PROCEEDINGS OF THE SEVENTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE, PART 2
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. B4, PAGES E447–E461, MARCH 30, 1987

The Nature of the Meteoritic Components of Apollo 16 Soil, as Inferred From Correlations of Iron, Cobalt, Iridium, and Gold With Nickel

RANDY L. KOROTEV

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri

Concentrations of Co, Ni, Ir, and Au in small samples of submature and mature soil from Apollo 16 are highly variable. Correlations of Fe, Co, Ir, and Au with Ni indicate that the variation in siderophile element concentrations results from variation in the concentration of Fe-Ni metal. From these correlations, the mean composition of the metal is inferred to be 5.6% Ni and 0.36% Co for a Ni/Co ratio of 15.5 ± 0.7, i.e., dissimilar to the chondritic ratio of 20–21. The Fe-Ni metal is also characterized by low Ir/Ni and Ir/Au ratios compared to metal in ordinary chondrites. Metal with a similar composition is also found in metal-rich, noritic impact melt breccias that occur as discrete rocks as well as small clasts in ancient regolith breccias at Apollo 16. Mass-balance models using lithophile element concentrations indicate that about 35% of the soil is noritic impact melt. The Fe-Ni metal associated with this component is sufficient to supply virtually all the ancient Fe-Ni metal found in the typical Apollo 16 soil (0.4–0.5%), i.e., no other source is required. The soil also contains 1–2% carbonaceous chondrite. The concentration of this component appears to be relatively constant from sample to sample and does not contribute significantly to the variation in siderophile element abundances. These two meteoritic components contribute nearly equal concentrations of Ni to the typical Apollo 16 soil.

INTRODUCTION

Studies by *Baedecker et al.* [1972, 1973, 1974] and *Wasson et al.* [1975*a,b*] show that concentrations of siderophile elements derived from meteorite impact are higher in Apollo 16 soil than in soil from other landing sites. These studies and those by *Anders et al.* [1973], *Krähenbühl et al.* [1973], *Ganapathy et al.* [1973, 1974], and *Hertogen et al.* [1977] also show that although siderophile elements in soil from mare areas derive mainly from the micrometeorite flux of carbonaceous chondrites, those in soil from the older highlands areas such as Apollo 16 derive primarily from a different population of meteorites, the "short-lived" population of *Baedecker et al.* [1972] or the "ancient" meteorites of *Anders et al.* [1973]. These old meteorites are believed to be those associated with the late accretion of the moon ending about 0.7 Ga after it formed, i.e., during the time the large basins were excavated. The Ir/Au ratios of some ancient meteorites were outside the range found today in chondrites [*Hertogen et al.*, 1977] and *Anders et al.* [1973] argue that the ancient meteorites differed from all present day meteorite falls, including irons.

In Apollo 16 rocks, siderophile elements occur primarily in metal grains [*Wänke et al.*, 1978; *Korotev* 1987]. Bulk compositions of metal grains found in Apollo 16 soil and rocks show that Ni and Co concentrations (typically 6% Ni and 0.3–0.4% Co) are within the "meteoritic range" as defined by *Goldstein and Yakowitz* [1971] based on iron meteorites [e.g., *Goldstein and Axon*, 1973; *Gooley et al.*, 1973; *Reed and Taylor*, 1974; *Misra and Taylor*, 1975; *Hewins and Goldstein*, 1975; *Hewins et al.*, 1976], but the compositions are outside the range for metal in ordinary chondrites [*Wlotzka et al.*, 1973; *Reed and Taylor*, 1974]. The simplest explanation, and the one favored by *Hewins et al.* [1976], is that the metal derives from the ancient meteorite component and that the metal composition of at least some ancient meteorites is unlike that of ordinary chondrites. Others have suggested, however, that the metal may not presently have the same composition as that in the impacting bodies if it has subsequently reacted with lunar silicates [*Wlotzka et al.*, 1973; *Reed and Taylor*, 1974; *Taylor et al.*, 1976; *Delano and Ringwood*, 1978*a,b*; *Wänke et al.*, 1979; *Palme*, 1980].

In this paper I: (1) use the covariation of siderophile element concentrations in samples of Apollo 16 regolith to determine the average composition of the Fe-Ni metal, (2) demonstrate that nearly all the Fe-Ni metal in the soil is contributed by the melt breccia component, (3) discuss the contribution of micrometeorites to the siderophile element budget of Apollo 16 soil, and (4) show that although the Fe-Ni metal and micrometeorite components contribute approximately equal concentrations of Ni to the soil, most of the variation in Ni concentration results from variable amounts of Fe-Ni metal.

DATA AND DISCUSSION

The Metal Component

Mature and submature soil. Figures 1 and 2 are plots of the concentrations of Fe and Co against that of Ni in small (10–50 mg) samples of Apollo 16 soil. The data are restricted to "typical" soil, i.e., samples with compositions similar to the soil in the vicinity of the lunar module [*Korotev*, 1981] and those that are mature or submature with respect to surface exposure by the criteria of *Morris* [1978]. Both these restrictions effectively exclude soil from the vicinity of North Ray crater (stations 7 and 13), which is both more anorthositic and less mature than typical Apollo 16 soil, and other relatively anorthositic samples such as 60051 and some core soils. Hence all samples plotted in Figures 1 and 2 have similar concentrations of lithophile elements; their Al_2O_3 concentrations range from 25.5% to 27.5%. This selection process was intended to yield a data set composed of samples with similar relative concentrations of siderophile elements from meteoritic sources as well as similar concentrations of indigenous siderophile elements such as Co (as a result of similar composition and abundance of mafic minerals). Of the 105 samples, 69 are from the Stone Mountain core.

Fe-Ni correlation. In Figure 1, the bulk of the data form a loose cluster at about 400 μg/g Ni and 4.2% Fe, but several points lie along a trend toward much higher Fe and Ni

Paper number 6B7269.
0148-0227/87/006B-7269$05.00

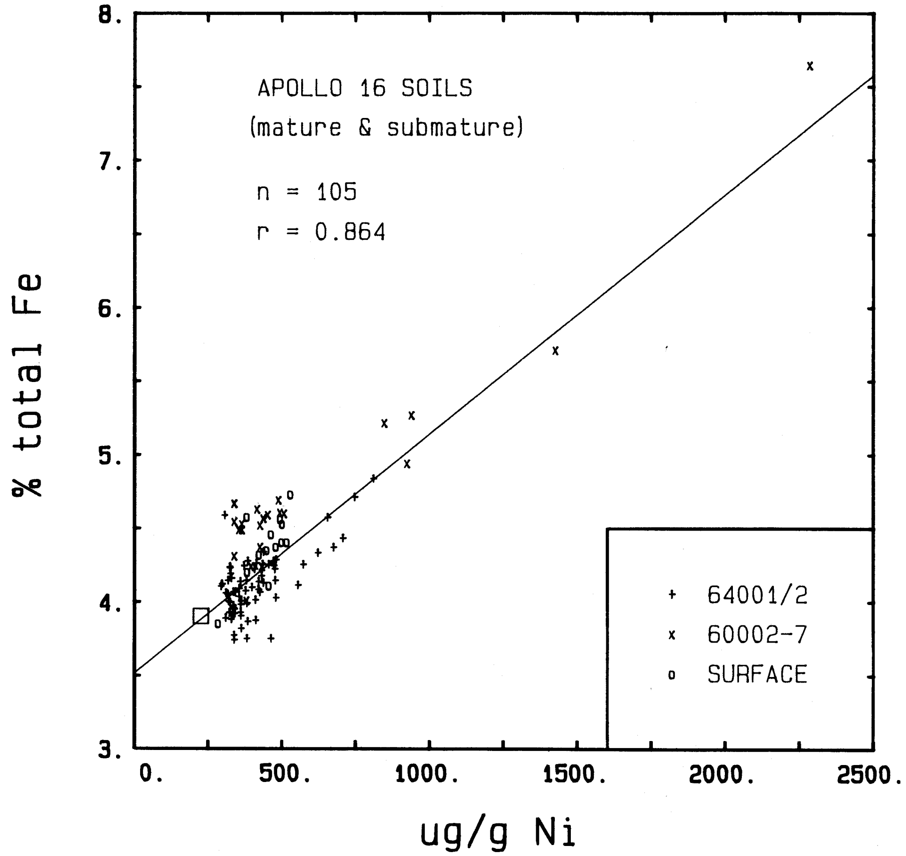

Fig. 1. Variation of Fe (total iron as Fe) with Ni in Apollo 16 soil. The solid line is the best-fit regression line obtained by the method of *York* [1969] (see Table 1). The variation can be explained by variable amounts of Fe-Ni metal containing 5.6% Ni (Fe/Ni = 16.9). The variation in Fe at a given Ni concentration results because the samples have similar, but not identical, ratios of mafic to felsic silicate minerals, i.e., the amount of Fe contained in mafic silicates is not constant among the samples. The slope of the line is determined by the few high-Ni samples. If these have different contents of mafic silicates than do the low-Ni samples, then the line does not necessarily extrapolate to the composition of the average metal. The square represents the average composition of the nonmetal portion of the soil as estimated by the model described in the text.

concentrations. This trend is caused by variation in the abundance of a component that is rich in both Fe and Ni. The mean composition of the (Fe,Ni)-rich component must correspond to a point on the line and extrapolation of the line to high Ni concentrations must intersect that point. This interpretation of correlation is similar to that of *Palme* [1980] and *Korotev* [1987], who discuss the theory and assumptions in more detail.

The (Fe,Ni)-rich component must be Fe-Ni metal. For 66 of these samples (64001), *Korotev et al.* [1984] show that the concentration of metallic Fe (magnetically determined) also correlates with Ni concentrations. The Fe/Ni ratio of the metal required to account for the correlation was 15.0 ± 1.6; i.e., the Fe-Ni metal contained about 6% Ni. Extrapolation of the best-fit line in Figure 1 to exactly 6% Ni yields a concentration for Fe of 101 ± 17%; i.e., Fe-Ni metal containing about 6% Ni accounts entirely for the trend of increasing total Fe with Ni in Figure 1. (All uncertainties quoted herein are two standard deviations based on the regression analysis.) The mean composition of the Fe-Ni metal causing the correlations must be 94% Fe, 5.6 (+0.5,−0.8)% Ni, and 0.36±0.02% Co to simultaneously explain the correlations in Figures 1 and 2.

The scatter in total Fe abundance at a given Ni concentration results because the samples are not all identical in lithophile element composition. Al_2O_3 concentrations in the samples range from 25.5–27.5% as a result of variation in the ratio of mafic components (primarily noritic melt breccias, as argued below) to Fe- and Mg-poor felsic components. Hence concentrations of elements associated with mafic components anticorrelate with that of Al (e.g., Fig. 7-2 of *LSPET* [1972] and Figures 1 of *Korotev* [1981, 1982]). The 2% range in absolute concentration of Al_2O_3 yields a 1% range in the absolute concentrations of both FeO and MgO because of closure and the relative invariance in concentrations of SiO_2 and CaO. This accounts in large part for the range in Fe concentration of 3.7–4.7% at the cluster of points at 300–500 μg/g Ni and for the deviations from the best-fit line at higher Ni and Fe concentrations (Figure 1).

The slope of the line is determined largely by the few metal-rich samples. If the ratio of mafic to felsic phases in the metal-rich samples is not typical of that of the metal-poor samples, then the line does not extrapolate to the mean composition of the metal, as was assumed above. This could be a source of systematic error that would affect the mean Ni content of the metal calculated above. All of the most metal-rich samples are from the 60002-7 core. Samples with low Ni concentrations from this core appear to be slightly richer in Fe than the 64001/2 samples that dominate the low-Ni cluster of points (Figure 1). If so, then the Fe/Ni ratio of the metal inferred above is systematically high and the actual mean Ni concentration of the metal is greater than 5.6%. It is unlikely that any error

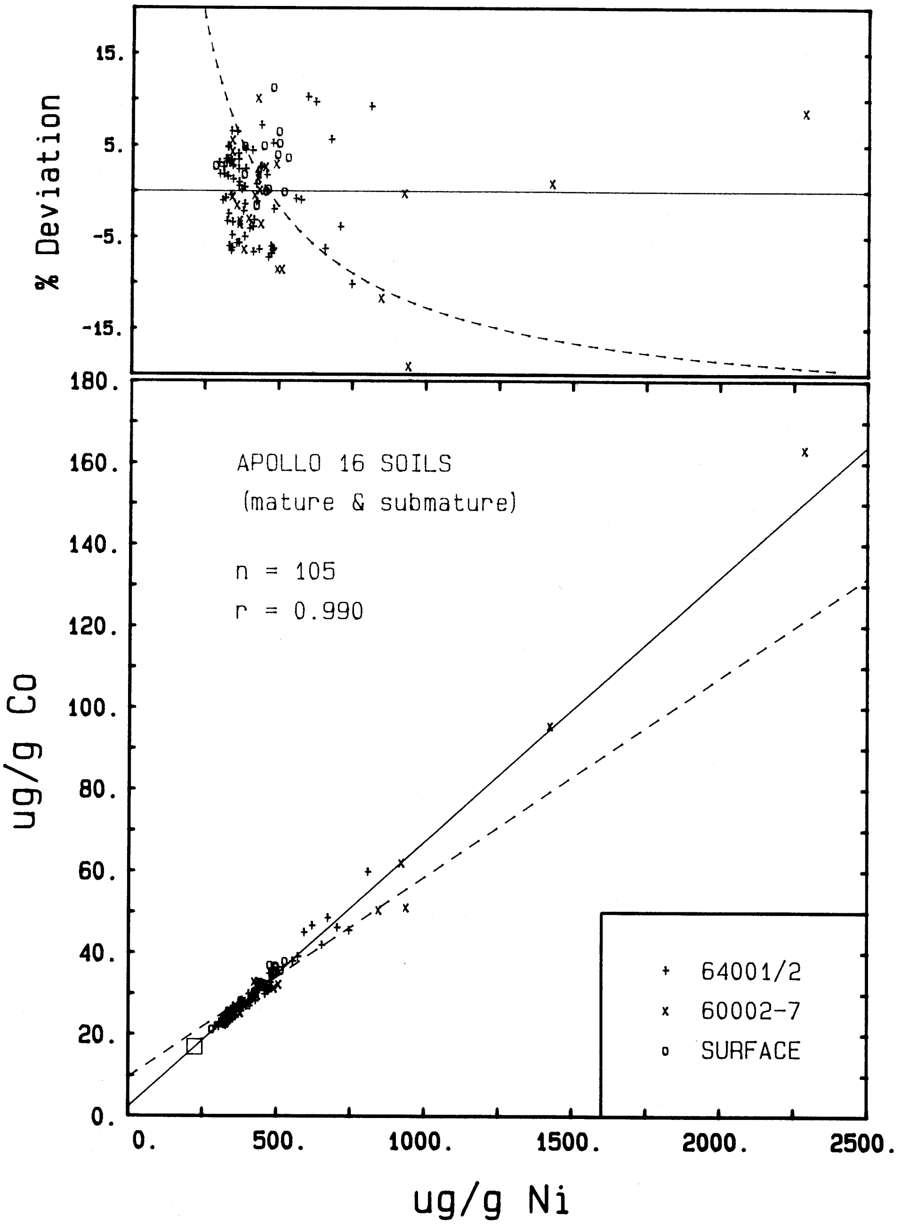

Fig. 2. Variation of Co with Ni in Apollo 16 soil. The solid line is the best-fit regression line. The correlation requires variation in the amount of a metal component with a mean Ni/Co ratio of 15.5. The dashed line represents addition or subtraction of a component with a chondritic Ni/Co ratio (20.5) to or from the mean composition of the soil. A few samples deviate from the mean in the direction of a chondritic component.

from this source is large because similar Ni concentrations are obtained by other techniques: 5–7% (direct analysis of individual metal grains in the soil [*Goldstein and Axon*, 1973; *Reed and Taylor*, 1974; *Hewins et al.*, 1976]), 5–6% (magnetic measurements [*Nagata et al.*, 1973; *Pearce et al.*, 1973]), and 5.5–6.5% (correlation of concentrations of Ni and metallic Fe [*Kerridge et al.*, 1975; *Chou and Pierce*, 1976]). For the purpose of later discussions, a value 6% for the mean Ni concentration of the metal will be used.

Note that the correlation technique used here provides information only about Fe metal that contains Ni. It cannot distinguish between (1) pure iron metal produced by solar wind reduction of iron silicates [*Morris*, 1978, 1980] or indigenous Fe metal with low Ni content such as found in pristine rocks [*Ryder et al.*, 1980] and (2) oxidized Fe in silicate minerals. In other words, the line in Figure 1 is a mixing line between Fe-Ni metal containing 6% Ni as one end member and all other components, some of which might contain forms of Fe that do not correlate with Ni, as the other. Note also from Figure 1 that a significant portion of the total Fe in some samples is not oxidized (nearly half the Fe in the sample richest in Ni). If no correction is made for Fe contained in Fe-Ni metal, certain petrologic parameters such as bulk mg′ [molar Mg/(Mg + Fe)] calculated from bulk analyses may be substantially in error [*Korotev et al.*, 1984].

Co-Ni correlation. Figure 2 shows the variation of Co with Ni. The correlation here is better than for the Fe-Ni data because a smaller fraction of the Co is associated with silicate minerals. Extrapolating the best-fit line (solid) to 5.6% Ni yields a Co concentration of 0.36% and a Ni/Co ratio of 15.5 ± 0.7 for

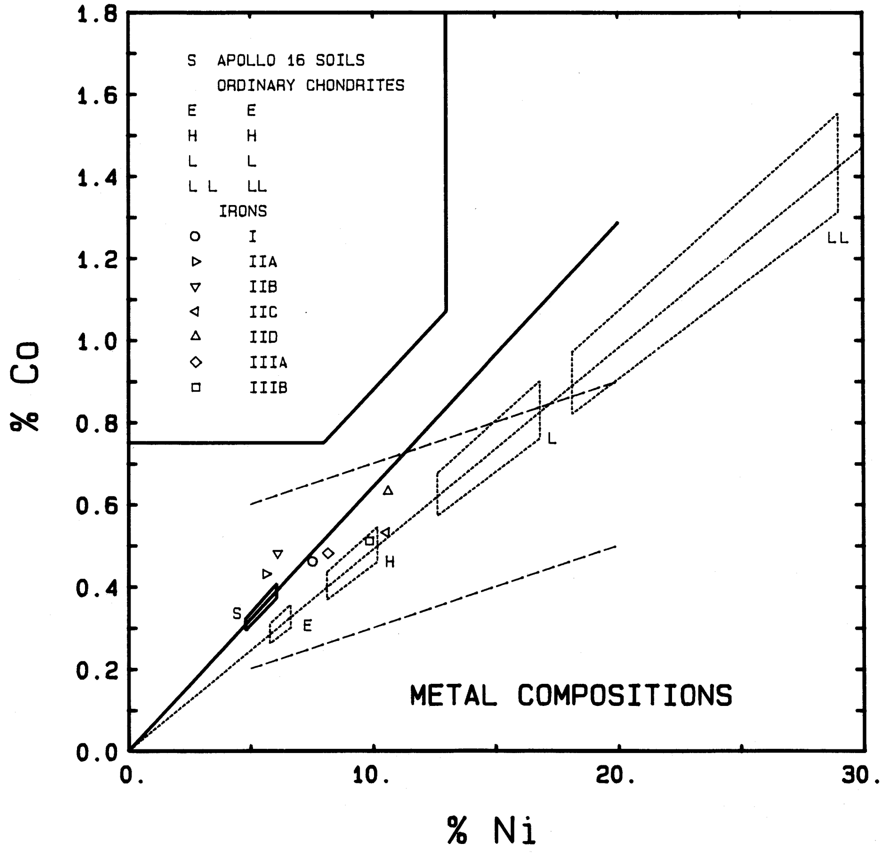

Fig. 3. Cobalt and Ni concentrations in various metal phases. The solid line is the extrapolation of the line in Figure 2. The quadrilateral (2 σ) at 5.6% Ni is the best estimate of the mean composition of the metal in the soil obtained from the regressions in Figures 1 and 2. Because of the possible systematic error discussed in Figure 1 and the text, the actual mean composition of the metal may be displaced slightly along the line to higher Ni concentrations. The dashed line represents the chondritic Ni/Co ratio (20.5). Fields (1 σ) representing the metal composition in ordinary chondrites are indicated (based on data of *Greenland and Lovering* [1965], *Nichiporuk et al.* [1967], *Baedecker and Wasson* [1975], and *Rambaldi* [1976, 1977]). The parallel broken lines represent the field for iron meteorites as defined by *Goldstein and Yakowitz* [1971]. Means for specific types of irons are also plotted (data from *Moore* [1971]).

the average metal. This ratio is outside the range of about 18–23 found in metal from ordinary chondrites but is in the range found in iron meteorites (Figure 3). The mean bulk composition of the soil metal is most similar to that of group IIA irons, but it does not match exactly that of metal from any specific type of meteorite. Unlike that for the Fe-Ni correlation, the slope of the regression line in Figure 2 is not overwhelmingly dictated by the high-Ni samples. Table 1 shows that the metal component required to explain the variation among samples with <500 μg/g Ni has the same Ni/Co ratio as that for the samples with >500 μg/g Ni. Table 1 also shows that there is no significant difference in Ni/Co in metal from samples from different areas of the site, e.g., from the deep drill core near the lunar module or from the Stone Mountain core at station 4. Including data from other laboratories also does not significantly affect the results.

Distribution of Ni concentrations. At this point it is interesting to speculate on the significance of the distribution of Ni concentrations in Figures 1 and 2. Sample masses range from 10 to 50 mg. The two highest Ni concentrations occur in samples weighing less than 12 mg. About 84% of the samples have between 280 and 500 μg/g Ni. The mean concentration for all samples is about 460 μg/g (Table 1). The lines in Figures 1 and 2 are essentially mixing lines between Fe-Ni metal and what we will call the "nonmetal" portion of the soil, even though it contains some metallic Fe with negligible Ni, as discussed above. The mean composition of the nonmetal portion of the soil must lie on the low-Ni end of the mixing lines somewhere between zero μg/g Ni and the sample with the lowest Ni concentration at about 280 μg/g Ni.

If at one extreme we assume that the nonmetal portion contains a negligible amount of Ni, then all the Ni is in the metal phase and the mean Ni concentration of the soil (460 μg/g) corresponds to 0.8% Fe-Ni metal. In this case the distribution of Ni values results because all samples contain many small metal grains, but a few samples contain one or more large grains. The cluster at low Ni concentrations might be an approximately normal distribution centered on about 400 μg/g Ni with a standard deviation of about 50 μg/g caused by many (50–100) small metal grains. At the other extreme, the cutoff at about 280 μg/g Ni is sharp; only immature and more anorthositic samples have Ni concentrations less than 280 μg/g Ni, suggesting that this concentration may represent that of samples totally devoid of Fe-Ni metal, i.e., that 280 μg/g is the Ni concentration in the nonmetal component. The difference between this value and the mean Ni concentration corresponds to about 0.3% Fe-Ni metal for the average sample. Hence the range of 0–280 μg/g for the possible concentration of Ni in the "nonmetal" fraction of the soil constrains the concentration of Fe-Ni metal in the average soil to 0.3–0.8%.

TABLE 1. Regression Data and Ni/Co Ratios in Metal Phase Causing Variation in Ni and Co Concentrations in Apollo 16 Regolith and Impact Melt Samples

	n	r	Mean Ni	Ni/Co		Co intercept		Source*
			μg/g	g/g	±	μg/g	±	
Regolith								
This lab								(1)
All soils	105	0.990	456	15.5	0.7	2.4	1.2	
<500 μg/g Ni	88	0.948	386	15.2	1.0	1.9	1.7	
>500 μg/g Ni	17	0.988	818	15.1	2.4	0.6	7.1	
64001/2	69	0.976	411	15.4	0.9	2.1	1.5	
60002-7	23	0.992	595	16.1	1.5	3.1	2.6	
Surface only	13	0.974	448	14.4	1.6	1.2	3.2	
With other data								
60002-7	26	0.991	607	15.4	1.4	2.0	2.7	(2)
Surface only	29	0.918	414	16.4	1.8	4.5	2.5	(3)
Ancient regolith breccias	16	0.948	300	16.8	2.4	4.1	2.1	(4)
Melt Rocks								(5)
Dimict breccia VHA	11	0.997	1150	17.3	0.8	4.0	2.0	
Type-1, "A16 KREEP"	26	0.979	840	19.3	2.2	8.4	4.0	
N. Ray Crater VHA	17	0.985	590	14.9	0.9	1.0	1.4	

Data were obtained from regression of Co against Ni by method of *York* [1969]. In all regression analyses presented here the concentrations of both elements were weighted by the factor of $1/x^2$ where x is 10% of the concentration value. In this way the slope of the line is not so strongly levered the few high-Ni points (which simply contain a larger fraction, perhaps a single large grain, of the Ni-rich component) as would occur if a constant weighting factor were used. Identical results are obtained for any fraction other than 10%. "Ni/Co" is the ratio for a point on the best-fit regression line at 6% Ni. Uncertainties are two standard deviations based on the regression analysis.

**Sources of data*: (1) *Korotev* [1982], *Korotev et al.* [1984], and *McKay et al.* [1986], excluding samples contaminated by steel, samples with > 11 μg/g Sc and, therefore, contaminated with mare basalt [*Korotev et al.*, 1984], and samples with >27 % Al_2O_3; (2) *Korotev* [1982] and *Boynton et al.* [1976, three samples of 60002]; (3) note (1) above plus *Wänke et al.* [1973], *Boynton et al.* [1975, 1976], and *Chou and Pierce* [1976]; (4) *McKay et al.* [1986]; (5) *Korotev* [1987].

In a later section, the actual mean concentration of Ni in the nonmetal fraction is estimated to be about 225 μg/g Ni; this value results mainly from the contribution of Ni from the component of carbonaceous chondrites. First, however, the origin of the Fe-Ni metal is discussed.

Relation of Fe-Ni Metal in the Soil to Impact Melt Breccias

In a companion paper, *Korotev* [1987] discusses the meteoritic component of Apollo 16 impact melt breccias of noritic or "LKFM" composition ("low-K Fra Mauro"; see *Reid et al.* [1977]). Most of these melt breccias are 3.8–4.0 Ga old (see summary of *Spudis* [1984]). The noritic impact melt breccias have the greatest concentrations of incompatible trace elements among common rocks at Apollo 16, i.e., they are the principal carriers of the KREEP component [see *Warren and Wasson*, 1979 and *Spudis*, 1984]. These rocks include some of the type-2 melt breccias [also known as "VHA basalts" ("very high alumina" [*Hubbard et al.*, 1973]) or "group-2" melt breccias] and the "type-1" melt breccias such as 60315 (also known as "group-1," "Apollo 16 LKFM," "Apollo 16 KREEP") [see *Floran et al.*, 1976; *Vaniman and Papike*, 1980; *Ryder*, 1981*a,b*; *McKinley*

TABLE 2. Concentrations of Some Elements in Clasts of Impact Melt Rock Separated From Three Regolith Breccias

	Fe %	Sc μg/g	La μg/g	Co μg/g	Ni μg/g	Ir ng/g	Au ng/g
Type-1 melt							
66035	7.77	15.7	60.8	80.3	1400.	22.	32.
60016	7.81	15.8	58.6	66.5	1130.	23.	27.
60016	8.10	15.2	56.5	77.6	1360.	21.	29.
60016*	5.75	13.6	55.9	42.3	740.	15.	15.
60016*	8.90	15.6	58.5	105.	1940.	36.	36.
66075	9.27	11.2	42.3	192.	3400.	68.	102.
60075	5.90	13.4	51.7	39.2	545.	12.4	9.6
66075	5.94	13.3	51.1	36.9	510.	10.7	10.4
66075	7.11	13.8	43.6	80.4	1300.	28.	25.
66075	5.79	13.4	49.1	35.8	500.	10.5	9.4
66075	5.84	13.2	50.7	34.2	460	10.5	7.2
mean	7.11	14.0	52.6	71.8	1210.	23.	28.
Type-2 melt							
66035	4.08	10.9	21.0	6.6	56.	<3.	<3.
66035	4.40	10.0	16.9	22.8	300.	3.0	7.3
66035	3.66	9.0	20.6	14.4	190.	3.8	<3.

*All analyses by M. M. Lindstrom [see *McKay et al.*, 1986] except these two, which are from *Wänke et al.* [1975].

et al., 1984; *Spudis*, 1984]. *Korotev* [1987] finds that (1) Ni concentrations in noritic melt breccias from Apollo 16 are very high compared to those in noritic melt rock from other sites because of a high content of Fe-Ni metal; (2) the composition of the metal, as inferred from correlations of siderophile element concentrations, is 6% Ni with a Ni/Co ratio of 15–19, i.e., similar to the soil metal but outside the range for metal in ordinary chondrites; (3) the Ir/Au ratio in the metal is low and outside the range for metal in chondrites (except perhaps EH chondrites) but is typical of that of ancient meteorite group 1H of *Hertogen et al.* [1977]; (4) the unusual metal composition cannot result from reaction of metal such as that found in ordinary chondrites with lunar silicates; (5) the metal derives from the impacting body responsible for the melt; and (6) both the bulk and trace-element composition of the metal is consistent with that of some iron meteorites. In this section we argue that nearly all of the Fe-Ni metal in the Apollo 16 soil is contributed by the component of old melt rocks.

Ancient Apollo 16 regolith breccias. Figure 4 (bottom) shows the correlation of total Fe with Ni for 20–50 mg samples of ancient regolith breccias from Apollo 16 [*McKay et al.* 1986]. These are breccias composed of lithified soil. In contrast to the present soil, they are characterized by very low values for exposure indices such as agglutinate content [*McKay et al.*, 1974] and I_s/FeO [*Morris*, 1978], high ratios of $^{40}Ar/^{36}Ar$, and high concentrations of excess fission Xe. *McKay et al.* [1986] conclude that these breccias were not formed from the present soil but are samples of well-comminuted material present on the lunar surface about 4 Ga ago, i.e., that they contain regolith formed during the late accretion of the moon.

The best-fit line through the regolith breccia data of Figure 4 (bottom) is distinctly different than that for the soil. The reason for this difference provides an important clue as to the source of the metal in the present soil. The major element compositions of the regolith breccias are more variable than those of the soil samples plotted in Figure 1; Al_2O_3 concentrations range from 25–30%. *McKay et al.* [1986] argue that a large portion of the compositional variation results from the variable amount of mafic impact melt rock contained in the breccias because most of the other components are more anorthositic. They show that the total Fe concentration of the regolith breccias correlates positively with the fraction of the lithic fragments (anorthosite, norite, troctolite, and crystalline melt matrix) that are impact melt rocks (i.e., "crystalline melt matrix"). Table 2 lists some compositional data for 14 melt clasts separated from three of these regolith breccias. Eleven are similar in composition to the type-1 melt rocks and three are at the low-Sc extreme [*Morris et al.*, 1986] of the range of type-2 melt rocks. The type-1 melt clasts have variable but high concentrations of Fe, Ni, and trace siderophile elements as a result of variable concentrations of Fe-Ni metal [*Korotev*, 1987]. Consequently, the concentration of Ni as well as Fe correlates roughly with the amount of impact melt observed petrographically (Figure 4, top: the petrography was not done on the same split used for the Ni analyses; otherwise the correlation might be stronger).

Hence most of the variation in total Fe concentration in Figure 4 results not from variation in metal content, as for the soil samples in Figure 1, but from variable amounts of its host impact melt rock, the predominant mafic component of the breccias. *McKay et al.* [1986] also noted the latter variation on the basis of the correlation of Sm with Sc in the breccias. As discussed earlier, the soil samples in Figure 1 are all nearly the same in bulk composition and thus the soils must contain a more nearly constant fraction of impact melt than the regolith breccias. Although Ni is carried by Fe-Ni metal in both the soil and breccias, the metal in the breccias is always a subcomponent of the melt-rock component, whereas for the high-Ni soil samples in Figure 1, the metal behaves as a discrete component that does not necessarily correlate with the fraction of melt rock in the soil sample. The Fe/Ni ratio of the metal differs from the bulk Fe/Ni ratio of the melt rocks because a substantial portion of the Fe in the melt rocks is carried in the oxidized form by the mafic silicates. The steeper slope for the correlation of Fe and Ni in the regolith breccias in Figure 4 results from the greater Fe/Ni ratio of melt rocks compared to Fe-Ni metal.

This explanation can be demonstrated quantitatively. It was noted earlier that the Fe-Ni regression line in Figure 1 intersected the point corresponding to the typical Fe-Ni composition of metal found in the soil when extrapolated to about 6% Ni. Extrapolation of the best-fit line for the regolith breccias in Figure 4 to 6% Ni (60000 μg/g) yields an unreasonable Fe concentration of 315%. However, extrapolation of the line to 1210 μg/g Ni, the mean Ni concentration of the 11 type-1 melt rock clasts in Table 2, yields an Fe concentration of 8.1%. This compares well with the actual mean Fe concentration of 7.1 $\pm$ 2.7% for the clasts. Thus the Fe-Ni correlation for the regolith breccias in Figure 4 is easily explained by variable amounts of type-1 melt rock containing Fe-Ni metal (or any other type of melt rock with a similar bulk Fe/Ni ratio).

Figure 5 is an expanded version of the low-Ni portion of the Co-Ni plot of Figure 2 for the soils. Also plotted are data for the ancient regolith breccias. Unlike Figure 4, the best-fit line through the data for the regolith breccias is the same line (within uncertainty) as that for the soil (the soil line, not the regolith breccia line, is shown on Figure 5; the regression data are listed in Table 1). The ancient regolith breccias have a lower average concentration of elements associated with mafic rocks than does the present mature soil [*McKay et al.*, 1986]. However, for those regolith breccias with Fe contents most similar to that of the soil (>3.5% Fe, i.e., those with a similar amount of melt-rock component), the Ni and Co concentrations are also similar. Figure 5 demonstrates that the component causing the variation in Ni and Co concentrations in the present soil is the same as that for the ancient regolith breccias, namely, Fe-Ni metal with a Ni/Co ratio of 15–17 derived from ancient melt rocks. The Ni/Co ratio in metal from different types of melt rock is variable; the ratios for the regolith samples lie within their range (Table 1).

I suggest the following scenario, which borrows heavily upon models of others, to explain the data. Noritic impact melt was formed about 3.9 Ga ago as a result of nearly total melting of some lunar highlands materials and its substrate following the impact of large planetesimals. Target material assimilated into the melt included rocks that were more mafic (norite, dunite, mare basalt) and rocks richer in incompatible trace elements (KREEP) than the present soil [*Reid et al.*, 1977; *Spudis*, 1984]. At least two, and possibly three or more, compositionally distinct types of noritic impact melt were produced in the Apollo 16 area, presumably from separate, local impacts [e.g., *Ryder*, 1981*b*]. These melts differed from melt of similar bulk composition ("LKFM") produced at other sites in containing a large amount (1–2%) of metal derived from their impactors. The one or more impactors (perhaps fragments of the same body) were rich in Fe-Ni metal and were probably iron meteorites [*Korotev*, 1987]. A substantial megaregolith produced by other impacts also existed at this time and fragments of the metal-

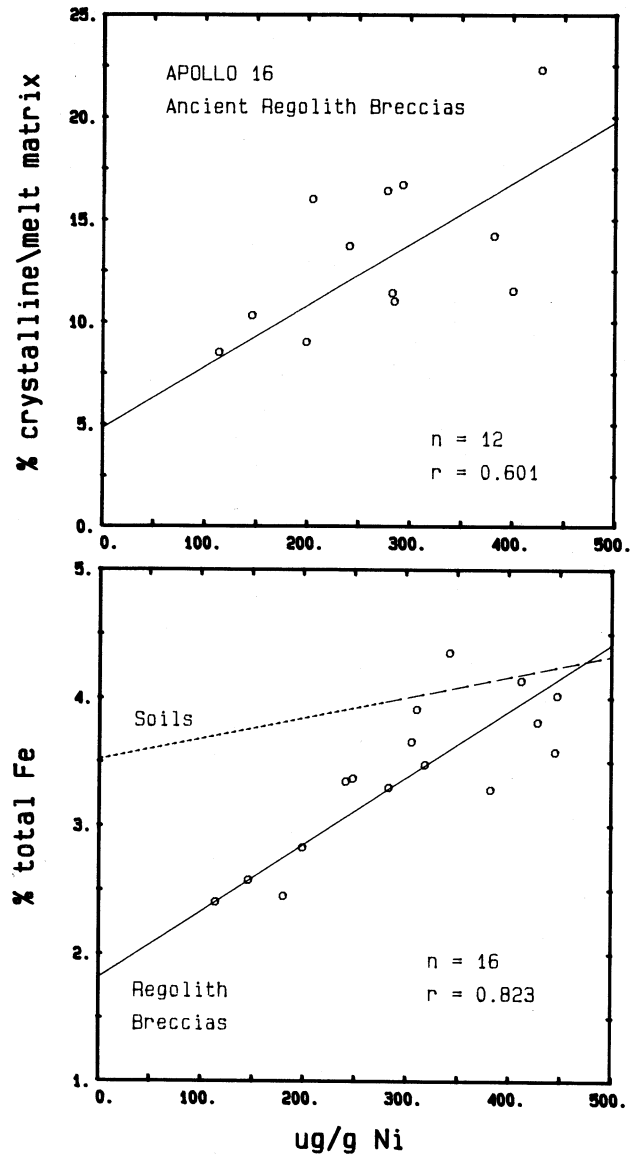

Fig. 4. Percent lithic fragments of impact melt rock ("crystalline/melt matrix," Table 4, *McKay et al.* [1986]) and total Fe concentration against Ni concentration (Table 10, *McKay et al.* [1986]) for ancient regolith breccias from Apollo 16. The solid lines are the best-fit lines to the regolith breccia data. In the lower plot, the other line is the line from Figure 1, i.e., the best-fit line to all the soil data; the broken portion represents the range of the soil data. The two lines have considerably different slopes because the variation for the soil samples results almost entirely from variable amounts of metal (Figure 1) whereas the variation in the regolith breccias results from variable amounts of impact melt rock. Nickel in the melt rocks is contained in metal, whereas most of the Fe is contained in mafic silicates. Unlike the soil samples, which are all of similar bulk composition and mineralogy (Figure 1), the regolith breccias vary much more in the ratio of mafic melt clasts to anorthositic matrix material.

rich, impact melt rock became an important component of this regolith [*McKay et al.*, 1986].

Later, some mechanism lithified part of this megaregolith to form the regolith breccias, some of which were preserved and sampled by the Apollo 16 mission. However, much of the surface regolith continued to mature. The distribution of rock types within the regolith changed, and at least one additional mafic material became an important component of the present-day Apollo 16 soil after closure of the regolith breccias [*McKay et al.*, 1986]. Continuing impacts by a distribution of smaller objects, including micrometeorites, caused comminution as well as aggregation by formation of agglutinates [*McKay et al.*, 1974]. During comminution, some Fe-Ni metal was decoupled from the melt rock that originally contained it and it now behaves as an independent component in the soils. As a result, metal content and siderophile abundances correlate grossly with the quantity of melt rock in large samples of both soil and regolith breccias, but among different small samples of soil with similar proportions of melt rock, Ni concentrations vary from variation in the quantity of free Fe-Ni metal (Figure 1). This scenario is consistent with the conclusions of *Baedecker et al.* [1972], *Anders et al.* [1973], *Wasson et al.* [1975*a,b*], and *Hertogen et al.* [1977], based on other arguments, that a portion of the siderophile elements in the Apollo 16 soil was contributed by meteorites associated with the late accretion of the moon.

Mass balance for Fe-Ni metal. A reviewer of this paper suggested that the siderophile elements did not necessarily have to be associated with the melt rock component of the megaregolith in order to explain the correlations for the regolith breccias in Figure 4. The correlations in Figure 4 (as well as the Sc-Sm correlations in Figures 10 and 12 of *McKay et al.* [1986]) can be explained by mixing of anorthositic materials with a previously well mixed regolith containing siderophile-poor melt rocks, a siderophile-rich meteoritic component, and KREEP. This scenario fails, however, because the component of metal-rich, noritic melt rock in the soil does indeed supply all Fe-Ni metal found there, as shown below.

The average of the mean Ni concentration in the three types of noritic melt rock discussed by *Korotev* [1987] is 860 μg/g (see also Table 1). With this value and the assumption that about 100 μg/g may not be associated with metal [*Korotev*, 1987], a mean concentration of 1.3% Fe-Ni metal containing 6% Ni is estimated for the melt rocks. This compares well with values obtained by direct magnetic measurement of melt rock samples: 0.32% (60315, type 1), 0.36% (60335, type 2), 1.21% and 1.44% (66095, type 2), and 1.36% and 4.45% (60315, type 1) [*Brecher et al.*, 1973; *Nagata et al.*, 1973; *Pearce et al.*, 1973]. Much of the variation in these values results from nonuniform distribution of metallic iron grains in the small sample size used for the measurement (<25 mg; *Brecher et al.* [1973]). Even Ni concentrations in different samples of melt from the same rock are highly variable [*James et al.*, 1984; *Korotev*, 1987]. In a later section, a range of 0.4–0.5% is estimated for the mean quantity of Fe-Ni metal in typical Apollo 16 soil. Assuming 1.3% Fe-Ni metal in the typical melt rock, a 30–40% component of noritic melt rock would supply all the Fe-Ni metal occurring in the average soil. This 30–40% includes all of the melt rock that may have been reworked by further impacts and is now a subcomponent of fragmental breccias, regolith breccias, and agglutinates. If the actual fraction of melt rock in the soil is less than 30–40%, then other sources of Fe-Ni metal must be considered.

Estimates based on other criteria indicate that the melt-rock component of the soil is, in fact, about 30–36%. *Ryder* [1981*b*] notes that melt rocks compose 30% of the population of returned rock samples from Apollo 16, a value that agrees with that of *Simonds et al.* [1976] for the sampled lunar highlands in general. However, *Spudis* [1984] estimates that the quantity of pure impact melt at Apollo 16 is only about 10%, and that 90% of this 10% is noritic (types 1 and 2). The 10% estimate is based on the petrographic occurrence of melt-rock fragments in the regolith and a correction for the fact that impact melt

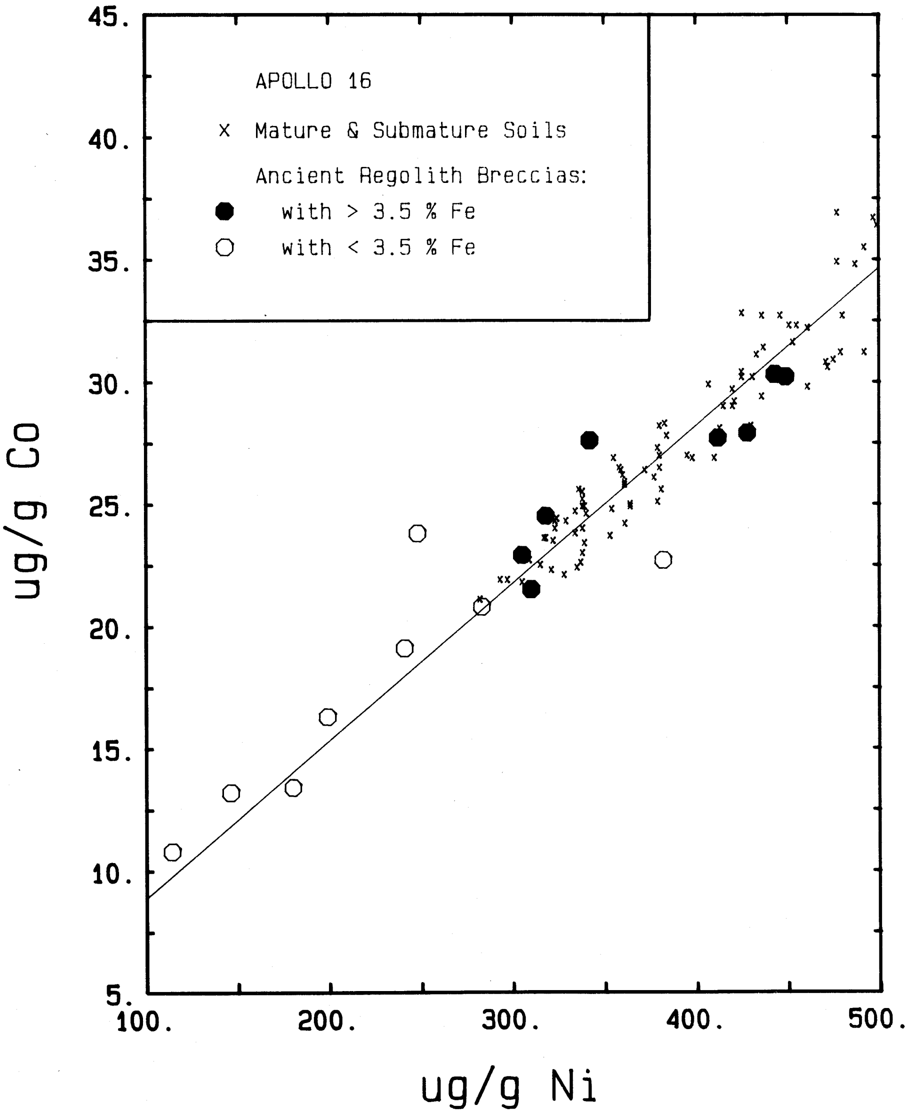

Fig. 5. Cobalt and Ni variation in ancient regolith breccias from Apollo 16 [*McKay et al.*, 1986]. The solid line is the same line as in Figure 2, i.e., the best-fit line to all the soil data. The regolith breccias plot along the same line, indicating that the metal component of the modern soil has the same Ni/Co ratio as that in the ancient regolith breccias (Table 1).

breccias contain up to 50% clastic material. The 30–40% estimate above is that for total melt rock component, not pure melt. Also, the 10% estimate of *Spudis* [1984] must seriously underestimate the overall fraction of impact melt rock contributing to the composition of the regolith because a large fraction of melt rock component must be contained in agglutinate particles, which themselves compose about 30–60% of submature and mature soil [*Heiken et al.*, 1973]. The melt-rock subcomponent of these glassy particles is not distinguishable petrographically. Likewise, the 30% occurrence of discrete melt rocks [*Ryder*, 1981*b*] underestimates the total occurrence because some melt rock is contained within rocks assigned to the other 70%, such as dimict and other polymict breccias.

A more appropriate estimate of the total quantity of noritic melt rock in the Apollo 16 soil can be obtained from a chemical mass balance for the lithophile elements. The noritic melt rocks are compositionally distinct from other soil-forming materials at the Apollo 16 site because they are the principal carriers of the KREEP component and hence are the principal source of incompatible trace elements. They also provide a large fraction of the elements associated with mafic mineral phases (Fe, Mg, Sc). The mixing models of *Kempa et al.* [1980] and *Morris et al.* [1986] estimate, respectively, mean values of 35 ± 8% and 36 ± 10% for the total amount of noritic impact melt in the Apollo 16 soil (excepting soil from the North Ray crater area). The remaining portion of the soil is modeled as a mixture of anorthosite, anorthositic norite, and a small component of mare basalt. Hence the quantity of noritic impact melt required to account for the concentrations of the major and trace lithophile elements in the soil is also that required by the arguments above to account for all of the Fe-Ni metal typically found in the soil. I conclude that no important source of metal other than the noritic impact melt rocks is needed to supply the Fe-Ni metal found in Apollo 16 soil.

Ir and Au. Because much of the Ni in the soil is carried by metal that derives from metal-rich melt rocks and because the siderophile element concentrations in the melt rocks are high compared to those in other rock types, we would expect, as noted by *Hertogen et al.* [1977], that the signature of trace siderophile elements would be similar in the soil and the melt

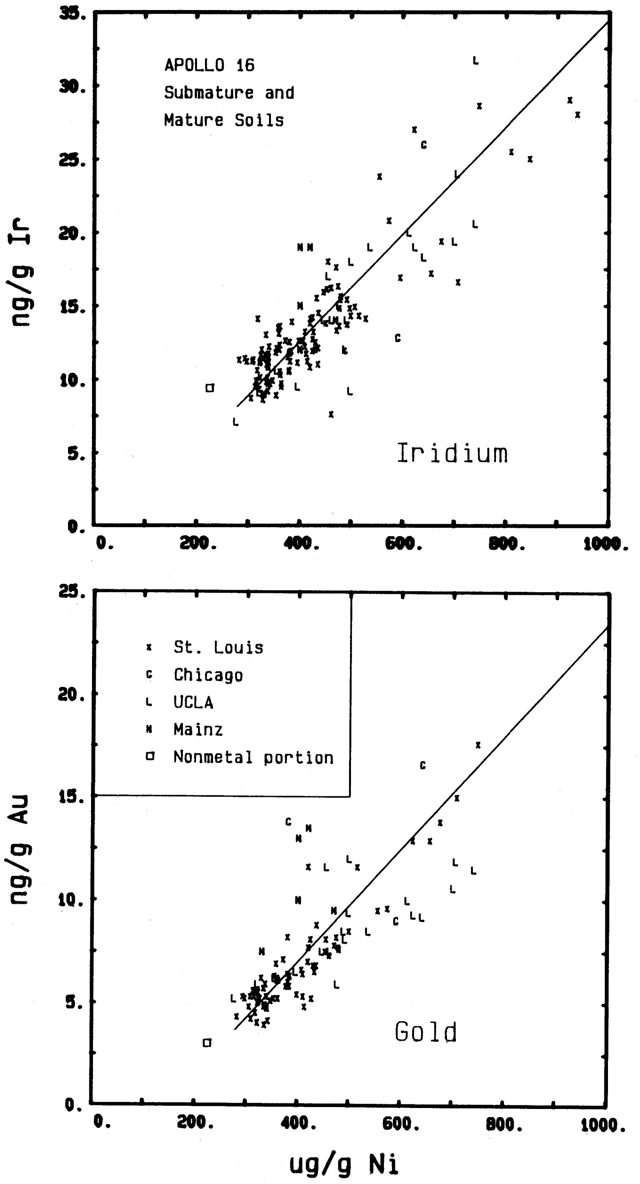

Fig. 6. Variation of Ir and Au with Ni in Apollo 16 soil. The solid lines are the best-fit lines to all the data. The square represents the mean composition of the soil after removing all Fe-Ni metal, as inferred from the results of the mixing model described in the text and Table 4. The high concentrations of Ni, Ir, and Au in the nonmetal portion result from the micrometeorite component. Although the samples contain a substantial component of chondritic micrometeorite, most of the variation in Ni, Ir, and Au (as well as Co and Fe) among the samples results from variable amounts of the ancient Fe-Ni metal component with nonchondritic Ir/Ni and Au/Ni ratios. Data are from sources listed in Figure 7.

rocks. If the Fe-Ni metal is the main source of Ir and Au, then we might expect the correlation of these elements with Ni to be similar for both melt rocks and soils.

Correlations of Ir and Au with Ni for Apollo 16 soil samples are shown in Figure 6. Table 3 lists the results of interpreting the correlations of Ir and Au with Ni for soil, regolith breccias, and two types of noritic impact melts as was described above Fe and Co, i.e., estimates of the mean Ir/Ni and Au/Ni ratios in the metal phase of each type of sample are listed. The ratios obtained for the metal in type-1 melt rocks (Ir/Ni = 19 ± 6 μg/g and Au/Ni = 24 ± 3 μg/g) agree reasonably well with the ratios for a single metal sphere from one of these breccias (65015: Ir/Ni = 17.5 μg/g and Au/Ni = 18.9 μg/g; *Wasson et al.* [1975*a*]).

Iridium/Nickel and Au/Ni ratios in metal from the two types of melt rock are about a factor of two lower and higher, respectively, than the ratios in metal from H-group chondrites (Table 3). These results are in agreement with the observations made by *Wänke et al.* [1978] regarding bulk Ir/Ni and Au/Ni ratios in a variety of Apollo 16 breccias. The low Ir/Ni ratio and high Au/Ni ratio lead to a low Ir/Au ratio for the melt rocks. The Ir/Au ratio is a principal discriminant among the ancient meteorite groups of *Hertogen et al.* [1977]. The low Ir/Au ratio in metal from Apollo 16 melt rocks is characteristic of ancient meteorite group 1H [*Hertogen et al.*, 1977] and most samples with the 1H signature are noritic melt rocks from Apollo 16 [*Morgan and James*, 1981]. Hence it is likely that most of the group 1H signature in Apollo 16 materials is carried by Fe-Ni metal derived from melt rocks [*Korotev*, 1987].

Ratios of Au/Ni are the same, within uncertainty, for the metal in the soil, regolith breccias, and melt rocks (Table 3). On the other hand, Ir/Ni ratios are more variable. Ratios for both types of melt rock are low at about half the chondritic ratio, although the difference between them is significant. As expected from the discussion above, the Ir/Ni ratio for metal in the ancient regolith breccias is very similar to that for the type-1 melt rocks because this type of melt rock is an important carrier of siderophile elements in the ancient regolith breccias (Table 2). At face value, however, the results of Table 3 imply that the mean Ir/Ni ratio for the metal in present soil is greater than that for metal from the melt rocks and is more similar to the chondritic value. Possible reasons for this apparent discrepancy are discussed later.

The Micrometeorite Component

Thus far, only the contribution of Fe-Ni metal derived from ancient impact melt rocks has been discussed. The soil also contains siderophile elements from a component of carbonaceous chondrites, derived mainly from micrometeorites [*Baedecker et al.*, 1972; *Anders et al.*, 1973; *Ganapathy et al.*, 1974; *Wasson et al.*, 1975*b*]. The flux of micrometeorites is believed to have been relatively constant with time and is the principal source of siderophile elements in soil from mare sites. (The "micrometeoritic component," as used here, would also include any contribution from recent crater forming events by chondrites, e.g., as at South Ray crater [*Anders et al.*, 1973; *Morris et al.*, 1986].)

The micrometeorite component appears to be more uniformly distributed among samples of typical Apollo 16 soil than is the ancient Fe-Ni metal. If the micrometeorite component were as highly variable among the samples as the Fe-Ni metal component, we would expect to find some samples plotting away from the main cluster of points in Figure 2 along the chondrite mixing line. There is no strong trend in this direction, although a few samples deviate from the mean in the chondrite direction (dotted line). This is reasonable because the micrometeorites are identified as either CI [e.g., *Ganapathy et al.*, 1974] or CM [*Wasson et al.*, 1975*b*] chondrites and, consequently, contain Ni in nonmetal phases that would be better mixed with the target rocks than would Fe-Ni metal. Also, the number of impacts by micrometeorites represented in a given soil sample must be large compared to the number of grains of Fe-Ni metal derived from melt rocks and this would cause the Ni from the micrometeorites to be more evenly distributed even if some Ni were reduced upon impact.

TABLE 3. Regression Data and Ratios of Ir and Au to Ni in Metal From Apollo 16 Samples Assuming all Ir and Au is Contained in the Metal Phase and the Ni Content of the Metal is 6%

	n	r	Ni intercept		(Au or Ir)/Ni			
			μg/g	±	μg/g	±	H-norm.	±
Iridium								
Mature and submature soils*								
This lab	109	0.936	40	40	35.	4.	0.76	0.09
All data	138	0.926	60	40	37.	4.	0.80	0.09
Ancient regolith breccias	16	0.860	-20	70	21.	5.	0.46	0.12
Impact melt rocks								
Type 1, "A16 KREEP"	22	0.868	60	240	19.	6.	0.41	0.13
Dimict breccia VHA	11	0.987	120	60	26.	3.	0.58	0.07
Gold								
Mature and submature soils								
This lab	72	0.919	150	30	27.	4.	2.1	0.3
All data	100	0.785	150	40	27.	4.	2.1	0.3
Ancient regolith breccias	16	0.608	40	14	25.	9.	1.9	0.7
Impact melt rocks								
Type 1, "A16 KREEP"	21	0.971	120	60	24.	3.	1.9	0.2
Dimict breccia VHA	7	0.972	130	150	24.	5.	1.8	0.4

All values were determined by regression of Ir and Au against Ni using the method of *York* [1969] (see Table 1). The line obtained was extrapolated to 6% Ni and the Ir or Au concentration calculated. The ratio is expressed both as μg/g (i.e., micrograms Ir or Au per gram of Ni) and normalized to the ratio in metal from H-group chondrites (45.4 μg/g for Ir and 13.1 μg/g for Au, based on metal from 12 H-group chondrites [*Rambaldi*, 1977]). The intercept of the regression line with the Ni axis is also given. All uncertainties are two standard deviations based on the regression analysis. Because the Ni intercept is small compared to 60 mg/g Ni, the (Ir,Au)/Ni ratios obtained are very nearly equal to the slope of the regression lines.

**Sources of data*: Soils—*Korotev* [1982], *Korotev et al.* [1984], *McKay et al.* [1986] (see Table 1), *Krähenbühl et al.* [1973], *Wänke et al.* [1973], *Wasson et al.* [1975*a*], and *Boynton et al.* [1976]. Regolith breccias—*McKay et al.* [1986]. Impact melt rocks—*Krähenbühl et al.* [1973], *Ganapathy et al.* [1973], *Laul et al.* [1974], *Wänke et al.* [1975, 1976], *Boynton et al.* [1975], *Wasson et al.* [1977, excluding one sample of 66081 that appears to be contaminated with Au], *James et al.* [1984], *McKinley et al.* [1984], and Table 2.

The effect of the micrometeorite component is most obvious in Figure 7, in which Ir and Au data for typical soil samples are plotted. These data are not as well correlated as we would expect if the soil samples simply contained variable amounts of a single meteorite component. Noritic impact melt rocks have low Ir/Au ratios, 0.2 to 0.3 (normalized to CI chondrites), because this is the ratio for the metal they contain. The ancient regolith breccias have similarly low Ir/Au ratios because their siderophile elements are carried by the melt-rock component. Most Apollo 16 soil samples have higher ratios, although none have ratios as high as the CI ratio. Most of ancient regolith breccias do not appear to have any significant amount of any component with an Ir/Au ratio as high as that found in CI chondrites. One single regolith breccia, 63507, does have a nearly chondritic Ir/Au ratio [*McKay et al.*, 1986]. Sample 63507 is unique among Apollo 16 regolith breccias. It is the most similar to the soil in bulk composition. It has the highest agglutinate content and largest value of I_s/FeO (comparable to submature soil), the lowest $^{40}Ar/^{36}Ar$ ratio, and the highest concentrations of siderophile elements (1020 μg/g Ni). In all regards, 63507 appears to have been formed by impact of a carbonaceous chondrite onto "modern" soil. In Figure 7, points for nearly all soil samples lie between those for ancient regolith breccias (dominated by the ancient meteorite component with the low Ir/Au ratio) and the modern regolith breccia (dominated by a meteorite component with a CI-like Ir/Au ratio). Hence a significant portion of the Ir (and a lesser portion of the Au) in Apollo 16 soil must derive from the micrometeorite component. This is essentially the explanation of *Wlotzka et al.* [1973] for why the Ir/Au ratio of Apollo 16 soil is greater than that of metal particles found in the soil.

Estimates for the proportion of carbonaceous chondrite component in Apollo 16 soil vary between about 1% and 2%. *Ganapathy et al.* [1974] estimated 0.92% from the correlation of volatile elements with ^{21}Ne exposure age. *Wasson et al.* [1975*b*] estimated a 2.2% component of extralunar material acquired since onset of regolith formation. Estimates for the quantity of meteoritic material in mare soil range from 1.0 to 1.5% [*Anders et al.*, 1973; *Wasson et al.*, 1975*b*] and should provide a lower limit to the quantity of micrometeorite component in Apollo 16 soil. If the difference between the mean Ni concentration in the present soil and that of the ancient regolith breccias (460−300 = 160 μg/g, Table 1) is attributed to a CI component (water-free), then 1.2% is required.

The intermediate Ir/Au ratio of the soil compared to that of the ancient metal and the micrometeorites allows another estimation of the fraction of each component in the typical soil. Table 4 gives details of the model. The concentrations of Fe, Co, Ni, Ir, and Au for the typical soil are modeled as a mixture of three components: indigenous material with negligibly small Ir and Au concentrations, a micrometeorite component with CI composition, and an ancient meteorite component represented by metal typical of that found in the melt rocks (Table 3). Mass balance for Ir and Au requires 0.4% Fe-Ni metal component and 1.7% micrometeorite component to account for the mean Ir and Au concentrations found in the soil. The latter value agrees reasonably well with the previous estimates discussed above. It may be an upper limit, however, for reasons to be discussed below.

Although the quantity of micrometeorite component in Apollo 16 soil predicted by the model exceeds that of the metal component by a factor of 4, the metal component is richer

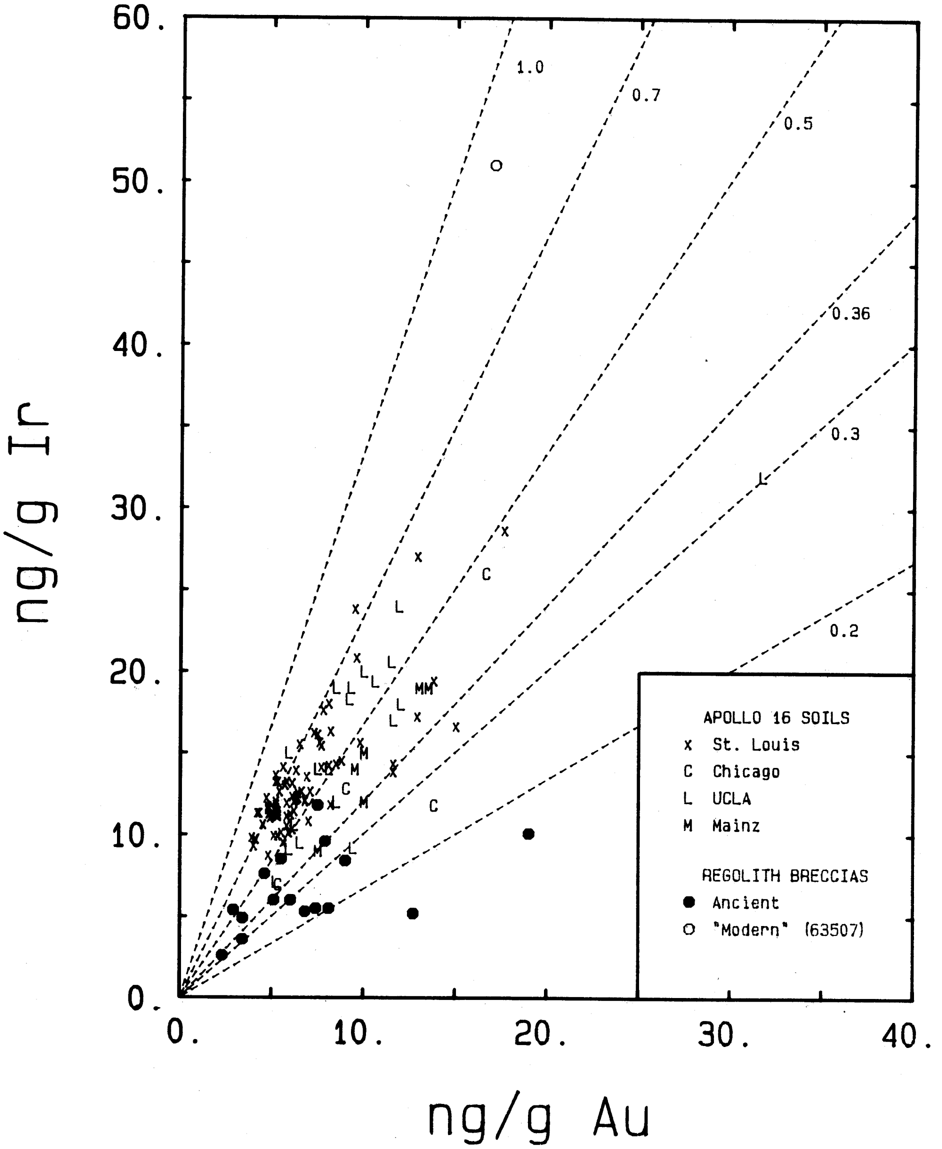

Fig. 7. Iridium and Au in Apollo 16 regolith breccias and typical soil. The dashed lines represent ratios to the Ir/Au ratio in CI chondrites (3.3). All soil samples have lower Ir/Au ratios than the chondritic value. Iridium/gold ratios in some ancient regolith breccias are particularly low, whereas the Ir/Au ratio in the "modern" regolith breccia 63507 is nearly chondritic. The line labeled "0.36" represents the chondrite-normalized Ir/Au ratio in metal from "VHA" impact melt found in Apollo 16 dimct breccias, and the line labeled "0.3" is approximately that for metal from "type 1" or "Apollo 16 KREEP"-type impact melt rocks [*Korotev*, 1987; *Wasson et al.*, 1975*a*]. These ratios are characteristic of ancient meteorite group 1H [*Hertogen et al.*, 1977]. Data are from: x—*Korotev et al.* [1984] and *McKay et al.* [1986]; C—*Krähenbühl et al.* [1973]; L—*Wasson et al.* [1975*a*] and *Boynton et al.* [1976]; M—*Wänke et al.* [1973]; regolith breccias—*McKay et al.* [1986].

in siderophile elements. Table 5 lists the fractional distribution of each of the five elements modeled in Table 4 among the three components. Results of the modeling indicate that the quantities of Co, Ni, Ir, and Au contributed to a typical soil by the two meteoritic components are roughly comparable, although the micrometeorite component contributes a larger fraction of the Ir and the metal component contributes a larger fraction of the Au.

Also listed in Table 4 are the concentrations of siderophile elements in the nonmetal portion of the soil, i.e., in the indigenous plus micrometeorite components, as estimated from the model. This composition is plotted on Figures 1, 2, and 6. Earlier, it was argued that the best-fit lines in these plots represented mixing lines between the metal and nonmetal fractions of the soil. Hence if the model presented above is reasonable, then the concentrations in the nonmetal fraction inferred from the model should plot on the mixing lines somewhere between 0 μg/g Ni and 280 μg/g Ni. The Ni concentration estimated by the model for the nonmetal portion is 225 μg/g. In all cases the composition estimated for the nonmetal portion of the soil plots reasonably close to the mixing lines.

The poorest agreement is for Ir. This is a numerical consequence of the observation made earlier that the Ir/Ni ratio estimated for the typical soil metal from the correlation of Ir and Ni in Figure 6 is greater by about 40% and 90% than that estimated for the metal from the two types of melt rocks (Table 3). I speculate that this may result because Ir/Ni (and Ir/Au) ratios in Fe-Ni metal from various types of melt rocks are not all the same and that those from the metal from the two types listed in Table 3 are lower than the average. Other

TABLE 4. Input Compositions, Results, and Assumptions of Model Accounting for Siderophile Elements in Apollo 16 Mature and Submature Soils in Terms of Mixtures of an Indigenous Component, a Micrometeorite Component (CI Chondrite), and Fe-Ni Metal Such as Found in Noritic Impact Melt Rocks

	Model Input			Model Results	
	Mean Soil*	Micrometeorite†	Fe-Ni Metal‡	Indigenous§	Nonmetal**
Fe %	4.26	22.2	93.6	3.59	3.90
Co μg/g	32.0	620.	3860.	6.6	16.9
Ni μg/g	460.	13000.	60000.	~0.	225.
Ir ng/g	14.7	560.	1350.	0.00	9.4
Au ng/g	8.6	176.	1440.	0.00	3.0
Ir/Au	1.71	3.19	0.94	-	3.19
Ni/Co	14.4	21.	15.5	-	13.3
Amount of component (%)	100.	1.68	0.39	97.9	(99.6)

Model assumptions and input parameters: The Ir and Au concentrations in the mean soil derive entirely from the micrometeorite and Fe-Ni metal component. Simultaneous solution of the mass balance equations for Ir and Au yields percentages of micrometeorite and metal component; the remainder is indigenous.

*Soil composition: Mean Ni concentration of Table 1 used. All other concentrations were calculated from regression lines of Figures 1 and 2 and Table 3 at mean Ni concentration.

†Micrometeorite composition: Values are those of *Wasson* [1985, Table D-1] for CI chondrites, corrected for 18% water.

‡Metal compositions: 6% Ni, Ni/Co = 15.5, Fe + Ni + Co = 100% (i.e., typical soil metal as discussed in text). Iridium and Au concentrations were calculated from mean Ir/Ni and Au/Ni ratios for metal from the two impact melt rocks from Table 3.

§Indigenous composition: Soil composition minus micrometeorite and metal components.

**Nonmetal composition: Soil composition minus metal component.

types of noritic melt rock occur (e.g., more aluminous varieties of the type-2 melt [*Ryder*, 1981*a*]). The two types listed in Table 3 are the only two for which a sufficient number of samples believed to be of the same melt sheet exist that an Ir/Ni ratio for the metal could be estimated [*Korotev*, 1987]. Also, if the Ir/Ni ratios are more variable in the various meteoritic components of the soil than are the ratios of Fe, Co, and Au to Ni, then the Ir/Ni ratio inferred for the soil (35–37 μg/g) may not be meaningful in the sense intended because the apparent correlation is not the result of simple two-component mixing.

If the abundance of Ir in the average soil metal is actually greater than that used in Table 4, then the amount of the micrometeorite component has to be less than 1.7%. For example, if the Ir/Ni ratio of typical Fe-Ni metal is as high as the 35 μg/g estimated from the soil data (Table 3), then the micrometeorite component is 0.7% and the Fe-Ni metal component is 0.5%. I regard this estimate and that of the model of Table 4 as reasonable limiting cases, i.e., mass balances for Ir and Au constrain the quantity of micrometeorite to 0.7–1.7% and the quantity of Fe-Ni metal to 0.4–0.5% for typical soil from Apollo 16.

Data and Model of Morris [1980]

For the 12 samples of mature and submature soil studied by *Morris* [1980], he obtains a mean value of 0.60 ± 0.16% total Fe-metal (>2–4 nm grain size) based on magnetic measurements. However, a portion of this, 0.14 ± 0.08%, is fine-grained, pure Fe metal produced by reduction of ferrous iron during surface exposure. With respect to the mixing relationship represented by Figure 1 and the model of Table 4, this metal is a subcomponent of the "nonmetal" component because the concentrations of pure Fe metal and Ni will not correlate. After subtraction of the portion resulting from reduction (Fe°_{a} of *Morris* [1980]), 0.46 ± 0.12% coarse-grained (>33 nm diameter) metallic iron remains. This value agrees well with the 0.4–0.5% Fe-Ni metal estimated in the discussion above. Thus if the coarse-grained metal observed by *Morris* [1980] does not contain any significant additional component of pure Fe metal (i.e., fine-grained metal that has coalesced to form particles >33 nm in diameter), then virtually all of it should be the same metal as the Fe-Ni metal already discussed, i.e., iron metal containing 6% Ni derived from melt rocks.

However, *Morris* [1980] argues that only about half of the coarse-grained metal he observes could come from sources like melt rocks. Based on many soil samples from six landing sites, he observes that the percent of coarse-grained Fe metal increases with the surface-exposure parameter I_s/FeO from about 0.17% at I_s/FeO = 0 to 0.49% at I_s/FeO = 100 (Figure 6 and equation (5) [*Morris*, 1980]). He argues that in addition to a "source" component that is constant with surface exposure (Fe°_{sm}, e.g., Fe-Ni metal from melt rocks), the coarse-grained metal also consists of a "micrometeorite" component (Fe°_{mm}) that correlates with soil maturity (I_s/FeO). He provides data and equations that allow calculation of the contribution of these two components. Using equation (6) and the data in Table 1 of *Morris* [1980], a mean value of 0.24 ± 0.14% Fe metal for the micrometeorite component in the 12 samples can be calculated. This leaves 0.22 ± 0.16% Fe for the source component. (The latter value can also be obtained less directly from equation (7b) of *Morris* [1980]; it is within error of the intercept of the correlation line at I_s/FeO = O, namely, 0.17% Fe.)

Taken literally, the model implies that half of the coarse-grained (and, presumably, Ni-bearing) metal in Apollo 16 soil either derives from micrometeorites or is in some way dependent upon the production of fine-grained, reduced iron. If 0.24%

TABLE 5. Fractional Distribution of Siderophile Elements Among Various Components in Typical Mature and Submature Soil From Apollo 16, as Estimated From Mixing Model Results of Table 4

	Indigenous	Micrometeorite	Fe-Ni metal
Fe	82	9	9
Co	20	33	47
Ni	~0	47	51
Ir	0	64	36
Au	0	34	66

Values in percent.

Fe is contributed by micrometeorites, then a 1% component of chondritic meteorite (any type) is required. As reviewed above, the total micrometeorite component of the soil is 1–2% (CI equivalent); hence by the model of *Morris* [1980], 50–100% of the total amount of iron contributed by micrometeorites would now have to be in metallic form. This could only be the case if most of the iron from the micrometeorites was reduced to metal upon or following impact, but this seems unlikely. The observation might also be explained if the micrometeorites were predominantly ordinary chondrites, but much evidence indicates that most of them are carbonaceous [e.g., *Anders et al.*, 1973; *Baedecker et al.*, 1973; *Brownlee et al.*, 1973; *Ganapathy et al.*, 1974; *Wasson et al.*, 1975*b*].

The discrepancy occurs because for Apollo 16 soils (at least) the correlation in Figure 6 of *Morris* [1980] does not result from the mechanism he suggests. *Morris* [1980] observes that "Since the concentration of metallic iron in source materials...can only be an accidental function of I_s/FeO, the slope of Fig. 5 reflects the rate of acquisition of micrometeoritic metal during maturation." For Apollo 16 soil, however, the correlation is not accidental and does not result from maturation. For the 12 samples of submature and mature Apollo 16 soil used by *Morris* [1980] there is no correlation of coarse-grained Fe with I_s/FeO (r = 0.27, intercept = 0.40 ± 0.13% Fe), suggesting that little or none of the coarse-grained metal is associated with micrometeorites. A positive correlation (with an intercept of zero, within uncertainty) is obtained, however, when immature Apollo 16 soils are included. The four immature soils from Apollo 16 used by *Morris* [1980] (three from the North Ray crater area) are all more anorthositic than the typical soils and are effectively mixtures of typical soil (high I_s/FeO, 30–40% noritic melt rock, 0.4–0.5% Fe-Ni metal) with fresh, anorthositic, crater ejecta (low I_s/FeO, little noritic melt rock, little Fe-Ni metal) [*Korotev*, 1981]. Hence for Apollo 16 soils (and perhaps for the other sites as well) the correlation of coarse-grained metal with I_s/FeO results simply from dilution. I conclude that most of the coarse-grained metal observed by *Morris* [1980] in Apollo 16 soil derives from impact melt rocks.

SUMMARY AND CONCLUSIONS

Two meteoritic components can account for the high concentrations of Ni, Co, Ir, and Au in Apollo 16 soil. One (the "micrometeorite component") is dominated by carbonaceous chondrites, whose source is primarily the micrometeorites accumulated since the end of the late accretion of the moon about 3.9 Ga ago [*Anders et al.*, 1973; *Hertogen et al.*, 1977]. The concentration of this component is relatively constant among samples of typical (submature and mature) soil from Apollo 16. The other (ancient component) is the "short-lived" component of *Wasson et al.* [1957*b*] or the "ancient meteorite component" of *Anders et al.* [1973] and *Hertogen et al.* [1977], which derives from late-accreting planetesimals. Siderophile elements in the ancient component are located in grains of Fe-Ni metal that in turn are (or at one time were) contained in noritic impact melt breccias ("VHA," "LKFM") produced about 3.9 Ga ago. The ancient metal is different from the metal found in ordinary chondrites in having a lower Ni concentration (typically 6%), lower Ni/Co ratio (15–19), lower Ir/Ni and Ir/Au ratios, and a higher Au/Ni ratio. Variation in the concentration of this ancient Fe-Ni metal among different samples of Apollo 16 soil is the primary reason for the variations in concentrations, and correlations among the concentrations, of siderophile elements. Apollo 16 melt rocks and soil have higher concentrations of meteoritic metal overall than samples from other sites. The average component of noritic melt rock in the soil is sufficient to supply essentially all the Fe-Ni metal found in the soil. *Korotev* [1987] argues that the Fe-Ni metal derives from the impactors producing the impact melts and that these were one or a few metal-rich, probably iron, meteorites. Ancient regolith breccias from Apollo 16, which are samples of lithified regolith from the time of the late accretion [*McKay et al.*, 1986], also contain this or a very similar ancient metal component, but have at most a very small amount of any chondritic component. A typical soil from Apollo 16 contains 0.7–1.7% of the micrometeorite component and about 0.4–0.5% of the Fe-Ni metal component. Removal of these two components from the soil leaves about 7 μg/g Co and a low concentration of Ni (certainly <100 μg/g, probably much less) as indigenous to the lunar igneous rocks that are precursors to the soil.

In this paper I have built upon and extended the previous works of the Chicago group of E. Anders and the UCLA group of J. T. Wasson, but have approached the subject of siderophile elements in the lunar highlands more from the viewpoint of lunar materials and processes than from that of the meteorites. I have attempted to clarify some points that, although evident from careful reading of the works of these two groups of investigators, are not common knowledge among those whose principal interest is using the lunar samples to understand the evolution of the lunar crust.

Acknowledgments. This work was supported by the National Aeronautics and Space Administration through grant NSG 9-56 to L. A. Haskin. The author thanks M. M. Lindstrom for the data in Table 2. Reviews by L. A. Haskin, D. J. Lindstrom, J. W. Morgan, R. V. Morris, and J. T. Wasson greatly improved the paper; however, some of these reviewers disagree with some of the conclusions.

REFERENCES

Anders, E., R. Ganapathy, U. Krähenbühl, and J. W. Morgan, Meteoritic material on the Moon, *The Moon, 8*, 3–24, 1973.

Baedecker, P. A., and J. T. Wasson, Elemental fractionations among enstatite chondrites, *Geochim. Cosmochim. Acta, 39*, 735–765, 1975.

Baedecker, P. A., C.-L. Chou, L. L. Sundberg, and J. T. Wasson, Extralunar materials in Apollo 16 soils and the decay rate of the extralunar flux 4.0 GA ago, *Earth Planet. Sci. Lett., 17*, 79–83, 1972.

Baedecker, P. A., C.-L. Chou, E. B. Grudewicz, and J. T. Wasson, Volatile and siderophile trace elements in Apollo 15 samples: Geochemical implications and characterization of the long-lived and short-lived extralunar materials, *Proc. Lunar Sci. Conf. 4th*, 1177–1195, 1973.

Baedecker, P. A., C.-L. Chou, L. L. Sundberg, and J. T. Wasson, Volatile and siderophile trace elements in the soils and rocks of Taurus-Littrow, *Proc. Lunar Sci. Conf. 5th*, 1625–1644, 1974.

Boynton, W. V., P. A. Baedecker, C.-L. Chou, K. L. Robinson, and J. T. Wasson, Mixing and transport of lunar surface materials: Evidence obtained by the determination of lithophile, siderophile, and volatile elements, *Proc. Lunar Sci. Conf. 6th*, 2241–2259, 1975.

Boynton, W. V., C.-L. Chou, K. L. Robinson, P. H. Warren, and J. T. Wasson, Lithophiles, siderophiles, and volatiles in Apollo 16 rocks and soils, *Proc. Lunar Sci. Conf. 7th*, 727–742, 1976.

Brecher, A., D. J. Vaughn, R. G. Burns, and K. R. Morash, Magnetic and Mossbauer studies of Apollo 16 rock chips 60315,51 and 62295,27, *Proc. Lunar Sci. Conf. 4th*, 2991–3001, 1973.

Brownlee, D. E., F. Hörz, J. F. Vedder, D. E. Gault, and J. B. Hartung, Some physical parameters of micrometeoroids, *Proc. Lunar Sci. Conf. 4th*, 3197–3212, 1973.

Chou, C.-L., and G. W. Pierce, Relationship between nickel and metallic iron contents of Apollo 16 and 17 soils, *Proc. Lunar Sci. Conf. 7th*, 779–789, 1976.

Delano, J. W., and A. E. Ringwood, Siderophile elements in the lunar highlands: Nature of the indigenous component and implications for the origin of the moon, *Proc. Lunar Planet. Sci. Conf. 9th*, 111-159, 1978*a*.

Delano, J. W., and A. E. Ringwood, Indigenous abundances of siderophile elements in the lunar highlands: Implications for the origin of the moon, *Moon and Planets, 18*, 385-425, 1978*b*.

Floran, R. J., W. C. Phinney, D. P. Blanchard, J. L. Warner, C. H. Simonds, R. W. Brown, J. C. Brannon, and R. L. Korotev, A comparison between the geochemistry and petrology of Apollo 16—terrestrial impact melt analogs (abstract), in *Lunar Science VII*, pp. 263-265, The Lunar Science Institute, Houston, 1976.

Ganapathy, R., J. W. Morgan, U. Krähenbühl, and E. Anders, Ancient meteorite components in the lunar highlands rocks: Clues from trace elements in Apollo 15 and 16 samples, *Proc. Lunar Sci. Conf. 4th*, 1239-1261, 1973.

Ganapathy, R., J. W. Morgan, H. Higuchi, E. Anders, and A. T. Anderson, Meteoritic and volatile elements in Apollo 16 rocks and in separated phases from 14306, *Proc. Lunar Sci. Conf. 5th*, 1659-1683, 1974.

Goldstein, J. I., and H. J. Axon, Composition, structure, and thermal history of metallic particles from 3 Apollo 16 soils, 65701, 68501, and 63501, *Proc. Lunar Sci. Conf. 4th*, 751-775, 1973.

Goldstein, J. I., and H. Yakowitz, Metallic inclusions and metal particles in Apollo 12 lunar soil, *Proc. Lunar Sci. Conf. 2nd*, 177-191, 1971.

Gooley, R. C., R. Brett, and J. L. Warner, Crystallization history of metal particles in Apollo 16 rake samples, *Proc. Lunar Sci. Conf. 4th*, 799-810, 1973.

Greenland, L., and J. F. Lovering, Minor and trace element abundances in chondritic meteorites, *Geochim. Cosmochim. Acta, 29*, 821-858, 1965.

Hertogen, J., M.-J. Janssens, H. Takahashi, H. Palme, and E. Anders, Lunar basins and craters: Evidence for systematic compositional changes in bombarding population, *Proc. Lunar Sci. Conf. 8th*, 17-45, 1977.

Heiken, G. H., D. S. McKay, and R. M. Fruland, Apollo 16 soils: Grain size analyses and petrography, *Proc. Lunar Sci. Conf. 4th*, 251-265, 1973.

Hewins, R. H., and J. I. Goldstein, The provenance of metal in anorthositic rocks, *Proc. Lunar Sci. Conf. 6th*, 343-362, 1975.

Hewins, R. H., J. I. Goldstein, and H. J. Axon, The relation of metal composition to rock type for clasts in Apollo 16 soils, *Proc. Lunar Sci. Conf. 7th*, 819-836, 1976.

Hubbard, N. J., J. M. Rhodes, and P. W. Gast, Chemistry of Very High Al_2O_3 lunar basalts, *Science, 181*, 339-342, 1973.

James, O. B., M. K. Flohr, and M. M. Lindstrom, Petrology and geochemistry of lunar dimict breccia 61015, *Proc. Lunar Planet. Sci. Conf. 15th*, in *J. Geophys. Res., 89*, C63-C86, 1984.

Kempa, M. J., J. J. Papike, and C. White, The Apollo 16 regolith: A petrographically constrained mixing model, *Proc. Lunar Planet. Sci. Conf. 11th*, 1341-1355, 1980.

Kerridge, J. F., I. R. Kaplan, C. Petrowski, and S. Chang, Light element geochemistry of the Apollo 16 site, *Geochim. Cosmochim. Acta, 39*, 137-162, 1975.

Korotev, R. L., Compositional trends in Apollo 16 soils, *Proc. Lunar Planet. Sci. 12B*, 577-605, 1981.

Korotev, R. L., Comparative geochemistry of Apollo 16 surface soils and samples from cores 64002 and 60002 through 60007, *Proc. Lunar Planet. Sci. Conf. 13th*, in *J. Geophys. Res., 87*, A269-A278, 1982.

Korotev, R. L., The meteoritic component of Apollo 16 noritic impact melt breccias, *Proc. Lunar Planet Sci. Conf. 17th*, this volume, 1987.

Korotev, R. L., R. V. Morris, and H. V. Lauer, Jr., Stratigraphy and geochemistry of the Stone Mountain core (64001/2), *Proc. Lunar Planet. Sci. Conf. 15th*, in *J. Geophys. Res., 89*, C143-C160, 1984.

Krähenbühl, U., R. Ganapathy, J. W. Morgan, and E. Anders, Volatile elements in Apollo 16 samples: Implications for highland volcanism and the accretion history of the moon, *Proc. Lunar Sci. Conf. 4th*, 1325-1348, 1973.

Laul, J. C., D. W. Hill, and R. A. Schmitt, Chemical studies of Apollo 16 and 17 samples, *Proc. Lunar Sci. Conf. 5th*, 1047-1066, 1974.

LSPET, Preliminary examination of lunar samples, Chap. 7 in *Apollo 16 Preliminary Science Report*, NASA SP-315, Washington, 1972.

McKay, D. S., R. M. Fruland, and G. H. Heiken, Grain size and the evolution of lunar soils, *Proc. Lunar Sci. Conf. 5th*, 887-906, 1974.

McKay, D. S., D. D. Bogard, R. V. Morris, R. L. Korotev, P. Johnson, and S. J. Wentworth, Apollo 16 regolith breccias: Characterization and evidence for early formation in the megaregolith, *Proc. Lunar Planet. Sci. Conf. 16th*, in *J. Geophys. Res., 91*, D277-D303, 1986.

McKinley, J. P., G. J. Taylor, K. Keil, M.-S. Ma, and R. A. Schmitt, Apollo 16: Impact melt sheets, contrasting nature of the Cayley Plains and Descartes Mountains, and geologic history, *Proc. Lunar Planet. Sci. Conf. 14th*, in *J. Geophys. Res., 89*, B513-B524, 1984.

Misra, K. C., and L. A. Taylor, Characteristics of metal particles in Apollo 16 rocks, *Proc. Lunar Sci. Conf. 6th*, 615-639, 1975.

Moore, C. B., "Co(27)" and "Ni(28)", in *Handbook of Elemental Abundances in Meteorites*, edited by B. Mason, pp. 215-228, Gordon and Breach, New York, 1971.

Morgan, J. W., and O. B. James, Apollo 16 breccias and melt rocks: Correlation between siderophile-element patterns, lithology, and location (abstract), in *Workshop on Apollo 16*, edited by O. B. James and F. Hörz, pp. 82-86, LPI Tech. Rpt. 81-01, Lunar and Planetary Institute, Houston, 1981.

Morris, R. V., The surface exposure (maturity) on lunar soils: Some concepts and I_s/FeO compilation, *Proc. Lunar Planet. Sci. Conf. 9th*, 2287-2297, 1978.

Morris, R. V., Origins and size distribution of metallic iron particles in the lunar regolith, *Proc. Lunar Planet. Sci. Conf. 11th*, 1697-1712, 1980.

Morris, R. V., T. H. See, and F. Hörz, Composition of the Cayley formation at Apollo 16 as inferred from impact melt splashes, *Proc. Lunar Planet. Sci. Conf. 17th*, in *J. Geophys. Res., 91*, E21-E42, 1986.

Nagata, T., R. M. Fisher, F. C. Schwerer, M. D. Fuller, and J. R. Dunn, Magnetic properties and natural remnant magnetization of Apollo 15 and 16 lunar materials, *Proc. Lunar Sci. Conf. 4th*, 3019-3043, 1973.

Nichiporuk, W., A. Chodos, E. Helin, and H. Brown, Determination of iron, nickel, cobalt, calcium, chromium and manganese in stony meteorites by X-ray fluorescence, *Geochim. Cosmochim. Acta, 31*, 1911-1930, 1967.

Palme, H., The meteoritic contamination of terrestrial and lunar impact melts and the problem of indigenous siderophiles in the lunar highlands, *Proc. Lunar Planet. Sci. Conf. 11th*, 481-506, 1980.

Pearce, G. W., W. A. Gose, and D. W. Strangway, Magnetic studies on Apollo 15 and 16 lunar samples, *Proc. Lunar Sci. Conf. 4th*, 3045-3076, 1973.

Rambaldi, E., Trace element content of metals from L-group chondrites, *Earth Planet. Sci. Lett., 31*, 224-238, 1976.

Rambaldi, E. R., Trace element content of metals from H- and LL-group chondrites, *Earth Planet. Sci. Lett., 36*, 347-358, 1977.

Reed, S. J. B., and S. R. Taylor, Meteoritic metal in Apollo 16 soils, *Meteoritics, 9*, 23-34, 1974.

Reid, A. M., A. R. Duncan, and S. H. Richardson, In search of LKFM, *Proc. Lunar Sci. Conf. 8th*, 2321-2338, 1977.

Ryder, G., Apollo 16 basaltic impact melts: Chemistry and relationships, in *Workshop on Apollo 16*, edited by O. B. James and F. Hörz, pp. 108-111, LPI Tech. Rpt. 81-01, Lunar and Planetary Institute, Houston, 1981*a*.

Ryder, G., Distribution of rock types at the Apollo 16 site, in *Workshop on Apollo 16*, edited by O. B. James and F. Hörz, pp. 112-117, LPI Tech. Rpt. 81-01, Lunar and Planetary Institute, Houston, 1981*b*.

Ryder, G., M. D. Norman, and R. A. Score, The distinction of pristine from meteorite-contaminated highlands rocks using metal compositions, *Proc. Lunar Planet. Sci. Conf. 11th*, 471-479, 1980.

Simonds, C. H., J. L. Warner, and W. C. Phinney, Thermal regimes in cratered terrain with emphasis on the role of impact melt, *Am. Mineral., 61*, 569-577, 1976.

Spudis, P. D., Apollo 16 site geology and impact melts: Implications for the geologic history of the lunar highlands, *Proc. Lunar Planet. Sci. Conf. 15th*, in *J. Geophys. Res., 89*, C95-C107, 1984.

Taylor, L. A., K. C. Misra, and B. M. Walker, Subsolidus reequilibration, grain growth, and compositional changes of native FeNi metal in lunar rocks, *Proc. Lunar Sci. Conf. 7th*, 837-856, 1976.

Vaniman, D. T., and J. J. Papike, Lunar highland melt rocks: Chemistry, petrology and silicate mineralogy, in *Proc. Conf. Lunar Highlands Crust*, edited by J. J. Papike and R. B. Merrill, pp. 271-337, Pergamon, New York, 1980.

Wänke, H., H. Baddenhausen, G. Dreibus, E. Jagoutz, H. Kruse, H. Palme, B. Spettel, and F. Teschke, Multielement analysis of Apollo 15, 16, and 17 samples and the bulk composition of the moon, *Proc. Lunar Sci. Conf. 4th*, 1461-1482, 1973.

Wänke, H., H. Palme, H. Baddenhausen, G. Dreibus, E. Jagoutz, H. Kruse, B. Spettel, F. Teschke, and R. Thacker, New data on the chemistry of lunar samples: Primary matter in the lunar highlands and the bulk composition of the moon, *Proc. Lunar Sci. Conf. 6th*, 1313-1340, 1975.

Wänke, H., H. Palme, H. Kruse, H. Baddenhausen, M. Cendales, G. Dreibus, H. Hofmeister, E. Jagoutz, C. Palme, B. Spettel, anad R. Thacker, Chemistry of the lunar highland rocks: A refined evaluation of the composition of the primary matter, *Proc. Lunar Sci. Conf. 7th*, 3479-3499, 1976.

Wänke, H., G. Dreibus, and H. Palme, Primary matter in the lunar highlands: The case of siderophile elements, *Proc. Lunar Planet. Sci. Conf. 9th*, 83-110, 1978.

Wänke, H., G. Dreibus, and H. Palme, Non-meteoritic siderophile elements in lunar highland rocks: Evidence from pristine rocks, *Proc. Lunar Planet. Sci. Conf. 10th*, 611-626, 1979.

Warren, P. H., and J. T. Wasson, The origin of KREEP, *Rev. Geophys. Space Phys., 17*, 73-88, 1979.

Wasson, J. T., *Meteorites: Their Record of Early Solar System History*, W. H. Freeman and Co., New York, 267 pp., 1985.

Wasson, J. T., C.-L. Chou, K. L. Robinson, and P. A. Baedecker, Siderophiles and volatiles in Apollo 16 rocks and soils, *Geochim. Cosmochim. Acta, 39*, 1475-1485, 1975*a*.

Wasson, J. T., W. V. Boynton, C.-L. Chou, and P. A. Baedecker, Compositional evidence regarding the influx of interplanetary materials onto the lunar surface, *The Moon, 13*, 121-141, 1975*b*.

Wasson, J. T., P. H. Warren, G. W. Kallemeyn, C. E. McEwing, and D. W. Mittlefehldt, SCCRV, a major component of highlands crust, *Proc. Lunar Sci. conf. 8th*, 2237-2252, 1977.

Wlotzka, F., B. Spettel, and H. Wänke, On the composition of metal from Apollo 16 fines and the meteoritic component, *Proc. Lunar Sci. Conf. 4th*, 1483-1491, 1973.

York, D., Least squares fitting of a straight line with correlated errors, *Earth Planet. Sci. Lett., 5*, 320-324, 1969.

R. L. Korotev, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130.

(Received June 12, 1986;
revised October 7, 1986;
accepted December 15, 1986.)