There you are, our mysterious and unknown Descartes highland plains, Apollo 16 is going to change your image.”

John Young could hardly have known the truth of his prediction when he first set foot on the lunar surface at the Apollo 16 landing site. His mission was the most surprising geologically and has generated the most controversy of all six Apollo landings. The Descartes region of the central lunar highlands, since its first serious consideration as a site for manned exploration 4 years earlier, had been strongly supported as a place to sample volcanic rocks much different from those of the maria and the basin margins. Three days of field exploration ranging 4 to 5 km from the lunar module failed to turn up a single recognizable volcanic rock. Instead, a variety of breccias, complicated beyond belief, were collected from every location. Crystalline rocks were found whose textures were clearly igneous (see frontispiece), but they were not volcanic. And therein lies the heart of the geologic mystery of Descartes.

“Well it’s back to the drawing boards, or wherever geologists go” (T. K. Mattingly, Apollo 16 Command Module Pilot from lunar orbit).

PREFACE

This volume contains the final results compiled by the Apollo Field Geology Investigations Team for the Apollo 16 mission. Some of the data presented here were reported in preliminary form shortly after the mission (ALGIT, 1972a. 1972b; AFGIT, 1973; Batson and others, 1972; Muehlberger and other?. 1972), hut most of the discussion and interpretations that follow are products of individual efforts which have incorporated much of the large body of data available from postmission studies of the rocks, the geophysical and geochemical data, and the extensive collection of photographs taken by the Apollo I6 astronaut crew on the lunar surface and from orbit. The chapter format was chosen to permit individual authors to develop their ideas independently, and we trust this approach will serve to stimulate rather than confuse the reader.

Our purpose in this volume is to summarize the field observations at the Apollo I6 site and to hring together the various interpretations placed upon these observations by the astronauts and the Field Geology Team. Much of the extensive geochemical and geophysical data puhlished since 1974 on the Apollo I6 site has not been incorporated or referred to here. The intent is not to provide a grand synthesis hut rather to document the local and regional geologic relations and to summarize what inferences can be made from them. Our expectation is that the volume will be used as a reference for researchers desiring tnore complete information on the geologic context of the Apollo 16 samples and on the interpretations of those intimately involved with the planning, execution, and analysis of the geologic exploration.

John Young, Charles Duke, and Kenneth Mattingly deserve special credit for the quality of their performance while exploring this complex area on the surface, from lunar orbit, and later in discourse with the lunar science community. Their continuing interest in the developing story of Descartes began with an unwavering enthusiasm for geologic training exercises in the field. With the able help of Anthony England, mission scientist and communicator during the EVA's. and Friedrich Horz, their geologic trainer in Houston, their competence as scientific investigators reached the high level shown by their ready adaptation to the unexpected conditions encountered on the mission.

A significant stimulus to the exceptional performance on the Moon was provided by the outstanding backup crew, Fred Haise. Edgar Mitchell, and Stuart Roosa, whose high scientific standards the prime crew was continuously challenged to surpass. We hope that the monthly mission-oriented field exercises planned and executed by members of the Field Geology Teatn prior to the Apollo I6 flight provided the variety of experience in field situations that enabled the crew to make the appropriate observations and geologic judgments required during the mission.

We received valuable assistance before, during. and after the mission from the following associates of the U.S. Geological Survey who are not credited elsewhere hut who nonetheless made significant contributions directly or indirectly to the preparation of this volume: N. G. Bailey, F. E. Beeson. B. M. Bradley. V. J. Fisher, M. H. Hait. E. D. Jackson, R. H. Jahns, D. F. .Johnson, J. S. Loman, R. S. Madden, R. Carroll, W’. E. Miller, R. A. Mills, J. C. Nuttall, D. L. Peck. R. F.. Sabala, 1.. T. Silver, R. B. Skinner. L. B. Sowers, G. A. Swann, H. F. Thomas.J. W. VanDivicr. and D. E. Wilhelms. Immensely helpful editing by James Pinkerton in preparing the manuscripts for publication was a monumental rask and is greatly appreciated.

M. B. Duke, Curator, and R. B. Laughon, Assistant Curator, Lunar Receiving Laboratory. Johnson Space Center, Houston. very kindly made arrangements for mrmbcrs of the Field Geology Team to study the Apollo I6 and I7 thin-section collections and to use their photographic equipment for illustrating some of the discussions in the field geology chapters of this report.

A. SUMMARY OF GEOLOGIC RESULTS FROM APOLLO 16

By WILLIAM R. MUEHLBERGER and GEORGE E. ULRICH

INTRODUCTION

The Apollo 16 mission to the central lunar highlands has provoked a variety of stimulating debates concerning the nature of the original lunar crust, the effects of impact processes on this crust, and the interpretation of lunar landforms from photographic evidence. Considerable disagreement remains about ultimate sources of the samples returned from the Cayley plains and the Descartes mountains. Although the major problems of origin and lunar processes may not be resolved in this volume, it is hoped that subsequent research will take into account the facts of field relations as recorded by the cameras and first-hand observations of the astronauts.

The arrangement of topics in this volume is partly chronologic in that discussions of geologic setting and mission planning are followed by sections on the field geology of four geographic areas sampled by the astronauts: central Cayley plains, North Ray crater, vicinity of South Ray and Baby Ray craters, and Stone mountain. These observation sections are followed by topical discussions on the petrology, regolith, South Ray ejecta distribution, optical properties, morphology, and stratigraphy of the landing site. A summary discussion of the source materials for the Cayley plains and Descartes mountains in the light of available data concludes the interpretive part of the volume. Supplementary sections on the surface photography and the documentation of samples collected by Apollo 16 are updated revisions of U.S. Geological Survey Interagency Reports, Astrogeology 48, 50, 51, 54, prepared immediately after the mission. Twelve folded plates in the separate case include nine plates of lunar surface panoramas mosaicked from 70-mm photographs and annotated with respect to geographic features and geologic data, a premission photomosaic map of the landing site (scale 1:25,000), a postmission geologic map of the landing-site region (1:200,000), and a postmission map of Imbrium-basin-related geology (1:5 million) for the near side of the Moon.

Some geographic names not yet approved by the International Astronomical Union are used informally in the text and figures where identification or reference to their location is considered essential to the discussion for purposes of context or clarification.

A glossary of abbreviations and acronyms used in the texts, illustrations; photographic and sample catalogs, and the photographic panoramas is appended to the volume.

The paragraphs that follow in this chapter are essentially abstracts of each of the succeeding separately authored chapters. Thus this section serves as an overview or extended abstract of the volume that incorporates the major conclusions reached in the independent chapters in the order in which they occur, beginning with the regional geologic setting and ending with the summary of geologic hypotheses.

Chapter A.-The Apollo 16 landing site permitted investigation of two geologic units that are widespread in the lunar highlands: light plains and mountainous “hilly and furrowed” terra, both superposed on old cratered terrain. Outside the landing area, they are embayed by, and are therefore older than, the maria. A volcanic origin for these units, generally accepted prior to the mission, was not supported by the mission results. Various hypotheses of impact-related origins have been proposed to explain the crudely stratified, impact-generated breccias found at the site.

Chapter B.-Apollo 16 was the only site within the central lunar highlands to be explored by astronauts on the surface. It is on the Cayley plains, which are relatively level as compared with the adjacent rugged Descartes mountains. The site is about 70 km west of the Kant plateau, which marks part of the third ring of the Nectaris basin, and about 600 km west of the center of that basin. Other multiringed basins that probably influenced the geology of the landing site are Imbrium, centered about 1,600 km to the northwest, and Orientale, centered 3,500 km to the west-southwest.

A geologic map of the landing site and vicinity (pl. 1) prepared after the mission illustrates a current interpretation of the distribution of geologic materials.

The geologic aspects of the Cayley plains and Descartes mountains can be summarized as follows: (1) The surface units are Imbrian in age; the plains surface has a cratering age that is similar to, if not identical with, that of Orientale basin ejecta cratering ages of the Descartes materials are not so well defined because of their rugged topography, but they are at least as old as Imbrian. (2) The site is within the "sphere of influence" of the Imbrium basin, as evidenced by the radial sculpturing of highlands northwest of the site and by the ridgy morphologic aspect of the Descartes mountains that appears nearly continuous with the Imbrium sculpture. Thus Imbrium ejecta and local material disrupted by the ejecta produced both the mountains and the plains. (3) Because of proximity to the Nectaris basin, the Apollo 16 stratigraphic column probably includes Nectaris basin ejecta at depth, but the basin is so old that these materials are no longer exposed, except perhaps in the lowest walls of the largest craters.

Chapter C.-The three lunar-surface traverses of the Apollo 16 mission were designed to insure maximum return of useful data for a community of scientists and engineers with widely varying objectives. Because the time available for geologic investigations and other experiments was limited, an intricate system of priorities was established for both station locations on each traverse and tasks to be performed at each station. The astronaut crew, John Young and Charles Duke, kept abreast of the planning and the constantly changing priorities, in addition to learning how to travel to and from the Moon. Their terrestrial field training for 18 months before the mission was designed to simulate the lunar traverses and to develop their skills in identifying and describing significant geologic features while photographically documenting and sampling the rocks and soils representing these features.

As a result, all primary geologic objectives were essentially achieved. Well-documented samples were returned from Cayley plains, North and South Ray crater ejecta and Stone mountain materials that may be representative of the Descartes mountains in this part of the lunar highlands. Photographic coverage of all sampling areas and the entire traverse route and telephoto views of all important points remote from the traverse area were obtained.

Chapter D1-D4 .-The central region of the Apollo 16 landing site was investigated at three locations, LM/ALSEP, station 1, and station 2. The samples documented probably represent materials of the underlying Cayley plains down to depths of 70 m or more and ejecta from more distant regions (specifically North and South Ray craters). The percentage of rock types collected from each station was clearly affected by time constraints and may therefore not be representative of the stratigraphic sequence. The most intensively sampled area, LM/ALSEP, probably yielded the most representative collection of the Cayley plains materials. The rock types are similar in all respects to those collected at other stations during the mission. They include fine- to medium-grained, moderately homogeneous crystalline rocks rocks; composed primarily of glass; and breccias, by far the dominant type. The variety of rock types collected indicates that the Cayley plains breccias are heterogeneous and suggests that they are composed of isolated pockets of both light and dark breccias deposited by a turbulent process.

Extensive sampling and photography on the rim (station 11) and near the outer edge of the continuous ejecta blanket (station 13) of North Ray crater provide a basis for stratigraphic interpretations in the northern part of Apollo 16 traverse area. Breccias on the rim and walls are of two main types, light matrix and dark matrix. The area1 distribution and petrographic relations of the boulders sampled or photographed suggest a generalized stratigraphic sequence within the crater and, by extrapolation, in the northern part of the landing site. The light-matrix boulders are friable, rounded, and heavily filleted. Their abundance on the rim and upper-crater wall suggests that they were derived from the upper part of the section. The dark-matrix boulders are coherent and appear to be the latest ejecta to fall on the crater rim. One of these, Outhouse rock, was the source of several igneous and metaclastic fragments. Most of the dark-matrix breccia smay be derived from a deeper horizon near the present crater floor.

Several types of evidence other than the fresh-rayed appearance argue for the youthfulness of North Ray crater. Spallation exposure ages of 27 to 51 m.y. have been reported for five North Ray rocks. Within that time interval, a very thin regolith (approximately a centimeter thick) formed locally; it thickens to 15 cm or more where it forms fillets around the friable light-matrix boulders.

South Ray and Baby Ray craters are fresh blocky craters in the southwestern part of the Apollo 16 landing site. Rays from South Ray can be traced as far as 10 km from the crater to the vicinity of North Ray crater. Although South Ray crater itself was not actually visited by the astronauts, Cayley plains materials ejected from it probably are present at most stations. Station 8 was purposely located on a bright ray from the crater to insure collection of South Ray materials;

dark-matrix breccias and light-gray igneous rocks were the two main rock types sampled. They appear to represent two lithologic units in South Ray crater, dark-matrix breccias being the upper unit.

The South Ray event, if correctly dated by the 1- to 4-m.y. exposure ages in the boulders, apparently deposited ejecta recognizable only in the coarse debris at station 8, about five crater diameters away. Associated soils are reported to give much older ages. No ejecta from the younger Baby Ray crater were recognized in the sample suite, although such materials may be present in small amounts.

Three sampling localities were established on Stone mountain at the south limit of the traverse area with the objective of collecting materials representative of the Descartes mountains. The two highest stations (4 and 5) appeared on premission photographs to be outside ray patterns related to South Ray crater, but contamination by South Ray ejecta appears likely at Station 4. The location of station 4a on the edge of ejecta from Cinco a crater suggests that samples collected might contain local material from a depth of 15 m on Stone mountain. Sampling at station 5, on the wall of a small crater shadowed from South Ray and void of visible blocky ray material, would be expected to include rocks of the Descartes mountains. Station 6, on a bench at the base of Stone mountain very near a ray, may be a mixture of fragments from the Cayley plains and materials of the Descartes mountains.

Chapter E.-Apollo 16 rocks are classified by a descriptive scheme into three groups: crystalline rocks, subdivided as igneous (C,) or metamorphic (C2); glass (G); and breccias (B,-B,), subdivided on the basis of clast and matrix colors and proportions. These rock-type symbols are used throughout this volume.

The crystalline igneous rocks consist of 1 certain and 1 possible anorthosite, 11 fine-grained ophitic to intersertal rocks of troctolitic to anorthositic composition, and 1 troctolite enclosed in fine-grained meltrock of the same composition. Derivation of the fine-grained igneous rocks by impact melting of feldspathic plutonic source rocks is indicated by the common occurrence of unmelted relics derived from coarse-grained plutonic rocks and a bulk compositional range like that of the plutonic rocks with essentially the same compositions.

Metamorphic crystalline rocks studied consist of 1 medium-grained granoblastic rock considered to be a product of metamorphism in a plutonic environment prior to excavation and 10 poikiloblastic rocks. Gradation from poikiloblastic to unequivocally igneous textures in these rocks is taken as evidence of metamorphic origin with minor melting.

Five breccia types have been derived by comminusion of a first-cycle breccia that consisted of anorthositic clasts in a fine-grained matrix ranging from melt texture to metamorphic texture. The first-cycle breccia is considered to be multiring-basin ejecta because it contains clasts of plutonic rock whose origin appears to be deep in the lunar crust. These breccias have been modified to varying degrees by subsequent smaller impacts.

Rocks representative of first-cycle breccias are sufficiently abundant in the Apollo 16 collection that least-metamorphosed samples may be identified. From some such samples displaying minimum modification, it should be possible to date the crystallization of the original crustal rocks, the preexcavation metamorphism of these rocks, and the time of excavation. A review of age data shows that most samples selected for isotopic measurement are so severely modified by subsequent impact that the ages are ambiguous. The samples petrologically most favorable for dating significant and identifiable events in the histories of the rocks are tabulated with the hope that they will help in obtaining unambiguous ages, because such data from Apollo 16 rocks are now so scarce that basin chronologies are only speculation.

The distribution of the various sample types shows no significant differences between Cayley and Descartes materials. Statistical and compositional data on soils support the view that the Cayley Formation and materials of the Descartes mountains are facies of the same ejecta deposit. The Cayley Formation may contain a somewhat higher proportion of matrix consisting of melt and powdered rock.

Chapter F.-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 of which are higher for South Ray than for North Ray crater.

The regolith thickness on the plains has a median value of between 6 and 10 m based on photogrammetric measurements of 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 the accumulation of mass-wasted debris on a softer, weaker bedrock that may underlie much of the Descartes mountains.

Regolith compositions for most of the site are chemically similar except for North Ray soils, which are significantly enriched in alumina and depleted in iron, titania, and nickel by comparison with the remaining 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 are a homogenized mixture of the bulk rock analyses from the entire site.

Chapter G.-South Ray crater ejecta totaling 5 to 10 million m^3 are scattered over the Apollo 16 landing site in an irregular pattern that reflects a nonuniform mantle of debris. The ejecta thin rapidly from about 10-15 m at the crater rim to an estimated 1 cm or less of equivalent uniform thickness at the southern sample localities (stations 4, 5, 6, 8, and 9) and to less than 1 mm at the northern localities (stations 11 and 13). The power function best describing this thinning has a slope of approximately -3.0. The fragment population on the lunar surface (for sizes larger than 2 cm) can account for most of the total volume of ejecta, although an equal amount of finer grained material can be accommodated by the model.

Ray material from South Ray Crater can be determined best by the combined evidence of computer-enhanced orbital photographs and the density of fresh rock fragments observed on the lunar surface. Station 8 has the highest potential for materials from South Ray; next most likely are stations 9, 6, 4, and 5. The probability of identifying South Ray ejecta from field data for areas farther away than these stations (3.5-4 km from the crater) is remote. Possible exceptions are station 2 samples taken within a bright ray patch in the central part of the landing site.

Chapter H.-An investigation of the photometric properties of the Apollo 16 landing site indicates that albedo values of several areas, including the rim of South Ray crater, are 50 to 55 percent, the highest measured at any Apollo site. Measurements for the sampled areas range from 15 percent at the central area, 20 percent in the Stone mountain and station 8 areas, to 24 percent at North Ray crater.

The polarimetric properties of the north and east wall of North Ray crater reveal that very little, if any, crystalline material is present in that area and that, most of the rocks are more highly shocked than the Fra Mauro breccias at Cone crater.

Chapter I.-Four highland terrain types have been morphologically defined in the Descartes mountains in and adjacent to the Apollo 16 landing site. Lineated patterns of crater chains, ridges and scarps, and crosslineations represent three of these. These features exhibit both erosional and depositional characteristics whose orientations show that they were formed by the Imbrium impact event. The main highlands mass probably is a tongue of Imbrium basin ejecta. The fourth highland terrain type is represented by isolated mountains inferred to be older Nectarian massifs projecting through the mantle of Imbrium ejecta.

The mountain terrain can be traced beneath the Cayley plains. The plains materials are thin enough along some margins to reveal a subdued reflection of the buried mountain terrain but thick enough in central parts to conceal the mountainous unit. The gradational character of the morphologic contact between plains and mountains does not indicate intergradation between the units but rather the overlapping of Cayley fill on the edge of slightly older mountain terrain.

The smooth to gently undulating surface of the Cayley plains indicates high mobility of the plains-forming materials at the time of their deposition. Of the hypotheses currently offered, the concept that the plains represent fluidized ejecta from one or more multiring basins is most consistent with the morphologic evidence.

Chapter J.-The ejecta deposits from craters that penetrated materials beneath the Apollo 16 landing site, together with the morphologic characteristics of the craters themselves, provide the best clues for a stratigraphic interpretation of the region. The Cayley plains, whatever their source, consist of three textural rock units: light-matrix breccias, dark-matrix breccias, and nearly holocrystalline rocks. These materials are locally mixed but form a gradational assemblage compatible with a crudely layered sequence of rocks whose chemical composition is grossly homogeneous.

At the north end of the traverse area, samples from the ejecta of North Ray crater reveal a population dominated by friable light-matrix breccias. These rocks, easily eroded, account for the convex upper slopes of the crater wall and the rounded and deeply filleted boulders on the rim and ejecta blanket. The lowermost materials of the crater's floor mound are most likely represented by coherent glass-rich dark-matrix rocks found as sparse unfilleted blocks on the rim. The third main lithologic type is coherent light-gray igneous-textured rock that occurs interstitially in light-matrix breccias and as inclusions within dark-matrix breccias. This type, the holocrystalline rocks, reaches sizes of 50 cm at station 8 and occurs as smaller angular rocks in the central part of the landing site.

The relative abundances of the holocrystalline rock and the dark-matrix breccias at stations 8 and 9 and the photographic evidence for layering within South Ray and Baby Ray craters suggest that the crystalline rocks occur as large lenslike masses underlying and grading upward into melt-rich to melt-poor breccias within the upper 150 m over much of the site. A discontinuous resistant layer at about this depth, becoming shallower in the South Ray area, may be reflected as benches in some crater walls (such as South Ray) and by floor mounds in other kilometer-size craters within the Cayley plains. In the south-central and eastern parts of the landing site plains and everywhere in the nearby mountains, evidence for this layer is lacking.

The materials of the Descartes mountains in and adjacent to the traverse area show little evidence of layering. The dominant rock type below the regolith at the highest point sampled on Stone mountain is most likely light-matrix breccia. The upper 100 m or so of the North Ray crater wall appears to have the same lithology, possibly representing similar materials of Smoky mountain. The lack of coherent blocks in the ejecta of a fresh Copernican crater (Dollond E), about 1 km in depth, 35 km south of the landing site, and the high reflectance of the Descartes mountains indicate that they are made up mainly of friable light-matrix breccias.

Chapter K.-Several hypotheses have been proposed to explain the origin of the terra plains and the hilly and furrowed terra, both of which are nonvolcanic according to evidence from the Apollo 16 mission. Orbital and surface results of the mission, together with post-mission photogeologic investigations, suggest that ejecta from the Imbrium basin constitutes a major part of both plains and mountains at this site.

The younger Orientale basin provides a model for investigating basin deposits. Both erosional and depositional landforms occur in the ejecta blanket around the basin, and conspicuous lineations, together with lobate escarpments, strongly indicate lateral flow of materials. Pitting and grooving by secondary impact occurred contemporaneously with deposition of primary hummocky ejecta. Smooth plains deposits appear to be a late-stage fluid facies that ponded in topographic lows. Extrapolation from this young well-preserved basin to the older and larger Imbrium basin implies similar origins for similar morphologic features. Hummocky ejecta, plains, and secondary craters are recognizable around Imbrium. The close spatial association of Cayley-type plains with the Fra Mauro formation is strong evidence for a genetic relation to Imbrium. Furthermore, ridged Fra Mauro-type materials shown on Apollo orbital photographs appear to extend as far as the Kant plateau, forming a depositional unit that partly filled the crater Descartes.

The hypothesis considered most defensible is that primary ejecta from the Imbrium basin, which itself must have included a mixture of preexisting crustal materials, and probably debris incorporated en route, formed rugged deposits as far away as the Kant plateau. The resulting Descartes mountains were sculptured penecontemporaneously by secondary projectiles, also from Imbrium. Fluid, perhaps partly molten, ejecta entrained in these debris flows pooled in topographic lows. The morphology of plains within the belt circumferential to Imbrium is produced by a planar facies of ejecta from Imbrium. Because the ages of the Cayley-type planar surfaces, as determined by crater-erosion models and crater-frequency distributions, are equivalent to those of Orientale ejecta, "crater-clocks" appear to have been reset in some way by the Orientale event.

The Cayley Formation may have been somewhat analogous to a gigantic ignimbrite-incorporating lenses or pods of molten material in a matrix of cooler debris that flowed into topographic lows and produced subplanar deposits. The molten blobs must have retained heat long enough and been of sufficient magnitude to mobilize and thermally metamorphose the debris around them. Since igneous textures developed, cooling must have been relatively slow locally, possibly allowing this partly molten material to acquire the anomalous remanent magnetism recorded at the surface.

The Cayley Formation and the materials of the Descartes mountains, both largely derived from the Imbrium basin, may be veneered by debris from the Orientale basin or smoothed by the seismic effects of that basin impact. Nectaris ejecta (Janssen Formation) is undoubtedly present at depth. Conclusive identification of these various basin deposits in the samples returned from the Apollo 16 site awaits further investigation.