Basis for Interpretation Regarding the Ages of the Serenitatis, Imbrium and Orientale Events

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Basis for interpretation regarding the ages of the Serenitatis, Imbrium and Orientale events

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[Plate 1]

One of the most important objectives of lunar study is to relate the lunar sample data to important lunar events. This paper utilizes as the basis of interpretation consideration of the following: (1) Photogeologic data, (2) The choice of a cratering model, (3) Estimates of temperature of impact ejecta and shock-induced heating, (4) Petrologic data of lunar breccias and their thermal and shock history, and (5) Meaningful age measurements. Both the author's interpretations and alternative views are discussed. The age of the Serenitatis event is not yet known. The interpreted age of the Imbrium event is between 3.90 and 3.84 Ga. The age of the Orientale event is 3.84 Ga.

1. INTRODUCTION

In this paper, I discuss the possible genetic relationships of the Apollo 14 and 15 samples to the Imbrium impact event, the Apollo 16 samples to the Orientale impact event and the Apollo 17 samples to the Serenitatis event. Establishing the ages of these events is an extremely difficult job. It requires the combined knowledge and well documented evidence (if available) of: (1) photogeologic data, (2) a cratering model applicable to the interpretation of large lunar basins, (3) temperature estimates of impact ejecta deposits and shock-induced heating, (4) the petrology of lunar breccias, including their complex thermal impact history, and (5) meaningful radiometric age measurements. Other useful information concerns the amount of melt produced by an impact event, the distinction between endogenic thermal metamorphism and impact induced heating, and criteria for determining the origin of melt rocks.

Because of the uncertainties involved in extrapolating experimental cratering data, and the paucity of data concerning the nature of the cratering process in well-preserved terrestrial meteorite craters, basic criteria that can be used to establish the relation between lunar samples and a specific important lunar impact event are often subject to debate. For example, how do we determine the place of origin of returned lunar highland samples? Are they of local origin, brought to the surface by secondary cratering or are they indeed ejecta from large lunar basins? The thermal history of a breccia should also be understood because such an understanding is critical for the interpretation of radiometric age measurements. Estimates of the volume, thickness and distribution of ejecta from a basin are needed to put some constraints on whether the ejecta from a given basin can be of significant thickness at a given landing site. In this paper I present the basis for my interpretation and discuss alternative views regarding the ages of the Serenitatis, Imbrium and Orientale impact events.

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† Paper written while on leave from U.S. Geological Survey.

2. Basic considerations

(*a*) *Photogeologic data*

The principles of superposition of cratering structures and ejecta, of degradation of crater morphology by erosion due to subsequent bombardment and the estimates of crater density have been used for the development of a geologic framework for lunar stratigraphy and history upon which the Apollo missions were planned and executed (Wilhelms 1970; Swann, Trask, Hait & Sutton 1971; Apollo Lunar Geology Investigation Team 1972; Apollo Field Geology Investigation Team 1973*a*, *b*). On these bases the relative ages of the basins discussed in this paper in chronological order, are: Serenitatis, Imbrium, and Orientale (Wilshire & Jackson 1972; Howard, Wilhelms & Scott 1974). Data on basin ages derived from sample studies should be consistent with the relative ages derived from photogeology.

There is another aspect of the photogeologic data pertaining to multi-ring lunar basins which has not received enough emphasis: the characteristics of morphological units of ejecta and the meaning of their distribution patterns with respect to the process of ejecta transport. Hummocky rugged ejecta deposits occur closest to the outermost rings of multi-ring basins. This hummocky and rugged terrain grades radially outward into terrain of lineated or furrowed valleys and ridges. The furrowed and lineated ridges and valleys then grade radially outward into relatively smooth, mantled rolling hills and depressions and light plains units. These three morphological units of ejecta can best be identified and mapped around the Imbrium and Orientale basins because these are the youngest multi-ring mare basins on the Moon and their ejecta are thus among the best preserved. The hummocky terrain around the Imbrium basin is known as the Apennine formation (Wilhelms 1970). Bordering and extending radially outward from the Apenine formation is the Fra Mauro formation. It is divided into two units, a ridge and valley unit directly adjacent to the Apennine formation and a smoother unit radially away from it (Wilhelms 1970). Although these two units are separately mapped (Eggleton & Offield 1970), no separate subformational names were proposed for them. The radially distributed linear ridges and valleys around Mare Orientale have been named the Hevelius formation (McCauley 1967). This formation grades outward into, and is intermixed with, the smoother rolling mantled units and light plains. The latter in most places have been mapped as the Cayley-type light plains. Chao, Hodges, Soderblom & Boyce (1975*a*) have interpreted the lunar light plains as mostly rolling, mantled to smooth Orientale ejecta. These plains are complex however and not all of them necessarily have the same origin.

The interpretation of whether the lineated or ridge and valley morphological units are erosional or depositional terrain is somewhat controversial. In some cases, a clear case can be made for erosion and in others deposition. I propose that these land forms are in most cases the product of erosion and subsequent deposition; perhaps later gravitational adjustment and 'faulting' may also contribute to its present topography. It seems certain that as the ejecta moved over the lunar surface, ejecta that were gouging and eroding the surface would have soon been slowed down and deposited. These ridges and valleys cannot be purely erosional, otherwise we must locate the vast amount of the missing ejecta further out that caused the erosion. The point often not mentioned but perhaps crucial to our understanding of ejecta transport and distribution is that these are probably products of low angle, ground-hugging and scraping, ejecta transport. The significance of this mode of transport will be clear below when it provides a basis for selecting a cratering model.

Also evident in photogeologic mapping is the occurrence of secondary craters produced by ejecta blocks from the primary crater; most of these occur from about one crater radius away from the primary structures. These secondary craters are easiest to identify where they are in clusters and associated with ejected ray materials. The significance of secondary craters will be discussed further below.

(*b*) *A cratering model most applicable to the interpretation of large lunar basins: the Ries crater*

In a previous paper (Chao 1974) I briefly reviewed experimental cratering data and the characteristics of the Ries terrestrial meteorite impact crater. I have explained that small experimentally produced craters cannot and should not be scaled to large lunar craters because the mechanics and physics of penetration and crater cavity development change drastically from microcraters to large size terrestrial craters, leading to irreconcilable inconsistencies such as angles of ejecta transport and the period or stage of the formation of the hottest ejecta. Because the Ries crater (Bavaria, Southern Germany) is large, 25 km in diameter, has well preserved ejecta, and has a depth to diameter ratio of about 1:33, like that of large lunar basins, I have selected it as the best analogue to be used in interpreting the processes that formed the lunar basins. In the following sections I rely on data on nature of ejecta distribution and superposition, evidence of low angle ejecta transport, and the sequence of development of the Ries crater for the interpretation of the relations between samples from several Apollo sites and major multi-ring basins.

Let me now briefly point out the most pertinent characteristics of the Ries crater, and demonstrate the merits of applying this information to interpreting lunar basins:

(i) The Ries crater was excavated in basement crystalline rocks overlain unconformably by several hundred metres of Mesozoic sandstones, shales and limestones. Four types of ejecta can be readily identified lithologically and mapped in the field: (1) Suevite, the hottest ejecta, consisting of glass particles and bombs, shocked crystalline rock fragments, and small amounts of clasts of sedimentary rocks (figure 1); (2) Polymict crystalline rock breccias, consisting of fragments of amphibolites, granitic gneisses and granitic intrusive rocks that are highly fractured with generally low to moderate degrees of shock; (3) Bunte breccia, consisting of fragments of purple, green and dark gray shale, brown sandstone, some lightly coloured limestones, and minor crystalline rocks that are largely unshocked; and (4) Gries and schollen, consisting of finely fractured, granulated and shattered limestone and large blocks of fractured limestone breccia, respectively. In general the limestone ejecta or Gries is distributed farthest from the crater. Bunte breccia occurs closer to the crater, and still closer are the polymict crystalline breccias. Suevite generally overlies the Bunte breccia. It is deposited as fallback ejecta within the basin and over the rim. Hence in a broadly simplified relation, the Ries ejecta represents an inverted stratigraphic sequence similar to, but more complex than seen at the Meteor Crater of Arizona; i.e. in the ejecta deposits rocks from the upper stratigraphic units are overlain by rocks from lower stratigraphic units, and rocks from the uppermost stratigraphic units were ejected the farthest.

(ii) The crater wall is underlain by horizontal Malm limestone undisturbed by the cratering process. Above the crater wall, schliffflãche (striated surfaces) are well developed (Wagner 1964). The striations are oriented radial to the crater and the ejecta that formed them, both Gries and Bunte breccia, were transported outward and away radially from the crater. The schlifffläche constitute field evidence of low angle, ground level scraping and gouging transport of masses of ejecta. New information documenting this manner of ejecta transport from the Ries will be given in a separate paper (Chao, in preparation).

(iii) As shown by 1200 m drill cores from a hole located 3.5 km northwest of the centre of the Ries crater, there is no melt layer present within the crater. The hottest ejecta was the glass-bearing suevite that forms a layer of fallback breccia within the crater. Preliminary fragment population studies suggest that impact melt, in the form of the glass fragments and bombs in suevite, constitutes much less than 1 % of the total ejecta.

(c) *Temperature estimates of impact deposits and shock-induced heating*

There are two important aspects of the characteristics of ejecta deposits, that are reflected by their clast assemblages: (1) the lithologic assemblage indicates the place of origin or nature of the source area and (2) the amount of glass and highly shocked fragments indicate the temperature of the ejecta deposit. The former characteristic is easy to understand and not controversial, but the latter in my opinion is commonly not understood and often misunderstood (Warner 1972; Wilshire & Jackson 1972). Hence I will discuss the latter in some detail here.

Effects of shock pressure in minerals and rocks have been described by many investigators (Chao 1967, 1968; Stöffler 1974). Estimates of shock-induced temperatures are generally lacking, but some estimates were attempted on the basis of mineralogical evidence (El Goresy 1964; Chao 1968). There has not been any direct measurement of temperature in shock-loadng experiments. Calculated temperatures based on various assumptions may have large errors. As has been previously discussed (Chao 1968), if a mineral is shock-heated beyond its ambient melting point, it will be converted to a vesiculated and flowed melt. Such heat is irreversible and is retained by the melt. This melt will be accelerated and cooled in flight due to shock acceleration and to loss of heat to the environment surrounding it after deposition. However, if a mineral is not shocked strongly enough to cause vesiculation and melting, then it would cool adiabatically quickly to temperatures of 200 or 300 °C, or some such temperatures (quantitative experimental data lacking) well below those effective for thermal recrystallization. It has been reported that material converted to glass in the solid state by shock (thetomorphic glasses) shows evidence of temperature below the ambient melting temperature, for example, thetomorphic glass with perthitic textures (Chao 1967). Thus most material that remains crystalline after passage of a shock wave has not been strongly heated. Hence the best

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DESCRIPTION OF PLATE 1

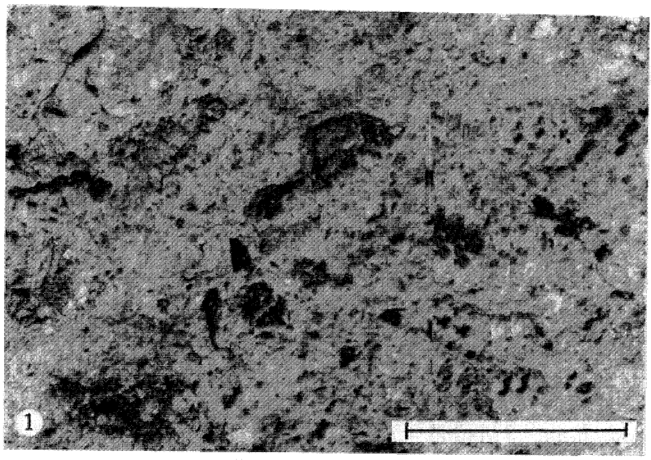
FIGURE 1. Photograph of suevite, the hottest impact ejecta from the Ries. The dark areas are impact glasses. Lighter areas are largely shocked and broken mineral and rock fragments. Bar scale 10 cm.

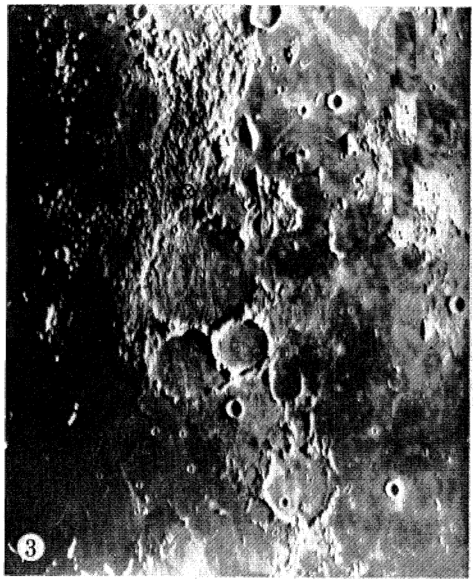
FIGURE 2. Composite of orbiter 4 photographs showing the southern rim of Mare Imbrium, and the hummocky and furrowed ejecta radial and traceable to Imbrium. The crater in the centre of the photograph is Eratosthenes, with the larger crater Copernicus to its lower left.

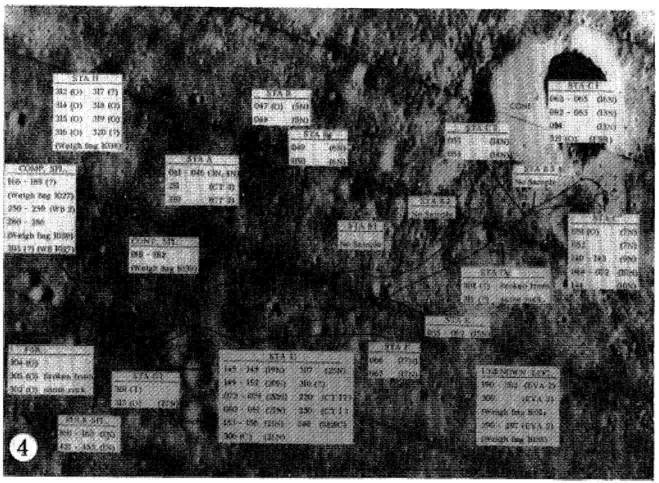
FIGURE 3. Photograph of an enlarged portion of the rectangular area shown in figure 2. Note the furrowed topography of the ejecta. The Apollo 14 landing site is indicated by the ⊗ cross symbol.

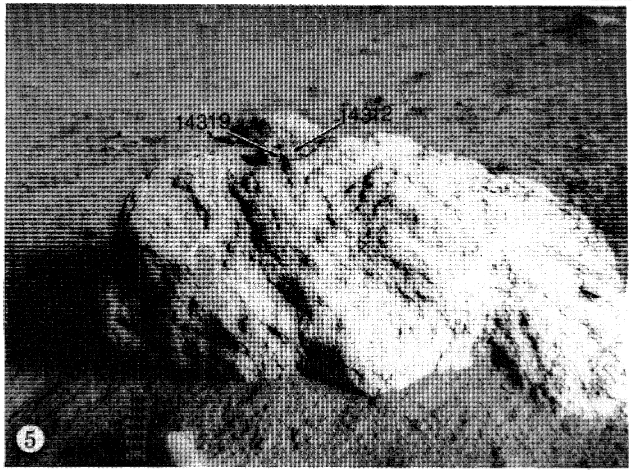
FIGURE 4. Photograph of the Apollo 14 landing site showing the Cone crater and location of the returned lunar samples (Swann *et al.* 1971).

FIGURE 5. Photograph of a boulder at station H (see figure 4). Note the turtle-shaped feature at the top of the boulder. Samples 14319 and 14312, both thermally annealed noritic breccias, were apparently lying loosely on top of this boulder when collected. N.A.S.A. photograph AS 14-68-9474.









Figures 1–5. For description see opposite.

available method for estimating the temperature of an impact ejecta or blanket is the amount of vesiculated glass present. Hot volcanic ash which consists nearly entirely of glass shards (i.e. melt) is therefore not a correct analog for impact ejecta. The hottest Ries ejecta, suevite, contains no more than about 75% by fragment count (not by volume) of glass (Chao 1973). In suevite the glass particles are separated and surrounded by powdered and crushed mineral fragments of much lower temperature and the extent of welding is limited to sparse particles adhering to the immediate surface of the glass. Detailed study of a large number of thin sections of suevite (Chao, unpublished data) shows no evidence of thermal recrystallization or welding in the matrix of the deposit. A rough estimate of the temperature of Ries suevite would be less than 700 °C, and may be on an average much below even this, perhaps less than 600 °C. A more precise estimate will be attempted when more fragment population data on glass distribution in suevite is obtained.

(*d*) *Petrology of lunar breccias and melt rocks and their complex thermal and deformational histories*

The study of the petrology of lunar breccias must be undertaken in order to characterize the ejecta deposit from which they have been collected. Three aspects of such studies should be emphasized: (1) Fragment population, which yields clues to the nature and bulk composition of the source area; (2) shock and thermal effects in clasts, which yield estimates of the temperature and shock history of the ejecta; and (3) the matrix textures of the breccia which give information on the number of shock events experienced by the bulk breccia after its formation and the evidence of post-consolidation versus pre-impact deepseated thermal metamorphism.

One of the most important objectives of the petrologic studies of melt rocks is the determination of the origin of the melt, whether it is the product of impact or igneous partial melting. Examples of melt rocks of this type are the basalts of the highlands, such as the feldspathic pigeonite basalts 77135 and 77115 of Apollo 17 (Chao, Minkin & Thompson 1974; Chao, Minkin, Thompson & Huebener 1975*b*), poikilitic rocks of Apollo 16, and rocks with intergranular to subophitic textures such as 14310 and 68415.

Unless we succeed in resolving and isolating some of these basic questions which bear directly on the interpretation of the radiometric age measurements, the lunar history will remain confused and cannot be reconstructed with any degree of reliability and confidence.

(*e*) *Meaningful radiometric age measurements*

Radiometric ages determined for lunar samples by various methods cannot be properly interpreted if the samples are not described and their origins not understood. Some of the problems in the interpretation of radiometric ages of highland rocks have been discussed (Chao 1973; Chao *et al.* 1975*a*). Here I summarize some of the basic considerations involved in using the measured ages of samples to estimate the dates of important major lunar events that formed or affected them: (1) The maximum age of an impact ejecta deposit is the age of the youngest melt rock it contains. Hence the Rb/Sr internal isochron ages of 14310 of the Apollo 14 samples from the Fra Mauro site and the 68415 sample from the Apollo 16 Descartes site are of critical importance. (2) The degree of thermal annealing or recrystallization of a breccia is a measure of the extent of re-equilibration of the various fragments it contains. If the fragments have been completely equilibrated by metamorphism, radiometric dates represent the age of the thermal metamorphism. If the sample is only partially re-equilibrated, then the radiometric age will have complex components due to the presence of clasts that retain evidence of earlier history. (3) If the breccia is loosely compacted, then it is possible that each fragment has retained its own age without subsequent shock or thermal metamorphic modification. These are generalized statements and should be used in conjunction with the other four items discussed above in order to put the radiometric age data in their proper geologic contexts and settings.

3. The Apollo 14 and 15 highland samples and the age of the Imbrium event

On the basis of experience and the study of the Ries crater, the best method for dating the Imbrium event would be to date samples of impact melts identified as produced by the Imbrium event. The best sites at which to look for Imbrium impact melts are the Apollo 14 and 15 sites. Unfortunately the Apollo 15 site at Hadley Rille is inside the rim of Imbrium (if the third ring of Imbrium is interpreted as the wall of the Imbrium crater). At this site, the chances of collecting such samples are poor because within the rim the fallback impact melts will be covered by Mare fill, the Apollo 15 Mare basalts. The only chance for collecting such Imbrium impact melts will be in talus materials from top of the rim. So far such impact melts have not been identified from the Apollo 15 returned samples, suggesting either that we are sampling the wrong place or that Imbrium impact melts may not be as abundantly distributed as we assume.

A search among the Apollo 14 samples also failed to identify a melt product which may represent the Imbrium impact melt. 14310 might be considered as a possible candidate, but this is unlikely. Its coarse, igneous texture suggests its derivation from a large body of melt, but not a large volume of melt, ejected from Imbrium that survived the transportation intact, some 450 km from the basin rim to the Fra Mauro site; deposited there, cooled and crystallized to produce 14310.

Therefore the search so far for the Imbrium impact melt has been unsuccessful. Our next best bet is to try to bracket the age of the Imbrium event from its ejecta material.

(*a*) *Photogeologic evidence*

On the basis of the photographs shown in figures 2 and 3, the furrowed ridge and valley materials at the Fra Mauro site are traceable back to the Imbrium basin as Imbrium ejecta. Within the furrowed terrain, figure 4 shows that many boulders were excavated and thrown out on their flank by the Cone crater event. Samples 14312 and 14319 were collected on top of the boulder, next to a feature that resembles a turtle (figure 5). Both samples were removed without effort, suggesting that they were not coherently and tightly bound by the matrix. Figures 2–5 are evidence that boulders from which samples 14312 and 14319 were collected may indeed be samples of Imbrium ejecta. If they were of local origin, they should not be a part of the furrowed ridge and valley terrain but buried by Imbrium ejecta.

As discussed above in the section on basic considerations, the furrowed ridge and valley deposits of the Fra Mauro site are part of the low angle ground hugging and gouging ejecta from Imbrium. Hence it is unlikely that secondary craters could have been an effective process at the Apollo 14 site for excavating pre-Imbrian local materials.

(*b*) *Temperature estimates of the Imbrium ejecta deposit at the Apollo* 14 *site*

On the basis of the occurrence of unannealed anorthositic polymict breccias (such as 14063) and the low seismic velocities of materials underlying the Apollo 14 site (obtained by active seismic experiments), I suggested (Chao 1973) that the Imbrium ejecta at this site is loosely consolidated and represents a low to moderate temperature deposit (less than 700 °C, see discussion above). The strongly thermally recrystallized hornfelsed breccias of noritic composition were interpreted as pre-Imbrian, probably thermally metamorphosed at depth prior to the excavation by the Imbrium event. As indicated by the hottest ejecta, suevite, from the Ries, it is very unlikely that ejecta material produced by local craters such as the pre-Imbrian Fra Mauro crater (Head & Hawke 1975) would be hot enough to produce the hornfelsed textures of 14311, unless it was completely enclosed in impact melts (which it was not). Although the Apollo 14 hornfelsed breccias have not reached the polygonal metamorphic textures of the equilibrated 15415 and 76535 rocks cited by Stewart (1975) as only possible at great depths, on the basis of his calculations the Apollo 14 hornfelsed breccias could not have been produced by annealing in an ejecta blanket several hundred metres thick, cooled on the lunar surface from a starting temperature of 1000 °C (an overestimate recognized by Stewart).

Table 1. General composition of Apollo 14 and 15, Apollo 16, and Apollo 17 materials

			Apollo 16		Apollo 17	
	Apollo 14	Apollo 15				
	fines	fines	fines		LRV6 fines	
	14259, 12 (1)	15091, 38 (1)	61220, 2 (1)	68415, 79 (2)	74121, 16 (2)	77135, 77 (3)
SiO_2	48.16	46.47	45.35	45.9	44.9	46.3
TiO_2	1.73	1.31	0.49	0.28	2.47	1.48
Al_2O_3	17.60	17.47	28.25	28.19	18.75	18.39
FeO	10.41	11.57	4.55	4.01	10.43	9.48
MgO	9.26	10.50	5.02	4.41	10.20	12.19
CaO	11.25	11.77	16.21	16.39	11.73	10.96
Na_2O	0.61	0.41	0.42	0.47	0.44	0.65
K_2O	0.51	0.18	0.09	0.06	0.14	0.23
P_2O_5	0.53	0.16	0.10	0.07	0.12	0.28
MnO	0.14	0.17	0.06	0.05	0.13	0.11
Cr_2O_3	0.26	0.24	n.d.	0.07	0.23	0.18
S	n.d.	n.d.	0.06	n.d.	n.d.	n.d.
total	100.46	100.25	100.60	99.90	99.54	100.25

(1) Chao *et al.* (1975*a*), (2) Nava (1974), (3) Winzer *et al.* (1974). n.d., not determined.

(*c*) *Nature and composition of the Apollo* 14 *and* 15 *materials*

Except for feldspathic basalts 14053 and 14310, the bulk of the Apollo 14 samples are hornfelsed breccias of noritic composition and unannealed polymict anorthositic breccias (Chao 1973). The bulk compositions of the Apollo 14 samples are reasonably similar to the Apollo 15 highland samples from the foothills of the Apennine Mountains at Hadley Rille. They are characterized by moderate Al_2O_3 and high 'kreep' (table 1). The similarity is consistent with the photogeologic evidence that the Apollo 14 and 15 materials have the same provenance.

(*d*) *Alternative interpretation*

An alternative interpretation is that the Apollo 14 materials are locally derived. The hornfelsed breccias are described as produced by pre-Imbrian local craters and brought up by secondary impacts by ejected blocks from the Imbrium basin (Head & Hawke 1975). Citing suevite from the Ries, I have indicated it is extremely unlikely that samples such as 14311 could have been produced by annealing in a hot ejecta of the crater Fra Mauro. I have also presented the interpretation that the furrowed ridge and valley deposits are products of low angle ejecta transport. Hence it is not a region with abundant secondary craters. On the basis of these considerations, I disagree with the proposal that the Apollo 14 samples are of local origin.

(*e*) *Age of the Imbrium event*

I reaffirm that the maximum age of Imbrium is the youngest age of the melt rock 14310. It has an internal Rb/Sr isochron age of 3.88 ± 0.04 Ga (Papanastassiou & Wasserburg 1971). The minimum age of Imbrium is the age of the first post-Imbrian mare lava flooding and pre-Orientale. As shown below, the probable age of the Orientale event is 3.84 Ga. Hence the best estimate of the age of the Imbrium event is between 3.90 and 3.84 Ga.

4. The Apollo 16 highland samples and the age of the Orientale event

The Apollo 16 site near the Descartes highland was originally chosen to collect samples of typical Cayley-type light plains material. This material was believed to be of volcanic origin and material of the adjacent Descartes highland was also believed to be of volcanic origin (Trask & McCauley 1972). The returned samples indicated that except for a few rocks (among them 68415), most of this material is impact breccia; and the lunar light plains, at least at this site, are not volcanic in origin.

(*a*) *Reinterpretations of the photogeologic data*

Chao *et al.* (1975*a*) reinterpreted the origin of the Cayley-type lunar light plains in order not only to deduce the place of origin of the Apollo 16 samples but to account for the moon-wide distribution of light plains. Such plains are photogeologically dated to be post-Imbrium and pre-Mare. In that paper, we argued that the Cayley-type light plains are Orientale ejecta on the basis of the contemporaneity of the Cayley-type material with the Hevelius formation, which is clearly Orientale ejecta. Recently, however, Neukum, König, Storzer & Fechtig (1975) have resolved different crater densities on different areas of light plains and interpret these results as meaning that the light plains cannot all be of the same age. I feel that their results do not necessarily contradict the hypothesis that many or most light plains are Orientale ejecta deposits (we do not claim that all light plains are of the same event or identical origin (Chao *et al.* 1975*a*)). The random distribution of impact craters on the lunar surface prior to reaching saturation is not likely to be of a single unique density; instead it should be represented by a range with variation of crater densities from place to place. I therefore expect that the variation of the crater counts of the light plains studied by Neukum *et al.* (1975) could realistically represent variations on the same surface.

(*b*) *The Ries cratering model and the lineated and smooth ejecta from Orientale*

In discussing the applicability of cratering models to lunar studies (Chao 1974), I emphasized the importance of low angle ground hugging ejecta transport. Comparison with the schlifffläche and roll-out type of ejecta (Chao, unpublished data) of the Ries suggests that the Hevelius formation around the Orientale basin (with its lineated trends, 'flow' lobes and deceleration 'dunes' (Trask & McCauley 1972)) is the best example of low angle ejecta transport in the lunar environment. Chao *et al.* (1975*a*) have interpreted the lunar Cayley-type light plains as the smooth facies of the throwout ejecta from Orientale.

(*c*) *The temperature estimates and nature of ejecta at the Apollo* 16 *site*

The Apollo 16 materials can be classified into the following major categories (Chao *et al.* unpublished data): (1) regolith breccias, (2) monomict anorthositic breccias and cataclastic anorthosites, (3) polymict feldspathic breccias, (4) thermally metamorphosed noritic to anorthositic breccias and hornfelses, (5) xenocrystic vesicular rocks with melt textures, (6) complex remobilized feldspathic breccias and (7) highly feldspathic basalts. In bulk composition, most of these rocks are quite high in lime and alumina content due to the presence of abundant calcic plagioclase, and low in alkalies and titanium (table 1).

As suggested by the nature of the returned hand specimens (although the relative abundance of each type is unknown) and the low seismic velocity at the site, the ejecta blanket here is probably loosely consolidated and the glass content is low. A large number of the samples studied show extensive microfracturing and only low to moderate degrees of shock. Those with intense shock history may be the results of impact and derivation from local craters. My impression is that the Apollo 16 site Cayley-type ejecta material is a low temperature ejecta, perhaps even lower in temperature than the Apollo 14 samples. This would be consistent with respect to the distance from its place of origin (Orientale), as inferred by analogy with the Ries cratering model.

(*d*) *Alternative interpretation and the single importance of* 68415

An alternative interpretation of the Apollo 16 samples is that they are of local origin unrelated to any specific large multi-ring structure. It is suggested that these samples were dug up by secondary craters produced by ejecta blocks from Imbrium or from local large craters (Oberbeck 1975; Oberbeck *et al.* 1975; Head 1975). Chao *et al.* (1975*a*) and Chao (1974) suggested, however, that secondary cratering does not excavate large volumes of local materials.

The characteristics of sample 68415 are highly significant with respect to the question of the possible local origin of the Apollo 16 rocks. 68415 is a highly feldspathic pigeonite basalt (Helz & Appleman 1973). Whether it crystallized from an impact melt (Helz & Appleman 1973) or from an endogenic partial melt (Walker *et al.* 1973) has not been resolved. Its Rb/Sr internal isochron age is 3.84 ± 0.01 Ga (Papanastassiou & Wasserburg 1972). The chemical composition of 68415 (Nava 1974) is identical to the composition characteristic of the Apollo 16 Cayley-type material (table 1). 68415 is the youngest melt rock at the Apollo 16 site (coarse fines of feldspathic basalt have been estimated to be about 10 % of the Apollo 16 samples from sites 1, 4 and 8–11 (Dungan, Powell & Weiblen 1975)). Its age sets the maximum age of this ejecta.

Implied in the local origin interpretation is that the material represents an older surface, an older ejecta from a large local crater. These ejecta whether they were from local craters, or from large nearby craters such as Theophilus or Nectaris must be older than the Imbrium ejecta (between 3.90 and 3.84 Ga). This is in direct contradiction with the age of 68415.

68415 is probably not an impact melt produced by a small local crater. Its homogeneous igneous textures suggest crystallization from a large volume of homogeneous melt of either endogenic origin or an impact melt of a very large basin-forming impact event.

(*e*) *The age of the Orientale event*

If we accept the arguments presented here and in Chao *et al.* (1975*a*), then the age of the Orientale event is 3.84 Ga, bracketed by the age of 68415 and the oldest mare basalt from Apollo 17.

5. The Apollo 17 highland samples and the age of Serenitatis

The Apollo 17 site was in part selected to sample the most prominent ring of rocks of Serenitatis basin, from the North and South Massifs. At this site, the geologic setting with respect to the Serenitatis basin is like that at the Apollo 15 site with respect to the Imbrium basin.

(*a*) *Photogeologic data*

The North and South Massifs are interpreted photogeologically either as uplifted wall rock or as ejecta of the Serenitatis basin. The samples from stations 6 and 7 at the foot of the North Massif came not from the top but from about 1/3 down from the top.

(*b*) *Nature and bulk composition of some of the North Massif rocks*

The principal highland rocks collected from the North Massif are represented by samples such as 77135 ('green-grey' breccia) and 77115 ('blue-grey' breccia). The petrology and petrogenesis of 77135, a xenocryst-bearing feldspathic pigeonite basalt, and 77115, a finer-grained similar basalt (Chao *et al.* 1975*b*) have been described. These Apollo 17 highland rocks and the soils and coarse fines from the South Massif have a bulk composition intermediate between those of the Apollo 14 and 15 sites and those at the Apollo 16 site (table 1). The data from table 1 thus represent the major compositions and rock types of the lunar highlands.

Unfortunately, no sample of Serenitatis impact melt has yet been identified or firmly established, hence again we are faced with a problem of bracketing the age of the Serenitatis event from samples of the Serenitatis ejecta. Moreover, in the case of the Apollo 17 samples, we have a further complication: we are not even sure which highland samples are truly Serenitatis ejecta.

(*c*) *Radiometric age of* 77135 *and its implication for the age of Serenitatis*

77135 is the youngest of 4 samples, based on geologic relationships, collected from the Station 7 boulder (Chao *et al.* 1974). If it is from Serenitatis ejecta, the Serenitatis event cannot be older than its crystallization age. However, if it is a part of the Serenitatis basin uplifted wall rock, its age should definitely be pre-Serenitatis. A Rb/Sr internal isochron age is not available for this rock but the ^{40}Ar/^{39}Ar age based on the interpretation of the release pattern is 3.87 ± 0.07 (Stettler, Eberhardt, Geiss & Grögler 1974; Stettler *et al.* 1975). The large uncertainty in this age is attributed to the fact that the 77135 sample was measured without separating out all the xenocrysts and xenoliths in the vesicular matrix. If the older xenocrysts and xenoliths have not been completely equilibrated with the melt, then the 3.87 represents the maximum age of 77135!

If 77135 is not an impact melt but an igneous melt and could be interpreted as intrusive into the Serenitatis wall rock, then the date of 3.87 Ga is not related to the Serenitatis event in any way. However, if 77135 is an impact melt produced by the Serenitatis event and injected into the Serenitatis wall, then the age of Serenitatis could be inferred as 3.87. If 77135 were an impact melt as a part of the pre-Serenitatis wall rock then the age of Serenitatis is less than 3.87 Ga. This would be a most uncomfortable age for Serenitatis since the most reasonable age for the Imbrium event is between 3.90 and 3.84 Ga.

Because of these yet to be resolved questions, at this moment, the age of the Serenitatis event is considered to be unknown.

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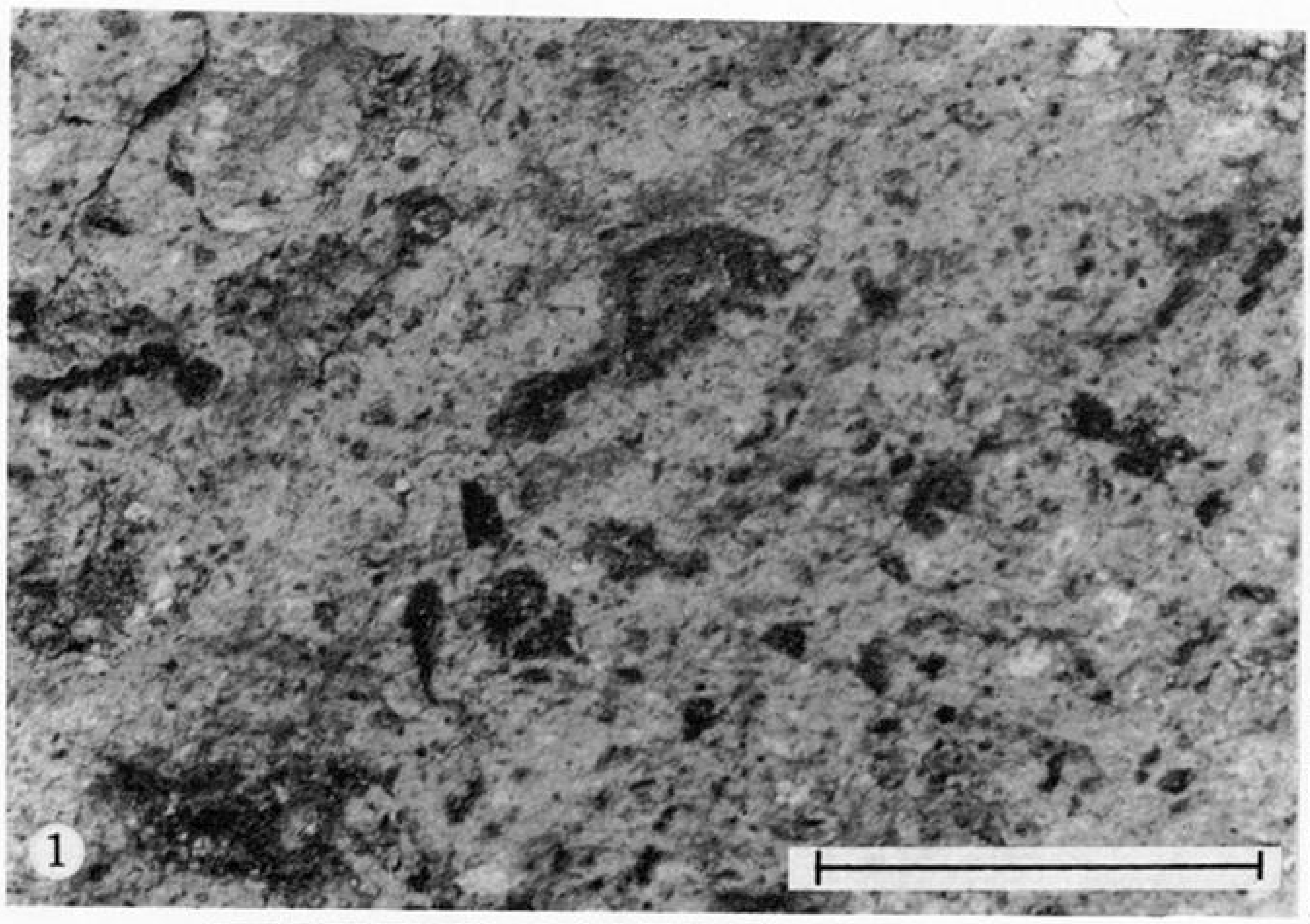

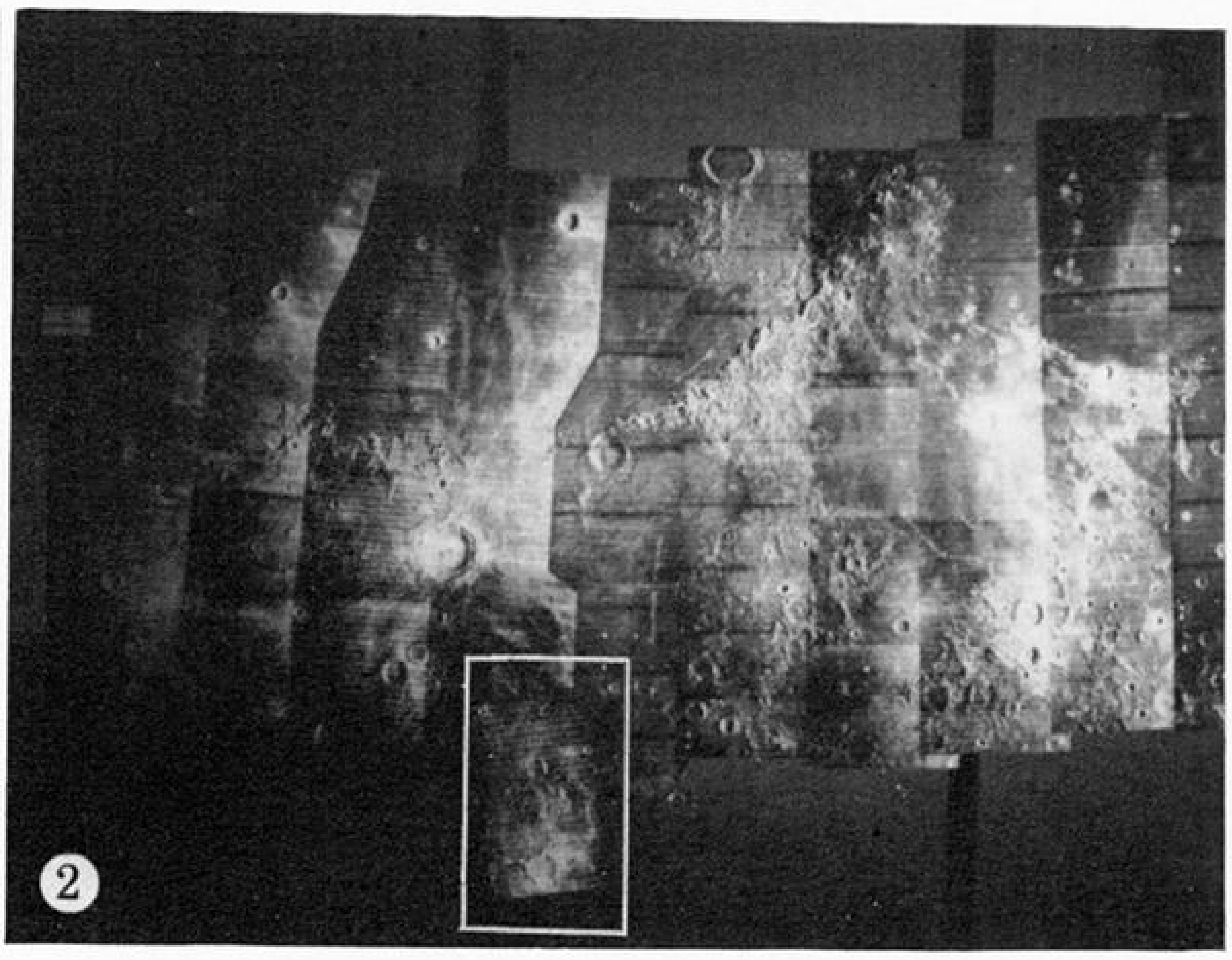

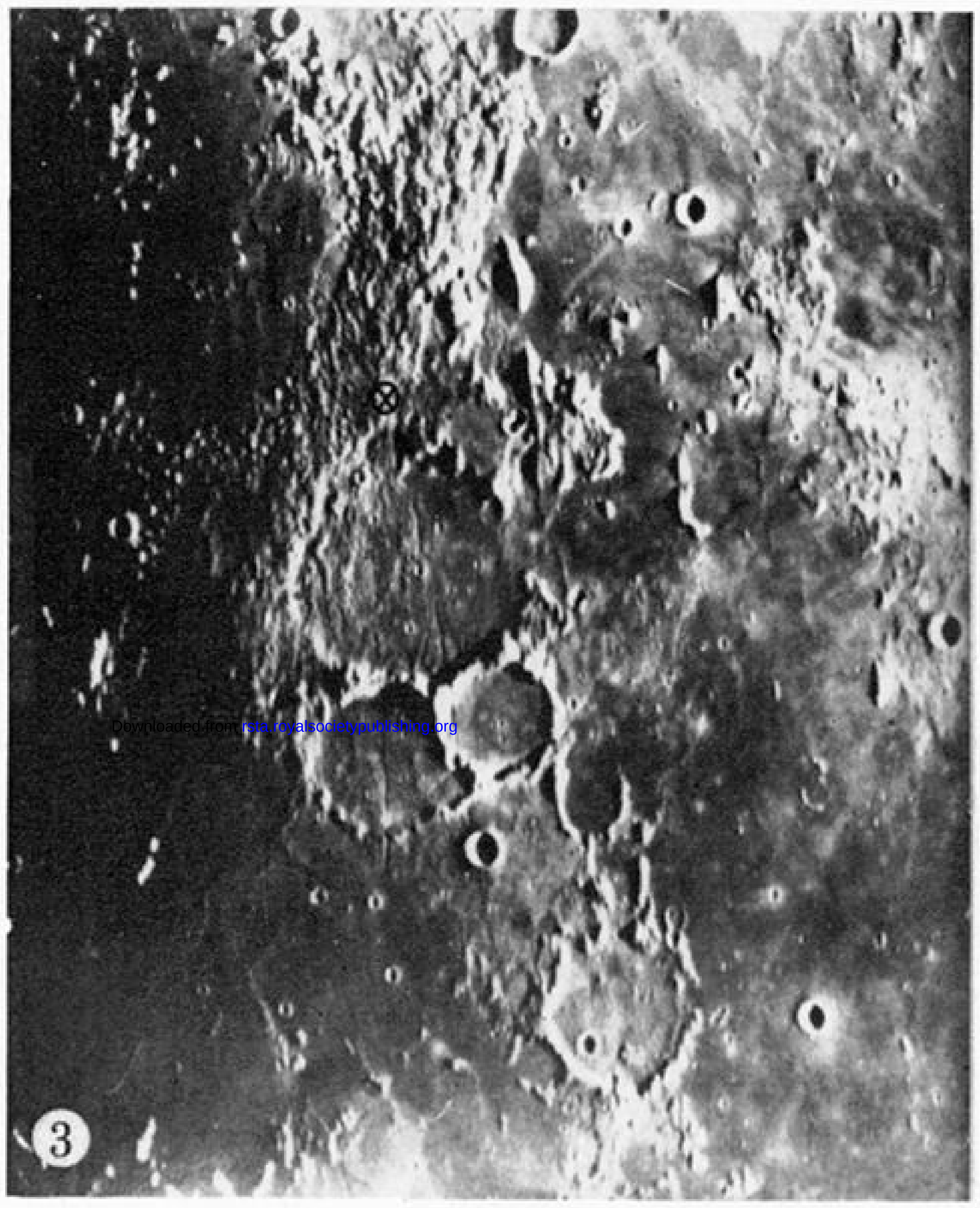

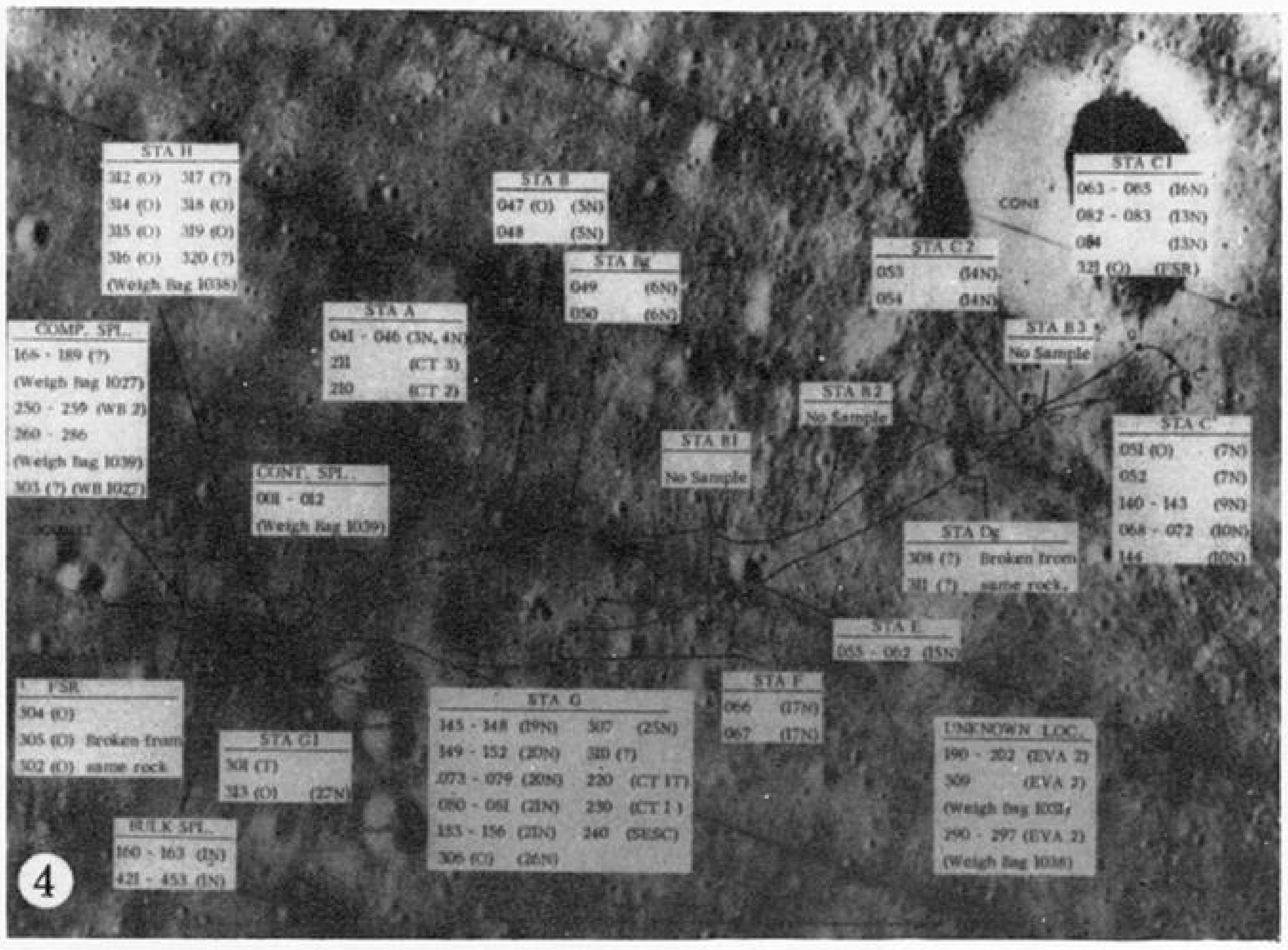

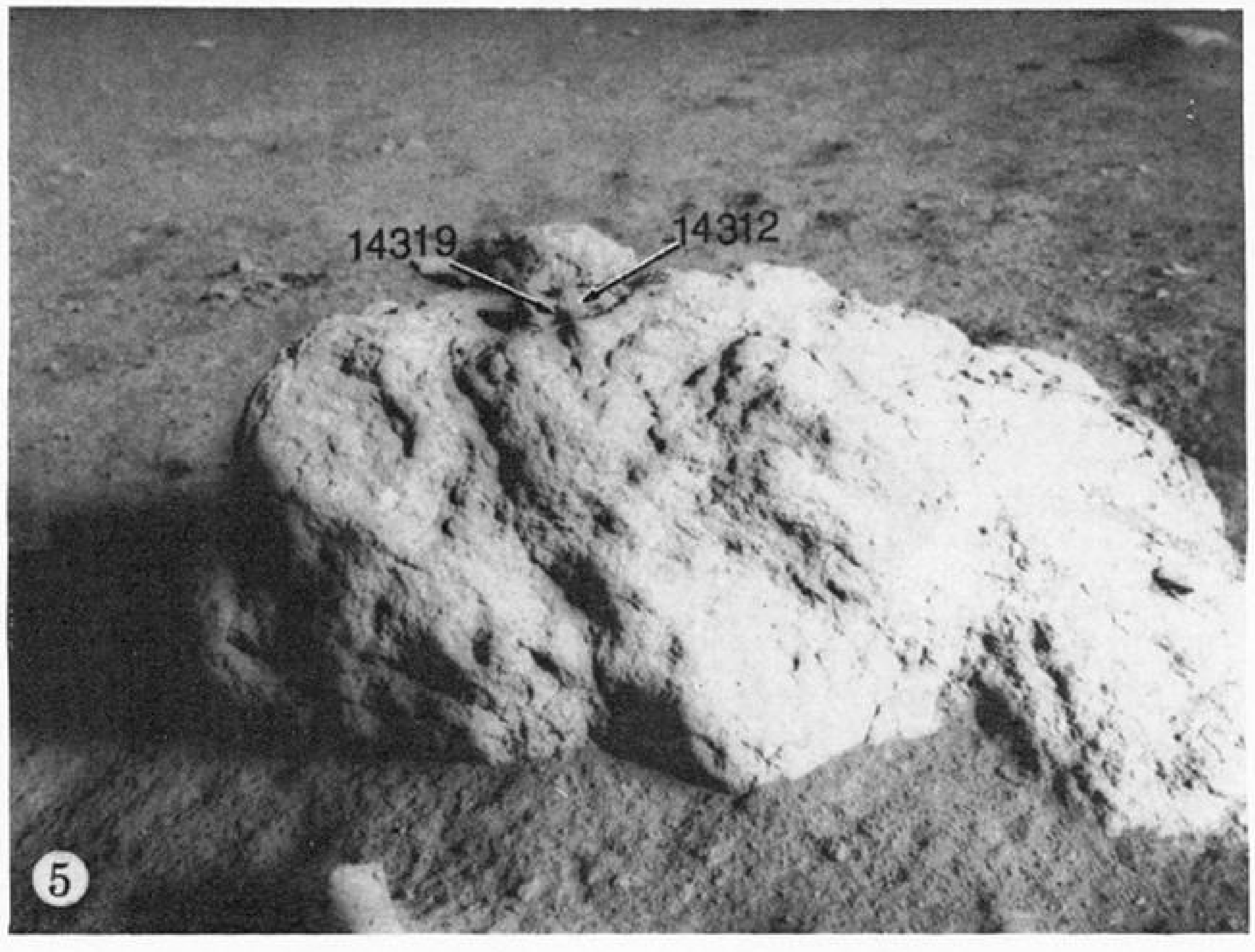

FIGURES 1–5. For description see opposite.