F I N A L   R E P O R T

To The

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

on

NASA GRANT NSG - 9022

"RADIOGRAPHIC ANALYSIS OF SEDIMENTARY STRUCTURES AND

DEPOSITIONAL HISTORIES IN APOLLO 15 CORES"

(NASA-CR-153265) RADIOGRAPHIC ANALYSIS OF SEDIMENTARY STRUCTURES AND DEPOSITIONAL HISTORIES IN APOLLO 15 CORES Final Report (Queens Coll.) 31 p HC A03/MF A01 CSCL 03B N77-27052

Unclas
G3/91 31851

by

Dr. Nicholas K. Coch

Department of Earth and Environmental Sciences

Queens College, C.U.N.Y.

Flushing, New York 11367

ORIGINAL CONTAINS

COLOR ILLUSTRATIONS

C O N T E N T S

I N T R O D U C T I O N

S U M M A R Y O F A C T I V I T I E S

R E S U L T S

Enhancement Methods

Sedimentary Structures

SHARP PLANAR CONTACTS

GRADATIONAL CONTACTS

REWORKED IRREGULAR CONTACTS

HORIZONTAL LAMINATIONS

INCLINED LAMINATIONS

ELONGATION FABRICS

SOIL CLASTS

Determination of Depositional Sequence

Comparison of Highlands and Mare Soils

Depositional Processes on the Lunar Surface

S U M M A R Y A N D C O N C L U S I O N S

R E F E R E N C E S C I T E D

A P P E N D I C E S

I Plates 1 - 3

II Reprints

Coch (1976a)

Coch (1976b)

Coch (1977)

INTRODUCTION

Considerable data was available on the petrology and geochemistry of the lunar regolith, from trench and scoop samples and deep drill stem sections (Heiken, 1975) when this research began in 1975. Data on sedimentologic properties of lunar soils (McKay et al, 1974) indicated that grain size and agglutinate content can both be used as indices of lunar soil maturity. With increasing soil maturity, grain size decreases, sorting improves and agglutinate content increases. Radiographs made of drill stems and drive tubes provided data on stratification in the lunar regolith which was helpful in the dissection of the drill stems (Heiken et al, 1972). For example, the radiographs of the Apollo 15 deepdrill stem indicated numerous stratigraphic contacts over the 236 cm. length of the core. (Carrier et al, 1972). While stratigraphic contacts could be seen in the drill stem radiographs, the small diameter of the drill stems made studies of any other sedimentary structures difficult.

The Apollo drive tubes are considerably wider than the drill stems and subtle sedimentary structures are more visible. Since both stereo and orthogonal radiographs were made of each drive tube, sedimentary features could be examined in detail (Fryxell and Heiken, 1971). If the drive tube radiographs could be oriented, it would be possible to determine the true lunar orientation for any directional sedimentary structures noted.

In early June of 1974, I visited the Johnson Space Center at the invitation of Dr. Jeffrey Warner to examine all the sedimentologic data available and to discuss possible research projects with a number of JSC staff. After a week of study of all available materials, I concluded that considerable additional data could be obtained from the drive-tube radiographs if they could be electronically enhanced to bring out subtle features not readily apparent in a visual analysis. Sample radiographs were analyzed on an SDS electronic image enhancer. Encouraged by these preliminary studies, I submitted a research proposal to NASA in the summer of 1975.

The proposed research was subdivided into the following phases:

1) Examine and enhance a set of drive tube radiographs which show good detail. Attempt to orient the core radiographs and obtain true lunar orientations for any directional sedimentary structures noted. Deduce the sedimentologic history of the core from the data obtained. Examine other kinds of image enhancing techniques (photographic, computer) which may provide additional data from core radiographs.

2) Examine all the core radiographs from a mission where both mare and highland sediment cores were obtained. Characterize the sedimentologic character of the regolith in both of these areas.

3) Compare the radiograph enhancement data with the core dissection data obtained from the dissection of the first drive tubes (60009 and 60010).

4) Examine the other sources of stratigraphic data, such as core peels and polished sections, to determine their potential in providing sedimentologic data.

5) Study the geologic and morphologic conditions at all of the Apollo coring sites. Examine the radiographs from all the Apollo missions to see if the generalizations on sedimentary structures and depositional sequences derived from the study of the Apollo 15 cores are applicable to all the other sites.

6) Utilize all the data obtained to make inferences on the character of sedimentary depositional processes on the lunar surface.

SUMMARY OF ACTIVITIES

This research commenced in June, 1974, when I spent a week at the Johnson Space Center looking over all of the sedimentologic data and deciding on a research plan. Preliminary results of the enhancement analysis of core 14220 were informally presented at the Lunar Core Conference at the Lunar Science Institute on January 23, 1975. During the Lunar Science Conference in 1975, arrangements were made for an intensive enhancement analysis of original radiographs to take place in late April and May, 1975.

A detailed analysis of Apollo 15 radiographs was made from April 27 to May 10. Numerous sedimentary features were noted, photographically documented, and discussed with JSC staff. A detailed photographic and computer enhancement program was designed with the Technicolor Group at JSC. High contrast copies of original radiographs were made in an attempt to bring out sedimentary features.

The original radiographs had been made on medical X-Ray films using medical X-Ray equipment. Standard radiographic analysis in sedimentologic research uses Industrial X-Ray units and films which give greatly increased detail. A comprehensive plan for re-radiographing all of the unopened drive tubes was submitted to the Curator in May, 1975. I had hoped to use these new radiographs as soon as they were made, but unfortunately the JSC radiography program was not carried out until the Spring of 1977.

The first two phases of the research were carried out by early 1976 and a paper summarizing the analysis of core 15011 was presented at the Seventh Lunar Science Conference (Coch, 1976a) and was published in the proceedings volume (Coch, 1976b).

The first half of 1976 was devoted to synthesizing the sedimentologic data from all the Apollo 15 cores. The data from this portion of the research is given in Lunar Science VIII (Coch, 1977). Tracing of clasts were made from radiographs following the method of Mahmood et al, (1974) in order to determine if there was any preferred orientation of the elongate clasts; the results of this study were inconclusive.

A comparison of radiographic data and core dissection descriptions was carried out during two weeks of study at JSC in June, 1976. Radiographs of drive tubes 60009 and 60010 were examined stereoscopically in great detail and the results were discussed with Stuart Nagle. The radiographs were enhanced and studied in the summer of 1976. All other types of stratigraphic data, such as core peels and polished core sections, were examined to determine their potential use in the research. After discussions with Stuart Nagle, it was concluded that these additional sources would not provide much new data.

The Fall of 1976 was devoted to familiarizing myself with the details of the geology and morphology at all the Apollo coring sites. In January 1977 a week was spent at JSC examining all of the Apollo core radiographs to determine which of them could provide new stratigraphic data. Arrangements were made to borrow sets of original radiographs for detailed enhancement studies at Queens College. Copies of the new radiographs will also be sent as soon as they are processed. It is anticipated that this research will extend far beyond the termination of the grant period. It is expected that this research will be completed in early 1978 at which time the results of the study will be prepared for publication.

RESULTS

Enhancement Methods

Photographic enhancement methods (Technicolor-JSC) did not provide adequate stratigraphic detail. The few colors provided could not adequately differentiate areas of subtle x-ray film density changes. Computer enhancement, based on microdensitometer scans of the radiographs, provided an excess of data which made it difficult to interpret stratigraphic patterns.

The electronic image enhancement method used in this study adequately brought out subtle sedimentologic features shown on drive tube radiographs. The comparison of dissection and radiographic enhancement methods of analysis for cores 60009 and 60010 proved inconclusive due to the difficulty of interpreting the stratigraphic sequence in these two particular cores. In addition, the radiograph copies provided for study were inferior to the originals and it was difficult to describe subtle sedimentary features accurately.

Sedimentary Structures

A number of sedimentary structures and types of stratification were noted in the detailed study of the enhanced radiographs.

SHARP, PLANAR CONTACTS (PLATE 1A)

Contacts along which sediment characteristics change markedly indicate a marked change in depositional conditions and/or sediment source. The example illustrated (Plate 1A) where a finer soil is sharply overlain by a coarser soil suggests transportation into the area of a less mature soil, possibly derived in part from a nearby impact event.

GRADATIONAL CONTACTS (PLATE 1B)

In gradational contacts, the position of boundaries between stratigraphic units can only be approximated. Gradational contacts may indicate a transport of newer upper unit sediments, similar to, but either slightly coarser or finer than the lower unit. Alternatively, such a contact may indicate graded bedding within one sedimentologic unit. Both normal and reverse graded bedding have been reported from the Apollo 15 (Heiken et al, 1972) and the Apollo 16 drill cores (Duke and Nagle, 1975). Lindsay (1974) believes that lunar graded bedding results from deposition of particles which are fluidized by the upward flow of escaping gasses in a base surge. According to Lindsay, normal grading results when gas supply is abundant and reverse graded beds occur when gas supply is limited.

REWORKED, IRREGULAR CONTACTS (PLATE 1C)

This type of contact almost certainly indicates a new transport mechanism which erodes an older stratigraphic unit. The overlying material is deposited on the eroded surface and includes both new soil and clasts of soil reworked from the underlying unit. It is possible that the irregular contact at the top of core 15010 was due to the breaking off of the top portion of the core upon separation of the two drive tube halves. The clear indication of the well laminated material deposited upon this irregular surface (Plate 1C) makes this seem very improbable.

HORIZONTAL LAMINATIONS (PLATE 1D)

This type of lamination is marked by the alignment of clast axes in many cases. The formation of horizontal laminations suggests the absence of topographic irregularities on the surface upon which the soil is being transported. Good examples of continuous horizontal laminations are well documented in drill core section 60003 (Duke and Nagle, 1975; Figure 10, p. 155).

INCLINED LAMINATIONS (PLATE 1,E,F)

Inclined laminae are suggested by the orientation of the long axes of elongate clasts. In one of the radiograph views, the laminations appear to be horizontal; this is the strike section (Plate 1E). In the orthogonal radiograph view inclined laminae are visible; this is the dip section (Plate 1F). Before identifying any inclined laminations, it is essential to examine lunar surface core documentation photographs to be sure that the core was inserted perpendicular to the lunar surface; this is the case for all of the cores in which inclined laminations were found. Apparent inclined laminations were seen in cores such as 14230 which were inserted at angles other than 90 degrees to the lunar surface.

If the radiographs can be oriented, the two orthogonal views can be used to obtain information on lunar surface sediment transport directions (Plate 3A). Utilizing terrestrial analogies, the transporting agent is assumed to come from the direction opposite to the dip direction of the inclined laminae.

ELONGATION FABRICS

During the analysis of orthogonal radiographs it was noted that the same clasts in certain core intervals had subspherical apparent shapes in one radiograph (Plate 1G), and elongate apparent shapes in the corresponding orthogonal radiograph (Plate 1H). This suggests that the clasts in the interval have a preferred orientation of their long axes. The direction of elongation of the clast axes would be parallel to the azimuth of the radiograph in which they have an elongate apparent shape. Opinion varies as to whether elongate particles orient themselves parallel or perpendicular to the transporting force, with geologic examples present for both of these fabrics. In examining areas with inclined laminations in core 15011 (Plate 1F), it appears that clasts are elongate parallel to the dip direction of the laminae. This suggests, but does not prove, that clasts in lunar sediments are oriented with their long axes parallel to the transport direction (Plate 3B).

SOIL CLASTS (PLATE 2A)

These discoidal shaped clasts are especially common in highland cores (15007, 15008, 15009) at the Apollo 15 site. They are subrounded and control the position of the fractures in the more cohesive highland soil (Plate 2A). The clasts have a radiographic image which is only slightly denser than the enclosing regolith and they may represent reworked pieces of a somewhat more compacted older soil from the same area.

Determination of depositional sequence

The physical properties of the regolith plus the sedimentary structures observed were used to determine the depositional history of core 15011 (Coch, 1976a,b). Somewhat more generalized sedimentological histories were determined for the other Apollo 15 cores for which less stratigraphic data could be obtained. The observations made, methods used, and conclusions reached are discussed in detail in Coch (1976b). As more and more Apollo core radiographs are examined in the coming months, greater knowledge will result in more detailed interpretations. The results of all this new data will be published in 1978.

Comparison of mare and highlands soils

A detailed analysis of all the Apollo 15 cores and representative cores from other missions (Plate 2) indicates that there are some generalized differences between the two soil end members. Mare and highland soils seem to be distinctly different in grain size, sorting, angularity of particles, clast to matrix ratio, and degree of development of sedimentary structures.

Comparison of radiographic film densities indicates that mare cores (Plate 2G,H) are richer in mafic rock components and highland cores are richer in anorthositic material. This observation is in agreement with that of Carr et al, (1972) who analyzed soil samples from the mare area of the Apollo 15 landing site. They concluded that the major constituents of mare regolith are what would be expected from gardened basalt, i.e., chiefly basaltic fragments, basaltic mineral fragments, and dark glasses laden with lithic and mineral debris. Mare cores (15010, 15011) are coarser (Butler et al, 1972), have a larger clast to matrix ratio and have more angular particles than highland cores (15007, 64001, and 76001). The differences in these sedimentary characteristics may result from the greater maturity of highland soils relative to mare soils. In areas where these two soil types are mixed, the resulting soil should show a mixture of the two characteristics.

Sedimentary structures such as laminations, directional indicators (inclined laminae) and preferred azimuthal orientation of long axes of elongate clasts are rarer in highlands cores. This may be the result of any of the following: 1) depositional processes or grain sizes not favoring the development of sedimentary structures in the highland regolith; 2) reworking of the more mature highland soils obliterating traces of previously formed structures; or 3) modification of sedimentary structures through mass wasting on the slopes of the lunar highlands.

The Apollo 17 LSPET (1973) commented on the similarity of highlands soils from different missions. In comparing the characteristics of core 76001 (Plate 2F) and the Apollo 16 cores, they state, "the x-radiograph of this massif derived soil (76001) is similar to those of the Apollo 16 drive tubes, probably because the anorthositic terrain of the massif and the Descartes highlands produce similar soil forming components. Both soils are: 1) relatively transparent to x-rays, with a very sparsely granular matrix; 2) relatively low in distinct rock fragments, possibly because of the abundance of semitransparent anorthosites; and, 3) extremely high in tiny opaque fragments of diverse shapes ranging from dendritic to spheroidal."

Depositional Processes of the Lunar Surface

The large number of sedimentary structures that have been described from both core dissection (Heiken et al, 1972); Duke and Nagle, 1975) and radiographic analysis (Coch 1976a,b,1977) strongly suggest that a variety of depositional processes are active on the lunar surface. Many of the cores show massive structure and the absence of well developed sedimentary features. Sequences such as these suggest extensive reworking of the lunar regolith with addition of random coarse debris from nearby impact events. On the other hand, the definite occurrence of sedimentary structures in many of the cores indicates that portions of the lunar regolith have experienced little if any reworking. The preservation of these structures suggest that insignificant erosion occurs in the deposition of stratigraphic units overlying units with well developed sedimentary structures.

The documentation of well developed elongate clast fabrics in at least one core (15011) indicates that a directed shear force was involved in the deposition of that sedimentary sequence. The base surge mechanism proposed by Lindsay (1974) is a mechanism which could produce such a fabric.

Summary and Conclusions

This research is the first attempt to discover and interpret the significance of sedimentary structures in the lunar regolith. All of the proposed research outlined in previous reports has been carried out and significant new data has been obtained. Radiographic analysis provides data on sedimentary structures that may not be obtained by even the most careful core dissections. Thus, the new data from this research should complement the data to be obtained from core dissection in the future.

Significant results of this research include the following: 1) documentation of various sedimentary structures in the lunar regolith; 2) the first use of sedimentary structures in oriented radiographs to determine paleocurrent directions during lunar regolith deposition (Coch, 1976a,b); use of sedimentary structures, grain sizes, clast shape and angularity to establish depositional histories in Apollo 15 cores (Coch, 1976); 4) synthesizing the sedimentologic data from study of all the Apollo core radiographs into sedimentological models of lunar highland and mare soils; and 5) utilizing all of the sedimentological data obtained to make inferences about the processes by which sediment is deposited on the lunar surface.

This research will continue into 1978 with an emphasis on examining the new radiographs being taken at the present time. Two publications are presently in preparation. The first deals with the use of radiographic enhancement techniques in the analysis of lunar sedimentary structures. the second paper deals with the dynamic interpretation of the sedimentary structures and depositional sequences in Apollo mare and highland cores.

I hope that the new data obtained by this research will be helpful in future core dissections and in the sampling and analysis of the other extraterrestrial soils which will be obtained in the future.

REFERENCES CITED

Apollo 17 Lunar Sample Preliminary Examination Team, 1973, Preliminary Examination of Lunar Samples, Ch. 7 in Apollo 17 Preliminary Science Report, 1973, NASA Spec. Public. 330.

Butler, J. C., King, E. A. and Carman, M. F., 1972, Size frequency distributions and petrographic observations of Apollo 15 Samples: In The Apollo 15 Samples, p. 45-47.

Carr, M. and Meyer, C., 1972, Chemical and petrographic characteristics of the regolith at the Apollo 15 landing site: In The Apollo 15 Lunar Samples, p. 48-49.

Carrier, W. D., Johnson, S. W., Carrasco, L. H. and Schmidt, R., 1972, Core depth relationships: Apollo 14 & 15; Proc. Third Lunar Sci. Conf. V. 3, p. 3213-3221.

Coch, N. K., 1976a, Radiographic enhancement analysis of sedimentary structures and depositional history in Apollo 15 Core 15011: Lunar Science VII, p. 163-165.

Coch, N. K., 1976b, Radiographic enhancement analysis of sedimentary structures and depositional history in Apollo 15 Core 15011: Proc. Lunar Sci. Conf. 7th, p. 113-122.

Coch, N. K., 1977, Sedimentary structures and depositional sequences in Apollo 15 mare and highlands cores: Lunar Science VIII, p. 196-198.

Duke, M. B. and Nagle, J. S., 1975, Stratification in the lunar regolith - a preliminary view: The Moon, V. 13, p. 143-158.

Fryxell, R. and Heiken, G., 1971, Description dissection, and subsampling of Apollo 14 core sample 14230: NASA Tech. Mem. X-58070, 16 p.

Heiken, G., 1975, Petrology of Lunar Soils: Reviews of Geophysics and Space Physics, V. 13, n. 4, p. 567-587.

Heiken, G., Duke, M., Fryxell, R., Nagle, S., Scott, R. and Sellers, G., 1972, Stratigraphy of the Apollo 15 drill core: NASA TMX-58101, 21 p.

Lindsay, J. F., 1974, Depositional Processes on the lunar surface: Lunar Science V, p. 450-452.

Mahmood, A., Mitchell, J. F., and Carrier, W. C., 1974, Grain orientation in lunar soil: Proc. Lunar Sci. Conf. 5th, p. 2347-2354.

McKay, D. S., Fruland, R. M. & Heiken, G. H., 1974, Grain size and evolution of lunar soils: Proc. 5th Lunar Sci. Conf., V. 1, p. 887-906.

PLATE 1

Radiographic images have been processed by edge enhancement (shadowing) or density contouring (color). Depth below lunar surface given in centimeters. The top of each core section is to the right in each figure.

A. Core 15009 (11-24.8cm interval). Single drive tube taken at station 6 on slope of Hadley Delta.
<u>Sharp</u> <u>contact</u> - between basal fine grained unit (left) and upper coarser grained unit (right) with clasts at 20.5cm depth. Association may represent deposition of less mature soil (11.0-20.5cm) over more mature soil (20.5cm and below).

B. Core 15007 (16.0-32.0cm interval). Bottom of double drive tube taken at station 2 in vicinity of St. George Crater on Apennine Front.
<u>Gradational</u> <u>contact</u> - between basal fine grained unit (left) and upper coarser grained unit (right) occurs over the interval from 23.0 to 25.0cm.

C. Core 15010 (0-10.0cm depth). Bottom of double drive tube taken at station 9A on mare at edge of Hadley Rille.
<u>Reworked</u> <u>contact</u> - between lower fine grained unit (left) and upper coarser grained unit (right) occurs at 6cm (photo top) to 4.5cm (photo base) contact is irregular and clasts of lower unit have been reworked into upper unit.

D. Core 15011 (0-9.0cm interval). Top of double drive tube taken at station 9A on mare at edge of Hadley Rille.
<u>Horizontal</u> <u>laminations</u> - suggested by aligned elongate clasts at several places in this core interval.

E. Core 15011 (24.5-28.1cm interval).
<u>Horizontal</u> <u>laminations</u> - suggested in 1R view by aligned equant clasts.

F. Core 15011 (24.5-28.1cm interval).
<u>Inclined</u> <u>laminations</u> - suggested in orthogonal 2R view. Dip angle of laminae decreases upward (to right) in core interval. Orthogonal reconstruction of laminations (Plate 3A) indicates true dip direction of laminae is parallel to the 2R orthogonal radiograph section.

G. Core 15011 (0-9cm interval).
Clasts have subspherical apparent shapes.

H. Core 15011 (0-9cm interval).
Clasts have elongate apparent shapes in orthogonal 2R radiograph. Orthogonal fabric reconstruction (Plate 3B) suggests long axes of clasts in this interval have a preferred orientation parallel to the azimuth of the 2R radiograph.

PLATE 1

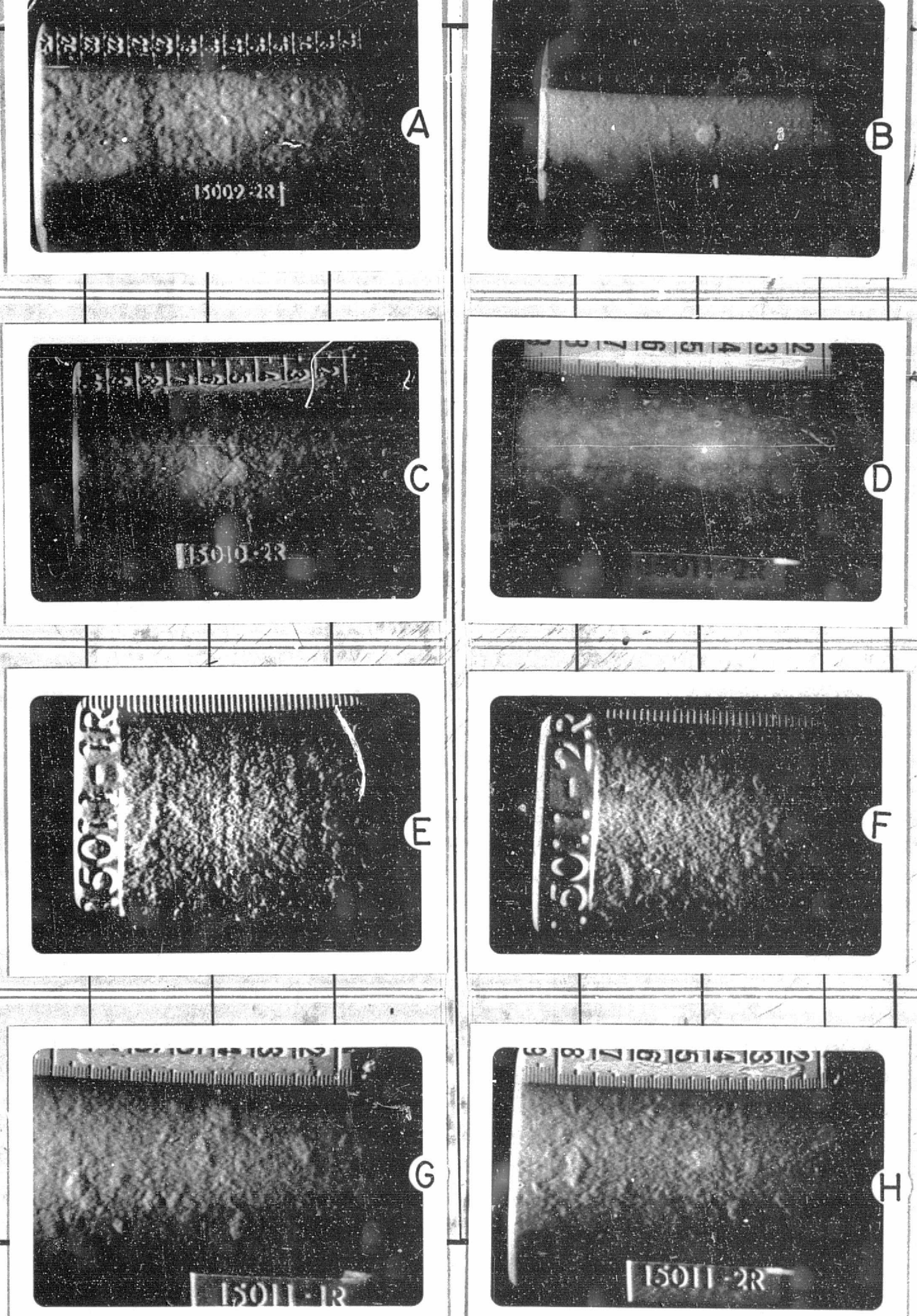


PLATE 2

Radiographic images have been processed by edge enhancement (shadowing) or density contouring (color). Depth below lunar surface given in centimeters. The top of each core section is to the right in each figure.

A. Core 15008 (9.3-20.4cm interval). Upper part of double drive tube taken at station 2 in vicinity of St. George's Crater on the Apennine Front.
Soil clasts - Well rounded clasts controlling the location of the voidal fractures in this cohesive soil.

B. Core 15011 (9.4-19.9cm interval).
Sharp stratigraphic contact - outlined by color density contours. Contact between coarser-grained unit B.(right) and finer grained unit C(left) at 17.0cm. See Coch (1976b) for details.

C. Core 15011 (18.0-29.0cm interval).
Sharp stratigraphic contact - between fine grained cohesive soil (unit C,right) and coarse grained soil (unit D,left). See Coch (1976b) for details.

COMPARISON OF MARE & HIGHLAND SEDIMENT CORES
(See Coch, 1977 for detailed description).

D,E,F. Typical highlands soils

D. Core 15007 (1R & 2R orthogonal views). Lower part of double drive tube taken at station 2 near St. George Crater on Apennine Front.

E. Core 64001 (1R & 2R orthogonal views). Lower of double drive tube. Taken at station 4 at highest elevation on Stone Mt.

F. Core 76001 (1R & 2R orthogonal views). Single drive tube from station 6 on North Massif.

G,H. Typical mare soils

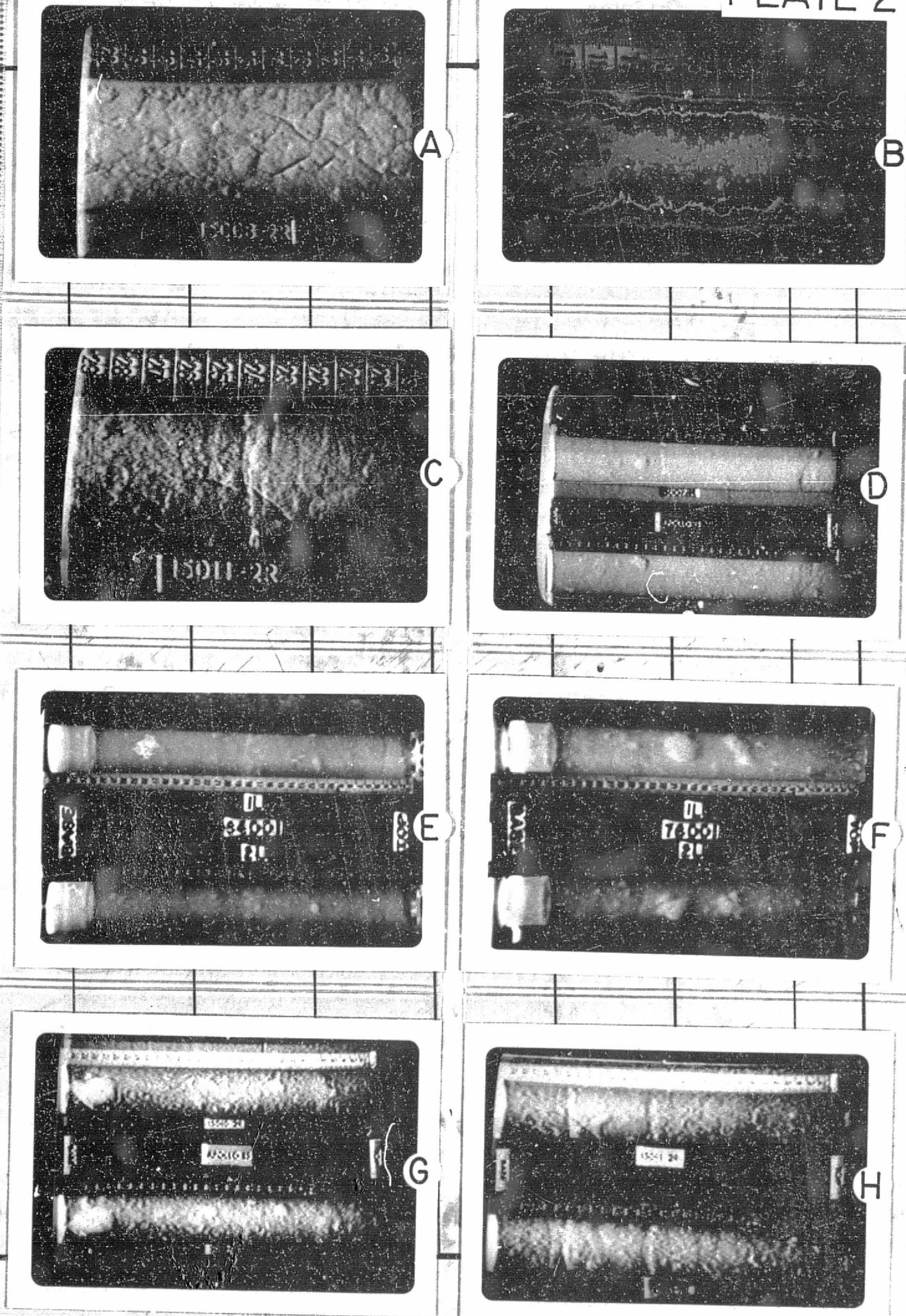
G. Core 15010 (1R & 2R orthogonal views)

H. Core 15011 (1R & 2R orthogonal views)

Highlands soils are characterized by a ~~high~~ low clast/matrix ratio, soil clods, massive structures and a general absence of sedimentary structures and a finer grain size.

Mare soils are characterized by a ~~low~~ high clast/matrix ratio, well developed sedimentary structures and a coarser grain size.

PLATE 2



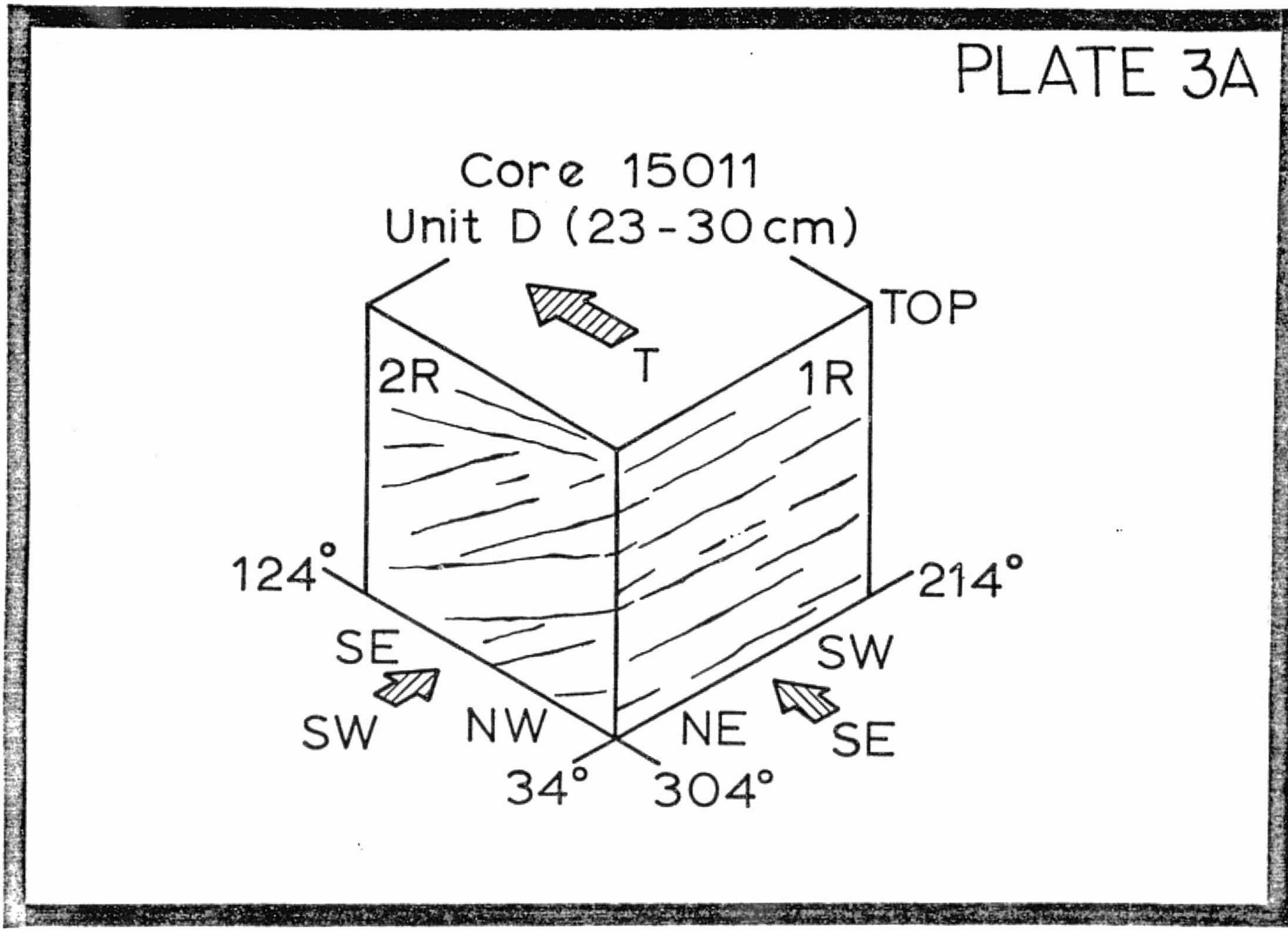


Plate 3A. Orthogonal reconstruction of inclined laminations in Unit D (23-30cm), Core 15011, Station 9A at edge of Hadley Rille. Directions of radiograph view indicated by arrows. Inferred direction of sediment transport on lunar surface indicated by arrow (T). All azimuths are true lunar orientations.

Note difference in appearance of sedimentary structures in the two orthogonal views. Magnitude of laminae dip decreases upward in unit.

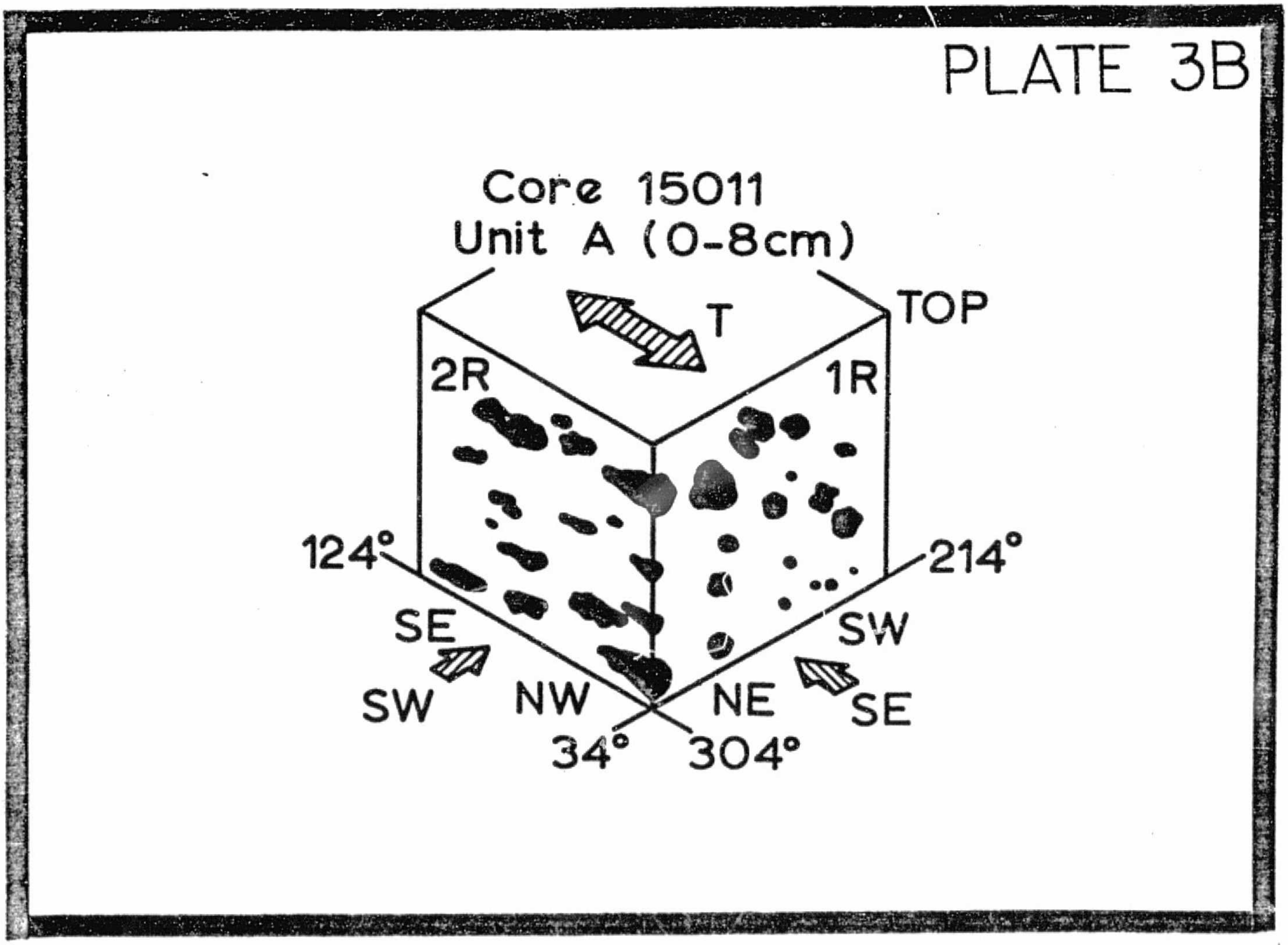


Plate 3B. Orthogonal reconstruction of grain fabric in Unit A (0-8cm), Core 15011, Station 9A at edge of Hadley Rille. Directions of radiograph view indicated by arrows. Double-ended arrow (T) indicates inferred possible directions of grain transport on lunar surface. All azimuths are true lunar orientations.

Note difference in appearance of sedimentary structures in the two orthogonal views.

Proc. Lunar Sci. Conf. 7th (1976), p. 113–122.
Printed in the United States of America

Radiographic enhancement analysis of sedimentary structures and depositional history in Apollo 15 core 15011

NICHOLAS K. COCH

Department of Earth and Environmental Sciences, Queens College, C.U.N.Y., Flushing, New York 11367

Abstract—Sedimentologic and stratigraphic information available from orthogonal stereo radiographs of drive tube 15011 was maximized utilizing electronic image enhancement techniques. Stratigraphic contacts, horizontal laminations, inclined laminations and preferred azimuth orientations of elongate clasts are the major sedimentary structures observed in the core radiographs. A method was devised to orient the core and provide true lunar orientations for the core radiographs. The depositional history of core 15011 involves four major stratigraphic units defined by differences in grain size, fabric, cohesiveness, and sedimentary structure associations. Directional sedimentary structures were used to indicate sediment dispersal. In the lowermost core unit, laminae inclined toward the lunar SE indicate sediment dispersal from the NW. In the uppermost unit, long axes of elongate clasts on horizontal laminations have a preferred lunar NW-SE orientation. This suggests a sediment dispersal from either the lunar NW or SE if the transporting force acted parallel to the long axes of the clasts.

INTRODUCTION

LITTLE DATA IS AVAILABLE on the sedimentary structure types, nature of stratigraphic contacts, and especially fabric and sediment dispersal indicators in the undisturbed lunar regolith. Core dissection (Nagle *et al.*, 1976) is providing new petrographic and stratigraphic information. However, the amount of sedimentologic and stratigraphic information available from core dissection is limited by two factors: (1) the nature of the dissecting process obscures the subtler sedimentary features and; (2) core dissection provides a three-dimensional view of the sedimentary features only after multiple dissections are made, which is a process requiring a long time. An excellent source of readily available three-dimensional stratigraphic data are the orthogonal stereo radiographs (1R, 1L, 2R, 2L) taken of each drive tube. However, even under ideal illumination conditions, only a portion of the stratigraphic detail can be obtained from these radiographs under normal viewing conditions. In addition, features noted on the radiographs (Mahmood *et al.*, 1974) can only be given *relative* orientations as the drive tubes were not oriented during the missions.

The aims of this study were to: (1) maximize the stratigraphic detail in the radiographs utilizing electronic image enhancing techniques; (2) determine the types of sedimentary structures present and the information they provide about depositional processes; (3) devise a method of orienting the drive tubes (and radiographs) so that directional sedimentary structures could be given *true* lunar orientations and thus used to infer sediment transport directions; and (4) synthesize this new stratigraphic data into a depositional model for core 15011.

Methods

The Apollo 15 drive tubes had not been oriented during the mission and an attempt was made to orient them using available data. Documentation photograph AS 15-82-11162 was oriented by Dan Kinsler (LSI) and Michael Duke provided azimuth measurements of drive tube hardware components visible in the photograph. Using all of this data, plus simulations on unused drive tubes where necessary, core 15011 (and the 15011 stereo radiographs) was oriented to within a lunar azimuth of ±5°.

The 15011 orthogonal stereo radiograph pairs (1R, 1L, 2R, 2L) were examined in detail to obtain as much stratigraphic information as possible. A corresponding set of orthogonal radiographs (1R, 2R) was then analyzed in great detail utilizing the various modes of an SDS 401/704 Data Color image enhancement system. The edge enhancement mode emphasizes radiograph film density changes and outlines clast shapes and linear features. This provides a "three-dimensional" representation of the radiographs which greatly increases stratigraphic detail. Orthogonal reconstructions of differences in attitudes of clasts and stratification, observed at the same level in both oriented orthogonal radiographs, were used to establish the three-dimensional orientation of these features.

Stratigraphy

Geologic setting

Drive tube 15011 is the upper half of a double drive tube taken at Station 9A, approximately 20 m north of the Hadley Rille (Fig. 1). Pre-sampling photography (AS 15-82-11159) indicates that the surface is generally level with no fresh craters apparent in the immediate vicinity of the coring site. Small subdued craters from less than 1 to 20 cm across are fairly common and small fillets are banked against many of the rock fragments in the sampling vicinity. The surface in the immediate vicinity of the core appears undisturbed by footprints or Rover tracks. Therefore, the uppermost part of the core, except for the disturbances caused by driving the core and subsequent handling should be representative of the undisturbed lunar surface (Swann *et al.*, 1972, p. 5–105).

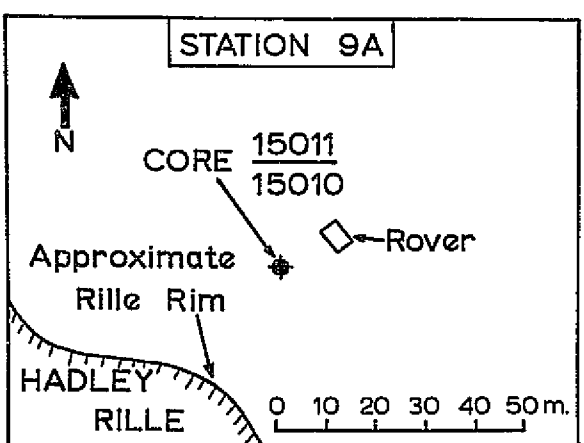


Fig. 1. Location of core site. Map modified from Swann *et al.* (1972, Fig. 5–115).

Stratigraphic subdivisions

Descriptions of the core, based on X-radiograph analysis, were made by the Lunar Sample Preliminary Examination Team who delineated three contacts in core 15011 (Duke and Nagle, 1974). Electronic image enhancement of the 1R and 2R orthogonal radiographs of this core (Fig. 2) confirms the existence of four major stratigraphic units and provides new and detailed stratigraphic data for each unit.

For purposes of estimation of clast to matrix percentages from the radiographs, clasts were defined as discrete particles larger than 1 mm; the remaining material was considered as matrix. The clast size data given for each unit is approximate as only *apparent* shapes of clasts are seen in radiographs and the true clast sizes cannot be determined until the cores are dissected. However, measurements of clast size and estimates of clast to matrix percentages from radiographs are useful in indicating the relative differences in sediment character between different stratigraphic units in the core. The four stratigraphic units are designated as A, B, C, and D from the top to the base of the core.

Unit A (0–8 *cm*)

The clasts of unit A are poorly sorted with a size range of 2–9 mm and an average size of about 3.5 mm. This unit is composed of about 45% clasts and 55%

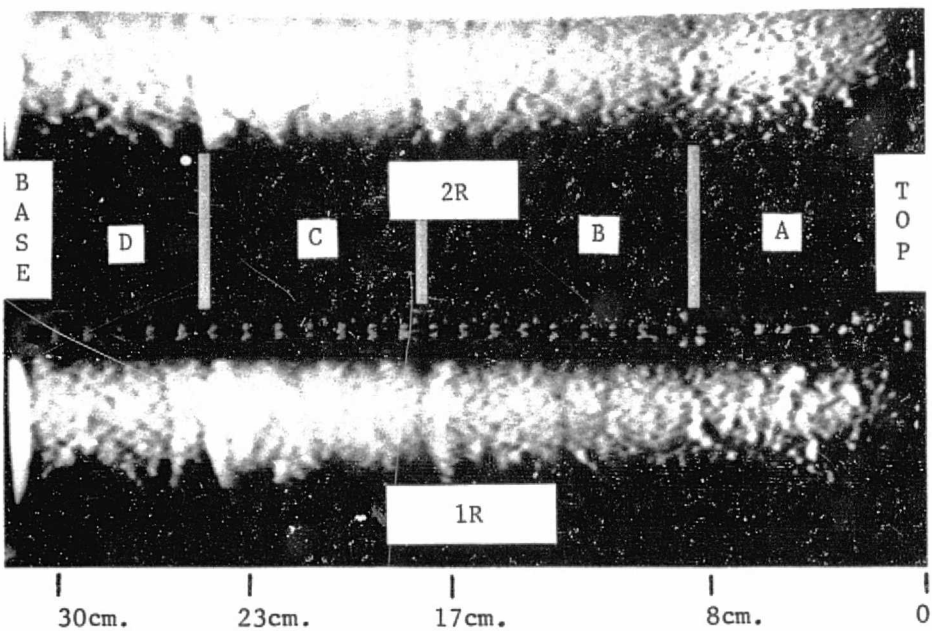


Fig. 2. Edge enhanced 1R and 2R orthogonal radiographs of core 15011 showing stratigraphic units described in text.

matrix. This core unit has a suggestion of some horizontal clast laminations. Some loss of sediment is indicated by the partial void space along the right side of the radiograph, but the sediment remaining is not disturbed as it exhibits a complete continuity of sedimentary structures across the width of the core (Fig. 2). The clasts in the 1R and 2R orthogonal radiographs differ in apparent shape. The apparent shapes of clasts in radiograph 1R (Fig. 3) are subspherical, whereas those in radiograph 2R (Fig. 4) are mostly elongate. The difference in apparent particle shape between these two orthogonal views of the same core interval suggests that the long axes of elongate clasts in unit A have a preferred orientation in a lunar NW-SE orientation (azimuth of radiograph 2R).

Unit B (8–17 *cm*)

This unit has smaller clast size, fairly good clast sorting and is more matrix rich than unit A. Clast size varies from 2 to 5 mm with an average clast size of about 2.5 mm. The unit consists of about 35% clasts and 65% matrix. The unit has a sharp contact with unit C below and a sharp to gradational contact with unit A above. The lower part (12–17 cm) of unit B is relatively coarser and more clast rich, whereas the upper portion (8–12 cm) is relatively clast poor and matrix rich, suggesting a size grading through the unit (Fig. 2). There are clear suggestions of horizontal laminations at several levels within this unit (Fig. 2).

Unit C (17–23 *cm*)

This unit is the finest grained, most cohesive and has the smallest percentage of clasts among all core units. Clast sizes are bimodally distributed with clast size ranging from 2 to 17 mm. One clast is 17 mm and the rest of the clasts range in size from 2 to 5 mm, with an average size of about 3 mm. The unit is composed of about 25% clasts and 75% matrix. The unit has sharp planar contacts with unit B above and D below (Fig. 2). A network of cracks, at varying angles, cut through the unit; no stratification features are visible.

Unit D (23–30 *cm, core base*)

This unit has fairly good clast sorting with clast size ranging from 2 to 5 mm and an average clast size of about 3.5 mm. The unit is composed of about 35% clasts and 65% matrix. Well-defined laminations are visible throughout the length of this unit. (A preliminary radiographic image enhancement analysis of 15010 core radiographs indicates that sediment very similar to that in unit D extends downward, across the double-drive tube contact, into the top 5 cm of core 15010.) Apparent clast shapes and lamination orientation differ in each orthogonal radiograph of unit D. Apparent clast shapes in radiograph 1R are subspherical and lie on well-developed horizontal laminations (Fig. 5). Apparent clast shapes in radiograph 2R are more elongate to irregularly shaped, and outline laminations dipping from upper right (photo base) to lower left (photo top) with dip angles

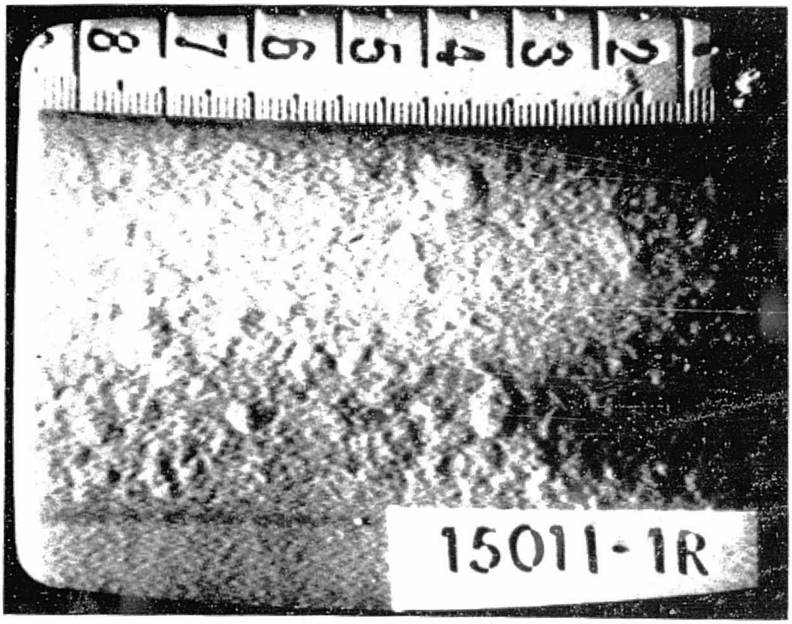


Fig. 3. Edge enhanced 1R radiograph of core interval from 0 to 9 cm. Subspherical apparent clast shapes dominant.

Fig. 4. Edge enhanced 2R radiograph of core interval from 0 to 9 cm. Elongate apparent clast shapes are dominant.

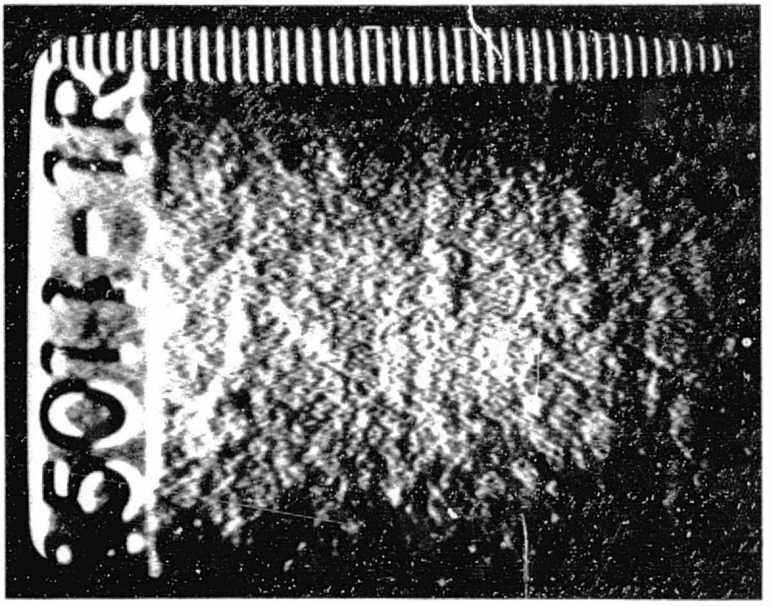


Fig. 5. Edge enhanced 1R radiograph of core interval 24.5–28.1 cm. Subspherical apparent clast shapes and horizontal laminations are well developed. Core top is to right of photo and scale is indicated by millimeter marks at top of photograph.

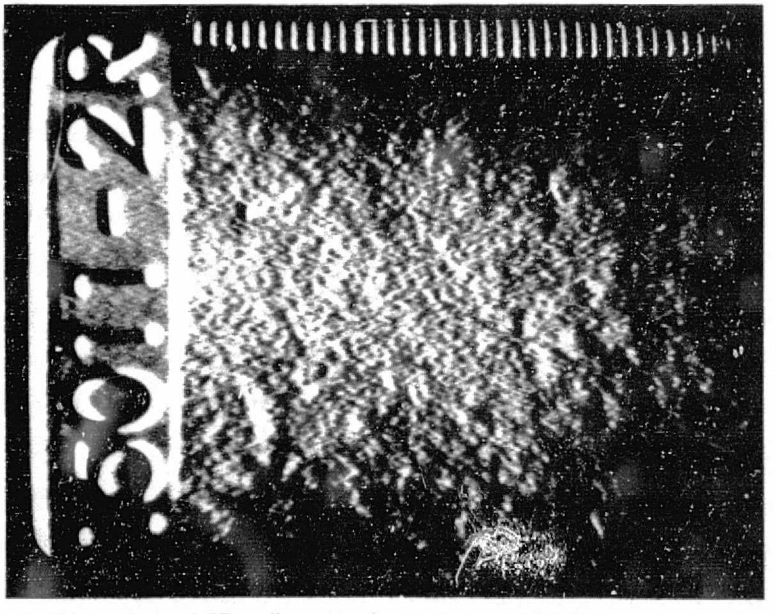


Fig. 6. Edge enhanced 2R radiograph of core interval 24.5–28.1 cm. Apparent clast shapes are irregular to elongate and outline laminae inclined from upper right (photo base) to lower felt (photo top). Dips of laminae decrease toward top of core interval. Core top is to right of photo and scale is indicated by millimeter marks at top of photograph.

decreasing upward (right) toward the upper part of the unit (Fig. 6). An orthogonal reconstruction of this data indicates that there are laminations in unit D which are dipping to the SE. There is also a suggestion that the majority of the clasts have their long axes preferentially aligned with the dip direction of these inclined laminae.

Depositional History

Sediment similar to unit D of core 15011 extends downward into the top 5 cm of core 15010 where it has an irregular (concave up) and erosional contact with a distinctly finer-grained unit (radiograph 15010-2R). The transported material of unit D eroded a portion of the underlying material and then gradually filled in the subtle depression with SE dipping clast-rich laminae derived from the NW (Fig. 7). The suggestion of preferred orientation of the elongate clasts parallel to the dip directions of the inclined laminations indicate that the clasts did not assume a random orientation on the laminae, but were oriented preferentially by a shear force acting parallel to the surface of the laminae during deposition. The angle of dip of the laminae decreases upward in unit D suggesting a near-level surface existed prior to the deposition of unit C.

A marked change in depositional regime occurred during the deposition of unit C as indicated by the sharp contact (Fig. 2) and marked change in sediment type. The fine grain size, low clast content, cohesive nature, and general absence of any stratification may suggest deposition by a grain-flow mechanism (Lowe, 1976).

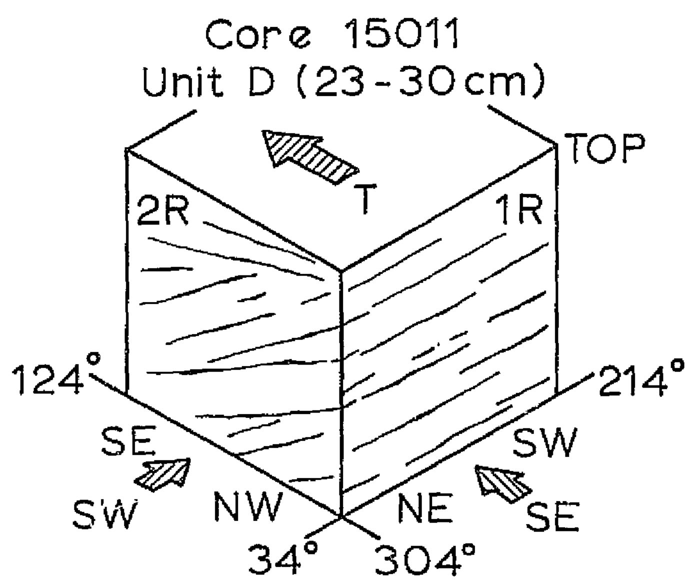


Fig. 7. Generalized orthogonal reconstruction of sedimentary fabric in unit D. Inferred sediment transport direction is indicated by arrow (*T*) on top of block. Arrows at base of block indicate direction of view of radiograph.

Alternatively, there could have been rapid local slumping of fine-grained material with isolated clasts. The sedimentary evidence available at present for this unit is insufficient to infer a more definite origin.

The deposition of the relatively clast-rich, coarser-grained, and upward fining unit B marks another sharp change in sedimentologic regime. The distinct horizontal lamination and absence of any preferred orientations of the elongate clasts on the laminae suggest a near-level surface and the absence of any persistent shear force. The unit may have accreted slowly by the random scattering of clasts and matrix by numerous small-scale impact events on a near-level surface. An alternative explanation is that the general upward fining in this unit was developed in one depositional event.

The well-developed preferred orientation of the long axes of elongate clasts throughout unit A indicates that the clasts moved freely and assumed an orientation under a continuous directed shear force. Analogies from terrestrial deposits (Harms *et al.*, 1972, p. 136–137) indicate that in such a fabric type elongate axes of clasts are oriented either parallel or perpendicular to the depositional force. At present there is no data relating depositional force direction and sedimentary fabric for lunar material and thus it is difficult to choose between these two possible dynamic conditions.

The preferred orientation of elongate clasts parallel to the dip direction (SE) of the laminations in unit D (Figs. 5 and 6) suggests that the depositing force acted parallel to the long axes of the elongate clasts during the deposition of unit D. Considering the data from unit D and the absence of any contrary evidence in the

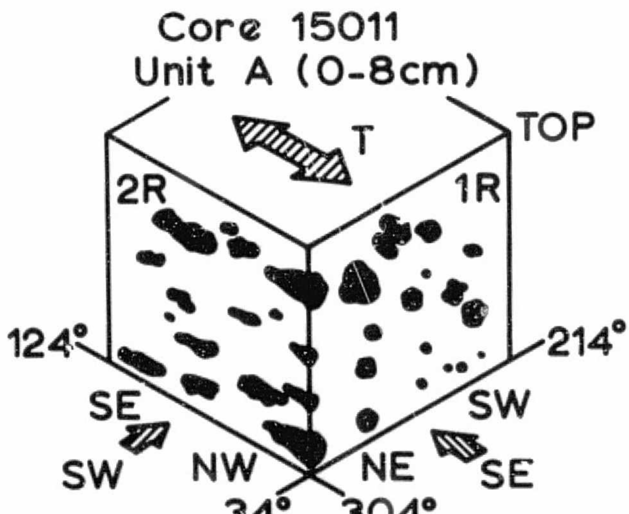


Fig. 8. Generalized orthogonal reconstruction of sedimentary fabric in unit A. Possible sediment transport directions are indicated by arrow (*T*) on top of block assuming transport directions are parallel to long axes of elongate clasts. Arrows at base of block indicate direction of view of radiograph.

core, it would appear that the long axes of elongate clasts in unit A were deposited under a continuous directed shear force from either the lunar NW or SE (Fig. 8). This tentative paleocurrent analysis is subject to change as we learn more about lunar sedimentary petrofabrics and their relationship to surface depositional processes. While the evidence for shear forces orienting the clasts in unit A is clear, further study will be necessary to determine the number of such events. A possible mechanism for clast orientation in unit A may have been a base surge as described by Lindsay (1974).

Summary and Conclusions

Analysis of oriented radiographs of core 15011 has provided new information on types of lunar sedimentary structures and true lunar sediment dispersal directions. This data has enabled inferences to be made as to rates and modes of deposition and extent of reworking of regolith in subsequent erosional/depositional events. The distinct rock-stratigraphic units (Fig. 2), and the presence of a continuous set of sedimentary structures within each unit (except unit C) suggest that major reworking occurs primarily along stratigraphic contacts. The regolith in core 15011 varies vertically (Fig. 2) and also three dimensionally (Figs. 7 and 8) as a result of both changes in depositional regime and directions of sediment transport. Continuing radiographic enhancement studies of other Apollo 15 cores along with future dissection of these cores will provide further information on sedimentary structures and depositional histories which may make core correlation possible. This correlation could be based on similarities in composition or sedimentary structure sequence. Similarly, units in different cores may be correlated on the basis of similar sequences of sediment dispersal patterns regardless of the composition of the layers.

Acknowledgments—This research was supported by NASA Grant NSG-9022. The portion of the study carried out at the Johnson Space Center was greatly aided by the help of Jeffrey Warner and Robert Pepin. Discussions with Grant Heiken, Dave McKay, Jeffrey Warner, William Phinney, Michael Duke, Charles Simonds, and Stuart Nagle were most helpful. Dean Malouta and Nancy Eichenberger were of great assistance in the operation of the image enhancement system. William Sarni drafted the figures and aided in manuscript preparation.

References

Duke M. B. and Nagle J. S. (1974) *Lunar Core Catalog*, p. 15-4. NASA publication JSC-09252.

Harms J. C., Southard J. B., Spearing D. R., and Walker R. G. (1975) Conglomerate: Sedimentary structures and facies models. In *Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences*, p. 133–161. SEPM Short Course No. 2 lecture notes.

Lindsay J. F. (1974) Transportation of detrital materials on the lunar surface: Evidence from Apollo 15. *Sedimentology* **21**, 323–328.

Lowe D. R. (1976) Grain flow and grain flow deposits. *J. Sediment. Petrol.* **46**, 188–199.

Mahmood A., Mitchell J. K., and Carrier W. D. (1974) Grain orientation in lunar soil. *Proc. Lunar Sci. Conf. 5th*, p. 2347–2354.

Nagle J. S., Duke M. B., Morrison D. A., Blanford G. E., and Crozaz G. (1976) Stratification in drive tubes 60010/60009 (abstract). In *Lunar Science VII*, p. 599–601. The Lunar Science Institute, Houston.

Swann G. A., Bailey N. G., Batson R. M., Freeman V. L., Hait M. H., Head J. W., Holt H. E., Howard K. A., Irwin J. B., Larson K. B., Muehlerger W. R., Reed V. S., Renilson J. J., Schaber G. G., Scott D. R., Silver L. T., Sutton R. L., Ulrich G. E., Wilshire H. G., and Wolfe E. W. (1972) Preliminary geologic investigation of the Apollo 15 landing site. In *Apollo 15 Prelim. Sci. Rep.*, NASA publication SP-289, p. 5-1 to 5-112.

Coch, N. K., 1977, Sedimentary Structures and Depositional Sequences in Apollo 15 Mare and Highlands Cores: Lunar Science VIII, pp. 196-198.

SEDIMENTARY STRUCTURES AND DEPOSITIONAL SEQUENCES IN APOLLO 15 MARE AND HIGHLANDS CORES, Nicholas K. Coch, Department of Earth and Environmental Sciences, Queens College, C.U.N.Y., Flushing, N.Y. 11367.

Image enhancement techniques have been utilized to detect and analyze sedimentary features on radiographs of Apollo 15 drive tubes. Corresponding orthogonal radiographs of the drive tubes were oriented within a lunar azimuth range of ± 5° providing true lunar orientations for directional sedimentary structures in the cores. Detailed analysis of each radiograph has provided new information on differences in regolith character in Mare and Highland areas at the Apollo 15 landing site.

15011

Core 15011 is the upper half of a double drive tube taken at station 9A at the Hadley Rille margin. The drive tube contains 4 major sedimentologic units (A, top to D, base) marked by changes in grain size, clast to matrix ratio and sedimentary structure types. The core has been described in detail by Coch (1976) who inferred directions of sediment transport at two levels within the core based on an orthogonal petrofabric analysis. Sedimentary features reported from this core include: Preferred orientation of long axes of elongate clasts (unit A); sharp grain size changes at all three stratigraphic unit contacts, and inclined laminae with long axes of elongate clasts plunging in a direction perpendicular to the strike of the laminae. (D) Core 15011 exhibits the best developed grain size variations, sedimentary structures and directional sedimentary features of all the Apollo 15 cores.

15010

Core 15010 is the bottom of the double drive tube taken at station 9A. This core contains 5 distinct stratigraphic units: unit D(top-6cm),E(6-10cm), F(10-19cm),G(19-26cm) and H(26-31cm,base). The soil in unit D is identical in sedimentary characteristics to the basal unit (D) in Core 15011. The irregular basal contact of unit D, and the evidence of reworking along the unit D-E contact, suggest that the transporting force which deposited unit D was capable of reworking the underlying finer grained unit E. Another possibility is that the irregular contact may be a portion of a meteorite crater excavated into the underlying unit E and infilled with the coarser and inclined laminae of unit D. In either case, petrofabric reconstruction suggests that the sediment transport was from lunar northwest to southeast during deposition of unit D (1). The five distinct stratigraphic units in Core 15010, along with the 4 distinct units in Core 15011, indicate the deposition of soils of significantly different maturity during the construction of the regolith profile at station 9A.

15009

Core 15009 is a single drive tube taken at station 6 along the Apennine Front near Spur Crater. The core contains three stratigraphic units: A(0-9cm),B(9-21cm), and C(21-37cm,base). Many of the sedimentary features in this core have been obscured by the development of an extensive network of cracks extending into the core from the top and basal void areas. Unit C contains a number of discoidal soil clasts surrounded by this crack network. The development of such a crack system suggests that the 15009 soil is quite cohesive. The two uppermost units (A&B) are largely devoid of any sedimentary features and are characterized by small clasts of material of a probable basaltic composition mixed with matrix material and other clasts of typical Highlands material.

15008

Core 15008 is the upper part of double drive tube 15008-15007 taken at station 2 along the Apennine Front near St. George Crater. The core is subdivided into 4 stratigraphic units: A(top-7cm), B(7-14cm), C(14-23.5cm) and D(23.5-29.0,base). The soils of core 15008 are predominantly fine-grained with isolated poorly sorted, subrounded clasts. The relatively coarser grained units A&C have a chaotic clast fabric and may represent an intermittent influx of fresher debris from nearby cratering events. This coarser material mixed with the more mature finer regolith on the Appennine Front forming poorly sorted units such as C and possibly A. Stratification features and sedimentary structures are rare and hiatuses in sedimentation may be marked only by thin layers of sub-horizontally oriented clasts.

15007

Core 15007 is subdivided into two major stratigraphic units: E(0-23.7cm) and F(23.7-32.0,base) which differ both in clast content and sorting. However, certain characteristics such as matrix supported clasts, the absence of stratification features and rather uniform distribution of clasts within the matrix, are common features of both units. These characteristics suggest a rather uniform sedimentation within both units with the basal unit reflecting a greater supply of coarser clasts during deposition than the upper unit.

Synthesis

While the Apollo 15 mission obtained cores from only one Mare site (15011/15010) and two sites in the Apennine Highlands (15008/15007 and 15009) analyses of these cores indicate that there are distinct differences in soil character between the two areas. Mare cores are distinctly coarser than cores from the Apennine Front. This observation agrees with the work of Butler (2) who made size analyses of Apollo 15 samples and found that samples from Apennine Front are finer than Plains samples. Comparisons of radiograph film densities suggest that the Mare cores (15011/15010) are richer in mafic rock components compared to the cores taken on the Apennine Front, which are relatively enriched in anorthositic material. Carr et al (3) analyzed soil samples from the Mare area of the Apollo 15 landing site. They concluded that the major constituents of Mare regolith are what would be expected from gardened basalt, i.e. chiefly basaltic fragments, basaltic mineral fragments and dark glasses laden with lithic and mineral debris. Mare cores contain a rich suite of sedimentary structures which are developed best in the coarser-grained soils. Highlands cores are largely devoid of sedimentary structures and rarely exhibit well defined stratification. Clasts in Mare cores are commonly in contact and have a preferred fabric. Clasts in Highlands cores are largely matrix supported and have a random clast fabric. Mare cores are relatively cohesive and marked by crack networks which extend vertically through the cores and isolate rounded clasts in the soil.

The overall absence of sedimentary structures in Mare cores may be the result of any or all of the following: 1) depositional processes, or grain sizes, not favoring the development of sedimentary structures; 2) reworking of the relatively mature Highland soils obliterating traces of previously-formed structures; or 3) modification of sedimentary structures through downslope movement of surficial material along the Apennine Front.

References

(1) Coch, N. K. (1976) Proc. Lunar Sci. Conf. 7th, p. 113-122.

(2) Butler, J. C., King, E. C., and Carman, M. F. (1972) Apollo 15 Lunar Samples, p. 45-47.

(3) Carr, M. and Meyer, C. (1972) Apollo 15 Lunar Samples, p. 48-49.

Coch, N. K., 1976, Radiographic enhancement analysis of sedimentary structures and depositional history in Apollo 15 Core 15011: Lunar Science VII, p. 163-165.

RADIOGRAPHIC ENHANCEMENT ANALYSIS OF SEDIMENTARY STRUCTURES AND DEPOSITIONAL HISTORY IN APOLLO CORE 15011, Nicholas K. Coch, Department of Earth and Environmental Sciences, Queens College, C.U.N.Y., Flushing, New York 11367.

Considerable data is available on the characteristics of lunar soils, whereas relatively little is known about the sedimentological and stratigraphic characteristics of the undisturbed lunar regolith. An ideal source of such data is the orthogonal (90 degrees) stereoradiographs taken of each drive tube. Normal viewing of the radiographs reveals some larger-scale features, but this type of study alone is inadequate to detect the subtle sedimentary structures necessary to establish the depositional history and sediment dispersal directions during sedimentation. If such detailed data could be obtained, it would complement later core dissection and provide stratigraphic data for more accurate sample selection and interpretation.

The overall purpose of this study of Apollo 15 radiographs is to develop methods for maximizing the stratigraphic data which can be obtained from the radiographs. Specific aims of the study are to: 1) utilize electronic radiographic image enhancement techniques to detect subtle sedimentary features and stratigraphic relations which are either not visible, or poorly defined, on the original radiographs: 2) determine the lunar azimuthal orientation for each orthogonal core radiograph in order to orient any directional sedimentary structures (inclined laminations, preferred orientation of elongate clasts, etc.) documented during the radiographic enhancement study and: 3) synthesize this data to determine the stratigraphic units and depositional history of a typical drive tube (15011). The techniques used, findings, and significance of the study are outlined below.

The Apollo 15 drive tubes were not oriented during the mission, and thus it was necessary to obtain this data from other sources. Documentation photographs (AS 15-82-11162) were oriented by Dan Kinsler (LSI) and data on radiographic techniques and azimuthal measurements of core tube hardware visible in the photographs were provided by the Curatorial staff. Using all of this data core 15011 (and the 15011 orthogonal stereoradiographs) were oriented to within an azimuthal range of 5 to 10 degrees. Since the radiographs pairs were taken at right angles to each other, differences in attitude of clasts and other sedimentary features occurring at the same level in both radiographs could be used to establish the orientation (strike, dip, azimuth, plunge, etc.) of the feature.

One pair (1R and 2R) of the orthogonal radiographs were selected for electronic image enhancement analysis. The radiographs were examined in detail using an SDS 401/704 Datacolor Image Enhancement system where relative radiographic film density is expressed as a series of color patterns on a display screen. The sedimentary features noted were photographically documented and measured. Where directional sedimentary structures were present, they were oriented relative to lunar North.

Core 15011 is the top half of a double drive tube taken at station 9A, near the Hadley Rille. Preliminary examination of the core radiographs (Apollo 15 Preliminary Science Report, Fig. 6-16) showed four stratigraphic units in the core. The present image enhancement study provides significant new information on the characteristics of these four units. Detailed descriptions of each unit is given below.

A. Top (0) to 8 cm.

Larger clasts and more clast-rich than unit B. Horizontal to subhorizontal orientation of clast-rich layers. Clasts in 1R radiograph have subspherical shapes whereas the same clasts in the 2R radiograph have elongate shapes. This data suggest that the elongate clasts in this unit have a preferred orientation of their long axes in a lunar NW-SE direction.

B. 8 to 17 cm.

Smaller clasts, more matrix-rich, and higher density than unit A. Gradational change into unit A suggests possible reworking along the upper contact. Definite horizontal laminations of varying thicknesses.

C. 17 to 23 cm.

Distinctly finer grained, denser and more cohesive than other core units. Sharp contacts with units above and below. Suggestions of numerous very thin horizontal laminations throughout unit.

D. 23 to 30 cm. (Base)

Similar in texture to unit A but laminations are more clearly defined and have different attitudes in each orthogonal radiograph. The change from horizontal laminations in the 1R radiograph to inclined laminations in the 2R radiograph indicates there are inclined laminations in unit D. The dip section of these laminae is the 2R radiograph which has an azimuthal orientation of 124-304 degrees, or lunar southeast to northwest. This reconstruction suggests that the laminations in unit D dip lunar southeast, and that the sediment forming these laminae was transported to the site from the northwest.

An attempt can now be made to reconstruct the depositional history of core 15011 from the stratigraphic data above. The oldest event recorded in the core is the deposition of inclined laminations of clast-rich material from the northwest (unit D). Perhaps this transported material was filling in a small topographic low accounting for the inclination of the laminae. A marked change in sedimentation regime occurred during the deposition of the overlying unit C. The fine-grain size, cohesive nature, and horizontally-laminated character of this unit suggests relatively uniform and slow rates of sedimentation with the absence of any coarse clasts. A sharp change in sedimentation occurred during the deposition of unit B where coarse clasts and horizontal laminations are characteristic. The last depositional event recorded in core 15011 is unit A, texturally similar to unit B, but with a suggestion of a preferred NW-SE orientation of elongate clasts. Such a fabric suggests that the sediments in this unit may have been deposited by a directed force either from the NW or SE. As similar stratigraphic studies are carried out on other core radiographs in the Apollo 15 series it can be determined whether the sedimentary features noted here are local or related to more widespread events.

This study indicates that significant new stratigraphic data can be obtained from core radiographs through image enhancement techniques utilizing orthogonal radiographs which provide a three-dimensional view of particles and sedimentary features. The method devised in this study for orienting the core radiographs will enable features seen on other radiographs to be related to true lunar azimuths. Where appropriate directional sedimentary structures are present, the sediment dispersal patterns for that level of the core can be determined. Later, this date can be related to other studies when the cores are extruded and sampled. If similarities are found between different cores, it may be possible to correlate depositional layers at the Apollo 15 site. This correlation could be based on similarities in composition or sedimentary structure sequence. Similarly, units in different cores may be correlated on the basis of similar sequences of sediment dispersal indicators regardless of the composition of the layers.