Annual Report for

"INVESTIGATION OF IN SITU PHYSICAL PROPERTIES OF SURFACE AND SUBSURFACE SITE MATERIALS BY ENGINEERING GEOPHYSICAL TECHNIQUES" Project, FY-64

by

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CONTENTS

INTRODUCTION

The "Investigation of In Situ Physical Properties of Surface and Subsurface Site Materials by Engineering Geophysical Techniques" project, or as it is generally referred to "In Situ Geophysical Studies", was begun on April 1, 1964. The purposes of the In Situ Geophysical Studies Project are: 1) to investigate the extent to which geophysical techniques can be used to determine the physical properties of surface and subsurface materials in small areas; 2) to determine the practicality of devising lunar geophysical experiments that could be done on early Apollo landings; and 3) to develop interpretation guidelines for these lunar geophysical experiments.

To accomplish these objectives two study sites would be selected in which a number of seismic profiles would be shot and recorded. The areas would be geologically mapped in detail, cores obtained of rocks in the study areas and measurements of physical properties carried out on samples obtained from cores and outcrops in the study areas. These objectives have been equalled or exceeded in almost all respects.

Although much of the data obtained during the first three months of operation of the In Situ Geophysical Studies Project have not been completely analyzed because of the short duration of the project, preliminary analysis of the data has led to several tentative conclusions. The results are, however, based on limited amounts of data and will probably require some modifications as more data is analyzed.

First, our data indicate that if the lunar surface is microseismically quiet (as suggested by the scientific consensus), and if attenuation rates of seismic energy are similar to those observed in thick cinder deposits near Sunset Crater, then energy transduced into the ground by a moderate blow of a geologic hammer can be detected at distances up to 500 feet. The fact that such energy can be detected at these distances means that many useful seismic experiments can be conducted on the lunar surface without using explosive energy sources. The second conclusion is that the energy spectra analyzed to date have a higher modal frequency than had been anticipated from exploration data published in geophysical literature. Maximum amplitudes were generally observed in the 80-140 cycles per second (cps) bandwidth. If this pattern persists, the sensitivity of instruments can be increased by restricting the band pass to a similar range, thereby maximizing the signal to noise ratio. These attenuation data have had an immediate use in the recommendations for active seismic missions for early Apollo designed around non-explosive energy sources.

Coring operations in the Kana-a lava flow near Sunset Crater have yielded three virtually complete cores of an entire flow unit.

The best core of the flow rock consists of about 27 feet of what appears to be a classic aa section. The top 13 feet consists of highly vesicular lava, the middle 12 feet consists of dense lava, and the lower 2 feet consists of lava with flattened vesicles. Analysis of the petrography and physical properties will provide a more complete understanding of an aa flow than is presently available in the geological literature.

Geologic operations consisted of reconnaissance of all likely sites in the Flagstaff area, field mapping of the exposed rocks on S. P. flow and Kana-a flow, and preliminary petrographic analysis of rock samples collected from these areas. Sites in the Mohave Desert, California were also reconnoitered as potential study areas.

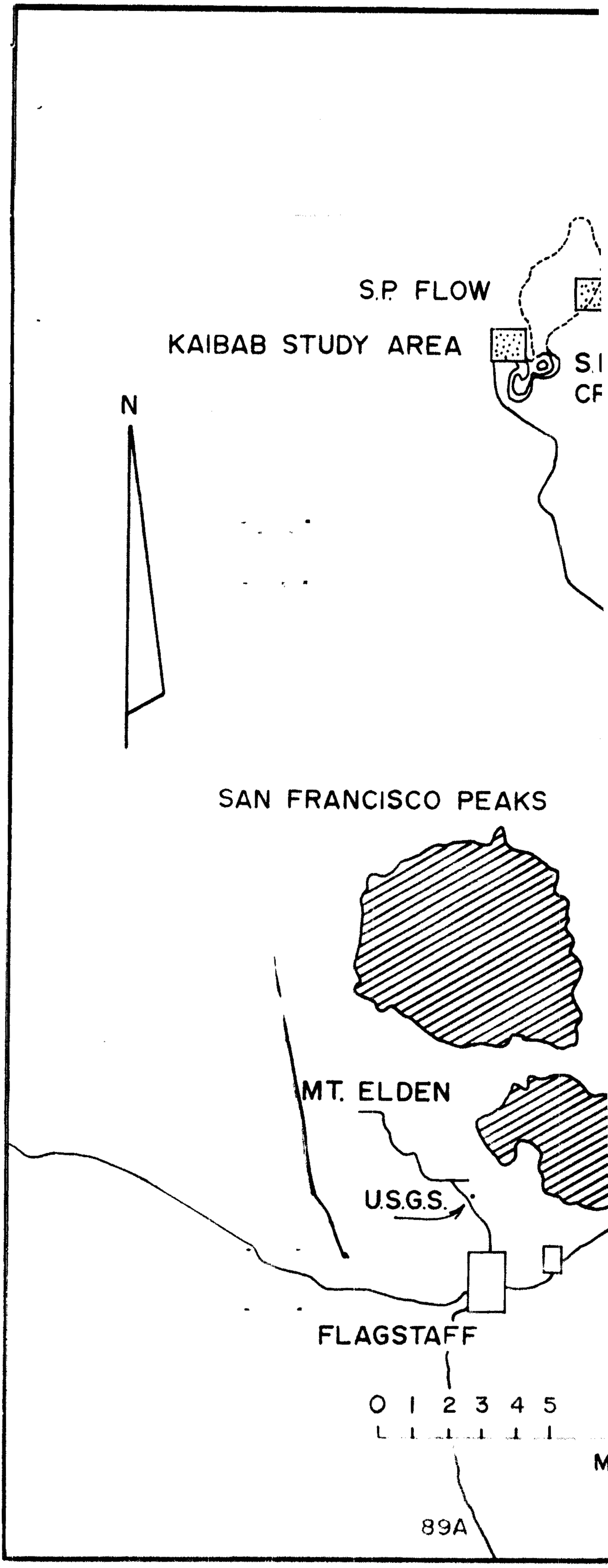
In addition to the above scientific results, a number of potential study sites have been reconnoitered, field procedures devised, equipment tested, and the staff organized. Field measurements were conducted over a period of about six weeks and data analysis was begun in the latter part of the report period. The professional staff of the project consists of the authors of this report and Dr. J. Cl. De Bremaecker (WAE), Associate Professor of Geophysics at Rice University in Houston, Texas. J. H. Whitcomb, seismologist, will join us in the summer of 1964.

Equipment used to date consists of an HTL 7000-B 12-channel wide-band unit and an SIE p-19 portable unit. A wide-band system (5-500 caps) including a Geo Space 111 amplifier and a Geo Space FM-300 magnetic tape recorder have been ordered and delivery has been promised during July, 1964. A drilling rig is being procured through MSC in Houston with delivery expected in late summer or early fall of 1964.

The ability to record records on magnetic tape will greatly reduce the number of shots required to analyze frequencies because a single shot can be replayed at different filter settings. Tape recording will also facilitate data analysis because records can be replayed at a variety of gain settings until the one is found which gives the clearest representation of the wave forms.

FIELD WORK AND DATA ANALYSIS

Introduction.- After reconnoitering potential study sites in the Flagstaff area, four sites were selected for study during FY-64 instead of two as originally specified in the Work Plan. Three of the sites are in volcanic terrains and were chosen because of the likelihood that similar areas exist on the lunar surface. The fourth area, which lies on a limestone mesa, was chosen in order to compare seismic results from fractured lava and loose cinders with results from consolidated rock. Reconnaissance indicated that each area presented peculiar scientific and logistic problems, some of which could not be overcome completely in FY-64. For example, the Kana-a flow is covered almost entirely with ash and geologic information is largely dependent on cores which in turn were not available until late in the report period. Kana-a was, however, easily accessible and consequently a large portion of the seismic effort was concentrated there. On the other hand, S. P. flow was exposed and samples could be readily obtained for mapping and laboratory analysis. However, it is not trafficable to vehicles and seismic work was limited to that which could be done with hand-carried equipment. It was clear, therefore, that if only two sites were used, some part of the crew would be used very inefficiently whereas with four areas, the entire crew could serve at near peak capacity. Figure 1 shows locations of the four sites.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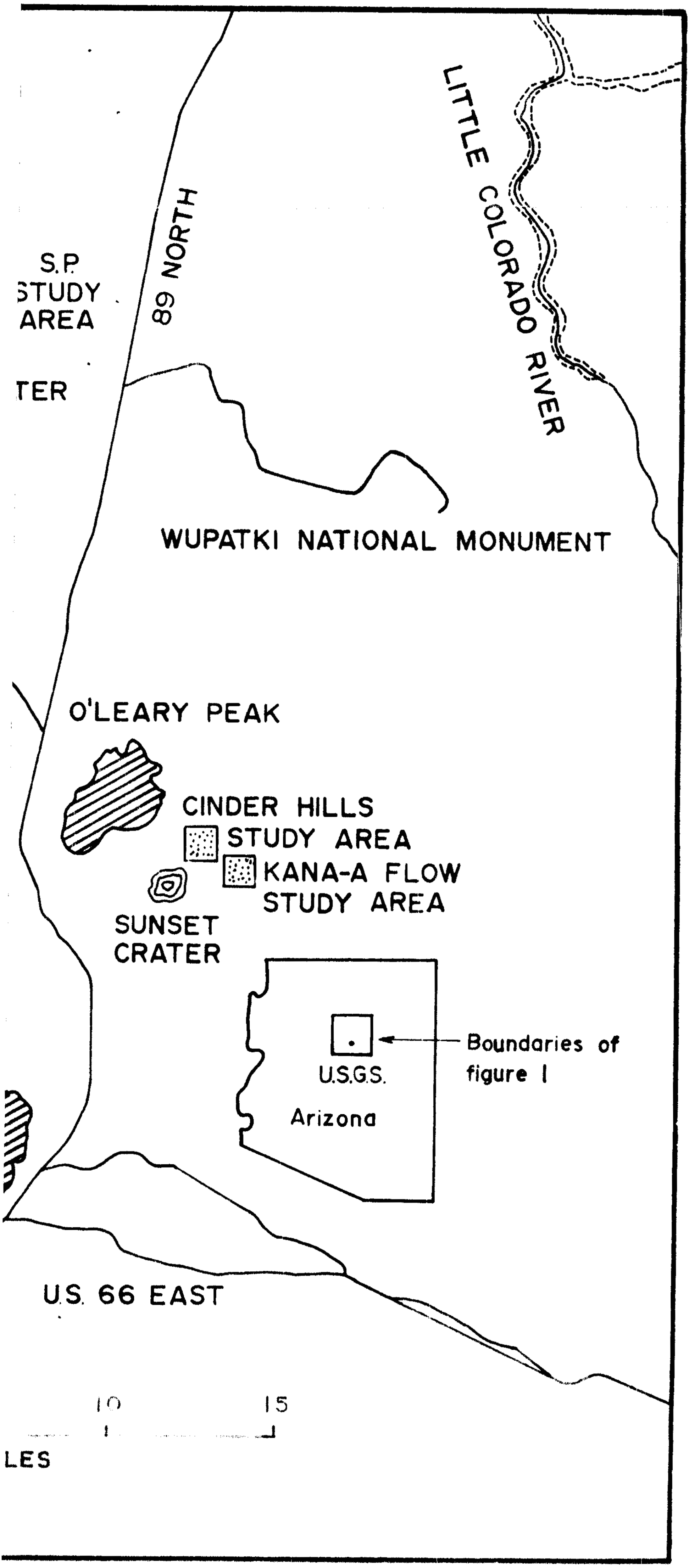

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The most extensively investigated area was the Kana-a flow east of Sunset Crater where we recorded 152 shots on 8 spreads. The large number of shots and spreads is due to the extreme variability and complexity of structure. Shooting included instrument tests, optimum shot size tests, refraction spreads to determine ash thickness, band pass shots for preliminary spectral analysis, shots at various distances from the spreads in order to determine attenuation, and velocity logging of core holes.

The second area of investigation is designated Cinder Hills, as it has no proper name. The Cinder Hills area lies northnortheast of Sunset Crater and consists of (50-100 feet) accumulations of loose ash and cinders erupted from Sunset Crater and other volcanoes in the area. Here we recorded only 58 shots on 4 spreads because as far as is known, structure is relatively simple and additional shots would probably have not yielded significantly more information. One problem encountered in the Cinder Hills area is the difficulty in obtaining samples. Both augering and coring have failed to bring up suitable samples, but other techniques, such as pregrouting and coring with a split core barrel, are under study.

The third area of investigation lies about 32 miles north of Flagstaff on the eastern edge of S. P. flow. The surface of S. P. flow cannot be negotiated by any of our four-wheel drive vehicles, consequently, data consists of 17 shots which were recorded on one spread using portable equipment carried in by hand. Permits have been obtained and negotiations are completed to bulldoze a trafficable road into the study area. Field investigation will be completed on S. P. flow when the road is finished.

The fourth area lies near S. P. flow on a small mesa formed by outcropping Kaibab Limestone. Here we have recorded 48 shots on 2 spreads. Limestone, of course, will not be encountered on the lunar surface, but it is a relatively rigid rock with uniform seismic properties compared to the lavas and provides data which can be compared with data collected in areas underlain by lava. The most significant result of the comparison of shots in this area is that good transverse waves are developed in the limestone, but no coherent transverse waves have been observed in the other areas.

Field geological studies of Kana-a and S. P. flow areas have been completed and the samples which were collected during field studies are currently being petrographically analyzed. Physical properties of 24 samples from the S. P. flow area have been determined; physical property measurements of samples collected from core drilling and outcrops in the Kana-a area are scheduled for later this summer.

SEISMIC INSTRUMENTS AND FIELD PROCEDURES

Field operations were begun on May 19, 1964 using an SIE P-19 portable refraction seismograph system. This equipment was used during the first of two field periods for reconnaissance and devising field procedures. This equipment, which could be carried in a jeep or hand carried by three men to relatively inaccessible locations, was used to record 27 seismograms during the initial field period. On June 2, a second period of field operations was begun using a truck-mounted HTL 7000-B instrument system. A total of 228 seismograms were taken with this equipment before field work for the fiscal year was terminated on June 23, 1964.

The HTL 7000-B system is mounted in a cab on an F-600 Ford body and consists of a 12-channel amplifier system, a control assembly, Log Level Indicator assembly, power supply, inverter, oscillograph and blaster.

For refraction shooting, the gain on the individual amplifiers is controlled by a 10-position switch, each having a 10 db step. Outputs of the individual amplifiers are matched by equalizing the reading on the test and ohmmeter scale when a signal of known voltage is applied to each amplifier.

The filtering system consists of both single and double section filters with several cutoff slopes. Frequencies on the low cut filters decrease in several steps from 210 cps to 18 cps and on the high cut filters from 320 cps down to 31 cps. The double section filter KK which was used in recording has a cutoff slope of 36 db per octave.

An internal ohmmeter system and a built-in oscillator signal system are provided to perform various tests such as measuring geophone resistances, leakage to ground, amplifier outputs, and making oscillator tests with varying signal strengths.

The Bi-Level switch on the control panel feeds twice the normal output of the amplifiers into one set of 12 galvonometers and half the normal output into another set of 12 galvonometers; the net result being a 4:1 ratio of amplifier amplitude outputs.

The Log Level Indicator (LLI) that accompanies the system is wired into channel six and is essentially a measure of the total energy of this amplifier. By use of calibration tests the input voltage can be determined.

The SIE P-19 system consists of a 12-channel amplifier unit, power supply, oscillograph, blaster and a 12 volt battery. The equipment is completely portable.

The amplifiers have four stages of gain which provide a usable sensitivity of one microvolt. Gain is controlled by a 10-position switch and sensitivity controls allow the output of the amplifiers to be evenly matched. The filtering system consists of three single section high cut filter positions at 30, 50 and 100 cps.

The following is a description of field methods that were used in all areas of study:

1) All spread locations were chosen so that the spread and shot points would be approximately level; exceptions are Spread BC (figure 13) on Kana-a flow, which is on the side of a hill and Spread CD (figure 24) on Cinder Hills where the shot points are offset more than 50 feet and are approximately 30 feet below average spread level.

2) All seismometers were leveled.

3) All seismometers were buried several inches to minimize the effect of the wind.

4) During the second field period, the No. 1 geophone was always at the north or east end of the spread and geophones 1, 4, 7 and 10 were horizontal with the axis in line with the spread, with the top of the geophone pointing to the north; geophones 2, 5, 8 and 11 were vertical, and geophones 3, 6, 9 and 12 were horizontal with the axis transverse to the spread and the cap pointing west.

5) When recording filter shots one blasting cap was used at offset distances of 10 feet, and one-eighth pound was used at offset distances of 160 and 210 feet.

6) All records were recorded on Bi-Level with the 7000-B instrument.

7) Oscillator test records were taken both before the first record and after the last record each day. These were fixed

gain calibration tests taken at the different sensitivities used during the day. The input voltages of the oscillator were 1, 3, 10, 30, 100 and 300 microvolts and 1, 3, 10 and 30 millivolts.

DATA ANALYSIS

Analysis begun during the report period consisted of picking and timing first arrivals, scanning records for evidence of coherent transverse motion, and measuring amplitudes of the first full wave for attenuation and preliminary spectral analysis.

The first arriving energy was picked and timed for conventional refraction analysis. Amplitudes of early arrivals were relatively high and easily picked. The only problem encountered in picking and timing occurred in those records where the velocity of the compressional wave through cinders was approximately the same as that through air. When it was discovered that these velocities were nearly identical in some areas, charges (both caps and dynamite) were buried in order to obtain a smaller air wave.

Coherent transverse motion has not been observed in data from the lava flows and cinders, but is easily discernible on some records from the Kaibab area. The transverse motion in the lava flow and cinders arrives at approximately the same time as compressional motion which suggests that the transverse motion was generated near the end of the ray path rather than near the shot point. When the data are digitized, it will be possible to "velocity filter" the arrivals. Arrivals which are obscured by noise in the original data may then become apparent. It is thought that this process will reveal coherent transverse motion in the data from the cinders and lava flows.

The principle of velocity filtering is as follows: let us assume a wave with a velocity V arrives at the first detector at t_1, at the second detector at $t_1 + d$, at the third detector at $t_1 + 2d$ and at the j^{th} detector at $t_1 + (j-1)d$. If a time delay of $(i-1)d$ is introduced in each channel (where i is the number of both detector and channel), and the amplitudes of all channels are added, then waves traveling with velocities V will interfere constructively and appear as energy peaks. Waves traveling at other velocities will interfere destructively. Attenuation corrections will be applied to amplitudes of each channel; without these, data from detectors close to the shot would have a disproportionate influence in the summation.

Although amplitudes of amplifier outputs in the 7000-B instrument were matched within a few percent, oscillator tests indicated that galvanometer outputs varied by as much as 50 percent. Consequently, the first step in analysis of data for frequency spectrum and for attenuation consists of measuring amplitudes on oscillator test strips and computing normalizing factors for each channel on both high and low levels. After completion of this step, amplitudes of first motion are measured on all channels of the field tapes. When this measurement is completed, amplitudes are normalized by multiplication of the factor mentioned previously and attenuations and band pass spectra are plotted.

As a first approximation of the attenuation function, it is assumed that the amplitude (A) of recorded seismic energy is inversely proportional to the distance (d) (from the shot) raised to some power (a) or $A=kd^{-a}$ where k is some constant. This function, when plotted on log log paper, appears as a straight line with a slope equal to a. Modifications in the assumed attenuation function will be made when warranted by the data.

A preliminary estimate of the spectrum was obtained by recording energy in the out-31, 30-66, 60-120, 120-215, and 210-320 cps bands as well as the total energy in the out-320 cps band. "Out" indicates that no low-cut filter was used other than the amplifier response which is 6 db down at about 5 cps. The data derived from this procedure are qualitatively significant and, as previously mentioned, suggest that lunar instruments should have peak responses higher than conventional refraction instruments. However, the data are quantitatively marginal. Specifically, the lower (out-31) and upper (210-320) bands are not even octaves and an increase in the number of bands is desirable. Changes will be incorporated in future procedures to increase the number of bands, and to make band widths uniform fractions of octaves. It is hoped that problems of analog to digital conversion can be overcome in the first half of FY-65. When the data are digitized, Fourier analysis will provide complete spectral response rather than band pass response as provided by FY-64 instrumentation.

STUDY AREAS

Kaibab.- The Kaibab study area was selected because of the necessity of comparison of seismic data recorded in the lava flows with seismic data recorded in an area of rigid rock. The Kaibab limestone, which is of Permian age, consists of a relatively thick sequence of limestone beds and interbedded limestone-clastic beds. The test area is located immediately west of the S. P. flow on top of a small mesa (figure 2). Outcrops in an adjacent valley indicate that the thickness of the Kaibab exceeds 80 feet in the study area. Almost no geologic mapping has been completed but cores in the area will be taken at a later date. Seismic experiments conducted in the area include refraction profiles, tests for charge size, instrument tests, band pass shots, and attenuation shots.

Seismic energy in the Kaibab study area differs from energy recorded in the lava fields in that it exhibits coherent motion in the transverse plane, however the nature and cause of this motion are not yet clear.

The Kaibab area was first investigated on May 19-20, 1964 when 24 records were taken using the SIE P-19 equipment. These records consisted mainly of seismometer duplication tests.

Two continuous spreads (A and B), each with four groups at 50 foot intervals, were recorded. Each group had three

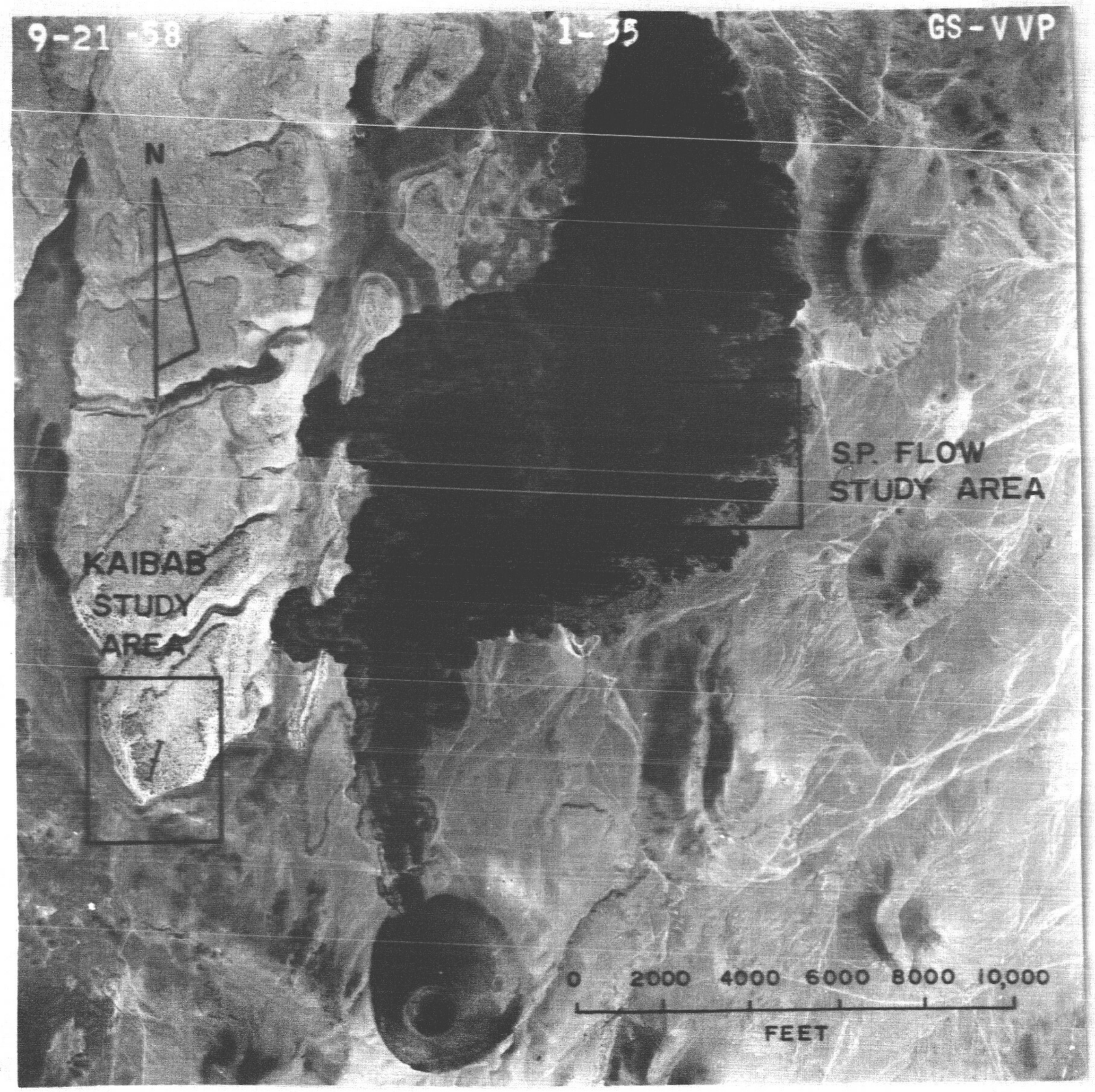
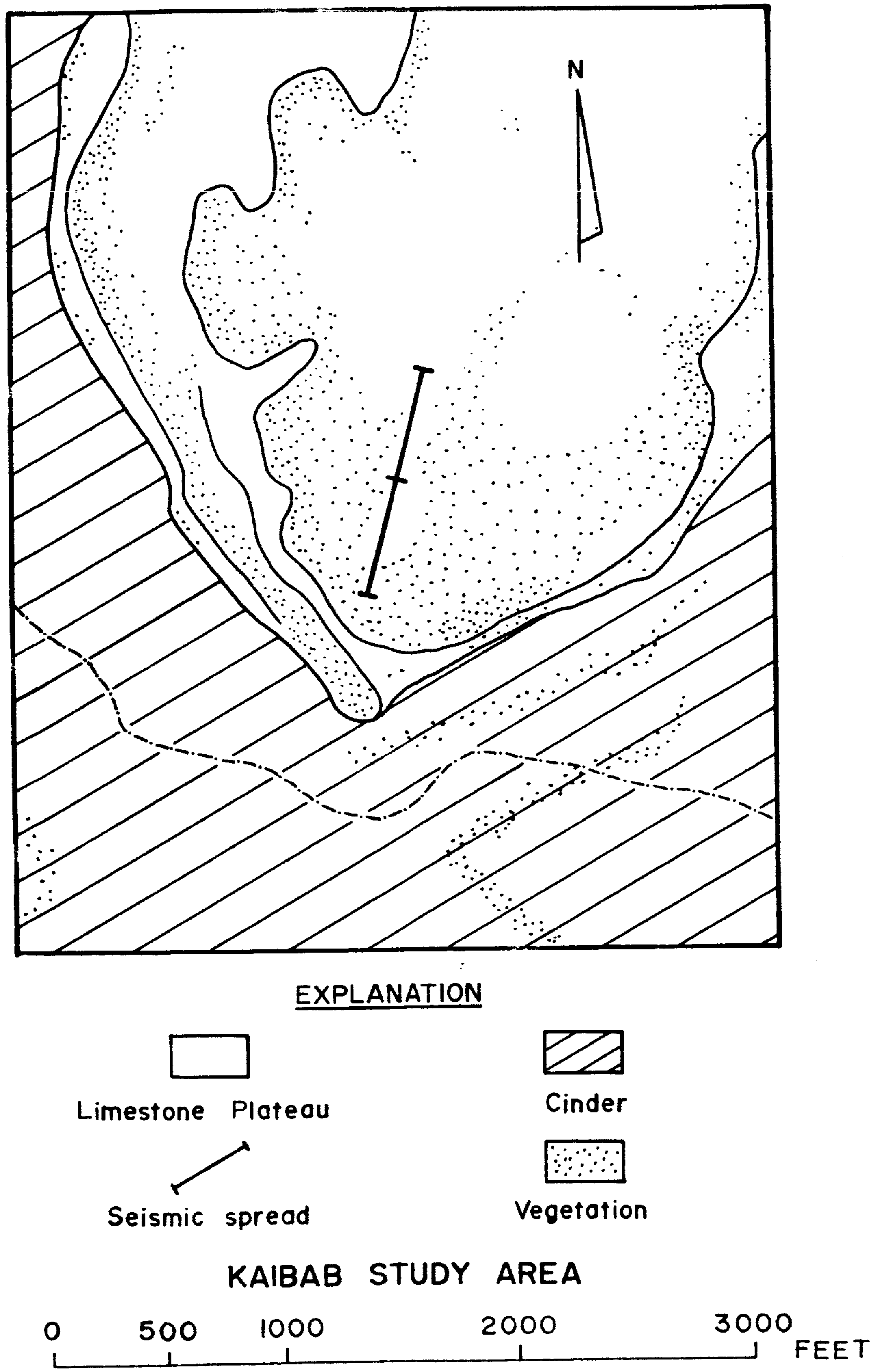


Figure 2. Aerial photograph showing locations of S. P. flow study area and Kaibab study area relative to S. P. crater and flow. Small lines within study areas indicate seismic spread locations.

seismometers placed together--one vertical, one horizontal in line with the spreads, and one horizontal transverse to the line of the spread. Spread A was recorded from several shots at offset distances of 100 and 263 feet north of the spread and at 200 feet south of the spread. Spread B was recorded from several charges shot 200 feet north and 200 feet south of the spread. One shot was tried with a two and one-half pound charge suspended three feet above the ground on a stick. Filter settings of 100-out and 50-out were tried along with different charge sizes varying from one-half to three pounds.

On June 19, 1964 the area was again investigated with the HTL 7000-B instrument. A total of 24 seismograms were recorded with this equipment. One refraction spread consisting of 12 vertical seismometers placed 50 feet apart was recorded from offset distances of 50, 100, 200, 300, 400 and 500 feet north of the spread and from 50 feet south of the spread. The filter setting used was 75 KK-out and the charge size was two and one-half pounds at a depth of one foot.

Filter shots were taken at two spreads located within the refraction spread (figure 3). These spreads had the same layout as described above; i. e. four groups of three seismometers each. Spread A_1 was recorded six times from an offset distance of 160 feet north using the following filter settings: 320 KK-out, 320 KK-210 KK, 215 KK-120 KK, 120 KK-60 KK, 66 KK-30 KK



KAIBAB STUDY AREA

and 31 KK-out, and once from an offset distance of 10 feet south with a filter setting of 320 KK-out. Spread A_2 was recorded the same way as A_1, only the offset distance for the six filter settings was 10 feet north and for the south shot point the distance was 160 feet. In other words, the shot points were the same, but the geophone spread was moved.

Frequency response curves are shown for Spread A_1 in figure 4. Frequency curves for Spread A_2 and attenuation curves for both spreads are currently being calculated.

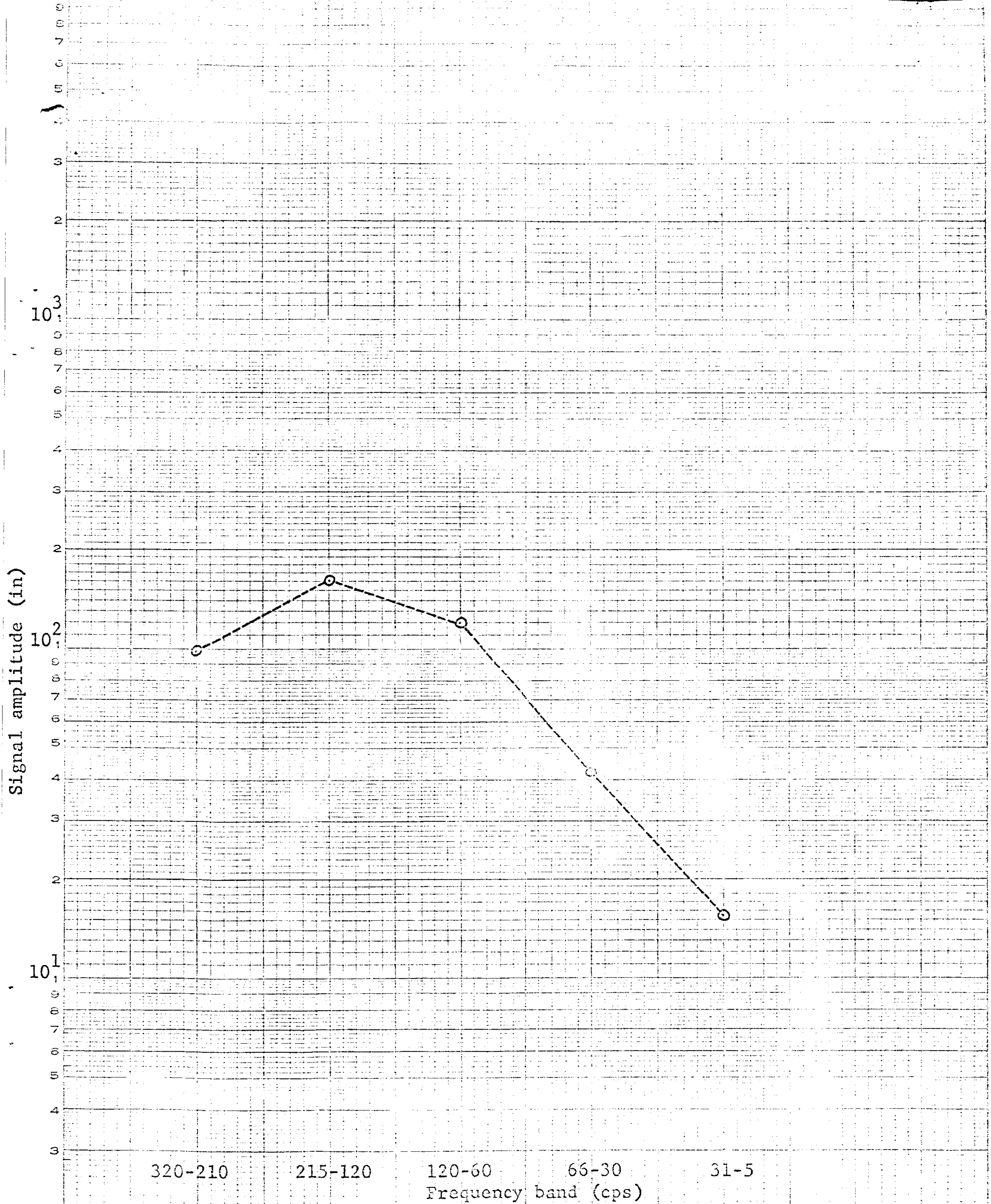


Figure 4. Seismic amplitudes observed in five frequency bands on Kaibab spread A_1 at a distance of 160 feet from 0.125 pounds of dynamite exploded on the surface. Amplitudes were scaled from oscillograph tapes and normalized but not converted to ground amplitudes.

S. P. flow.- S. P. flow is a recent basaltic lava flow, located about 32 miles north of Flagstaff, Arizona, on the northern edge of the San Francisco volcanic field. Geologic mapping is essentially complete but seismic work has been delayed pending completion of a trafficable road.

S. P. flow emerges at the base of S. P. Mountain, a contemporary cinder cone, and extends northward in a slightly sinuous fashion for about 4.5 miles (figure 2). The flow is about 1,000 feet wide at S. P. Mountain and expands northward to a maximum width of about 2.4 miles in its middle part. The average thickness at its narrow southern end is about 40 feet, but the flow thickens northward and in its wider northern three-quarters, ranges in thickness from 150 to 200 feet. This thicker part includes the area of study. The S. P. flow poured out onto an erosional surface cut in the Kaibab Limestone of Permian age and probably also in places in older Quaternary volcanic deposits. Sabels (1960, p. 192) assigns an age of 1500 years to the S. P. flow on the basis of a comparison of thermoluminescence with the Bonito flow, 17 miles to the southeast. The Bonito flow has been dated at 900 years by dendrochronology (Smiley, 1958). The relief of this erosion surface, as shown on the western side of the flow, is locally more than 80 feet.

S. P. flow is an excellent example of block lava as described by Finch (1933) and Wentworth and MacDonald (1953, p. 32). The surface consists mainly of loosely packed, angular, equant, polygonal blocks of lava that range from 4 inches to 6 feet across and average about 2 feet (figures 5 and 6). Estimates of porosity of the loosely packed rubble ranges from 20 to 35 percent. The blocks are in general smooth, but commonly have a thin, one to two inch thick, scoriaceous layer on one side, which probably represents the original cooling surface. Blocks are now largely randomly oriented and only in scattered small areas do they fit tightly together in their original orientation (figures 7 and 8). These smooth, equant blocks contrast sharply with the platy, spinose, clinkery character of true aa lava, as characterized by the Bonito and Kana-a flows in the Sunset Crater area.

Blocks forming the upper surface of the flow are heaped in small ridges that rise as high as 50 feet above the general level of the flow. In plan view the ridges of blocks show a definite relation to the flow direction of the various lobes of the flow (figure 9). It is obvious that the forces that formed the rubble from tightly jointed lava did not move the blocks far from their original position. Some ridges are crescentic with their convex side down-stream and appear to owe their shape to drag on the sides of the lobes. Others are subparallel to the lobe margins and the direction of flow, whereas still others occur in straight sets that appear to intersect each other at obtuse angles. It is common for the crescentic ridges to be

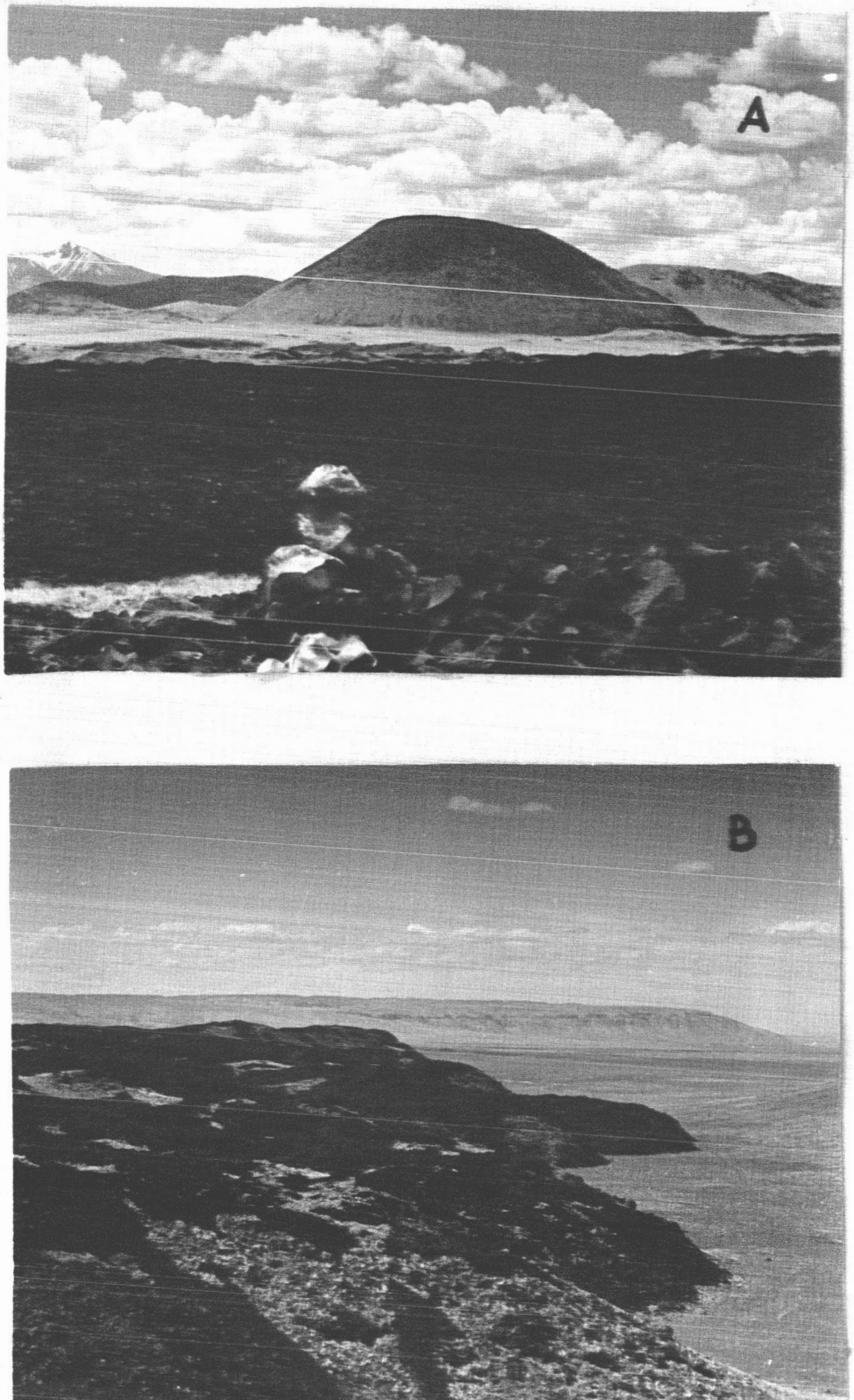


Figure 5. Views of the surface of S. P. flow. A - Looking south from study area toward S. P. crater. B - Looking north along the edge of the flow. Plateau in the distance consists of sedimentary rocks.

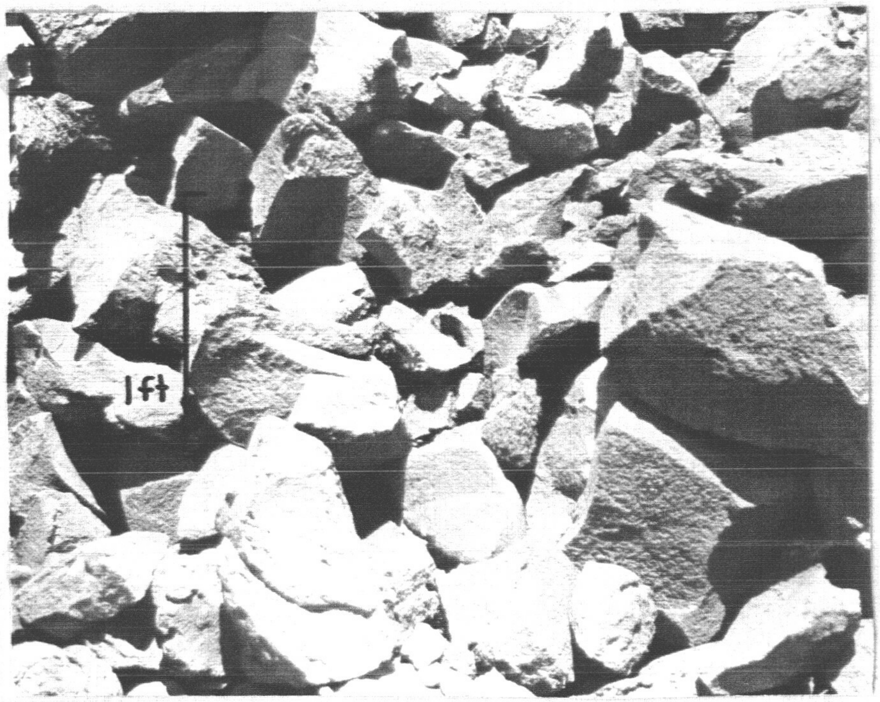


Figure 6. Close-up of surface of S. P. flow showing rubbly texture.

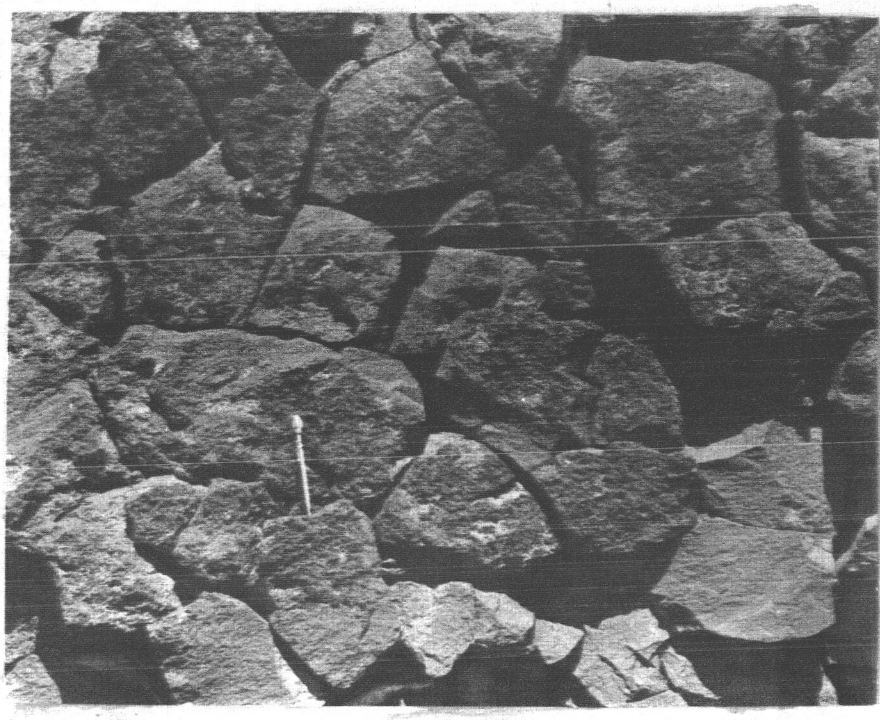


Figure 7. Close-up of surface showing tightly fitted polygonal blocks in their original orientation.

Figure 8. Mass of blocks still tightly fitted together.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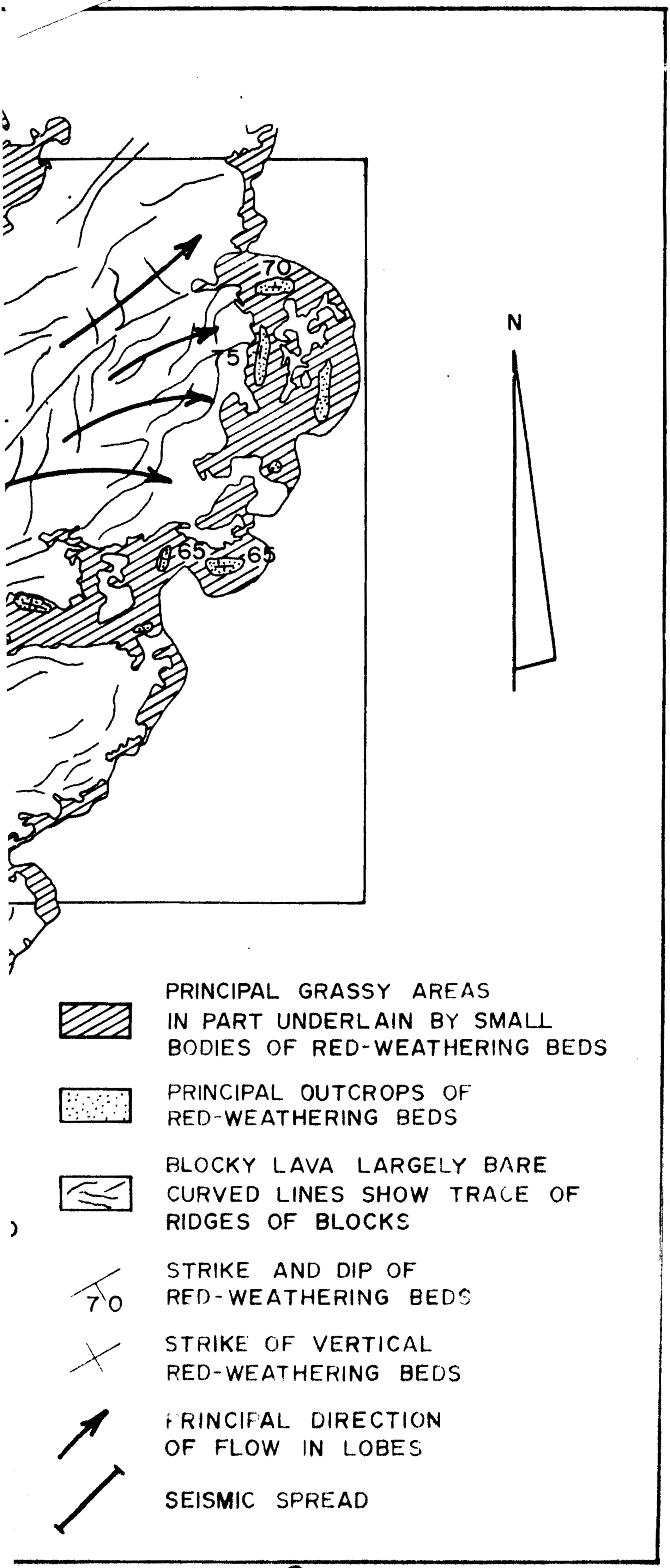
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PRINCIPAL GRASSY AREAS IN PART UNDERLAIN BY SMALL BODIES OF RED-WEATHERING BEDS
PRINCIPAL OUTCROPS OF RED-WEATHERING BEDS
BLOCKY LAVA LARGELY BARE CURVED LINES SHOW TRACE OF RIDGES OF BLOCKS
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STRIKE AND DIP OF RED-WEATHERING BEDS
STRIKE OF VERTICAL RED-WEATHERING BEDS
PRINCIPAL DIRECTION OF FLOW IN LOBES
SEISMIC SPREAD

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sigmoidal in outline and to be truncated by the longer ridges that parallel the lobes. This fact suggests that longer ridges represent shear zones between lobes, or segments within the lobes, between which the crescentic ridges have been deformed. The intersecting straight sets of ridges suggest conjugate sets of shear fractures or folds. In any case it is apparent that the flow pattern even within the small area of study is complex. The present rubbly character of the surface is due in part to polygonal jointing caused by contraction during cooling, and in part due to lava movements during and after the cooling of the surface. The depth of the loose rubble is not known, but the presence of small domes and blunt pinnacles on top of the flow, and more irregular masses on the sides in which the blocks fit tightly together, suggests that the rubble is underlain at shallow depth by a highly jointed but fairly solid, continuous rock mass. The upper part of the continuous mass may be irregular with high points possibly represented by the above-mentioned small domes and pinnacles. It seems probable that each lobe of the flow is a fairly continuous, coherent unit, save for large scale fractures related to collapse structures and large scale voids such as lava caves and tubes.

According to Wentworth and MacDonald (1953, p. 62-63), viscous flows that produce block and aa lavas generally advance over debris that has fallen from their own fronts. Thus a layer of loose rubble is to be expected below the continuous rock mass.

The front of the S. P. flow rises steeply from 120 to 160 feet in the northern part of the flow, and it is probable that a considerable amount of rubble would be derived from such a steep front and over-ridden by the main part of the flow. The thinner, subsidiary lobes would have little or no basal rubble layers. A substantial rubble layer is to be expected in the area of study.

The S. P. flow is generally lacking pyroclastic debris, soil, and vegetation, but minor areas of grassy soil occur along the edges of the flow and in narrow tongues that project into the flow, chiefly between the major lobes. In addition small patches of grassy soil are sparsely scattered through the bare block lava of the interior surface of the flow. The soil on which the grass grows appears to be almost entirely derived from a red-weathering partly pyroclastic rock, which is the only important minor rock type in the flow. This rock consists of medium gray and dark red mottled, very fine grained, almost nonvesicular basalt interbedded with loosely cemented, red-weathering, scoriaceous, lapilli tuff. The beds range in thickness from 1 inch to a few feet, and either rock type may be locally predominant. The soil is largely derived from the easily weathered tuff, the outcrops of which are commonly surrounded by a grass-covered apron of unconsolidated lapilli that washes down-slope and in places covers the block lava.

The reddish tuff and basalt beds are generally steeply dipping, and form steep, jagged masses that project prominently above the general level of the block lava (figure 10). The red-weathering beds occur in discontinuous units ranging from a few feet to a few tens of feet in thickness. They are confined to the margins of the flow and to narrow areas between the major lobes of the flow. The largest such interlobe area extends inward from the western side of the flow; in addition to the reddish tuff and basalt beds, this area contains hornitos (spatter cones) and other features associated with gas activity that are entirely lacking elsewhere in the flow. The position of the red-weathering beds, their disrupted tilted structure, and their highly oxidized pyroclastic character all point to their being the product of an earlier, more explosive eruption that was broken-up by the advance of the predominant block lava. Whether or not the earlier eruption was related to the S. P. eruption cannot be determined on the basis of present evidence, but the apparent restriction of the red-weathering beds to the margins of the main lobes of the S. P. flow suggests that they are the products of an earlier phase of the S. P. eruption.

The predominant blocky basalt is dark gray to grayish black, fine grained, and finely vesicular; the blocks are weathered mottled dark brown, reddish brown, and yellowish brown. Small phenocrysts, which average about 1 mm in length, of plagioclase, pyroxene, and rarely olivine are sparsely scattered through the rock. Nearly every specimen examined contains a few, rounded,

Figure 10. Steep jagged mass of reddish tuff and basalt projecting above the general level of the flow.

clear, quartz grains, which range in diameter from 1 to 2 mm. The vesicles are generally tube-like and distinctly flattened; their width ranges from less than .5 to 5 mm, and averages about 1 mm, and their length ranges from 1 to 10 mm, and averages about 2 mm. The degree of flattening ranges from extreme in sheet-like vesicles to slight in subcirular vesicles. Irregular vesicles are present, but are generally much less common than in the Kana-a flow. The vesicularity of the rocks at the surface of the S. P. flow ranges from less than 5 to 50 percent and averages about 15 percent. The lower levels, as seen from the sides of the flow, seem less vesicular than the upper, but the fragmental character of the sides makes it impossible to be certain of the position in the flow of rock masses exposed there.

The lava of the S. P. flow is lower in olivine and probably less basic than the Bonito and Kana-a flows. Its striking block structure is probably a reflection of its more viscous character. Its darker color is due to its finer texture and high glass content. The following approximate model composition given by Hodges (1962, p. 22) seems reasonable in the light of our preliminary petrographic work; only the percentage of vesicles should be increased to about 15 percent.

Olivine	3%
Plagioclase	30%
Pyroxene	21%
Magnetite	8%
Glass	30%
Quartz	trace
Vesicles	8%
	100%

Preliminary analysis of 23 thin sections indicate that lava of the S. P. flow is quite uniform in texture and composition. The chief variation is in the degree of vesicularity, which ranges from less than 10 to more than 30 percent and corresponds to the calculated porosity of the laboratory tests. No other type of porosity, such as interstitial, was seen in this section.

The rock has a porphyritic hyalopilitic texture mainly composed of elongate laths of plagioclase and stubby prisms of pyroxene set in a base of brown glass. The plagioclase laths in general show a distinct fluidal orientation that bends and swirls around the phenocrysts, which are mainly pyroxene. The grain size ranges from .01 mm to 5.0 mm, and averages about .07 mm. The plagioclase is mostly calcic andesine, indicating that the rock is probably a basaltic andesite or an andesitic basalt. Details of preliminary petrography are as follows.

Plagioclase. 20-26%--Generally multiply twinned; normal zoning from An_{40} at rim to An_{63} at core, however, most crystals range from An_{44} to An_{52}. Plagioclase laths range in length from .01 to .75 mm, and average about .07 mm; those in the range .2 to .75 mm are called phenocrysts, but in many sections there seems to be a continuous gradation in size from smallest to largest. The margins of the plagioclase crystals are slightly corroded by the glassy groundmass. In general, no important differences could be seen between the various sizes of plagioclase crystals, but one large, highly resorbed crystal was seen, which is probably a xenocryst, foreign to the lava.

Pyroxene. 20-24%--The pyroxene is generally colorless and monoclinic, however, it is commonly zoned and three generations of crystals are present: (1) fine (average about .02 mm), equant grains of the groundmass, not noticeably zoned or corroded; (2) small phenocrysts (average about .1mm) rounded, strongly corroded by glassy groundmass, subhedral prisms, distinct oscillatory zoning (including "hourglass" zoning), sparse simple and multiple twinning; $2V_z$ about 40° to 45°, phenocrysts disseminated through rock; (3) larger phenocrysts (average about .8mm), euhedral, not noticeably corroded, oscillatory zoning and "hourglass" zoning; sparse simple and multiple twinning; $2V_2$ about same as smaller phenocrysts, one euhedral crystal had a rounded core that probably represents an enclosed smaller phenocryst.

More work has to be done to pin down the compositions of the pyroxenes, preliminary analysis suggests that they are probably augite.

Olivine. $<$ 1-3%--Clear, uncorroded euhedra ranging from less than .06 to .1 mm in length, reaction rims are absent.

Glass. 25-36%--Brown, clear, with abundant clear bubbles, averaging about .001 mm in diameter, that have low relief and no birefringence, possibly gas or fluid; glass has index of about 1.54, which gives a silica content in the range 56 to 65%.

Magnetite. Trace--Disseminated euhedral cubes and octahedra averaging about .01 mm, locally oxidized to hematite or limonite, variations in magnetite, either original or due to oxidation, could account for variations in the magnetic susceptibility. For example, samples 1 and 16, which are highest in magnetic susceptibility, are also richest in magnetite.

Vesicles. 10-30%--Generally flattened and irregular, no noticeable filling, average about 2 mm in length and range from .2 mm to 5 mm or more.

Diameter of quartz grains averages from 1 to 2 mm; they are generally highly resorbed and surrounded by a reaction rim of brown glass and fine augite cyrstals. According to Hatch and others (1961, p. 326), primary quartz in basalt occurs in the groundmass, and can be associated with olivine only in equilibrium. In view of this the relatively large quartz grains with reaction rims are strongly suggestive of xenocrysts; the commonly friable, underlying Coconino Sandstone through which the lava must have moved to the surface is a likely source for these grains.

With the exception of tensile strength tests, the complete suite of physical properties measurements as originally specified in the work plan has been run on 24 samples from outcrops on the S. P. flow. Tensile strength will be determined for all future samples. The data from the physical property measurements are summarized in figure 11. Compressional and shear wave velocities were determined by 3 different methods; pulse, bar resonance, and computation from static determinations of Young's modulus and

Poisson's ratio. Bar resonance measurements will be dropped from future tests because they are redundant and require recutting of the cores. All other measurements can be conducted on the NX (2 1/8 inch diameter) core from the holes if ends of the core samples are cut and planed.

The discrepancies between values of Poisson's ratio determined by bar resonance and values of the ratio determined by pulse and static tests are not understood. Those values determined by static and pulse measurements are thought to be better because they are more nearly mutually agreeable and because they agree more closely with values in the literature where Poisson's ratio is generally about 0.250.

The S. P. flow was investigated during the first field period with the SIE P-19 portable equipment. All equipment was hand-carried onto the flow by three men. Seventeen records were taken during the two days.

One spread, which consisted of four groups with an interval of 50 feet and three seismometers per group mounted on one base plate, was recorded on this flow. The seismometers had the same layout as described above for the Kaibab area. This spread was recorded from offset distances of 100 and 200 feet north and from 100, 200 and 300 feet south of the spread. Charge sizes varying from one-half to three pounds were tried, both on the surface and buried at depths of two to two and one-half feet.

Sample Number	Core condition	Porosity (percent)	Bulk Density (g per cc)	Grain Density (g per cc)	Magnetic Susceptibility (10^{-6} emu)
1		14.6	2.40	2.81	1378
2	Good. Intermediate size vesicles	15.8	2.35	2.79	512
3	Good. Large vesicles	15.0	2.39	2.82	294
4	" " "	11.3	2.49	2.80	524
5	Good. Large vesicles	20.3	2.25	2.82	371
6	" " "	10.6	2.52	2.82	584
7	Good. Intermediate size vesicles	17.2	2.30	2.78	311
8	Good. Intermediate size vesicles	20.2	2.24	2.81	200
9	Good. Large vesicles	20.0	2.25	2.81	339
10	Good. Intermediate size vesicles	18.4	2.30	2.82	602
12	" " " "	12.4	2.46	2.81	334
13	" " " "	27.7	2.03	2.81	351
14	Good. Large vesicles	19.1	2.29	2.84	272
15	Good. Intermediate size vesicles	15.9	2.35	2.80	462
15*	" " " "	17.3	2.32	2.80	571
16	Fair. Pre-existing fracture. Small vesicles	12.2	2.48	2.83	1811
18	Good. Small vesicles	6.8	2.62	2.81	421
19	Good. Large vesicles	21.6	2.20	2.80	485
19*	" " "	24.0	2.17	2.85	877
21	" " "	16.9	2.34	2.81	521
22	Good. Intermediate size vesicles	19.3	2.29	2.83	617
23*	Good. Large Vesicles	13.9	2.40	2.79	299
24*	" " "	31.0	1.91	2.77	301
26	" " "	24.0	2.14	2.82	269
27	" " "	22.9	2.17	2.81	349

* - Measured perpendicular to rock fabric; all other measurements made parallel to fabric.

Figure 11(a). Physical properties of rock samples collected from the S. P. study area.

Sample Number	Unconfined Compressive Strength (psi)	Young's Modulus (10^6 psi) Static	Pulse	Resonance
1			7.86	7.95
2	14,700	11.9	7.82	8.14
3	17,500	8.42	7.32	6.79
4			9.80	9.57
5	19,800	7.53	6.03	7.48
6			8.58	9.17
7	18,100	6.32	6.93	7.05
8	20,300	6.64	7.79	7.73
9	13,600	5.45	6.61	6.81
10	14,700	5.08	6.97	7.12
12			9.15	10.06
13			5.19	5.35
14	19,800	7.79	8.23	8.25
15	23,200	7.37	8.23	9.09
15*			7.71	8.29
16	17,500	9.35	9.38	9.60
18	40,100	10.1	9.87	10.15
19	14,100	5.31	6.64	6.80
19*	17,500	6.75	6.77	7.22
21			7.88	8.18
22	17,500	6.11	7.16	7.61
23*	20,300	6.84	7.73	8.46
24*	15,200	5.32	5.69	5.49
26			5.91	5.55
27	14.100	5.55	6.34	6.55

* - Measured perpendicular to rock fabric; all other measurements made parallel to fabric.

Figure 11(b). Physical properties of rock samples collected from the S. P. study area.

Sample Number	Poisson's ratio			Vs (fps)	
	Static	Pulse	Resonance	Pulse	Resonance
1		.279	.139	9.745	10.396
2	.24	.248	.194	9.952	10.384
3	.28	.229	.117	9.610	9.714
4		.280	.205	10.692	10.892
5	.23	.298	.210	8.758	10.107
6		.238	.185	10.110	10.681
7	.29	.274	.199	9.364	9.714
8	.25	.257	.197	10.137	10.348
9	.20	.246	.150	9.360	9.889
10	.20	.239	.175	9.518	9.882
12		.242	.221	10.535	11.147
13		.275	.083	8.634	9.517
14	.27	.264	.258	10.259	10.302
15	.21	.289	.252	10.036	10.708
15*		.284	.268	9.806	10.240
16	.26	.283	.273	10.463	10.628
18	.23	.238	.226	10.618	10.823
19	.19	.291	.232	9.321	9.663
19*	.24	.294	.220	9.467	10.076
21		.254	.182	9.979	10.484
22	.25	.279	.216	9.532	10.085
23*	.22	.293	.259	9.614	10.200
24*	.23	.266	.225	9.338	9.329
26		.234	.093	9.114	9.391
27	.16	.279	.191	9.214	9.708

* - Measured perpendicular to rock fabric; all other measurements made parallel to fabric.

Figure 11(c). Physical properties of rock samples collected from the S. P. study area.

Sample Number	V_p (fps) Pulse	V_p (fps) Resonance	Shear Modulus (10^6 psi) Pulse	Shear Modulus (10^6 psi) Resonance	Bulk Modulus (10^6 psi) Pulse
1	17.606	16.055	3.07	3.49	5.93
2	17.191	16.845	3.13	3.41	5.17
3	16.202	14.744	2.98	3.04	4.49
4	19.345	17.887	3.83	3.97	7.43
5	16.322	16.687	2.32	3.09	4.97
6	17.238	17.177	3.47	3.87	5.46
7	16.787	15.847	2.72	2.94	5.11
8	17.716	16.838	3.10	3.23	5.33
9	16.121	15.416	2.65	2.96	4.33
10	16.244	15.774	2.81	3.03	4.44
12	18.053	18.024	3.68	4.12	5.91
13	15.496	14.113	2.03	2.47	3.84
14	18.126	18.030	3.25	3.28	5.82
15	18.412	18.598	3.19	3.63	6.49
15*	17.864	18.178	3.00	3.27	5.96
16	19.027	19.026	3.66	3.77	7.22
18	18.098	18.187	3.99	4.14	6.27
19	17.182	16.355	2.57	2.76	5.46
19*	17.516	16.809	2.61	2.76	5.09
21	17.421	16.816	3.14	3.46	5.38
22	17.218	16.749	2.80	3.13	5.40
23*	17.764	17.882	2.99	3.36	6.22
24*	16.540	15.669	2.25	2.24	4.05
26	15.475	14.014	2.40	2.54	3.71
27	16.632	15.704	2.48	2.75	4.77

* - Measured perpendicular to rock fabric; all other measurements made parallel to fabric.

Figure 11(d). Physical properties of rock samples collected from the S. P. study area.

The filter setting was 100-out for all shots.

These data essentially consist of refraction profiles with bc·· horizontal and vertical detectors. The data are being analyzed in order to determine the layering within the flow and in order to detect and measure transverse motion if it exists.

Kana-a flow.- The Kana-a flow is located about 15 miles northeast of Flagstaff, Arizona, and outcrops extend from about 1 mile east of Sunset Crater northeastward about 5 miles to the flow's end (figure 12). It is an olivine basalt whose composition is similar to that of the Bonito flow which is being used as a test area for other lunar projects, such as Surveyor, Rover, Apollo, and Lunar Terrain Analysis. The Bonito flow is under the management of the U. S. Park Service which has imposed stringent conditions on experimentation on Bonito flow in order to preserve the natural state and beauty of the area. The necessity of roads on the flow for seismic work and associated core drilling would undoubtedly disfigure the flow to an undesirable extent. Consequently, the Kana-a flow was selected as a test site because of its accessibility and the similarity of conditions with the Bonito flow. The area of the flow which has been currently under investigation is covered with 0 - 20 feet of ash, but an area of exposed flow has been located near the south end of the flow and will be investigated during FY-65.

The flow follows a narrow valley that is flanked by older cinder cones and flows; its width ranges from about .15 to .70 miles. It is generally mantled by ash, except for a small patch about .1 mile wide and .3 mile long near the end of the flow. However, the flow can be readily traced by numerous, small outcrops

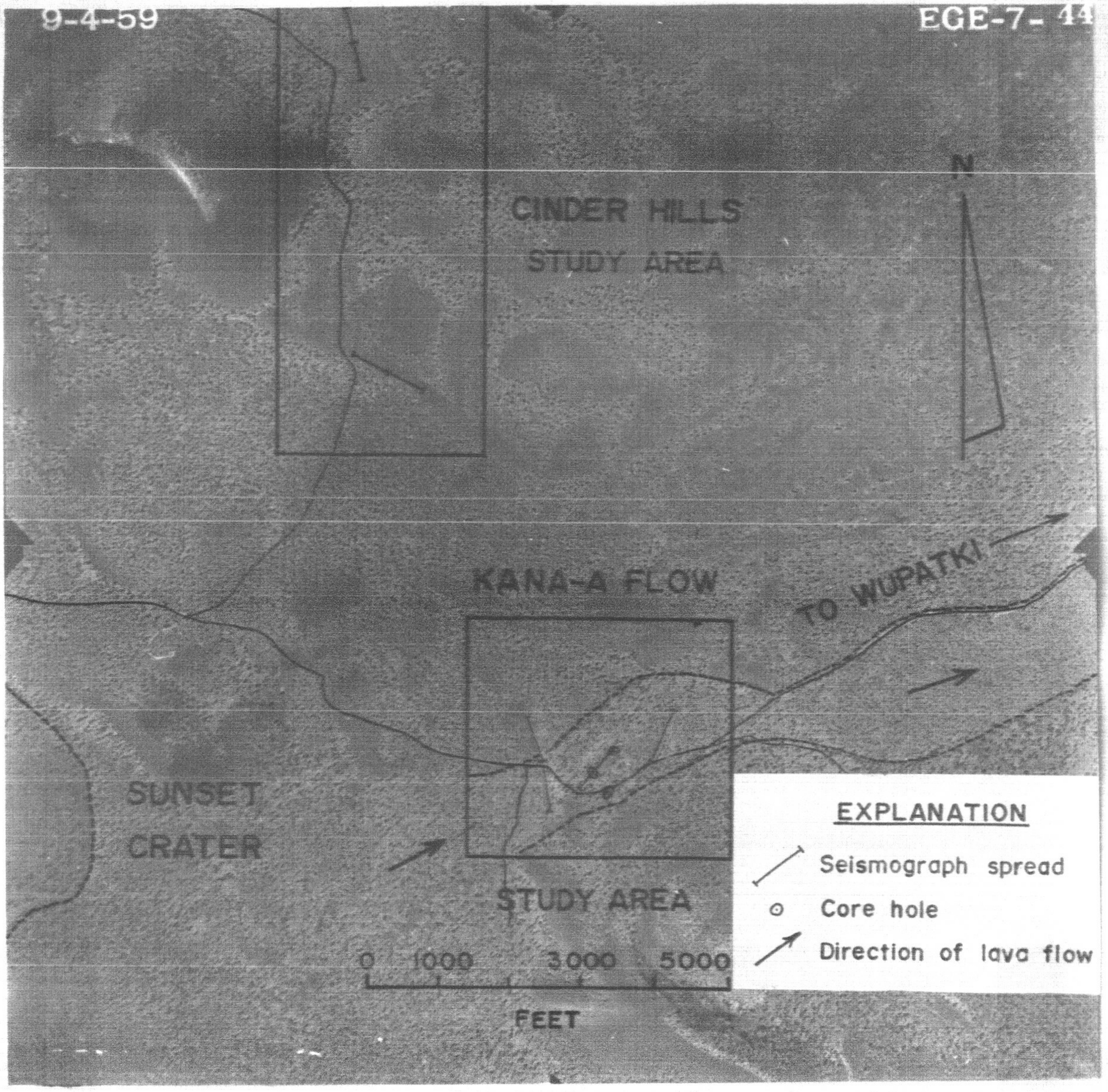
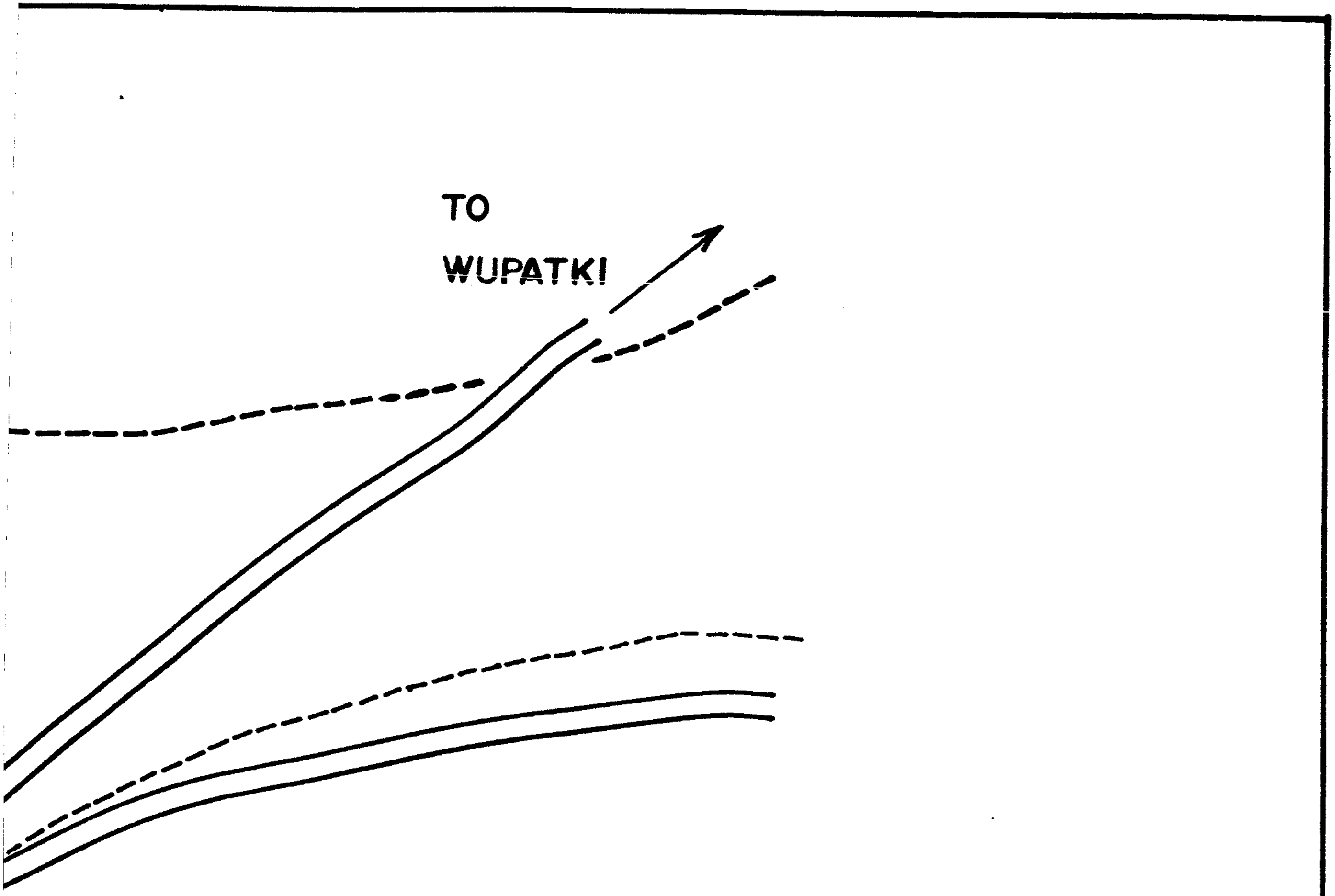


Figure 12. Aerial photograph showing Kana-a flow study area. Cinder Hills study area, seismograph spreads, core holes, and prominent nearby topographic and cultural features.

of jagged aa lava that project upward through the ash (figure 14). The margins of the flow can be approximately delineated on aerial photographs by a distinct contrast in vegetation between the flow and the surrounding terrain. The area between the westernmost outcrop of the Kana-a flow and Sunset Crater is entirely overlain by thick ash deposits. It is therefore impossible to determine whether the flow issued from the vent beneath the crater itself or from one nearby.

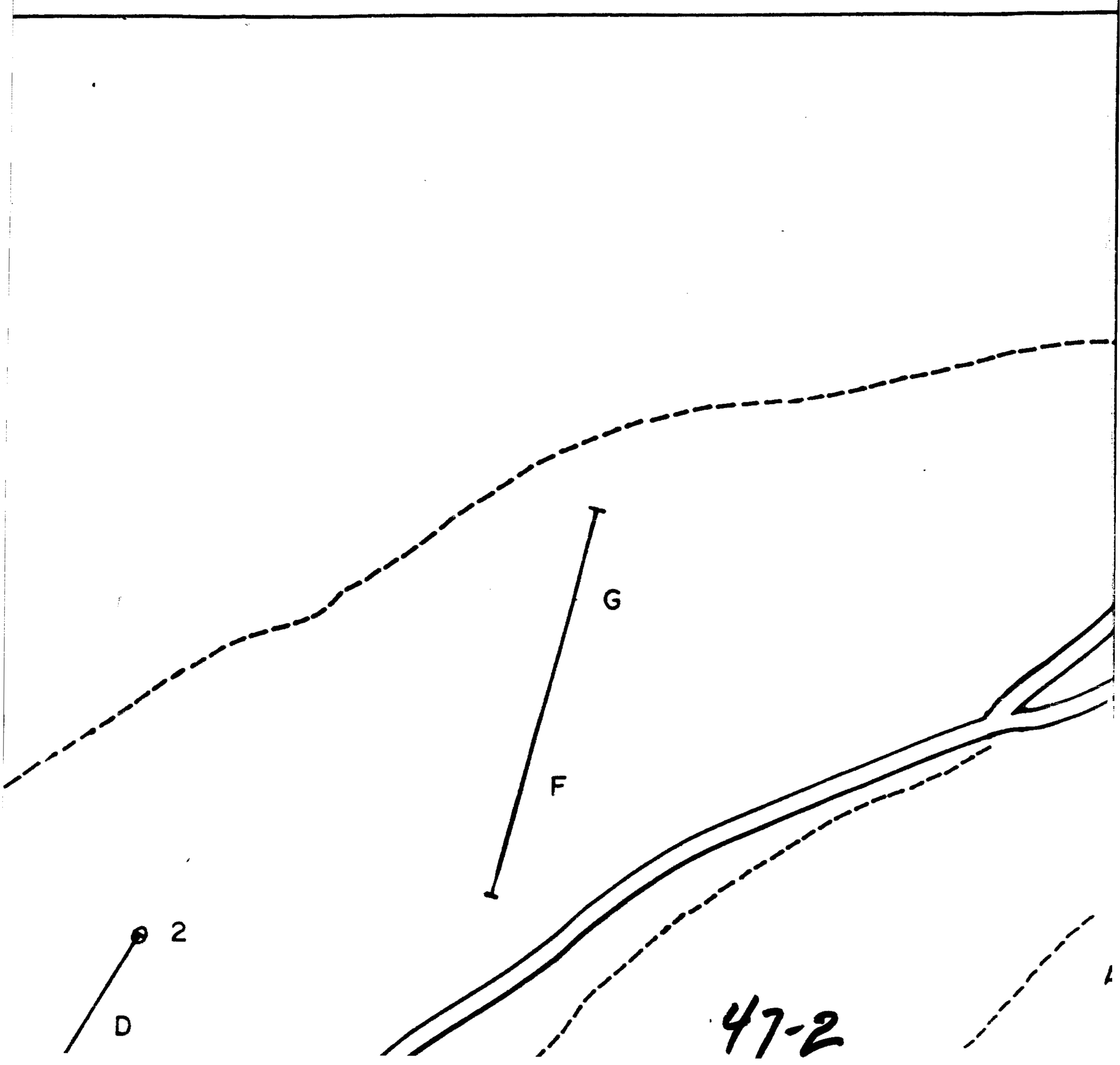
The area of study is located at the western end of the outcrop of the flow (figure 12 and 13). In the eastern part of this area the ash is very thin, probably averaging only a few feet, and outcrops of lava are abundant, however, in the western part of the area south of the Wupatki Road (figure 12), the ash is very thick, and outcrops of the lava are rare. Pine trees and low bushes are sparsely scattered in the ash, but grass is nearly absent and broad patches of bare ash separate the trees and clumps of bushes (figure 14).

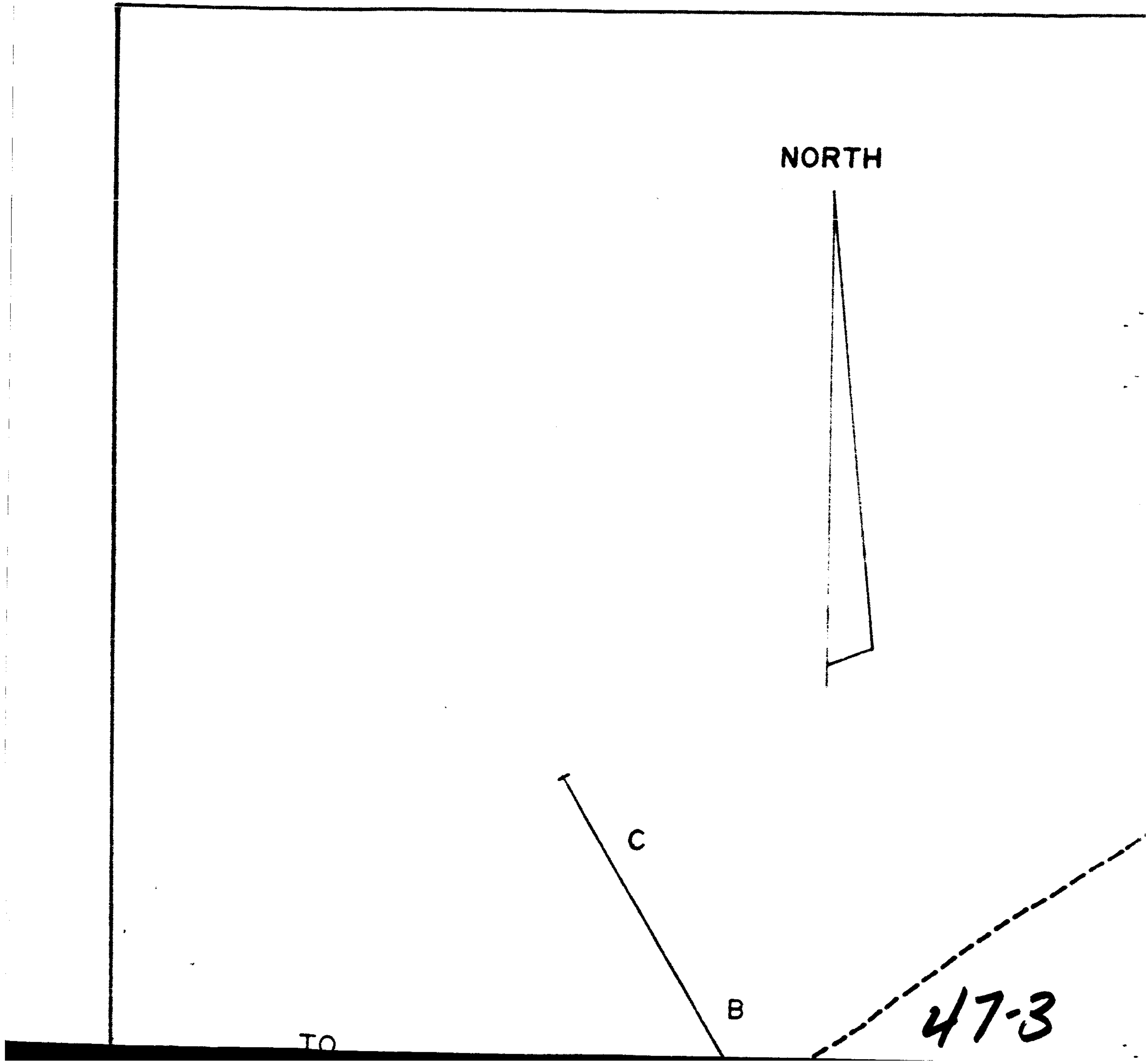
The ash mantle of the Kana-a flow thins northeastward away from its source, Sunset Crater (Colton, 1950, p. 33). This thinning, however, is complicated by numerous local irregularities. The ash-free area near the northeast end of the flow is considered by Hodges (1960, p. 67) to be an indication that the lava and ash eruptions were contemporaneous. In her view, the ash-free toe of lava was produced by a final drainage of lava from the



APPROXIMATE BOUNDARY OF FLOW

49-1


G
F
2
D
47-2

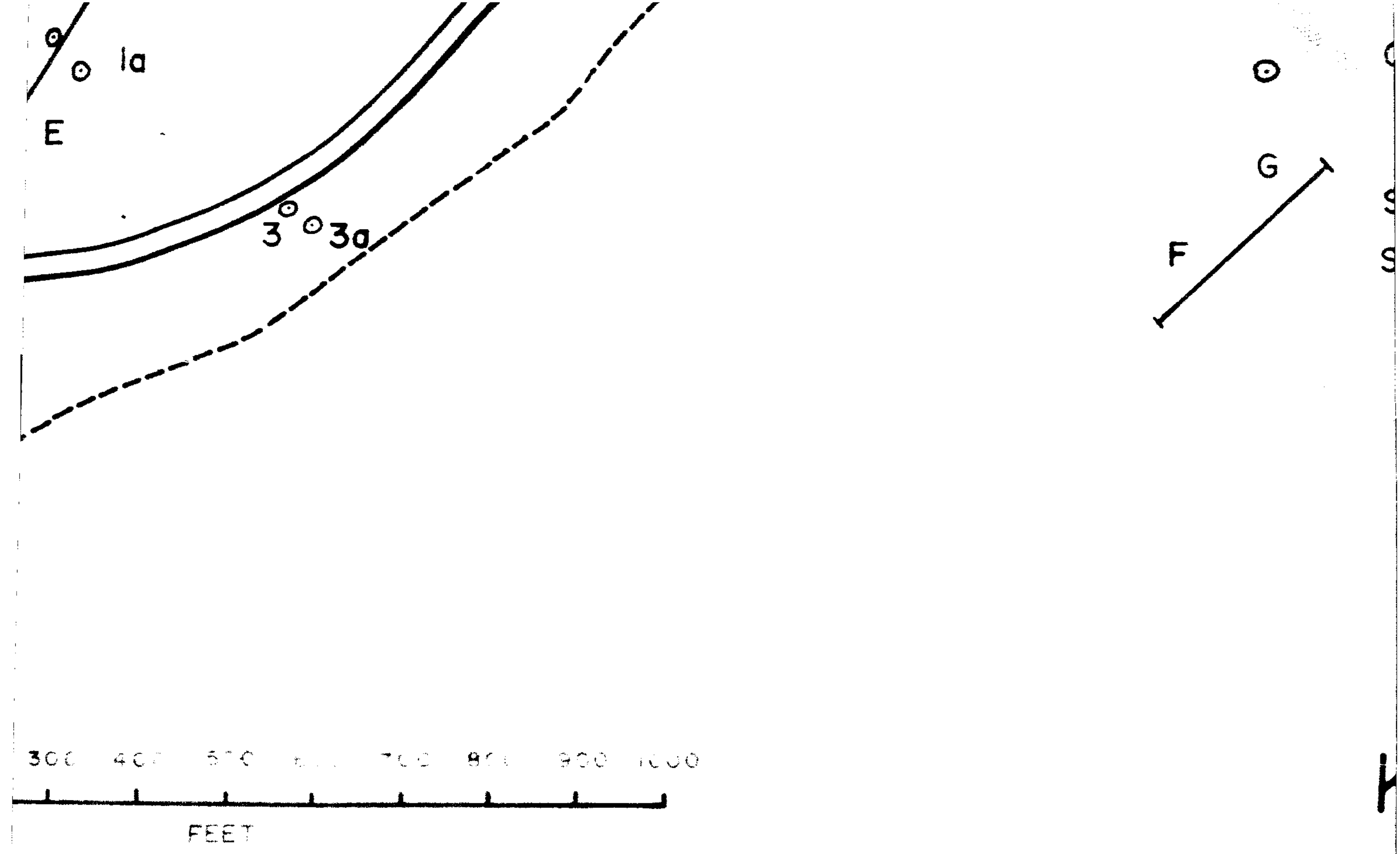

NORTH
C
B
TO
47-3

:ORE HOLE AND NUMBER

;EISMIC SHOT LINES SHOWING
PREAD DESIGNATION

‹ANA-A FLOW

47-4



spreads and coreholes

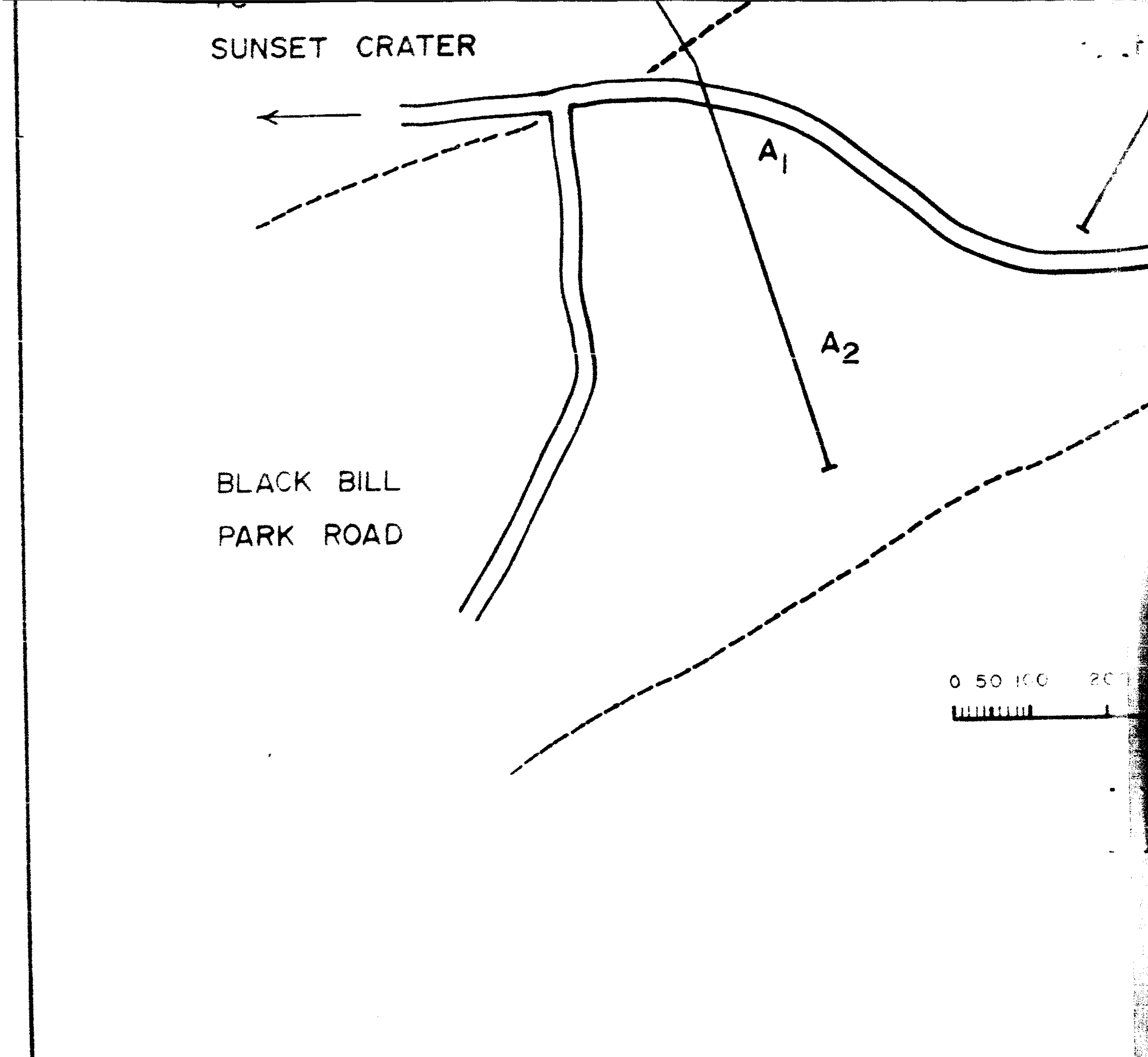


Figure 13. Kana-a study area showing location and designation of seismic

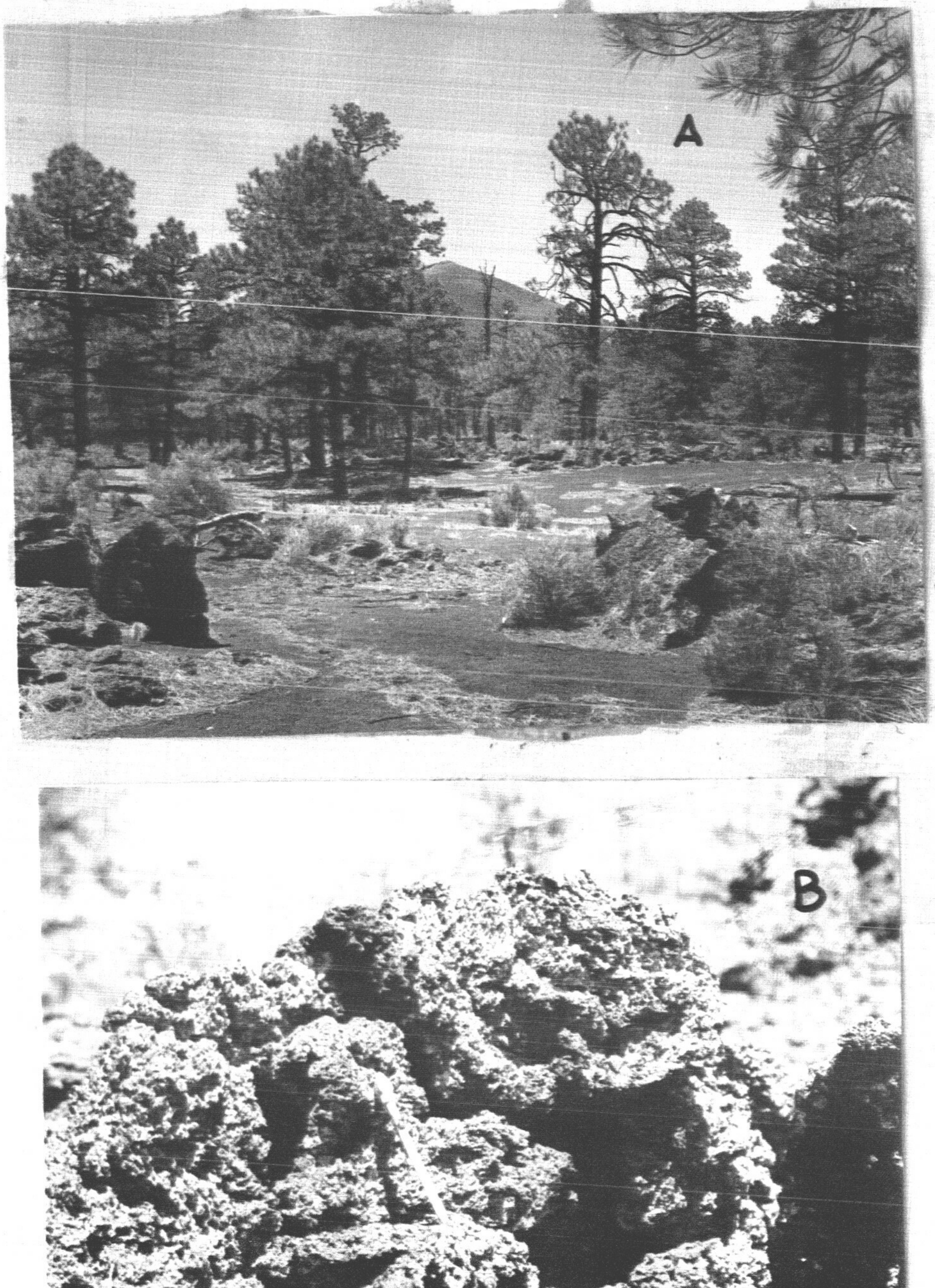


Figure 14. Lava cropping out through ash in Kana-a study area. A - View showing outcrop, ash, and vegetation. B - Detail of outcrop.

largely solidified flow after the close of the ash eruption. The contemporaneity of lava and ash eruptions tends to be substantiated by the thermoluminescence study of Sabels (1960, p. 192), who assigned an age of 1400 years to the Sunset Crater (cinder cone) and 1500 years to the Kana-a flow. The contemporaneity of lava and ash eruptions would insure that the original surface of the Kana-a flow is virtually untouched by erosion.

The grain size of the ash mantle ranges from ¼ to 4 mm in diameter. Hodges (1960 p. 63) states that the ash becomes finer grained to the northeast away from Sunset Crater, averaging about ¼ to ½ mm in diameter at the end of the flow and about 3 mm nearest the crater. The statement appears generally true, but surface indications of grain size variations are misleading, and our observations indicate that the grain size variation of the ash is more complex. The wind winnows out the fines and in places leaves a concentrate of coarser grains that gives an erroneous impression of the original grain size. A few pits, 2 to 3 feet deep, dug in the ash in the study area, indicate that the ash is deposited in beds that range from .5 foot to more than 3 feet in thickness. The grain size in these beds varies markedly from bed to bed with some suggestion of grading upward from coarse to fine. In fact, the range in grain size within a few vertical feet is at least as great as the lateral surface range given by Hodges for the 6 miles extent of the flow (¼ mm to 3 mm in diameter). It seems likely, then, that each bed represents an episode of ash eruption and grades from coarser to finer upward as well as laterally away from the source.

The ash is only slightly weathered and yellowish brown, weathered grains are sparsely scattered through the predominantly dark gray, fresh grains. In a few places, mostly near the hornitos and other phenomena associated with gas activity, ash grains are oxidized to various shades of red. In general, ash grains are rounded, scoriaceous, and glassy. The glass is commonly devitrified to some degree and in more weathered grains it is completely devitrified.

The Kana-a flow itself is typical aa lava (Wentworth and MacDonald, 1953, p. 57-63) and the surface that projects above the ash consists of jagged, spinose, vesicular, clinkery blocks and plates, which are commonly tilted up at various angles (figure 15). Small breached domal structures and hornitos (or remnants thereof) are common on the flow, especially in the study area. One nearly perfect hornito about 10 feet high, composed of welded reddish agglomerate piled around an open, cylindrical vent sits astride a lava cave in the western part of the area of study, north of Wupatki Road (figure 16). The lava cave is about 50 feet long, 10 feet wide, and 2 to 15 feet high, and trends NE roughly parallel to the direction of flow. The ceiling of the cave is studded with lava stalactites as

Figure 15. Jagged, tilted plates of aa lava projecting through ash in Kana-a study area.

Figure 16. Hornito in Kana-a study area. This cone sits over a lava cave 50 feet long, 10 feet wide and from 2-15 feet high.

much as 6 inches long. In places small, grooved "pushups" project a few feet above the flow. In general, outcrops of lava and linear features within the outcrops are elongate parallel to the direction of flow and in spite of the ash mantle, give an indication of the structural grain of the flow. Figure 12 shows the principal flow directions as based on the above linear outcrops. In contrast to the situation prevailing in the nearby S. P. flow, the highly irregular surface of the Kana-a flow beneath the ash is generally firmly attached to the underlying more massive part of the flow.

The lava is medium gray to medium dark gray, and weathers dark gray; locally, especially near hornitos, reddish hues are common. It is fine grained, though distinctly coarser than the lava of the S. P. flow, and is very sparsely and finely porpyritic. Olivine and plagioclase phenocrysts occur in about equal amounts, but the larger (average about 2 mm in diameter), rounded, glassy green olivine crystals are much more conspicuous. The plagioclase phenocrysts occur as thin laths less than 1 mm long. The Kana-a lava is much more vesicular than the S. P. lava; the vesicles being larger and less flattened. Such flattening as does occur does not show a noticeably preferred orientation. The vesicles range in diameter from less than 1 mm to more than 20 mm and average about 5 mm in diameter. Many tend to be irregularly tubular and are perhaps as abundant as subspherical forms; the larger vesicles tend to be more irregular. Vesicle fillings are extremely rare and are composed chiefly of calcite.

Outcrops in the area of study indicate that the high vesicularity extends downward at least 15 feet. The vesicularity ranges from 10 to 50 percent and averages about 25 percent; the upper parts of the clinkery crust tend to be more vesicular than the more massive flow below. This crust consists of more or less randomly oriented plates and blocks in which the vesicle orientation no longer reflects the direction of flow. In addition, the flow surface has larger scale domes and blisters in which the vesicules have been tilted to various angles relative to the general surface of the flow. However, in the main part of the flow, below these surface features, vesicle orientation should show a definite relation to the direction of flow. They are probably elongate parallel to the direction of flow (Wentworth and MacDonald, 1953, p. 62), but the limited exposures did not allow this relation to be verified.

The Kana-a lava is an olivine basalt with a modal composition similar to that of the Bonito flow. Hodges (1962, p. 28) gives the approximate modal composition of the Bonito flow as follows:

Olivine	15%
Plagioclase	45%
Pyroxene	10%
Magnetite	20%
Vesicles	10%
	100%

This composition is thought to be a reasonable approximation for the Kana-a lava, but the percentage of vesicles given is well below the average of 20 to 25 percent seen in surface outcrops. The texture is generally holocrystalline, microporphyritic, and intergranular. Rounded phenocrysts of olivine lie in a groundmass of subparallel labradorite laths, equant grains of magnetite, and interstitial pyroxene. Glass is rare, but when present it is dark with magnetite inclusions. The olivine and pyroxene are partially resorbed and embayed by the groundmass. Alteration is minor, but has produced iddingsite, zoisite, calcite, and hematite. Plagioclase laths and the elongated vesicles are subparallel, a fact that strongly suggests that both lie subparallel to the direction of flow.

A total of 152 seismograms were recorded in this area; 6 on May 27, 1964 with the SIE equipment and 146 with the 7000-B instrument during nine days field time.

The 6 records taken with the SIE equipment consisted of three refraction spreads shot 10 feet off each end. The spreads had 12 groups, one vertical seismometer per group, with an interval of 50 feet. The charge size used was two and one-half pounds buried four feet. Spread A was recorded on a 50-out filter while a 100-out filter was used on spreads B and C.

With the 7000-B instrument, four refraction spreads were recorded on different parts of the flow in order to measure the thickness of the ash, determine the velocity of seismic energy in the ash and the velocity in the underlying lava. These data will be used in conjunction with surface geology, coring, and core hole geophysics to prepare a subsurface map of the flow. The location of three of these spreads (A_1A_2, BC and DE) are equivalent to spreads A, B, and C, respectively, mentioned above. Figure 13 shows location of A_1A_2, BC, and DE. They were recorded from offset distances of 50, 100, 200, 300, 400 and 500 feet north of the spreads. A charge size of five pounds buried about two feet was used on spreads DE and FG while only two and one-half pounds buried about one and one-half feet was used on spreads A_1A_2 and BC. A 75 KK-out filter was set on all spreads except the first one that was recorded, DE, where a 120 KK-out filter was used.

On each of the refraction spreads A_1A_2, BC and DE three short spreads were recorded for frequency analysis. These spreads consisted of four groups of three seismometers each, two horizontal and one vertical, with a group interval of 50 feet. On refraction spread FG only two spreads were laid out for the frequency analysis. Each of the above spreads were recorded with the same filters itemized for the Kaibab area. The same shot point locations were used for all filter spreads within a refraction spread so the offset distances are either 10, 160 or 210 feet. Spreads B and F were also recorded from a hit on the ground with a shovel on a wide band filter, 320 KK-out. Frequency response curves calculated for spreads C and D are shown in figures 17 and 18.

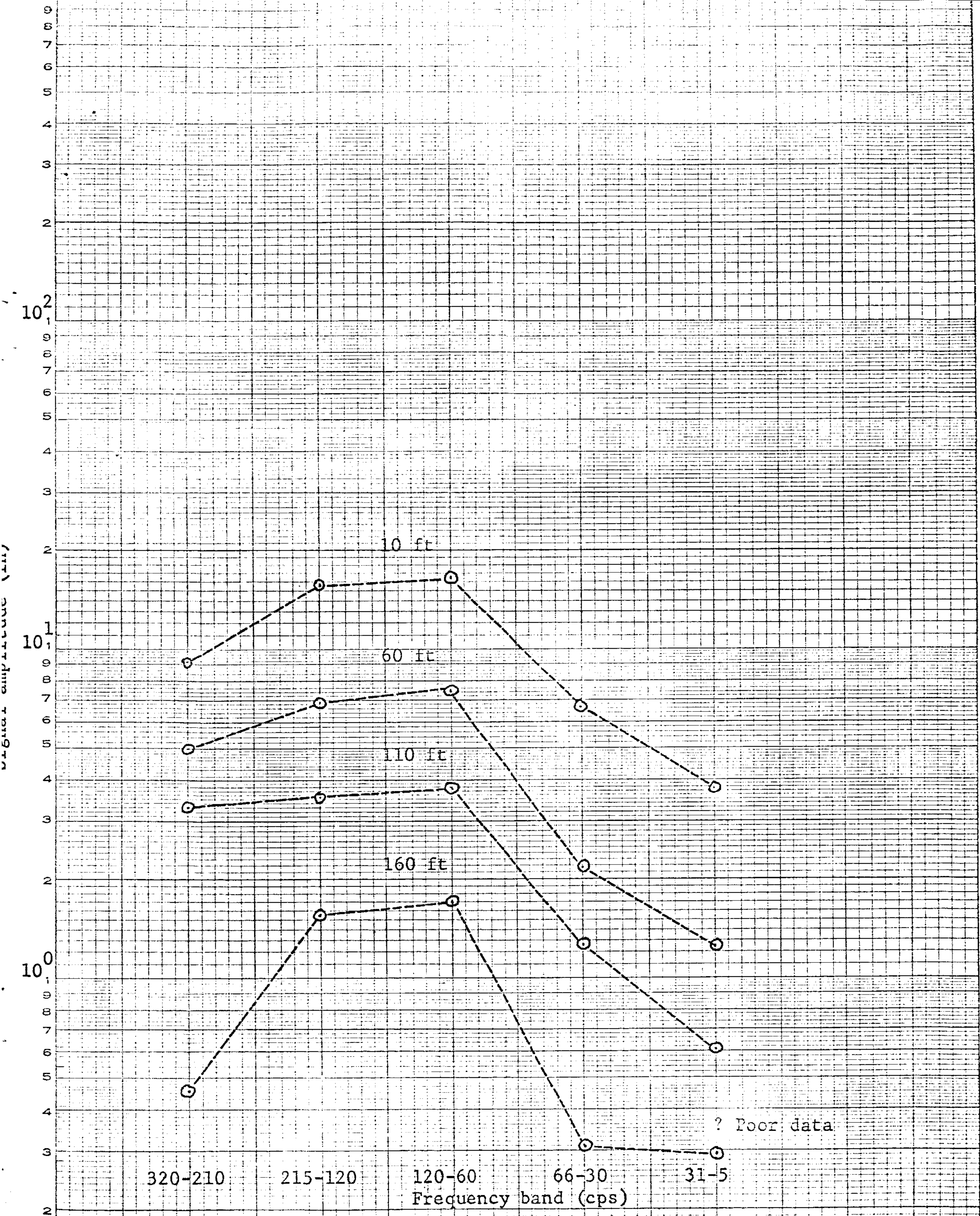


Figure 17. Seismic amplitudes observed in five frequency bands on Kana-a spread C at distances of 10, 60, 110, and 160 feet from a cap exploded on the surface. Amplitudes were scaled from oscillograph tapes and normalized but not converted to ground amplitudes.

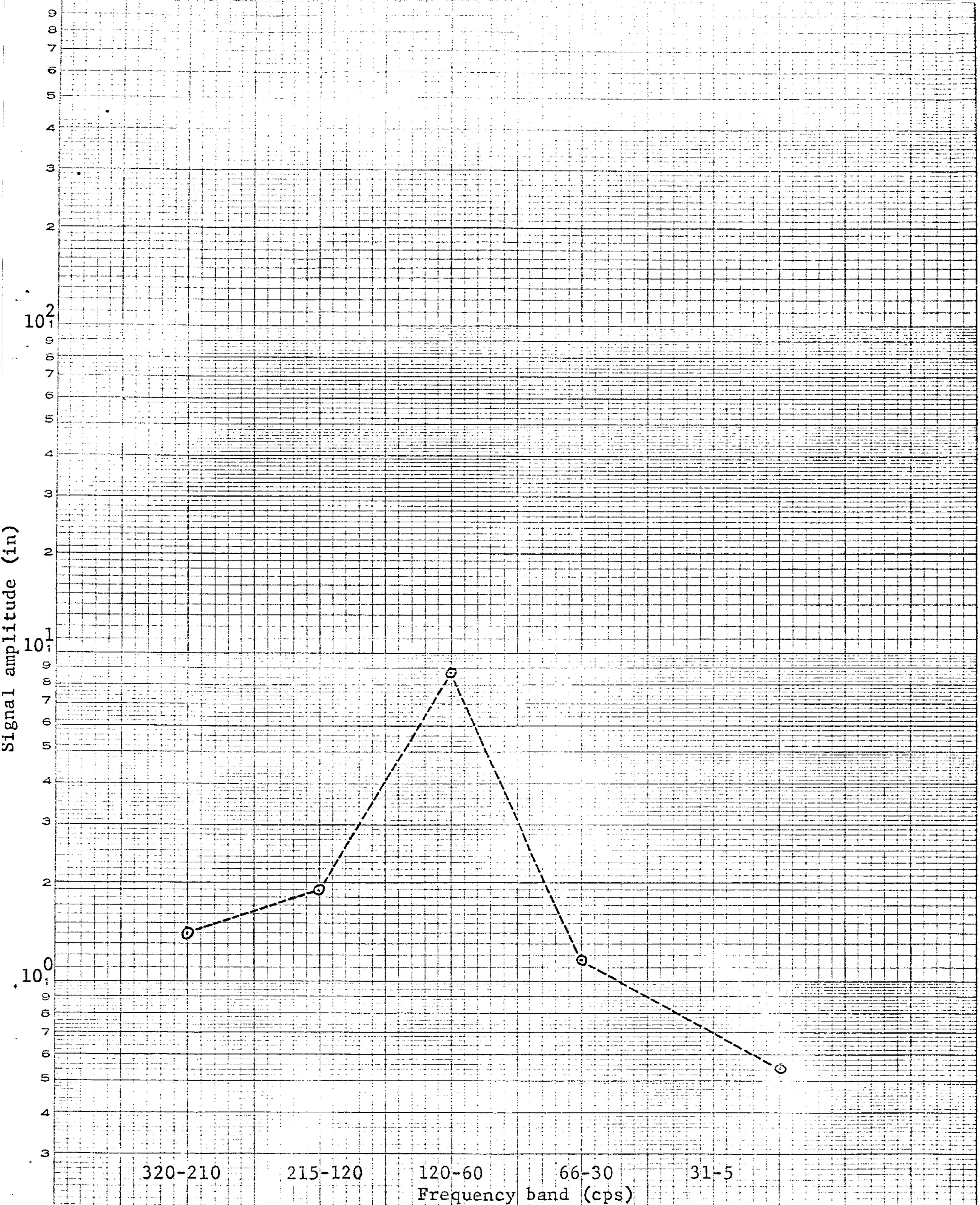


Figure 18. Seismic amplitudes observed in five frequency bands on Kana-a spread D at a distance of 160 feet from a cap exploded on the surface. Amplitudes were scaled from oscillograph tapes and normalized but not converted to ground amplitudes.

Besides the refraction and filter shots recorded on this flow, two uphole surveys were shot in Core Hole Numbers 1A and 3A (figure 13). The spread for these surveys was four groups of three geophones each laid out from the hole. The first group was at a distance of approximately four feet from the hole and other groups were at intervals of 50 feet. Hole 1A was surveyed every three feet from the bottom at 39 feet up to 15 feet. The hole collapsed at two feet after the 15 foot shot. Hole 3A was also shot every three feet from the bottom at 40 feet up to 12 feet. Another shot taken at five feet collapsed the hole at two feet. These velocities determined from these holes are shown in figures 20 and 23.

There have been 5 holes drilled to maximum depths of 40 feet in the Kana-a flow study area. The locations of these holes are shown in figure 13, geologic and velocity logs of the holes are shown in figures 19, 20, 21, 22, and 23. A total of 170 feet was drilled with NX cores (2 1/8"). The drilling was difficult in the lava. Specific difficulties included destruction and loss of a rock bit in hole No. 1 while reaming of the hole (the hole was not completed because the piece of the bit could not be recovered from the bottom); and another hole (3) was abandoned when it caved in during drilling. A third hole caved in before velocity logging could be completed.

The No. 2 hole (figures 13 and 21) is the most significant insofar as it yielded a virtually complete vertical section of

Figure 19.

GEOLOGIC LOG OF DRILL HOLE

U. S. Geological Survey

Project IN SITU - KANA-A FLOW - HOLE #1

State Arizona | County Coconino | Range 9E Township 23N | Section

Total Depth 32' | Ground Elev. | Inclination | Bearing

Begun 6/8/64 | Finished 6/9/64 | Driller Rudy Gracey | Water Table None

Core Box Nos.

Drilled with Mayhew 1000

Drilling Notes	Hole Type & Size	Core Run and Recovery	Elev.	Graphic Log	Depth	Sample	Physical Condition and Classification
	4½" Rotary					B	Cinders - loose
Hit rock at 15'. Start coring at 17'. Core Bit #A3823.	3-3/4" Core	5'Run 3'Recov.				C	Basalt - vesicular
Core Bit #A3824		10' 5' Recov.				C	Basalt - vesicular
Lost Bearings from Rotary Bit while cleaning hole - abandoned & moved to #1A		15' 8'					

Figure 20.

GEOLOGIC LOG OF DRILL HOLE

U. S. Geological Survey

Project IN SITU - KANA-A FLOW - HOLE 1-A

State Arizona | County Coconino | Range 9E, Township 23N | Section

Total Depth 40'-0" | Ground Elev. | Inclination | Bearing

Begun 6/9/64 | Finished 6/10/64 | Driller Rudy Gracey | Water Table None

Core Box Nos.

Drilled with a Mayhew 1000

Drilling Notes	Hole Type & Size	Core Run	Recovery	Elev.	Graphic Log	Depth	Sample	PHYSICAL CONDITION and CLASSIFICATION	VELOCITY LOG
	4½"					0–5		Cinders	Estimated 1500 fps
Core Bit #A3823	3-3/4" Core	5'	4.9'			10	C	Basalt	
		5'	3.0'			15	C	Weathered Zone 16'±	3000 fps
		10'	8.6'			20–25	C	Weathered Zone 21'±	
		4'	2.6'			30	C		9000 fps
		2'	1.2'				C		
Ran Barrel-No Sample Recovered of cinders						35–40		Cinders	1000 fps

Figure 21.

GEOLOGIC LOG OF DRILL HOLE

U. S. Geological Survey

Project IN SITU - KANA-A FLOW - HOLE #2

State Arizona | County Coconino | Range 9E Township 23N | Section

Total Depth 40'-0" | Ground Elev. | Inclination | Bearing

Begun 6/11/64 | Finished 6/12/64 | Driller Rudy Gracey | Water Table None

Core Box Nos.

Drilled with a Mayhew 1000

Drilling Notes	Hole Type & Size	Core Run and Recovery		Elev.	Graphic Log	Depth	Sample	Physical Condition and Classification
	4½" Rotary							Cinders
Core Bit #A3823	3-3/4" Core	5.0'	3.8'					Basalt - Vesicular to 17' ±
		5.0'	5.0'					Dense to 29' ±
		10.0'	10.0'				C	Vesicular to 31' ±
		5.5'	5.5'					
Ran Barrel - No Sample		9.5'						Cinders
		35.0'	24.3'					

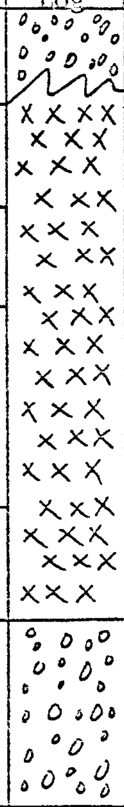


Figure 22.

GEOLOGIC LOG OF DRILL HOLE

U. S. Geological Survey

Project IN SITU - KANA-A FLOW - HOLE #3

State Arizona | County Coconino | Range 9E Township 23N | Section

Total Depth 18' | Ground Elev. | Inclination | Bearing

Begun 6/12/64 | Finished 6/12/64 | Driller Rudy Gracey | Water Table None

Core Box Nos.

Drilled with a Mayhew 1000

Drilling Notes	Hole Type & Size	Core Run and Recovery	Elev.	Graphic Log	Depth	Sample	PHYSICAL CONDITION and CLASSIFICATION	VELOCITY LOG
	4½" Rotary				5		Cinders	
Core Bit #A3824	3-3/4" Core	1.0 0.7		x x x x		C	Basalt - Vesicular	
Ran Barrel - No Recovery	3-3/4" core	9.0			10 15		Cinders	
Hole caved necessitating moving rig to hole #3A		1.0 0.7			20			

Figure 23.

GEOLOGIC LOG OF DRILL HOLE

U. S. Geological Survey

Project IN SITU - KANA-A FLOW - HOLE #3A

State Arizona | County Coconino | Range 9E, Township 23N | Section

Total Depth 40'-0" | Ground Elev. | Inclination | Bearing

Begun 6/13/64 | Finished 6/13/64 | Driller Rudy Gracey | Water Table None

Core Box Nos.

Drilled with a Mayhew 1000

Drilling Notes	Hole Type & Size	Core Run and Recovery	Elev.	Graphic Log	Depth	Sample	PHYSICAL CONDITION and CLASSIFICATION	VELOCITY LOG
	4½" Rotary						Cinders	1150 fps
Core Bit #A3824	3-3/4" Core	5.0 5.0 10.0 6.6 15.0 11.6				C	Basalt - Density to 12 ±', then vesicular	3000 fps
Ran Barrel - No Recovery							Cinders	2400 fps

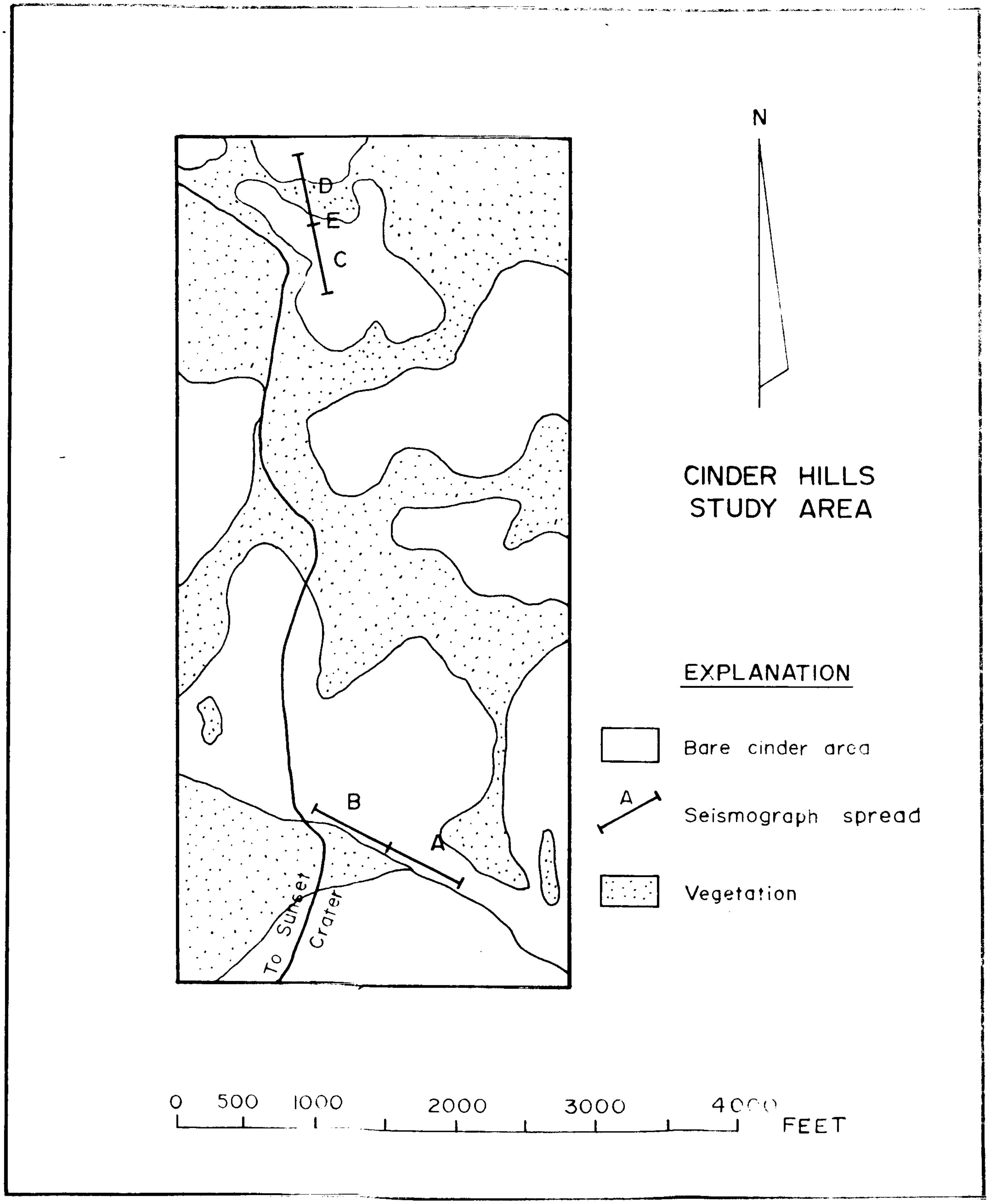
aa lava flow approximately 27 feet thick. The upper 13 feet consists of highly vesicular lava, the lower 2 feet consists of flattened vesicular lava and the intermediate 12 feet consists of dense basalt.

Four additional 40 foot holes are planned for this area. Measurement of physical properties will be made on samples selected from the 9 holes when the drilling is completed. The cores have been macroscopically examined by one of us (Loney); and thin sections of the rocks are being made for petrographic analysis.

Cinder Hills.- The Cinder Hills area lies northnortheast of Sunset Crater and consists of accumulations of ash whose thickness ranges from 50 to 100 feet according to seismic refraction data. Locations of 4 spreads which were recorded here are shown in figure 24. Tests included refraction, band pass, and attenuation shots. During four days of study with the 7000-B instrument, 58 seismograms were recorded in the Cinder Hills area.

Two refraction spreads (AB and CD), (figure 24) separated by about one-half mile, were laid out and recorded in the same manner as in the Kana-a area. Also, as in the Kana-a area, two short spreads were recorded on each refraction spread for a frequency analysis study. Spread A was laid out between groups 9 and 12 and spread B between groups 6 and 9 of refraction spread AB. Spread C was between groups 6 and 9 and spread D between groups 3 and 6 of refraction spread CD.

A short refraction spread (E) was placed between groups 4 and 6 of spread CD. This spread consisted of 12 vertical geophones placed at intervals of 10 feet. Using a 320 KK-out filter, a recording was made by hitting the ground with a shovel at the Number 12 geophone position. Other recordings were made using caps at offset distances of 10 feet and charges of one-eighth and two and one-half pounds at distances of 100 feet. Although data from this area are incompletely analyzed at the present time, some approximate frequency spectra determined from the data recorded in the area are shown in figure 25.


N
D
E
C
B
A
To Sunset Crater
CINDER HILLS
STUDY AREA
EXPLANATION
Bare cinder area
A
Seismograph spread
Vegetation
0
500
1000
2000
3000
FEET

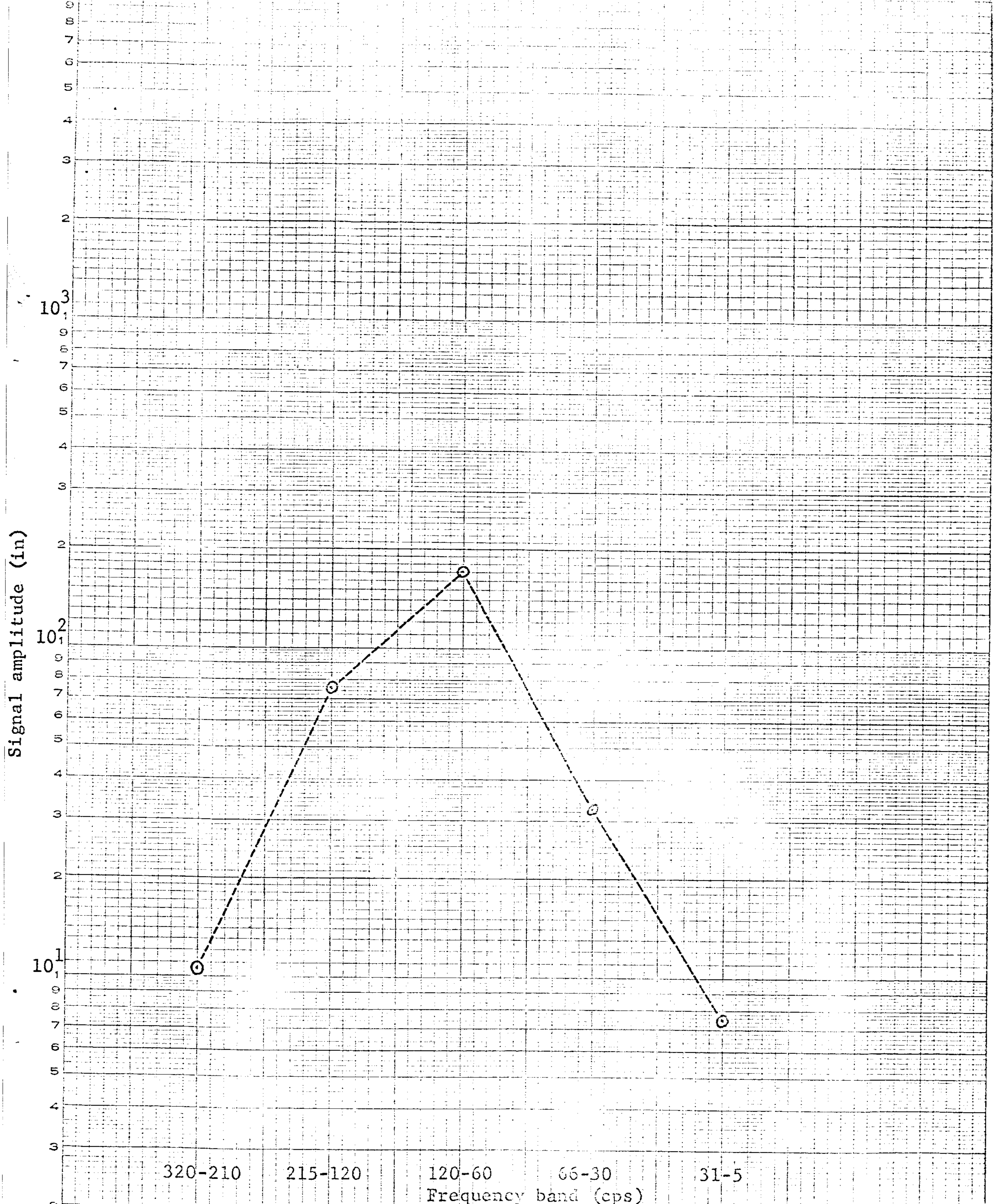


Figure 25. Seismic amplitudes observed in five frequency bands on Cinder Hills spread B at a distance of 160 feet from 0.125 pounds of dynamite exploded on the surface. Amplitudes were scaled from oscillograph tapes and normalized but not converted to ground amplitudes.

Shallow pits dug in the area indicate that the cinders are bedded in much the same manner as those cinders which cover the Kana-a flow. However, we have been unable to collect satisfactory samples of these cinders which show relatively undisturbed bedding. The project driller, N. G. Bailey, is investigating commercially available soil sampling devices which might obtain satisfactory samples. Some core barrels are made which include small spring-loaded trap devices near the base of the barrel to prevent loose material from falling may be successful in obtaining samples. Another technique which has been used successfully in some engineering sampling consists of drilling a small hole using a plaster of paris base mud. The mud flows through the core barrel then out into the surrounding material.

The coring device is withdrawn and the mud allowed to harden. Then the hole is redrilled with a larger diameter core bit and a relatively undisturbed sample is withdrawn. Thin sections can be prepared from the sample or the mud can be dissolved with a weak acid for grain analysis.

LUNAR TECHNIQUE DEVELOPMENT

During field studies in the Kana-a and Cinder Hills areas, a series of tests involving non-explosive energy sources were conducted. On the basis of these tests it seems likely that lunar seismic refraction profiles can be recorded over distances of 500 feet or more without use of explosive energy sources. The assumptions on which this statement is based are as follows: 1) there is negligible microseismic noise on the lunar surface, 2) energy attenuations on the lunar surface are of the same order as those observed in the four areas investigated in FY-64, 3) geophone output, line impedance, and other lunar equipment characteristics are the same as those of equipment used during the tests, and 4) the lunar amplifier has a peak to peak noise threshold of 10^{-2} microvolts or less.

These conclusions are based on attenuation measurements made by using the amplitude of the first full seismic arrivals. Details of the analysis are as follows. Let the amplitude of the ground motion be A, the distance to the shot point be d, and k and a be constants. Then experimental evidence indicates that the amplitude can be empirically related to the distance by the expression $A = kd^{-a}$. At a distance of 50 feet, output of vertical component geophones was approximately 100 microvolts. If we assume that $a \leqq 4.0$, which is an unusually large value, then the amplitude of the signal will exceed the assumed amplifier noise threshold of 10^{-2} microvolts at distances up to approximately 500 feet.

The authors' previous experience and data published in the geophysical literature indicate that highest attenuations are encountered in unconsolidated materials. Initial tests in the Cinder Hills area yielded an attenuation constant (_a_) of -1.8 which is about the same magnitude reported by Kovach and others (1963) who measured attenuations in alluvium (_a_ = -2.3) and weathered granite (_a_ = -1.4). However, latest experimental data from the lava and cinder areas yield attenuation constants (a) ranging from about -1.5 to about -4.0. There is no obvious relationship between the cohesiveness of the rock at the surface and the attenuation constant; in fact, the largest attenuation rate so far, a = -4.5, was observed in data from the Kaibab area. The cause of this phenomenon is obscure. It may well be, however, that cinders are well-consolidated at depth or that peculiar velocity versus depth relations exist in one or the other areas.

During the report period Joel S. Watkins and Norman G. Bailey assisted in the astronaut field program at the Philmont Boy Scout Ranch near Cimarron, New Mexico in order to give astronauts practical experience in the conduct of seismic operations. Short (100 feet and 500 feet) seismic refraction lines were laid out in a small valley partially filled with alluvium. Astronauts laid cable, hooked up geophones, fired shots, and interpreted data which revealed depth and velocity of water table and of underlying bedrock. Miniaturized seismic equipment weighing less than 100 pounds was obtained from the experiment to give added sense of realism to the training.

PROBLEMS, FUTURE PLANS, AND SUMMARY

Problems.- The only major problem encountered in the program to date has been the extremely heavy load placed on the project geologist. It has been his responsibility to review the literature for likely sites, reconnoiter the most likely study sites, map the distribution of surface rocks in these sites, collect samples and conduct petrographic analyses of the rocks, and assist in planning of locations of seismic spreads. These numerous duties prevent him from extending mapping into areas adjacent to the study areas, and limit the degree of detail to which he can perform petrographic analyses. For optimum project efficiency another geologist will have to be added to the project.

A second problem of uncertain magnitude was revealed by the drilling programs carried out so far. The first 5 holes cored in the Kana-a flow area resulted in unusually heavy wear on diamond core bits. If wear of drill bits in other lavas is as heavy as that in holes of the Kana-a flow, some modifications in budgeting will have to be made to provide funds for a much higher rate of bit replacement than had originally been anticipated.

Future plans.- Three potential sites, Meteor Crater, Arizona, Amboy Crater, California, and Pisgah Crater, California have been reconnoitered. Mono Craters area, California, is being reconnoitered during preparation of this report. It is anticipated that field studies will be initiated in these areas during the first half of FY-65.

Among those sites which have not been reconnoitered but have received serious consideration is Pahute Mesa at the Nevada Test Site in Southern Nevada. Preliminary arrangements have been made with Survey personnel working at the Test Site to conduct seismic refraction and reflection tests in the welded tuffs of Pahute Mesa. The tuffs are bedded and should yield reflections. This will be the first attempt at seismic reflections by the In Situ project. The normal suite of attenuation, frequency spectra, and P and S wave velocity measurements will be conducted at the same time. A number of deep wells have been drilled on Pahute Mesa and the possibility of a suite of inhole logging measurements is being investigated.

In conjunction with the Apollo Mission Simulation studies being conducted by Don Elston of the Astrogeology Branch of the U. S. Geological Survey, plans are being made to reconnoiter a group of sites which are also under consideration as test sites for the Apollo Mission Simulation studies. The Amboy and Pisgah craters, California were reconnoitered in conjunction with Steve

Gawarecki of the Remote Sensing project directed by William Fischer, Theoretical Geophysics Branch, U. S. Geological Survey, Washington, D. C. Other sites selected in the future will be coordinated with other lunar project requirements insofar as possible.

As previously mentioned, project capabilities will be significantly enhanced in FY-65 by the addition of one new seismograph in July, 1964, a drill rig in late summer or early fall, and a second seismograph in late fall or early winter. This equipment will allow simultaneous recording of 16 3-component geophones at various distances from shots and in various configurations for maximum information in each area. The drilling rig assigned to the project will be used for extensive coring operations at test sites and some shot hole drilling.

The tape recording capability of the new seismographs will facilitate digital analysis because data can be electronically digitized and formatted for computer usage in a fraction of the time required to do so from paper tapes.

Operations during FY-65 will be expanded into non-volcanic terrains such as loose, dry alluvium and consolidated igneous and metamorphic rocks to provide a more complete picture of the variation of seismic properties as a function of physical properties. Sand dunes near Amboy flow, California have been examined as a possible site of investigation.

A number of caves have been discovered in volcanic areas reconnoitered to date. These caves, which are best developed in the Pisgah flow, are a hazard to heavy equipment used in terrestrial investigations and will undoubtedly be equally hazardous during lunar operations. It is thought that these caves can be located by sonic resonance recorded by seismometers over the caves. The phenomenon which will be investigated is similar to that used as one pounds the interior wall of a house trying to locate a stud in order to hang a picture. The "hollow" sound observed in areas without studs is caused by the low resonant frequency of the wallboard-air system. The wallboard-stud system has a higher resonant frequency which can sometimes be detected with the unaided ear. Magnetic and gravity surveys will also be carried out in the vicinity of the caves. Calculations indicate that such surveys can successfully locate larger caves.

Summary.- Operations conducted in FY-64 have generally met or exceeded goals presented in the Work Plan. A few changes were made, however, in order to take advantage of field conditions and increase project efficiency, the most important of which was the increase in study areas from a proposed two to an actual four.

Preliminary data suggests that (1) non-explosive energy sources can be detected to distances up to 500 feet on the lunar surface with instrumentation comparable to that presently available, and (2) frequencies observed at short distances are higher than originally expected. These two facts will be of value in the design of lunar seismic missions and instrumentation.

The In Situ Geophysical Studies project is being coordinated with the Apollo Mission Simulation project, Remote Sensing project, and Astronaut training project to the extent that joint reconnaissance of potential sites have been made, data exchanged, and and observed and assisted in astronaut training program.

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