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MISCELLANEOUS PAPER NO. I-754

**DANNY BOY EVENT**  
**PROJECT 1.6: MASS DISTRIBUTION**  
**MEASUREMENTS OF CRATER EJECTA**  
**AND DUST**

**POR 1815 (WT), APPENDIX B**  
**VOLUMETRIC EQUALITIES OF THE CRATER**

by

L. K. Davis  
A. D. Rooke, Jr.



December 1965

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**Defense Atomic Support Agency**

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**U. S. Army Engineer Waterways Experiment Station**  
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ABSTRACT

The results of various previously reported investigations of the Danny Boy event are utilized to compute and compare the volumes of ejected material and volumes attributable to other crater-formation mechanisms. Imbalance of the volumetric contributions is attributed primarily to the uncertainty of the ejecta density in the lip region. Approximately 65 percent of the rock material dissociated by the explosion was permanently ejected from the crater; less than 2 percent of the ejected material was deposited beyond 3 crater radii from ground zero. Comparisons are made with high-explosive and nuclear detonations in desert alluvium.

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#### PREFACE

The study reported herein was performed as a supplement to POR/WT-1815, "Project 1.6: Mass Distribution Measurements of Crater Ejecta and Dust," for the Danny Boy event of Operation Nougat. The project was under the direct supervision of Mr. J. N. Strange, Chief of the Engineering Research Branch, and under the overall supervision of Mr. G. L. Arbuthnot, Jr., Acting Chief of the Nuclear Weapons Effects Division, U. S. Army Engineer Waterways Experiment Station (WES). Messrs. L. K. Davis and A. D. Rooke, Jr., prepared both the project report (POR/WT-1815) and this appendix.

Analyses of the Danny Boy crater lip lithology and exploratory drilling operations through the true crater cavity were performed by personnel of the WES Soils Division.

During the preparation and publication of this appendix, Col. John R. Oswalt, Jr., CE, was Director of the WES and Mr. J. B. Tiffany was Technical Director.

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## DEFINITIONS

Apparent crater	The visible crater, bounded at the top by a plane representing original ground surface
Crater cavity	That portion of the crater which is initially contained and which is formed by vaporization and compression of earth material surrounding the explosion energy source. Its radius is designated $r_c$
Crater lip	The distinctly raised portion of the earth mass immediately surrounding the apparent crater
Depth of burst (DOB or Z) (also depth of burial)	Depth below original ground surface of the effective center of the explosion energy source where no severe ground slope is involved. When the slope cannot be ignored, the shortest distance from zero point to the ground surface is used
Ejecta (throwout)	Earth material permanently ejected from the crater as a result of the explosion
Fallback	Dissociated material between the true and apparent crater boundaries.
Ground zero (GZ)	The hypo- or epicenter of the explosion

True crater

The crater prior to fallback, bounded at the top by a plane representing original ground surface. It represents the surface of undissociated material. Its depth and radius are designated  $d_t$  and  $r_t$ , respectively

Upthrust

Permanent upward movement of original ground surface surrounding the true crater

Zero point (ZP)

The center of the detonation; the effective center of the explosion energy source

## APPENDIX B

### VOLUMETRIC EQUALITIES OF THE CRATER

#### CHAPTER B.1

##### INTRODUCTION

###### B.1.1 OBJECTIVE

The purpose of this appendix is to compare the relative significance of various cratering mechanisms (compression, plastic flowage, ejection, and vaporization) by studying the volumetric contributions of these mechanisms to the formation of the Danny Boy crater. Observations are based on information contained in POR/WT-1815 (Project 1.6, Event Danny Boy) and in reports of subsequent investigations by U. S. Army Engineer Waterways Experiment Station (WES) personnel and other researchers.

###### B.1.2 SUMMARY OF PREVIOUS INVESTIGATION

The Danny Boy event was detonated 5 March 1962 at the U. S. Atomic Energy Commission's Nevada Test Site (NTS). The device was buried at a depth of 110 feet in basalt and had a yield of 0.43 kt (Reference 1).

The Project 1.6 experimental layout consisted of an array of tarpaulins placed in a concentric circular pattern about ground zero (GZ). After the shot, when the residual radioactivity permitted, samples of ejecta (including dust) deposited on the tarpaulins were recovered, weighed, and analyzed for particle size. The nearest samples to GZ were recovered at a radial distance of 310 feet and the most remote at 880 feet. Mass distribution per unit area and size distribution were tabulated and shown graphically as functions of radial distance from GZ. The amount of deposition was found to decrease sharply with distance. Particle size

similarly decreased with distance from GZ, the percentage of fines increasing rapidly beyond the 310-foot collector ring. The results of similar experiments were summarized and compared with Danny Boy data by means of dimensionless plots.

### B.1.3 SCOPE OF PRESENT INVESTIGATION

Approximately one year after the completion of Project 1.6, WES personnel excavated a trench through the Danny Boy crater lip, with the centerline of the trench bearing South  $67^{\circ}30'$  West from GZ. The purpose of the trench was to expose the uplifted original ground surface near the crater edge, permitting an analysis of the composition of the ejecta in the lip. In addition, several slant holes were drilled into the true crater in order to delineate the radius of the cavity surrounding the zero point. The location of the cavity surface was determined by comparing core samples recovered from the holes, radiation levels along the hole lengths, and the presence of glass produced by the fusing of the basalt around the cavity walls (Reference 2).

The results of these investigations were utilized to compute the volumes of the lip ejecta, the lip upthrust, and the true crater, including the true crater cavity. These volumes were then compared with the volumes of the apparent crater and the ejecta as measured in Project 1.6.

## CHAPTER B.2

### RESULTS OF CRATER INVESTIGATIONS

#### B.2.1 CRATER LIP SURVEY

Figure B.2.1 shows the lithologic profiles of the north and south sides of the trench excavated through the crater lip. Figure B.2.2 is a circumferential profile of the interior slope of the crater lip and the upper portion of the apparent crater, showing the maximum lip height, the height of upthrust, and the upper limit of the fallback material. An average height of upthrust of 14.3 feet was determined from the circumferential profile, and the radial extent of the upthrust, 220 feet, shown in Figure B.2.1 was assumed to be representative of the entire circumference of the crater. From this information, an average profile of the uplifted ground surface was constructed on the average profile of the crater lip (ejecta surface) as shown in Figure B.2.3.

The average bulk density of the crater ejecta and fallback was estimated to be  $3,620 \text{ lb/yd}^3$ , based upon ejecta sampling reported in Reference 3. Based upon References 2 and 4, the in situ density of the basalt is taken to be  $4,250 \text{ lb/yd}^3$ .

#### B.2.2 CRATER DIMENSIONS

Figure B.2.4 is an average cross section of the Danny Boy crater. The lip dimensions were taken from Figure B.2.3, the radius of the cavity from the postshot drilling results, and the apparent and true crater dimensions and configurations from References 5 and 3, respectively.

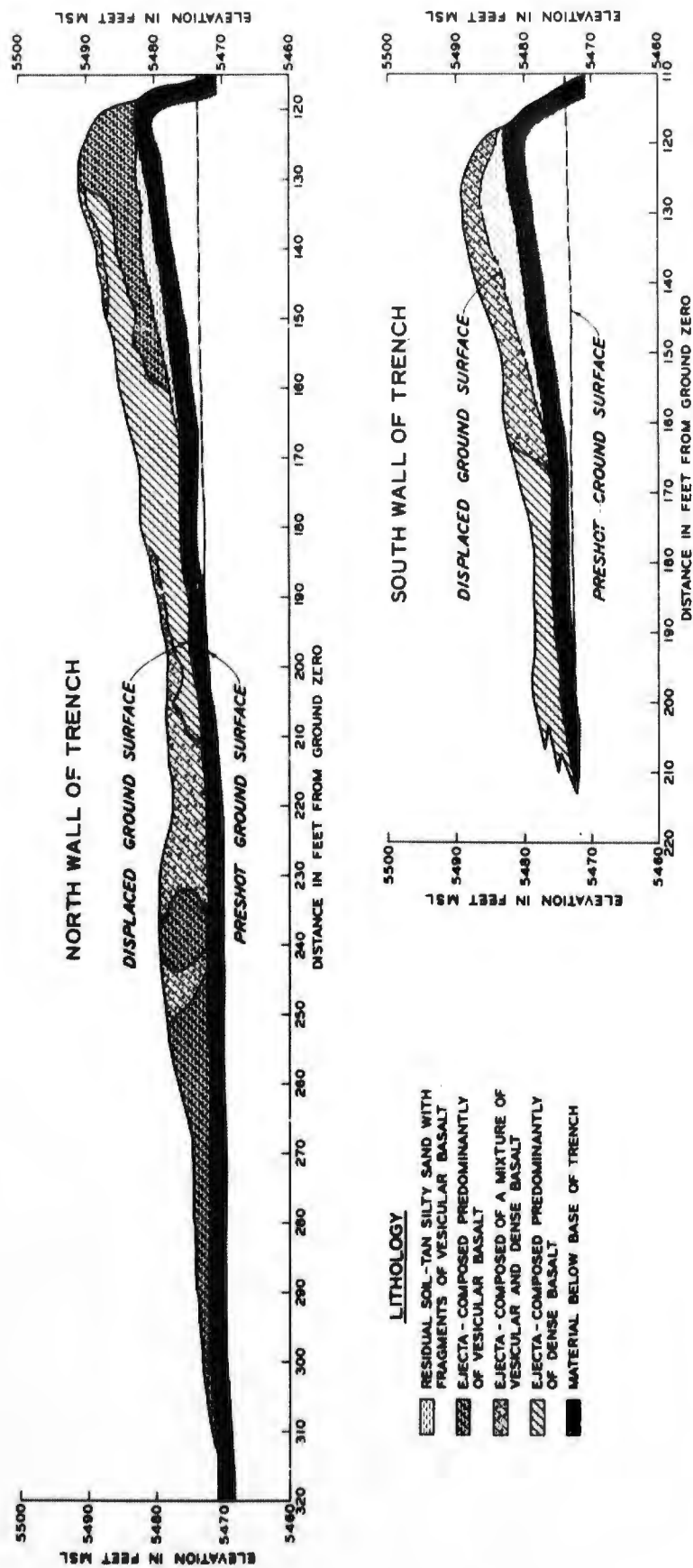


Figure B.2.1 Lithologic profiles of trench through Danny Boy crater lip (from unpublished study by Lt. R. C. Nugent, Soils Division, WES). Elevations are referred to mean sea level (MSL).

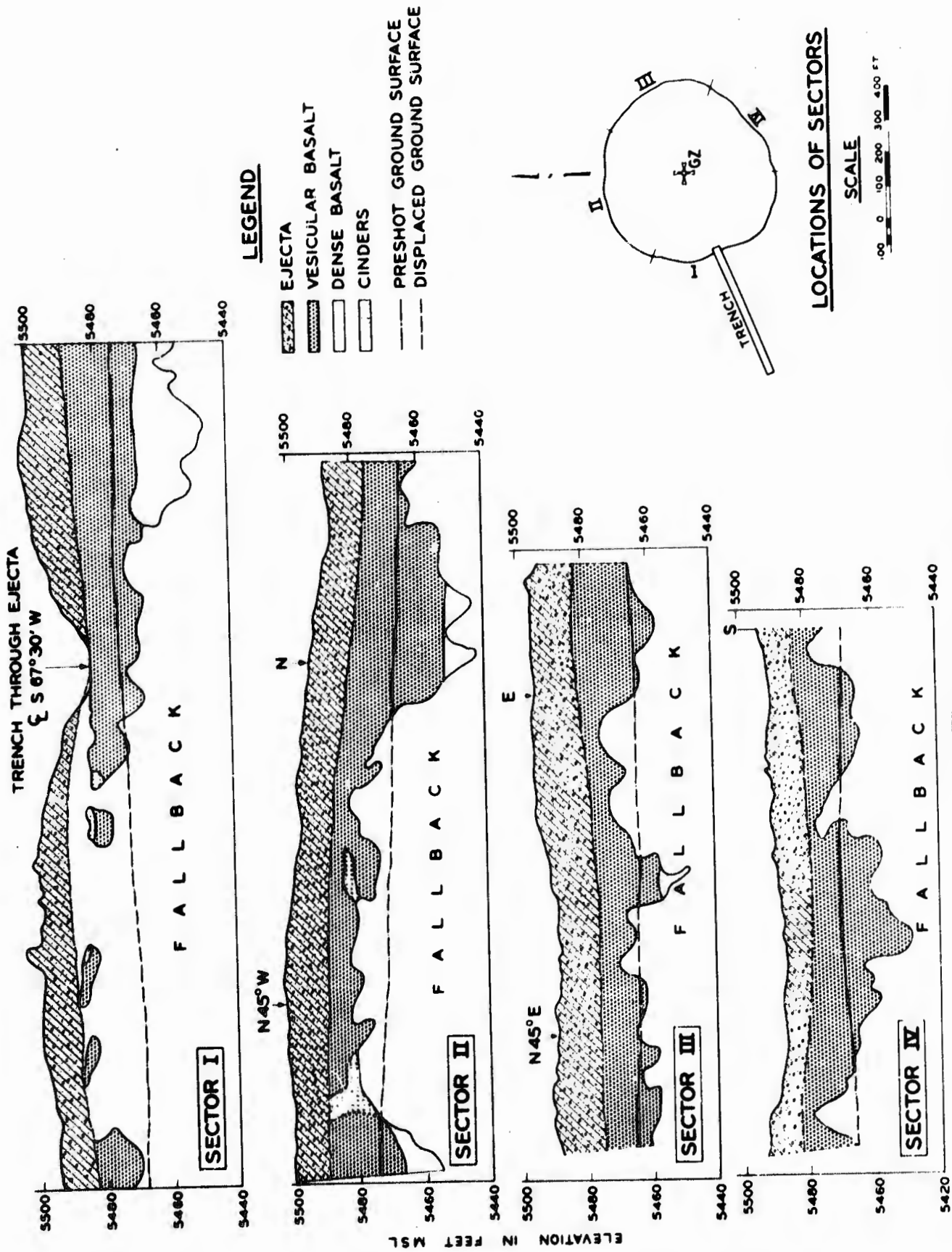


Figure B.2.2 Lithology of the Danny Boy crater interior slope (from unpublished study by Lt. R. C. Nugent, Soils Division, WES). Directions in true bearing angles are indicated by abbreviations in Sectors I-IV.

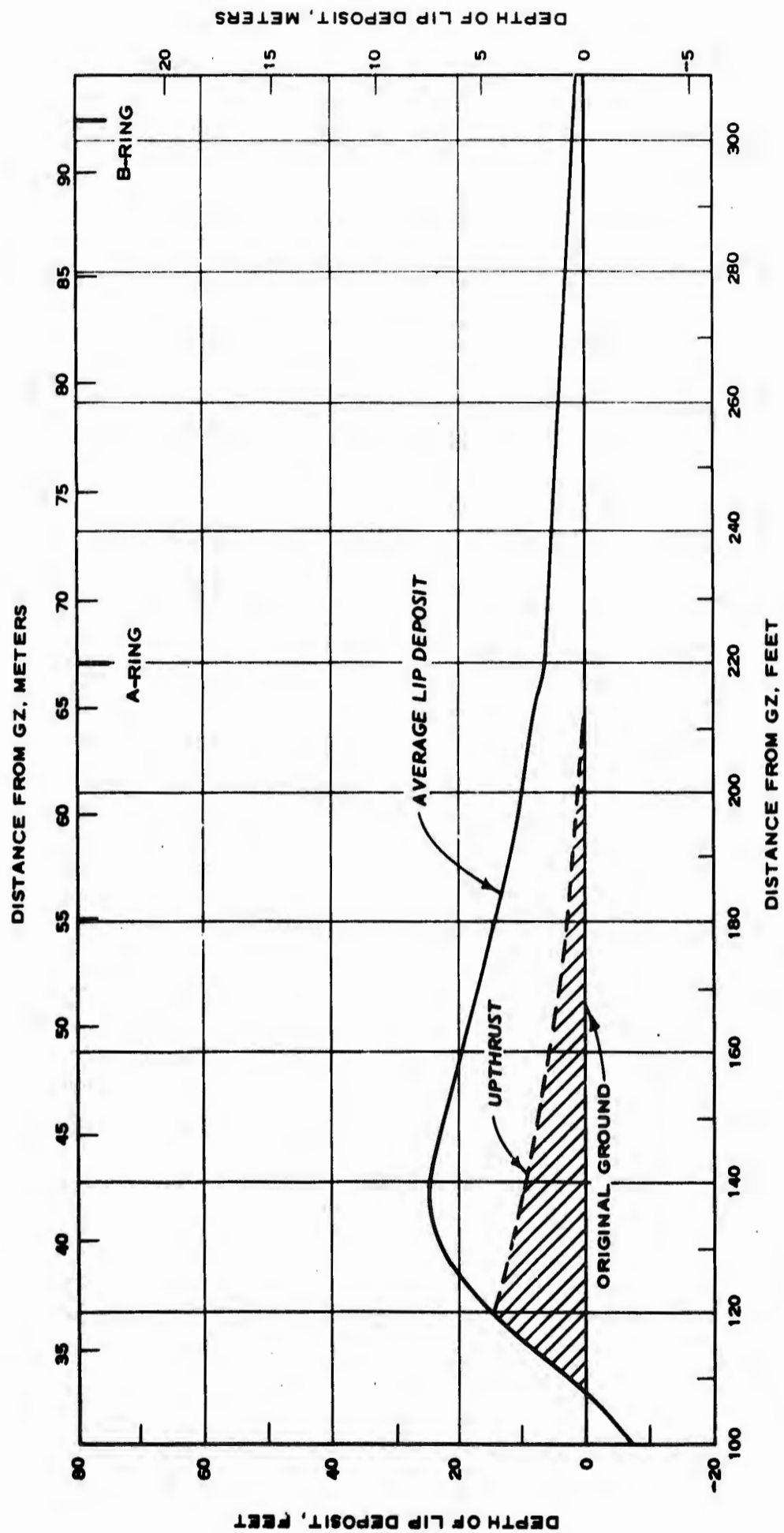


Figure B.2.3 Profiles of average ejecta and upthrust surfaces in crater lip. Upthrust taken from unpublished study by Lt. R. C. Nugent, Soils Division, WES.

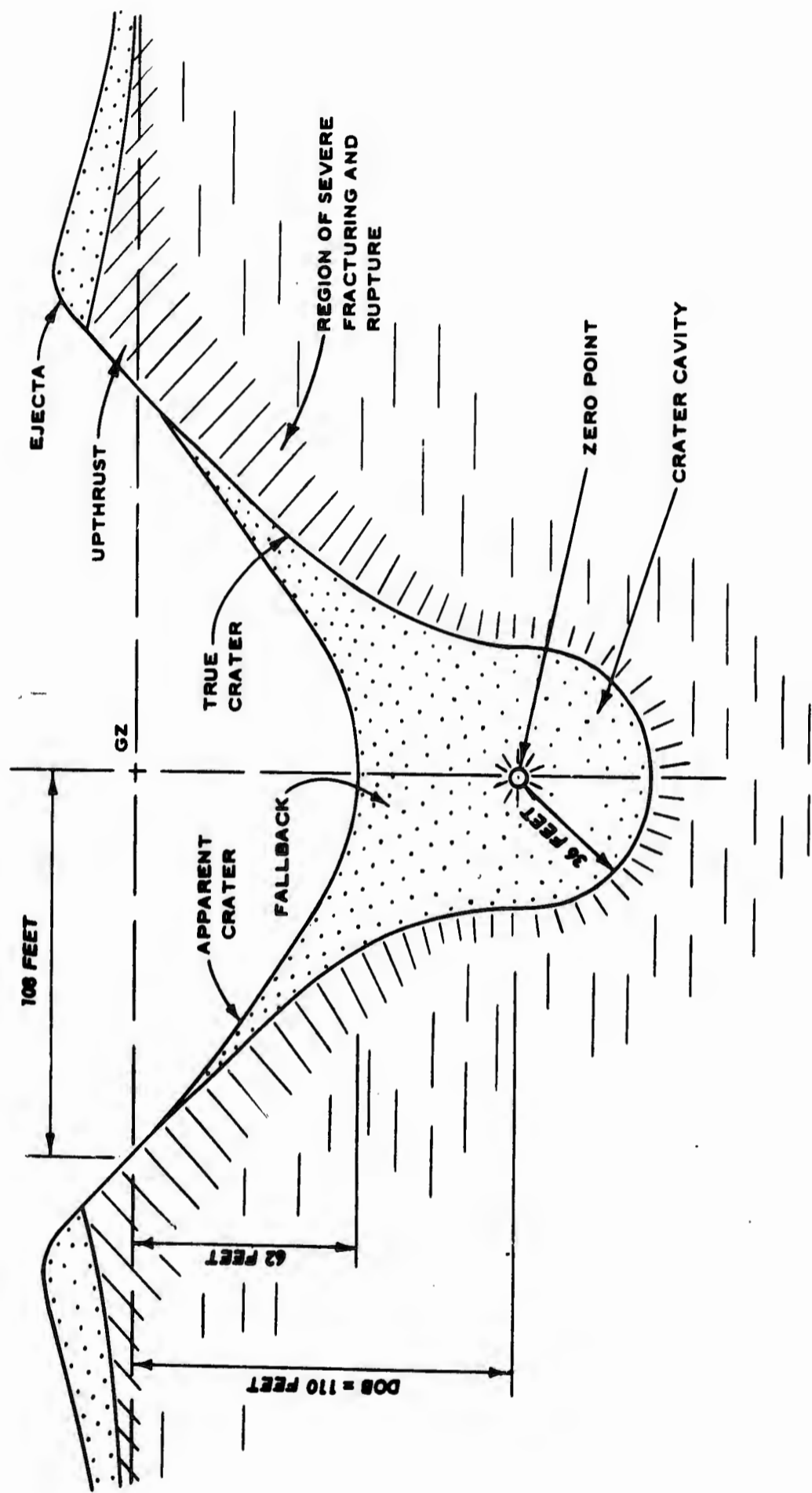


Figure B.2.4 Profile of Danny Boy crater, identifying crater regions and showing dimensions of apparent and true craters, depth of burst, and cavity radius.

## CHAPTER B.3

### DISCUSSION

#### B.3.1 VOLUMETRIC RELATIONS

A number of volumetric equalities for craters have been resolved from a near-surface cratering study by WES (Reference 6). For craters in soil, these relations are:

$$v_t = v_{dis} + v_c + v_f + v_v \quad (B.3.1)$$

$$v_{dis} = \frac{\rho_1}{\rho_0} (v_e + v_{fb}) \quad (B.3.2)$$

$$v_{fb} = v_t - v_a \quad (B.3.3)$$

$$v_l = k v_e + v_u \quad (B.3.4)$$

$$v_u = v_f \quad (B.3.5)$$

- Where:
- $v_t$  = volume of true crater
  - $v_{dis}$  = volume (preshot) of material dissociated by the explosion
  - $v_c$  = volume of crater due to compression (compaction)
  - $v_f$  = volume of crater due to plastic flowage of the medium
  - $v_v$  = volume of vaporized material
  - $\rho_0, \rho_1$  = preshot (in situ) and postshot densities of cratered material, respectively
  - $v_e$  = volume of ejecta
  - $v_{fb}$  = volume of fallback
  - $v_a$  = volume of apparent crater
  - $v_l$  = total volume of crater lip
  - $k$  = a constant representing the fraction of ejecta volume contributing to the formation of the crater lip
  - $v_u$  = volume of upthrust region

Equations B.3.1 through B.3.4 also apply to craters in rock. However, for practical considerations, rock is assumed to be incapable of flowing under a hydrodynamic stress unless the stress is sufficiently large to transform the material into a liquid state. Since the melting of rock in a nuclear detonation has been observed to be confined to a thin lining on the interior of the cavity, there is no significant contribution to the crater volume by this mechanism, and Equation B.3.5 does not apply to a rock medium.

### B.3.2 CAVITY FORMATION

The cavity radius ( $r_c$ ) of 36 feet determined from postshot drilling appears to be consistent with the results of previous underground nuclear detonations. The Neptune, Blanca, Logan, and Rainier events at NTS created cavities with scaled radii of  $50 \pm 3 \text{ ft/kt}^{1/3}$  (Reference 7). The scaled cavity radius for the Danny Boy event was  $48 \text{ ft/kt}^{1/3}$ . The scaled cavity radii of the Danny Boy, Neptune, and Blanca events, all of which vented (the last by a subsidence mechanism), were 47 or  $48 \text{ ft/kt}^{1/3}$ , while those of the contained shots, Logan and Rainier, were 50 and  $52 \text{ ft/kt}^{1/3}$ , respectively.

Cavity growth is related to gross upward movement of the overburden as well as to compression and vaporization of the medium surrounding the nuclear device. However, the lower part of the cavity appears to be formed almost entirely by compression and vaporization. Since this is the only volume of compression applicable to the final crater formation (the compacted medium surrounding the upper part of the cavity is dissociated upon venting),  $v_c$  can be readily estimated once  $v_v$  has been calculated. The

volume of vaporized rock for the Danny Boy crater is given in Reference 2 as about 12 cubic yards, an insignificant quantity in comparison with the uncertainties existing elsewhere in the volumetric computations. If it is assumed that half of the vaporized material came from the lower part of the cavity,

$$v_c = [(2/3)\pi r_c^3] - v_v/2 = 3,610 \text{ yd}^3 \text{ }^1 \quad (\text{B.3.6})$$

Any possible contribution by compression in the sides of the true crater above the cavity is ignored in this procedure.

### B.3.3 TRUE CRATER FORMATION

A general understanding of the probable mechanics of crater formation is necessary to an analysis of the crater volumes created. Figure B.3.1 is a graphical representation of the stages of formation of the Danny Boy crater.

Calculation of the true crater volume was accomplished by assuming that its shape above the zero point was that of a rectangular hyperboloid (Reference 3). Thus, confining the discussion for the moment to the upper portion of the true crater, the equation of the crater wall can be represented by

$$\frac{x^2}{r_c^2} - \frac{y^2}{r_c^2} \approx 1$$

where  $r_c$  represents the values of both the semitransverse and semiconjugate axes and  $x$  and  $y$  are horizontal and vertical coordinates,

---

<sup>1</sup>  $v$  indicates last significant figure.

respectively. The volume of the upper portion of the true crater can be determined by considering the entire crater from original ground surface to the depth of burst (DOB or Z) to be inclosed within a right circular cylinder of radius equal to the true crater radius ( $r_t$ ), and then subtracting the volume generated by rotation of the area under the true crater side (see Figure B.3.2a). Thus, with the volume of the lower portion of the cavity added, an equation for the true crater volume can be written as follows:

$$\begin{aligned}
 v_t &= \text{volume of cylinder} - \text{volume under hyperbola} + \text{volume of lower} \\
 &\quad \text{portion of cavity} \\
 &= \pi r_t^2 Z - \left[ 2\pi \int_{r_c}^{r_t} x(x^2 - r_c^2)^{1/2} dx \right] + (2/3) r_c^3 \quad (\text{B.3.7})
 \end{aligned}$$

This reduces to

$$v_t = 4.030 \times 10^6 - 2.205 \times 10^6 + 9.725 \times 10^4 = 1.922 \times 10^6 \text{ ft}^3$$

or 71,200 cubic yards. As will be noted in Figure B.3.2a, this procedure probably results in a somewhat lesser volume than that of the assumed hyperbola and hence in a  $v_t$  larger than the actual.

#### B.3.4 EJECTED MATERIAL

From Equation B.3.1, the volume of in situ rock dissociated by the explosion is

$$v_{\text{dis}} = v_t - (v_c + v_f + v_v)$$

The variables  $v_f$  and  $v_u$  are interchangeable in a soil medium but apparently unrelated in competent rock. Because of the physical properties of rock, it seems clear that  $v_f$  did not contribute to the Danny Boy crater formation. Since flowage did not occur, the upthrust was apparently the

result of spallation in general and bulking of the material immediately surrounding the crater rim. These effects were attributed to the action of the compressive shock wave and its reflection at ground surface and to gas expansion in the cavity. Any volume initially formed by compression in the upward direction is later negated by venting, so it is concluded, at least for practical purposes, that the energy expended to form the upthrust region actually made no contribution to crater size. It seems likely that the same mechanism may occur to some extent in a deep burst in soil.

Using the quantities previously developed,

$$v_{\text{dis}} = 71,200 - (3,610 + 0 + 12) = 67,578 \text{ yd}^3$$

Either the dissociated material was ejected completely from the crater to form the ejecta portion of the lip and the dust cloud, or it fell back into the true crater to form the apparent crater. From Equation B.3.2,

$$v_e + v_{\text{fb}} = \left( \frac{\rho_0}{\rho_1} \right) v_{\text{dis}}$$

The ratio  $\frac{\rho_0}{\rho_1}$  is approximately  $4,250 \text{ lb/yd}^3 + 3,620 \text{ lb/yd}^3$ , or 1.17.

Therefore,

$$v_e + v_{\text{fb}} = 1.17 (67,578 \text{ yd}^3) = 79,000 \text{ yd}^3$$

The volume of the apparent crater, as determined by planimetric measurement, was found to be 38,200 cubic yards. From Equation B.3.3,

$$v_{\text{fb}} = v_t - v_a = 71,200 - 38,200 = 33,000 \text{ yd}^3$$

Therefore,

$$v_e = 79,000 - 33,000 = 46,000 \text{ yd}^3$$

The compaction which initially occurs in the material above the cavity (prior to venting) is not taken into account in these equations. The comminution which accompanies venting probably negates most of the initial density change.

In the dust cloud formed by the explosion, particles which were essentially windborne were transported far from GZ. From a careful estimate of the mass of the Sedan dust cloud (a nuclear event near optimum depth in desert alluvium), it was concluded that in that event approximately 1 percent of the apparent crater mass was thus deposited beyond about 20 crater radii from GZ (Reference 8). Although the Danny Boy Project 1.6 layout extended much farther than this, the deposition from the cloud could not, at the greater distances, be distinguished by weight or volume from dust accumulations from other sources. Observation of the event, however, indicates that the scaled ejecta volume attributable to the dust cloud was much smaller than that of Sedan, which should be expected from a consideration of the differences in the cratered media. As a rough estimate, probably less than 0.5 percent of the apparent crater volume, or about 150 cubic yards of earth material, was in the Danny Boy cloud.

With the completion of the crater lip investigations, direct measurement of the ejecta volume is possible. Using the profiles of Figure B.2.3 and mathematically rotating geometric sections about the GZ axis, volumes of the lip and upthrust regions can be computed. Thus,  $v_l = 78,800$  cubic yards and  $v_u = 20,500$  cubic yards. The volume of ejecta in the lip equals  $v_l - v_u$ , or 58,300 cubic yards. To this must be added the volume of ejecta deposited beyond the lip but within the general crater area and that transported far away by the dust cloud. To find the former, a new

mass distribution equation was computed by the method of least squares, using only collector rings C, D, and E (440 to 880 feet from GZ). Ring B (310 feet from GZ) was excluded because the stations on this ring which were not recovered were actually under the outer edge of the lip, and the results of the old equation ( $\delta = 2.96 \times 10^{18} R^{-8.85}$ ) were thus biased. The new equation is

$$\delta = (1.42 \times 10^{19}) R^{-8.86} \quad (\text{B.3.8})$$

Where:  $\delta$  = mass distribution in kg/meter<sup>2</sup> <sup>2</sup>

R = radial distance from GZ in meters

The metric system is used here to permit direct comparison with the equation for rings B through E developed in the main report to which this is an appendix. Using Equation B.3.8 and integrating from the outer edge of the average crater lip to infinity,

$$E_w = 2\pi \int_{67 \text{ m}}^{\infty} \delta R \, dR \quad 3 \quad (\text{B.3.9})$$

where  $E_w$  equals total weight of ejecta deposited beyond crater lip but within general crater area. The concept of this integration and revolution is shown graphically in Figure B.3.2b. Substituting,

$$E_w = 2\pi \int_{67}^{\infty} (1.42 \times 10^{19} R^{-8.86}) R \, dR = 3.86 \times 10^6 \text{ kg} \quad 4$$

<sup>2</sup> Multiply kg/meter<sup>2</sup> by 0.205 to obtain lb/feet<sup>2</sup>.

<sup>3</sup> Multiply meters by 3.28 to obtain feet.

<sup>4</sup> Multiply kilograms by 2.205 to obtain pounds (weight).

or  $8.52 \times 10^6$  pounds. Using the postshot density given on page 3, this weight is found to represent a volume of 2,360 cubic yards. Thus, by direct measurement, the entire volume of ejected material -- lip, close-in deposit, and windborne -- is 61,000 cubic yards, to the greatest accuracy justified by the input data. A logarithmic plot of mass distribution versus radial distance from GZ for Danny Boy, revised to include data points computed for the crater lip, is contained in Figure B.3.3. The Sedan event, similar in geometry but much larger in yield and in a different medium, is included for comparison. Danny Boy crater volumes are recapitulated, to the greatest justifiable accuracy, in Table B.3.1.

The discrepancy between directly measured and inferred ejecta volumes (~15,000 cubic yards) represents the uncertainty of these measurements and/or inferences. The most likely sources of error are the true crater volume and the density factor,  $\rho_0/\rho_1$ . Subsurface exploration of the true crater has been necessarily limited, and a considerable uncertainty exists as to its size; also, the assumption of a hyperboloid configuration results in an error (Section B.3.3). While the density factor appears to be based upon a good sample (almost 1 percent of the total ejecta volume), its value is suspiciously low. Errors in either true crater volume or the density factor would tend to discredit the inferred method, so the volume of ejecta listed in Table B.3.1 is the direct measurement rounded off to the nearest 10,000 cubic yards. Division of the accumulated ejecta and fallback volumes by  $v_{dis}$  yields a density factor of approximately 1.38, which may more nearly represent the true density factor  $\rho_0/\rho_1$ .

### B.3.5 CORRELATION WITH PREVIOUS EXPERIMENTS

Using the foregoing computations, Figure B.3.2, and data from the main text of this report (POR/WT-1815) a plot of ejecta deposition versus distance from GZ has been prepared and is presented in Figure B.3.4. For comparison, an envelope of data for shots in desert alluvium (from Reference 9) has been included. The envelope includes shot geometries from near-surface to near-optimum DOR's. Figure B.3.5 (from Reference 6) is a plot of apparent crater volume versus total volume of ejecta for a similar range of shot geometries in alluvium, to which the Danny Boy data have been added. The upper and lower limits of these data were established by the direct and inferred ejecta measurements, respectively.

TABLE B.3.1 DIMENSIONS AND VOLUMES OF DANNY BOY CRATER REGIONS

Metric equivalents: 1 foot = 0.305 meters  
 1 cubic yard = 0.765 cubic meters

Crater Region	Depth or Height	Average Radial Extent from GZ Axis	Volume
	feet	feet	cubic yards
Apparent crater	62 <sup>a</sup>	108	38,000
True crater	146 <sup>a</sup>	108	71,000
Fallback	84 <sup>a</sup>	100	33,000
Lip (total)	25 <sup>b</sup>	310	79,000
Lip (ejecta)	11 <sup>b</sup>	310	58,000
Lip (upthrust)	14 <sup>b</sup>	220	21,000
Ejecta (total)	--	--	60,000
Crater cavity	36 <sup>c</sup>	36	3,600
Dissociated material	--	--	68,000
Melted material	--	8 <sup>d</sup>	75
Vaporized material	--	4 <sup>d</sup>	12

<sup>a</sup> Below GZ.

<sup>b</sup> Average maximum height above original ground surface.

<sup>c</sup> Below zero point.

<sup>d</sup> Ignoring device configuration (i.e. assuming true point source of energy).

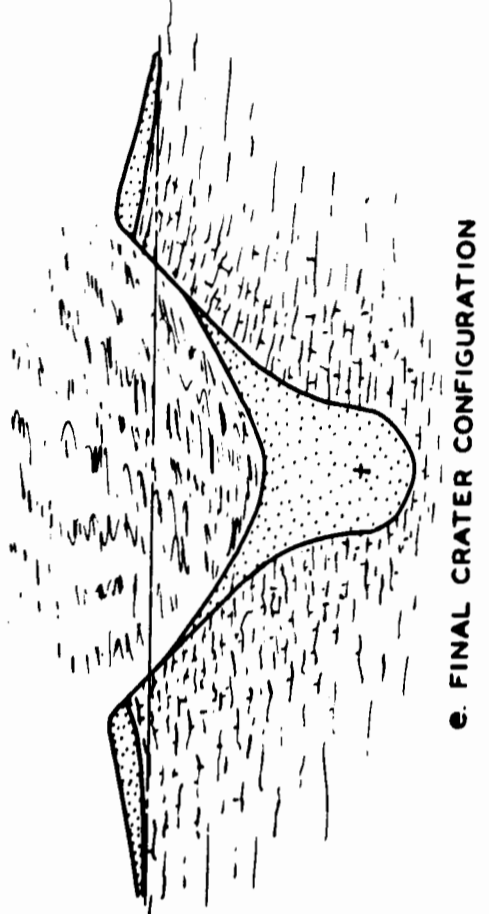
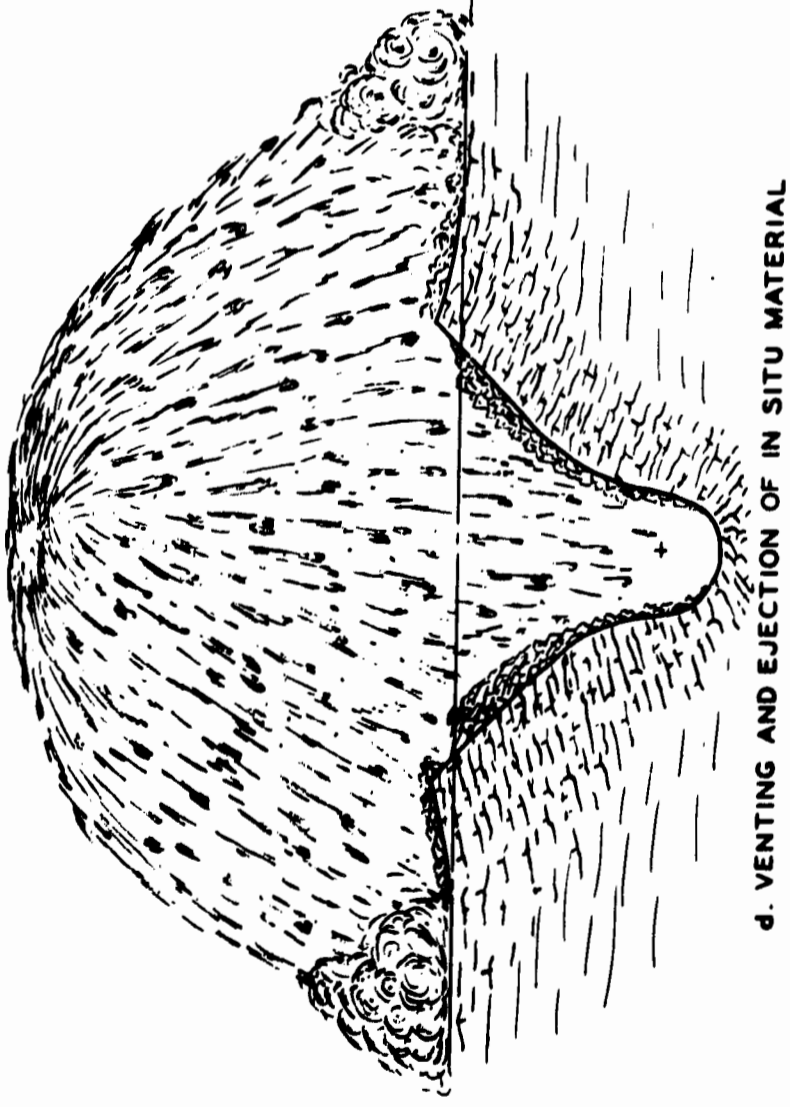
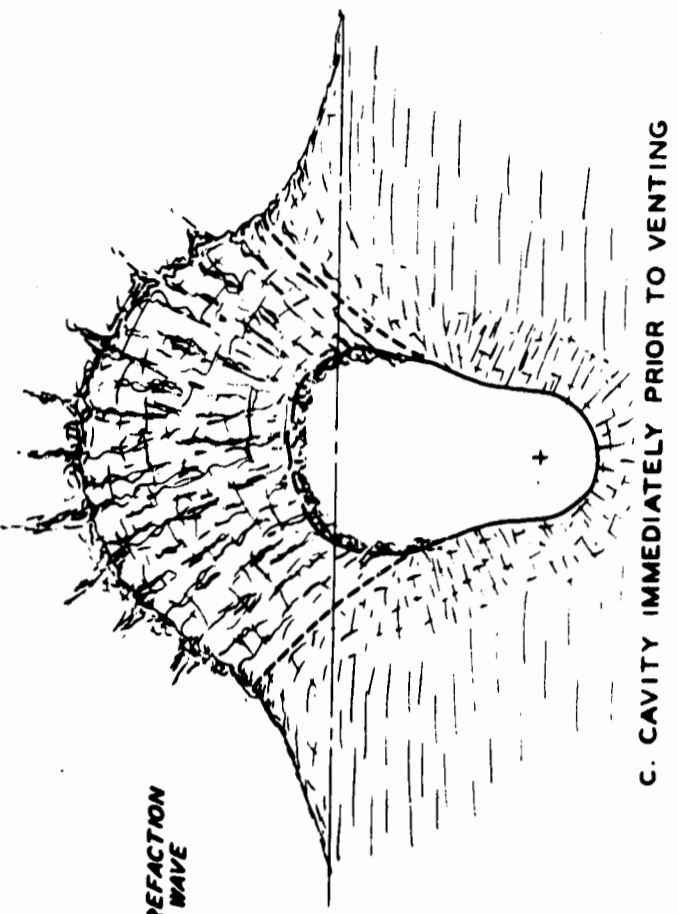
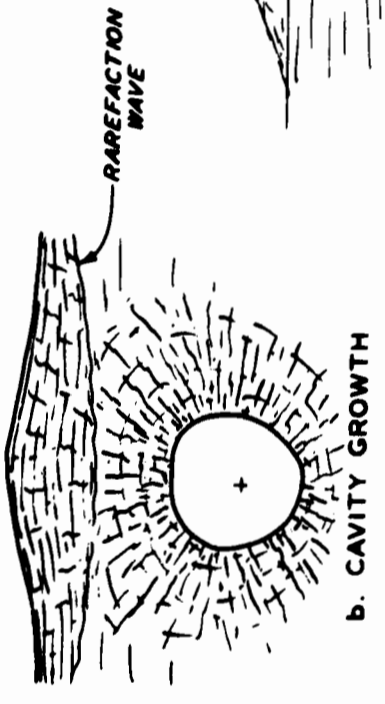
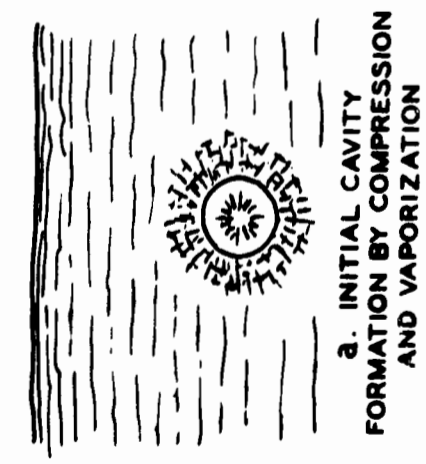
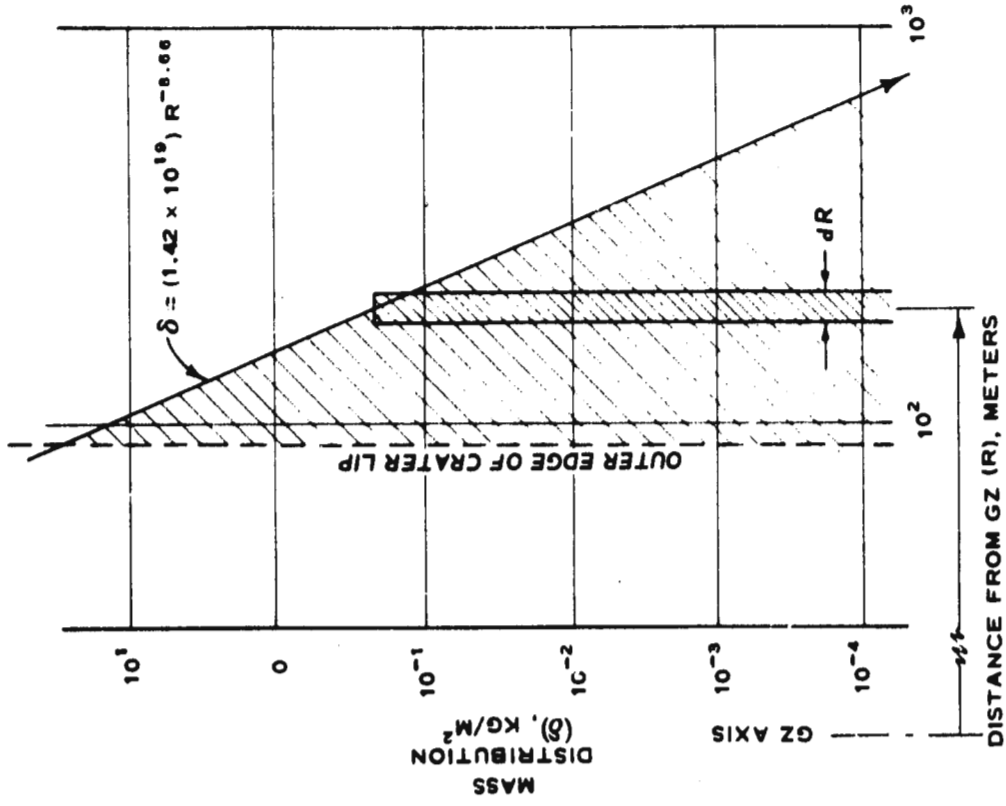
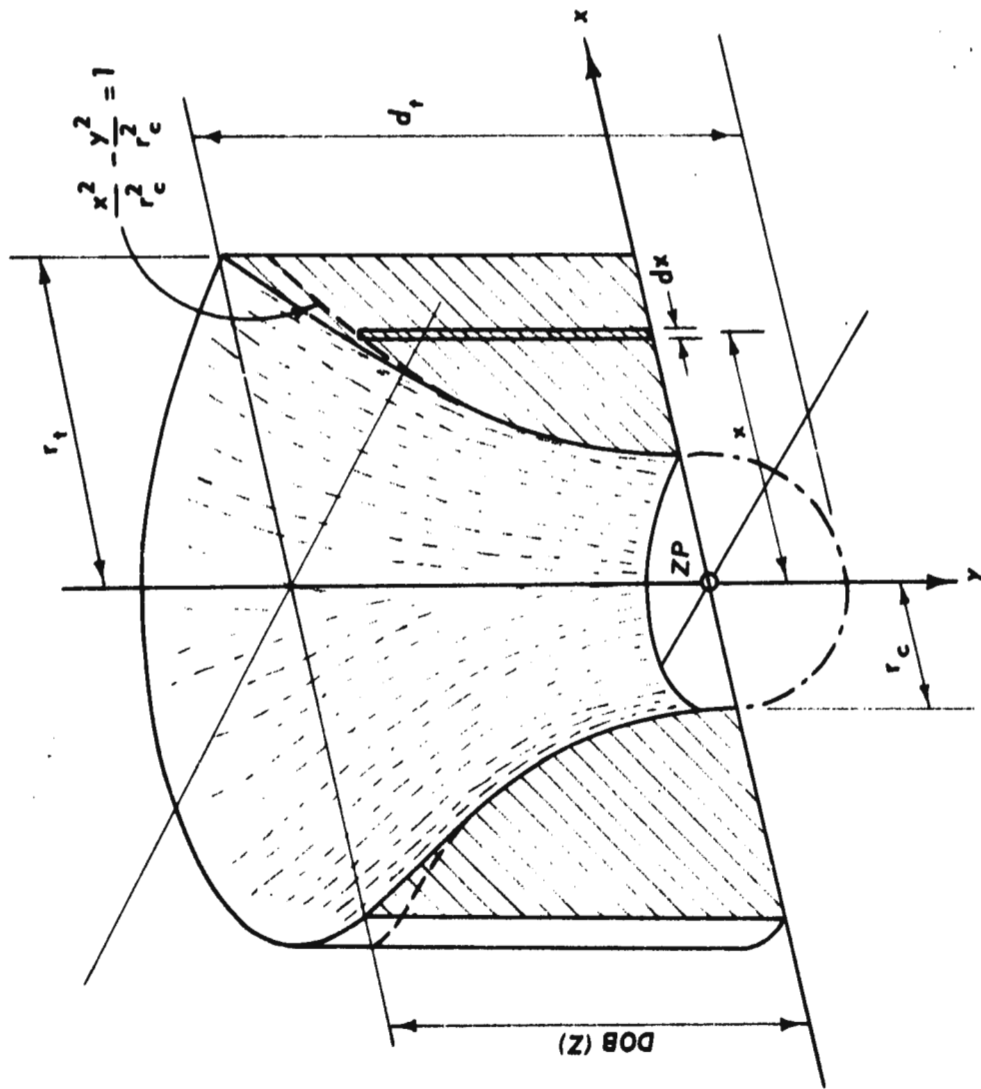


Figure B.3.1 Danny Boy crater formation.



- a. Concept of true crater volume determination. Dashed line illustrates true hyperboloid, solid line the actual crater shape.
- b. Concept of ejecta volume determination.

Figure B.3.2 Schematics illustrating methods of volumetric computations.

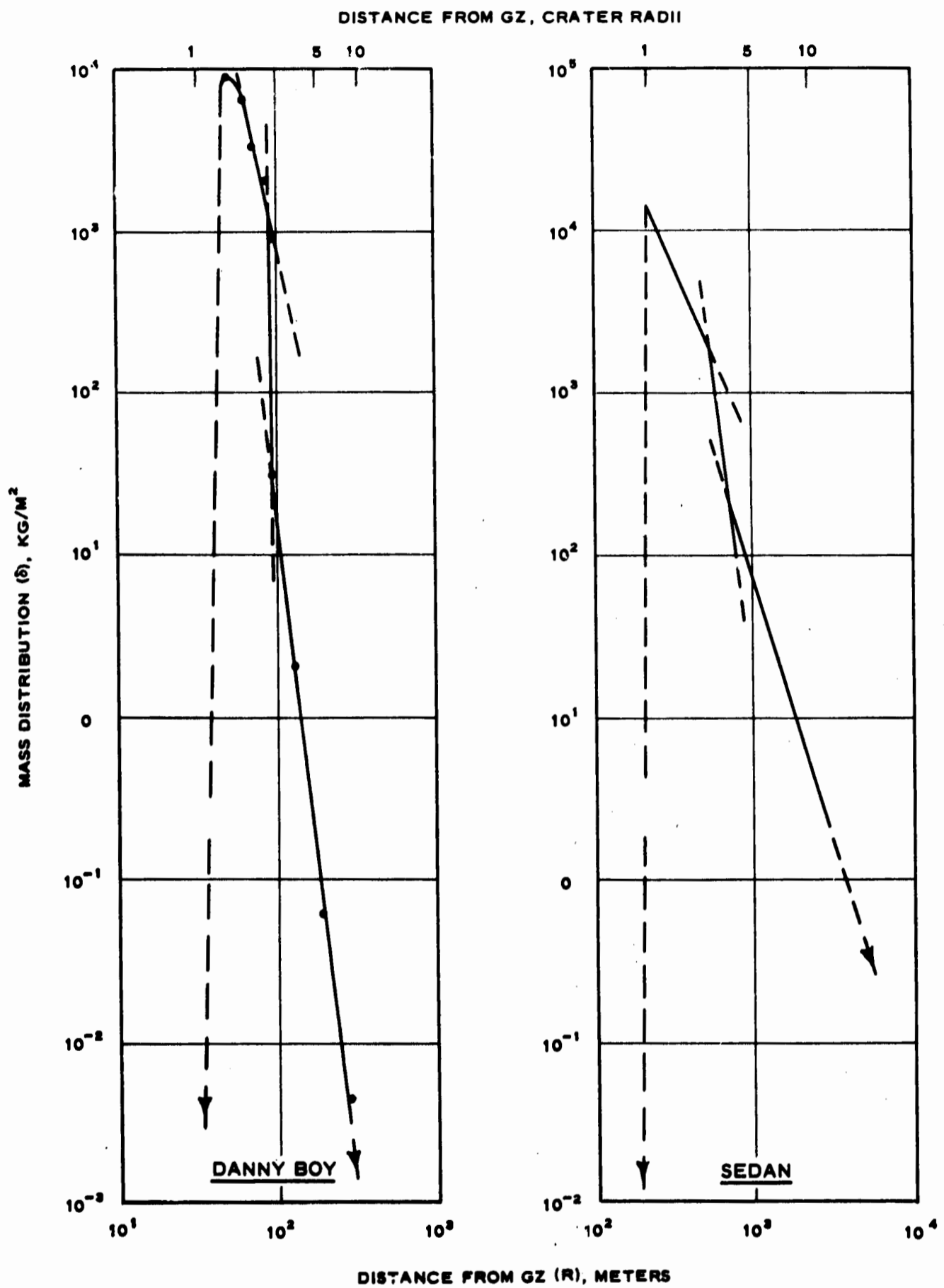


Figure B.3.3 Average mass distribution of ejecta versus radial distance from GZ, including lip ejecta, for Danny Boy. Plot for the Sedan event is included for comparison (Reference 8).

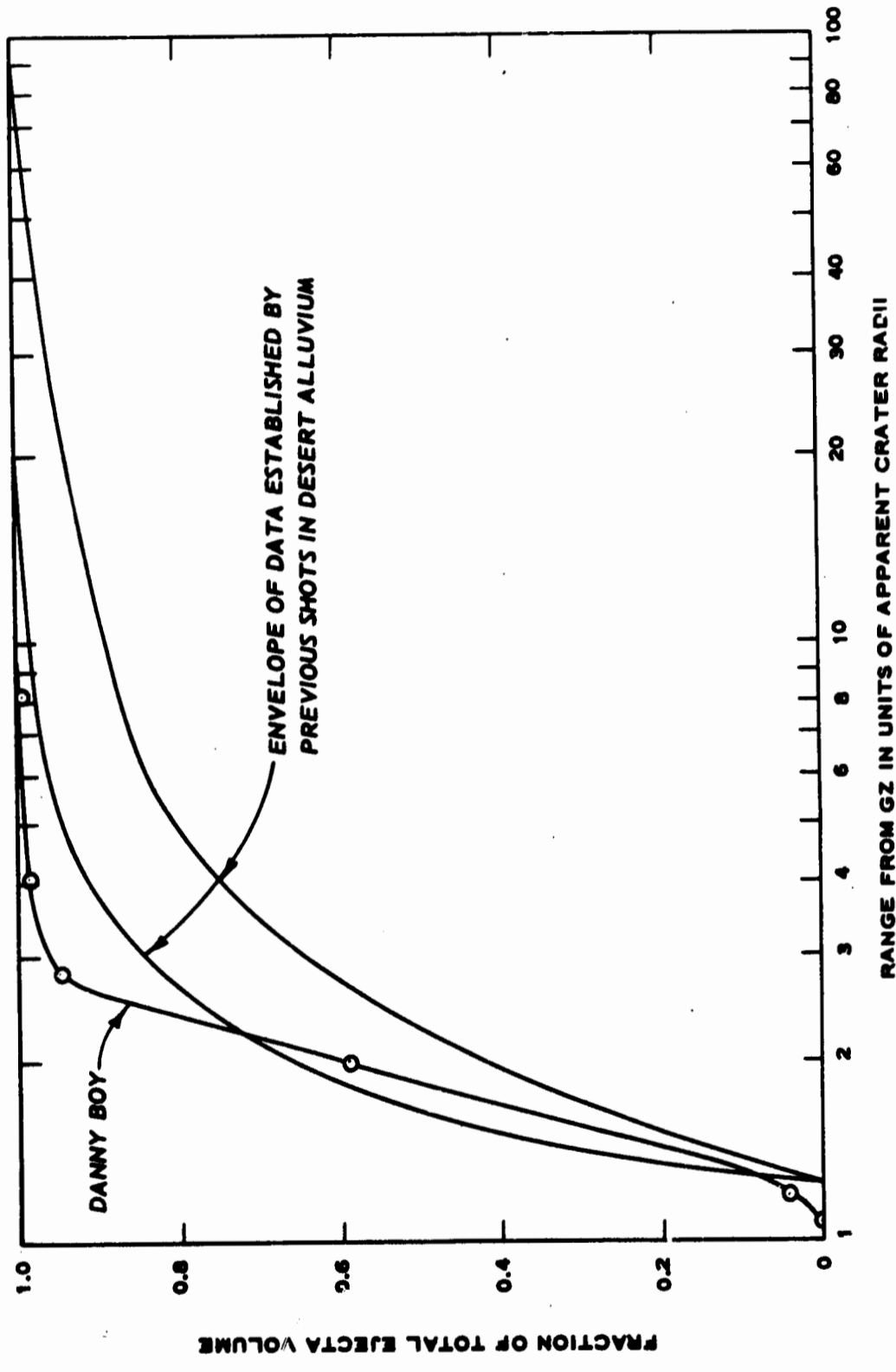


Figure B.3.4 Fraction of total ejecta volume as a function of range from GZ. Envelope is from Reference 9.

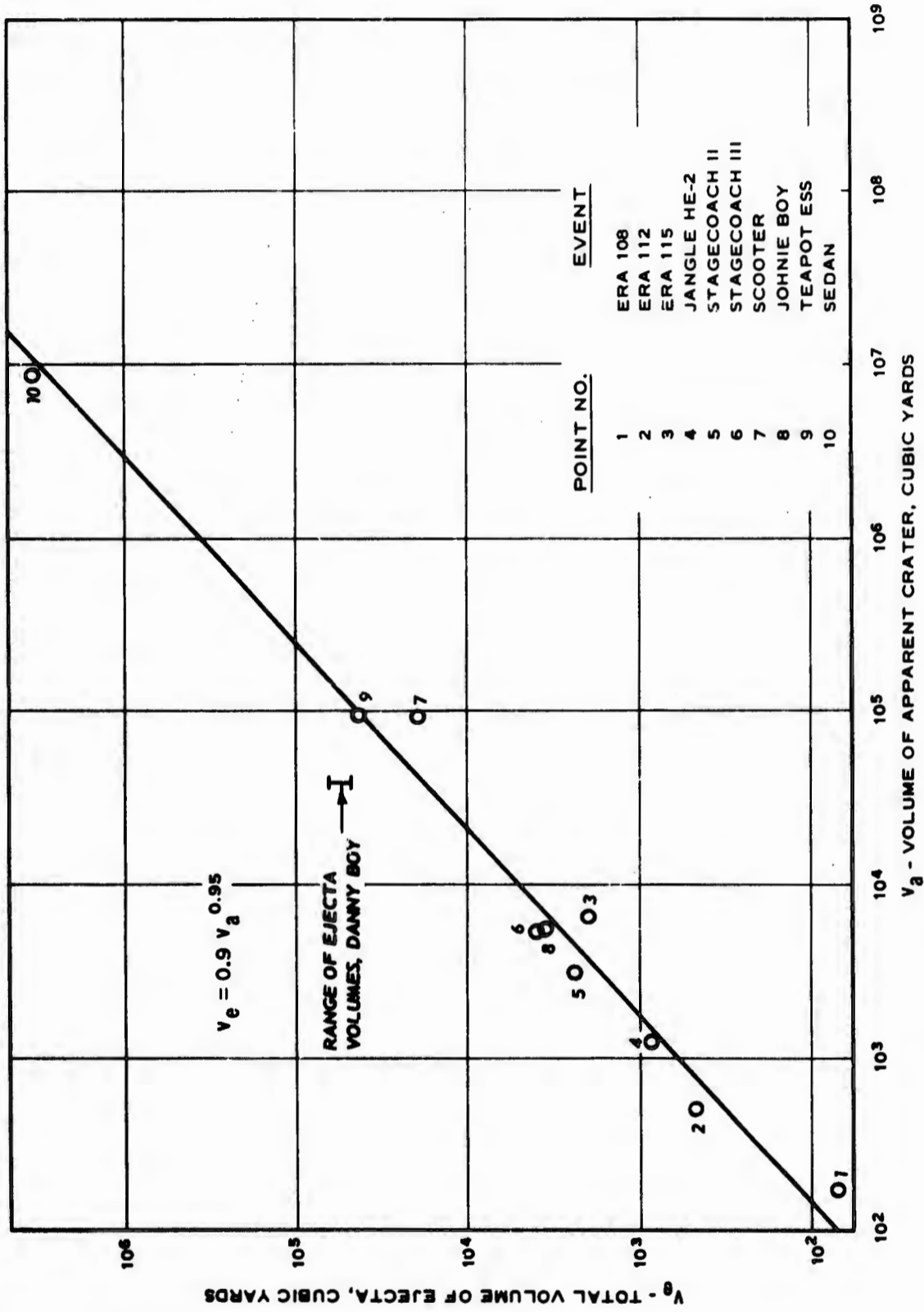


Figure B.3.5 Range of Danny Boy ejecta volumes compared with shots in desert alluvium (from Reference 6). ERA refers to Engineering Research Associates, Inc.

## CHAPTER B.4

### CONCLUSIONS AND RECOMMENDATIONS

#### B.4.1 CONCLUSIONS

A large difference is observed between direct and inferred measurements of ejected material for the Danny Boy crater. An examination of the various crater volumes reveals that:

1. The apparent crater volume amounts to slightly more than half of the true crater volume.
2. Approximately 65 percent of the material dissociated by the explosion, representing a volume about 1.6 times that of the apparent crater, was permanently ejected from the crater; the remainder fell back within the confines of the true crater. Thus, a significantly larger percentage of ejecta was realized on this event than in similar shots in dry soil.
3. Ejecta accounted for almost three-fourths of the crater lip volume; upthrust of the original ground surface was responsible for the remainder.
4. More than 98 percent of the ejected material fell within 3 crater radii of GZ to form the lip. Distribution of ejecta was generally much closer to GZ than for shots in dry soil.

#### B.4.2 RECOMMENDATIONS

For future cratering experiments, it is recommended that preshot plans and preparations include an experimental array and measurement techniques that will facilitate quantitative analysis of the crater formation in terms of the contributions provided by each cratering mechanism.

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