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# ASTROGEOLOGIC STUDIES

## ANNUAL PROGRESS REPORT

August 25, 1962 to July 1, 1963

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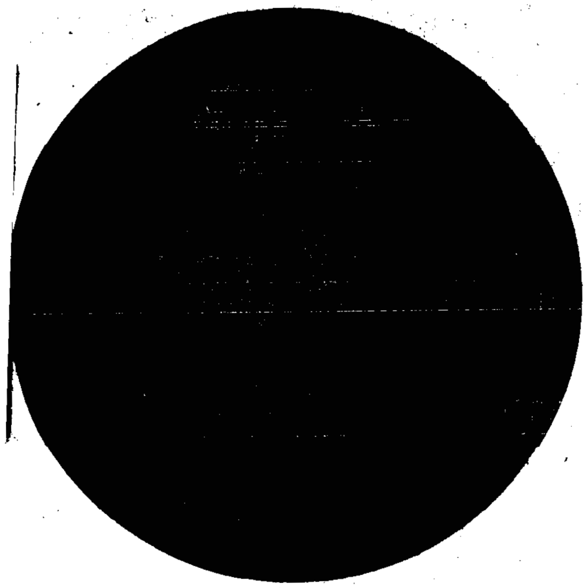

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UNITED STATES GEOLOGICAL SURVEY


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SUMMARY

June 1964



This report concerns work done on behalf of the National Aeronautics and Space Administration.

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

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CONTENTS

# INTRODUCTION

This Annual Report is the fourth of a series describing the results of research conducted by the U.S. Geological Survey on behalf of the National Aeronautics and Space Administration. This report, which covers the period August 25, 1962 to July 1, 1963, is in four volumes corresponding to four main areas of research: Part A, Lunar and Planetary Investigations; Part B, Crater and Solid State Investigations; Part C, Cosmochemistry and Petrography; and Part D, Studies for Space Flight Program. An additional volume presents, in abstract form, summaries of the Papers in parts A, B, C, and D.

The major long-range objectives of the astrogeologic studies program are to determine and map the stratigraphy and structure of the Moon's crust, to work out from these the sequence of events that led to the present condition of the Moon's surface, and to determine the processes by which these events took place. Work being carried out that leads toward these objectives includes a program of lunar geologic mapping; studies on the discrimination of geologic materials on the lunar surface by their photometric, polarimetric, and infrared properties; field studies of structures of impact, explosive, and volcanic origin; laboratory studies on the behavior of rocks and minerals subjected to shock; study of the effect of stress history on the solid state properties of rocks; study of the chemical, petrographic and physical properties of materials of possible lunar origin and the development of techniques for their microanalysis and nondestructive analysis; and engineering studies in aid of the design of space flight experiments and the planning of space missions.

Part A: Lunar and Planetary Investigations (with map supplement), contains the preliminary results of detailed geologic mapping on a 1:1,000,000 scale of a major part of the equatorial belt of the Moon. Detailed geologic relations in certain areas and some regional geologic problems are discussed.

Part B: Crater Investigations, includes a study of a naturally occurring analogue of a secondary cratering event; a report on the progress of shock equation of state studies; reports on the high pressure polymorphs of silica, stishovite and coesite; and preliminary reports on field investigations conducted on meteorite craters of Campo del Cielo, Argentina, and the crypto-explosion structure of Flynn Creek, Tennessee.

Part C: Cosmochemistry and Petrography, includes reports on the chemistry of tektites, their behavior during heating, the nature of the magnetic spherules visible in some tektites and evidence for their presence in submicroscopic sizes in others. Reports on metallic iron and copper in stony meteorites are also included.

Part D: Studies for Space Flight Program, includes reports on the determination of lunar slopes by photometric methods; a method for outlining isotonal areas on the lunar surface; a derivation of the expected frequency of small craters on the lunar surface; and a report on the change of effective strength of target materials with crater size. Reports on a search for matter in the Earth-Moon libration regions, infrared studies, x-ray fluorescence of tektites, photogrammetry of small craters, and computer analysis of the pattern of varying albedo over the lunar terrain are also included.

The following reports were published during the reporting period August 25, 1962 to June 30, 1963:

Carr, M. H., 1962, A shock wave technique for determination of densities at high temperatures using strain gauges (abs.): Am. Geophys. Union Trans., v. 43, no. 4, p. 455-456.

Chao, E. C. T., 1963, Geological occurrences of some southeast Asian and Austrailian Tektites (abs.): Am. Geophys. Union Trans., v. 44, no. 1, p. 93.

Chao, E. C. T., and Littler, Janet, 1963, Additional evidence for the impact origin of the Ries basin, Bavaria, Germany (abs.), in Abstracts for 1962; Geol. Soc. America Spec. Paper 73, p. 127.

Cuttitta, Frank, Chao, E. C. T., Annell, C., Carron, M. K., and Fletcher, J. D., 1963, The alkali content of Texas Tektites (abs.): Am. Geophys. Union Trans., v. 44, no. 1, p. 93.

Eggleton, R. E., and Marshall, C. H., 1962, Pre-Imbrian history of the lunar surface (abs.): Am. Geophys. Union Trans., v. 43, no. 4, p. 464.

Fahey, J. J., 1963, Separation of coesite and stishovite (abs.), in Abstracts for 1962: Geol. Soc. America Spec. Paper 73, p. 149.

Gault, D. E., Shoemaker, E. M., and Moore, H. J., 1962, The flux and distribution of fragments ejected from the lunar surface by meteoroid impact (abs.): Am. Geophys. Union Trans., v. 43, no. 4, p. 465.

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Hackman, R. J., 1963, A lunar isotonal map (abs.): Photogramm. Eng., v. 29, no. 3, p. 477-478.

Linnes, K., Shoemaker, E. M., and Sternberg, S., 1962, Television photography, in A review of space research--Report of the summer study conducted under the auspices of the Space Science Board of the National Academy of Sciences at the State University of Iowa, Iowa City, Iowa, June 17-August 10, 1962: Natl. Acad. Sci.-Natl. Research Council Pub. 1079, p. 4-13 - 4-17.

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Mason, A. C., and Hackman, R. J., 1962, Photogeologic study of the Moon, in Kopal, Zdenek, and Mikhailov, Z. K., eds., The Moon--Symposium no. 14 of the International Astronomical Union: London, Academic Press, p. 301-315.

Mead, C. W., Chao, E. C. T., and Littler, Janet, 1963, Metallic spheroids from Meteor Crater, Arizona (abs.): Am. Geophys. Union Trans., v. 44, no. 1, p. 87.

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Moore, H. J., Gault, D. E., and MacCormack, R. W., 1962, Fluid impact craters and hypervelocity--high velocity impact experiments in metals and rocks (abs.): Am. Geophys. Union Trans., v. 43, no. 4, p. 465.

Morris, E. C., and Stephens, H. G., 1962, Photographic investigation of the Earth-Moon libration regions $L_4$ and $L_5$ from Mt. Chacaltaya, Bolivia (abs.): Am. Geophys. Union Trans., v. 43, no. 4, p. 465.

Roach, C. H., Johnson, G. R., McGrath, J. G., and Sterrett, T. S., 1962, Thermoluminescence investigations at Meteor Crater, Arizona: Art. 149 in U. S. Geol. Survey Prof. Paper 450-D, p. D98-D103.

Shoemaker, E. M., 1963, Application of photographic photometry to the geology of the lunar surface (abs.), in Proceedings of the Conference on lunar exploration, Blacksburg, Va., August 1962: Virginia Polytechnic Inst., Eng. Expt. Stat. ser. no. 152, pt. B, paper 10, 1 p.

Shoemaker, E. M., 1963, Astrogeology, a new horizon (abs.), in Abstracts for 1962: Geol. Soc. America Spec. Paper 73, p. 241.

Shoemaker, E. M., 1963, Impact mechanics at Meteor Crater, Arizona, in Middlehurst, Barbara, and Kuiper, G. P., eds., The solar system, vol. IV--The Moon, meteorites, and comets: Chicago, Univ. Chicago Press, p. 301-336.

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Steg, L., and Shoemaker, E. M., 1962, Libration point satellites, in A review of space research--Report of the summer study conducted under the auspices of the Space Science Board of the National Academy of Sciences at the State University of Iowa, Iowa City, Iowa, June 17-August 10, 1962: Natl. Acad. Sci.-Natl. Research Council Publ. 1079, p. 4-34-4-35.

Thorpe, A. N., Senftle, F. E., and Cuttitta, Frank, 1963, Magnetic and chemical investigation of iron in tektites: Nature, v. 197, no. 4870, p. 836-840.

Thorpe, A. N., Senftle, F. E., and Cuttitta, Frank, 1963, Magnetic and chemical studies of iron in tektites (abs.): Am. Geophys. Union Trans., v. 44, no. 1, p. 92-93.

## Summary of Part A

Geologic mapping of the Moon at a scale of 1:1,000,000 forms the base for the lunar investigations of the Geological Survey for the National Aeronautics and Space Administration. The geologic maps of the Kepler and Letronne quadrangles have been published in color. Preliminary geologic maps of the Copernicus quadrangle by E. M. Shoemaker and R. J. Hackman and Apennine Mountains quadrangle (now called Montes Apenninus) by R. J. Hackman were transmitted to NASA previously. Maps accompanying this report include a recompilation of the Montes Apenninus quadrangle by R. J. Hackman based on excellent new photography taken at the 120" reflecting telescope at Lick Observatory, and preliminary geologic maps of the following quadrangles: Aristarchus by H. J. Moore, Timocharis by M. H. Carr, Riphaeus by R. E. Eggleton, Hevelius by J. F. McCauley, and Mare Humorum by S. R. Titley. Mapping of the Ptolemaeus, Colombo, Theophilus, and Mare Vaporum quadrangles is in progress and will be completed in fiscal year 1964. Mapping also is in progress in the Mare Undarum, Langrenus, Pitatus, Grimaldi, Julius Caesar, Taruntius, and Mare Serenitatus quadrangles, and these will be completed in fiscal year 1965.

Maps forwarded to date cover more than a million square miles or two million six hundred thousand square kilometers. By the end of fiscal year 1965, the maps of the lunar equatorial belt, amounting to more than three million square miles, should be completed.

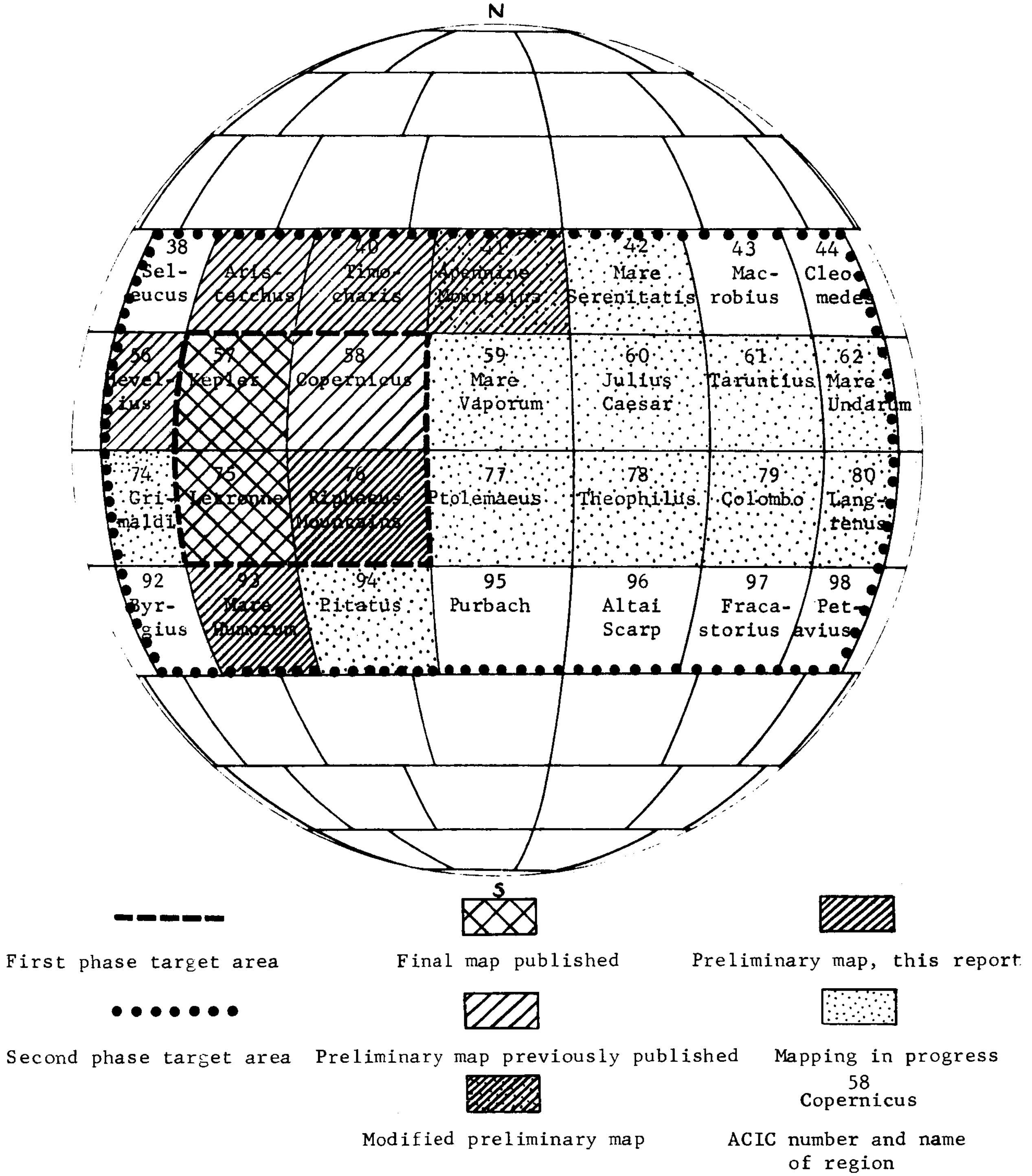


Figure 1. Index map of the Moon showing status of geologic mapping at a scale of 1:1,000,000.

With the completion of mapping the first phase target area, the Lansberg Region--comprising the Copernicus, Kepler, Letronne and Riphaeus quadrangles--which is the nominal target area for the unmanned lunar probes of the Ranger and Surveyor projects, a re-evaluation was made of the fundamental assumptions underlying the discrimination of lunar stratigraphic units. The validity of the Copernican system, chiefly consisting of deposits of ray craters, Erathosthenian system of deposits of post-mare craters without rays, and the Imbrian system, including the Archimedian series, consisting of deposits of pre-mare craters, and the Apennian series, consisting of regional deposits related to the formation of the Imbrium basin, on which the Archimedian crater deposits rest, was affirmed. A major change introduced in the stratigraphic nomenclature in the central part of the Moon is the removal of the Procellarum mare material from a time stratigraphic unit - the Procellarian System - to a rock stratigraphic unit - the Procellarum Group - with two formations, mare material and dome material, that are included in the Archimedian Series of the Imbrian System. The change was made necessary by the realization that Archimedian type craters and mare material have a long and complex inter-related history.

The typical lithostratigraphic breakdown of the rock units comprising the deposits of major lunar craters are: crater rim material, floor material, slope material, central peak material, and ray material, These rock units have been given formational rank and in many places two or more lithofacies in each unit have been discriminated.

The major part of the regional deposit of the Apennian Series, probably derived by ejection from the Imbrium Basin during its excavation, has been described in the Riphaeus quadrangle by R. E. Eggleton and named the Frau Mauro Formation. Another widespread unit which rests on the Frau Mauro Formation on the southern margin of the Imbrium Basin in the Montes Apenninus quadrangle has been designated the Apennine Bench Formation by R. J. Hackman.

Geologic mapping in the Timocharis Quadrangle by M. H. Carr has led to the recognition of features suggesting that an erosional process has occurred on the lunar surface. Study of the numerous secondary craters related to the Copernicus and Eratosthenes primary craters has shown that the Copernicus secondary craters have distinct outlines, well-defined rim crests, and commonly have cuspate outlines, whereas the Eratosthenes secondaries of equivalent size have indistinct outlines that are not cuspate, have rounded rim crests, and are less deep. Because Eratosthenes is demonstrably older than Copernicus, the Eratosthenes secondaries are thought to be a degraded form of Copernicus secondaries. Similar differences are found between the Rima La Hire I and Rima La Hire II. Rima La Hire II has a distinct outline and steep walls. Rima La Hire I is indistinct, has rounded walls, and is very shallow. Hence Rima La Hire I is thought to be an older degraded rill.

D. E. Wilhelms has encountered complex stratigraphy extending into the pre-Imbrian in his preliminary study of the Taruntius Quadrangle. Of unusual interest is the material of the Palus Somni which is smooth but has higher albedo than mare material of the Procellarum Group and is partly ringed with groups of small craters along its margins. In addition, in the Procellarum Group there appear to be at least two mappable types of mare material, one type being characterized by a distinct waviness of the mare surface. On the non-wavy mare material domes are probably more abundant than in any quadrangle studied so far. The majority of the domes have summit craters, but one has a small hill at its summit instead. Many craters on the maria seem to be aligned and there are also a number of rimless craters; Wilhelms suggests many of these craters are of volcanic origin.

E. C. Morris has traced the distribution of the Apenninian Series in the western half of the Julius Caesar Quadrangle. He finds that the Apenninian Series has partly filled in the southeastern portion of the pre-Imbrian crater Julius Caesar more than the northwestern part, a relation that is interpreted to be the result of deposition of the Apenninian Series from low angle ballistic trajectories originating within the Imbrium Basin. Beneath the Apenninian Series there may also be a deposit of material derived from the region of Mare Serenitatis which partly fills the southern portion of Julius Caesar more than the northern. The combined result is a depositional floor sloping slightly west of north.

Geological mapping of the Aristarchus Quadrangle by H. J. Moore has revealed a number of unusual features of probable volcanic origin. Broad circular or elliptical hills in the Harbinger Mountains, some with craters at their summits, have sinuous rilles on their flanks that extend on out onto adjacent mare surfaces. The material of the hills is similar in albedo to the mare material and has gradational contacts with the mare material. Moore has called it the Harbinger Mountains Formation which he interprets as consisting probably of volcanic flows or ash falls and flows. The Harbinger Mountains Formation may be of either Imbrian or Eratosthenian age. Other material of possible volcanic origin, including material underlying Schroter's Valley and material comprising a group of hills near the head of the valley, named the Cobra Head Formation, and material associated with a number of smaller sinuous rilles, has been placed by Moore in the Copernican System.

Mapping in the Hevelius Quadrangle by J. F. McCauley has led to investigation of the regional stratigraphic relations around Mare Orientale, a basin 320 kilometers in diameter, on the western limb of the Moon. Two new rock stratigraphic units of Imbrian age have been recognized in the region around the Orientale Basin; 1) the Cordillera Group, comprising a regional deposit surrounding the basin and apparently similar in origin to the Apenninian Series, and 2) the Cruger Group, composed of crater materials superimposed on the Cordillera Group and overlain by the Procellarum Group. Both the Cordillera and Cruger Groups are in the Archimedian Series.

Some of the oldest rock units were found by D. P. Elston during mapping on the Colombo Quadrangle. The oldest unit crops out in an arc of low hills of subdued relief peripheral to the northeast part of the Nectaris Basin and is informally named the Pyrenees Formation. It is interpreted to be the remnant of a regional blanket of material around the Nectaris Basin. The next younger unit comprises a distinctive group of crater deposits, characterized by the crater Gutenberg. The plan outline of this class of craters commonly is markedly polygonal, and crater floor material consists of jumbled blocks. Resting on the Gutenberg Crater deposits is a blanket of material that forms a plateau and highlands area in the northern part of the Colombo Quadrangle. This material, informally named the Censorinus N Formation, overlies, wholly or in part, several Gutenberg-type craters whose forms are still distinguishable through the blanket. The Censorinus Formation is interpreted to be part of a regional blanket of material derived during an event that occurred to the north. The youngest unit of probable pre-Imbrian age in the quadrangle forms as a patchy veneer of smooth material on the Censorinus N Formation, and may be equivalent to other smooth materials of regional extent found peripheral to the Serenitatis and Imbrium Basins.

New stratigraphic units of Imbrian to pre-Imbrian age were also recognized by S. R. Titley in his study of the Humorum Quadrangle. These are the Humorum Group, composed of a rim and a bench unit, and the Gassendi Group, representing the deposits of craters younger than Humorum Group but flooded by mare material of the Procellarum Group of Imbrian age. The units of the Humorum Group are peripheral to the Humorum Basin, a feature 300 km in diameter, the rim unit constituting part of a regional deposit apparently analogous to the Fra Mauro Formation and the Cordillera Group of McCauley.

## Summary of Part B

Brian J. Skinner and Joseph J. Fahey have investigated the inversion rate of Meteor Crater stishovite, a very dense form of $SiO_2$ in six-fold coordination, which inverts to silica glass in four-fold coordination. The inversion rate, determined at ten temperatures between 300° and 800°C and extrapolated to the time for total inversion of stishovite to silica glass, indicate the virtual impossibility that stishovite can be formed and preserved at the surface of the earth by any mechanism other than meteorite impact.

Coesite and stishovite, the high pressure polymorphs of silica, were recovered by Joseph J. Fahey from the shocked Coconino Sandstone at Meteor Crater by repeated treatments using hydrofluoric acid, but much less readily than is quartz, and can be obtained by repeatedly heating the host material with a 5 percent solution of hydrofluoric acid at 25°C. Colloidal and suspensoidal particles of coesite can then be separated from the residual quartz by repeated shaking and decantation in water.

Further, detailed geologic mapping by E. M. Shoemaker and R. E. Eggleton on the east flank of the nearly circular Sierra Madera disturbance in West Texas, identified three previously unrecognized units: The Tessey Formation of Permian age, a thin section probably of the Bissett Formation of Triassic age, and a thin unit of probably Triassic claystone. The presence of these units shows there is no significant angular unconformity between the rocks of Permain and Cretaceous age. To date, the detailed mapping has been confined to a zone of thrust faults and related folds that surround a central lens of megabreccia. The thrusts dip toward the center and the upper plates are displaced outward. Within each thrust plate the beds are buckled and locally cut by subordinate thrust faults and be steeply-dipping normal reverse and tear faults. Horse blocks of the basement Sandstone of Cretaceous age occur along the thrusts and tear faults. Eastward from the center of the structure, displacement on the thrust faults decreases, thrusts die out in asymmetrical anticlines with axial planes dipping back toward the center, and the intensity of buckling decreases.

The additional data are compatible with the concept that the structure resulted from meteoritic impact.

An expedition consisting of representatives from Lamont Geological Institute, Direcion de Geologia y Mineria, Argentina, Mellon Institüte, and Carnegie Institute of Technology, and Daniel J. Milton of the Geological Survey made the first detailed examination of the Campo del Cielo, Argentina meteorite and crater field. The expedition confirmed the impact origin of several craters, located and mapped seven craters, and acquired a newly found iron meteorite of about three tons for the U. S. National Museum. In addition, the number of small iron meteorites collected from this field was increased from a handful to more than 400 establishing Campo del Cielo as probably the largest known meteorite strewn field. Excavation of the best preserved crater revealed charcoal that may represent wood buried beneath loose throwout and burned in a fire caused by the meteorite fall. $Carbon^{14}$ age of charcoal was determined by Wallace Broecker of Lamont Observatory as 5,800, ±200 years.

A group of fresh, low velocity impact craters formed by a 950-foot rock fall of Toroweap Sandstone into the dry sand bed of the Little Colorado River, about 15 miles west of Cameron, Arizona was studied by D. P. Elston and D. J. Milton. One crater, having a diameter 5-7 feet and a depth of 2 feet, was formed by impact of a block of sandstone weighing about 175 pounds into a nearly level, slightly coherent sand bank. An apron of ejecta was deposited asymmetrically in a direction dominently away from the source of the rock fall and consisted of (1) a continuous blocky sand ejecta blanket extending from the crater lip to as much as four feet from the crater, and (2) a discontinuous sand ejecta blanket, in part ray-like, that extended to about 14 feet from the crater. The blocky blanket formed a distinct "hummocky" crater rim deposit. Geologic relations indicate that the material of the discontinuous blanket was deposited upon and beyond the crater rim deposit and was derived from the deepest part of the crater. Fragments of the impacting projectile were deposited in elongate trains traceable up the crater wall, across the blocky ejecta apron, and into the ray-like areas, forming the roughest material in the discontinuous blanket. Craters such as this provide a good approximation of secondary impact craters, which are thought to be important features contributing to lunar topography.

Geologic mapping of the Flynn Creek, Tennessee, cryptoexplosion structure has been nearly completed by D. J. Roddy. The field studies have delimited, in an otherwise undeformed area, a circular deformed rim of Ordovician rocks, about 2.2 miles in diameter, enclosing an intensely brecciated rock consisting of rock fragments of Middle and Upper Ordovician age. The upper surface of the breccia is in the form of a crater, 300 feet deep, which contains a centrally raised structure of intensely disturbed rocks of Middle Ordovician age. The structure formed sometime in the interval that includes Late Ordovician to early Late Devonian time. A thin marine deposit of bedded breccia and cross bedded dolomite, possible basal Chattanooga, and an anomalously thick section of Chattanooga Shale of early Late Devonian age were deposited in the crater-form structure. The character of the breccia, the presence of shatter cones, the gross structural form, and the apparent lack of gravity and magnetic anomalies in detailed geophysical surveys, are compatible with a meteoritic impact origin.

Work has continued by M. H. Carr on the development of a rapid, inexpensive technique for explosively shock loading materials to permit the study of their behavior under varying pressure conditions. The most fruitful use of this technique is in shocking rock materials to known peak pressures so that the effects of known shocks on a variety of materials can be studied. This experimental technique can be used to obtain the Hugoniot or shock equation of state of a rock material and consists of passing an explosively generated shock wave through an-aluminum rod and then through the specimen. The time of passage of the shock wave past strain gauges on the aluminum and specimen are measured and the shock speeds are determined. From the two shock speeds, the shock equation of state can be determined by an impedance match solution, provided the shock wave in the specimen is a single step function. The technique, applied to copper, gave results that are in good agreement with the previously determined Hugoniot for copper. The results for Yule Marble indicate that a multiple wave structure is generated; thus an impedance match solution is invalid and no Hugoniot curve can be constructed. Results on Vacaville Basalt show that the measured speed of the shock wave is not pressure dependent and was essentially constant at 5.76, $\pm$.23km/sec over the pressure range studied. These results are similar to that found for gabbro by other workers, and may result from measurement of an elastic precursor at pressures less than 200 kb.

## Summary of Part C

New analyses for major and minor elements and physical-property determinations on 6 australites and 6 javanites have been made by F. Cuttitta, E. C. T. Chao, M. K. Carron, J. Littler, J. D. Fletcher, and C. Annell. New minor element analyses have also been performed on 6 indochinites, 1 additional javanite, 15 philippinites, and 2 thailandites. The new data indicate that Australasian tektites comprise at least two distinct chemical populations which are characterized by differences in 1) indices of refraction and specific gravities, 2) MgO/CaO ratios, 3) Cr, Ni, and Co contents, and 4) Cr/Ni ratios. The analyzed australites are similar to philippinites in that both kinds of tektites have MgO/CaO less than one and have low Cr, Co, and Ni contents. Indochinites and javanites are characterized by MgO/CaO values greater than one and Cr, Co, and Ni contents that are higher, in general, than in australites and philippinites. Physical and chemical data, such as these, point toward a better understanding of the extent of intermixing of tektites within each of the various regions comprising the Australasian strewnfield, and thereby, a means of reconstructing fall patterns.

E. C. T. Chao, E. J. Dwornik, and J. Littler have reported new mineralogic, petrographic, and chemical data on metallic spherules present in philippinites from the Ortigas site of Mandaluyong near Manila, Philippines, and in indochinites from Dalat, South Viet Nam. Most of the spherules contain kamacite, schreibersite, and troilite. Schreibersite is interstitial to the round or elongate, fine-grained kamacite, or forms blebs in a matrix of this kamacite. Where abundant, schreibersite forms a network throughout the entire spherule. Troilite generally comprises small round inclusions in the schreibersite. The amount of schreibersite in the spherules ranges from less than 5 to about 35 modal percent and the troilite constitutes as much as 5 modal percent.

The composition of the phases present in the metallic spherules was determined by use of the electron probe. The kamacite from metallic spherules in 9 philippinites contains from 1.6 to 4.5 percent Ni. The average Ni contents of kamacite in each of 3 analyzed spherules from indochinites are 4.7, 10.0, and 12.9 percent. The average Ni contents in each of 4 schreibersite grains in a single indochinite spherule ranges from 12.1 to 15.8 percent.

The spherules in the tektites are very similar to the meteoritic spheroids from Meteor Crater, Arizona, in texture and mineral assemblage. It is concluded that the spherules in the tektites were formed as molten droplets from an impacting meteoritic body which was instrumental in producing the tektite glass.

The magnetic properties of metallic spherules in tektites from Isabela, Philippine Islands, have been investigated by F. E. Senftle, A. N. Thorpe, and R. R. Lewis. Five metallic spherules from a single tektite were studied. They ranged from 0.02 to 0.04 cm in diameter and from 0.07 to 0.28 mg in mass. An electron probe analysis of one spherule confirmed the report of Chao and others (1962) that silicon, if present, is less than a few tenths of a percent.

Magnetic susceptibility measurements on the spherules were made by the Faraday method using a quartz helical spring balance. Measurements were taken at temperatures ranging from 303° to 77°K. The susceptibility was found to be independent of temperature and approximately the same in all spherules for given field strengths up to 6000 oe. Measurements of magnetic susceptibility as a function of field strength at 298° and 77° K showed that saturation occurs at relatively high field strengths compared to the saturation of pure iron. The specific magnetization of two of the spherules is about 1.85 Bohr magnetons per atom in fields in excess of 6000 oe. The permeability of the spherules is close to 1.38.

The large field - and temperature - independent susceptibility (0.03 emu/g) is not to be expected for an iron alloy of the composition of the spherules (about 3 percent Ni and 97 percent Fe). Some Ni and low-Si iron alloys lack magnetic saturation except at high fields as do the spherules, however, such alloys have very large permeabilities in contrast to the low permeability of the spherules. Also, the specific magnetization of the spherules is much higher than would be expected for a low-Ni iron alloy, but can be accounted for by the presence of Fe-Ni phosphides. These considerations indicate that the apparently abnormal magnetic properties of the spherules cannot be a direct result of their chemical composition.

The field-independent susceptibility of the spherules, except in very high fields, indicates the absence of a magnetizing field within the spherule. Considerations of the resultant field inside a spherule as a function of the applied field, the shape of the spherule, and the saturation magnetization shows that the field - and temperature - independent susceptibility is a direct result of the shape of the spherules.

The saturation of the spherules at relatively high field strengths indicates that the use of the equation of Owen (1912) and Honda (1910) to detect gross ferromagnetic impurities in tektites is valid only if there are no spherules present. Thus, the presence of spherules less than 1µ in diameter cannot be detected by this method or by microscopic examination.

Senftle, Thorpe, and Lewis have also found that measurements of magnetic susceptibility as a function of temperature is a possible technique for the detection of submicroscopic, metallic spherules.

The presence of a temperature-independent component of the susceptibility appears to indicate the presence of submicroscopic spherules. If the presence of spherules is established for tektites in general, it will give additional evidence of a meteoritic origin for tektites when combined with the known existence of relatively high phosphorus and nickel contents of the metallic spherules.

Additional magnetic susceptibility measurements by Thorpe and Senftle on 18 tektites from various strewn fields have shown a relatively large temperature-independent component of the magnetic susceptibility in all cases. The data indicate that this component is the result of submicroscopic iron spherules in the tektites. An investigation of the color of tektites in terms of the magnetic measurements and of the optical absorption spectra suggests that the basic color of all tektites is green or greenish-blue. The brown to black coloration in some tektites appears to be due to finely dispersed $Fe_2O_3$ and/or many submicroscopic, metallic spherules.

The vapor pressure and vapor fractionation of Philippine tektite melts of approximately 70 percent $SiO_2$ have been studied by L. S. Walter and M. K. Carron. The total vapor pressure at temperatures ranging from 1500° to 2100°C pressure is 190 $\pm$40 mm Hg at 1500°C, 450 $\pm$50 mm at 1800°C, and 850 $\pm$70 mm at 2100°C. Determinations were made by visually observing the temperature at which bubbles began to form at a constant low ambient pressure. By varying the ambient pressure, a boiling point curve was constructed. This curve differs from the equilibrium vapor pressure curve due to surface tension effects. This difference was evaluated by determining the equilibrium bubble size in the melt and calculating the pressure due to surface tension, assuming the latter to be 380 dynes/cm.

The relative volatility from tektite melts of the oxides of Na, K, Fe, Al, and Si has been determined as a function of temperature, total pressure and oxygen fugacity. The volatility of $SiO_2$ is decreased and that of $Na_2O$ and $K_2O$ is increased in an oxygen-poor environment. Preliminary results indicate that volatilization at 2100°C under atmospheric pressure caused little or no change in the $Na_2O$ or $K_2O$ percentage. The ratio $Fe^3/Fe^2$ of the tektite is increased in ambient air at a pressure of $9 \times 10^{-4}$ mm Hg ($=10^{-7.4}$ atm $O_2$, partial pressure) at 2000° C. This suggests that tektites were formed either at lower oxygen pressures or that they are a product of incomplete oxidization of parent material with a still lower ferric-ferrous ratio.

C. S. Annell has investigated the analysis of solutions by emission spectroscopy as a technique for the quantitative determination of the major constituents of tektites and meteoritic materials. Use of rotating disc apparatus in conjunction with high voltage spark excitation produces the characteristic spectra of many elements present in these materials. The spectral intensities can be measured and quantitatively related to known standards. Studies of experimental factors show that excellent working curves covering the elemental ranges exhibited by known tektites are obtained for aluminum, iron, magnesium, calcium, and titanium. Methods for detecting or determining other elements present in tektites are being studied.

A spectrographic method for the determination of Cs, Rb, and Li in less than 10 ppm concentrations in tektites has also been developed by Annell. A 1 ppm analytical limit for Cs was obtained using a 3-meter concave grating spectrograph. The method was primarily designed to determine the Cs content of tektites, with adaptation to Rb and Li determinations. The precision of the method was checked by duplicate determinations of Cs, Rb, and Li in bediasites from Texas and tektites from Southeast Asia and Indonesia.

M. K. Carron has developed modifications of Wilson's (1960) method for the determination of ferrous iron in milligram amounts of silicates. The modifications provide a means for high-precision determinations of ferrous iron in tektites using ordinary semi-micro laboratory equipment. The method presented here employs more dilute solutions of vanadium (V) (0.0139N) than proposed by Wilson. The excess vanadium (V) remaining in solution, after oxidation of the ferrous iron of the sample, is titrated with a 0.0139N ferrous ammonium sulfate solution, using a semi-micro burette graduated to 0.02 ml. The results obtained by the proposed method show excellent agreement with those obtained spectrophotometrically.

Methods using semi-micro X-ray fluorescence analysis of 50 mg samples of tektites have been developed by H. J. Rose, Jr., F. Cuttitta, M. K. Carron, and R. Brown. Determinations of $SiO_2$, $Al_2O_3$, total iron, $K_2O$, CaO, $TiO_2$, and MnO are in agreement with those obtained by conventional chemical techniques.

Metallic iron, occurring as a minor constituent in the basaltic achondrites, has been investigated by M. B. Duke. New electron probe analyses and petrographic data have been obtained from kamacite in six eucrites and one howardite. The low nickel content of kamacite in eucrites has been verified. Emission spectrographic analyses for nickel in pyroxene from several types of stony meteorites (Duke, 1963) and new electron probe analyses for nickel in the coexisting kamacite give a distribution factor that is in fair agreement with experimental determinations at atmospheric pressure and magmatic temperatures. The low nickel content of the metal and the generally low total nickel content of the basaltic achondrites is interpreted as due to fractionation between metal and silicate phases during magmatic differentiation of the basaltic achondrites. The nickel distribution supports other mineralogical and textural evidence that these rocks formed at relatively low pressures.

Metallic copper from the Norton County achondrite has also been investigated by Duke in collaboration with Robin Brett, of the Carnegie Geophysical Laboratory. Electron microprobe analyses of the copper indicate an iron content of 4.2 weight percent (Keil and Fredriksson, 1963).

However, phase equilibria relations from the system Cu-Fe-S (R. A. Yund, pers. comm.) suggest that the copper was formed below 475 $\pm$25°C, the temperature at which iron solubility in copper is negligible. Therefore, new electron probe microanalyses wave made of copper grains (5μ to 20μ) from the chondrites Miller, Penokee, and Bath. Iron contents ranging from 1.1 to 4.5 weight percent were obtained. Determinations varied within single copper grains, suggesting that analytical uncertainties were involved.

In order to assess the magnitude of $CuK_{\alpha}$ induced $FeK_{\alpha}$ radiation arising from outside the analyzed copper grains, four iron fragments were polished and given coats of metallic copper ranging from 0.8 to 3.5μ in thickness. These were analyzed with an ARL and the U. S. G. S.

microprobe. The intensity of induced FeK$\alpha$ radiation apparently decreases exponentially with the thickness of the copper layer, but is equivalent to 3 weight percent or more for iron covered by 3.5$\mu$ of copper. The lower the excitation potential or the lower the X-ray take-off angle, the smaller is the fluorescence effect.

On the basis of the phase equilibria data and the experiments with copper-coated iron, it is suspected that the analyzed values of iron in copper are unreasonably high due to fluorescence effects. It is necessary, therefore, to analyze large grains or separate the copper from the matrix in order to determine the true iron content.

## Summary of Part D

A photometric technique for measurement of lunar slopes has been developed by D. E. Wilhelms. The technique is based on the assumption that for slopes on lunar surface material of uniform albedo, the apparent brightness depends only on the angle of incidence of the sun's rays; therefore, slopes of equal brightness at two separate points differ by the difference of angle of incidence between the points. The angle of incidence can be determined at all points on any photograph whose time of exposure is known; if the slope at one point is known, the other can be easily calculated.

Horizontal areas are used as the known slopes. Brightness of segments of .75 to 1.5 km square of the lunar surface are determined by a microphotometer, along traverses perpendicular to the terminator. The record is in the form of both an inked line on a chart and a punched paper tape. With the chart, the curve which passes through horizontal segments can be drawn for each albedo unit (normal albedo must be mapped in advance by other techniques, such as that described below, using full-moon photography). The curve then serves as a comparison curve against which brightness of non-horizontal slopes can be matched. Angular distances in lunar longitude from the terminator, which closely correspond to the inclination of the sun's rays, are scaled off on the chart. By measuring the difference in longitude between the segment of unknown slope and the point of equal brightness on the comparison curve, the calculation of the slope is readily made.

By means of the punched tape, the calculations can be performed by computer. Since the report period, J. F. McCauley has successfully automated the technique, including automatic derivation of the comparison curves, and applied it to a large portion of the lunar equatorial belt, using existing telescopic photographs. In the future when photographs obtained from spacecraft become available, it should be possible to measure slopes of smaller segments than .75 km by refinement of the technique. Terrain maps obtained by this method are of great importance in planning unmanned and manned spacecraft landings.

Details of construction of an isotonal map of the Lansberg region are given by R. J. Hackman. Areas of equal density, determined by microphotometer, were outlined on a full-moon photograph. A high-contrast positive print (transparency) was used which enhanced tone differences in dark areas (maria), while suppressing those of light areas (terrae and rays).

While the densitometer was measuring density along traverses across the transparency, the lines of traverse were being automatically plotted on a Cronopac print of the same area on the same scale. The densitometer curves were recorded simultaneously on graph paper. These curves were compared periodically with a curve run over a standard density wedge, and the standard wedge steps scaled off on them; the curves were thereby divided into density units. The segments along the traverse corresponding to each of the density units were plotted on a 1:2,000,000 enlargement of the photograph. With these segments (along with 600 spot measurements) as control, and tonal patterns as visual aids, isotonal lines connecting points of equal density were drawn on the photograph. For the final portrayal of the map, the isotonal lines were transferred to ACIC Mercator projection lunar topographic charts by means of a Sketchmaster.

The tone values obtained are relative. They are compared with absolute normal albedo measurements made by other investigators by other methods.

Similar tone values are often a clue to correlation of lunar geologic units separated from one another. An isotonal map such as the one compiled correlates tones with greater precision than the unaided eye because the eye is influenced by surrounding tones. Also, small tonal variations that would escape the eye are detected by the densitometer. Isotonal maps are a prerequisite to the construction by photometric methods of lunar terrain maps, as described above, because effects of albedo must be separated from effects of variation in slope.

Kenneth Watson gives a historical summary of lunar infrared emission studies, and against this background, describes the investigations to be carried out in this field by the Branch of Astrogeology. Information from both temporal and spectral distribution of infrared emission will be utilized in interpretation and correlation of lunar geologic units. Both broad-band and narrow-band emission within the two major atmospheric windows of 8-14µ and 18-24µ will be examined. The broad-band studies will provide information on the distribution of thermal properties at and near the surface, while narrow-band studies will primarily provide information on the grain-size distribution of the lunar material, and possibly, in the case of bright-ray craters, a limited amount of compositional analysis. An important line of research will be the computation of models, supported by experiment and observation, to explain the infrared emission. At present, studies are being made on the use of models of the lunar photometric function to derive the variation of absorbed solar energy as a function of the inclination of the sun's rays.

Calculations of the density of small (telescopically unobservable) craters on the lunar surface are given by H. J. Moore. The results differ significantly from extrapolations of frequencies of telescopically observable craters 1 kilometer in diameter or larger. By combining data on hypervelocity impact cratering and data on the distribution of interplanetary dust, micrometeoroids, meteoroids, and asteroids, it is calculated that a billion-year-old surface composed of rock or sand would be completely covered with primary craters of all sizes up to 1 meter across in various stages of destruction. If craters 100 meters in diameter are destroyed by erosion and infilling in a billion years, about 10 percent of such a surface could be covered by well preserved craters between 1 and 10 meters in diameter, 10 percent by well preserved craters between .1 and 1 meter, and 10 percent by well preserved craters between .01 and .1 meter. The remaining surface area would be covered by primary craters .01 to 10 meters in diameter that are more than three-tenths destroyed, by rare larger craters, and by secondary impact craters. Secondary craters should be about one-tenth as abundant as primary impact craters of the same size except around large young primary craters, where secondary craters would be abundant.

Higher rates of crater destruction, as might result from flow of material or burial by volcanic products, would substantially alter these predictions. A smaller crater density is expected on surfaces younger than one billion years.

H. J. Moore, D. E. Gault, and E. D. Heitowit show experimentally that there is a decrease in effective target strength in basalt with increasing size of hypervelocity impact craters. The results are consistent with defect theory, which predicts a decrease in strength with increasing size of specimens containing defects. The experiments refute predictions that the amount of mass ejected for each unit of projectile energy (corrected for the projectile-target density ratio) should be constant.

Photogrammetric techniques for the construction of topographic and structural maps of small experimental impact craters are described by R. V. Lugn. Two overlapping photographs of the crater are taken normal to the surface of the target block. Vertical and horizontal scales are determined by comparing measurements of the crater with corresponding measurements made on the stereo model. Then, topographic and structural maps are prepared using standard procedures. These methods are essentially the same as those used in conventional aerial mapping.

Continued investigations of the Earth-Moon libration regions $L_4$ and $L_5$, at Mt. Chacaltaya, Bolivia, are reported on by E. C. Morris, J. Ring, and H. G. Stephens. The libration points, lying in the orbital path of the Moon 60 degrees ahead of and behind it, are points of equilibrium where centrifugal forces balance gravitational forces. It was hoped to observe clouds of particles ("Kordylewski's clouds") which may be trapped at these points. During the summer and fall 1963, 17 photographic plates of $L_4$ and 28 plates of $L_5$ were taken with a 12-inch focal length aerial camera. Visual examination and microphotometer measurements of the plates failed to show any brightening in the region of the libration points. Further statistical analysis of the plates is planned. In addition, photoelectric scans were made with a 6-inch-diameter Maksutov-Cassegrain telescope. Data from the scans are being reduced; preliminary reductions show no indication of the presence of a cloud. With further reductions, it is hoped to place an upper limit on the possible cloud brightness. The particle density corresponding to this brightness will be calculated.

X-ray fluorescence analyses of tektites, using 50 milligram samples, have been performed by H. J. Rose, Jr., F. Cuttitta, M. K. Carron, and R. Brown. X-ray fluorescence spectroscopy had been applied previously in the analysis of materials of geologic interest, but larger samples had hitherto been required. Six Java tektites, representative of the range of indices of refraction and specific gravities from a large collection, were analyzed both by X-ray fluorescence and chemical methods, and the results compared. The analyses, including those of the light elements, are closely similar.

A. T. Miesch and C. W. Davis have written computer programs designed to analyze microphotometric data from lunar photographs. Standard statistical parameters such as the mean, standard deviation, skewness, kurtosis and frequency distribution are computed from the data for a particular geologic unit. Also polynomial regression curves are fitted to the data so that regional variations in reflectivity may be distinguished from local variations. Serial correlation surfaces are computed for data from the same geologic unit. These surfaces provide a means of measuring the coarseness in texture of the albedo patterns and also provide a useful tool for correlation of rock units. The program as a whole enables the reflectivity variation of different geologic units to be described in quantitative terms. Correlation between rock units is thereby facilitated and a better understanding of the nature of the reflectivity variations is achieved.