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**POSTSHOT GEOLOGIC INVESTIGATIONS
OF THE DANNY BOY NUCLEAR
CRATERING EXPERIMENT IN BASALT**

Livermore, California

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Joseph F. Leisek

March 13, 1964

Frontispiece. Aerial view of Danny Boy crater.

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ABSTRACT

In March 1962 a low-yield nuclear event code-named Danny Boy was detonated in a basalt medium at the Nevada Test Site. The explosion created a visible crater 250 to 280 feet across and approximately 90 feet deep, with an approximate volume of 52,000 cubic yards. The apparent crater (the portion of the visible crater below original ground level) has a radius of 102 to 115 feet, a depth of 64 feet, and a volume of approximately 33,500 cubic yards. Because of the rock type, the experiment lends itself to practical application in many mining and construction situations. This report describes the Danny Boy crater geology in some detail.

INTRODUCTION

The Danny Boy event, conducted under the technical direction of Lawrence Radiation Laboratory, was a low-yield cratering effects experiment in a basalt medium in Area 18 at the Nevada Test Site. The test was sponsored by the Department of Defense. However, certain experiments were funded by the Plowshare Program and a number of Plowshare objectives were accomplished during the course of this nuclear event.

This report details the geological features of the basalts exposed in the Danny Boy crater and explains to some extent how these features controlled crater and ejecta configuration. Preshot geology, fallback patterns, and glass dispersion around the crater are discussed. Sequential development of the explosion is also shown.

LOCATION

The Danny Boy crater is located on the Nevada Test Site in Area 18, approximately 37 miles northwest of Mercury, Nevada (Fig. 1).

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Fig. 1. Map showing Danny Boy site location.

Nevada State Coordinates

N 859,541

E 587,977

Geodetic Coordinates

N 37° 06' 39.79"

W 116° 21' 53.82"

METHOD OF INVESTIGATION

Studies of the crater area have been conducted by Lawrence Radiation Laboratory, Stanford Research Institute, United States Coast and Geodetic Survey, United States Geological Survey, Sandia Corporation, U. S. Army Engineers, Waterways Experiment Station and Nuclear Cratering Group.

At the time of preparation of this report, Waterways Experiment Station was conducting an extensive drilling program for the Nuclear Cratering Group to further delineate geologic characteristics of the Buckboard Mesa Area. The United States Geological Survey carried out extensive preshot geologic and seismic studies of the basalt area.

A detailed geologic study of the Danny Boy crater area was conducted by the Lawrence Radiation Laboratory-Nevada Geology Group. Preshot and post-shot topographic maps and aerial photographs were used to implement extensive field examination of the area. Photo stations on the crater lip, set by the Holmes and Narver Survey Group, were used to delineate accurately the crater lip and for photographic study of the crater walls and fallback. A plane-table-and-alidade survey of the crater geology was made by the Lawrence Radiation Laboratory-Nevada Geology Group. Cross sections of the crater area were constructed using large scale topographic maps, plane table surveys, and field observation of the crater and ejecta area.

Waterways Experiment Station has completed excavation of a trench through the crater lip. This trench, bearing S 67° 30' W from ground zero, exposes the uplifted original ground surface and the character of the throw-out debris. Waterways Experiment Station also conducted postshot drilling in the trench and crater, attempting to outline the crater rupture zone. A borehole camera was used to supplement results of this core drilling program.

High speed motion pictures of the explosion, taken by the Lawrence Radiation Laboratory-Nevada Photograph Group, are used to diagram the crater genesis.

GEOLOGY

The Danny Boy event took place on Buckboard Mesa. This mesa is a northeast-southeast trending, elongated remnant of a series of basalt flows which issued from a fissure or vent near the base of a small cinder cone at the northeast end of the mesa. The mesa is about 5-1/2 miles long by 2-1/2 miles wide, with a gentle slope toward the east and southeast. Surface relief is moderate with the exception of the cinder cone at the northeast end. Elevation at the ground zero point was 5473.68 feet. Relief within 300 feet of the surface ground zero point does not exceed 25 feet.

Ross B. Johnson, Geologist, United States Geological Survey, describes the mesa in this manner (1):

"Buckboard Mesa near the head of Forty-Mile Canyon is capped by an isolated sheet of nearly flat-lying basalt. The basalt varies irregularly in thickness from 50 feet to more than 200 feet, and the wedge edges of the original flow have been removed by erosion. The source of the basaltic lava was apparently a small volcanic cone of Quaternary or late Tertiary age near the north end of the mesa and the lava seems to have moved down and filled a small valley that previously had been cut into underlying tuff beds of the Oak Spring Formation. The irregularity of the erosion surface over which the lava flowed accounts in large part for the great variation in thickness of the present day basalt cap.

"The basalt is light gray to black, aphanitic, and dense, and although it is nearly homogeneous texturally, mineralogically and chemically, it varies widely in density and porosity. The basalt sheet is nearly structurally underformed and is cut by a single normal fault of small displacement near the north edge of the mesa. However, the sheet is broken by many joints that appear to have been caused by cooling of the lava. The joints vary greatly in density and attitude throughout the area of outcrop of the basalt. Although, in general, the joints appear not to have a preferred pattern, locally they may display a distinct parallelism for short distances. Most of the joints are arcuate or wavy along their extents, but a few are straight. The joints are generally short, some extending for only a few feet. Dip of the joint planes ranges from a few degrees to vertical and the dip of individual joint planes

may vary through the same extremes. Straight and slight arcuate joints less than 50 feet long that dip from 75-90 degrees are most common. "

Crater Area Stratigraphy

Basalt. In the crater area the basalt cap consists of a series of nearly horizontal and overlapping flows (Fig. 2). The upper 10 to 50 feet of the exposed flow is dark black and extremely vesicular, grading at the base into a dense, nonvesicular black basalt. The vesicles found in the upper basalt are elongate, up to 3 inches long and usually paralleling the direction of flow. The percentage of vesicles and their size decrease toward the base of the upper flow. They almost disappear at the contact.

The dense, nonvesicular black basalt is discontinuous and is not found at the base of the vesicular basalt in every exposure. This dense black zone varies from zero to 10 feet in thickness, with an average thickness of 3 feet.

Near and at the base of the dense black basalt are many thin, discontinuous ash and/or cinder beds. These beds are absent in many areas of the outcrop, making the contact between the dense black basalt and the underlying basalt sinuous and difficult to determine. A dense gray-black basalt underlies the black basalt and extends below the deepest exposed outcrop in the crater. This lower unit has a granular appearance due to a large amount of very small olivine-augite-magnetite crystals present in the basalt. The preflow valley consists of tuffaceous alluvium and tuff. A complete physical property description of the Buckboard Mesa and other nearby basalts can be found in refs. (2) and (3).

Ash and Cinder. The ash beds are exposed along the entire crater wall, with the exception of a portion of the northwest quadrant where a reddish-brown cinder lens outcrops. The ash is buff to yellow-white and almost entirely unconsolidated. The cinders are reddish-brown and are distributed throughout the ash. In places the cinders are fused in relatively large masses 1 to 2 feet in thickness.

The ash and cinder beds range from less than an inch to 3 feet in thickness. The beds occur between the overlapping flows, although usually confined to a 2- to 10-foot-wide transition zone in the dense black basalt just above the contact of the black and gray-black basalts.

Fig. 2. Stratigraphy through edge of Danny Boy crater.

An indistinct cinder lens in the northwest quadrant of the crater wall contains reddish-brown blocks and bombs scattered through the cinders. This lens apparently extends from the northwest where abundant cinders and larger fragments are exposed in a high-explosive crater.

Jointing

Jointing is present in the surface basalt flows to extreme degrees, but diminishes with depth as the basalt becomes more dense. Joints are not expressed as visible openings in the more dense basalt, but are represented by definite planes of weakness which have considerably influenced the size and shape of fragments derived from the basalt.

Joint spacing varies widely over the entire mesa, ranging from a few inches to several feet. An average spacing would be from 2 to 5 feet.

The joints seem to show no preferred orientation, with the numerous sets having greatly varying strikes and dips. Although most of the joints exposed in the crater are high-angle, there are many low-angle systems. These low-angle joints exhibit many fresh breaks, leading to the conclusion that these are planes of weakness that were opened by the force of the explosion, through compression and rarefaction waves.

Most high-angle joints exposed in the crater exhibit considerable weathering from the surface to their point of disappearance. Large amounts of calcium carbonate and siliceous material have been deposited along these joints. (See Table I.)

Table I. Partial list of joints mapped in crater.

N 65 W 80 SW	N 85 W 35 NE	N 20 E 40 NW	N 65 E 15 NW	N 50 W 70 SW	N 45 W 35 NE
N 20 W 55 SW	N 55 E	N 35 W 80 SW	S 85 W 70 SE	N Vert.	N 55 E 85 SE
N 5 E 70 NW	N 55 W 30 SW	N 25 W 30 SW	N 55 E 80 SE	N 20 E 50 NW	N 50 W 30 NE
N 70 NW	N 33 W 38 SW	N 20 W 35 NE	N 65 E 15 NW	N 6 W 55 SW	N 3 E 44 SE
N 15 E 75 SE	S 45 W Vert.	N 45 W 83 SW	N 3 E 36 SE	N 15 E 70 NW	N 65 E 15 NW
N 5 W 45 SW	W 45 S	N 65 E 55 SE	N 75 W 75 NE	N 65 E 15 NW	N 15 E 70 NW
	N 5 E 33 SW	N 42 W Vert.	N 15 W 71 SW	N 65 E Horz.	S 40 W 55 NW

CRATER PARAMETERS DEFINED

In order to describe clearly the Danny Boy crater and surrounding area, the following terms are defined (see Fig. 3):

Visible Crater: The crater including the thrown out debris, which has been deposited above preshot ground level.

Apparent Crater: The part of the visible crater below the preshot ground elevation.

True Crater: The boundary (below preshot ground level) between the loose broken fallback material and the material that has been crushed and fractured but has not experienced significant vertical displacement. (For a more comprehensive definition see Short (4).)

Rupture Zone: The area outside the crater which has experienced permanent horizontal and vertical displacement.

Lip Uplift: The degree of permanent vertical displacement suffered by the original ground surface.

Cavity: The chamber created by the explosion, through melt and expansion, before cratering occurs.

DESCRIPTION OF DANNY BOY CRATER

The Danny Boy device was detonated at a scale depth of burial (SDOB) of 142; actual depth was 110 feet or 33.5 meters below the surface. Detonation took place at 10:15:00.118 A. M., Pacific Standard Time, March 5, 1962.

The explosion created a nearly circular crater with a slight northeast-southwest elongation (Fig. 4). Crater parameters are given in Table II.

Table II. Danny Boy crater parameters.

	Visible crater	Apparent crater	True crater
Maximum diameter (ft)	280	230	230
Minimum diameter (ft)	257	204	204
Average diameter (ft)	263	216	216
Depth (ft)	88 (av)	64	146
Volume (cu yd)	52,700	36,300	78,500
Volume of upheaval (cu yd)	--	24,500	--
Volume of lip fallback (cu yd)	--	55,700	--
Swell factor (%)	--	25 (approx)	--

RECOMMENDED CRATER NOMENCLATURE

- D_a . . . Maximum depth of apparent crater below preshot ground surface measured normal to the preshot ground surface.*
- D_{al} . . . Depth of apparent crater below average apparent crater lip crest elevation.
- D_{ob} . . . Normal depth of burst (measured normal to preshot ground surface).
- D_t . . . Maximum depth of true crater below preshot ground surface.
- D_{tl} . . . Depth of true crater lip crest below apparent crater lip crest.
- Ejecta . . . Material above and or beyond the true crater and includes: (1) foldback; (2) breccia—ballistic trajectory; (3) dust—aerosol transport; etc.
- Fallback . . . Material fallen inside the true crater and includes: (1) slide blocks; (2) breccia and stratified fallback—ballistic trajectory; (3) dust—aerosol transport; (4) talus; etc.
- H_{al} . . . Apparent crater lip crest height above preshot ground surface.
- H_{tl} . . . True crater lip crest height above preshot ground surface.
- L_{ac} . . . Apparent crater lip crest.
- L_{tc} . . . True crater lip crest.
- R_a . . . Radius of apparent crater measured on the preshot ground surface.
- Note: The radius measurements pertain only to single charge craters and represent average dimensions. If crater shape deviates substantially from circular, the direction of measurement must be specified. An average radius value can also be determined by dividing the plan area by π and taking the square root.
- R_{al} . . . Radius of apparent lip crest to center.
- R_{ds} . . . Outer radius of displaced surface.
- R_{eb} . . . Radius of outer boundary of continuous ejecta.
- R_{lb} . . . Outer radius of true lip boundary.
- R_t . . . Radius of true crater measured on the preshot ground surface.
- R_{tl} . . . Radius of true lip crest to center.
- R_{zt} . . . Distance between the zero point and the true crater surface measured in any specified direction. When measured in a direction below the zero point is equivalent to lower cavity radius.

- S_a . . . Apparent crater surface, e.g. rock-air or rubble-air interface.
- S_{al} . . . Apparent lip surface.
- SGZ . . . Surface ground zero.
- S_d . . . Displaced ground surface.
- S_p . . . Preshot ground surface.
- S_t . . . True crater surface, e.g. rock-air or rock rubble interface.
- V_a . . . Volume of apparent crater below preshot ground surface.
- V_{al} . . . Volume of apparent crater below apparent lip crest.
- V_t . . . Volume of true crater below preshot ground surface.
- V_{tl} . . . Volume of true crater below true crater lip crest.
- Z . . . Vertical depth of burst (equivalent to D_{ob} when crater is formed on a horizontal surface).
- ZP . . . Zero Point—effective center of explosion energy.
- Note: The following definitions apply to linear craters only. Linear crater refers to the excavation formed by overlapping crater effects resulting from a row of charges. All above terms applicable to single craters apply also to linear craters with the exception of the radius terms which are replaced by the width terms below.
- W_a . . . Width of apparent linear crater measured on the preshot ground surface.
- W_{al} . . . Width of apparent lip crest measured across linear crater.
- W_{ds} . . . Width of displaced surface measured across linear crater.
- W_{eb} . . . Width of outer boundary of continuous ejecta measured across linear crater.
- W_{lb} . . . Width of true crater outer lip boundary measured across linear crater.
- W_t . . . Width of true linear crater measured on the preshot ground surface.
- W_{tl} . . . Width of true linear crater lip crest measured across crater.

*All distances, unless specified otherwise, are measured parallel or perpendicular to preshot ground surface.

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Fig. 3. Crater cross section illustrating parameters.

Uplift and Rupture Zone

The walls exhibit considerable uplift around the entire crater perimeter. The original ground surface at the crater lip is elevated as much as 28 feet, with an average uplift of 19 feet. This uplift is primarily due to joint expansion and spallation effects.

The expansion of joint systems or similar planes of weakness must have compensated for a large amount of the initial cavity growth prior to cratering and before extensive spalling occurred.

Inspection of the crater walls discloses that every visible joint system has been reactivated and expanded by the explosion effects. Many of the low-angle systems were opened as much as 12 inches. Vertical joint sets exposed in the crater shell have been forced open several inches and add to the overall crater uplift (Fig. 5).

Postshot drilling outside the crater periphery by Waterways Experiment Station has tentatively established a lateral extent of blast-induced openings to at least 207 feet from the ground zero point. Visual inspection of the recovered core indicates that high-angle fractures were affected almost as extensively as the low-angle sets. Visible uplift can be observed for another 100+ feet, which implies a rupture zone extending at least 300 feet from ground zero (see Fig. 6). The original ground surface is exposed in the trench excavated through the lip debris.

It is not unreasonable to conclude that joint expansion and fracturing along original planes of weakness extend outside the limit of visible uplift.

Figure 7 shows a geopanoramic view of the crater interior, and Fig. 8 gives three geologic cross sections through the crater.

Lip Uplift

Joint alignment and weathering had a definite effect upon the degree of lip uplift. Areas of the crater shell which expose fresh, unweathered basalt, with low-angle jointing, show a much greater degree of uplift than do areas of extreme weathering. Jointing in the highly weathered areas (Fig. 9) exposes fewer fresh, broken surfaces than appear in areas of greater uplift.

The basalt underlying the surface flow does exhibit some fracturing, probably along planes of pre-existing weakness. These fractures all show fresh broken surfaces and extend up to several feet in length, but expansion is confined to fractions of an inch.

Fig. 4. Geologic map showing Danny Boy crater and area covered by throwout.

Fig. 5. Vertical and horizontal joint displacement evident in side of crater.

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Fig. 6. Section through lip of crater.

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Fig. 7. Geopanoramic view of crater interior.

Fig. 8. Geologic cross sections through crater.

Fig. 9. Weathered basalt exposed in side of crater showed fewer freshly broken surfaces than appeared in unweathered basalt.

Crater Fallback

Fallback refers to the ejected material which returns to the crater interior. Fallback in the crater consists of fragments averaging about 1-1/2 feet in diameter, with the largest exposed boulder measuring approximately $15 \times 8 \times 8$ feet. There appears to be a greater concentration of boulders over 3 feet in diameter in the crater, due to the fragments rolling toward the crater bottom after their initial landing (see Fig. 10). If these 3-foot-plus fragments were distributed over the area contained within the surface plane of the apparent crater, their concentration would be approximately the same as in the thrown-out debris beyond the crater edge.

The fallback slopes exceed 37° as a result of the relative steepness of the outcrop walls and the extreme angularity and large size of the debris. These slopes are stable at the present time, and stability should tend to increase under the combined effects of gravity and weathering.

LIP AND THROWOUT MATERIAL

Debris on the crater lip accounts for a minor amount of the total lip height. The average lip height is 24 feet, with the lip debris being 2 to 10 feet deep. (See Fig. 11; also Figs. 6 and 7.) The average lip debris depth is 5 feet. The thrown-out material thickness increases to a maximum depth of approximately 30 feet at a distance of 20 to 30 feet from the rim of the crater and thins outward.

It is estimated that 60-90% of the thrown-out material is deposited within 50 feet of the crater rim. This figure depends upon the bulking factor of the debris. The bulk of the material ejected from the crater assumed a nearly vertical trajectory, allowing the material to return relatively close to the point of origin. Fragments of the concrete emplacement pad and large fragments of surface basalt with traces of the emplacement hole perimeter were found within a few feet of the crater rim.

Material blasted from the crater has an approximate average diameter of 1-1/2 feet. (A more precise figure must await the result of sizing tests.) A relatively high percentage of debris outside the crater is composed of boulders from 3 to 10 feet in diameter (5). There seems to be no apparent sizing or zoning of the debris as exposed in the trench cut in the southeast lip, although directly adjacent to the rim there appears to be a slightly higher

Fig. 10. View of crater side and bottom, showing concentration of larger boulders toward the bottom.

Fig. 11. Circumferential lip profile.

percentage of black vesicular fragments. This is true also in the two trenches dug for bulk measurement studies.

Although most of the throwout is deposited near the rim, many large boulders up to 4 feet in diameter were thrown to the outer edge of the debris.

The debris size fragmentation, in some respects, can be compared to joint frequency and spacing. The black vesicular fragments representing the highly jointed areas are much smaller and exhibit many weathered faces. The dense unjointed basalt fragments are extremely large and show few weathered faces. These blocks are up to 15 feet in diameter.

The dense basalt does exhibit planes of weakness discernible as hairline fractures through the blocks. It is evident that these fractures exercised some control over the block size.

The debris fell in an ellipsoidal pattern around the crater, with an elongate lobe extending approximately 550 feet northeasterly and 400 feet southwesterly of ground zero (see Fig. 4). An appreciable number of fragments were thrown about 300 feet to the northwest and the southeast.

The elongation of the throwout pattern can be related to areas of minor lip uplift. Extensive weathering plus reasonably strong joint systems with a general northwest-southeast alignment caused a general weakening of the rock mass and allowed an increased ejecta dispersal in the northeast-southwest directions.

Joint alignment and weathering along the joint surfaces did not materially affect the crater configuration but these factors did contribute to control of ejecta size and dispersal.

Accurate particle size distribution information is not available although some sampling stations were set around the expected crater perimeter. The area was graded prior to the explosion and a light snowfall immediately preceding the event did make for an accurate definition of the ejecta area.

Glass

Glass found around the crater falls into two general types: (1) a thin, light-green to dark-green glass spattered on a few basalt fragments, and (2) a light-green to dark-gray vesicular glass. The first type of glass may be up to 3/4 inch thick and assumes a "pahoe-hoe" or pillow structure. After the melt was formed, the glass was blasted out and upward, splattering and coating the basalt but retaining sufficient fluidity to allow the pillow structure to form prior to congealment (Fig. 12). This pillow glass is slightly vesicular although the openings are not as numerous or large as found in the second type of glass.

Fig. 12. Two principal glass types found around crater.

The second type of glass is light green to dark gray and extremely vesicular with a general density less than one. It occurs as fragments up to 4 inches thick and intimately mixed with small, partially melted basalt fragments. This glass resembles furnace coke in general appearance, being dull in comparison with the pillow glass which generally has a slightly vitreous lustre. The vesicular glass and basalt were admixed in flight; very little seems to have been spattered or deposited in appreciable amounts on basalt fragments found around the crater. No radiometric or physical property data are available concerning the Danny Boy glass types at this time.

The glass is generally low in gamma radiation, none over 8 mR/hour but with alpha readings as high as 100,000 cpm (6).

Deposition of Glass

The glass is unevenly distributed around the crater. Most of the fragments are concentrated near the crater rim and close to the debris surface, although minor amounts can be found 75-100 feet from the rim.

Inspection of the WES trench on the rim of the crater discloses that the glass is deposited on or near the surface. This seems to indicate that the glass was thrown out at the end of the explosion when extreme spallation of the cavity area occurred.

Very little glass is in evidence in the crater itself. Evidently the glass and glass-coated basalt assumed enough of a horizontal trajectory to escape the crater area, or the glass is generally buried below the surface debris in the crater. Radiation levels of the glass and general areas of deposition are extremely low, ranging from 5 to 10 mR/hour. The levels in the crater are slightly lower, approximately 5 mR/hour at contact. A general description of the crater radioactivity shortly after the explosion is given in ref. (3).

EXPLOSION GENESIS

High speed motion pictures taken by the Lawrence Radiation Laboratory-Nevada Photography Group can be used tentatively to diagram the detonation, bubble development, and crater parameters (Fig. 13).

After the initial shock wave passes the surface ground zero point (time approximately 0.0085 sec) the cavity bubble begins to express itself at the surface.

PHOTO 1

PHOTO 2

PHOTO 3

PHOTO 4

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Fig. 13. Composite photo-schematic illustrations showing sequence of crater formation.

Photo 1 shows the bubble beginning to expand toward the surface. At this point the volume of the uplifted dome at the surface is nearly equal that of the expanding bubble, or approximately 9000 cubic yards. The true crater radius is already established, in this early frame, at about 108-110 feet.

Photo 2 illustrates the basalt beginning to shatter and a rupture zone developing. At this point the bubble is still expanding straight upwards with spallation of the walls and cavity contributing to general uplift around the crater. It should be noted at this time that the bubble diameter approximates the upper surface of the blasted material. This indicates that as the bubble pushed its way to the surface it forced the basalt ahead of it as a shattered cylindrical block. Subsequent spallation opened the crater to its present size.

Photo 3 shows the debris maintaining a cylindrical shape with a few of the outermost fragments beginning to fall back. The debris at this time has an almost vertical trajectory with a very small horizontal component.

Maximum spallation should have occurred by the time this frame was taken. The true crater has formed and the rupture zone should have reached its maximum extent.

A 45° vector can be drawn from the workpoint to the outer limit of the true crater. This could be a usable technique in defining size of future craters with a comparable SDOB. Data from the Sedan investigation substantiates this proposal (7). Preliminary results of explosives research carried out in a sandbox model by J. W. Skrove and R. A. MacArthur, Lawrence Radiation Laboratory-Nevada Geology Group, indicate that this 45° supposition should be more fully investigated (8).

Photo 4 illustrates the slight amount of horizontal trajectory assumed by the debris. Maximum height is reached at 235 feet by the blast material. The cylindrical shape of the debris column indicates the general position of return. In this case, most of the fragments are falling within and close to the crater rim.

At no time during the explosion was any fire or fireball detected in the debris. In Photo 3 a small puff of white smoke can be seen at the base of the debris column. Postshot investigation of this area shows no evidence of this emission. However, any vent would be obliterated by rupturing action and subsequent fallback.

Some flipover or direct overturning of the crater lip may have occurred; however, examination of the walls of the trench discloses scanty evidence, if any, to support flipover occurrence.

Figure 14 is a composite photograph showing six stages in the Danny Boy explosion.

SPALLATION AND GAS ACCELERATION EFFECTS

Nordyke and Wray point out that spalling should be the dominant cratering mechanism in a hard, dry noncarbonaceous rock such as the Buckboard Mesa basalts (3).

Because of the lack of gas acceleration evidence, it is assumed from surface examination that spallation affected the crater at least as much as any other mechanism.

The extreme degree of lip uplift and the near-vertical trajectory assumed by the blast debris are definite spalling results. If gas acceleration was a significant factor in the explosion, there should be a much wider dispersal of the explosion debris, particularly melt products. As most of the glass is found near the crater rim, it is assumed that gas had little effect upon the glass dispersal.

As a smaller, less significant factor in the absence of gas effects, it was observed that no distinct cloud formed over the blast area and that no fire or fireball was seen (3).

The Nuclear Cratering Group (through their agency, WES) drilled a hole from the bottom of the crater through the fallback material and the underlying basalt into the pre-basalt alluvium.

Even though core recovery in this drill hole was low, the results indicate that the basalts underlying the cavity are fractured and dislocated to a far greater extent than had previously been considered.

Drilling could not determine a definite break between the fallback material and the underlying basalt. The high frequency of core loss indicates that the disturbed basalt may reach to a depth of 125 feet below the apparent crater bottom or 43 feet below the proposed cavity edge.

Because of drilling problems encountered in the WES drill hole in the crater bottom, the hole was not logged to a point where any information could be gathered. The hole will be completed and logged in the near future.

It is proposed here that the effects of spallation are nearly as great downward as outward, where uplift and fracturing were noted to exceed 300 feet from GZ.

N-6109

Fig. 14. Composite photograph showing six stages in the explosion.

POSTSHOT DRILLING AND EXCAVATION

A postshot drilling and coring program to recover cavity glass samples and delineate the true cavity edge was carried out under the direction of N. Short, Lawrence Radiation Laboratory-Livermore, in late 1962. As outlined in his report, Short was unable to rely upon core recovery and drilling information to accurately define the cavity edge (4).

Radiation logs of the postshot drill holes show a cavity radius of 33 to 34 feet. Short assigns the cavity a radius of 36 ± 2 feet.

Core recovered from the WES drill hole in the crater bottom is free of radiation except for a thin layer of glass on a fragment face found between 13 and 16 feet below the surface. This glass is a dark green-black with a vitreous, nonvesicular appearance. Five mR/hour gamma and 25,000 cpm alpha readings were taken on the glass (6).

Bulk Density Experiment

In order to estimate the debris characteristics of the basalt, a bulk density measurement experiment was conducted in the lip throwout debris and at the bottom of the apparent crater. The experiment was simple, consisting of digging two trenches in the lip debris and a pit at the crater bottom, weighing the debris, and surveying the excavations for volume of rock removed.

The first trench was dug on a line N $67^{\circ} 30'$ E from GZ; its volume was 105 cubic yards. Weight of the rock removed was 318,900 lb, giving a density of 3037 lb/cu yd and a bulking factor of 28%.

The second trench was dug on a line N $22^{\circ} 30'$ W from GZ, and its volume was 475 cu yd. The weight of rock removed was 1,777,250 lb, giving a density of 3700 lb/cu yd and a bulking factor of 16%.

The first trench was terminated due to an exceptionally large boulder measuring 10-15 ft at the exposure. The second trench was terminated when enough material had been removed to allow reasonably accurate calculation of the bulk density. The removed material is stockpiled awaiting a sizing experiment.

Aside from the boulder in the first trench, no exceptionally large fragments were encountered. The largest boulder removed weighed 20,000 lb. It was a dense gray basalt.

The average in situ density of the Buckboard Mesa basalts is taken as 4400 lb/cu yd. All calculations are based on this figure.

Radiation Level of the Debris

Monitoring of the debris was carried on as excavation progressed. None of the stockpiled material measures over 5 mR/hour. Most of the debris carried nothing over a background (1 mR/hour) count. Very little glass was discovered in the material. Single fragments of glass gave up to 5 mR/hour gamma and up to 7200 mrads/hour. These higher values were from a glass fragment (6).

CONCLUSIONS

It is pointed out that joint frequency and weathering in the Buckboard Mesa basalts have little control over the final crater configuration, but any crater variations that do occur can be attributed to these two geologic factors. Size and shape of particles thrown out, and the pattern formed, can be traced to such controlling factors as joint spacing and frequency.

In further cratering experiments similar to Danny Boy it can be assumed that most of the debris and radiation products will fall within 200 feet of the crater rim, with 60-90% within 50 feet of the lip.

Volume of removed and broken rock calculated for the explosive yield shows the device to be not nearly as efficient as the Scooter explosion, a 0.5-kt high explosive charge in alluvium.

RECOMMENDATIONS

Experience with the Danny Boy event leads to the following recommendations for improving collection and analysis of geologic data on future cratering events:

1. Extensive preshot drilling program to outline the crater area geology and stratigraphy.
2. Surface joint frequency studies conducted as thoroughly as possible.
3. Thorough mapping of the emplacement hole to accurately delineate the joint frequency and stratigraphic section at the ground zero point.
4. A system of surface marking such as oil, asphalt, or colored cement for accurate determination of the original ground surface in postshot crater investigations.

5. Extensive debris sampling stations set around and out from the expected crater perimeter. These could be excavated pits, large tarps, boxes, or other catchment devices.

6. To determine the extent of horizontal and vertical displacement of the medium surrounding the crater, a system of 5- to 10-foot lengths of pipe placed in the ground in radial lines from the ground zero point. These would resemble fence posts and could be located accurately in postshot investigations.

7. Extensive photographic coverage of the detonation, with particular attention given to timing.

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