on average composition for the upper crust, after Taylor and McLennan, 1985.
[2] Based on probable composition of Venera 8 material as inferred in this paper (see Table II).
[3] Based on average composition for 63 anorthositic norites and troctolites in Luna 20 fines, after Prinz *et al.*, 1973.

A common aspect of all these models is the necessity for a significant component of continental crust. Similarity of the Venera 8 material to the terrestrial material just in the trace elements U and Th allows a similar conclusion to be reached for the venusian material. If this is so, a large volume of continental crust must exist on Venus.

The landing site of Venera 8 is in the rolling plains province (Masursky *et al.*, 1980). Nikolayeva *et al.* (1988, 1990a,b) has argued on the basis of topography that tesserae on Venus may be outcrops of continental crust. The rolling plains province has been proposed to be a crustal sandwich, with basalts above and continental crust below (Nikolayeva *et al.*, 1990a, b). What kind of geologic-tectonic setting can provide for the formation of continental evolved material in the rolling plains province? This is my second geochemical question for the MAGELLAN Geological Team.

Planetary Terra Crust

The term 'terra crust' has been proposed by Nikolayeva *et al.* (1990b) to denote essentially feldspathic material composing highland non-volcanic terrains on the terrestrial planets. The presence of this common planetary feature had been deduced by Yaroshevsky and Florensky (Florensky *et al.*, 1981). Topographic and geologic aspects of terra crusts are discussed in detail by Nikolayeva *et al.* (1990a). Here I would like to discuss a chemical aspect of this topic.

The normative mineralogy of terra crust materials of Earth (average upper crust), Moon (average anorthosite norite), and Venus (the inferred compositional range of the Venera 8 material) is shown in Table III. This demonstrates the essentially feldspathic composition of all the materials, though alkali feldspars are predominant in the terrestrial and Venusian terra crust materials, and calcic feldspars are predominant in the lunar crust material. These differences are discussed in detail elsewhere. Here it is to be noted that feldspathic material is known to be low in density. Perhaps, reversing the lunar emphasis on mass concentrations (mascons), it would be useful to search on Venus for mass deficiency locations (massmins), related to continental crust concentrations? This is my third geochemical question for the Magellan Geological Team.

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