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INITIAL BASALT TARGET SITE SELECTION EVALUATION FOR THE MARS PENETRATOR DROP TEST

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16. Abstract

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ABSTRACT

This report describes potential basalt target sites for an air drop penetrator test and discusses the criteria involved in site selection. A summary of the background field geology and recommendations for optimum sites are also presented.

INTRODUCTION

This report discusses the essential characteristics of nine basaltic flows that were investigated during the month of January and February 1976 for potential penetrator basalt targets. All flows are recent (younger than 10,000 yrs) and relatively fresh (devoid of extensive weathering, vegetation, and geologic alteration). The search for a suitable target site was focused in southern California, Arizona, and New Mexico to avoid snow cover and to establish a site that is within reasonable proximity to both Sandia Laboratories and Ames Research Center personnel.

SCIENCE RATIONALE FOR SITE SELECTION

In choosing a suitable basaltic rock target for the Mars penetrator subsurface mission, two important factors are important for selection: (1) the rock must fit into the engineering constraints of the penetrator for rock targets, and (2) the target rock should be very similar to those that the penetrator might encounter on Mars.

The engineering design by Sandia Laboratories, Albuquerque, New Mexico, (Sandia Labs. publication Sand-74-0130, Mars Penetrator Subsurface Science Mission) calls for an impact velocity of 150 m/s. At this velocity, the penetrator will "... penetrate to a depth of 1 meter in a basaltic lava with a 2500 N/cm^2 unconfirmed compressive strength, a bulk density of 2 gm/cm^3 and a porosity of 30 percent."

The majority of Martian surface basalts fall under two general categories, shield volcano flows and flood basalts. In selecting a suitable target we based our efforts on the characteristics of these two morphological flow types and the basalts that form them. Shield volcanoes on Earth form from large amounts of very fluid (low viscosity) flows. These flows tend to be thin (3-12 m) and move downslope very rapidly and build broad, low dome-shaped mountains. The Hawaiian Islands have formed mostly from shield volcano construction (tholeiitic pahoehoe and aa lavas). Shield volcano lava flows, comparable to those that we might expect on Mars, are called pahoehoe and are intermixed with another type of flow called aa. Pahoehoe lava is characterized by smooth, billowy, or ropy surfaces (Figs. 1 and 2). These flows may be thin layered or massive with vesicularity greatest towards the top of the flow and decreasing downward. In pahoehoe lavas, gases dissolved in the crystallizing liquid come out of solution slowly and the gas bubbles that are formed are still expanding when the flow stops moving. Vesicles tend to be spheroidal, although they may take an elongated, elliptical, or stretched form as the lava congeals during the last stages of movement. In contrast, aa flows have a rough, rubbly surface composed of masses of clinkers that tend to pile up into loosely consolidated clinker piles. Outgassing of aa is rapid, thus the gas bubbles may be more irregular in shape and more numerous than in pahoehoe. Most flows emerge from the vent as pahoehoe and may change to aa downslope, and the two types commonly intergrade.

Pahoehoe lavas form structures that have a bearing on the selection of a suitable test site. During the consolidation of pahoehoe, oval dome-like hills (tumuli) form which are commonly cracked from buckling (Fig. 3) and grade into pressure ridges (Fig. 4). Both of these structures result from moving lava with the solidified surface crust being pushed against stationary crust downslope. Collapse depressions (Fig. 5) also form in response to low structural strength of underlying material. All of these structures are undesirable for optimum testing conditions.

Flood basalts form from very fluid lavas that erupt from fissures scattered over a wide area and do not form dome-like volcanoes, but form "flood or plateau basalts." These basalts are tholeiitic in composition as are the shield volcano basalts (see below). Flood basalt flows on the Earth are thick (up to 50 m) and are extremely voluminous (50,000 - 200,000 cubic miles).

Tholeiitic basalts, which form the major portions of shield volcanoes and flood basalts, are chemically characterized by containing SiO_2 contents of between 46 and 51% (low viscosity), low K_2O contents, low Fe_2O_3/FeO ratios, and are fairly homogeneous in composition over large flow areas.

Most of the tholeiitic basalts investigated in this study are termed olivine basalts (contain $\sim$3-8% olivine phenocrysts). Lunar and meteoritic basalts are closer in chemical similarities to tholeiites compared with other types of terrestrial basalts.

In summary, the basalt target rock for the air drop penetrator test should possess a porosity of $\simeq$ 30%, be consistent with tholeiitic composition, and form relatively featureless flat structures. Additional, more-detailed selection parameters are discussed in the next section.

DETAILED CRITERIA USED IN SITE SELECTION

In addition to the lava type, flow characteristics, and general aspect of the flow, field evaluation of each potential site was made on a detailed set of rock characteristics and field conditions. These include porosity and porosity homogeneity of the rock, vertical and horizontal fractures, type of surface covering and depth, rock toughness, flat target footprint (target area) and target accessibility for motorized vehicles. Land ownership and airstrip accessibility were also considered.

Porosity is defined as the fraction of the bulk volume of a rock that is void space. Engineering development requires that to penetrate 1 m of basalt, a total porosity of $\geq$ 30% is required. Moreover, the porosity should be relatively evenly spaced and homogeneous to a depth of 1 m for optimum penetration conditions. The bulk of void space in basalts result from outgassing of the lava as it enters the zone of lower pressure at or near the surface. The lower pressure forces the gases to come out of solution and thus forms bubbles (vesicles) in the liquid lava. At this stage the lava consists of three physical phases; liquid, gas, and solid crystals. Rapid cooling retains many of the bubbles as vesicles. A highly gas-charged lava will, on proper cooling conditions, yield a high porosity rock. Flows typically have high porosities near the top surface and decreases with depth.

Fractures are formed from shrinkage cracking in the cooled lava crust. The greatest number of vertical and horizontal fractures develop near the surface. Both vesicles and fractures contribute to rock weakness and provide the overall void space.

For this test, it is undesirable to have a thick covering of any material on the basalt surface. Loose material less than a meter and preferably less than 0.3 m is considered to be within the tolerable limit. Large boulders, vegetation, rubble piles, aa lava, and an irregular surface (collapse structures, pressure ridges, and tumuli) are also undesirable.

Rock toughness is a rough estimate of the rock's strength. If a rock rings and splinters when struck with a hammer, it is hard, brittle, and has a high degree of toughness. If on the other hand, the rock responds to a hammer blow with a dull thud, and it pulverizes to a powder, then it is soft and low in toughness.

The potential sites must have an air drop target footprint of at least 200' x 100' and the target site must be trafficable to motorized vehicles.

Evaluation criteria for each investigated potential basalt target site are given in table 1.

BASALT FLOWS INVESTIGATED AND EVALUATION

All basalt target site location are shown on a reference map (Fig. 6).

Carrizozo (Malpais) and McCarty's Flows

These flows consist of quartz-to-olivine tholeiite pahoehoe and aa flows. Both are relatively recent and fresh with limited cover material other than cinder piles and extensive vegetation on a portion of the McCarty's flow. They both suffer from the same problems of highly irregular surfaces (irregular aa lava covering, cinder piles, very numerous collapse depressions and tumuli structures, poor fracture index, porosity inhomogeneity and lack of a flat surface target area). Flow and surface characteristics are shown in Figs. 7 and 8. Field estimates of surface rock porosity show a considerable range, although average estimates in small target areas are ∿ 30 percent. Laboratory surface porosities are nearly 30 percent (appendix) but the bottom (0.7 m from the surface) porosities are only 24 percent (appendix). McCarty's surface sample porosities = 26 percent (appendix).

Amboy Flows

The Amboy Crater lava flows show typical features of other lava fields. The irregularity of the surface is locally severe although there are several large-to-small flat regions which probably represent lava ponds. In addition, other flat areas referred to here as plateaus offer potential target sites and emphasis is placed on one particular plateau, referred to as plateau #2

(Figs 9 and 10). The relief of this plateau is very slight (Fig. 10) and the surface is relatively devoid of cover; only a thin layer of windblown sand and fist-sized (and smaller) lava blocks are present (Figs. 11). The plateau stands about 1-2 m above an encompassing depression and affords good cross-section observations.

Field study indicates that the entire plateau is homogeneous with respect to surface and one-meter depth porosities. Field estimates suggest surface porosities of between 25-35 percent and one-meter depth porosities of 20-30 percent. Laboratory measurements show surface porosities of two samples range between 24 and 27 percent; one bottom sample has a porosity of 24 percent (appendix). These samples were selected for a flow average to a depth of one meter; they are not meant to represent optimum porosities.

Vertical fractures range from 5 to 20/meter and horizontal fractures range from 2 to 5 for a depth of one meter. Characteristics of the plateau (one-meter depth) are shown in Figs. 12 and 13.

Petrographic studies of thin sections made from Amboy pahoehoe samples indicate that basalts of plateau #2 are olivine tholeiites with a volume of 5 percent olivine, which is present as phenocrysts and microphenocrysts (Fig. 14). The matrix consists of plagioclase laths which show somewhat vague flow orientation, clinopyroxene, and ilmenite. Moreover, observations of the matrix shows a high grain density (low abundance of micropores) and little matrix glass (Fig. 15). The high grain density and low glass abundance contribute to the high degree of toughness of the Amboy basalt.

Pisgah Crater Flows

The Pisgah flows contain a very large proportion of aa lava and the flow terrain is considerably rougher than Amboy. A few flat "plateaus" do occur and characteristics of the pahoehoe lava are similar to Amboy pahoehoe. The main drawback to Pisgah as the test site is the small target footprint. The largest accessible potential target site measures only 100' x 60'.

Mountain Spring Flows

These flows are located in the China Lake Naval Weapons Center Station and consist of multiple flows that formed a plateau several hundred meters thick (Fig. 16). Extensive erosion has dissected and rounded the plateau to the point that there is not a suitable target site. In addition, the top 2 meters are extensively altered from weathering.

Indian Wells Valley Flows

Only a portion of these extensive flows, located on the western edge of China Lake Naval Weapons Center Station, was available for investigation due to bad weather conditions and Range testing. The observed portion (Fig. 17) shows an upper 1-2 m of fairly porous pahoehoe intermingled with aa lava. Cinder piles are present on the surface in addition to < 0.3 to several meters of sand and soil overburden.

Big Pine Flows

These rather extensive flows are located just south of Big Pine, CA. Areas free of snow cover were found to contain fairly porous pahoehoe covered by scattered cinder piles, pressure ridges, and some aa flows. The terrain is generally hummocky and no suitable flat target surface was found.

SP Crater Flows, Arizona

The large cinder cone (SP Crater) and fresh related flows are located ≈ 40 km north of Flagstaff. The flow surface is extremely rugged and only one small, relatively flat surface was found. The rock is very porous, but unfortunately it is andesitic in composition and does not fit our profile of a suitable basalt rock type.

Strawberry Crater Flows, Arizona

The crater and flows are located 35 km northeast of Flagstaff. The flows are very hummocky, covered with 1-3 m of sand and soil, and have very low porosity.

SUMMARY AND RECOMMENDATIONS

A summary of the basalt target test site evaluation is given in Table 1. In addition to the criteria evaluation for each site, we have established an arbitrary scording system to aid in assigning a quantitative value for each potential site. A perfect suitability score = 165;

the highest score for any of the potential sites is Amboy, followed by Pisgah, and Indian Wells Valley (Table 1).

We recommend that the Amboy Crater flows be selected for conducting the initial basalt rock penetrator drop test. Whereas these flows meet most of the major and minor criteria, the rock is extremely tough and the probability of a successful full penetration of 0.5-1 m is low. On the other hand, the tough nature of the Amboy basalts is not too dissimilar to other pahoehoe rocks investigated in this report or to tholeiitic pahoehoe in general. This test should establish an upper limit to the penetrability of Martian basaltic rocks.

ACKNOWLEDGEMENTS

We thank Dr. Carl Austin of the Naval Weapons Center, China Lake; Dr. Ronald Greeley of Santa Clara University; Dr. Wendell Duffield of the U. S. Geological Survey, Menlo Park; Dr. Wolfgang Elston of the University of New Mexico; and Dr. Edward Wolfe of the U. S. Geological Survey, Flagstaff, Arizona; for their help and suggestions during the evaluation of the basalt flows.

Table 1. SUMMARY EVALUATION OF PENETRATOR BASALT TEST SITES*

Parameters: Sites:	Porosity (>30%)	Porosity Homogeneity with depth (1 m)	Porosity Homogeneity (spacing between vesicles)	Vesicle Size (fine to large)	Fractures, Vertical (per meter)	Fractures, Horizontal (per meter)	Surface covering (<0.3 m)	Surface Conditions (Type of cover, amount, etc.)	Rock Toughness (high, medium, low)	Flat Target Footprint (200'x100')	Target Accessibility	Target Land Ownership (BLM, Private, Gov't, State)	Airstrip Nearby	Target Suitability Perfect Score = 165 (arbitrary)
Carrizozo Flows, NM	/	No	E	M	1/m	0/m	Yes (some)	Poor	High	No	No	BLM, G	?	49
McCartys Flows, NM	X	Varies	V	M	2-3/m	0-1/m	Yes	Fair to Poor	High to med	No	?	BLM S	?	86
Amboy Crater, CA	X	Yes	W	L-M	5-20/m	2-3/m	Yes	Good	High	Yes	Yes	SP BLM	Yes	145
Pisgah Crater, CA	X	Yes	W	L-M	5-10/m	1-2/m	Yes	Good	High	Yes ?	Yes	BLM P	Yes	128
Mt. Spring Flows, CA	/	Varies	E	M	2-3/m	1/m	No	Poor	Med	No	Yes	G	Yes	66
Indian Wells Valley, CA	X	Yes	E	M	3-5/m	1-2/m	Yes (some)	Fair	High	Yes	Yes	G	Yes	119
Big Pine Flows, CA	X	Yes	E	M	3/m	1/m	No	Fair to Poor	High to med	No	Yes	BLM P	Yes	87
SP Crater Flows, AZ	X	Yes	E	S-M	5/m	1/m	?	Fair	High	No	Yes	BLM	No	102
Strawberry Crater Flows, AZ	/	No	V	M	0-1/m	0-1/m	No	Poor	High	No	?	BLM	No?	25

Legend: / = partial E = even V = variable L = large ≥ 1 cm
X = complete W = wide M = medium < 1 cm S = small < 0.5 cm

*These 9 sites studied and evaluated in detail; 10 others rejected.

APPENDIX

MEASUREMENT OF POROSITY

Porosity is defined as the fraction of bulk volume of a rock that is void (pore) space. Porosity is determined by the following equation:

$$\%\ \text{porosity} = \frac{\text{pore volume}}{\text{bulk volume}} \times 100\%.$$

Bulk density and grain density were also determined by the following equations:

$$\text{bulk density} = \frac{\text{sample weight}}{\text{bulk volume}},$$

$$\text{grain density} = \frac{\text{sample weight}}{\text{grain volume}},$$

where bulk volume= pore volume + grain volume. The measuring procedure used to determine porosity was adapted from that used by J.S. Watkins, 1967.

Procedure.

1. The rocks were cut into rectangular solids having surfaces at approximately right angles.
2. Since the rock surfaces were not exactly at right angles, the lengths of each of the corresponding four edges were measured and averaged to get the length, width, and height of the rocks.
3. Bulk volume was calculated, being equal to the average length x average width x average height of the rocks.
4. The rocks were dried at 105° C. for several days to remove moisture, and then weighed.
5. The rocks were next crushed to a fine powder so that all small isolated pore spaces would be exposed.
6. The powdered rocks were placed into volumetric flasks and a measured amount of kerosene was added from a burette to cover the sample.
7. The volumetric flasks were then evacuated and agitated until all the trapped air in the sample was removed.
8. Additional kerosene was measured and added to bring the volume of kerosene and crushed rock in the flasks equal to the flasks' capacity.
9. The grain volume was determined; grain volume= flask volume - volume of added kerosene.
10. Then from the above formulas total porosity, bulk density, and grain density can be calculated.

Bibliography.

Watkins, J.S., 1967, Investigation of in situ physical properties of surface and subsurface site materials by engineering geophysical techniques. U.S. Geological Survey open file report.

Results of analyses.

Analyst: George R. Polkowski

Amboy Plateau #2 Top 60 cm.
Total Porosity= 26.65%
Bulk Density= 2.156 g./cc.
Grain Density= 2.940 g./cc.

Amboy Plateau #2 Bottom 60 cm.
Total Porosity= 24.02%
Bulk Density= 2.218 g./cc.
Grain Density= 2.919 g./cc.

Amboy Plateau #2 Top 0.75 m.
Total Porosity= 24.78%
Bulk Density= 2.212 g./cc.
Grain Density= 2.940 g./cc.

McCartys
Total Porosity= 26.18%
Bulk Density= 2.165 g./cc.
Grain Density= 2.933 g./cc.

Carrizozo Top
Total Porosity= 29.14%
Bulk Density= 2.066 g./cc.
Grain Density= 2.916 g./cc.

Carrizozo Bottom
Total Porosity= 23.82%
Bulk Density= 2.338 g./cc.
Grain Density= 3.069 g./cc.

Big Pine
Total Porosity= 25.94%
Bulk Density= 2.211 g./cc
Grain Density= 2.985 g./cc

Indian Wells Valley
Total Porosity= 28.91%
Bulk Density= 2.004 g./cc
Grain Density= 2.819 g./cc

The above Amboy Plateau values compare closely to those using similar methods of J.S. Watkins, 1967, in his U.S. Geological Survey results.

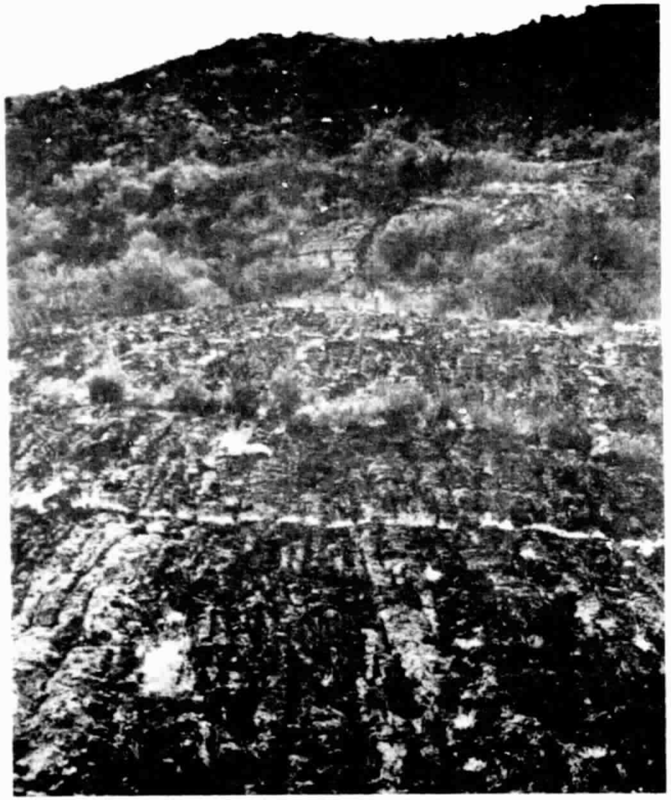

Figure 1. Ropy, relatively flat pahoehoe surface with aa lava flow in background. McCarty's Flow, New Mexico.

Figure 2. Irregular ropy pahoehoe surface with one-meter wide shrinkage fracture. McCarty's Flow, New Mexico.

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Figure 3. Large (1-2 m) shrinkage fracture atop a tumulus in the Carrizozo flows. Depth of fracture is 3-4 m.

Figure 4. Highly porous basalt (35%) on the site of a pressure ridge. Note the jumbled condition of the basalt. Carrizozo flows.

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Figure 5. Collapse depressure profile. Distance from the top to bottom (not shown) of the depression is 7 m; diameter is ≈ 24 m. Carrizozo Flows.

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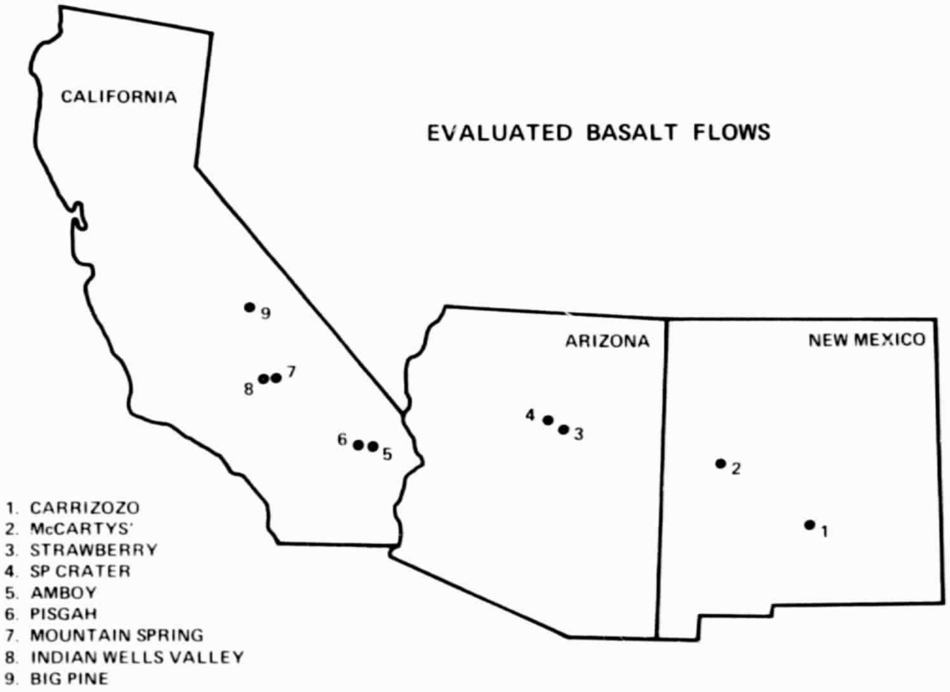

Figure 6. Location map of fully evaluated basalt flows.

Figure 7. Surface conditions of Carrizozo flows. Note numerous collapse depressions. Carrizozo Flows.

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Figure 8. Collapse depression showing merging of aa flow on the left with pahoehoe on the right. McCarty's Flows.

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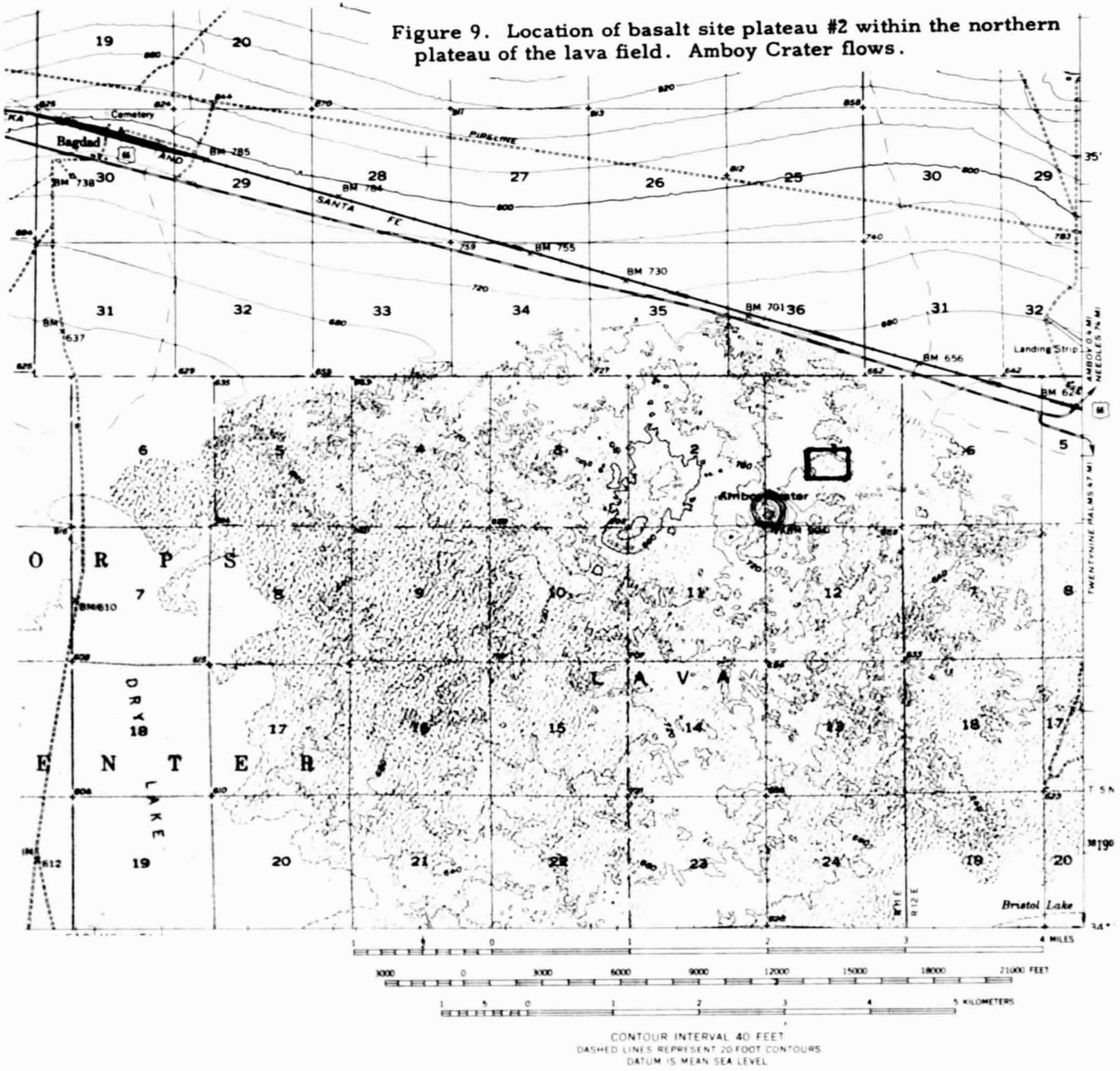

Figure 9. Location of basalt site plateau #2 within the northern plateau of the lava field. Amboy Crater flows.

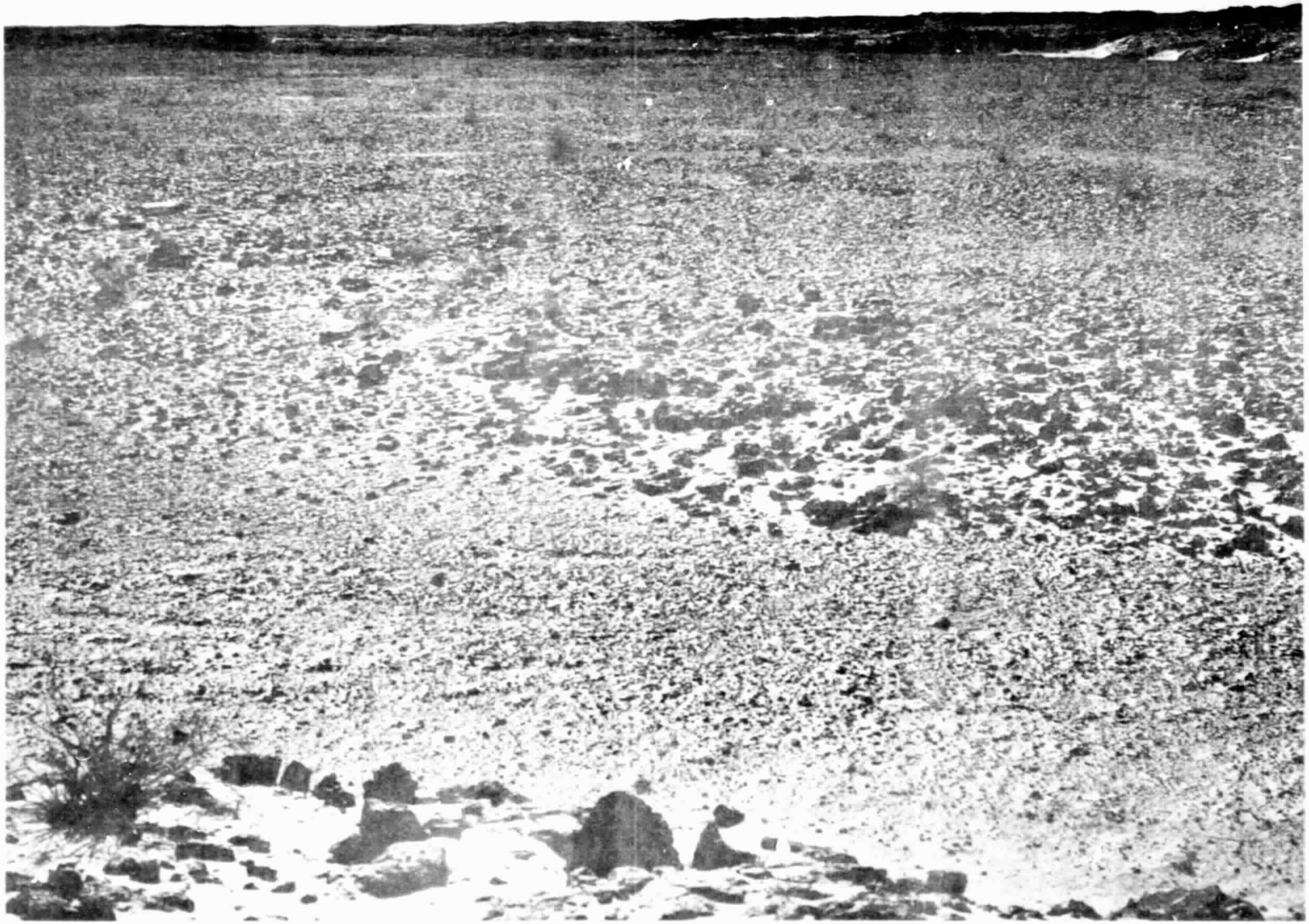

Figure 10. View of the flat plateau #2, Amboy Crater flows. (Photograph courtesy of R. Greeley)

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Figure 11. Nature of the surface of plateau #2 showing thin sand covering with fist-sized lava fragments. Amboy Crater flows. (Photograph courtesy of R. Greeley)

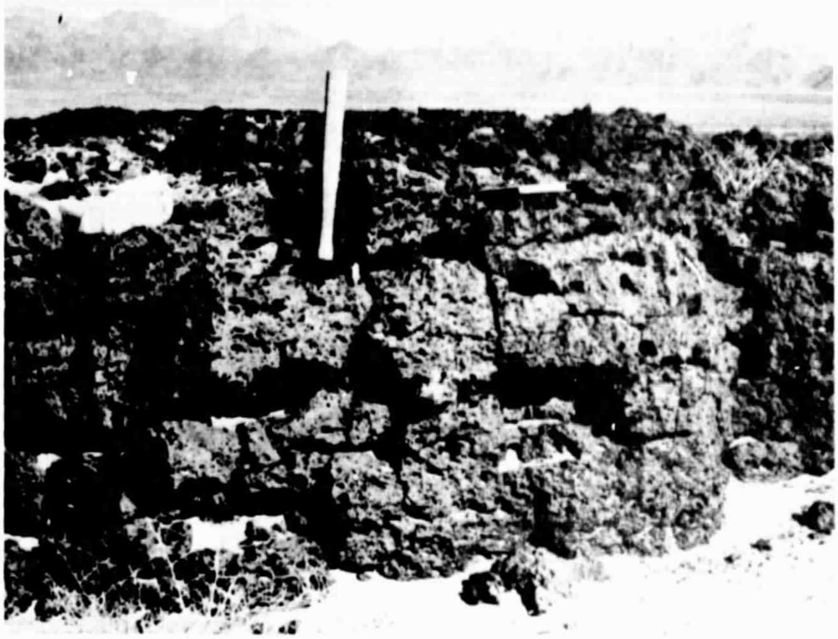

Figure 12. Cross-section view of plateau #2 showing homogeneous porosity with depth and fractures. West side. Amboy Crater flows.

Figure 13. Cross-section view of plateau #2 showing increase of vesicle size with depth, fractures, and surface conditions. East side. Amboy Crater flows.

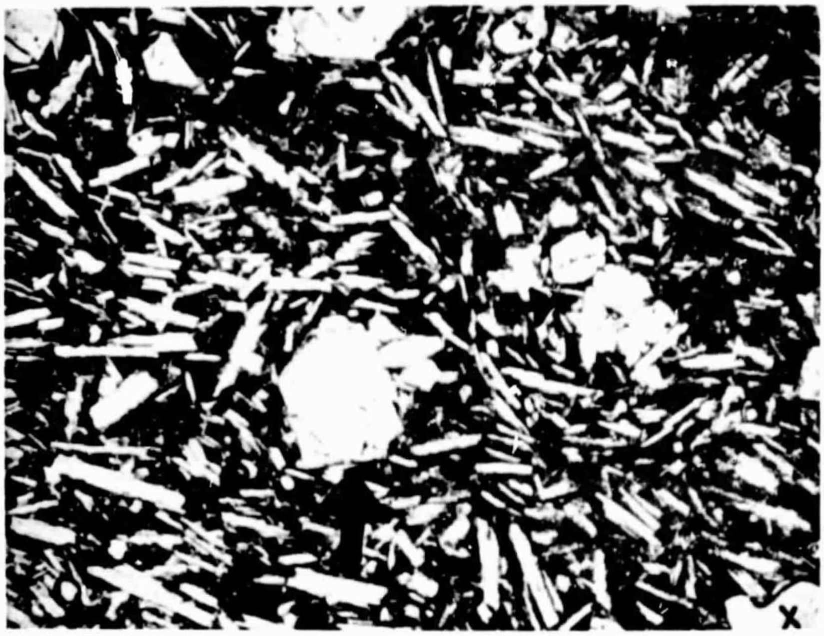

Figure 14. Photomicrograph of Amboy olivine tholeiite lava from plateau #2. Large arrow points to olivine microphenocryst, smaller arrow points to pyroxene glomerocrysts, and the X's indicate vesicles. Field width = 3.08 mm.

Figure 15. Photomicrograph of the basalt matrix in Figure 14 showing plagioclase laths, matrix clinopyroxene (medium gray), small glass patch with skeletal ilmenite (indicated by arrow) and pores (indicated by X's). Field width = 0.52 mm.

Figure 16. Mountain Spring basalt flows.

Figure 17. Indian Wells Valley flow surface in fore- and middle-ground; older flow truncated by a fault shown in background.

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