No. 151 BASALT MELTS IN A SIMULATED LUNAR ENVIRONMENT

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ABSTRACT

Hawaiian basalt samples were melted and partially outgassed *in vacuo* in order to obtain a material comparable to that extruded onto the lunar surface. Surface characteristics, internal structure, and bearing strength are described. Densities averaging 0.22 gm/cm^3 and bearing strengths as high as 9 kg/cm^2 were encountered.

1. Apparatus and procedure

Dobar and his associates produced laboratory samples of rapidly-solidified extrusive rock magma in a simulated lunar vacuum (1964), their Bamolivac experiment *(basalt molten in vacuum)*. The investigation was conducted at pressures as low as 0.5 mm Hg.

The current study augments these findings with data for basalts melted under pressures as low as 10^{-5} mm Hg. The effect of zero gravity has not been introduced into the experiment.

A high-temperature vacuum system was built for LPL by Dr. Stuart Hoenig of the Field Emission and Space Systems Laboratory of the University of Arizona (Hoenig 1966). This device (Fig. 1) consists of a closed-front oven, with pyrometer attachment, containing one end of an Inconel-600 tube of about one meter in length. The rock specimen is melted in the heated portion of this tube in a continuously-evacuated nitrogen atmosphere. Fragments of tholeiitic basalt from Hawaii, weighing between 30.4 and 75.0 grams, were placed in boats constructed of epoxy-bonded firebrick. Boat dimensions were 2.3 × 5 × 11 cm.

The melting procedure began with the temperature rising slowly to about 600°C, at which point the specimens were outgassed for about one hour. Thereafter, the temperature was increased to the melting range of 1175-1220°C. Almost immediately following melting, the specimens began to expand and fill the boats. After a period of this froth development, the specimens were quickly withdrawn to the far end of the tube for "rapid" cooling.

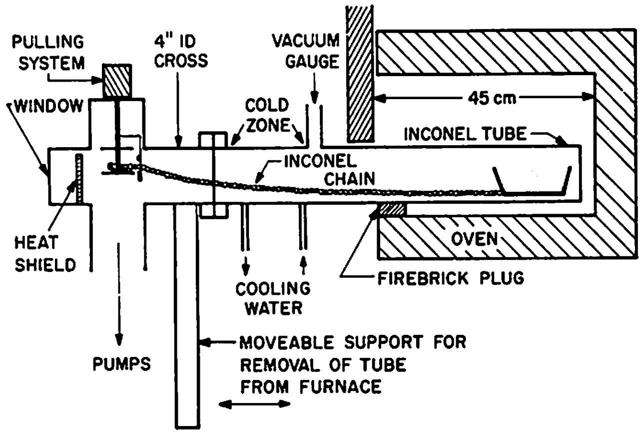

Fig. 1 Vacuum furnace with pulling assembly (Hoenig 1966).

2. *Structure of the rock froth*

The original basaltic material was a dull reddish-brown scoria. After melting and frothing, the internal structure of the resulting black specimens contained numerous vesicles which diminished in size toward the surface (Fig. 2).

Observation through the glass inspection port at the end of the melting tube showed the formation and deflation of billows during active frothing. Instantaneous deflation followed as massive gas bubbles worked their way to the surface and escaped. Smaller gas bubbles remaining near the surface appeared to be more stable by virtue of small size only, not having sufficient buoyancy to overcome the viscosity of the melt. The bubbles did not show preferential surface locations in the boats. Billow formation and deflation occurred normally about every 20 seconds. A breadload shape was imparted to the specimen due to the shape of the boat and the fact that the surface tension of the melt was sufficient to restrain the material from flowing over the side.

Apart from the delicate glass films covering surface pores and interior vesicles, the general *internal structure* of the rock is quite strong.

Surface skin *thickness* for the froth varies from 0.1 to 30 mm, but averages about 4-5 mm. In some locations, the crust extends completely to the floor of the boat, but generally there are large pockets or voids which reach from the floor upward to the thin skin. Interior voids measured in resolidified specimens were as large as 2.5 cm high and 4.0 cm wide (Fig. 3a).

Surface roughness is related to the amount of volatiles remaining in the rock melt at the time of cooling. During the formation of billows, gas bubbles appeared and formed holes at the surface if they burst. Few of these surface bubbles remained intact after exposure to laboratory conditions due to the fact that surface tension at each surface bubble location increased with the degree of cooling and contraction until most of the bubbles ruptured. Comparison of Figs. 2 and 4 shows the effect of volatile content on the degree of vesiculation of the specimens.

3. *Vesicles*

If outgassing is incomplete, a smooth and undulating glassy surface is formed. About equal numbers of fresh bubble breaks having sharp edges occur along with healed-over breaks which are subdued in form, have smooth edges, and are not open to the interior of the specimen (Figs. 5 a-b). Passage of volatiles from depth occurs as a result of rupture of bubble skins as adjacent bubbles touch. Our experiment produced a variety of void sizes and shapes, dependent probably on the viscosity and volatile content of the melt.

Surface area-density of pores in general is inversely related to ambient pressure during initial prolonged heating of the specimen. Estimated density of surface pores in all cases is greater than a few pores per square centimeter as long as outgassing was incomplete. The contrasting surface characteristics produced under variable vacuum pressure may be seen in Figs. 5 a-b (high density of pores and low pressure) and Figs. 5 c-d (low density of pores and higher pressure).

The near-surface structure has a very high porosity, since nearly all surface vesicles are interconnected. Before the fragile vesicle skins break, they

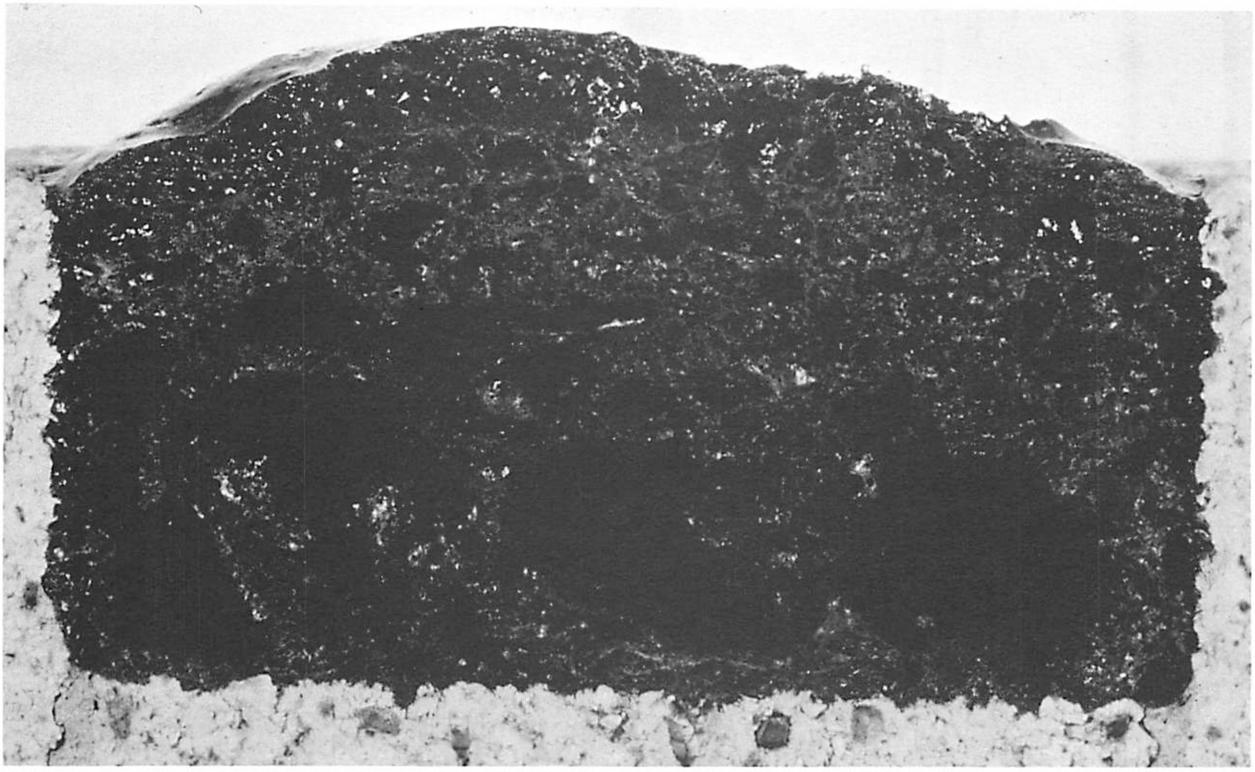

Fig. 2 Cross section of rock froth produced at p = 0.015 mm Hg. The low-density vesiculated structure is due to volatiles remaining in the melt at time of crystallization.

show optical interference colors due to the thin skin effect. The surface pores are usually circular in plan, as would be expected in a surface of equidirectional tension. However, at times the pores are elliptical due to flow of the melt during release of gas at the surface.

4. *Loss of volatile constituents*

Loss of volatile constituents was measured for ten specimens in terms of original weight. The loss ranged from 0 to 9.7% with an average of 4.3%. No relationship with other variables was detected.

Outgassing of the rock during the experiment led to development of glossy exterior surfaces. However, in specimens which were somewhat incompletely outgassed, the smooth exterior surface microstructure still had a more glossy appearance than that of the more dense and semi-glossy (or slag-like) interior. The glossy material extended only to a few millimeters of depth below the surface.

Two specimens melted at a pressure of 0.9 mm Hg after an extensive outgassing period of 12 hours at 200°C showed that the glossy surface was produced only when the specimen was withdrawn for rapid cooling. The three factors responsible for glossy surfaces on the specimens were: (1) large expansion, (2) nearly complete outgassing, and primarily (3) rapid cooling.

5. *Color and surface reflectivity*

A specimen, melted at atmospheric pressure and *rapidly* withdrawn, solidified into a dense mass with a glossy black surface covered with numerous small vesicles, usually with broken skins. These vesicles have rounded edges and radial fractures intersecting the pores at the surface. Specimens melted and slowly cooled at atmospheric pressure have a lusterless surface covered with a greater number of pores, most of which have sharp edges.

Under pressures of 10^{-4} mm Hg a lusterless surface is formed during slow cooling. The surface of these specimens gradually sags over the entire boat while occasional bubbles break through the surface. The resulting surface is generally unbroken but very irregular (Fig. 5d). If, under these conditions, the specimen is almost completely outgassed and rapidly cooled, a smooth semi-glossy surface forms (Fig. 5c) underlain by numerous closely spaced vesicles whose thin skins remain intact.

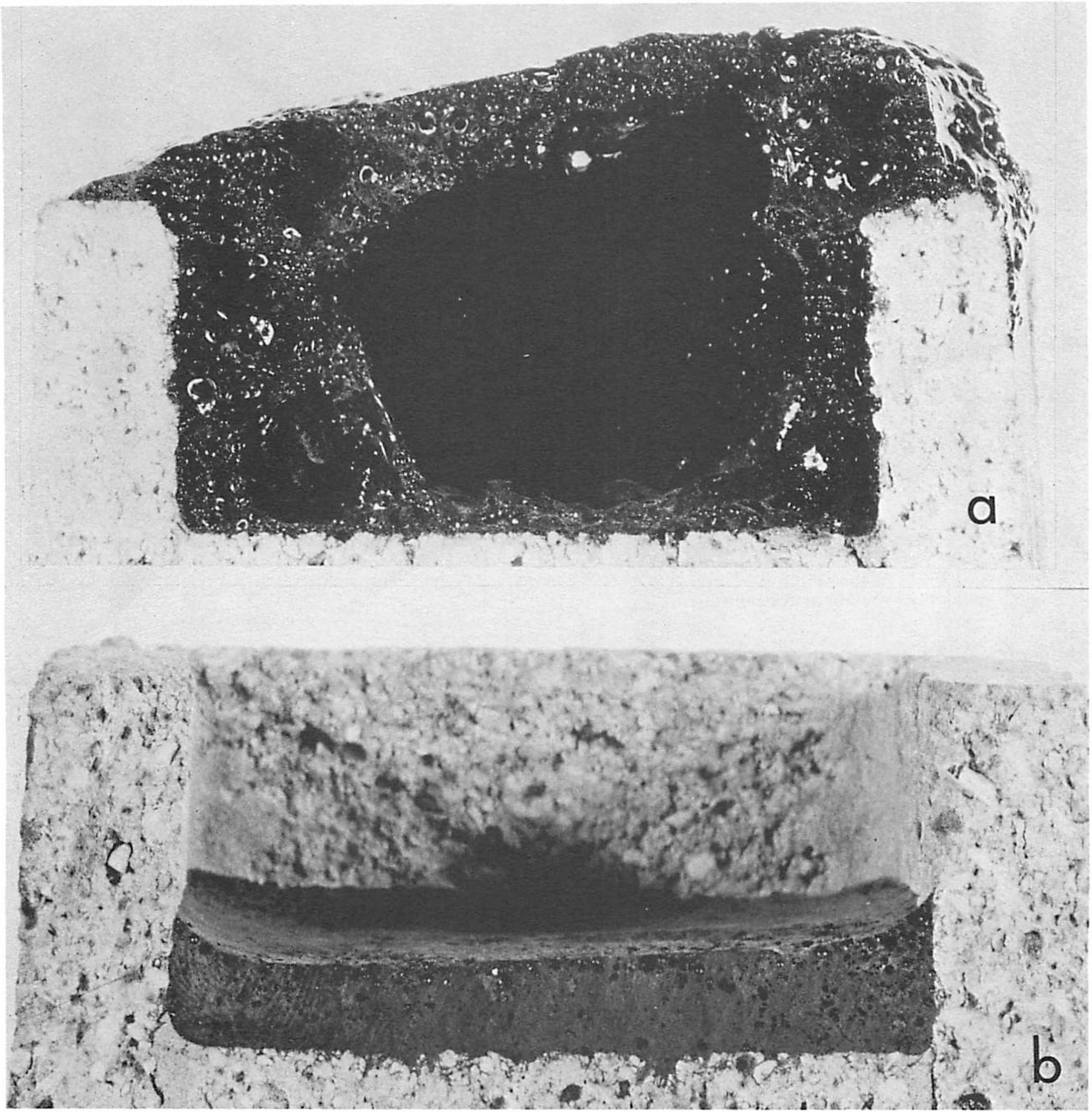

Fig. 3 Cross-sectional views showing the expansive effect of reduced ambient pressure. Fig. 3*a* indicates the maximum extent of expansion, during high-vacuum melting (2.7×10^{-4} mm Hg) (46 grams of rock). The specimen is retained as a billow with a single large subsurface cavity and a relatively thin surface. Fig. 3*b* is the result of melting of 2.4 times as much material (by weight) as that shown in Fig. 3*a*, but at atmospheric pressure. Both specimens measure 5.3 cm across the base of dark rock.

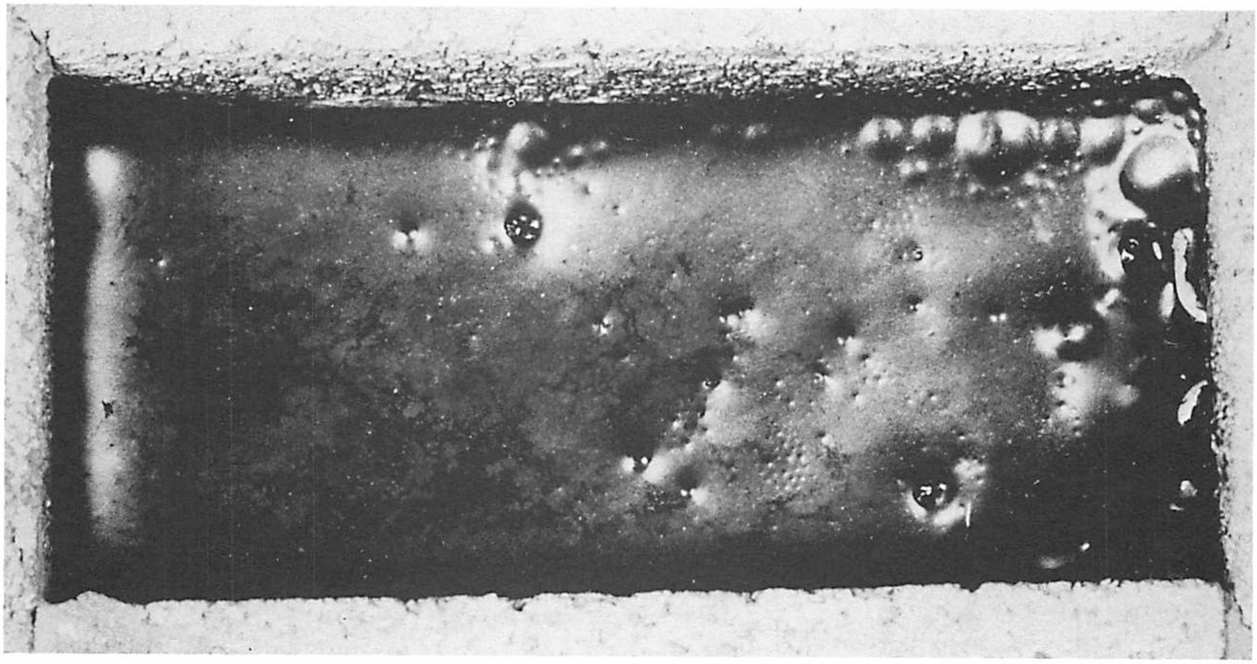

Fig. 4 Completely outgassed specimen (tholeiitic basalt) weighing 45.5 grams. Outgassing of the rock melt over 24-hour period resulted in highest vacuum attainable with test device (7×10^{-6} mm Hg), a very dense specimen, with a very small number of vesicles at the surface. These are seen as clusters of gas pockets. Length of boat, 11 cm.

6. *Bulk density*

Original sample density averaging about 1.73 grams/cm^3 was compared with the post-melt bulk densities for seven of the specimens which were preserved as billows of froth. Boats were measured and to these volumes were added the volumes of the billows which extended above the boats. Impressions of the billows were made in moist Ottawa sand covered with a thin polyethylene film with water being used to measure the displaced volume. The new densities ranged from 0.15 to 0.40 gm/cm^3. Density variations are dependent upon gas pocket formation under the crust and upon timing of retrieval of the boat while the specimen is in an inflated state. Withdrawal of the boat to the cooler end of the tube was accomplished by pulling a chain over the entire distance, and this probably induced vibrations which could have easily disturbed the billow. With these limitations in mind it can be stated that a value of 0.22 gm/cm^3 is the average inflation density for the treated specimens.

7. *Bearing strength*

Four specimens of the rock froth were subjected to uniaxial compressive loading on half-sections of sawed boats. The method utilized was identical to that described by Dobar, *et al.* (1964), in which silicate-froth specimens were stressed in a Soil Test unconfined compression device. Stress was applied over a 6.45 cm^2 cast plaster contact pad. The strength values obtained ranged from 3.24 to 9.05 kg/cm^2 with one specimen exhibiting two strength values of 5.64 and 9.05 kg/cm^2 for different halves of the boat. Strength is dependent upon location of larger sub-surface voids and the position and integrity of intervening columns supporting the surface. The specimens were confined on three sides by the walls of the boats which were located no more than 1.5 cm from the edge of the bearing pad. Dobar's silicate-froths ("Simolivac") gave values of 1.2 to 4.4 kg/cm^2.

8. *Summary*

The descriptions presented in this study are thought to depict the material which may be found on the lunar surface immediately following the eruption of extrusive lavas of basaltic composition. Wide variations can be expected in the general types of texture depending upon the variable of volatile content, chemistry, and distance traveled from the vent. For lunar extrusive flows, the reduced lunar gravity, resulting in a reduced buoyancy of the gas bubbles, favors a further decrease in bulk density, both at the surface and at depth. In view of these factors, it

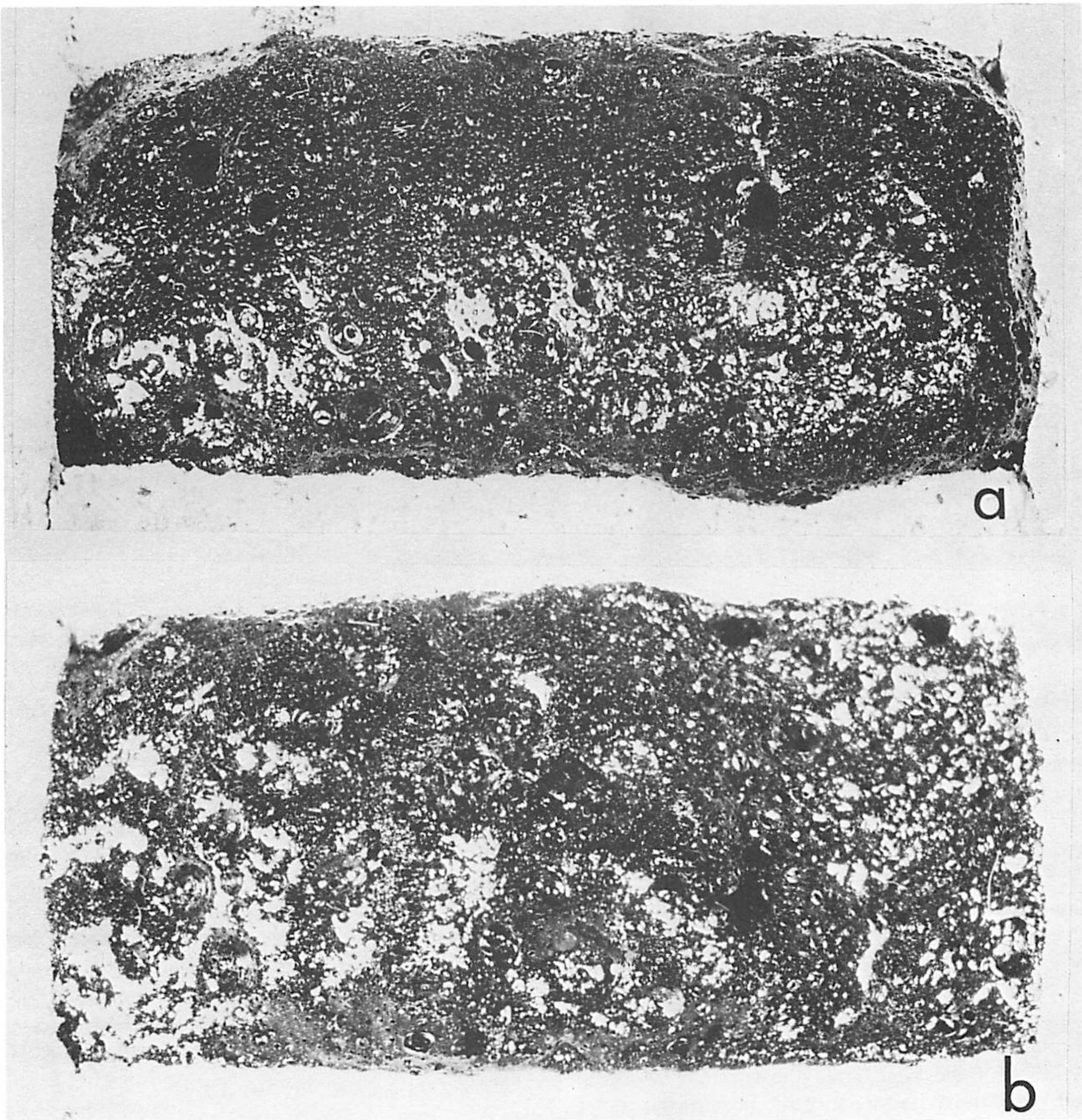

Fig. 5 Effect of different pressures and cooling rates on tholeiitic basalt (Hawaii): specimens *a* (46.0 gm) and *b* (30.4 gm) were produced at pressures of 7.5 and 1.0×10^{-4} mm Hg. This high vacuum accounted for glossy surfaces containing numerous vesicles in the interior. Specimens *c* (50.0 gm) and *d* (75.0 gm) were melted at a considerably higher pressure (0.015 mm Hg) and have less surface vesicle density, smoother surfaces, and less froth volume (volume is decreased by factors of up to 4 in comparison with the specimen shown in Fig. 5*a*). Specimen *d* was slowly cooled (at 0.015 mm Hg) and shows the resultant deflated structure and decreased surface reflectivity. Length of boat, 11 cm.


c
d

is felt that the rock produced in this study may approximate a *maximum lunar extrusive rock density* and may possibly exhibit *maximum bearing strength* values for such material.

The experiment did not take into consideration two additional variables present in the lunar environment. The first of these is that of reduced lunar gravity which would give rise to formation of gas bubbles at a depth approximately six times that of terrestrial counterparts. The second variable is that of the direction of heat flow. On the lunar surface heat would flow *from* the melt *to* the free surface. However, in the experiment, the direction of heat flow was reversed and the heat source was placed outside of the melt. These departures from lunar conditions were not evaluated.

It is understood that fragmentation and erosion of the lunar terrain subsequent to lava eruptions would disrupt surfaces such as those described here, producing the pulverized surface photographed by lunar probes.

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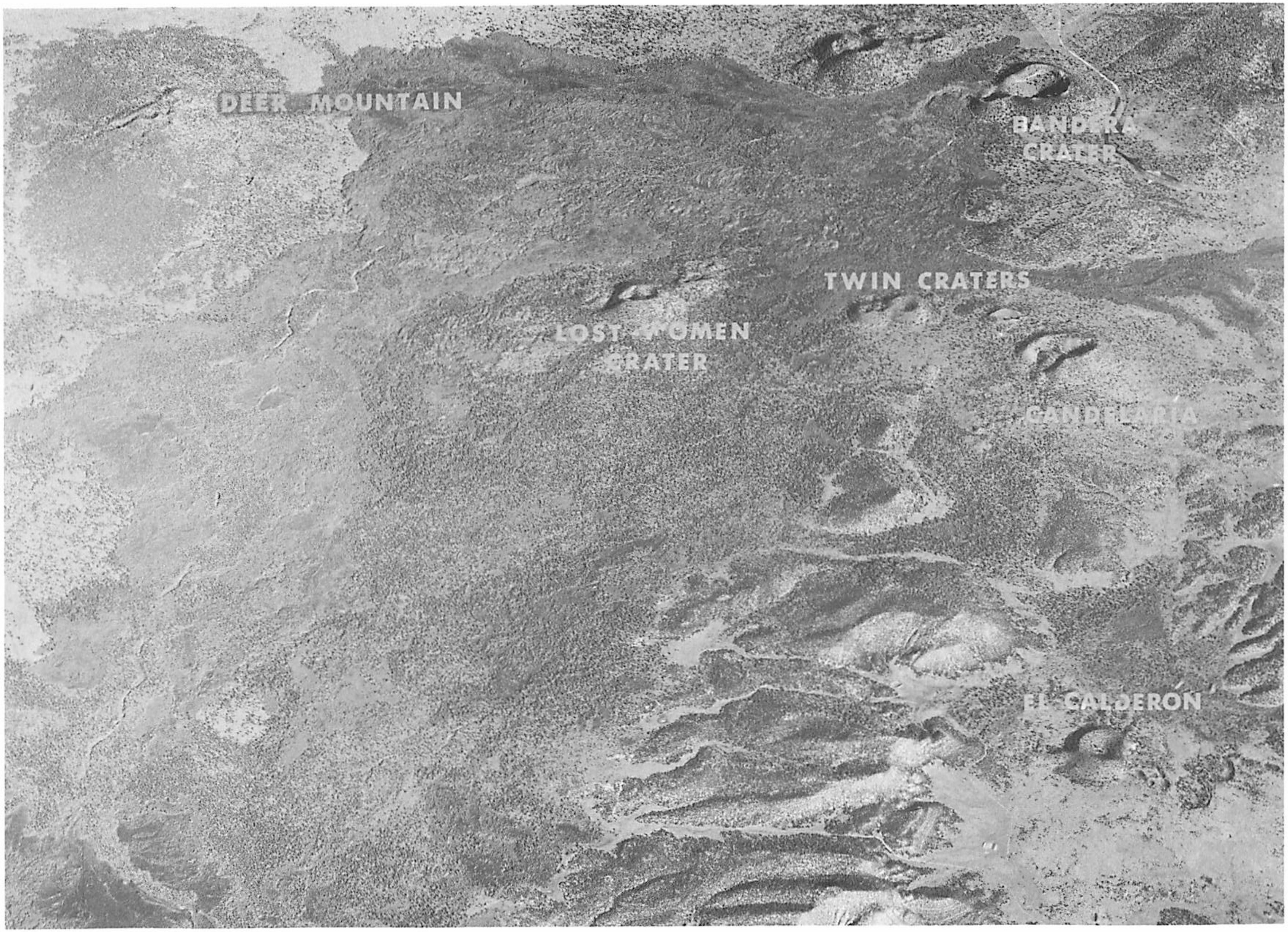
REFERENCES

Dobar, W. I., Tiffany, O. L., and Gnaedinger, J. P. 1964, "Simulated Extrusive Magma Solidification in Vacuum," *Icarus,* 3, 323–331.

Hoenig, S. A. 1966, "Low Cost, 1300°C Vacuum Furnace," *J. of Vacuum Sci. and Tech.*, 3, 351–352.



Low oblique aerial photograph of the Bandera lava field showing principal craters and collapsed lava tubes. The view is to the NW with foreground about 8 km across. (U.S. Govt. Photo, 1965).