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CRATER SURVEY

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March–May 1954

Headquarters Field Command
Armed Forces Special Weapons Project
Sandia Base, Albuquerque, NM

June 1955

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cratering
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Photographic observation and fathometer measurements of CASTLE Shots 1, 3, and 4 were made to assist in the prediction of craters produced by megaton weapons. The Shot 1 crater could have been predicted satisfactorily from the IVY Mike Shot. Shot 3 crater was smaller than predicted on that basis. Both craters were larger than predictions based on simple scaling of the JANGLE surface shot, even if some allowance is made for the difference in soils.

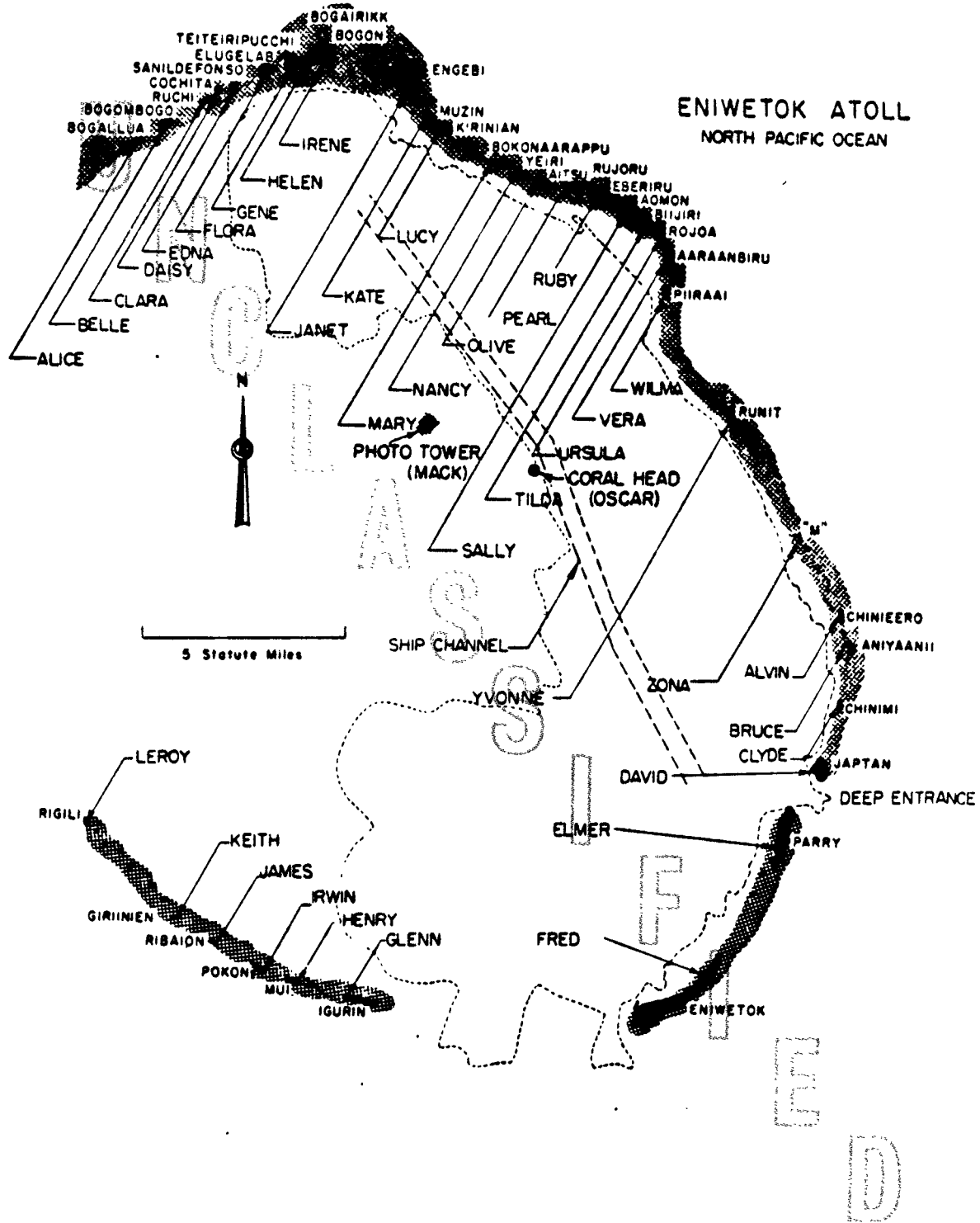DD FORM 1 JAN 73 1473   EDITION OF 1 NOV 65 IS OBSOLETE

FOREWORD

This report has had classified material removed in order to make the information available on an unclassified, open publication basis, to any interested parties. This effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

The material which has been deleted is all currently classified as Restricted Data or Formerly Restricted Data under the provision of the Atomic Energy Act of 1954, (as amended) or is National Security Information.
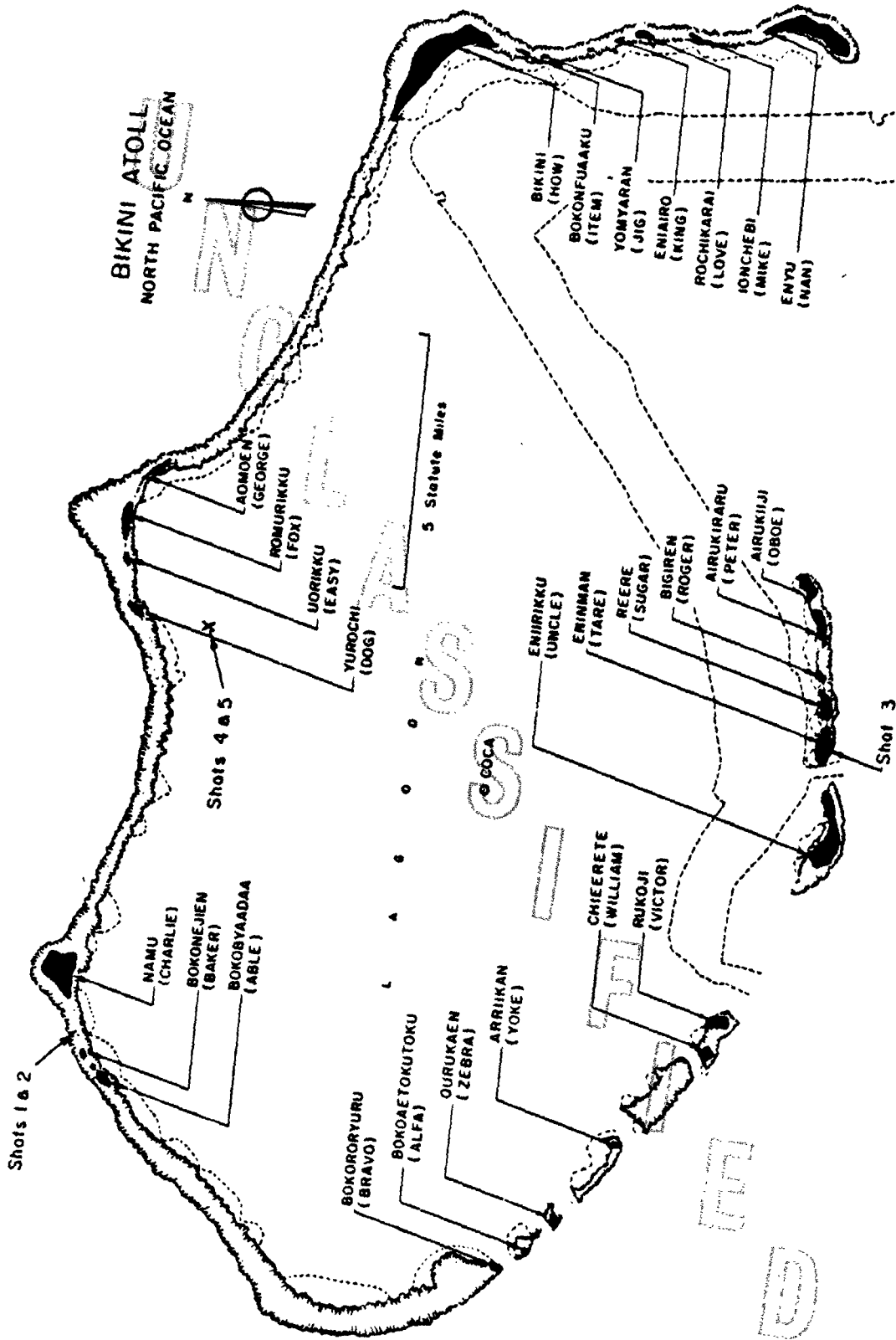
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It is the belief of the individuals who have participated in preparing this report by deleting the classified material and of the Defense Nuclear Agency that the report accurately portrays the contents of the original and that the deleted material is of little or no significance to studies into the amounts or types of radiation received by any individuals during the atmospheric nuclear test program.

I

ENIWETOK ATOLL
NORTH PACIFIC OCEAN

5 Statute Miles

BIKINI ATOLL
NORTH PACIFIC OCEAN

BIKINI (HOW)
BOKONFUAAKU (ITEM)
YOMYARAN (JIG)
ENIAIRO (KING)
ROCHIKARAI (LOVE)
IONCHEBI (MIKE)
ENYU (NAN)

5 Statute Miles

AIRUKIRARU (PETER)
AIRUKIIIJI (OBOE)

LAOMOEN (GEORGE)
ROMURIKKU (FOX)
UORIKKU (EASY)
YUROCHI (DOG)

ENIIRIKKU (UNCLE)
ERINMAN (TARE)
REERE (SUGAR)
BIGIREN (ROGER)

Shot 3

Shots 4 & 5

CHIEERETE (WILLIAM)
RUKOJI (VICTOR)

NAMU (CHARLIE)
BOKONEJIEN (BAKER)
BOKOBYAADAA (ABLE)

ARRIIKAN (YOKE)

OURUKAEN (ZEBRA)

Shots 1 & 2

BOKOAETOKUTOKU (ALFA)

BOKORORYURU (BRAVO)

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GENERAL SHOT INFORMATION

	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
DATE	1 March	27 March	7 April	26 April	5 May	14 May
CODE NAME (Unclassified)	Bravo	Romeo	Koon	Union	Yankee	Nectar
TIME*	06:40	06:25	06:15	06:05	06:05	06:15
LOCATION	Bikini, West of Charlie (Namu) on Reef	Bikini, Shot 1 Crater	Bikini, Tare (Eninman)	Bikini, on Barge at Intersection of Arcs with Radii of 6900' from Dog (Yurochi) and 3 Statute Miles from Fox (Aomoen).	Eniwetok, IVY Mike Crater, Flora (Elugelab)
TYPE	Land	Barge	Land	Barge	Barge	Barge
HOLMES & NARVER COORDINATES	N 170,617.17 E 76,163.98	N 170,635.05 E 75,950.46	N 100,154.50 E 109,799.00	N 161,698.83 E 116,800.27	N 161,424.43 E 116,688.15	N 147,750.00 E 67,790.00

* APPROXIMATE

ABSTRACT

Photographic observation and fathometer measurements of CASTLE Shots 1, 3, and 4 were made to assist in the prediction of craters produced by megaton weapons.

The more important numerical data are as follows:

Shot	Yield	Location	Crater Radius (ft)	Estimated Max.Depth (ft)
1	14.5 MT	Surface-reef	3000	240
3	110 KT	Surface-island	400	75
4	6.5 MT	Surface-water (160 ft water depth)	1500	250

The Shot 1 crater could have been predicted satisfactorily from the IVY Mike Shot. Shot 3 crater was smaller than predicted on that basis. Both craters were larger than predictions based on simple scaling of the JANGLE surface shot, even if some allowance is made for the difference in soils.

The Shot 4 crater, produced by a shot on the surface of water having a scaled depth λ_w = 0.05, was detectable but relatively small. A tunnel underneath it would probably have been breached but no hazard to navigation was produced.

An extrapolation procedure based on smaller TNT explosions permits the prediction of the radius of the crater produced by a nuclear explosion under a wide range of circumstances. The range of uncertainty is believed to be larger than a factor of two.

FOREWORD

This report is one of the reports presenting the results of the 34 projects participating in the Military Effects Tests Program of Operation CASTLE, which included six test detonations. For readers interested in other pertinent test information, reference is made to WT-934, Summary of Weapons Effects Tests, Military Effects Program. This summary report includes the following information of possible general interest.

a. An over-all description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the six shots.

b. Discussion of all project results.

c. A summary of each project, including objectives and results.

d. A complete listing of all reports covering the Military Effects Tests Program.

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ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The immediate objective of the crater survey, was to determine the dimensions of the apparent craters formed by Shots 1, 3, and 4.

The long-range objectives of the work were to obtain data to assist in the prediction, for military purposes, of the crater produced by any large nuclear weapon fired under any circumstances. Two situations were of particular interest in this regard in Operation CASTLE. These were (a) a surface burst on land, and (b) a surface burst in relatively shallow water.

1.2 MILITARY SIGNIFICANCE

The major military interest in craters stems from the observation that the limiting distance of important damage to well constructed underground fortifications lies only a relatively short distance outside the crater. For the prediction of such damage it is clear that the shape of the crater near the rim is more important than its shape, or depth, near the center.

Of somewhat less military interest is the crater produced by a surface shot in shallow water. Both the limiting distance of damage to tunnels and the possibility of damming a harbor by the formation of a crater with a shallow, or above-water lip, are matters of some concern.

1.3 LIMITATIONS ON THE OBJECTIVES

In the investigation of craters formed by smaller explosions it has been recognized that while the crater surface apparent to the eye was relatively easy to measure, there was nevertheless a disturbance in the earth, caused by the explosion, to some depth below this upper surface. The lower boundary of this volume of disturbed earth has become known as the "true crater" in contradistinction to the upper surface, which has been called the "apparent crater." While the term "true crater" may be slightly misleading in its implications, it seems reasonably clear that for the purposes of determining the limitations of damage to underground fortifications the lower surface of the volume of disturbed earth

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(or true crater) is of greater significance than the apparent crater.

While for small craters it is physically and economically feasible to determine the boundaries of both the "apparent" and the "true craters," for very large craters, the problem of excavation to determine the true crater becomes so extensive as to be impractical. The difficulty of measuring the true crater becomes even more severe under circumstances where the crater is water-filled and where the level of radioactivity remains for some time high enough to prohibit extensive work. Both of these situations existed in CASTLE. Because of these difficulties and other considerations it was decided to limit the crater surveys on CAS-TLE to the measurement of the apparent craters formed by those detonations located at zero sites not used for prior detonations. Because of changes in shot locations during the operation, the project effort was limited to Shots 1, 3, and 4.

1.4 BACKGROUND

At an early stage in the planning two techniques were seriously considered in addition to those actually used. These were, first, the use of a high-power fathometer developed by the Navy Electronics Laboratory (NEL) which was considered to have a reasonable probability of penetration of the layer of mud or disturbed earth separating the apparent from the true crater. The second technique was designed to supplement the penetrating fathometer as a means of determining the true crater. This technique involved the production of holes through the crater either by drilling or jetting techniques. Several methods of detecting the surface separating the true crater from undisturbed earth were considered. The decision not to use either of these procedures was made on the bases, (1) that the drilling or jetting would add a large cost to the project, (2) that a penetrating fathometer would not be reliable without the supplementary information gained by the drilling or jetting, and finally, (3) that information regarding the apparent crater would be very nearly as valuable for purposes of prediction of target damage as would measurements of the true crater.

1.5 THEORY

The laws of similitude imply that the effects of an explosion of any (known) size in any medium are related precisely to the effects of an explosion of any other size in the same medium, provided the medium fulfills certain rather stringent conditions. Experimental measurements using conventional explosives such as TNT lead to some optimism that craters produced by such explosives can be predicted with an accuracy almost entirely adequate for military purposes, even though it is clear that some properties of the medium (earth) in which the explosive is fired are very sensitive parameters in affecting the crater.

The situation regarding craters produced by nuclear explosives is less satisfactory. First, the evidence is meager, since, prior to CAS-TLE there have been only three such explosions on which crater measurements were made; namely, IVY Mike, JANGLE underground, and JANGLE surface. Second, the existing evidence leads to pessimism regarding the validity of scaling from conventional to nuclear explosion effects.

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The failure of crater scaling from conventional to nuclear explosions is believed to result both from the enormous disparity in energy release (and this also applies between kiloton and megaton nuclear explosions) and also from the important difference in energy partition in the two types of explosions.

In general it is known that the dimensions of the crater (radius or depth) are affected or determined by the total energy release, the depth of the charge and the character of the medium (earth) in which the charge is fired. If these parameters operate independently, then one could write an empirical equation in the form

$$R = f(W) \cdot f(D_c) \cdot f(m)$$

or in the form

$$R = f(W) + f(D_c) + f(m)$$

where R is the radius
W is related to energy release, energy density, and detonation velocity
D_c is the depth of the charge
m is related to the medium.

In this case the separate contribution of each of the parameters can be determined easily. If, however, the parameters are interdependent it is necessary to use the form

$$R = f(W, D_c, m)$$

and the effect of varying any one of the parameters is much more complicated because it depends on the values at which the other parameters are maintained.

There is general agreement among investigators that the parameters affecting craters are in fact extensively interrelated. The universal use of scaling concepts, particularly in regard to the scaled depth of charge is evidence in point. Thus, in regard to the effect of energy release and depth of charge a satisfactory form for the equation is

$$R = f(W) \cdot f(W, D_c),$$

or as a more specific example,

$$R = W^{\frac{1}{k}} \cdot f(\lambda_c)$$

where k is approximately 3. The inclusion of an additional term to represent the effect of different mediums could be in several forms,

among which are:

$$(1) \quad R = f(W) \cdot f(W, D_c) \cdot f(m)$$
$$(2) \quad R = f(W, m) \cdot f(W, D_c)*$$

In attempting to correlate crater data from TNT blasts with those from nuclear explosions, it has in the past appeared useful to include a factor less than unity (0.3 to 0.9) in the value of W assigned to nuclear charges in terms of equivalent tons of TNT, based on radiochemical data. This has been justified by the fact that the energy partition is totally different for the two types of explosives and that the nuclear weapons deliver radiant energy while conventional explosives do not. It is believed, however, that at best correlation will be uncertain, and with the advent of megaton weapons the disparity of sizes is so great that good correlation should not be expected.**

The effect of charge depth (or height) (λ_c) is fairly well established for TNT. If scaled crater diameter is plotted against scaled charge depth, it is clear both from experiment and physical reasoning that the curve will be concave downward, since no surface crater is produced if the charge is sufficiently high above the surface or sufficiently deep below it. For TNT, the maximum of this curve is rather broad and occurs in the range of $1 < \lambda_c < 3$, where λ_c is in ft/(lb TNT)$^{1/3}$.

The effect of the medium, $f(m)$, has been shown to be as large as a factor of 2 in field experiments with TNT. Unfortunately, the specific properties of the medium which affect the crater are not yet established. It is postulated that strength, either shear or tension, and density are sensitive parameters. It is possible that the elastic moduli are also important. In regard to strength, it is of course the strength under shock load conditions that is important. It is very difficult to make laboratory tests under shock load conditions and the heterogeneous character of earth makes the extrapolation from laboratory to field conditions very uncertain. Thus, while appropriate values for strength under shock load are not known, it appears clear that the strength under such conditions may differ widely from the strength under static load.

The density of the medium may in a theoretical sense affect crater size significantly. In practice, however, the range of densities found is trivial compared to the range of strengths and hence the density is believed to be a parameter of only minor importance in affecting the crater.

As has been mentioned, the application of similitude principles

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* The data at hand have seemed to the author to fit better into an equation of Form (2) than into one of Form (1), namely

$$R = (WE)^{\frac{1}{m}} \cdot f(\lambda_c)$$

as elaborated in Chapter 4. It is to be noted that these two forms are drastically different in the implications of extrapolation from less than kiloton charges up to megaton charges.

** Thus Fig. 3.14 has been plotted with no consideration of relative efficiency, while in Fig. 4.11 a relative efficiency of 60% for nuclear charges compared to TNT has been used.

places certain requirements on the medium. At a minimum for the purposes of crater investigation, it is required that the properties of the medium at equivalent locations (scaled) in two experiments must be identical. This requirement is completely met if the two media are homogeneous, isotropic, and identical. The properties of earth, however, are greatly affected by overburden pressure. Thus in a static sense the properties of earth are grossly dependent on actual (not scaled) depth below the surface, and in a dynamic sense these properties will be similarly affected by the pressure produced by the explosion. Thus one of the fundamental conditions for the proper application of simple scaling laws is violated. The greater the range of size of explosion, and hence of depths, the more serious this violation becomes.

A further difficulty with the application of theory occurs in situations such as existed on CASTLE, where two media, earth and water, were involved, and where the earth was saturated so that forces were transmitted by a complicated combination of intergranular forces and hydraulic pressures.

CHAPTER 2

EXPERIMENT DESIGN

2.1 SHOT PARTICIPATION

The craters resulting from the following three shots were surveyed as a part of this project.

TABLE 2.1 - Shot Location

Shot	Shot Location
1	On the reef in the northwest section of Bikini Atoll.
3	On an island in the southern section of Bikini Atoll.
4	In the lagoon in the northeast section of Bikini Atoll.

The reasons for limiting participation to these three shots have been described in section 1.3. It should be noted that for the purposes of crater measurements it is necessary to determine the surface or bottom contours prior to the explosion and again subsequent to the explosion. While in a scientific sense it would be desirable to measure the crater shortly after zero time so as to avoid modification of the crater by the action of water waves and currents, no feasible way of accomplishing such a prompt measurement has been conceived. Hence the crater survey operations in one sense involved no participation during the explosion and the interval immediately following it. Actually, the time planned for the re-entry of the survey group after each shot was bounded by the time judged to be required for the radiation level to decay to a value such that 4 to 8 hr exposure would not result in a total dose amounting to an important fraction of the allowable total dose for the whole operation, namely 3900 mr.

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2.2 INSTRUMENTATION PLAN

The usefulness of knowledge of bottom depth is dependent on corresponding knowledge of the geographical location where the depth measurement is made. In fact, the problem of determining the location of the ship is more complicated and difficult than the determination of depth. For this reason more effort was devoted to the location procedures than to the depth measurements, both in the planning and preparation phase and in the measurement phase.

2.2.1 Depth Measurement

Depth was measured with a standard recording sonic echo fathometer designed for small ships, Model NK-6. This fathometer operates at 14.25 kcps and at a repetition rate of 1/sec on the "foot" scale, which has a maximum of 200 ft.

The transducer, of the double-unit magnetostriction type, was mounted outboard of the LCU assigned to the project, and the recorder was mounted inside a trailer which also housed equipment for tracking and plotting. The fathometer recording paper had a depth scale of 1 in. per 30 ft of depth and a paper speed of 1 in./min. Since the speed of the boat during survey operations was about 6 knots or 600 ft/min, the chart represents a bottom profile with the depth dimension expanded by a factor of approximately 20.

The calibration was accomplished by two procedures. First it was determined by finding a uniform hard bottom and checking the fathometer readings against a lead line. By this method a satisfactory calibration was accomplished in about 4 hr with all points grouped closely around a straight line showing a 2-ft zero error and a slope such that the fathometer read 80 ft when the actual (lead line) depth was 90 ft.

The second procedure for calibration made use of a corner reflector. This reflector was lowered directly below the fathometer head on a cotton line which had been previously measured and marked. The calibration by this method gave the result that the fathometer read depth correctly except for a 2-ft zero error (which is accounted for by the fact that the transducers were approximately 2 ft below the water surface).

Since the surveys were taken under varying tide heights, it was necessary to reduce all depth readings to a common datum plane. The plane used was that on which the tide tables are based, namely 1/2 ft below mean low-water springs. Recording tide-gages were operated by Holmes and Narver, Inc., (H&N) at several islands in the atoll. The gage readings were within 1/2 ft of the published tabular values.

The time interval spanned by a survey was ordinarily no more than 4 hr and the tide change during such an interval was less than 2 ft. Consequently the tide correction for each survey has been made by plotting the tabular values from the tables, drawing a smooth curve, and noting the nearest integral foot of tide height at the mid-time of the survey. This value of tide height was subtracted from the depth values noted by fathometer (after taking account of its calibration).

2.2.2 Location Procedures

The location of the ship was determined with the assistance of four types of equipment. For the most part they represent independent methods. The equipments were:

     (1) Raydist, an electronic navigation device
     (2) Sextants
     (3) Alidades combined with a gyrocompass Mk. 18
     (4) Taut wire equipment

The Raydist principle is that the distance between two points can be measured by counting the number of standing radio waves between the two points. More specifically the difference in radius from two shore points is determined by measuring the difference in the number of standing waves. In the actual equipment this is accomplished by measuring the phase of a 400-cycle beat note at three fixed receiving stations. This beat note is produced by transmitters of approximately 12.5 mc, one of which is fixed and the other on the ship being tracked.

The Raydist equipment as actually used involved installations requiring 60-cycle power at each of four shore points. Each of these shore installations had a transmitter and three of them had receivers in addition. On shipboard the installation, which of course required an additional source of 60-cycle power, was comprised of three receivers, a transmitter, and equipment for the phase comparison.

While Raydist equipment permitted the determination of the ship's position easily to within 20 ft, it had the limitation that the ship's location was determined only relative to some fixed point where the ship must have been. This fact combined with the fact as noted that five sources of 60-cycle power were required (four on shore at isolated locations and one on the ship) proved to be one of the major headaches in the actual operation of the equipment, since if any of the five power supplies failed, it was necessary to repeat the run and return the ship to the known starting point.

The sextants used were standard Navy issue except that they could be read to 10 sec. The general limitations on the use of sextants were found to be very extensive, since three well defined shore points whose location is known are required and the strength of the fix approaches zero as the ship approaches the circle determined by the three shore points. There is the further limitation that if very distant shore points are used, then even the full angular accuracy of the sextants results in relatively poor absolute precision of the fix. Finally, the capability for finding and retaining ill-defined objects with the sextants was much poorer than with the alidades. For these various reasons, in practice the sextants were used only as a backup procedure for locating the ship and were used only occasionally.

A gyrocompass Mk. 18 was installed on the boat for the use of this project, and two repeaters, one on the flying bridge and the other on the forward starboard 40 mm gun mount, were installed. These repeaters were complete with alidades having a magnification of about 2.5. In practice the alidades and gyrocompass proved to constitute the best method of positioning the ship and this equipment was used either

in conjunction with Raydist or taut wire in nearly all runs.

The taut wire equipment consisted of a drum about 20 in. in diameter which could be controlled by a hand-operated brake, together with a pulley and counter for measuring the amount of wire reeled out and a balance complete with fish scale for measuring wire tension. This equipment was felt to be the most reliable of all the procedures for locating the ship and was used on all surveys. It proved, however, to have some important limitations. For one thing, the wire did not run freely and tended to go into oscillation if the boat's speed was too high. In fact, this upper limit on the boat's speed was very close to the lower limit which was required for proper steering of the boat. Occasional runs were encountered in which analysis indicated that the anchor had not remained fixed.

2.3   TEST PROCEDURES AND DISCUSSION

2.3.1   Preshot Surveys

Preshot surveys were made to the extent possible in the circumstances of each shot.

For Shot 1 the only preshot survey possible was to determine the water depths on the lagoon side of the reef. As was expected, only a very small sector of the area which was ultimately within the crater could be reached by the survey boat before the shot. This survey was performed using all of the aids to boat location, and served as a very useful comparison and trial of the various methods.

The preshot survey of the Shot 4 location permitted a much more extensive survey since the shot point was in navigable water. A complete and fairly detailed bottom survey was accomplished for roughly 2 square miles of bottom in the area of the shot point. In this area primary dependence was placed on the Raydist equipment for location of the boat since shore points were distant and hard to see.

The preshot survey of Shot 3 was comprised of contours run on Tare Island by the H&N surveyors combined with a bottom survey made by the project group using both Raydist and shore fixes. Since the shot yield was smaller than expected and the crater was almost landlocked, the only significant preshot survey was made by the H&N surveyors.

In addition to the surveys by which elevation and position were determined, aerial photographs were taken of each shot point for use in comparison with postshot photographs. Such photographs were taken of all shot points regardless of whether a bottom survey at the shot was contemplated.

2.3.2   Postshot Surveys

The post-Shot 1 survey was made using all four location aids listed under section 2.2.2. Since very few shore points could be identified and they were poorly located for surveying purposes, a series of three buoys was placed in a line on the lagoon side of the crater to serve as sextant aids. The buoys proved to be useless because they could not be seen for the required distance under the light conditions which existed.

In addition to the bottom survey, aerial photographs of the crater were taken promptly after the shot. In addition, to assist in tracking the boat carrying the fathometer, aerial photographs were taken at 2 min. intervals during the time the boat was in the crater.

The fathometer showed that the crater had refilled with very loose sand or mud to a uniform depth after the shot. In the placement of the barge for Shot 2, which was to be fired at the same ground zero location as Shot 1, the H&N group made lead line soundings prior to the placement of marker buoys and moors for the barge. The data on those soundings are also included in this report as evidence of the crater shape.

The post-Shot 1 survey was conducted on the sixth day after the shot. At the time of the survey, the radiation level 10 ft above the water surface was 25 to 75 mr/hr. Measurements by other groups demonstrated that the levels on the land areas surrounding the crater were much higher.

After the accomplishment of the post-Shot 1 survey and the pre-Shot 3 and pre-Shot 4 surveys, a discussion was held of the extent of further effort merited in light of the uncertainties as to times and locations of the remainder of the shots. In these discussions it was brought out that the expected result of Shot 3 would be to remove the western end of Tare Island to a depth of 50-100 ft. Since the preshot survey of the water surrounding it showed that the island had quite steep sides, it was felt that the measurement of the crater would have very small value for the prediction of craters in locations where the earth approached a uniform plane rather than a mountain top. In the same discussion it was also confidently predicted that the result of Shot 4 would be a relatively minor disturbance at the bottom.

As a result of these discussions it was agreed that a curtailment of effort regarding the postshot survey of these two shots was appropriate and the conclusion was reached that adequate data would be obtained if three taut wire runs could be obtained approximating three crater diameters and that these runs could be deferred for Shot 3 until after Shot 4. Consequently the project group left the forward area on 1 April and returned to the forward area on 29 April, immediately after Shot 4.

The actual postshot survey of the Shot 3 crater was somewhat modified because the yield was much smaller than had been predicted and hence the crater, instead of encompassing all of the western end of the island, was much nearer to being landlocked within the western end of the island. In acceding to the pressure of the continuing shot schedule for CASTLE, it was decided not to reestablish the Raydist equipment for the postshot measurements for Shots 3 and 4, and as had been predicted the landmarks available for visual location of the ship were inadequate. In addition, because of the tight shot schedule then existent, the photographic airplane was not able to rendezvous with the boat to assist in the location during the fathometer surveys. Consequently the crater dimensions were determined first by the fathometer equipment on the ship combined with taut wire equipment and later by aerial photographic mapping techniques. In actual operation it was found extremely difficult to maneuver the LCU in the narrow confines

of so small a crater and it proved impossible to run cross wind in sufficiently straight courses to make taut wire measurements effective; hence, for two of the three runs a modified procedure was developed on the spot by which the boat's anchor cable was marked off, the boat was allowed to drift across the crater, and was then pulled back by the anchor winch.

The post-Shot 3 aerial survey was made a few days after the shot but prior to Shot 4. From this survey a post-shot contour map showing, of course, only the section above the waterline was constructed.

The post-Shot 3 fathometer survey was made on 1 May, the 24th day after the shot. Shot 4 had intervened and the water-wave resulting from Shot 4 had washed over the lip of the Shot 3 crater. This had the effect of smoothing and lowering the lip to an unknown extent (believed to be slight), filling in the bottom of the crater and reducing the level of radioactivity. During the crater survey, the radiation level 10 ft above the water surface was about 50 mr/hr and above the lip 1500 mr/hr to 3500 mr/hr.

In the postshot survey in the vicinity of Shot 4 there was a similar pressure of time. A barge was being put into place for a later shot and it was impossible to approach close to the presumed center of the Shot 4 crater. Three taut wire runs were obtained but for the reason just stated all are chords rather than diameters. Additional data in regard to this crater were obtained from the Scripps Institution of Oceanography, who had run a fathometer survey two days previously to permit assurance to the captain of the USS Curtiss that it was safe for the ship to proceed into the area. The fathometer surveys in this area, as in the other craters, showed a very flat bottom, obviously the result of filling-in of mud or fine sand to obscure the bottom of the crater. In addition to the fathometer data, information regarding lead-line depth and length of chain on buoys and moors was obtained from the H&N group responsible for placement of the barge for the later shot.

RESULTS

3.1 GENERAL

The results of the crater survey are summarized in Table 3.1.

TABLE 3.1 - Results of Crater Survey

Shot	Yield (TNT Equip.)	Location	Radius (R) (ft)	Estimated Maximum Depth (D) (ft)	Scaled Radius (ft lb$^{-1/3}$)	$\frac{D}{R}$
1	14.5 MT	Surface-reef	3000	240	0.98	0.08
3	110 KT	Surface-island	400[1]	75[2]	0.66	0.19
4	6.5 MT	Surface-water (160 ft water depth)	1500[3]	250 90[4]		0.06

Notes: (1) At original ground level which was approximately 15 ft above sea level. The slope of the above-water lip from original ground level down to sea level varies over a wide range. To the south it is quite steep and the radius in that direction ranges from 380 to 410 ft. To the east and west, however, the slope is extremely gentle and the radius figure is consequently uncertain and of little significance. The maximum radius appears to be greater than 600 ft.

    (2) From original ground level.

    (3) Since there was no lip the radius is not well defined.

    (4) The estimated maximum depth of 250 ft below sea level or 90 ft below the original lagoon bottom.

In studying large craters, either on the site or in a report, it

is easy to overlook the fact that the depth is quite small when compared to the diameter. To make this point clear the upper part of Fig. 3.1 has been drawn to show typical profiles of Shots 1, 3, and 4, all to the same scale and with the same scale for vertical depths and horizontal depths. These same profiles are repeated in the lower part of Fig. 3.1 where vertical distances are enlarged by a factor of 10. This expansion of depths has been made in all of the following figures.

It will be noted from Fig. 3.1 that the depth on Shot 3, relative to diameter, is very much greater than on Shot 1. In scaled terms the thickness of sand below the shot point and above the water was much greater on Shot 3 than on Shot 1. It is probable, however, that the greater relative depth of Shot 3 is primarily a function of the yield, since it seems to be well established that small explosion craters have greater relative depth than large ones.

3.2   SHOT 1

Figure 3.2 is a preshot photograph of the Shot 1 area on which the CASTLE grid is shown. On Fig. 3.3, which is the postshot photograph of the same area, in addition to the CASTLE grid, three lines (A-B, C-D, and E-F) have been drawn. These lines represent the tracks that the survey ship followed while the profiles presented in Fig. 3.4 were obtained. On these and all other profiles zero elevation has been taken as the datum plane on which the tide tables are based: 0.5 ft below mean low-water springs.

The survey with the sonic fathometer showed a uniform flat bottom at a depth of 170 ft. This flat bottom undoubtedly represents the upper surface of mud and suspended sand which was settling in the crater. In mooring the barge for Shot 2 at the same ground zero, H&N obtained lead line soundings of 240 ft and it is believed that this figure represents the depth of the crater of Shot 1.

3.3   SHOT 2

Since Shot 2 was fired on a barge in the center of the Shot 1 crater, no military significance attaches to the crater formed by it and no fathometer measurements of it were made; an aerial survey, however, was made and a photograph is shown as Fig. 3.5.

3.4   SHOT 3

Figures 3.6 and 3.7 are pre- and post-Shot 3 photographs. It should be noted that these photographs are to a different scale than Figs. 3.3 and 3.4 so that the size of the craters cannot be compared from the photographs.

Figures 3.8 and 3.9 are contour maps showing the situation for Shot 3 before and after the shot, respectively. In the upper part of Fig. 3.10 these two contour maps have been combined to show the contours of the difference in elevation produced by the shot. On this same chart, the location of the traverses run by the LCU are also shown. In the lower part of this figure and in Fig. 3.11, crater profiles are shown

for the traverses indicated. It will be noted that the east-west profile particularly shows that the slope of the lip is very slight and that there is almost no elevation above the original ground level. As a result of this gentle slope the radius at original ground level becomes difficult to determine and very sensitive to elevation errors in the contour maps.

The upper part of Fig. 3.10 is a map of the Shot 3 area showing the traverses made by the ship while the data for the profiles were being taken. The profiles are shown on the bottom of Fig. 3.10 and Fig. 3.11. Mark numbers are shown on the traverses and on the profiles. It is to be noted that the survey of Shot 3 was made 24 days after the shot itself and that the wave produced by Shot 4 had completely inundated the lip of the Shot 3 crater. Because of the high level of radioactivity it was not possible to accomplish any survey of the above-water portion of the crater and consequently the diameters and the height of the lip at the original ground level are subject to some uncertainty.

3.5   SHOT 4

Figures 3.12 and 3.13 show a similar map and profiles of the Shot 4 area. Again the numbers on the figures correspond to mark numbers taken during the survey. As noted in section 2.3.2, because of the interference of other activities on the day the survey was made, it was not possible to run diametral traverses and, as shown on Fig. 3.12, the chord traverses actually depart from the center rather far. For this reason a diametral profile, ABCDE, has been estimated from the results of the three chord profiles shown. Prior to the shot the lagoon floor at the shot point was at a depth of 162 ft. The bottom in the vicinity was quite irregular, with a general slope toward the center of the lagoon and with a large number of coral heads. The post-shot survey indicated that the effect of the shot was to pulverize or depress the bottom directly under the shot point and to destroy the coral heads in the vicinity. Mud or fine (almost suspended) sand was deposited as indicated in the profiles at a uniform depth of about 180 ft. Lead line soundings by H&N during the placement of the barge for a later shot gave a depth of 250 ft.

3.6   COMPARISON WITH OTHER SURFACE SHOTS

On Fig. 3.14 crater radius is plotted as a function of yield (log scales both ways) for all surface shots for which data are readily available. These data include 256 lb TNT charges in clay and silt-gravel at Utah and Nevada, together with similar charges in wet clay and sand at Camp Cooke. All the other points are nuclear explosions ranging from the JANGLE surface shot in Nevada to CASTLE Shot 3, IVY Mike, and CASTLE Shot 1 in the Pacific. Thus, the points plotted include a wide variation in soil characteristics and an extremely wide variation in yield. It is particularly to be noted that no account has been taken of the gross difference in energy partition between TNT and nuclear explosives. While the points plotted (with the single exception of the

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JANGLE surface shot) lie within the bounds of scaled radius = 0.5 and scaled radius = 2, it must not be concluded that craters in the future will lie within these bounds. At a minimum, analysis to indicate the effect of soil characteristics and the change in energy partition will be required before reasonable bounds for crater predictions can be specified. It is also to be noted that the height of burst is a sensitive parameter in affecting crater dimensions from "surface" shots.
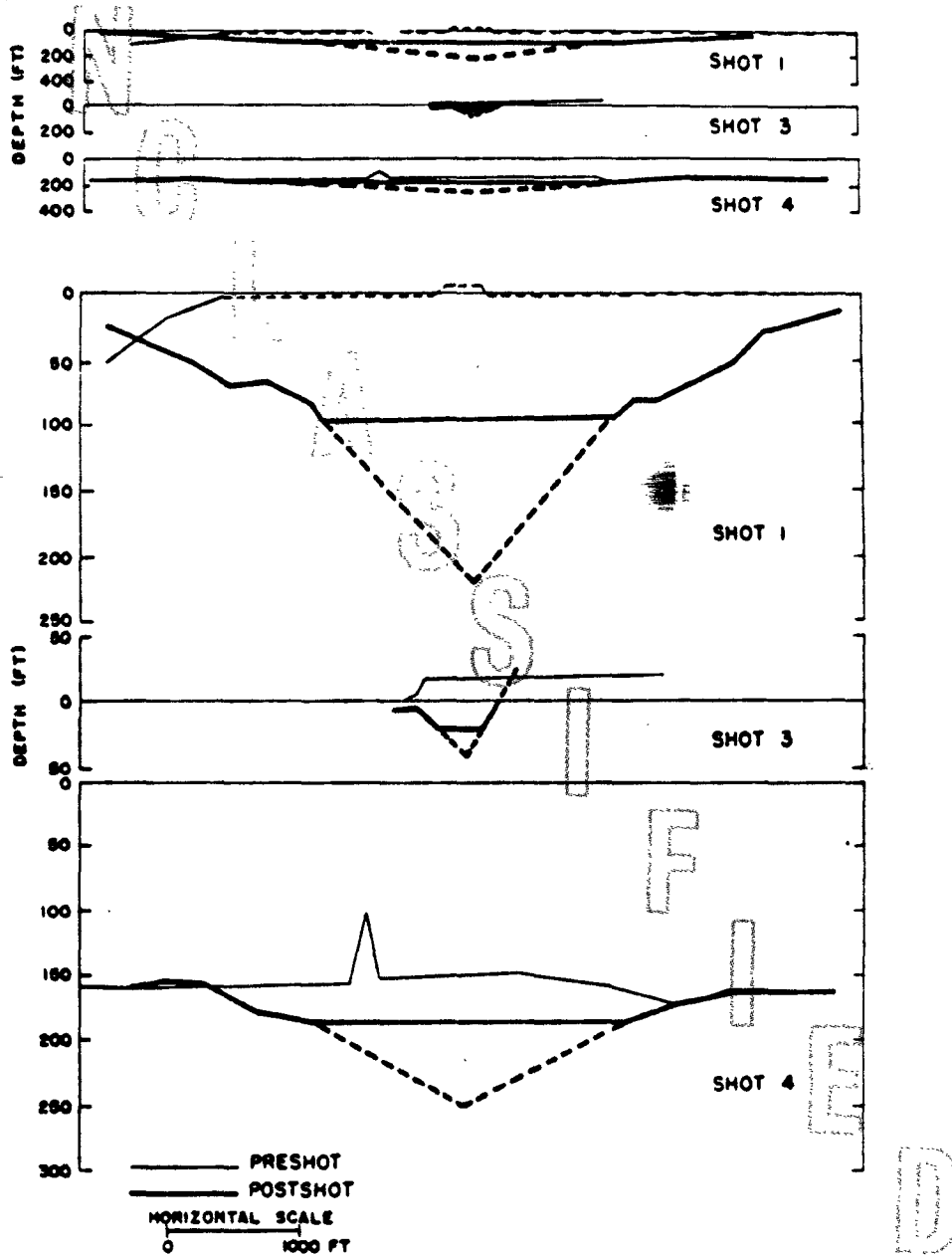
Fig. 3.1 Representative Crater Profiles, Shots 1, 3, and 4

Fig. 3.2   Preshot 1 Area

28
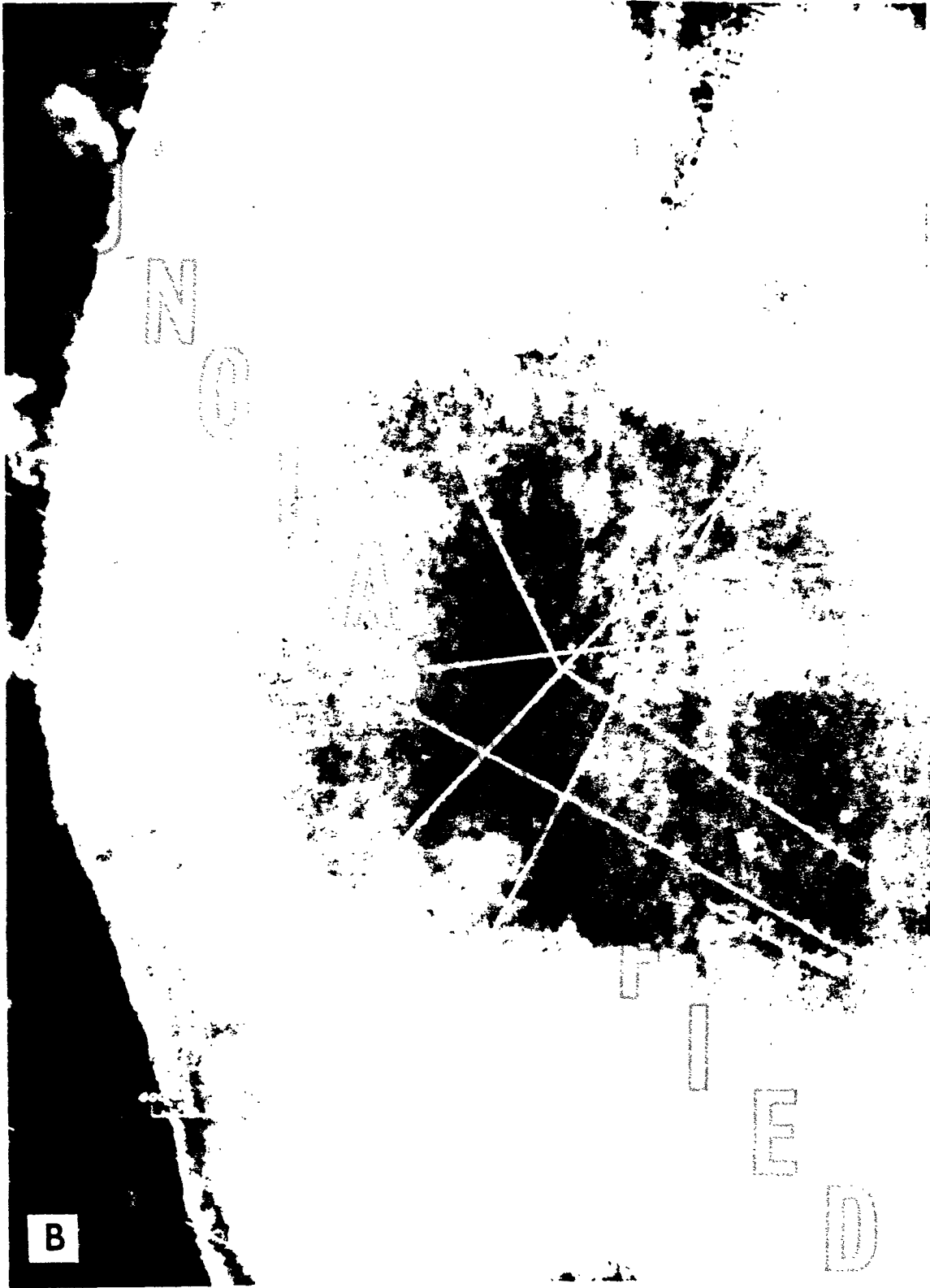
Fig. 3.3 Postshot 1 Area
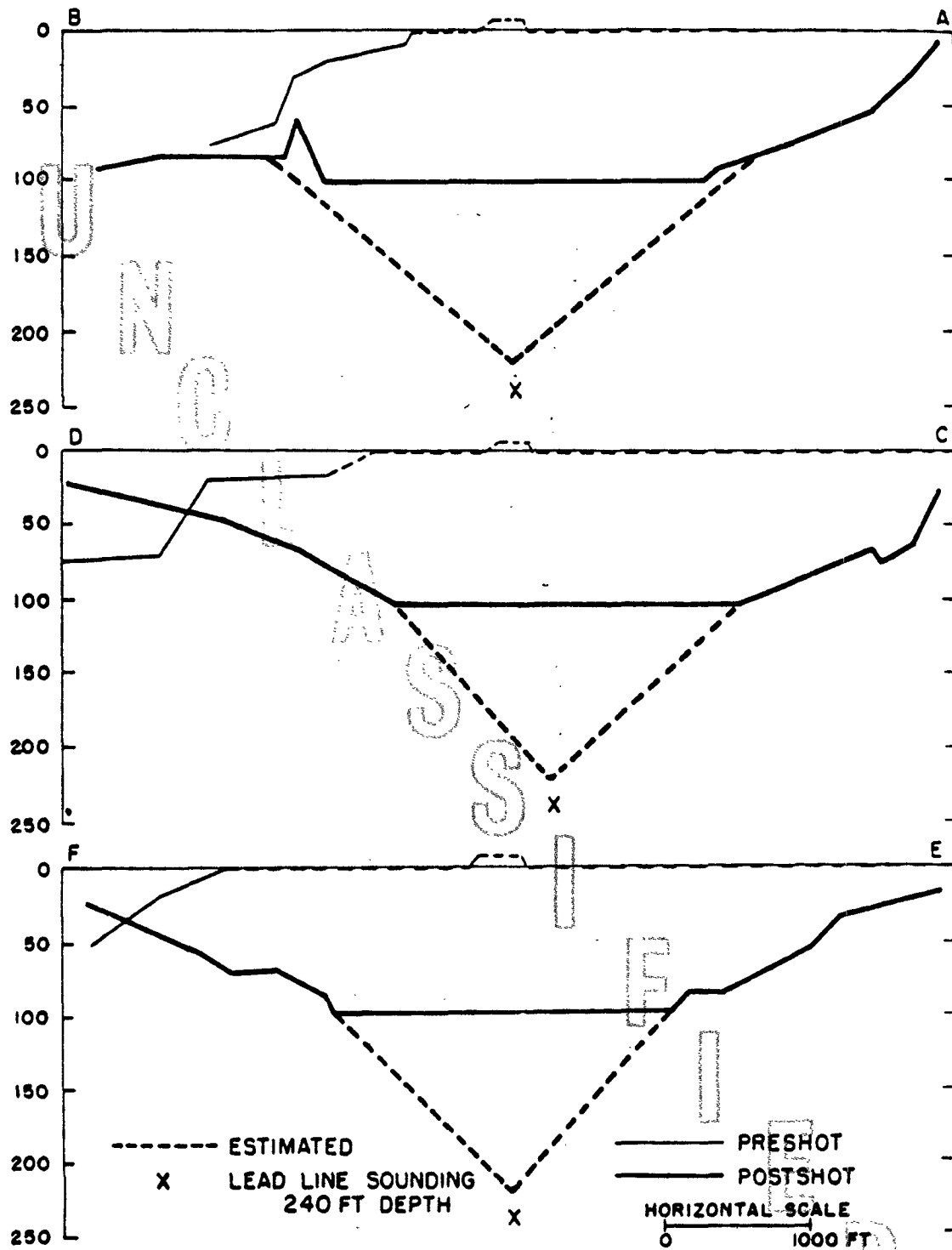
Fig. 3.4 Crater Profiles, Shot 1
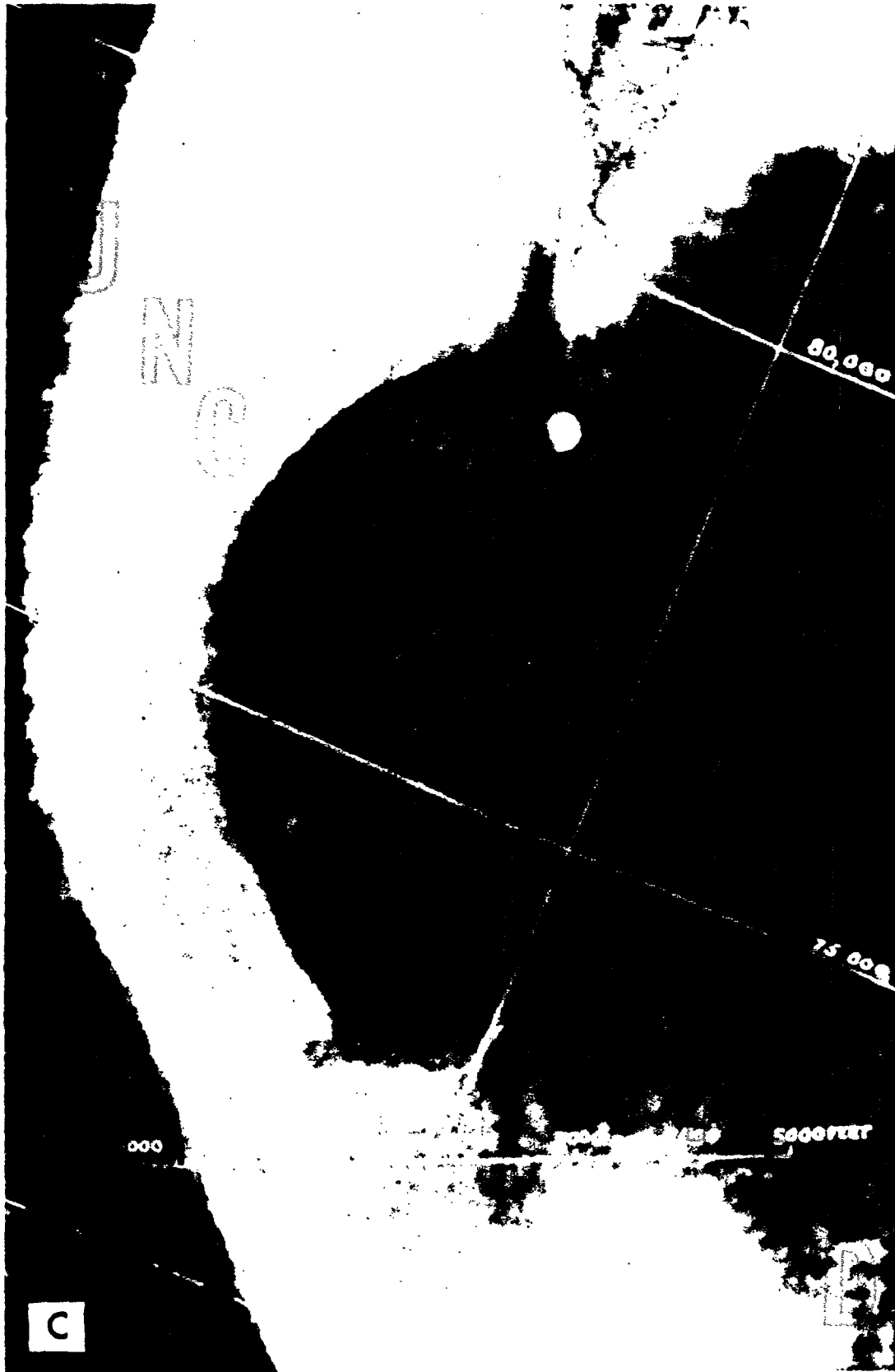
Fig. 3.5   Postshot 2 Area

31

Fig. 3.6 Preshot 3 Area

32
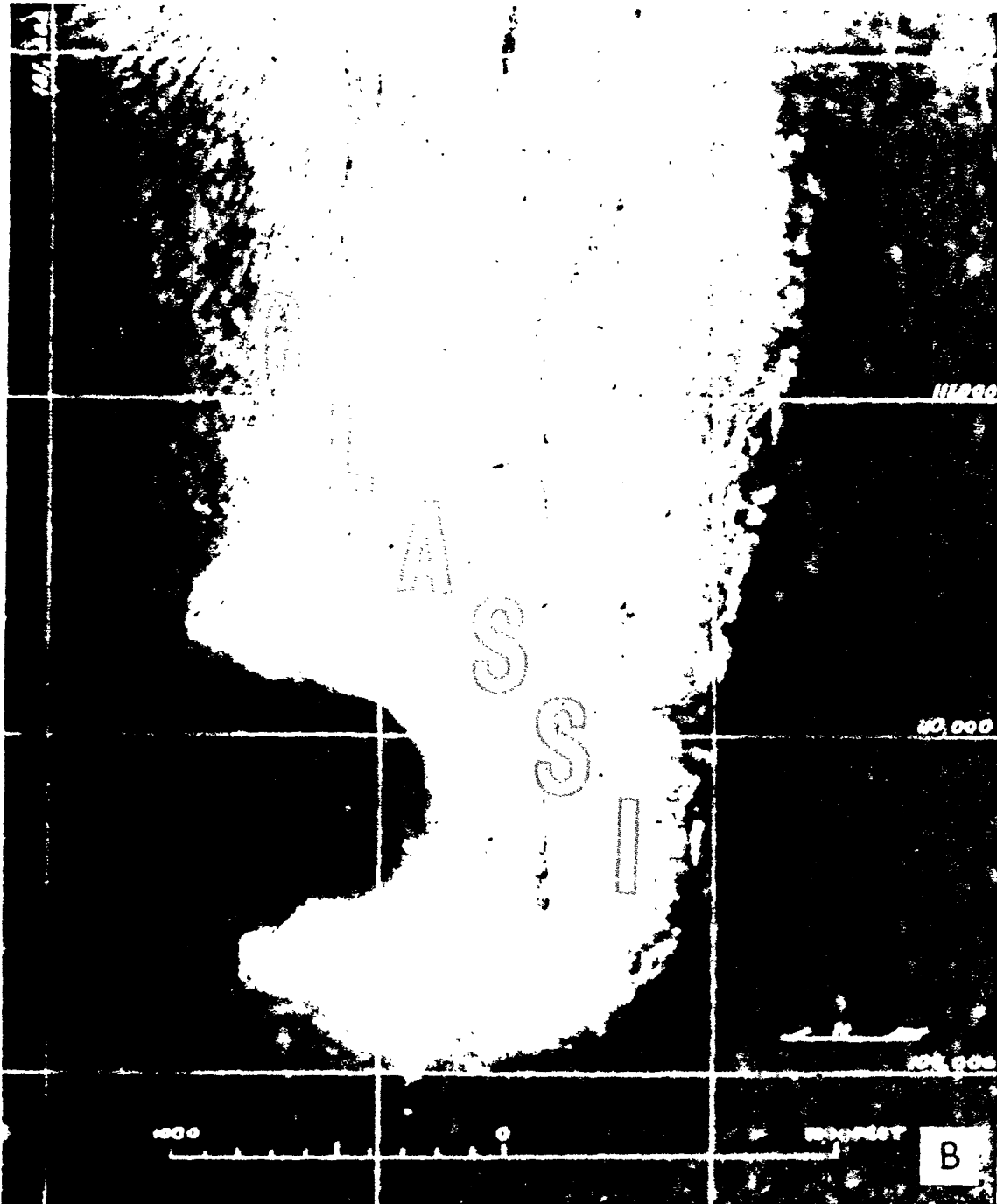
Fig. 3.7 Postshot 3 Area

33
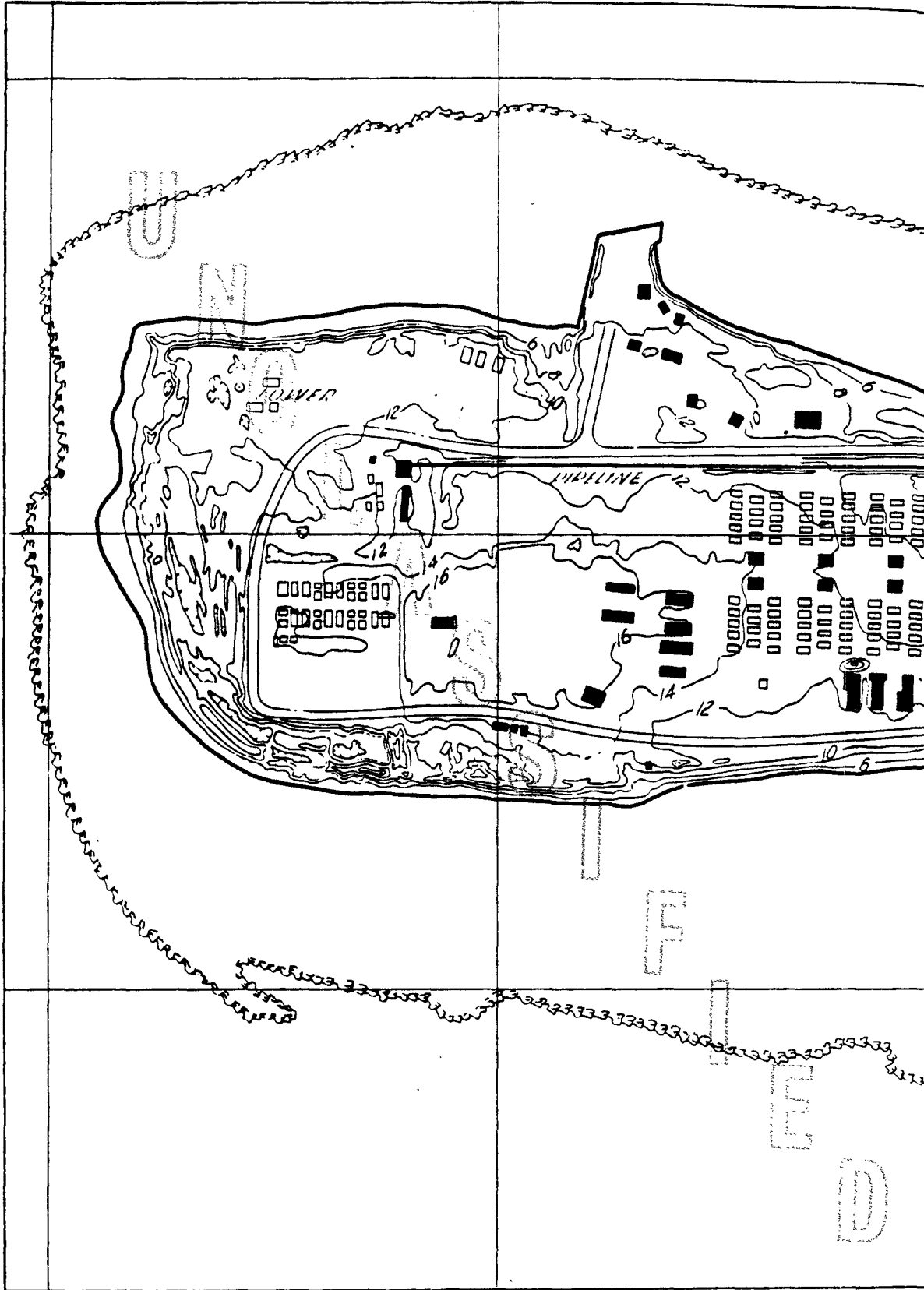
Fig. 3.8 Preshot 3 Contours

34
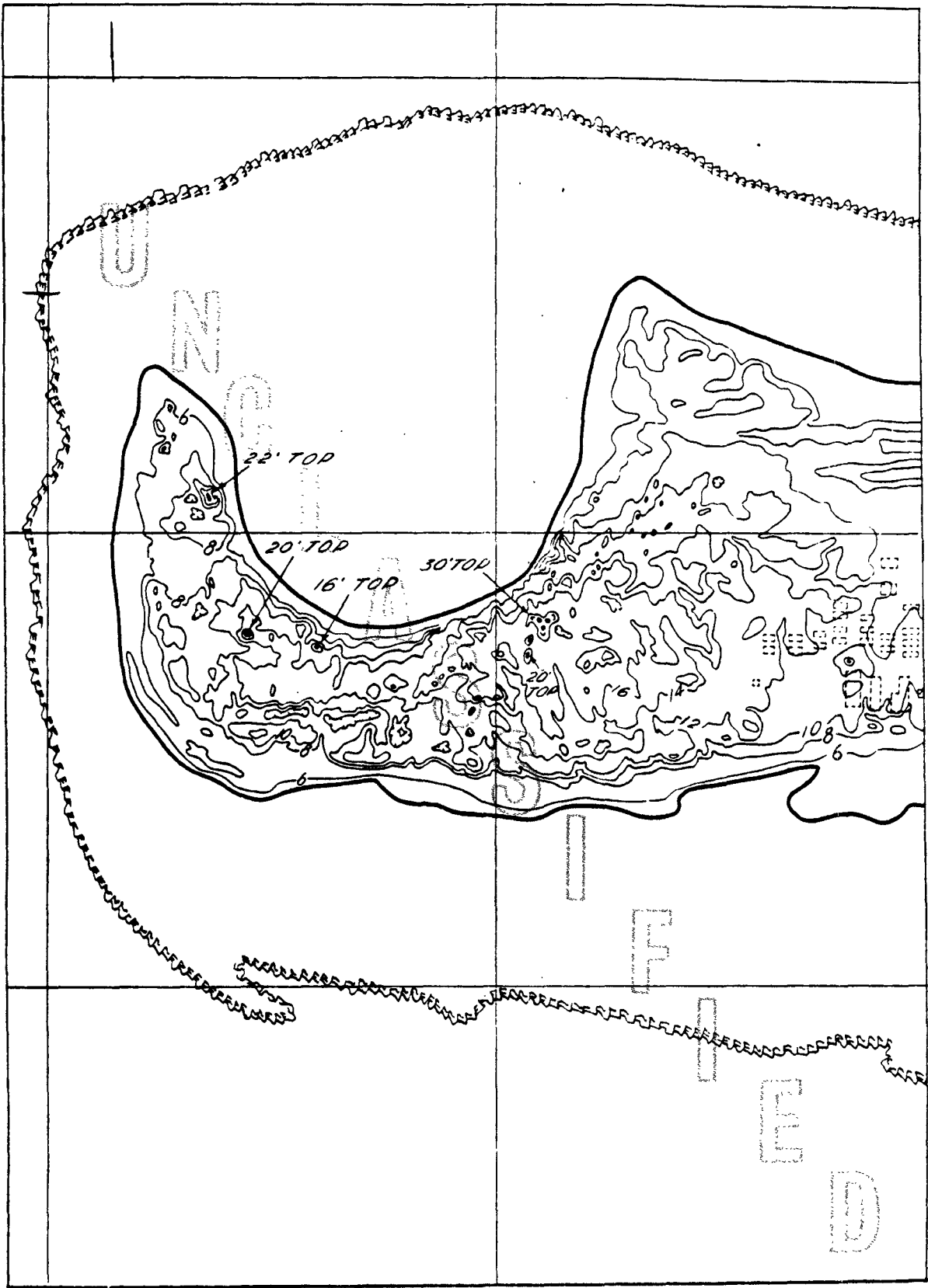
Fig. 3.9 Postshot 3 Contours

35

Fig. 3.10 Difference Contours, Traverses, and Profile, Shot 3

36
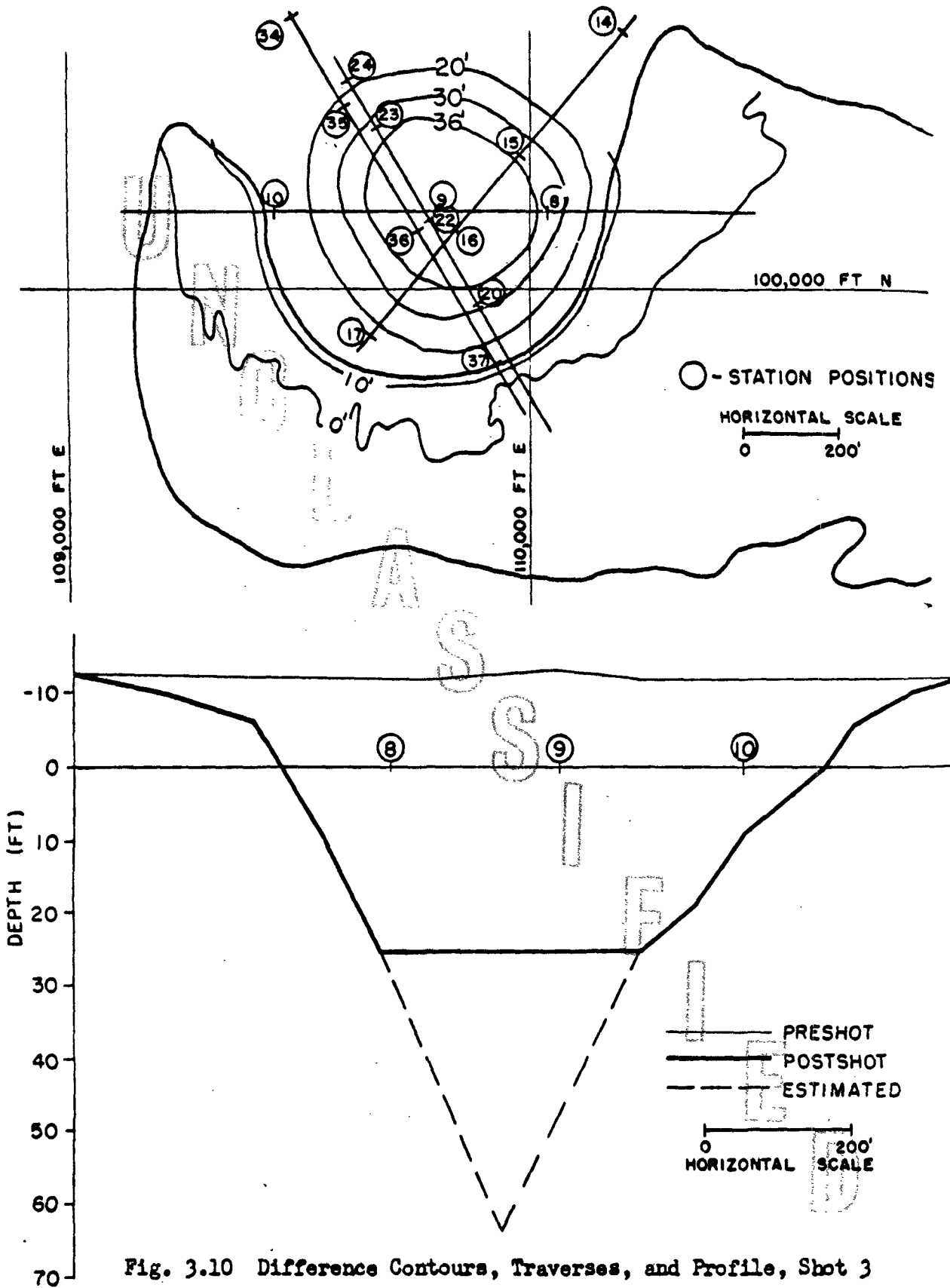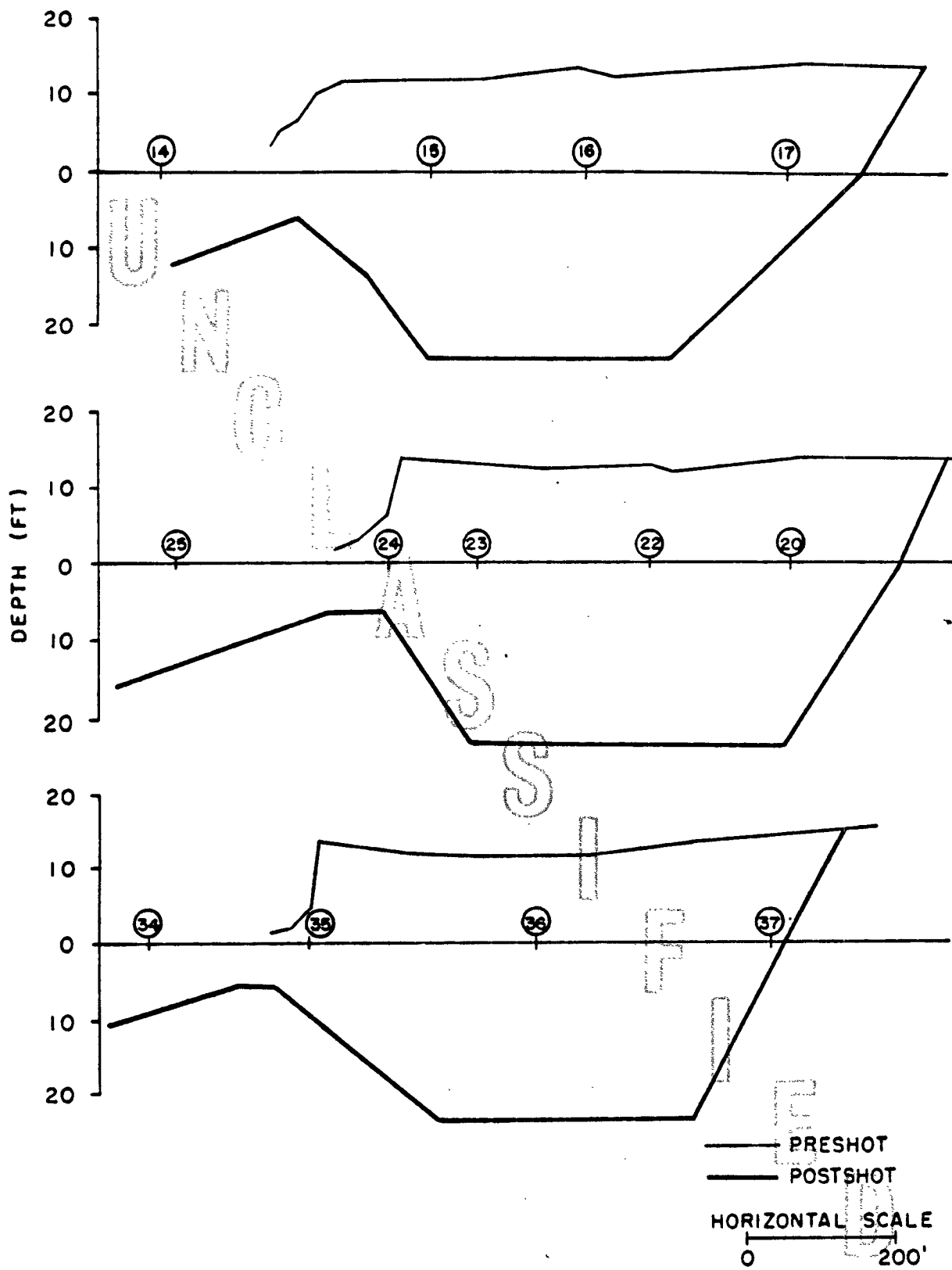
Fig. 3.11 Crater Profiles, Shot 3

Fig. 3.12 Map, Shot 4

38
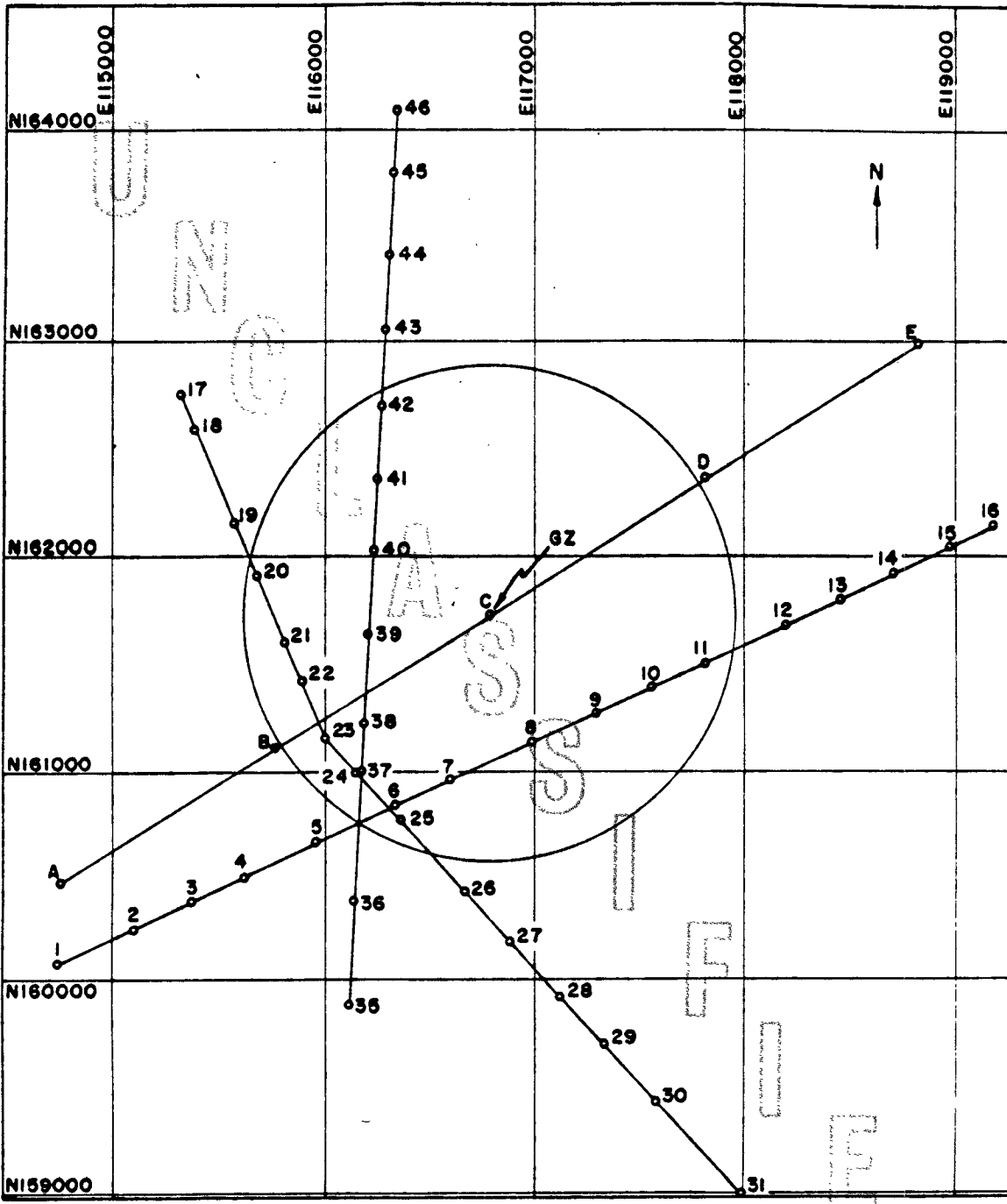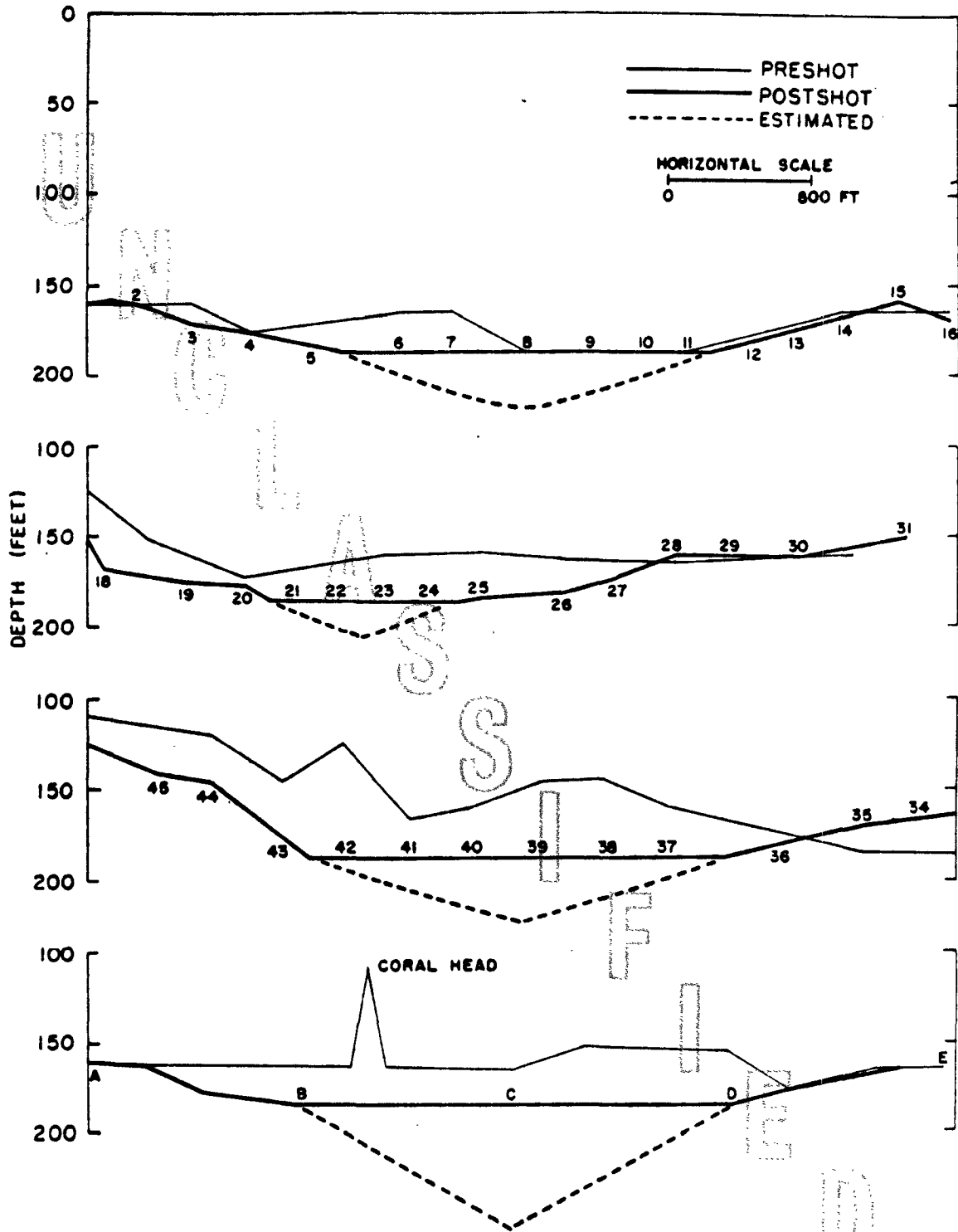
Fig. 3.13. Crater Profiles, Shot 4

	YIELD	SOIL	RADIUS (FT)	(λ)	SHOT
1	256 LB	WET SAND	10.2	1.61	MOLE 307
2	256 LB	DESERT ALLUVIUM	6.4	1.01	MOLE 206 (NEVADA)
3	1.2 KT	DESERT ALLUVIUM	45	0.34	JANGLE-S (NEVADA)
4	110 KT	CORAL	400	0.66	CASTLE-3
5	10.5 MT	CORAL	3120	1.13	IVY MIKE
6	14.5 MT	CORAL	3000	0.98	CASTLE-1
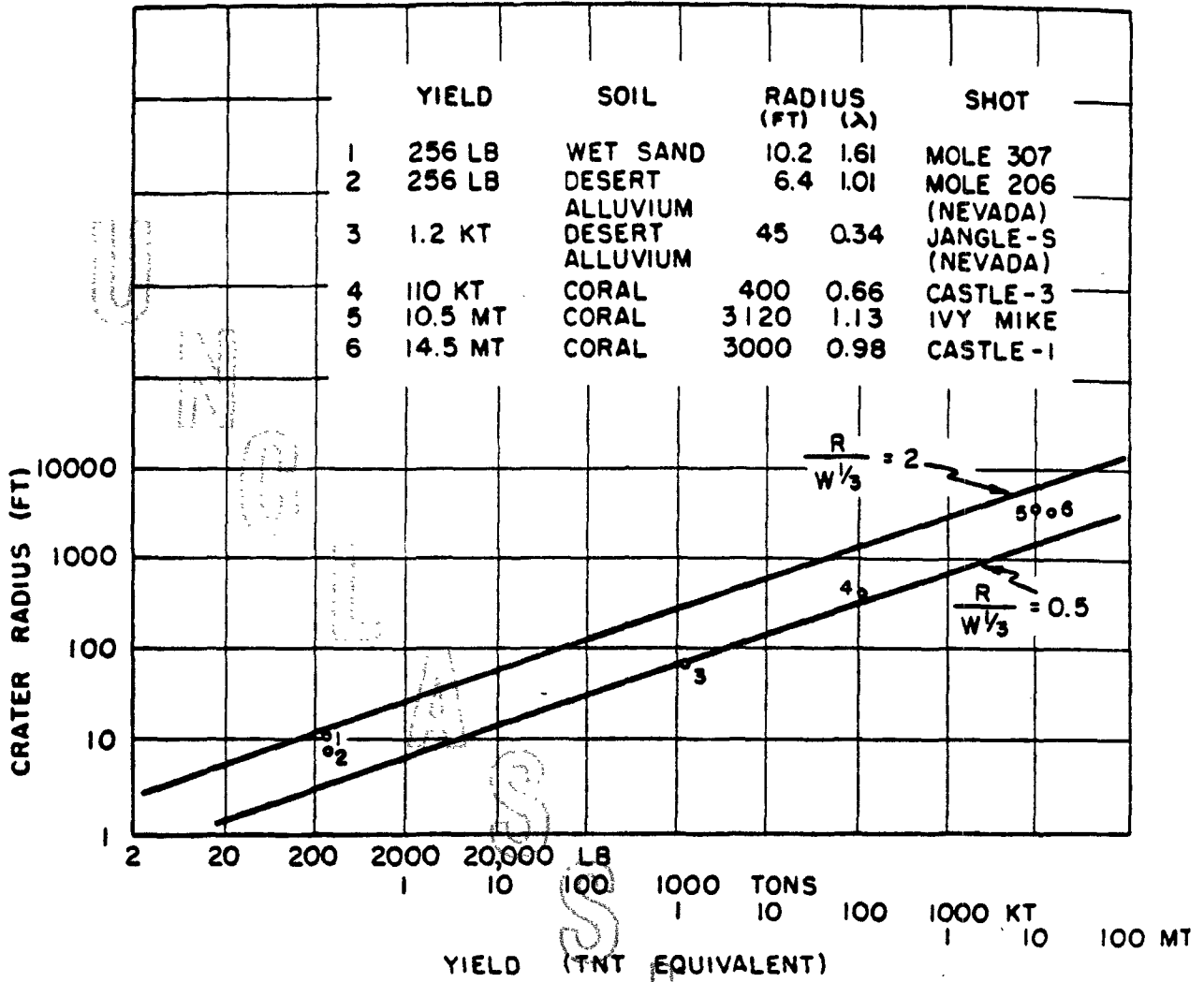
Fig. 3.14 Crater Radius as a Function of Yield, Surface Shots

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PREDICTION OF CRATERS

4.1 BACKGROUND

The data required in regard to any specific megaton explosion for which a prediction of the crater is desired are (1) the yield, (2) the type of soil, and (3) the depth or height of burst. With this information, it is then appropriate to look at the existing evidence and measurements and to develop rational procedures for extrapolation or interpolation.

The craters from explosions high above the surface are significantly different from those formed by lower explosions in that they are depressions rather than excavations. It is believed that such craters are of relatively minor importance from a military standpoint and they are, therefore, not considered here.

As mentioned in section 1.3, it is believed that an attempt to distinguish true from apparent craters becomes less and less realistic as larger and larger yields are considered. In this report, only apparent craters are considered.

In previous analyses of crater data, the horizontal dimension used has sometimes been diameter and sometimes radius, and these values have been measured sometimes from lip to lip and sometimes at the original ground level. In this report, only radius at original ground level is considered.

In reviewing the existing data from a broad point of view and with the objective of crater prediction for megaton explosions in mind, the following facts stand out:

1. All the data from which soils can be compared are contained in experiments involving relatively small quantities of TNT.

2. In those situations where more than one explosion has been fired under presumably identical conditions, an important scatter of the dimensions of the resulting craters is apparent.

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3. The range over which these data must be extrapolated in order to permit prediction of megaton craters is enormously greater than the ranges of extrapolation commonly accomplished in engineering or scientific fields. The situation is roughly equivalent to an attempt to predict the penetration of the projectile from a new anti-tank gun through armorplate based on observation of many measurements of the penetration of BB's from an air rifle through tin cans plus a few measurements of the penetration of .45 pistol bullets through pine.

As a result of these facts any extrapolation procedure is inevitably associated with quite a large uncertainty in the final result. In making any extrapolation it is believed, consequently, that it is of major importance to indicate the order of magnitude of the uncertainty involved as well as the extrapolation itself.

At the outset of any attempt to develop extrapolation procedures, one is faced with a philosophical choice. On the one hand he may look critically into the mechanism of the phenomenon and on the basis of physical or, in this case, mechanical analysis, study the causes, the effects, and the influence of specific parameters. Alternatively, he may adopt the attitude that, in a complicated phenomenon such as crater formation, the mechanisms by which causes and effects are interrelated are so illknown as to be for the moment, unknowable, and hence conclude that the appropriate approach is the empirical extrapolation of the existing data into the range of parameters where prediction is desired. It is the author's opinion that the second approach is the more realistic one under the circumstances involved in the present problem and that is the approach described in the remainder of this report. The most important deviation from past thinking occasioned by this approach is that cube root scaling is on this basis discarded as a primary tool in the extrapolation and is used only for assistance in relatively minor aspects. In adopting an empirical approach, it would of course, be absurd to ignore the information, however meager, in regard to the physical mechanism and particularly in the distinction between the mechanisms occuring in TNT and in nuclear explosions. On the other hand, it is believed that too much dependence on cube root scaling is likely to give the illusion of a precision in prediction unjustified by the facts.

The development described below was undertaken within the framework that the desirable result from a military standpoint is the construction of graphical or analytical relations such that knowledge of the yield, soil, and depth will permit easy prediction of the crater dimensions. It is postulated that the shape of a crater for the craters of interest is primarily dependent on its size and hence the first attempt is to predict crater radius in terms of the three parameters just mentioned, with the expectation that a later analysis can be made to predict depth and other shape aspects once the radius prediction has been accomplished.

4.2   DEVELOPMENT OF THE EXTRAPOLATION METHOD

It was decided to study first the effect of soil type, second the effect of depth, and third the effect of yield. In looking at the available information it was at once apparent that in regard to both soil type and depth the data on megaton explosions are useless, since these shots were all fired at one depth (essentially zero) and in one soil type ("coral" atoll); hence, it was finally recognized that the germane approach appeared to be to look first only at TNT data and from these data to establish an extrapolation procedure; second, to adjust the values of the parameters so that the JANGLE underground and JANGLE surface shots would be consistent; and finally, to investigate the sensitivity of the procedure and compare the results with the measurements of nuclear craters in the Marshalls.

Nevada soil is an appropriate one to look at first since there are considerable HE data and data from two nuclear shots. In that soil data are available in the range λ_c = -0.13 to + 1.0. Within this range greatest interest lies in the neighborhood of λ_c = 0.14. The data on the TNT shots of this scaled depth are plotted in Fig. 4.1 which shows crater radius plotted against yield on log paper both ways. Figure 4.2 is a similar plot for data on TNT at scaled depth λ_c = 0.50 and λ_c = -0.14 (minus indicates above the surface). The scatter of the points shown on these graphs is typical of the scatter shown in every case where several essentially identical shots have been fired. It is believed conservative to say that the uncertainty in the value of radius for any specific combination of soil type, charge size, and charge depth is at least 10 per cent. Consequently the plus and minus 10 per cent limits at the maximum and minimum charge sizes shown here are marked on Fig. 4.1. For extrapolation purposes, the reciprocal slope, m, of the most probable line is found to be 3.4.* To permit an estimate of the uncertainty in extrapolation, maximum and minimum slopes within the 10 per cent uncertainty just mentioned have also been plotted. These slopes are found to be m = 3.0 and m = 4.1. This elementary analysis has been undertaken with the data on Fig. 4.1 only and lines of the slopes so determined have then been drawn on Fig. 4.2. The analysis has been limited to Fig. 4.1 both because the scaled depth λ_c = 0.14 is of major interest and also because a greater range of yields for TNT shots is available for this scaled depth than for any other.

It is apparent that m, the reciprocal of the slope when crater radius is plotted against yield on a log-log basis, is related to R and W in the following way:

$$R = KW^{\frac{1}{m}} .$$

In the remainder of the report "m" is referred to as the "scaling exponent."

Now, using the best fit value for m, 3.4, and the experimental data of Tables A.4 and A.6, the solid line on Fig. 4.3 has been

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* The actual value measured on the graph is 3.39. It is believed, however, that the second figure is of somewhat doubtful validity and hence all such numbers are rounded off to two figures.
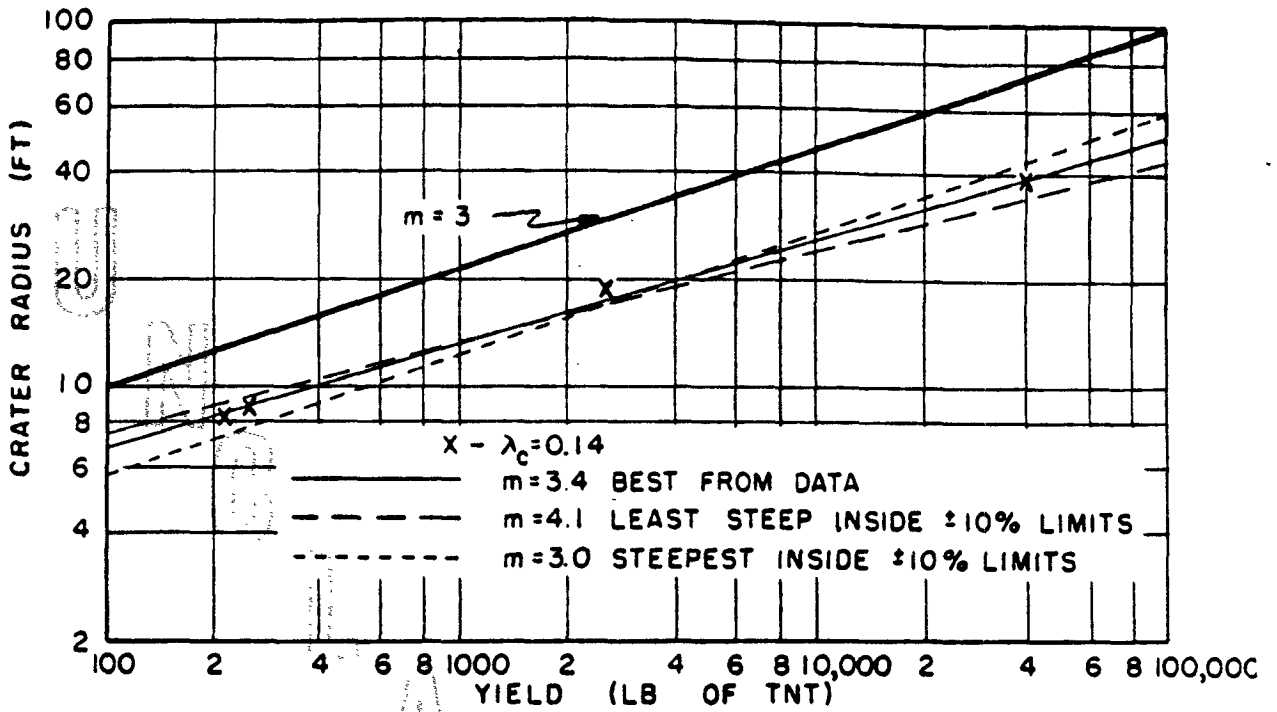
43

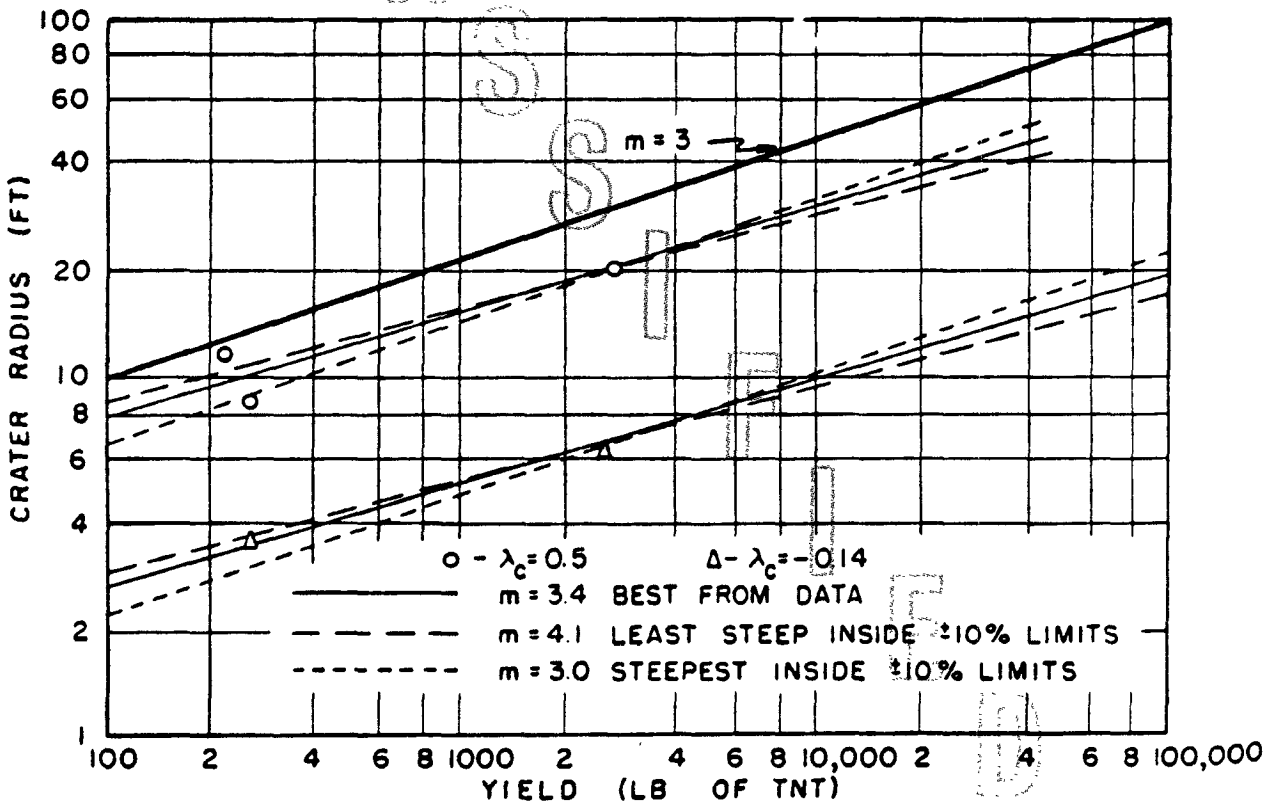**Fig. 4.1 Crater Radius vs Yield, Nevada, $\lambda_c = 0.14$**

Fig. 4.2 Crater Radius vs Yield, Nevada, $\lambda_c = 0.5$ and $\lambda_c = -0.14$

44
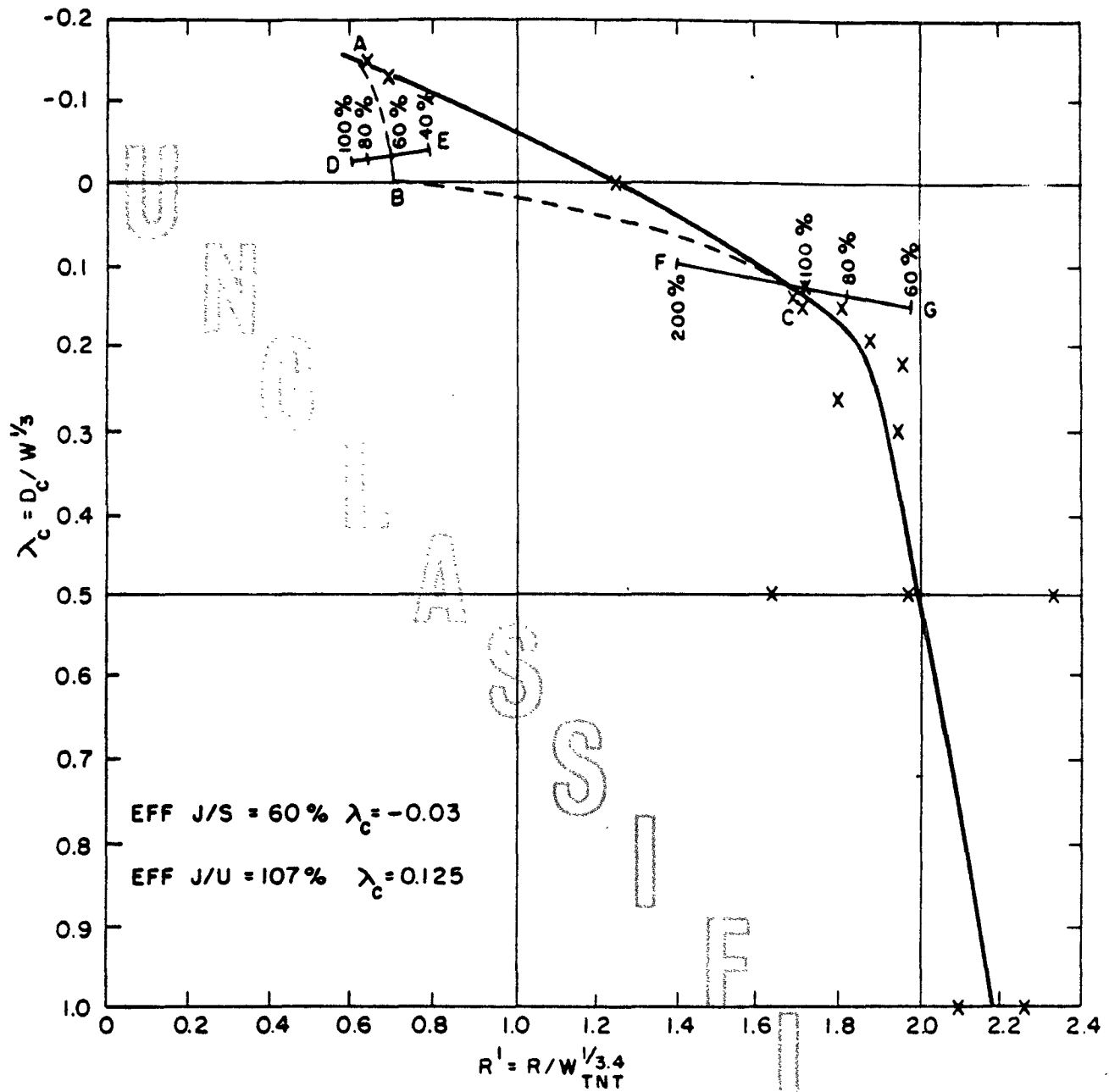
Fig. 4.3 Scaled Crater Radius vs Scaled Charge Depth,
Nevada (m = 3.4)

constructed. On this figure the scaled radius (on the basis m = 3.4), is plotted against the scaled charge depth (on the basis m = 3).*

The next step is the determination of the curve for nuclear charges based on this curve for TNT charges. In this procedure consideration must be given to the difference in mechanism of nuclear and TNT bursts, particularly for bursts on the surface or at very low heights above the surface.

In the early stages of a nuclear explosion fired at or near the interface between air and earth, the shock wave velocity is very much higher in the air than in the earth;** hence, at a time when the nuclear explosion process has proceeded to the point where the average energy density***within the boundary of the shock wave is equal to the average energy density at the surface of a spherical TNT charge which has been detonated at its center, the envelope of the nuclear explosion is essentially hemispherical. If average energy density is a good criterion of crater size and shape, then on this basis the crater formed by a given nuclear energy release on the surface should be similar to the crater formed by a TNT charge of the same yield fired well above the surface.**** The crater resulting from a nuclear surface charge should differ extensively from that produced by a TNT charge whose c.g. is at the surface, both because of the different mechanism mentioned above and because a hemispherical excavation was required before the TNT charge could be placed.

Consider a nuclear charge at λ_c = -0.13. Within its shock wave the total energy will be identically the same as that within a sphere of TNT tangent to the surface when both shock waves reach the surface. This argument can be summarized by saying that the crater radius produced by a low aboveground nuclear shot should be essentially independent of height, and (if the efficiency were 100 per cent) should have about the same value as that produced by a TNT shot at λ_c = -0.13. On this basis the dotted curve in the region AB has been drawn on Fig. 4.3.

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* Since the range of scaled depths is small in the interval of greatest interest, the distinction between determining scaled depths on the basis m = 3.0 and on the basis m = 3.4, is relatively trivial and will not affect the conclusions reached in this analysis.

** D.T. Griggs, in predicting the effects of JANGLE U[1]/computes shock wave velocities in air to be approximately 25 times those in soil in the radius range from approximately λ = 0.1 to λ = 1.0. Similarly, Porzel, in predicting the effects of IVY Mike,[2]/estimates shock velocities in the air and water soaked sand for high overpressures such that in the early stages of a nuclear explosion the ratio of velocity in air to velocity in soil may be as high as 1000:1.

*** By "average energy density" is meant the total energy contained within the shock wave, divided by the total volume within it.

**** Actually, as Porzel points out,[2]/ at a time when the nuclear shock wave has reached the same radius as that of the TNT sphere of equivalent energy release, (and hence when average energy densities are equal) there is still an enormous difference in the two situations since the mass enclosed within the shock wave in the case of TNT is some 1500 times that in the nuclear case. Hence, in the nuclear situation the pressures are very much higher and the durations shorter than in the TNT situation.

Since the energy partition in the two types of explosions is significantly different, particularly in the roughly 15 per cent of the yield of a nuclear explosion which takes the form of prompt radiation, it seems necessary to consider an efficiency factor less than 1 for nuclear explosions as far as the cratering effects are concerned.* Experimentally, evidence on this point is meager in the extreme, being limited to the JANGLE surface and JANGLE underground shots. At this point it is useful to consider the numerical data on the JANGLE surface and the JANGLE underground shots. The data from these two shots can be placed on this curve with efficiency as a parameter; thus the curve DE on Fig. 4.3, represents the JANGLE surface shot for a radiochemical yield of 1.2 KT times the efficiencies shown on the curve, with radius scaled on the basis m = 3.4 and charge depth (height) scaled on the basis m = 3. Similarly the curve FG represents the JANGLE underground shot data on the basis 1.2 KT times the efficiencies shown there, using the same procedure. It will be seen that curve DE for the JANGLE surface shot intersects curve AB at an efficiency of about 60 per cent and that curve FG representing the JANGLE underground shot intersects the TNT curve at an efficiency of 107 per cent. It is not suggested that these values of efficiency are correct, but their comparative values are at least in the direction expected. It is recognized that, in accordance with the definition of the equivalent TNT charge, the efficiency of the JANGLE surface shot should be defined as the value at the intersection of curve DE with the solid curve. It is nevertheless believed that there are such gross differences in mechanism between nuclear and TNT explosions in this region of close above-surface shots that the equivalence should be divided into two parts, one of which is concerned with the disparity in the form of the blast wave and the other is concerned with the remaining elements of efficiency. It is felt that the value of 107 per cent obtained on this curve for the JANGLE underground shot is probably unrealistic for the following reason. It is clear that values of the scaling exponent m, and values of efficiency, can be paired to fit any crater measurement from a specific yield and depth. Since it is felt that efficiencies at greater depths than 17 ft should probably be higher than at that depth and since it is also felt unlikely that nuclear efficiencies are higher than 100 per cent, it appears that this value of efficiency for the JANGLE underground shot is on the high

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* For present purposes, efficiency may be defined as the ratio of the total energy release of an equivalent TNT charge with that of a nuclear explosive. The equivalent TNT charge may be defined as the charge which at the same actual (not scaled) depth produces the same crater. Since in both TNT and nuclear explosions it seems reasonably established that only a small fraction of the total energy released can be accounted for in crater production, there is no philosophical reason why the efficiency of a nuclear explosion as defined above need be limited to 100 per cent; however, at all times of interest in the formation of craters the pressure within a nuclear explosion is higher than that within the equivalent TNT explosion and hence at the time venting takes place a greater fraction of the energy in a nuclear explosion should be dissipated to the air.

side of reality. Since this unrealistic efficiency is paired with the value m = 3.4, it is consequently likely that this value of m is also too high.

The procedure described for constructing both the TNT and the nuclear curves shown on Fig. 4.3 can be performed equally well using values of m other than the most probable value of 3.4. Other appropriate values of m as indicated on Fig. 4.2 are 3.0, representing both conventional cube root scaling and the lower limit of slope on the basis of the 10 per cent uncertainty in experimental values postulated earlier, and 4.1 representing the upper limit. Both curves have been plotted together on Fig. 4.4.

Since, for military purposes, it is believed that the data for extrapolation should be available in the simplest possible form for quick use without computation, the nuclear curves shown on Figs. 4.3 and 4.4 have been re-plotted in the form of radius in feet against charge depth in feet, with yield as a parameter. This has been done on Fig. 4.5, in which for each yield shown both the most probable value (m = 3.4) and the limiting values m = 3.0 and 4.1 are shown.

The estimates for this soil for the most probable value of m (m = 3.4) are re-plotted on Fig. 4.6. Range of uncertainty (m = 3.0 and m = 4.1) are indicated by short horizontal bars attached to each of the parametric yield curves.

The same kind of analysis has been carried through for dry clay, dry sand, wet clay, and sandstone and the results of these analyses are included in Figs. 4.7 through 4.10. In the case of these other soils no nuclear data are available and hence the efficiencies found in the Nevada soil have been used in the following fashion. For the most probable value of the scaling exponent m in each of these other soils, the variation of efficiency with depth at Nevada for m = 3.4 has been used. Similarly, for the lowest value of m for each of these other soils the same variation of efficiency with depth has been used as was found at Nevada for the lowest value of m there, namely, 3.0. The corresponding analysis has been made for the upper limiting value of m.

The most probable and limiting values of m for all the soils reported here are listed in the table below. In each case, the available data have been plotted in the same form as was shown on Figs. 4.1 and 4.2, the best straight line was drawn for those points and then values of radius 10 per cent above and below the curve were marked at the upper and lower limits of the charge sizes considered.* By this procedure, the limiting values of m have the greatest range for those soils in which no large TNT charges have been fired, and this is appropriate, since in fact the extrapolation is less certain in such cases.

In the case of wet clay, Fig. 4.8, so little TNT data are available that crater radius has been predicted only for the most probable value of the scaling exponent m.

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* It was decided not to review TNT data from charges less than 200 lb.

48
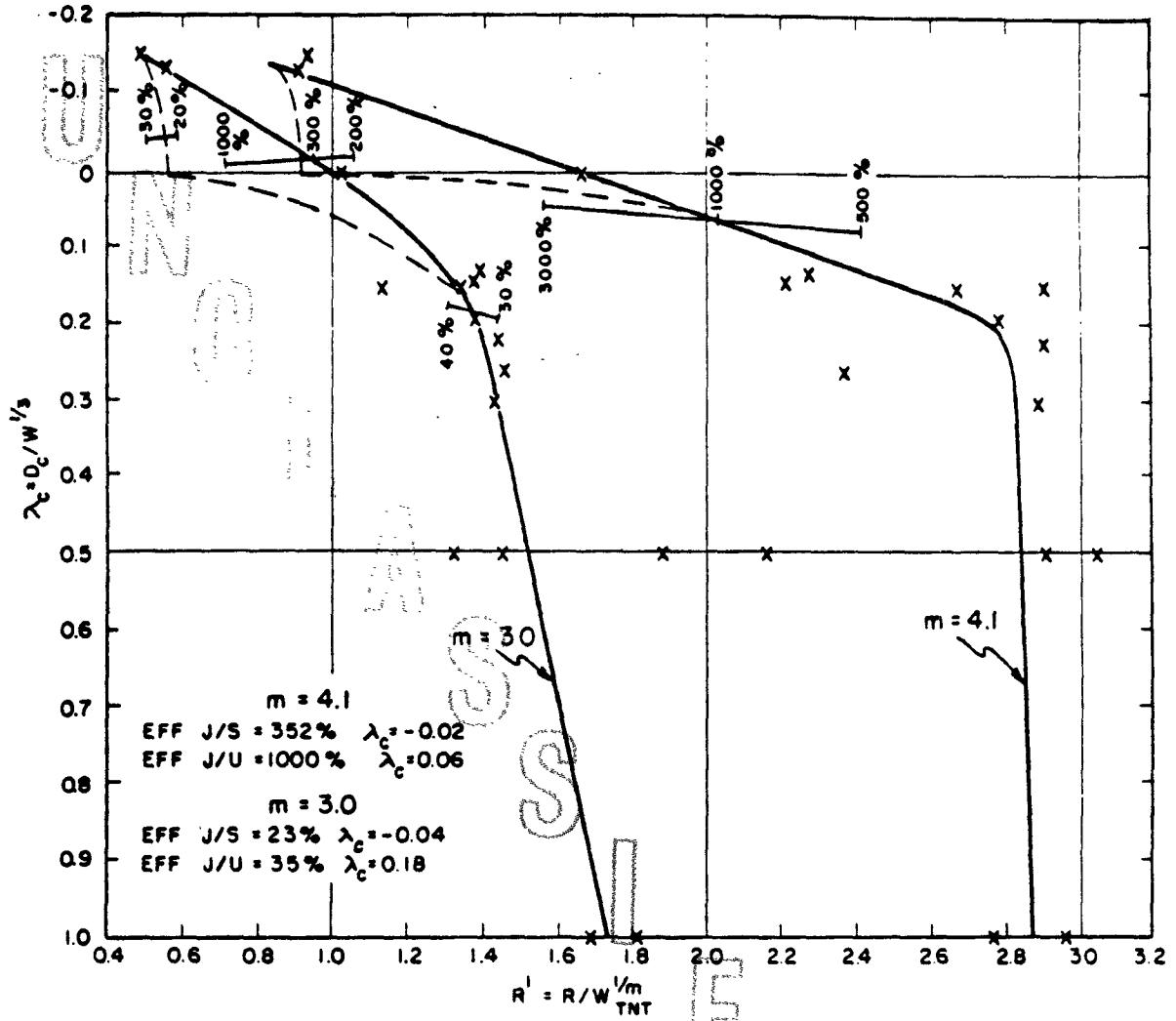
Fig. 4.4 Scaled Crater Radius vs Scaled Charge Depth, Nevada (m = 3.0, m = 4.1)

49
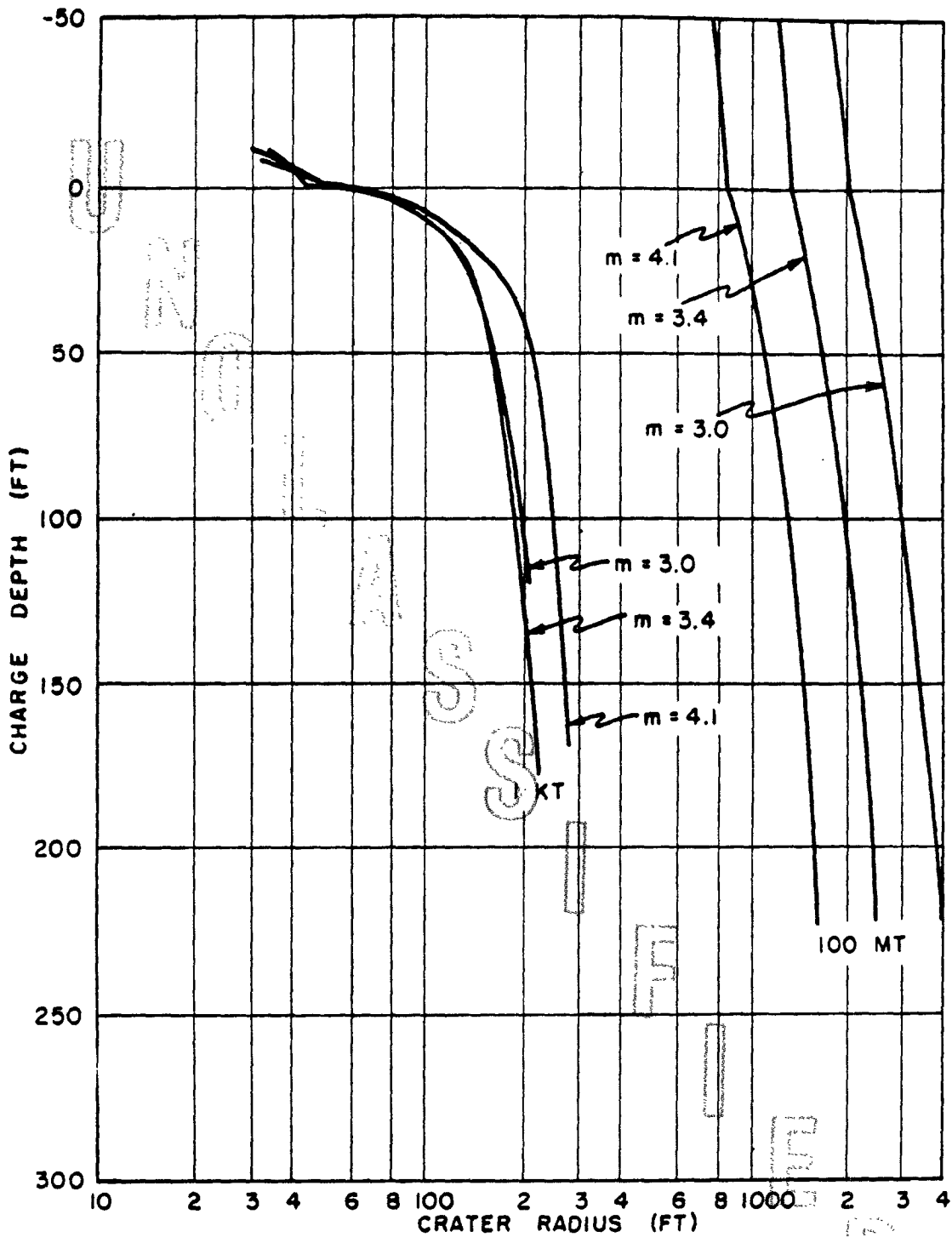
Fig. 4.5 Crater Radius vs Charge Depth, Nevada,
Showing the Range of Uncertainty
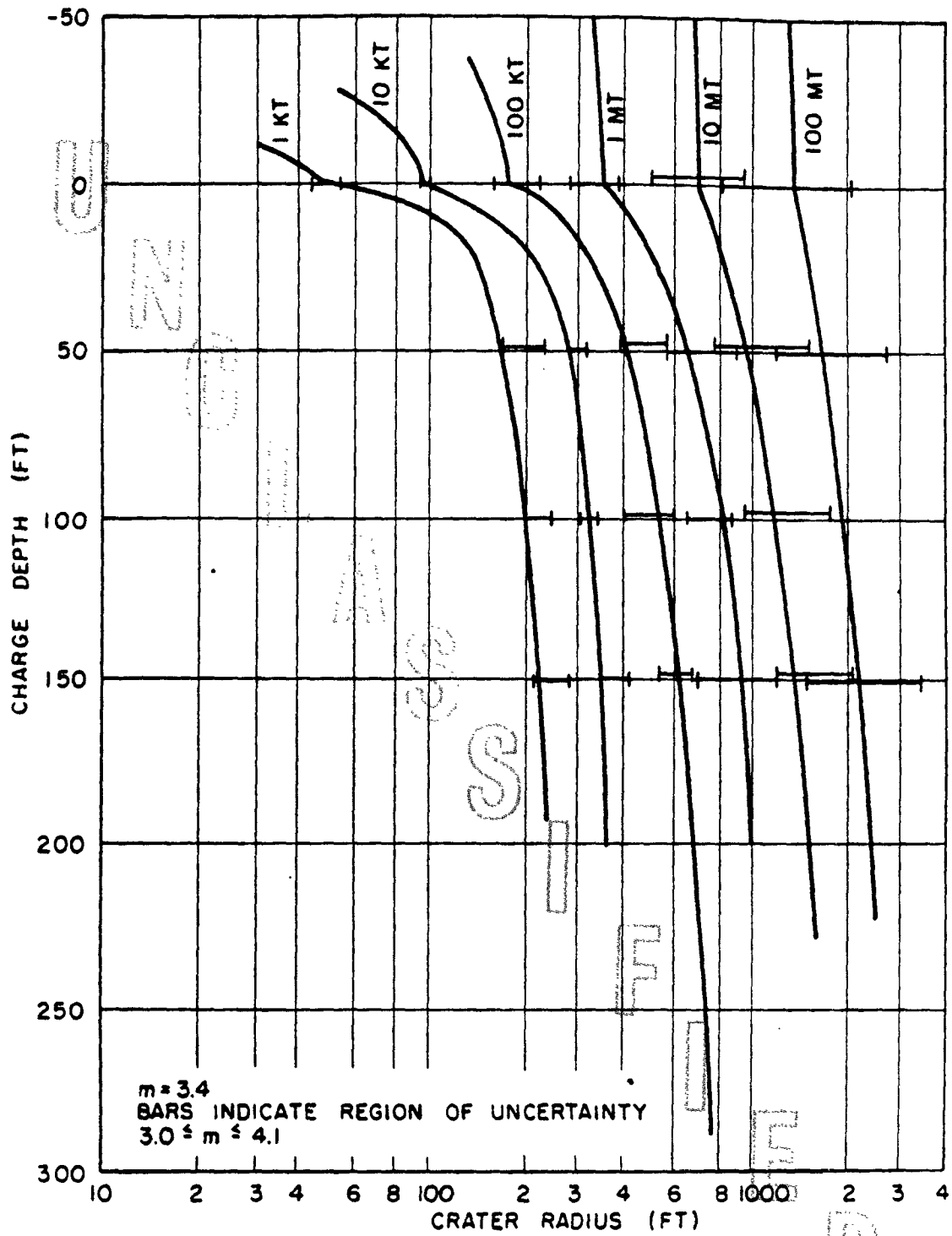
Fig. 4.6 Crater Radius vs Charge Depth, Nevada

51
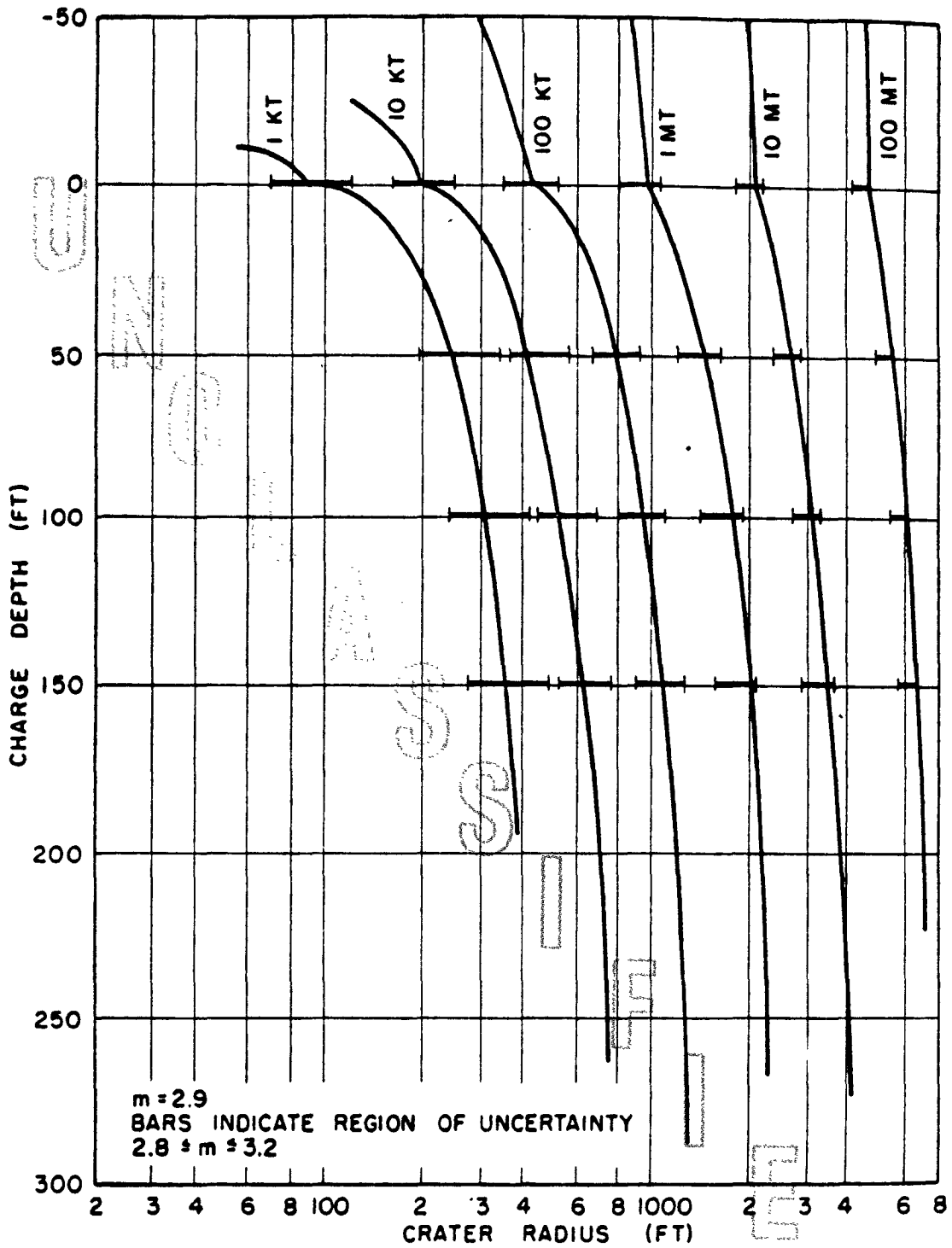
Fig. 4.7 Crater Radius vs Charge Depth, Dry Clay

52
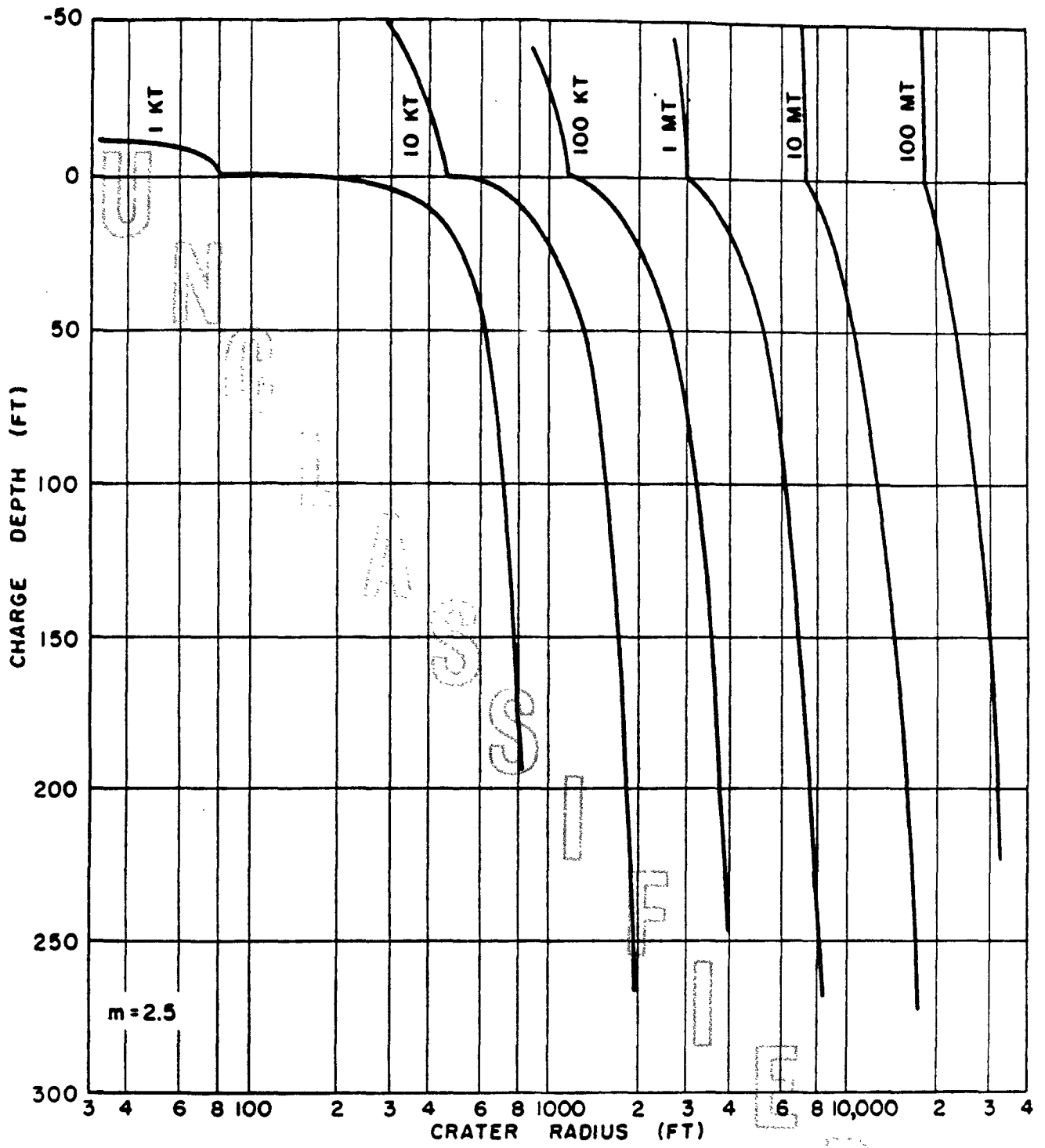
Fig. 4.8 Crater Radius vs Charge Depth, Wet Clay
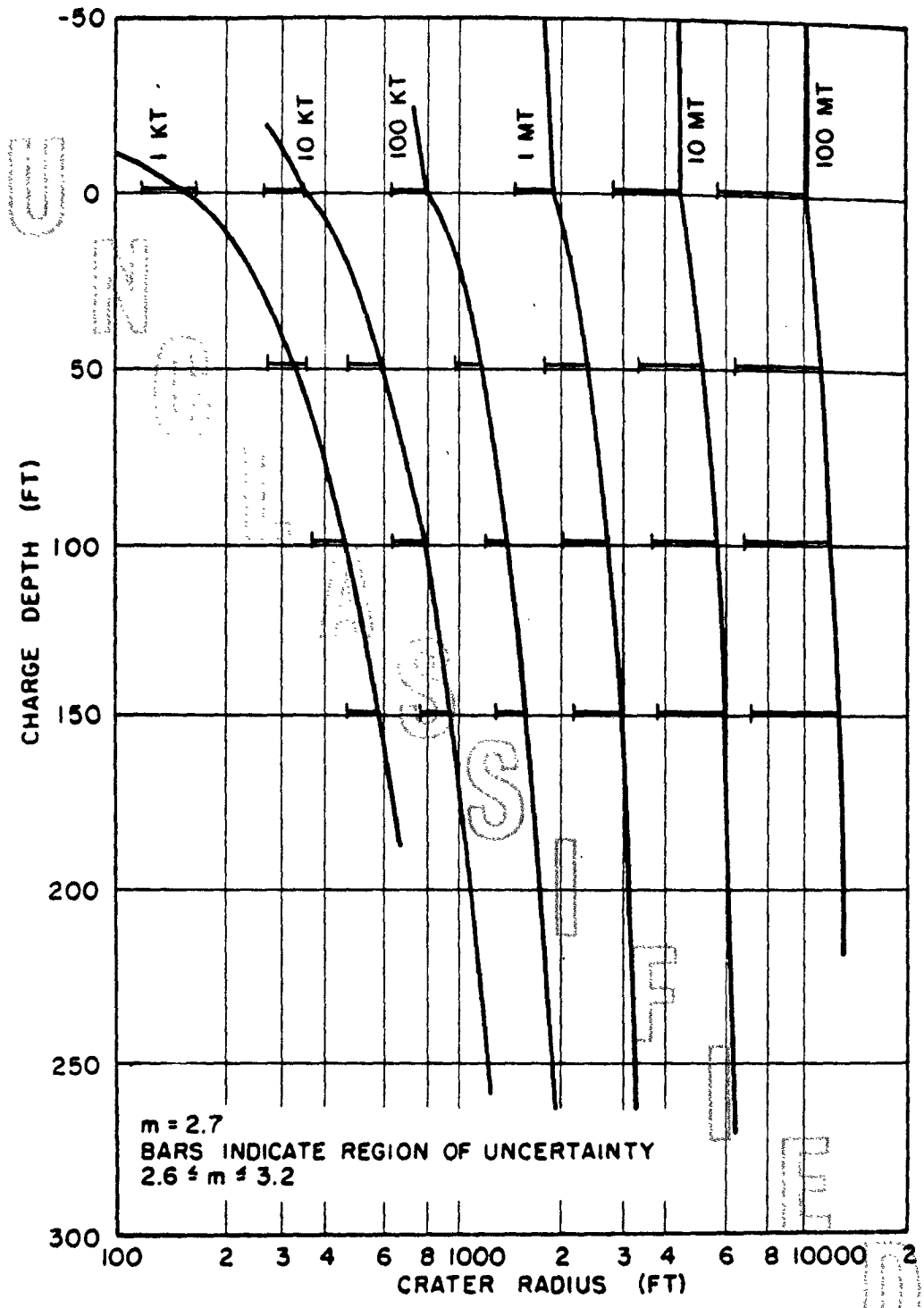
Fig. 4.9 Crater Radius vs Charge Depth, Dry Sand

The figure plots CHARGE DEPTH (FT) on the vertical axis (from -50 at top to 300 at bottom) against CRATER RADIUS (FT) on the horizontal logarithmic axis (from 100 to 20000). Curves are labeled 1 KT, 10 KT, 100 KT, 1 MT, 10 MT, and 100 MT.

Notes on the figure:

m = 2.7
BARS INDICATE REGION OF UNCERTAINTY
2.6 ≤ m ≤ 3.2
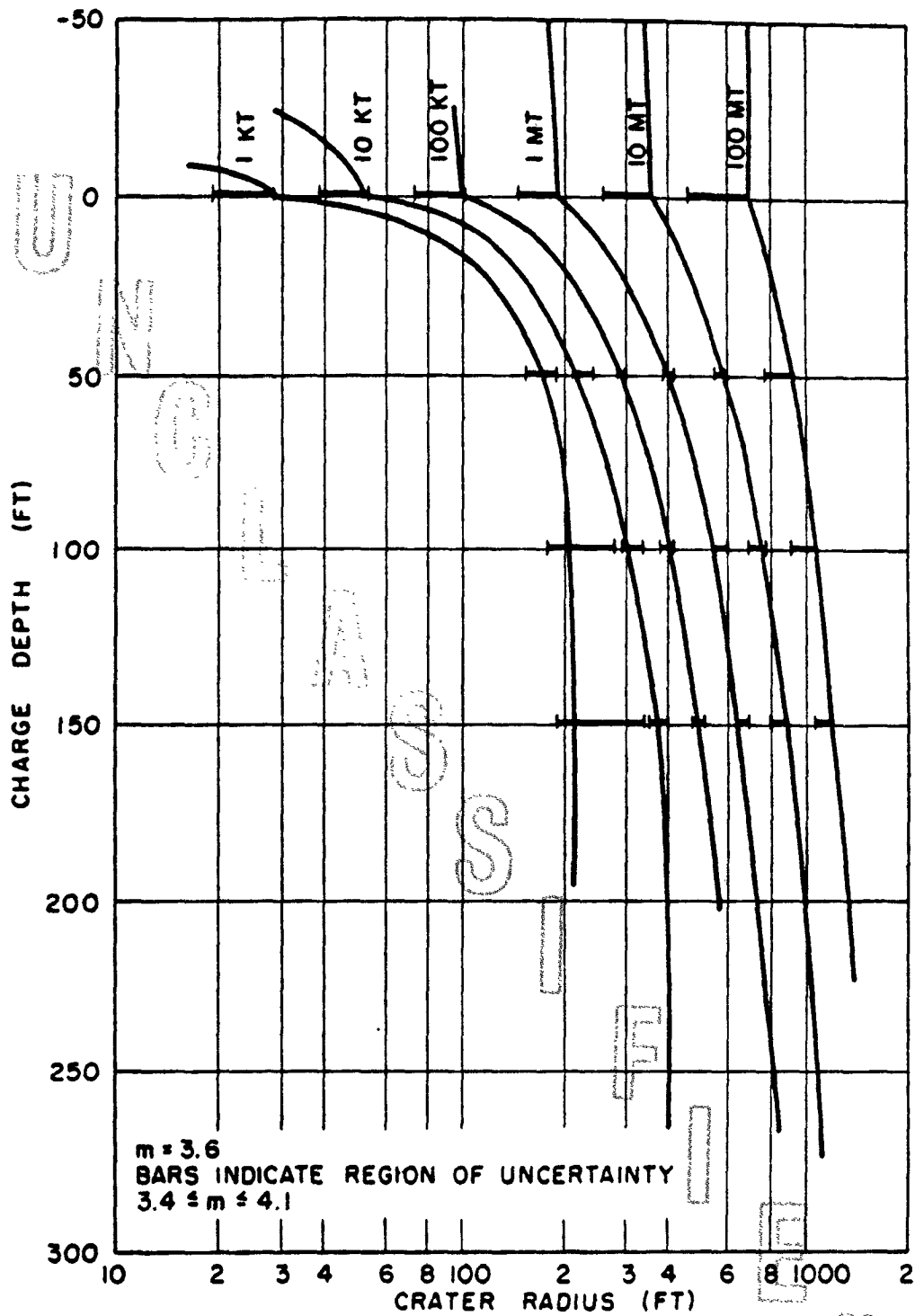
Fig. 4.10 Crater Radius vs Charge Depth, Sandstone

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TABLE 4.1 - Scaling Exponent, m, for Several Soils

Soil	Most Probable	Minimum	Maximum
Nevada	3.4	3.0	4.1
Dry Clay	2.9	2.8	3.2
Wet Clay	2.5	2.0	3.3
Dry Sand	2.7	2.6	3.2
Sandstone	3.6	3.4	4.1

In Fig. 4.11 the results for surface charges in various soils are shown. For each soil the line drawn is that for the most probable value of m. On this curve also are shown the nuclear craters at Nevada and in the Marshalls. In plotting the results of the nuclear explosions on this figure, the value of efficiency found for the JANGLE surface shot for the scaling exponent m = 3.4, namely 60 per cent, has been assumed to be applicable to the explosions in the Pacific. The logarithmic grid has been adjusted in the region of 1 KT to include this efficiency for all larger yields. Hence the graph can be entered directly with the value of radiochemical yield. This graph gives a realistic indication of the uncertainty in crater prediction depending on the properties of the soil.

All data that have been used in the development of the extrapolation method presented here are summarized in Appendix A. This appendix also includes data for some TNT shots, namely those in wet sand, as well as some nuclear charges, such as Trinity, which were not used in the actual analyses presented here.*

4.3 COMMENTS ON THE EXTRAPOLATION METHOD

It should be noted explicitly that the extrapolation method described here is based on an empirical equation of the form

$$R = f(W, m) \cdot f(\lambda_c)$$

or

$$R = (WE)^{\frac{1}{m}} \cdot f(\lambda_c)$$

where E is an efficiency which depends on medium, scaled charge depth, and type of explosive. As mentioned in section 1.5, this is not the only form of equation which can be postulated, and defended. The available data are so meager, and their scatter around the curve representing any specific equation is so great, that it is not possible at present to establish unequivocally the relative validity of alternative forms of the empirical equation.

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* The wet sand TNT results were not used because data on only one charge size was found and hence a value of slope could not be established. A value for Trinity was not used because the scaled height is greater than that of interest in this report.
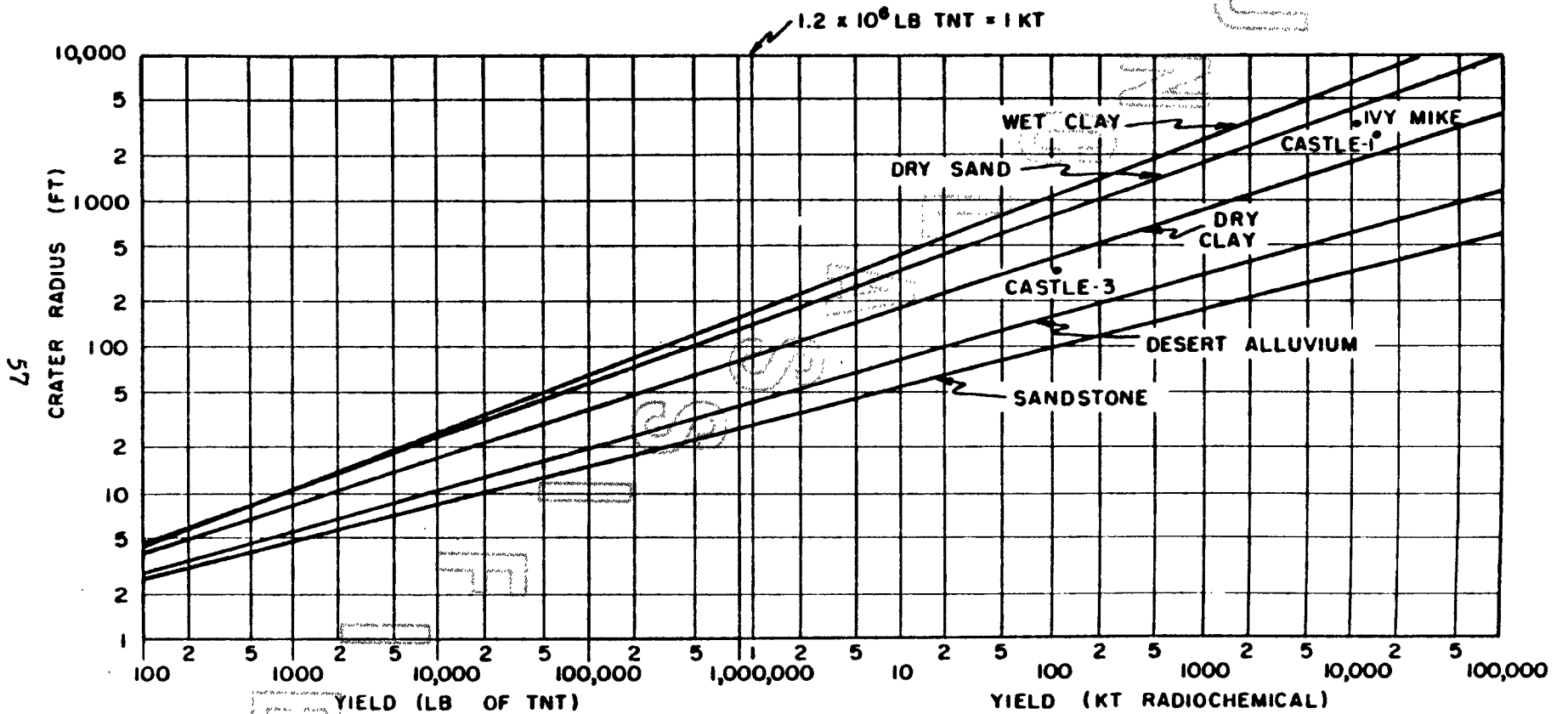
Fig. 4.11 Crater Radius vs Yield, Surface Shots in Various Soils. Scale is adjusted
assuming a nuclear efficiency of 60 per cent, i.e., 1 KT = 0.6 x 2x10⁶ lb TNT.

The suggestion has been made that an equation of the form

$$R = (WE)^{1/3} \cdot f(\lambda_c) \cdot f(m)$$

is more satisfactory.* When either form is used for the extrapolation of TNT data to megaton nuclear explosions, a certain range of uncertainty in R is shown, resulting from reasonable values assumed for the uncertainty in $f(\lambda_c)$ and $f(m)$. The uncertainty in R shown by the suggested equation form is smaller than that shown by the equation form used in the main body of this report.

Another and more important benefit adduced for the suggested form is that the predicted crater radii for megaton explosions have a smalle spread when soil characteristics are changed.

It is the opinion of the author that the benefits indicated are illusory and that the form used in the main body has a slightly better basis. The true value of crater radius produced by a megaton explosion in any medium other than that existing in the Marshall Islands will remain unknown until such a shot is fired and the resulting crater measured. In the meantime, it is felt that caution in stating the expected values and their uncertainties is of vastly greater military use than over-optimism.

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* One piece of information which has been put forward as favoring the suggested form of equation is the result of some cratering experiments in the Marshall Islands. These experiments were run under the directio of Dr. H. Kirk Stephenson, currently on the staff of the National Scien Foundation. Quoting from Memorandum SWPEF 2/924 (354.2) dated 26 Nov. 1954, "1. A series of high explosive shots were fired on Elugelab (Flor Island, Eniwetok Atoll in the spring of 1952. These shots consisted of a combination of R-7-HDA(c-2)R-7-HCA(Tetrytal), primacord, and blast ing caps piled in a beehive shape on the surface which had been excavated down to the high tide level. A dike was established around the charge to prevent wave interference but this proved ineffective. In addition to seismic shock information, the crater radii were determined The crater data obtained from these HE shots at the Pacific Proving Grounds may be used to establish a soil factor for comparing saturated coral with Nevada soil. A summary of the data is as follows:

W(tons TNT Equivalent)	$W^{1/3}$ $(lbs)^{1/3}$	Scale height to c.g.(λ_c)	Crater Radius R_c - ft.	$R_c/W^{1/3}$
1	12.6	0.06	27.5	2 18
5	21.5	0.06	32	1.49
10	27.1	0.06	37.5	1.39
15	31.1	0.06	45.5	1.47
20	34.2	0.06	50	1.47
			overall average	1.60
			Average if first shot omitted	1.46."

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(footnote cont.)

The corresponding HE data from Nevada taken from Tables A.4 and A.6 give a value for $R_c/W^{1/3}$ of about 0.8. If one uses the suggested form of the equation and hence assumes that the effect of soil is independent of the effect of charge size, then one might say that craters in the Marshalls should be expected to be 1.8 to 2.0 times as large (in radius) as craters from identical charge sizes and depths in Nevada.

In a similar manner it is found that the value for $R_c/W^{1/3}$ for megaton surface shots in the Marshalls is about 1.0, while that for the kiloton surface shot in Nevada is 0.34, which implies that Marshall craters will be some three times larger than Nevada craters. Actually, if the small but finite value of $D_c/W^{1/3}$ is taken into account, particularly for the JANGLE surface shot, the analysis suggests that scaled crater radii for nuclear charges in the Marshalls are twice as large as for those in Nevada. Since this is the same figure that was obtained for HE craters, it is tempting and not implausible to say that all scaled crater radii in the Marshalls will be very close to twice those in Nevada.

While the precise data quoted from the AFSWP memorandum were not at hand during the development of the extrapolation method described in section 4.2, some prior discussion of them was held with Dr. Stephenson by telephone. At that time it was Dr. Stephenson's feeling that the data themselves were somewhat unreliable because all the craters were water-washed before measurement. In addition it seems improper to assume that the characteristics, for cratering purposes, of the water-saturated coral sand involved in the HE tests are identical with the characteristics of the more coherent water-saturated coral rock involved in the nuclear shots.

SUMMARY OF AVAILABLE CRATER DATA

TABLE A.1 - Nuclear Crater Measurements*

Shot	Soil	RC Yield	Height of Burst (ft)	Height of Burst (λ)	Crater Radius** (ft)	Crater Radius** (λ)	Crater Depth (ft)	Crater Depth (λ)
TRINITY	Dry Sand	23.8 KT	100	-0.277	550	1.52	9.5	0.026
GREENHOUSE Dog[a]	Sat.cor. sand		300	-0.546	390	0.71	2.0	0.0036
GREENHOUSE Easy[a]	Sat.cor. sand	46.7 KT	300	-0.664	418	0.925	2.4	0.0053
GREENHOUSE George[a]	Sat.cor. sand		200	-0.266	570	0.756	10.0	0.0133
JANGLE Surface	Desert Alluvium	1.2 KT	3.5	-0.026	45	0.336	17	0.127
JANGLE Underground	Desert Alluvium	1.2 KT	-17	0.127	129	0.961	53	0.396
IVY Mike[a]	Sat.cor. sand	10.5 MT	35	-0.0127	3120 (2800)[b]	1.125 (1.02)[b]	164	0.0593
CASTLE 1	Sat.cor. sand	14.5 MT	7	-0.002	3000	0.98	240	0.078
CASTLE 3	Sat.cor. sand	110 KT	13.6	-0.023	400	0.66	75	0.124
TEAPOT Ess	Desert Alluvium		-70		147		90	

Sat. cor. sand = saturated coral sand

* All data except CASTLE and TEAPOT data are obtained from Cratering Produced by Nuclear Weapons, W.R. Perret, Sandia Corporation Technical Memorandum, Ref. Symbol 1922-2-(23) January 2, 1954.

** All crater radii are measured at original ground level.

a Due to scour from water rushing back in, and to aging (for GREENHOUSE) measured diameters may be large by 10 to 30 per cent, measured apparent crater depths may be shallow by a factor of 2 or more.

b In Memorandum SWPEF 2/924 (354.2) dated 26 November 1954, the statement is made that plotting the IVY Mike data on an expanded vertical scale gives a value for crater radius of 2800 ft ($\lambda = 1.02$).

TABLE A.2 - TNT Crater Measurements in Dry Sand, Dry Clay, and Wet Clay*
Underground Explosion Test Program
Site: Dugway Proving Grounds

Soil	Round	Charge Weight (lb TNT)	Charge (ft)	Depth (λ)	Crater (ft)	Radius** (λ)	Crater (ft)	Depth (λ)
Dry Sand	101	320	-3.5	-0.51	4	0.59	0.5	0.07
	102	320	0.0	0.0	7.68	1.12	2.5	0.37
	103	320	1.3	0.19	10.88	1.59	6	0.88
	104	320	3.5	0.51	12	1.75	6.5	0.95
	105	320	7.0	1.02	15.5	2.26	8.5	1.24
	106	320	14.0	2.04	16.75	2.45	4.5	0.66
	107	320	21.0	3.07	13.5	1.97	3.5	0.51
	108	2,560	2.6	0.19	19	1.39	9.75	0.71
	109	2,560	7.0	0.51	24.75	1.81	8.5	0.62
	110	320	3.5	0.51	13	1.9	7.5	1.10
	111	8	2.5	1.25	6	3	4	2
	112	2,560	7.0	0.51	30	2.2	12	0.88
	113	320	3.5	0.51	14	2.0	6.75	0.99
	114	8	2.5	1.25	6	3	3.5	1.75
	115	40,000	17.5	0.51	75	2.19	23	0.67
	116	320	8.75	1.28	18.5	2.7	9	1.32
Dry Clay	301	320	-3.5	-0.51	2.5	0.37	1	0.15
	302	320	0.0	0.00	7.25	1.06	4	0.58
	303	320	1.3	0.19	9	1.3	5.5	0.80
	304	320	3.5	0.51	10.5	1.5	6	0.88
	305	320	7.0	1.02	11.75	1.72	7	1.02
	306	320	14.0	2.04	15	2.2	1	0.15
	307	320	21.0	3.07	10	1.46	1	0.15
	308	2,560	2.6	0.19	20	1.46	12	0.88
	309	2,560	7.0	0.51	21.5	1.57	15.5	1.13
	310	320	3.5	0.51	11	1.6	7	1.02
	311	8	2.0	1.0	4	2	2.5	1.25
	312	2,560	7.0	0.51	26	1.90	15	1.09
	313	320	3.5	0.51	12.75	1.86	8	1.17
	314	8	2.5	1.25	4.5	2.25	3	1.5
	315	40,000	17.5	0.51	64	1.87	42	1.23
	316	110	2.45	0.51	9	1.87	6	1.25
	317	2,560	7.0	0.51	23	1.68	15.5	1.13
	318	320,000	35.0	0.51	120	1.75	60	0.88
	319	2,560	7.0	0.51	23	1.68	13.5	0.98
	Sym.	320	7.0	1.02	12.5	1.83	7	1.02
Wet Clay	401	8	2.5	1.25	7	3.5	5	2.5
	402	320	2.5	0.36	18.75	2.74	10	1.46
	403	2,560	5.0	0.36	41.75	3.05	12.75	0.93
	404	320	2.5	0.36	17.5	2.56	11.5	1.68
	405	8	2.5	1.25	6	3	4.1	2.05

* Obtained from Appendix G, Underground Explosion Test Program, Final Report, Volume I, Soil Engineering Research Associates, August 30, 1952.
** All crater radii are measured at original ground level.

TABLE A.3-TNT Crater Measurements in Limestone,Granite,and Sandstone*
Underground Explosion Test Program
Site: Dugway Proving Ground

Soil	Round	Charge Weight (lb TNT)	Charge Depth (ft)	(λ)	Crater Radius** (ft)	(λ)	Crater Depth*** (ft)	(λ)
Lime- stone Granite	501	320	6.6	0.97	11.2	1.64	9.1	1.33
	502	320	2.5	0.365	8.3	1.21	3.9	0.57
	601	320	-2.5	-0.365	1.20	0.175	...	....
	602	320	0.0	0.00	8.43	1.23	1.7	0.25
	603	320	2.5	0.365	9.70	1.42	2.6	0.38
	604	320	5.0	0.73	14.5	2.12	5.0	0.73
	605	320	12.5	1.83	17.1	2.50	6.1	0.89
	606	320	25.0	3.65	5.20	0.76	2.0	0.29
	607	320	2.5	0.365	14.4	2.11	5.3	0.78
	608	320	2.5	0.365	14.0	2.05	4.6	0.67
	609	2,560	5.0	0.365	25.2	1.84	10.2	0.75
	610	2,560	5.0	0.365	23.1	1.69	8.7	0.64
	611	320	2.5	0.365	13.4	1.96	5.0	0.73
	612	320	17.0	2.49	13.2	1.93	7.6	1.11
Sand- stone	801	320	-2.5	-0.365	0.0	0.0	0.0	0.00
	802	320	0.0	0.0	5.6	0.82	2.3	0.34
	803	320	2.5	0.365	11.6	1.69	4.8	0.70
	804	320	5.0	0.73	14.0	2.04	7.6	1.11
	805	320	12.5	1.82	9.3	1.36	14.9	2.17
	806	320	25.0	3.65	0.0	0.00	a	a
	807	320	2.5	0.365	14.3	2.09	5.1 b	0.75
	808	320	2.5	0.365	13.1	1.91	5.8	0.85
	809	1,080	3.75	0.365	19.0	1.85	8.6	0.84
	810	2,560	5.0	0.365	32.6	2.38	9.7	0.71
	811	2,560	5.0	0.365	25.1	1.83	10.5	0.77
	812	2,560	5.0	0.365	23.3	1.70	11.0	0.80
	813	10,000	7.9	0.365	39.4	1.83	16.1	0.75
	814	40,000	12.5	0.365	56.5	1.65	26.9	0.79
	815	40,000	12.5	0.365	70.5	2.06	26.9 b	0.79 b
	816	40,000	12.5	0.365	53.6	1.56 c	27.5 b	0.80 b
	817	320,000	25.0	0.365	94.8	1.38 c	47.0	0.69
	818	320	2.5	0.365	17.5	2.56	6.0	0.88
	819	320	2.5	0.365	15.6	2.28	6.5	0.95

*Obtained from Underground Explosion Test Program-Technical Report No. 4, Granite and Limestone, Volume I and from Underground Explosion Test Program-Technical Report No. 5, Sandstone, Volume I, Engineering Research Associates, Feb. 15, 1953.

**All crater radii are measured at original ground level.

***Average Crater depth (D_k) is the average of the measurements of the vertical distance from the deepest point of the crater, not necessarily directly under the charge, to the surface, one measurement being made on each of the four vertical sections available for each crater. This depth is not significant unless the deepest point is below the bottom of the excavation made to place the charge. The charge hole was obliterated by all the detonations at the sandstone site except Round 306.

Notes on Table A.3 (Continued)

a-The damage did not extend to the surface and is not comparable with other rounds; the sides of the original charge hole were damaged up to an average slant distance of 5.6 ft from the center of gravity of the charge.

b-Crater shape was estimated; the breakthrough volume is not included.

c-Average of eight measurements scaled from the vertical crater sections.

TABLE A.4 - TNT Crater Measurements in Desert Alluvium, Operation JANGLE*

Operation: JANGLE HE Shots
Site: Nevada Proving Grounds (Yucca Flat)

Round	Charge Weight (lb of TNT)	Charge (ft)	Depth (λ)	Crater (ft)	Radius** (λ)	Crater (ft)	Depth (λ)
HE-1	2,560	2.01	0.15	18.2	1.33	6.5	0.47
HE-2	40,000	4.63	0.15	38.6	1.13	14.9	0.44
HE-3	2,560	6.79	0.50	19.8	1.45	10.8	0.79
HE-4	2,560	-2.01	-0.15	6.4	0.47	1.9	0.14
HE-5	2,560	4.02	0.30	19.6	1.43	7.8	0.57
HE-6	2,560	3.00	0.22	19.7	1.44	6.7	0.49
HE-7	2,560	2.58	0.19	18.9	1.38	6.9	0.50
HE-8 b	216	1.08	0.18	a	a	a	a
HE-9 b	216	0.83	0.14	8.2	1.37	3.5	0.58
HE-10b	216	3.00	0.50	11.3	1.88	5.5	0.92

*Obtained from Some HE Tests and Observations on Craters and Base Surges, D. C. Campbell, Armed Forces Special Weapons Project, Operation JANGLE Project 1(9)-3, 1 November 1951. (WT-410).

**All crater radii are measured at original ground level.

a-Partial detonation

b-Results from a corresponding 177-lb Pentolite charge are not included in this summary.

TABLE A.5 - TNT Crater Measurements in Dry Clay, Project MOLE*

Project: MOLE (Stanford Research Institute)
Site: Dugway Proving Grounds

Round	Charge Weight (lb of TNT)	Charge (ft)	Depth (λ)	Crater (ft)	Radius** (λ)	Crater (ft)	Depth (λ)
101	256	6.35	1.00	11.1	1.73	5.5	0.86
105	256	6.35	1.00	10.9	1.72	6.0	0.94
102	256	3.18	0.50	10.5	1.65	6.3	0.99
102A	256	3.18	0.50	9.5	1.50	5.4	0.85
106	256	1.65	0.26	9.1	1.43	6.2	0.98
107	256	0.0	0.00	6.6	1.04	3.9	0.61
104	256	-0.83	-0.13	4.4	0.69	1.5	0.24

TABLE A.6 - TNT Crater Measurements in Desert Alluvium, Project MOLE*

Project: MOLE (Stanford Research Institute)
Site: Nevada Proving Grounds (Yucca Flat)

Round	Charge Weight (lb of TNT)	Charge (ft)	Depth (λ)	Crater (ft)	Radius** (λ)	Crater (ft)	Depth (λ)
202	256	6.35	1.00	11.5	1.81	5.7	0.90
212	256	6.35	1.00	10.7	1.69	6.1	0.96
203	256	3.18	0.50	8.4	1.32	4.0	0.63
204	256	1.65	0.26	9.2	1.45	2.9	0.46
205	256	0.83	0.13	8.8	1.39	2.5	0.39
206	256	0.0	0.00	6.4	1.01	1.9	0.30
207	256	-0.83	-0.13	3.5	0.55	1.4	0.22

* Obtained from Small Explosion Tests - Phase I of Project MOLE, R.B.
Vaile, Jr., Stanford Research Institute, January 1953.

** All crater radii are measured at original ground level.

TABLE A.7 - TNT Crater Measurements in Wet Sand, Project MOLE*

Project: MOLE (Stanford Research Institute)
Site: Camp Cooke, California

Round	Charge Weight (lb of TNT)	Charge (ft)	Depth (λ)	Crater (ft)	Radius** (λ)	Crater (ft)	Depth (λ)
304[a]	256	4.83	0.75	18.6	2.94[a]	6.6[a]	1.04[a]
301	256	3.18	0.50	19.1	3.01	...	....
302	256	3.18	0.50	19.9	3.14	6.3	0.99
309	256	3.18	0.50	15.6	2.45	6.1	0.96
310	256	3.18	0.50	16.8	2.64	5.2	0.82
305	256	1.65	0.26	14.3	2.26	6.3	0.99
306	256	0.83	0.13	12.8	2.01	3.7	0.58
307	256	0.00	0.00	10.2	1.61	4.8	0.75
308	256	-0.83	-0.13	8.8	1.39	4.0	0.63

a - Round 304 was shot in the crater of Round 303.

TABLE A.8 - TNT Crater Measurements in Wet Clay, Project MOLE*

Project: MOLE (Stanford Research Institute)
Site: Camp Cooke, California

Round	Charge Weight (lb of TNT)	Charge (ft)	Depth (λ)	Crater (ft)	Radius** (λ)	Crater (ft)	Depth (λ)
311	256	3.18	0.50	15.5	2.45	11.2	1.76
312	256	3.18	0.50	17.8	2.80	9.0	1.42
313	256	-0.83	-0.13	5.8	0.91	3.4	0.53

* Obtained from Small Explosion Tests - Phase II of Project MOLE,
L. M. Swift and D. C. Sachs, Stanford Research Institute, May 1954.

** All crater radii are measured at original ground level.

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