F. REGOLITH OF THE APOLLO 16 SITE

By VAL L. FREEMAN

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INTRODUCTION

The lunar regolith is generally defined as the relatively unconsolidated fragmental material that forms the surface layer of the Moon. The term is used for all loose surficial debris and for subunits that can be recognized, such as regolith above, beneath, and mixed with the ejecta of North Ray crater. It is commonly assumed that regolith is solely the product of repeated meteorite bombardment, that is, the accumulation and mixing of impact crater ejecta on the lunar surface. Accordingly, the median thickness of regolith above some stratum is related to the time elapsed since formation of that stratum (Shoemaker, 1971). In this report, the term regolith is used in the several senses defined. "Soil" is used as a synonym for the regolith.

This report describes the regolith at the Apollo 16 site, provides new measurements of its thickness, and examines the composition of the soils in comparison with the rocks within the site.

APPEARANCE OF THE REGOLITH

Premission investigations of the Apollo 16 site suggested that differences in regolith would be found. Rays of high albedo extending across the surface from South Ray, North Ray, and Baby Ray craters were seen in orbital photographs (pl. 2). The Cayley plains (LM landing area) and the Descartes mountains (Stone mountain) were considered to be underlain by different bedrock types that would be reflected by differences in composition of regolith. The astronauts on the surface were able to recognize the rays by changes in abundance of rock fragments and secondary craters but otherwise found the surface appearance of the regolith the same throughout the area traversed. No difference between regolith on the Cayley plains and on Stone mountain was observed. An unexpected finding was the presence of a white layer just below the surface at most of the stations (Muehlberger and others, 1972).

The regolith appeared to the astronauts as a gray, rocky soil unit with a heavily cratered surface that seemed to lack truly flat areas. The LM touched down in one of, the smoothest areas available local relief, amounted to only a few meters except for a fresh 30-m crater immediately east of the LM. The crew observed that this area might be the floor of a very subdued 180-m crater.

The surface along the traverses was crossed by long rays of two ages shown by premission mapping (Elston and others, 1972c), an older set radiating from North Ray crater and a younger set from South Ray crater. The crew's description of the surface gives a picture of the composition and form of a young ray and valuable data on the aging of rays as discussed below. During the three traverses, they crossed many ray segments (fig. 1) on different azimuths, at various distances from their source craters, and under different lighting conditions.

The fresh rays were distinguished by the crew on the basis of concentrations of rock fragments on the surface, the presence of large blocks, the high angularity of the rocks, the absence of dust on the rocks, the presence of secondary craters, and, under favorable lighting conditions, higher albedo of the ray area. No topographic form was associated with rays, and no color or other property of the fire-grained (granules or finer) surface materials was described that would distinguish ray areas from interray areas. The greatest concentration of blocks was seen on Survey ridge within a ray from South Ray crater (fig. 2*A*), whereas interray areas were generally devoid of blocks (fig. 2*B*). The discontinuous patterns of rays viewed from orbit (fig. 1) within traverse areas apparently do indicate irregularities of the original distribution of ejected rocks. Near Survey ridge, the crew observed that the cobble concentration was clearly the greatest near the center of the ray, decreasing gradually toward the edge. Elsewhere, they were moderately certain of the edge of a ray. Probably both sharply delineated edges and gradational edges of rayed ejecta are common, as indicated by the types of variation in albedo seen on photographs (fig. 1).

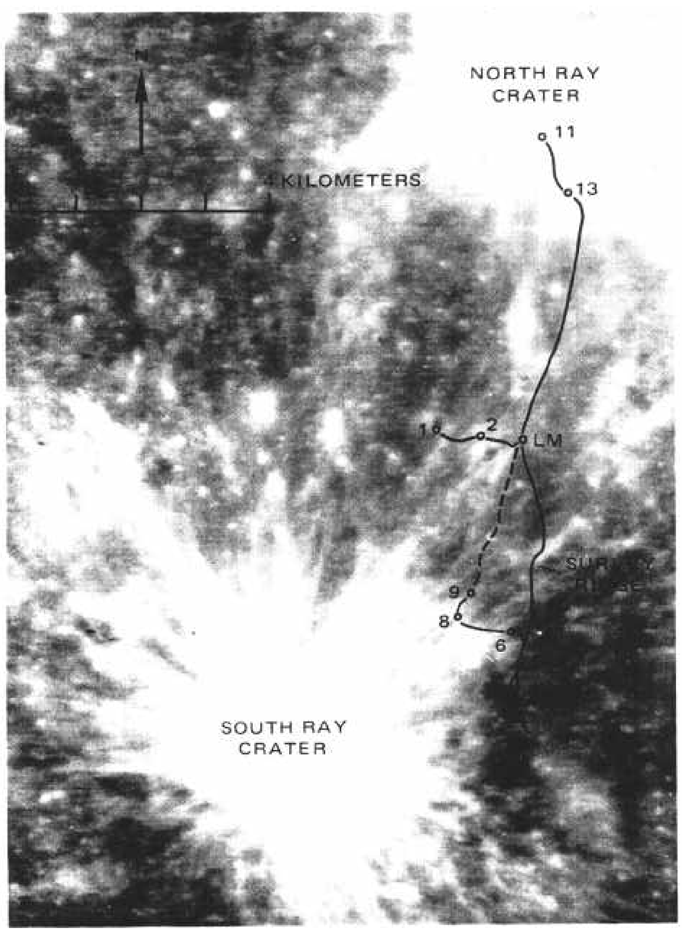


FIGURE 1.-Apollo 16 traverse area. Apollo 16 panoramic camera frame 5328, computer enhanced to show ray patterns from North and South Ray craters: sun elevation 60°.

On the surface. the astronauts thought they could recognize several rays from North Ray crater. `From a distance, they could see very large blocks forming a North Ray ray on the slopes of Smoky mountain. Near Palmetto crater, they noted a concentration of 20- to 30-cm blocks that also appeared to be a ray from North Ray crater. Photographic measurement of visible blocks (Schaber, this volume, fig. 4; Muehlberger and others, 1972) clearly show the blocks on these older rays and ejecta blanket of North Ray crater to be less abundant than those on rays from South Ray crater (fig. 3). Many blocks in the older rays were reported by the crew as rounded and dust covered.

THICKNESS OF REGOLITH

Premission work by Oberbeck (197lb) on regolith thicknesses predicted less than 6.7 m (range of 3.1 to 6. 7 m) at the Apollo 16 site. Oberbeck obtained a calculated thickness of 22 m using the total crater population and assuming that all of these craters are of impact origin and that greater density of craters correlates with a greater thickness of regolith. To explain this difference, Oberbeck (1971b, p. 9) suggested that because most of the craters are subdued and probably of impact origin "a deep regolith has been produced. However, it is further suggested that the regolith and impact craters have been mantled by a deposit that was indurated after deposition. This would produce the subdued appearance of the large craters and provide an indurated formation that could subsequently be modified by recent impact craters to produce a thinner, regolith deposit."

The preliminary geologic report after the mission

(Muehlberger and others, 1972) suggested a regolith thickness of 10 to 15 m based on the position of a bench in Buster crater.

A new attempt is made here to determine regolith thickness using the relation of crater shape to thickness (Quaide and Oberbeck, 1968) and measurements from a stereo model of Apollo 16 panoramic camera photographs. Ten craters with terraced or concentric internal shapes, indicating an underlying harder layer were examined (fig. 4). The depth from the average ground surface beyond the rim deposit to the top of the hard layer was measured by R. Jordan (U.S. Geological Survey) for each crater. The regolith thickness thus obtained ranged from 3.5 to 8.7 m; reproducibility of measurements was within about 2 m. Half of the craters gave thicknesses of 6.0 to 6.8 m. The only crater other than Buster that permits an estimate of regolith thickness substantiated by lunar-surface photographs is WC crater, 700 m south of the LM. It is about 40 m in diameter, and the photographs of WC ejecta taken from the LRV indicate that bedrock was reached. The WC ejecta contains abundant blocks; a regolith thickness of 6.7 m above bedrock was measured photogrammetrically for WC crater. Other craters in the landing area are larger than the craters cited but are "V" shaped indicating local areas of thicker regolith.

These new measurements of regolith thickness at points of concentric craters are in very close agreement with the results obtained by Oberbeck (1971b) using diameters of the craters. His postulated older, thicker (22 m) regolith and its covering deposit upon which the presently active regolith has formed were not found on careful examination of the Apollo 16 panoramic camera photographs. Other methods of obtaining the thickness of regolith have yielded different results, summarized here.

The thickness of the regolith in the area of the active seismic experiment was determined as 12.2 m by Kovach and others (1972, p. 10-1). Although the passive seismic experiment did not measure the regolith thickness directly, Latham and others (1972, p. 9-1) stated: "The signal character and background noise at each station have distinctive characteristics apparently related to the depth and elastic properties of the regolith at each site. To explain these differences, the Apollo 16 station, compared to Apollo 12, 14, and 15, must overlie the deepest or weakest regolith, or both, acceding to criteria now applied. This condition also would explain the much higher sensitivity of the Apollo 16 station."

Zisk and others (1972) concluded from 3.8-cm radar data that there is little distinction between Cayley plains and Descartes mountain areas. "The 70-cm radar shows that the Cayley regolith is freer of meter-sized boulders to depths as great as *** 10 to 15 m at the landing site *** than is the Descartes regolith." Muehlberger and others (1972, p. 6-26) stated that "the thickness of the regolith on Stone Mountain, based on crater shapes, is similar to that on the Cayley plains." Only one crater on Stone mountain, about 100 m in diameter 4 km east of Crown crater, has a terrace indicating the top of a hard layer. Using Oberbeck's (1971b) relation of depth to diameter, the thickness there above a hard layer is less than 12.5 m.

An average thickness of regolith at the Apollo 16 site is difficult to determine from direct observations. The thicknesses found on the Cayley plains range from 3.1 to 15 m. The 12.2-m thickness at the active seismic site is probably greater than the median because the seismic line lay across the ejecta deposits of a very large subdued crater. A subjective evaluation of the data presented above is that on the Cayley plains the median regolith thickness above some bench-forming layer is between 6 and 10 m, generally about 7 m.

Stone mountain has a smaller number of visible craters than the Cayley plain. This is true for the relatively flat top as well as for its steeper slopes. Especially striking is the distribution of 1-1.5-km craters, common on the plain and absent from Stone mountain (fig. 5). As they are of several ages on the plain, not members of a single cluster, it is highly unlikely that original distribution could account for their absence from Stone mountain unless Stone mountain is much younger, and the returned samples do not support a younger age. It is therefore concluded that craters of 1-km diameter have existed on Stone mountain but have been destroyed there at a more rapid rate than on the plain, possibly because of a very weak bedrock, as well as mass movements of debris under the influence of gravity, and shaking of seismic or impact origin.

The 5- to 10-m thickness of regolith indicated on the Descartes mountains by radar and concentric craters represents areas of average thickness on the upper surface, not the lower slopes. Regolith of this thickness might have formed since mass movements stripped the area of an older regolith or since formation of some hard layer on the older regolith. It is probably not the total thickness formed in place since emplacement of the underlying bedrock.

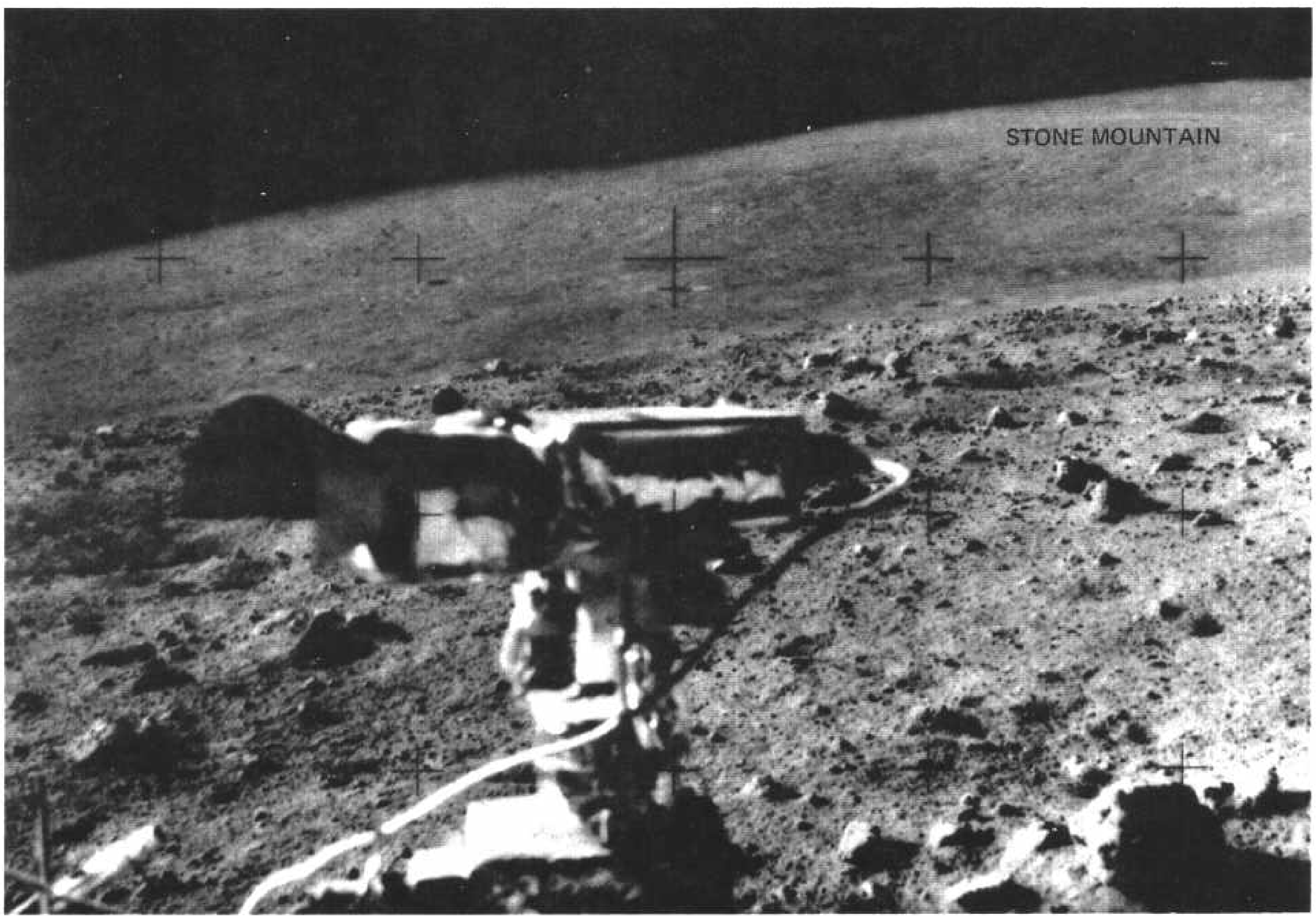
The zone of thick accumulation of mass-wasted debris extends up Stone mountain to an abrupt change in slope about 300 m southeast of Crown crater, a sharprimmed 100-m crater with no visible boulders in its ejecta. A regolith thickness of at least 20 m is suggested in this part of the Descartes mountains.

COMPOSITION OF REGOLITH

The samples from the Apollo 16 site have a high degree of chemical consistency indicating that they were derived from a local suite of rocks. Only a few small rock fragments found in the rake samples are exotic and probably not representative of the Descartes area (Warner and others, 1973; Steele and Smith, 1973; Delano and others, 1973). The local suite of rocks is distinct from the rocks found at other Apollo sites (Rose and others, 1973), including the Apollo 14 site that sampled the Fra Mauro Formation. As can be seen from results of orbital chemistry (Adler and others, 1973; Metzger and others, 1973), the Descartes area is typical of the lunar highlands in general. Materials of the Descartes mountains and the Cayley plains are not separable chemically (Delano and others, 1973), although Ulrich and Reed, and Hodges and Muehlberger (this volume) argue that rocks with the highest degree of impact melt may occur within the plains.

Regolith samples were taken from all stations within the Apollo 16 site. They represent both Cayley plains and Descartes mountains, and rays from North and South Ray craters, as well as thin younger regolith on the rim of North Ray crater, and older regolith remote from fresh craters.

In evaluating the chemistry of these samples and the related rocks, only four elements, Fe, Ti, and Al as oxides, and Ni, are considered (tables 1 and 2), but the results of analyses for these are in general agreement with conclusions of other workers using other elements. In average $A1_20_3$; and TiO_2 content, the regolith from all stations does not differ greatly except for stations 11 and 13. Station 11 soils, on the rim of North Ray crater, contain less titanium and more aluminum than regolith elsewhere. Soil at station 13, on the ejecta blanket of North Ray crater, contains a slightly greater amount of titanium and about the same amount of aluminum as station 11 regolith. The difference



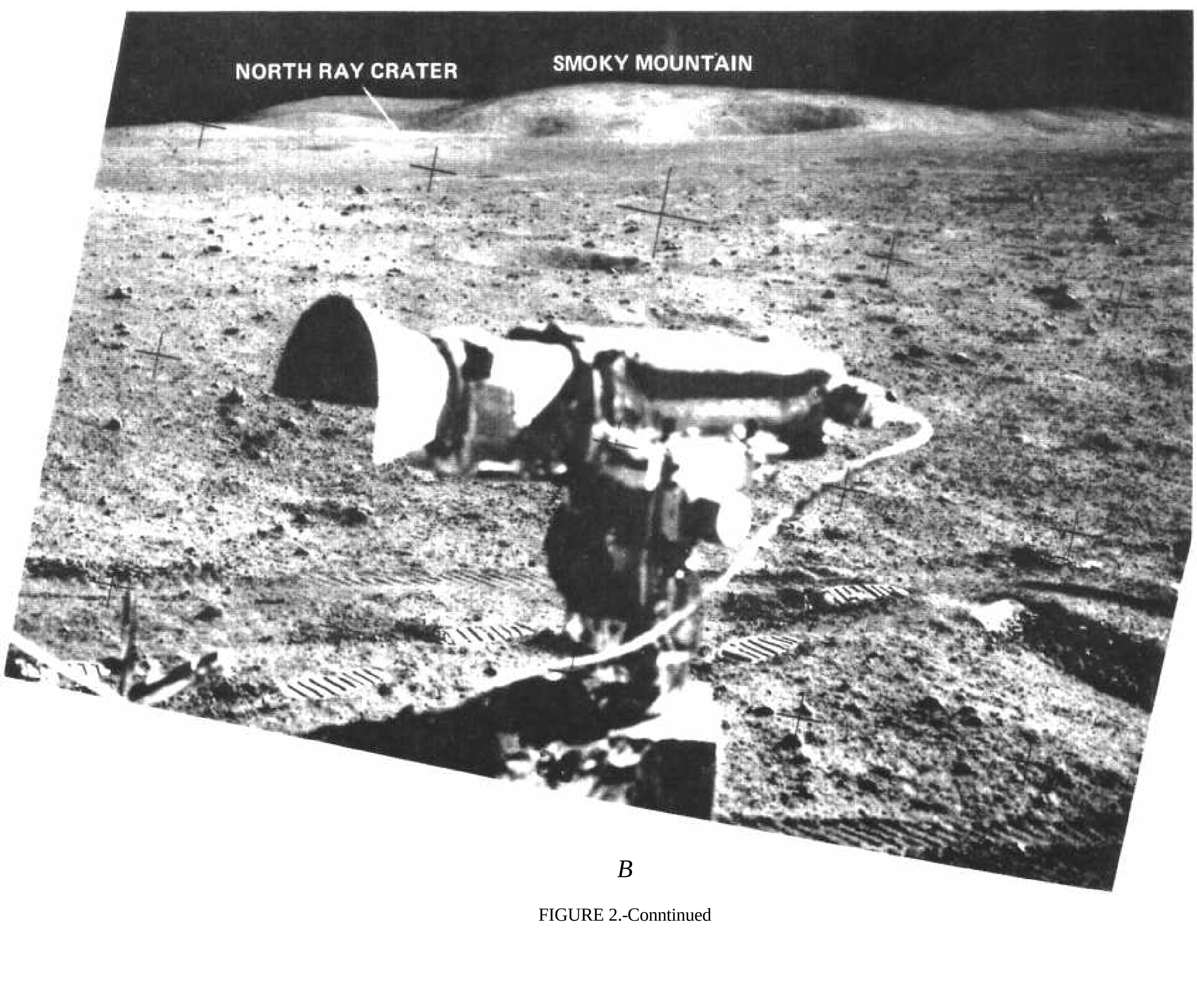
A

FIGURE 2.-Comparison of lunar surface within and between rays from South Ray crater. A, Area within blocky ray on Survey ridge, 5 km from South Ray crater. View is southeast. Photograph AS16-110-17891. B. Area between rays near station 8, 3.3 km from South Ray crater. View is northeast. Photograph AS16-108-17703.

in titanium may reflect a contribution from Shadow rock at station 13, which has a relatively high ratio of titanium to aluminum. In absolute amounts of iron, titanium, and aluminum (fig. 6), the regolith samples fall into two groups: (1) stations 11 and 13, dominated by North Ray ejecta with high aluminum content and (2) the remaining stations, with only small differences. Station 4 soils on Stone mountain tend to be intermediate chemically between values at North Ray crater and those from the plains.

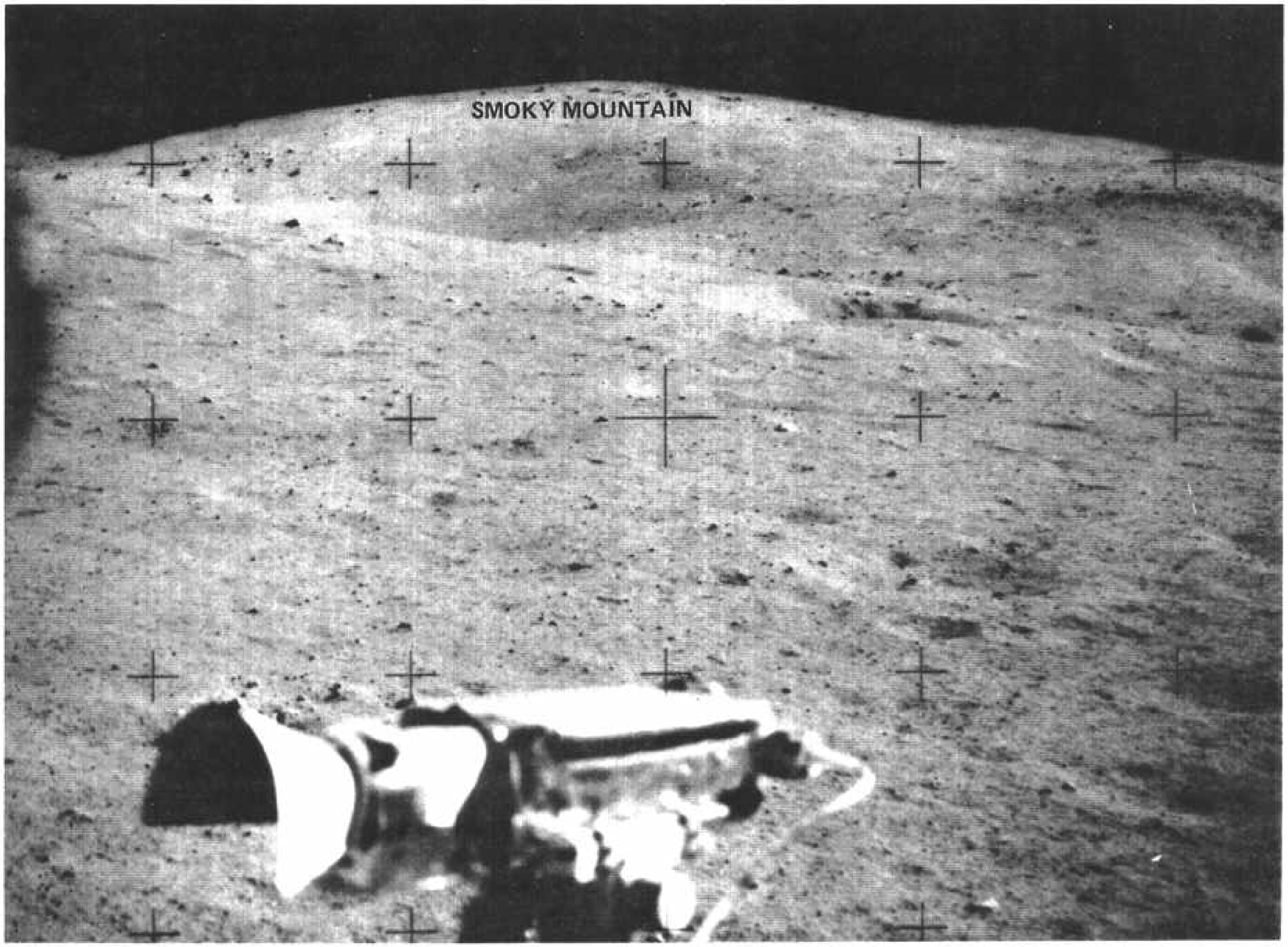
The variation of TiO_2 relative to Al_2O_3 (fig. 7) shows analyses of both rock samples and regolith samples. The regolith samples are grouped near the center of the scatter of rock samples except for a tail of regolith samples collected from North Ray rim (station 11). Similar variations are shown in the Al_2O_3-FeO diagram (fig. 8). The plots indicate that the regolith was formed by a mixing of the compositions of the rock samples. There is no significant difference in the regolith composition of stations 4, 5, and 6 (on Stone mountain) and stations on the Cayley plain in these plots, although station 4 soils approach North Ray compositions in Ti and Ni. The regolith samples from the plain and the mountain, though similar to each other, are different from regolith samples collected at other Apollo landing sites, including highland stations at Apollos 14, 15, and 17.

Regolith samples that show a unique composition attributable to North Ray crater ejecta are those taken on the rim or continuous ejecta blanket of the crater. No composition identifiable as South Ray crater ejecta added to the soil can be distinguished in the analyses. Ray materials, even as young as those from South Ray crater, apparently are not identifiable by major element content of the regolith. This supports the suggestion that fine-grained materials are lacking in the



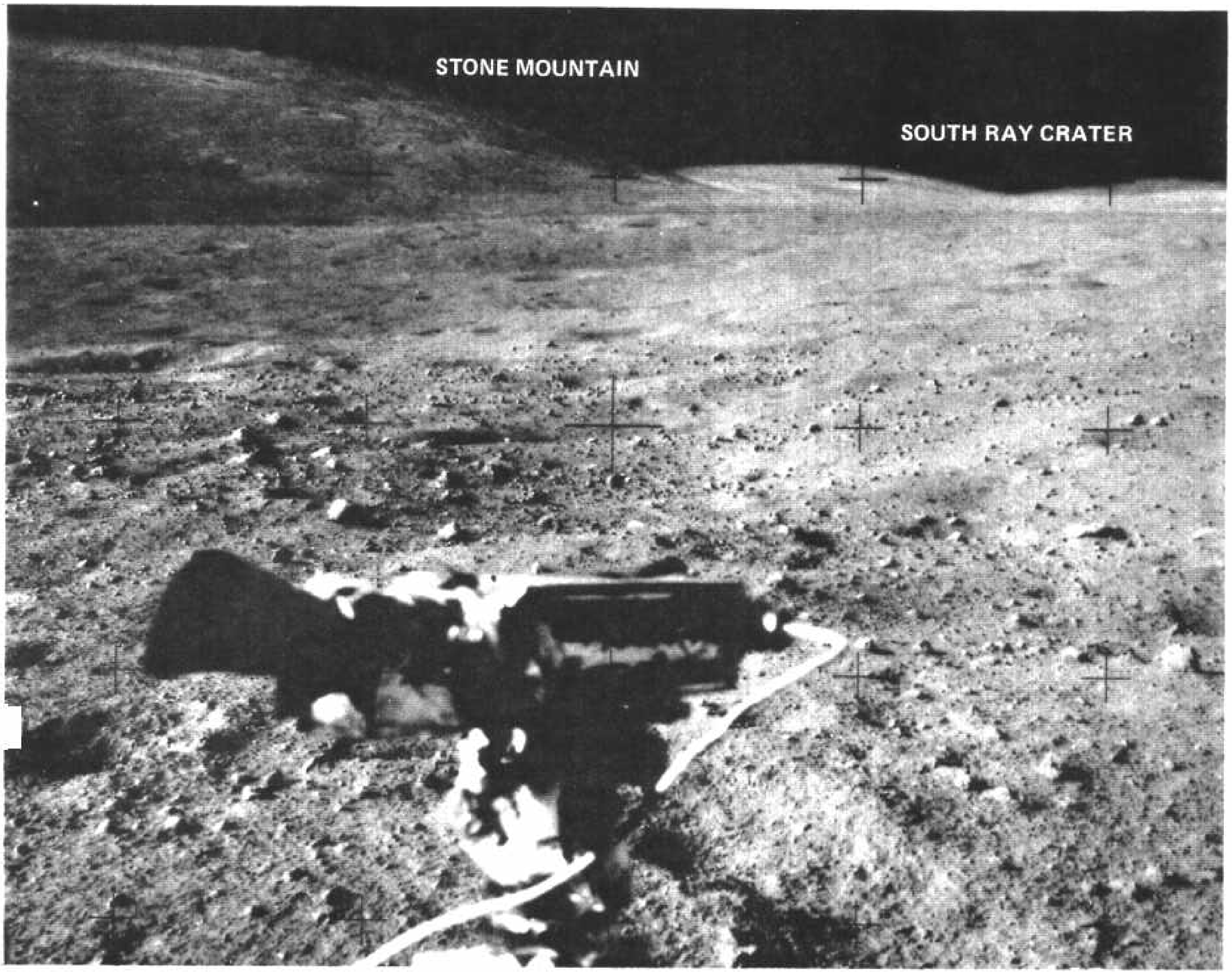
B

FIGURE 2.-Conntinued



A

FIGURE 3.-Comparison of old and young ray-covered areas. A, Area of old ray deposit 1.5 km from rim of North Ray crater AS16- 111-14143, view is northeast. B, Area of young ray deposit 4.5 km from rim of South Ray crater. AS16-110-17898, view south.



B

FIGURE 3.-Continued.

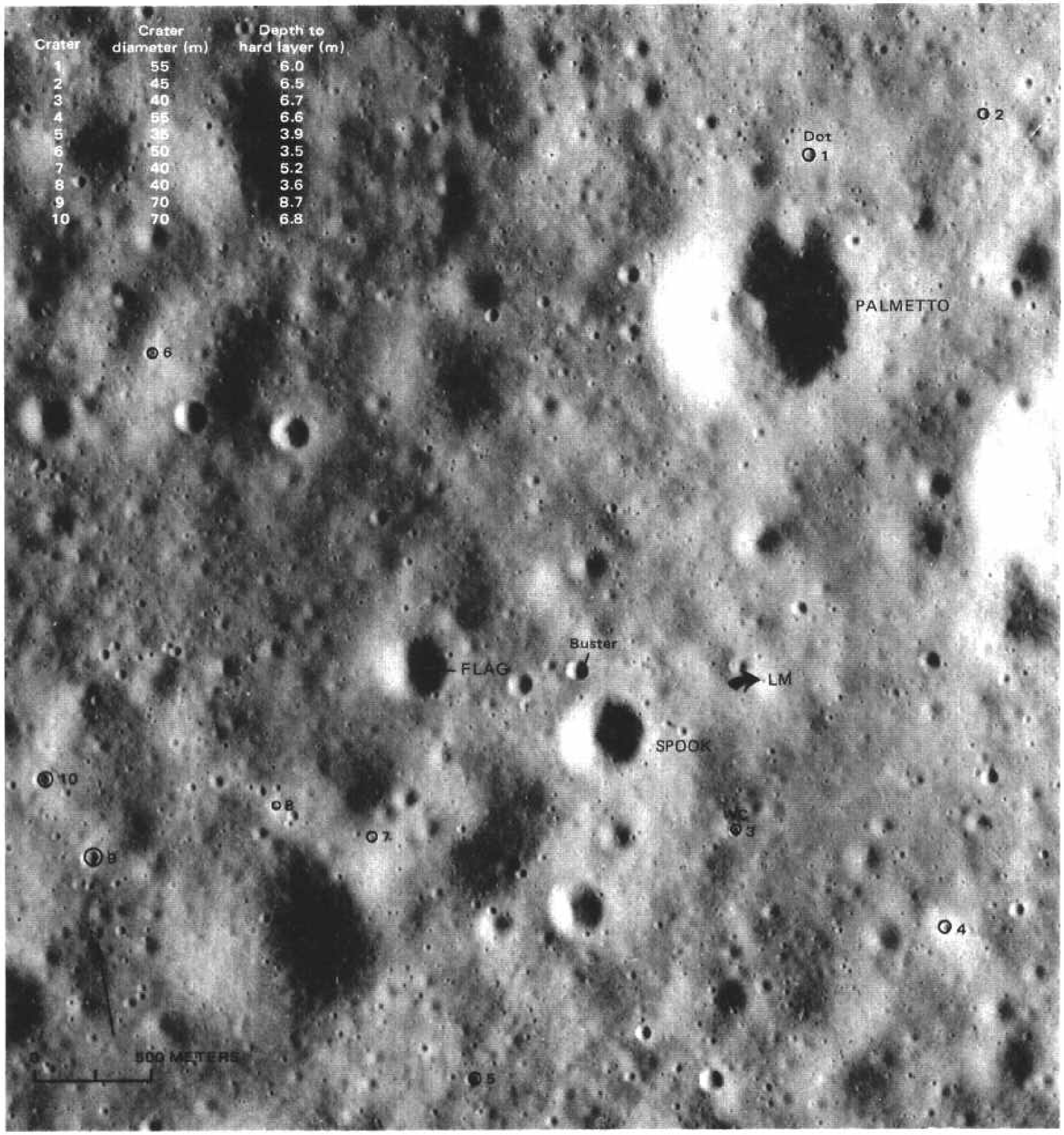
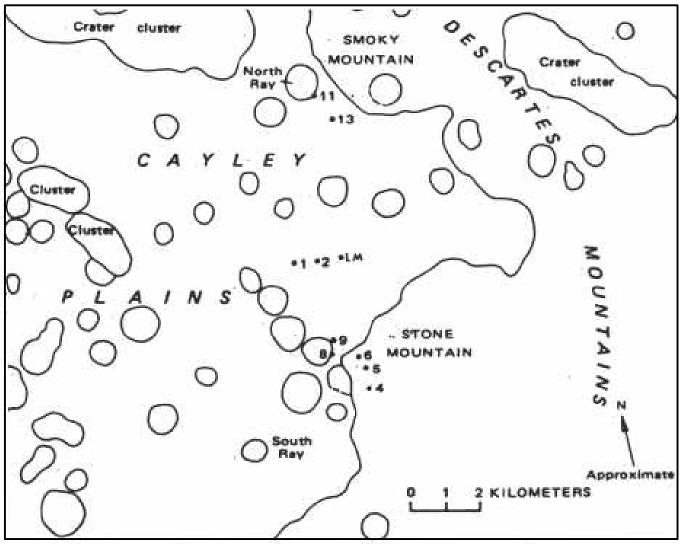


FIGURE 4.-Locations of concentric craters used to estimate depth of regolith. Apollo 16 panoramic camera frame 4623.



rays of South Ray crater (McKay and Heiken, 1973).

The variation of nickel relative to iron in the rocks and soils from the Apollo 16 site is shown in figure 9. The trend line that results from addition of nickel and iron in proportions equal to the average composition of meteoritic matter (Mason, 1962, p. 164-5) has been added to the diagram. Several pairs of data points are joined for comparison: (1) .sample 67455 from a lightmatrix breccia boulder at station 11 with sample 67481, a soil probably derived from light-matrix breccia (ALGIT, 1972b, p. 161 and 167); (2) an average for all station 11 rocks with the average of all soils from the same station; (3) sample 61221, from the white

<FIGURE 5.-Apollo 16 region showing Cayley plains, Descartes mountains, and outline of craters of about 1 km in diameter. After Hodges (1972a).

TABLE 1.-*Apollo 16 soil analyses for $A1_20_3$, TO_2, and Ni*

[Averages of values from numbered references, in weight percent; Ni in parts per million]

Sample No.	Al_2O_3	TiO_2	FeO	Ni	References Numbered in Accompanying list
60051	28.5	0.44	4.50	270	18
60501	26.4	0.60	5.49	415	2,9,16,17
60601	26.61	0.66	5.55	403	1,5,7,10,15
61141	26.45	0.58	5.12	355	3,10
61161	26.3	0.58	5.25	400	10
61181	27.1	0.66	5.47	340	5
61221	27.65	0.68	4.96	135	1,3,7
61241	27.03	0.67	5.30	230	1,3,7
61281	27.12	0.54	5.07	440	3
61501	26.83	0.52	5.23	372	1,5,10
62241	27.4	0.57	5.12	414	3,11
62281	27.1	0.57	5.5	380	15
63321	28.9	0.35	4.67	311	19
63341	29.0	0.60	4.54	345	19
63501	28.1	0.50	4.67	322	4,19
64421	27.66	0.55	4.94	323	1,4,10,17
64501	27.0	0.55	4.2	320	2,7
64801	27.40	0.56	5.18	300	4,5,17
64811	26.9	0.49	5.59	290	18
65501	26.1	0.70	5.96	390	9,16
65701	26.56	0.66	5.69	414	1,5,7,10,17
65901	26.5	0.61	5.8	500	15
66031	27.8	0.60	5.46	417	19
66041	26.45	0.65	5.90	428	1,3,15,16
66081	26.14	0.67	6.12	446	1,3,15,16,17
67461	29.7	0.35	4.14	120	10,17
67481	29.1	0.41	4.42	147	1,9
67601	28.16	0.46	4.05	145	1,7
67701	28.79	0.38	4.08	145	5,17
67711	29.4	0.26	2.96	90	18
68121	26.4	0.58	5.67	422	17
68501	26.78	0.57	5.40	420	4,5
68821	26.2	0.50	5.40	550	18
68841	26.5	0.58	5.65	296	1,17
69921	26.16	0.61	5.61	422	3,15
69941	25.6	0.65	5.62	492	3,7,15
69961	26.27	0.60	5.73	530	3,15

TABLE 2.-*Apollo 16 Tock analysis for $A1_20_3$, TO_2, and Ni*

[Averages of values from numbered references, in weight percent; Ni in parts per million]

Sample No.	Al_2O_3	TiO_2	FeO	Ni	References Numbered in Accompanying list
60015	35.7	....	0.26	....	5
60017	31.4	0.15	2.76	207	3,5
60018	24.5	0.62	4.76	210	5
60025	34.9	0.08	0.54	16	3,6,7,8
60315	17.2	1.29	9.35	703	1,2,3,4,5
60335	24.9	0.61	4.65	256	1,3,6,7
61016	26.7	0.68	4.42	335	1,3,8,9,10,11
61156	22.9	0.64	7.88	184	1,4
61295	28.3	0.56	4.52	114	1
62235	19.4	1.11	9.650639	1,4,11	
62275	33.1	0.04	2.20	....	12
62295	20.3	0.71	6.13	313	3,4,6
63335	30.9	0.42	3.23	26	1
64455	22.4	0.65	5.47	540	7
64567	21.62	0.72	7.08	....	20
64815	17.33	1.7	9.5	....	20
65015	20.6	1.20	8.45	349	4,5,7,9,13
66095	24.58	0.73	6.59	482	1,8,9,11
67016	31.0	0.03	3.7	65	11
67075	32.8	0.07	2.24	1	1,7
67115	31.2	0.24	2.60	62	3
67435	15.9	0.05	5.8	....	12
67455	30.5	0.25	3.88	22	3,10
67629	24.0	0.85	5.29	350	7
67915	29.4	0.5	2.95	....	8
67955	27.7	0.27	3.84	108	1
68415	28.7	0.32	4.02	116	1,3,6
68416	28.5	0.31	4.30	176	3,4,14
68815	27.2	0.49	4.75	206	1
69935	31.5	0.22	2.34	302	3
69955	35.2	0.01	0.36	43	3

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layer in the trench at station 1 is joined with sample 61241, the overlying gray layer possibly derived from the white layer (ALGIT, 1972b, p. 75); (4) an average of all rocks at the Apollo 16 landing site with the average of all soils at the site.

The nearly parallel trend of the lines connecting rocks and soils indicates an addition. of nickel and iron in similar proportions during the process of soil formation. The divergence of this trend from that of Mason's indicates that the composition of added meteoritic material at the Apollo 16 site is more Fe-rich (or Ni poor) than that on Earth.

SUMMARY

The appearance of the regolith is generally that of a rocky gray soil. Rays from young craters in hard substrata are distinguishable mainly as local concentrations of blocky fragments. The brightness of a ray appears to result from a combination of the density and the angularity of fragments, both higher for South Ray than for North Ray crater.

The regolith thickness on the plains has a median value between 6 and 10 m based on photogrammetric measurements of depth to the first bench in 10 concentric craters. The thickness of regolith on Stone mountain ranges from a minimum of 5 to 10 m to more than 20 m and may vary greatly owing to accumulation of mass-wasted debris on a softer, weaker bedrock that may underlie much of the Descartes mountains.

Regolith compositions for most of the Apollo 16 site are chemically similar except for North Ray soils, stations 11 and 13, which are significantly enriched in alumina and depleted in iron, titania, and nickel by comparison with soils from other stations. Soils from station 4 tend to be intermediate in titania and nickel content with respect to soils from the plains and North Ray crater. As a group, the soil samples cluster near the middle of the compositional ranges representing the rocks from all stations.

Iron and nickel show a marked increase from a parent rock to the soil produced by its disintegration. A similar change is seen between the average compositions of rocks and soils and between two soils in superposition. Analyses indicate a component of meteoritic material richer in iron (or poorer in nickel) than the average meteoritic material on Earth.

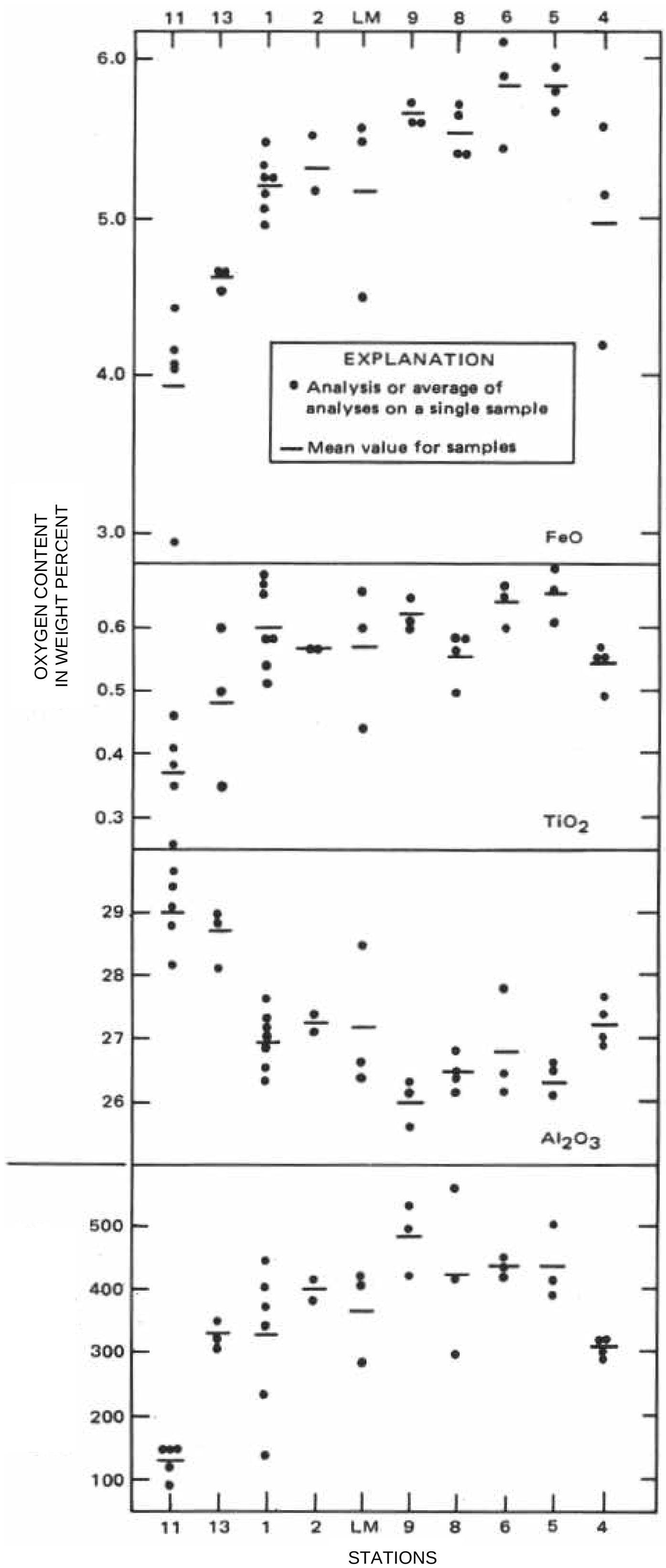

FIGURE 6.-Plots of analyses for FeO, TiO_2 Al_2O_3, and Ni for soil > samples taken at traverse stations.

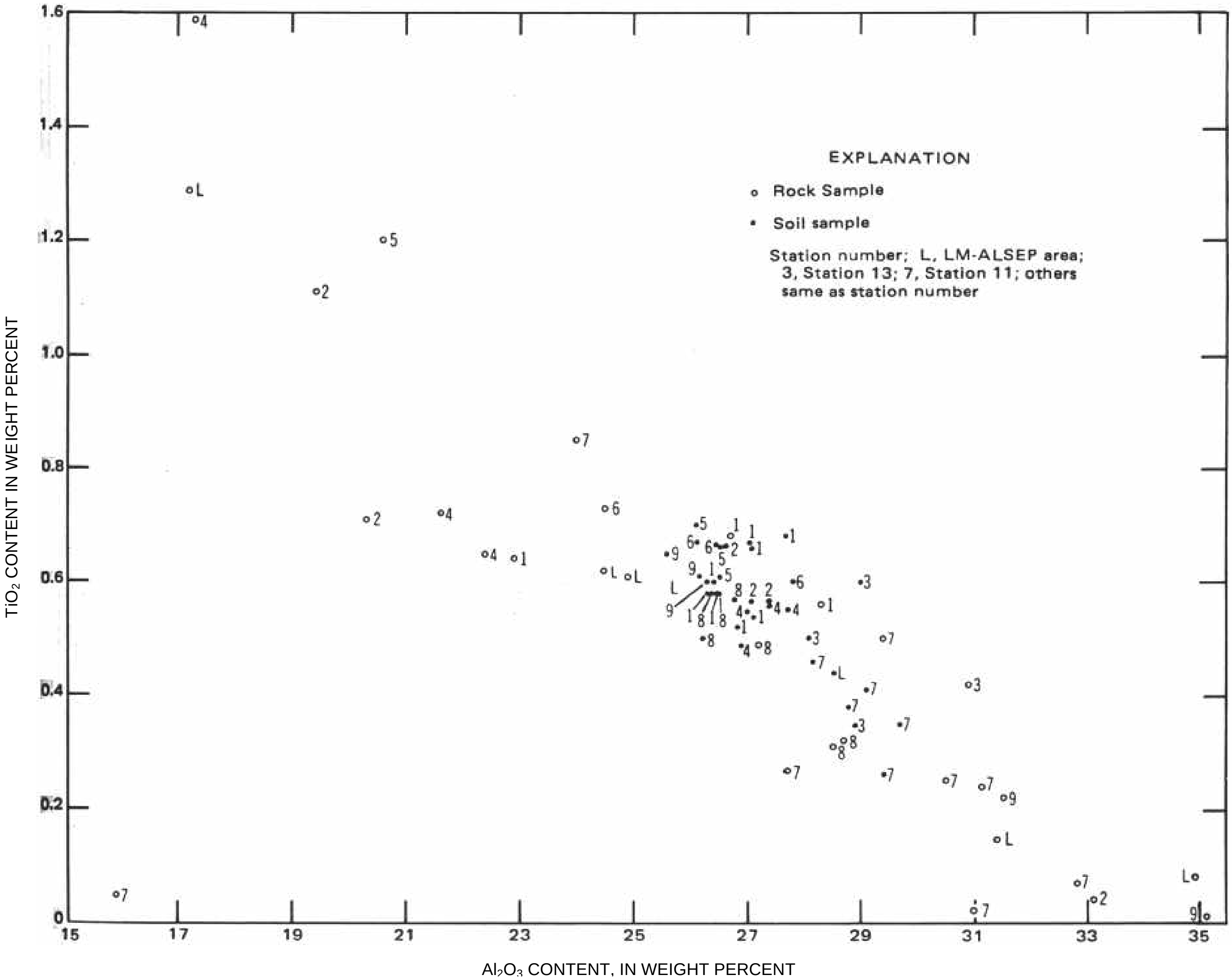

FIGURE 7.-Plot of TiO_2 relative to $A1_20_3$, for rock and soil samples. Points are averages of all available analyses of each sample.

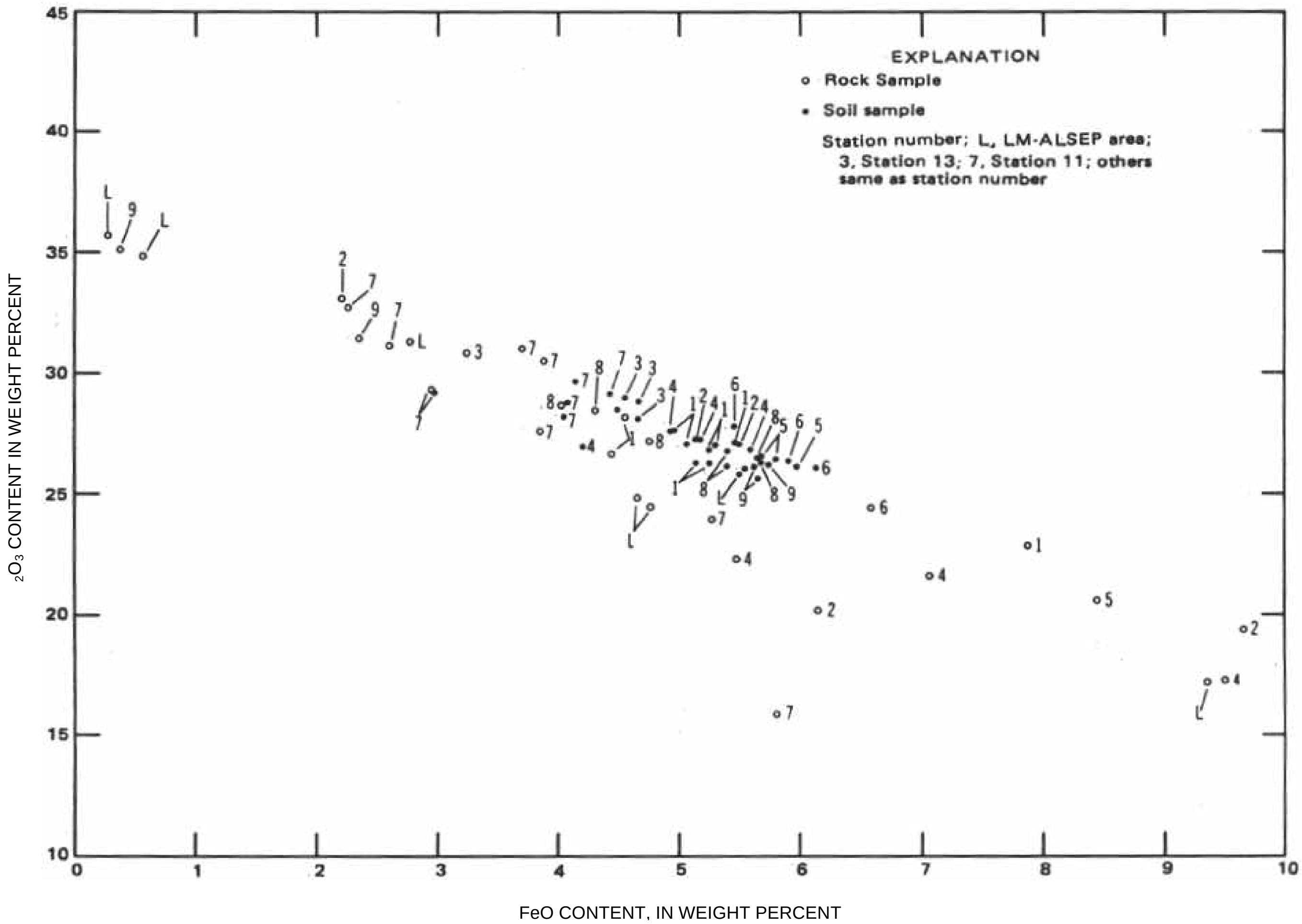

FIGURE 8.-Plot of Al_2O_3 relative to FeO of rock and soil samples. Multiple analyses of same samples are averaged.

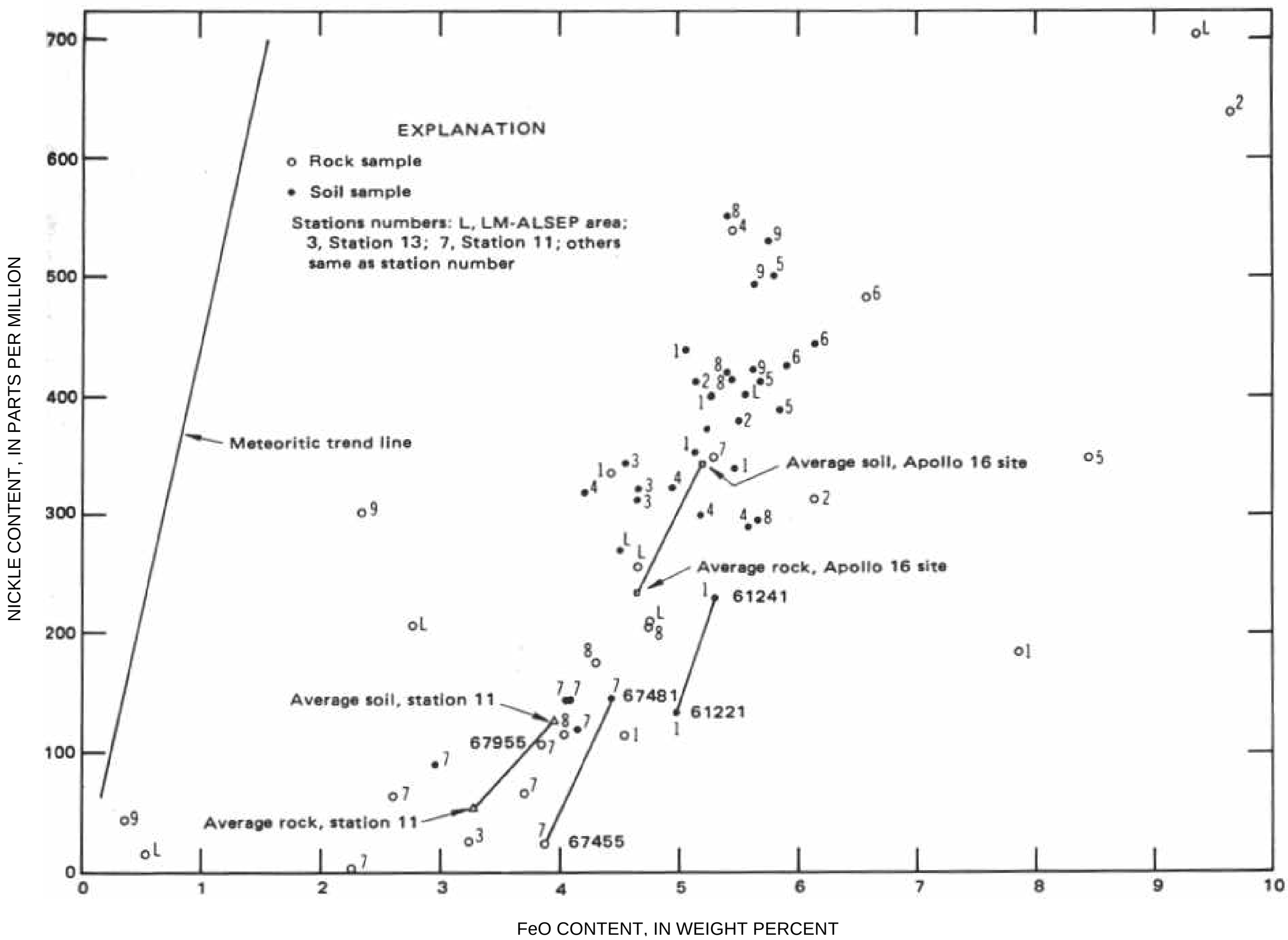

FIGURE 9.-Plot of nickel relative to FeO of rock and soil samples. Multiple analyses of same samples are averaged. The meteoritic trend line is calculated from average meteorite composition (Mason, 1962) and assumes Fe/Ni remains constant at 17 for material added in soil formation.