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ANALYSIS AND INTERPRETATION OF VIKING INORGANIC CHEMISTRY DATA

(Mars Data Analysis Program)

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ANALYSIS and INTERPRETATION of VIKING INORGANIC CHEMISTRY DATA

The Viking x-ray fluorescence spectrometer data have been analyzed for all samples collected at the two landing sites. Interpretations have been published in two papers:

"On the Original Igneous Source of Martian Fines," A.K. Baird and B.C. Clark, Icarus 45 (1981) 113-123.

"The Salts of Mars," B.C. Clark and D.C. Van Hart, Icarus 45 (1981) 370-378.

The final numerical results which, combined with the data in the publications above, constitutes this final report may be found in the pages which follow. These final concentration data have been submitted for publication to the Journal of Geophysical Research.

ABSTRACT

Of the twenty-one samples acquired for the Viking x-ray fluorescence spectrometer, seventeen were analyzed to high precision. Compared to typical terrestrial continental soils and lunar mare fines, the Martian fines are lower in Al, higher in Fe, and much higher in S and Cl concentrations. Protected fines at the two lander sites are almost indistinguishable, but concentration of the element S is somewhat higher at Utopia. Duricrust fragments, successfully acquired only at the Chryse site, invariably contained about 50% higher S than fines. No elements correlate positively with S, except Cl and possibly Mg. A sympathetic variation is found among the triad (Si, Al, Ca); positive correlation occurs between Ti and Fe. Sample variabilities are as great within a few meters as between lander locations (4500 km apart), implying the existence of a universal Martian regolith component of constant average composition. The nature of the source materials for the regolith fines must be mafic to ultramafic.

INTRODUCTION

For the first in situ analysis of the inorganic chemical composition of surface material on the planet Mars, miniature energy-dispersive x-ray fluorescence spectrometers were designed to fit within an available space on the Viking Lander. Spacecraft constraints upon configuration, deployment, mass, and heat sterilizability of the experiment package limited the instrument design. It was hoped that 3 to 5 Martian samples could be analyzed for about a dozen elements. Altogether 21 samples were delivered to the two instruments, and 15 elements were analyzed for in most samples. Descriptions of the instrument design have been published previously (Clark and Baird, 1973; Toulmin et al., 1973; Clark et al., 1977). Preliminary reports on analytical results at both landing sites were published soon after the initial data were received (Clark et al., 1976; Baird et al., 1976). In this paper, we present our findings for the major and minor element concentrations in all samples taken at the two landing sites. These are based upon extensive data correction procedures and upon laboratory simulations using a flight qualified instrument identical to those on Mars, operated under Martian conditions of temperature, pressure, and atmospheric composition.

METHODS

Introduction

To the extent that built-in instrument flexibility was possible, and Viking mission operations permitted, the experimental investigation was adaptive. Ground surface deployment was never an option. The only instrument operation variables were spectral scan times, use of calibration targets, and commanded changes in detector gain. All three were used to enhance the quantity and quality of collected data; over 12,000 spectra were taken during the nearly two years of instrument operation. An additional area of adaptive methodology was the planning of acquisitions; sampling designs and approaches to facilitate accurate sample comparisons are discussed below.

Sampling

The Viking Landers were equipped with a retractable boom capable of reaching a semicircular area about 3 m wide and 170 degrees in azimuth (Fig. 1). The sampling device at the end of the boom consists of a collector assembly with one fixed and one movable jaw providing an opening of a maximum of 4 x 2 cm. The opened collector can be inserted into sample material with 40 lbs/inch thrust before "stalling" occurs. The collector head also is equipped with a "backhoe" trenching device usable in the boom-retraction mode. After sample acquisition the collector can be retracted and one or more of the following three delivery modes to the x-ray instrument used: 1) upright collector, movable jaw (upper) vibrated, and entire contents delivered; 2) inverted collector, jaw (now lowermost) vibrated, and only material less than 2 mm delivered through a screen in the jaw; or 3) vibration as in 2) performed outboard of Lander, collector returned to upright and delivery performed as in 1) delivering only material greater than 2 mm.

Thus, only materials under 2 cm could be delivered to the x-ray instrument, and these without pre-treatment of any sort. There was no facility for drilling, grinding, or coring of rock material. Several acquisitions of duricrust (the consolidated formations which appear to be clods and peds of the loose fines) were followed by outboard sievings. The intent was to remove adhering fines material before delivery to x-ray. At the top of the receiving funnel, a screen with 1 cm openings prevented any larger pieces from entering and potentially jamming the delivery chute. A total of 25 cc of material is required to fill the analytical chamber of the x-ray instrument and in most instances several deliveries were made in an attempt to fill the chamber. The surface sampler could not be operated under live-time control and no corrections to a given sequence of boom/jaw movements could be made. Sampling success was judged from the x-ray spectra acquired from the actual acquisition and occasional camera images interleaved with and following boom movements. No details of commanded sampler movements are presented here (see Moore and Dowey, 1981). In a previous paper (Baird et al., 1977), we reported on sampling strategies and techniques for the first ten samples acquired on Mars. A summary of the characteristics for all analyzed samples is given in Table I.

Data Analysis

A description of the instrument and detailed discussion of the methods of data analysis has been published previously (Clark et al., 1977). Briefly, each x-ray fluorescence analyser contains four proportional counter (PC) detectors with sensitivities optimized for different elements. Detector PC-1 is optimized for Mg and Al; PC-2 for Si, S, and Cl; both have good response for K, Ca, and Ti. The remaining two detectors, PC-3 and PC-4, were intended for analysis of Fe and certain trace elements. In our previous work (Clark et al., 1976), the three elements K, Ca, and Ti were derived from PC-2 data alone. However, the history of detector performance on Mars showed that the PC-1 detectors were superior to the PC-2's in terms of both gain and resolution stability. Our final reported results are, therefore, based upon K, Ca, and Ti values as derived from PC-1 spectra. Concentrations for these elements when calculated from PC-2 data are, in general, in excellent agreement. Final values for Si, S, and Cl are derived from PC-2 data; Fe is derived from PC-4.

Adjustment of the spectra to a standard energy scale is by a two-point energy calibration. The procedure, called STRECH, assumes a linear model and applies gain and offset corrections in such a way that the number of counts per unit energy increment is exactly conserved. A study of the data set led to the following approach. For PC-1, the two energy points were the aluminum peak from the built-in calibration flag and the radiation source backscatter peak in the sample spectra. For PC-2, the calibration flag calcium peak was combined with the sample backscatter peak to obtain the gain-to-offset ratio. This ratio was then assumed constant and used with backscatter peak location to establish the energy scale. The STRECH'ed spectra were therefore "tied" to key reference points. In the case of PC-1, the results showed unambiguously that Mg is detected in the samples since the composite Mg/Al peak is always shifted toward Mg from the Al-calibrator tie-point. Conversely, the composite K/Ca peak is <u>not</u> shifted toward K from the Ca-calibrator reference position, demonstrating that the Ca/K ratio is very large for Martian samples.

Another correction to the data is a background continuum spectrum due to cosmic rays, the on-board radioisotope thermoelectric generators (RTG's) and induced radioactivity in the Lander structure. The spectral form of the correction was taken to be that of the dominant component, the RTG background. Increases of level with time were derived from analysis of the background measured by the carbon-14 detectors in the biology instrument (see Clark et al., 1977) and analysis of PC-4 calibration plaque spectra. The absolute background intensity was taken initially as the level predicted for the landing date, based upon pre-launch measurements. It was then adjusted slightly to form a self-consistent data set between the earlier and later samples.

The final correction for PC-1 and PC-2 involved a stray radiation component due to scatter from the sample support structure. This component was derived from calibration plaque measurements, and in the case of PC-2 on Lander 1, by a one-point empirical adjustment to make Ca and Ti values consistent with PC-1 results.

An extensive program to simulate the results on Mars using the spare flight instrument was also undertaken. Numerous analog samples were prepared from geologic materials ("pure" minerals) as well as chemical oxides. Components were first dried in a vacuum oven, weighed, and blended together in a roller mill. It was then found necessary to intimately mix the components by grinding with a motorized mortar-and-pestle. Important effects were found on the relative intensity of x-ray peaks for certain elements, especially for sulfur and chlorine, as a function of grinding time. With grinding times of 8 hours or more, the intensities stabilize for most elements and the elemental concentrations calculated from pre-flight rock calibration standards result in analogs whose spectra match the Martian samples. Hence, concentrations are reported as deduced from the calibrations, and the grinding experiments are used to establish limits of absolute error due to "matrix" effects. An exception is the case of aluminum. This element is difficult to handle in the mathematical model because of uncertainties in the influence of the secondary fluorescence from the PC-1 aluminum entrance window. For this reason, the final Al_2O_3 values were based upon correlation with laboratory measurements of analog samples run in the spare flight unit.

RESULTS

Local Geologic Relationships

At both Lander sites blocks, boulders and cobble-sized rocks (to 1 meter diameter) sit in and on apparently very fine reddish material either in distinct drift forms or as irregular hummocky masses. Most of the rocks appear to be more or less vesicular volcanics (Binder et al., 1977; Mutch et al., 1977), although other workers have found terrestrial examples of vesiculated blocks which are produced by erosion of igneous or sedimentary meterials. Futile attempts to scratch or mar their surfaces with the sampler boom suggest they are not coated with soft weathering rinds.

Small pebble-sized particles, as well as material of grit and coarse sand sizes (sizes below best camera resloution), *seem* to be scattered irregularly around the surface at both Lander sites, at some local areas in high concentrations. But these materials, of great interest as potential samples of Martian rocks, which could be acquired and analyzed by the X-ray instrument, turned out to be duricrust, not rock; i.e., plate-shaped fragments 0.5 cm or so thick lying in and on the regolith surface in a manner suggestive of caliches on Earth. At Lander 1 the material had the same composition as fines except for higher content of S and Cl (presumably, cementing salts) and a bulk density of only 1.2 gm/cm^3. At Lander 2, such acquisitions were unsuccessful, apparently because of weaker cementation which caused the crust to break up during sampling. We are forced to conclude that, for reasons not understood, pebble-sized *rocks* do not exist at the Lander sites.

Fine materials acquired for analysis came from a variety of micro-sites at the Landers: surface skims, direct penetrations of a few centimeters, trenches dug by the backhoe, "tailings" piles of trenching operations, and beneath rocks moved by the collector boom.

The nature and location of samples is listed in Table 1 and their positions plotted in Figures 1a and 1b in relation to all other sampler activities. Martian day or days (sols) of acquisition(s), the depth from which the sample came, and the type of delivery by the collector to the X-ray instrument are also noted in this table.

Composition of Samples

The results of analyses are given in Table II. Although only elemental concentrations are actually measured, we have elected to express the values in terms of equivalent oxides for two reasons: most geologists are much more familiar with this form of tabulation, and there is good reason to believe that the Martian fines have been subjected to strong oxidizing species in the atmosphere (Hunten, 1979).

For most elements, the nominal concentrations are very little changed from interim values reported earlier (Clark et al., 1976; Baird et al., 1976). The titanium content has been revised downward as a result of refinements in the knowledge in the electronic gain of the instruments, made possible by the long-term operation on Mars and the more extensive use of the calibration flag later in the mission. Based upon improved gain knowledge, the laboratory simulation experiments, and a better understanding of the window fluorescence correction for detector PC-1, we also now believe the aluminum to be higher and the magnesium to be somewhat lower than previously reported.

In Table II, concentrations are reported only to the number of digits having relative significance. Numbers in parentheses are less certain because of temporary fluctuations in detector resolution. Missing values reflect missing data due, for example, to servicing of Voyager by the Deep Space Net. Several samples (C-3, C-4, C-10, and C-12) were of insufficient volume to allow analysis to the precision limit of the instrument. We should state, however, that all four of these partial samples were definitely of the same compositional family as the samples listed.

Analytical Uncertainties

Three levels of uncertainty, or error, are associated with the data. These uncertainties, tabulated at the bottom of Table II, are also in units of concentration (per cent by weight) and are intended to represent our best estimate of the 90% confidence limit for each error. "Instrument Precision" is the ability of the instrument to obtain the same result in separate analyses of the same sample. This uncertainty category is generally by far the smallest of the three; instrument repeatability as determined on Mars is excellent. Exceptions are Mg, whose x-ray emissions are of low energy and low yield, and Si, which would otherwise be more accurate were it not for the interference from the unexpectedly high sulfur in the Martian samples.

"Calibration Uncertainty" arises from the facts that a) only solid rock slabs rather than powders were permitted in the instruments prior to flight (a Viking Mission requirement), and b) none of these calibration standards are close in composition to the Martian samples. Uncertainty for aluminum is high because of detector window fluorescence effects.

Matrix Limitations are a source of absolute error in the results due to the possibilities of heterogeneties leading to absorption/enhancement effects;

these heterogeneities could include different particle size distributions for different mineral constituents, large particles, and discontinuous coatings on particles. In laboratory analog tests, grinding of the sample generally resulted in dramatic increases in the S and Cl peaks, moderate increase in the Al peak and moderate decreases in the Si, and Ca, and Fe peaks. After 6 to 8 hours of mortar-and-pestle grinding, no further changes were observed. (Much more drastic effects are observed colorimetrically: only about 1% of an intensely colored material such as hematite can dominate a natural soil color if the two are ground together; tumbler mixing requires ten times as much hematite to produce the equivalent effect.) Presumably many of the effects are attributable to superficial coating of larger grains by smaller grains of distinctly different composition. In initial mixtures, the relatively coarse crystallites of the S and Cl salts are obscured by coating with the superfine SiO_2 and Fe_2O_3 powders. Indeed, the S and Cl peaks are barely visible in x-ray spectra of these mixtures. We may state, then, that <u>if</u> there are relatively coarse salt grains within the Martian soil samples, then the true salt content could be much higher than our nominal value. For this reason, the SO_3 content as reported may be a lower limit, and the matrix uncertainty is accordingly given limits of -2% to +6%. Conversely, if the S and Cl minerals were sufficiently fine, they could coat other grains and our numbers could be an overestimate. This is a case we have never experienced in either natural or artificial samples.

Asymmetric uncertainties are also assigned to MgO and Al_2O_3 because even thin, superficial coatings (e.g., iron oxide stains) could be suppressing the low-energy fluorescent x-rays emitted by Mg and Al. Finally, we should point out that if Fe is actually present as very coarse particles, say 100 micrometers in diameter, the true Fe content could be as high as 30% Fe_2O_3. This cannot be the case because the oxide sum would be far more than 100%. In general, we believe there is sound evidence that the Martian soil has already been subjected to an extensive abrasion history, and that the material is probably fine-grained on the scale of micrometers, is very homogeneous and free of uniform stains. If true, the absolute error limits could be significantly smaller than as stated.

No conclusive evidence for potassium could be found in any of the x-ray flourescence spectra. Because of various limitations we conservatively assign an upper limit of 0.5% by weight for K_2O. Results for trace elements are not reported in this communication, but will be published later. Bromine has been detected in some samples, especially C-5. We may also generalize that, except for ultramafic materials, most terrestrial and lunar igneous rocks contain considerably larger abundances of one or more of the four trace elements Sr, Zr, Y and Rb, than do any of the samples analyzed on Mars (see Clark et al., 1976).

DISCUSSION

These chemical results are important to demonstrate what Mars is not made of. A variety of pre-Viking concepts, such as pink feldspar, limonite beds, and 60% SiO_2 (based upon orbital infrared spectroscopy) must be discarded. We have previously noted that the element profile is not consistent with highly differentiated source material, such as continental siliceous igneous rock on earth, regardless of whether the fines are derived from mafic igneous material directly, or indirectly via chemical weathering (Baird et al., 1976; Toulmin et al., 1977).

Deduction of a unique, exclusive model for the origin of Martian fines may not be possible from these data alone. Certain conclusions can nonetheless be reached, independent of which model is selected for interpretation.

Universal Martian Regolith

As noted in the earlier publications of preliminary results, compositions of samples at the two widely separated landing sites are strikingly similar. For example, sample C-9 at Chryse is nearly indistinguishable from U-3 at Utopia, in all elements. Averages of "protected" samples, i.e., samples from deep trenches or from under rocks, are also remarkably identical for the two landing sites, as seen in Table III. Only the S, Cl and Ti components indicate detectable differences. Even the presumed salts differ by only about 10% on a combined anion basis ($Cl^- + SO_3^=$). If salts are brought into the soil by local aqueous transport, then it is very difficult to see how soils enormous distances apart could have become enriched to so similar a degree. It would also seem prerequisite that the soil be first globally mixed, to homogenize the silicates, and then invaded by salt. It is perhaps more likely that eolian transport, in spite of its ability to segregate minerals under many circumstances, has either blended the various mineral components (including salts), or by its abrasive action has produced homogeneity down to and below the scale of transportable grains. On earth, even sand sheets and dunes often contain distinct layers of heavy/light or large/small particles of contrasting chemical compsition. These chemical data offer no evidence in favor of chemical sorting by the wind on Mars.

Since the soil units observed at the Viking 1 site are comparable spectroscopically with the widely distributed bright regions on Mars (Guinness, 1981), and because of the uniformity of our results, the possibility that much or all of Mars is blanketed by a single fines unit of uniform composition cannot be discounted. Unless Martian igneous activity has been uncommonly homogeneous (in chemical terms), it then follows that the universal fines are a composite mixture of the original material, or the chemical weathering products of <u>several</u> different igneous types.

<u>Differences Among Samples</u>

The concentrations of Si, Fe, and Ca in protected fines are indistinguishable, but the Viking 1 landing site is apparently slightly richer in Ti and Cl, and contains somewhat less S than the more northerly Viking 2 site. The four crust samples taken at site 1 (samples C-2, -3, -5 and -13) all contain about 50% more S than loose fines. At site 2, where no samples of crust were successfully acquired, the total variation of S content was within the ±4 to ±8% maximum variation also observed for the elements Si, Al, Fe, Mg and Ca in all fines samples. Duricrust samples are thus interpreted as sulfate salt-enriched and cemented varients of the fines material. Sample C-8, of fines taken in the same area where C-5 crust fragments were sampled, contains less S than any other sample, at either site.

Correlations

Numerous correlations have been sought within our data set. Caution is to be urged since (1) the samples are very similar, (2) there are only 17 samples with high-precision analyses, and (3) the sampling technique was not designed for this task. Nonetheless, the data do seem capable of yielding certain trends.

Protected fines contain Fe_2O_3 in the 17% range, whereas exposed surface fines contain 18%, with notable exception of C-1 and U-5. This could indicate a slightly higher iron content for surficial fines, although statistical limitations in the number of samples taken and the measurement precision of the instrument (±0.5% concentration by weight for this element) prevent a firm conclusion. There appears to be no correlation between S content and depth at which samples of fines were taken; C-6, obtained at the deepest point (23 cm) sampled on Mars, contains essentially the same S as neighboring surface material, samples C-1 and C-7.

Positive correlation of a major cation with S is to be expected. Three candidate cations, Ca, Fe, and Al are in fact uncorrelated or negatively correlated with S, as is obvious in Figure 2. Only Mg trends in the same direction as S, and the instrumental precision is unfortunately too poor to establish this correlation as anything more than tenuous (see Clark and Van Hart, 1981, for a discussion of probable salt types).

The three elements Si, Al, and Ca appear to be coupled; to a lesser extent, Fe also follows these trends. A constant ratio of Al_2O_3 to SiO_2 of about 0.25 is not inconsistent with the meager data which is relevant. In spite of the concordance between CaO and Al_2O_3, there is apparently too little of the latter to account for all Ca as anorthite. Baird and Clark (1981) have pointed out that the original igneous source material could have been pyroxene-rich, olivine-poor rocks containing labradorite feldspar and magnetite. The relatively minor changes in the revised chemical values presented here do not change this conclusion.

One of the clearest correlations is Ti with Fe, a rather surprising result since the two detectors analyzing for these two elements view orthogonal, non-overlapping surfaces of the sample. A plot of these data is given in Figure 3. Titanium is a well known interstitial substitute for iron atoms in many iron-bearing minerals.

Origin of the Martian Fines?

It was first noticed that the elemental profile measured on Mars has much in common with certain nontronite clay samples (Baird et al., 1976). It was proposed by Toulmin et al. (1977) that volcanic magma may have reacted with ground ice or glaciers to produce smectite-containing palagonite materials. A number of workers (Gooding, 1981; Allen et al., 1981; Evans et al.,1981; Newsom, 1980; Berkley and Drake, 1981; Clark, 1978; Banin et al., 1981; Gibson, 1981) are pursuing this idea through comparison of terrestrial analog samples with our data and the spectral reflectance observations of Mars in the visible and infrared (Hunt et al., 1973; Toon et al., 1977; Singer et al., 1979); in many cases investigators are collecting additional samples in the field or conducting experimental weathering studies.

The origin of the high S and Cl content is commonly ascribed to aqueous leaching of the soil to produce evaporite beds, but alternative sources have been proposed by Clark and Baird (1979), and Settle (1979). An argument that differential chemical weathering is not required to explain the composition of Martian fines and that the fines could have a totally igneous origin, has been put forward by Baird and Clark (1981).

SUMMARY

1. The analysis of major and minor element chemistry of samples of Martian surface materials taken during the Viking missions has been completed.
2. The analyses have been made at high precision for many elements. Absolute accuracies are model dependent; nominal results are reported under the assumption of a fine-grained homogeneity on the scale of micrometers.
3. The average composition of samples at two widely separated sites are nearly identical, implying the occurrence of a widespread uniform soil unit.
4. The results do not lead to a unique interpretation for the origin of the fine material, but almost certainly require that the source materials be predominantly mafic to ultramafic in nature.

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Table I. Sampling Summary

SAMPLE #/ LOCATION	SOL	# OF ACQUIS.	ACQUISITION/ SAMPLE TYPE	DEPTH (cm)	DELIVERY/SAMPLE LEVEL IN CHAMBER
C-1 Sandy Flats	8	2	2 Normal mode scoops into front of pre-existing trench - Fines	0 to 7.5-9.5	2 Fines deliveries: 60 sec HF vibration through sieve - Full
C-2 Rocky Flats	34	2	2 Normal mode scoops into undisturbed surface - Crust	0-6	2 deliveries of coarse material: 60 sec HF vibration through sieve. Delivered by 60 sec LF vibration through jaw - Full
C-3 Rocky Flats	40	2	2 Normal mode scoops into pre-existing trench - Crust; Fragments 2-5 cm across	0-6	2 deliveries of coarse material: 90 sec HF vibration through jaw - Partial
C-4 Sandy Flats	91	1	1 Normal mode scoop into undisturbed surface - Fines	0-5	Spill of fines from biology experiment delivery 45 sec HF vibration through sieve - Partial
C-5 Atlantic City	177-80	4	1 Normal mode scoop into undisturbed surface. 3 normal mode scoops in same trench - Crust fraction of blocky material	0 to 6-7	2 deliveries of coarse material: 120 sec HF vibration through sieve. Delivery by 60 sec LF vibration through jaw - Full

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Table I Continued

SAMPLE #1 LOCATION	SOL	# OF ACQUIS.	ACQUISITION/ SAMPLE TYPE	DEPTH (cm)	DELIVERY/SAMPLE LEVEL IN CHAMBER
C-6 Sandy Flats (Deep Hole)	229 250	2	2 Skim scoops into bottom of deep hole after backhoeing - Fine material	22	2 Fines deliveries: Delivery #1 by 120 sec vibration through sieve Purge #1 by 60 sec LF vibration through jaw Delivery #2 by 60 sec HF vibration through sieve Purge #2 by 60 sec LF vibration through jaw - Full
C-7 Jonesville	285 286	2	2 Skim scoops into undisturbed surface - Fines	1-2	2 Fines deliveries: 60 sec LF vibration through jaw - Full
C-8 Rocky Flats	311 312	2	2 Normal mode scoops into undisturbed surface - Fine material	0-4	2 Fines deliveries: 60 sec HF vibration through sieve, 30 sec LF vibration through jaw - Full
C-9 near Bashful Rock	378	1	1 Normal mode scoop from area behind Bashful Rock - Fines	0-3	1 Bulk delivery with jaw open - Full fill
C-10 Angie's Place	430 431	4	4 Skim scoops into undisturbed surface Coarse material	0- 2 or 3	4 deliveries of coarse material - Partial fill
C-11 Rocky Flats (Deep Hole #2)	468	1	1 Normal mode scoop after 23 backhoe strokes - Bulk	1-6	1 Bulk delivery with jaw open using rotating head - Partial

Table I Continued

SAMPLE #/ LOCATION	SOL	# OF ACQUIS.	ACQUISITION/ SAMPLE TYPE	DEPTH (cm)	DELIVERY/SAMPLE LEVEL IN CHAMBER
C-12 Rocky Flats (Deep Hole #2)	502	2	2 Normal mode scoops after 24 backhoe strokes on SOL486 - Bulk	1-6	2 Bulk deliveries with jaw open using rotating head - Partial
C-13 Deep Hole #2 Tailings	581	16	16 Normal mode scoops into tailings pile - Rocks and beneath	0 to 11-14 (below tailings surface)	16 deliveries of coarse material with jaw open using rotating head after 90 sec HF vibration through sieve to eliminate all but crust - Full
U-1 Bonneville	29 30	2	2 Normal mode scoops into undisturbed surface - Fines	0 to 4-6	2 Fines deliveries: 90 sec HF vibration through sieve - Full
U-2 Notch Rock (under)	131	1	1 Normal mode scoop into undisturbed surface previously covered by rock - Fines	0 to 4-6	1 Fines delivery: 90 sec HF vibration through sieve. Purge by 120 sec LF vibration through jaw - Full
U-3 Spalling Valley	161	2	2 Normal mode scoops into previously dug trench made by 2 normal mode scoops - Fines	0 to 3.5-4.0	2 Fines delivery. 90 sec HF vibration through sieve. Purge to rock pile using 60 sec LF vibration through jaw - Full
U-4 Badger Rock (under)	185	2	2 Normal mode scoops into previously dug trench. Sample from area originally under rock - Fines	0-3	2 Fines deliveries: 90 sec HF vibration through sieve. Purge using 60 sec LF vibration through jaw - Full

Table I Continued

SAMPLE #1 LOCATION	SOL	# OF ACQUIS.	ACQUISITION/ SAMPLE TYPE	DEPTH (cm)	DELIVERY/SAMPLE LEVEL IN CHAMBER
U-5 Physica Planitia	388	2	2 Skim mode scoops into undisturbed surface. Each skim scoop make trench, first trench partly superposed on second - Bulk	0-2.3	2 Bulk deliveries: 60 sec LF vibration at 45° collector head position - Full
U-6 Spalling Valley (Intermediate Deep Hole)	417	1	1 Normal mode scoop into deep hole after 24 backhoe strokes - Fines	5.5-6.0	1 Fines delivery: 60 sec LF vibration through sieve. No Purge - Full
U-7 Spalling Valley (Deep Hole)	422	2	2 Normal mode scoops into deep hole after 24 additional backhoe strokes (48 total strokes) - Fines	12	2 Fines deliveries: 60 sec LF vibration through sieve. No Purge - Full

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Footnote to Table 1:

Sol: Solar days at Mars, post landings

Normal mode: insertion of jaw at angle into surface

Fines: uncemented drift material

Crust: cemented duricrust

Bulk delivery: delivery mode 2), see text

Coarse delivery: delivery mode 3), see text

HF vibration: high frequency jaw vibration (8.8 Hz)

LF vibration: low frequency jaw vibration (4.4 Hz)

Skim: sampler subparallel ground surface

Purge: sampler dump outboard of Lander

TABLE II. SUMMARY OF ELEMENTAL COMPOSITIONS (EXPRESSED AS OXIDES)

Sample	Type	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O*	TiO_2	SO_3	Cl
C-1	Fines	(43)	7.5	17.6	6	6	0	.65	7	.7
C-2	Crust	(42)	-	17.3	-	5.5	0	.57	9	.7
C-5	Crust	42	6.9	17.4	7	5.6	0	.60	9.5	.9
C-6	Deep Fines	44	7.3	17.3	6	6.0	0.04	.61	6.7	.8
C-7	Fines	44	7.4	19.0	5	6.0	0	.63	6.8	.6
C-8	Fines	43	7.1	18.8	6	5.8	0	.71	5.9	.65
C-9	Bulk	45	7.5	18.9	5	6.0	0	.71	7.2	.8
C-11	Deep Fines	-	7.2	17.7	6	5.4	0	.64	-	-
C-13	Crust	(43)	7.0	18.2	7	5.4	0	.59	9	.9
U-1	Fines	42	a	18.9	a	5.8	0.03	.60	8.4	.3
U-2	Under Rock	43	a	17.6	a	5.8	0.02	.63	8.1	.6
U-3	Fines	44	a	18.3	a	5.95	0	.64	7.6	-
U-4	Under Rock	44	a	16.9	a	5.7	0	.52	7.9	.45
U-5	Bulk Skim	43	a	16.3	a	5.3	0	.44	8.3	.6
U-6	Deep Fines	42	a	17.1	a	5.5	0	.48	7.9	.3
U-7	Deep Fines	42	a	17.5	a	5.5	0	.51	7.6	.4
U-8	Bulk	41	a	-	a	5.6	0	.47	(8.5)	-
Uncertainty Estimates:										
Instrument Precision		± 2	± 0.4	± 0.5	± 1	± 0.2	± 0.15	± 0.1	± 0.7	± 0.25
Calibration Uncertainty		± 3	± 2.5	± 2	± 1	± 1	± 0.1	± 0.1	± 2	± 0.2
Total Uncertainty **		± 6	± 4	-2 to +5	-3 to +5	± 2	+0.5	± 0.25	-2 to +6	-0.5 to +1.5

a. Magnesium and aluminum values for all Utopia samples are consistant with Chryse sample values, but details are not reported because of noise bursts in data. (see text).

* All K_2O values are as calculated from the data. Non-zero values are, however, all below the estimated intrinsic instrumental precision limit of $\pm 0.15\%$ and therefore should be considered as insignificant values.

** Absolute errors which could result if the Martian soil matrix strongly deviates from the assumed fine-grained homogeneity. Also includes precision and calibration uncertainties.

Table III. Comparison of "Deep" Samples Average Composition

	Chryse	Utopia
Samples:	C-6,C-11	U-2, -4, -6, -7
SiO_2	44	43
Al_2O_3	7.3	(7)*
Fe_2O_3	17.5	17.3
MgO	6	(6)*
CaO	5.7	5.7
K_2O	<0.5	<0.5
TiO_2	0.62	0.54
SO_3	6.7	7.9
Cl	0.8	0.4
Other **	2	2
TOTAL	91	90

* Mg and Al assumed same as at Lander 1 site.

** Includes such elements as P, Mn, and Na, none of which could be unambiguously detected by our instrument.

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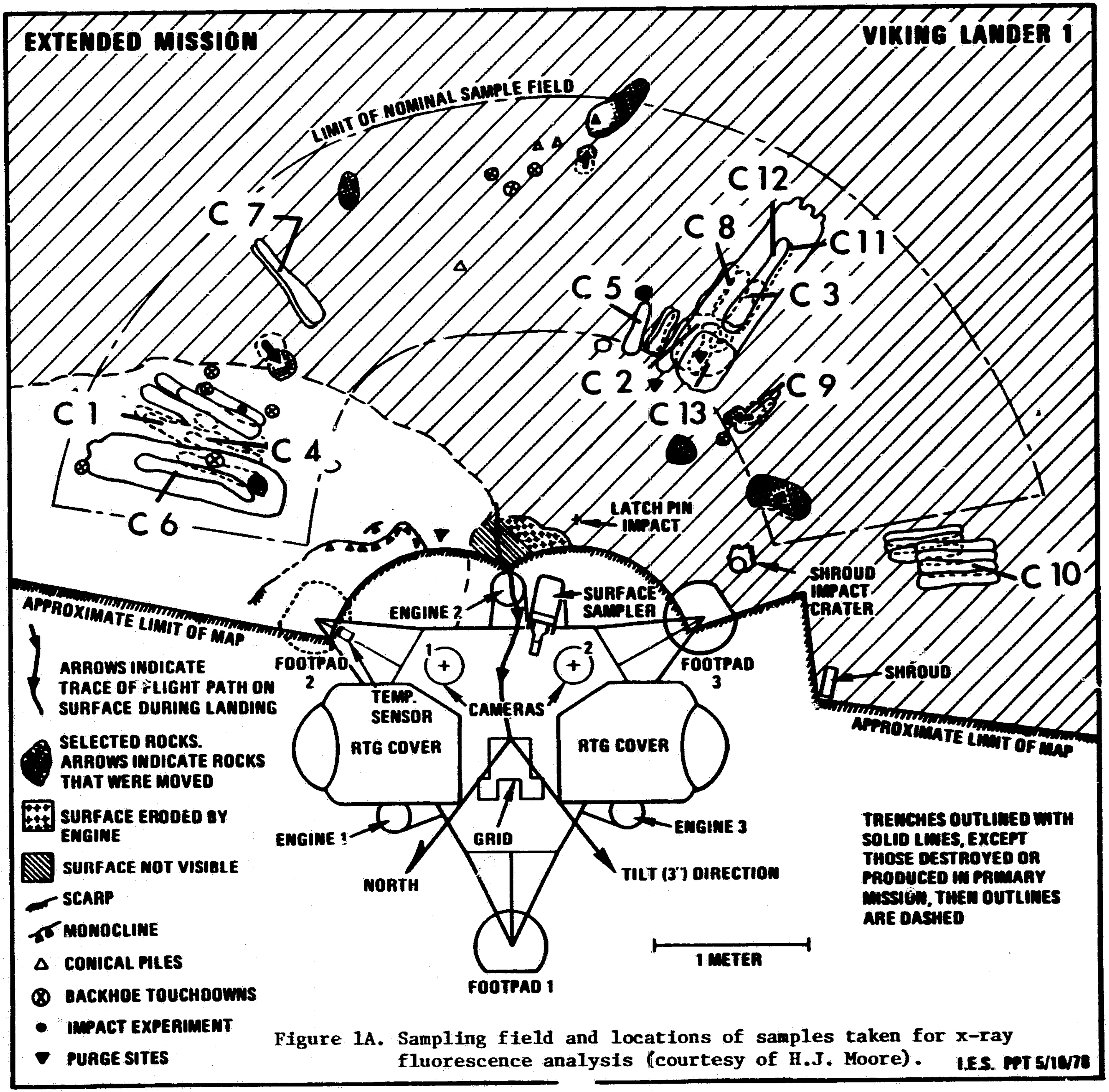

Figure 1A. Sampling field and locations of samples taken for x-ray fluorescence analysis (courtesy of H.J. Moore).

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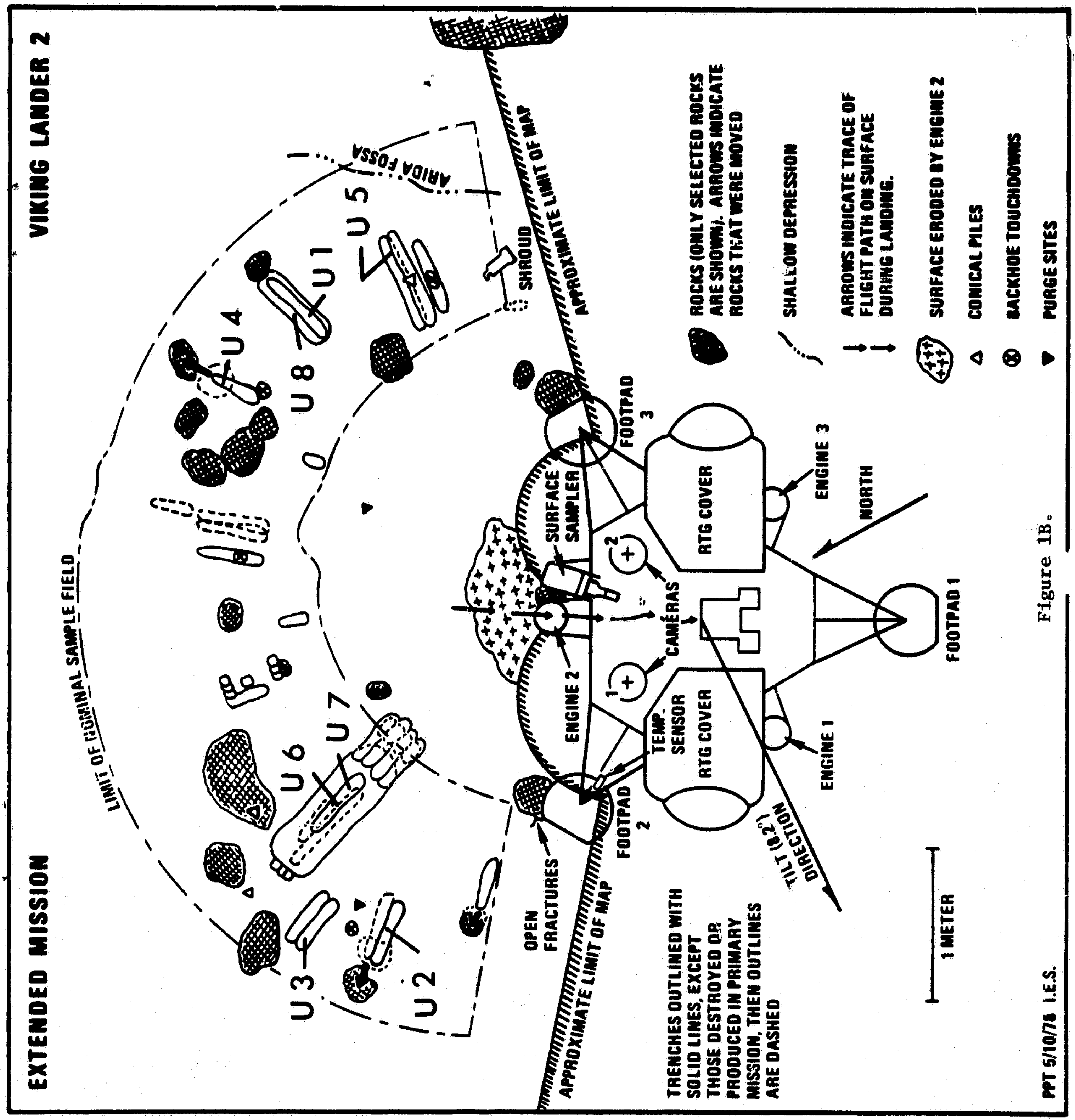

Figure 1B.

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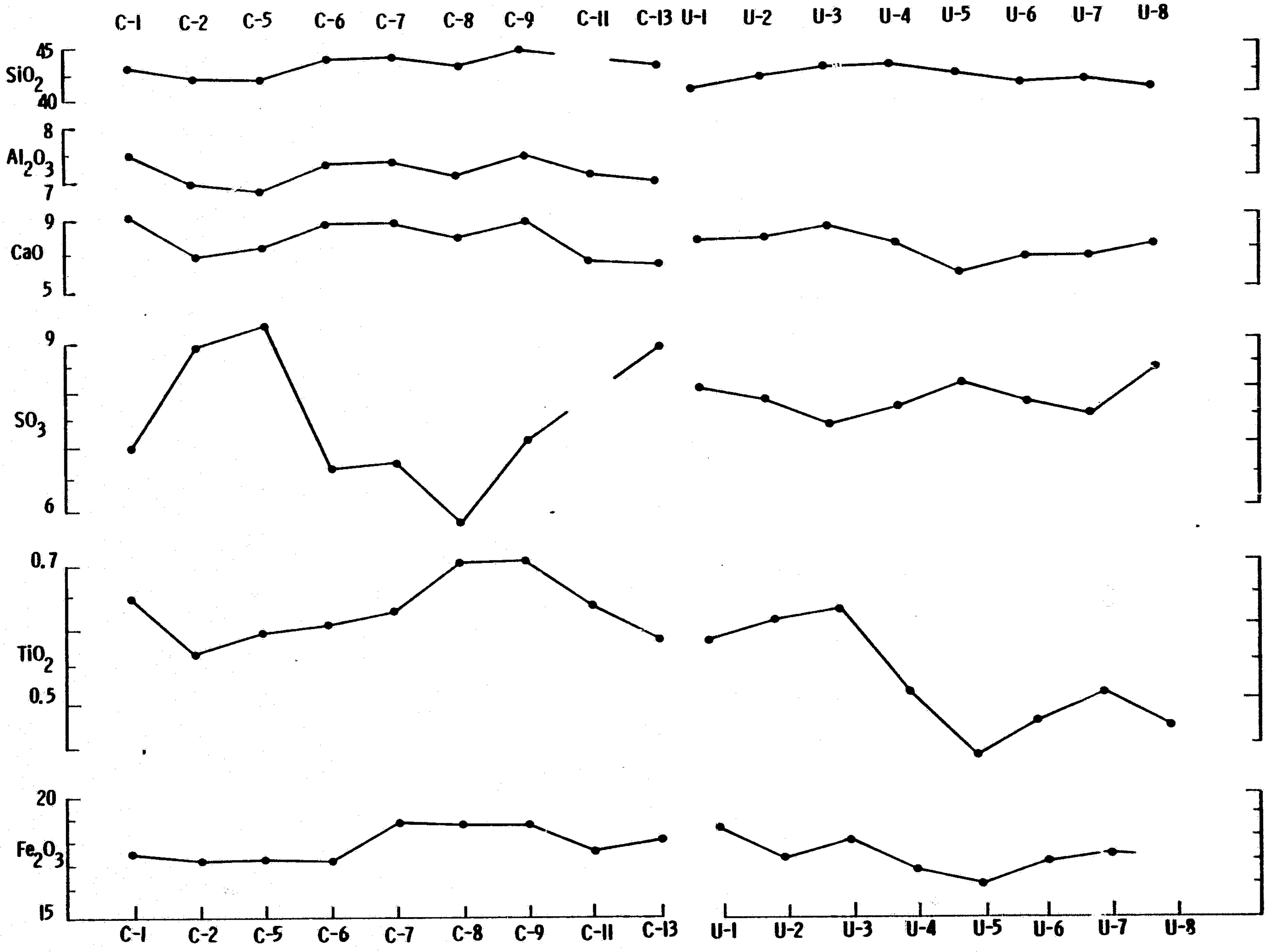

Figure 2. Analytical results, ordinate: percent concentration by weight, plotted on the same logarithmically-scaled basis for each oxide; abscissa: sample number (C=samples taken at Chryse Planitia; U=samples taken at Utopia Planitia).

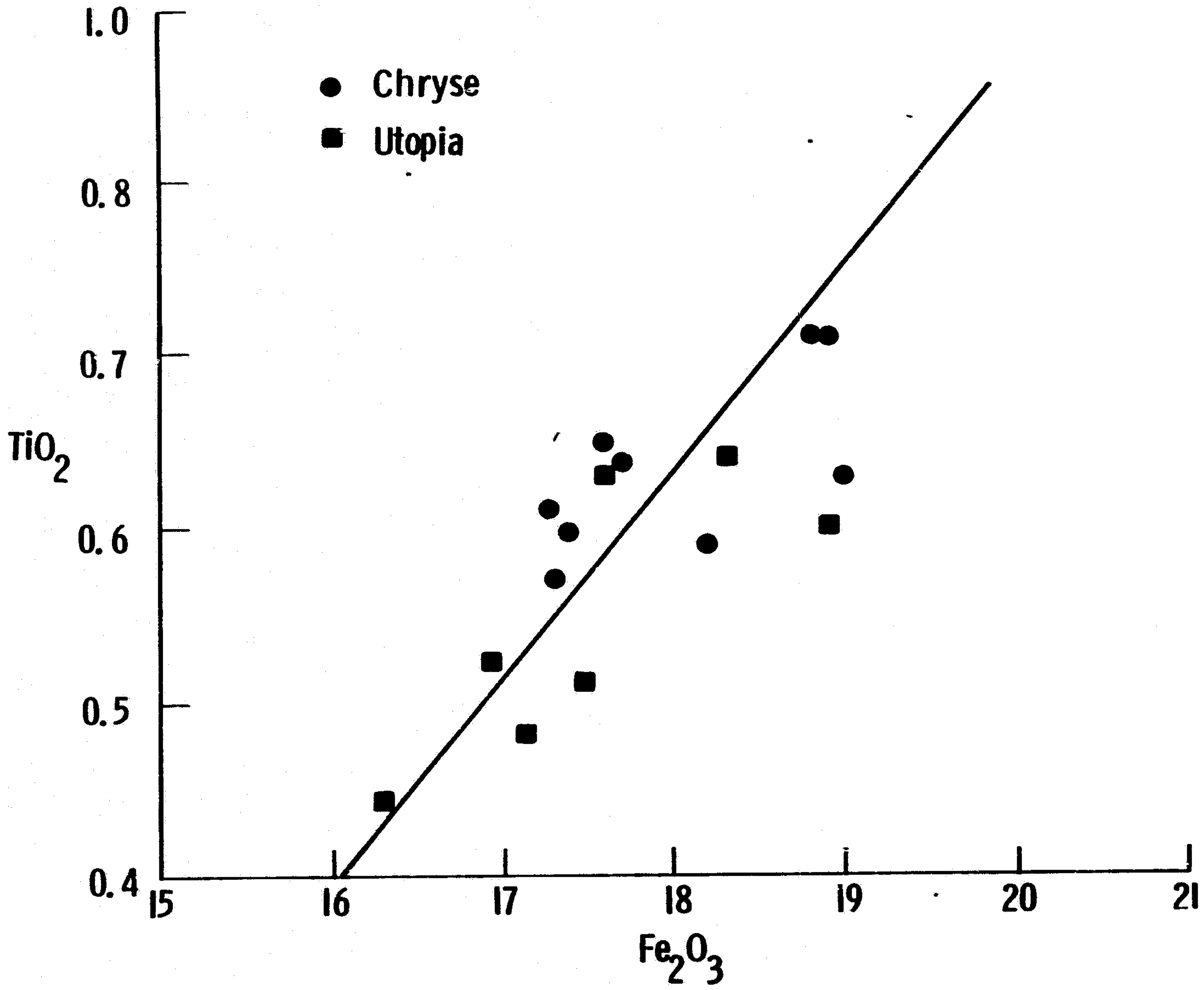

Figure 3. Correlation of titanium concentration with the concentration of iron. Data from both landing sites indicate a positive correlation between the two elements (expressed as oxides).