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GEOLOGIC STUDIES OF UNDERGROUND NUCLEAR EXPLOSIONS RAINIER AND NEPTUNE FINAL REPORT

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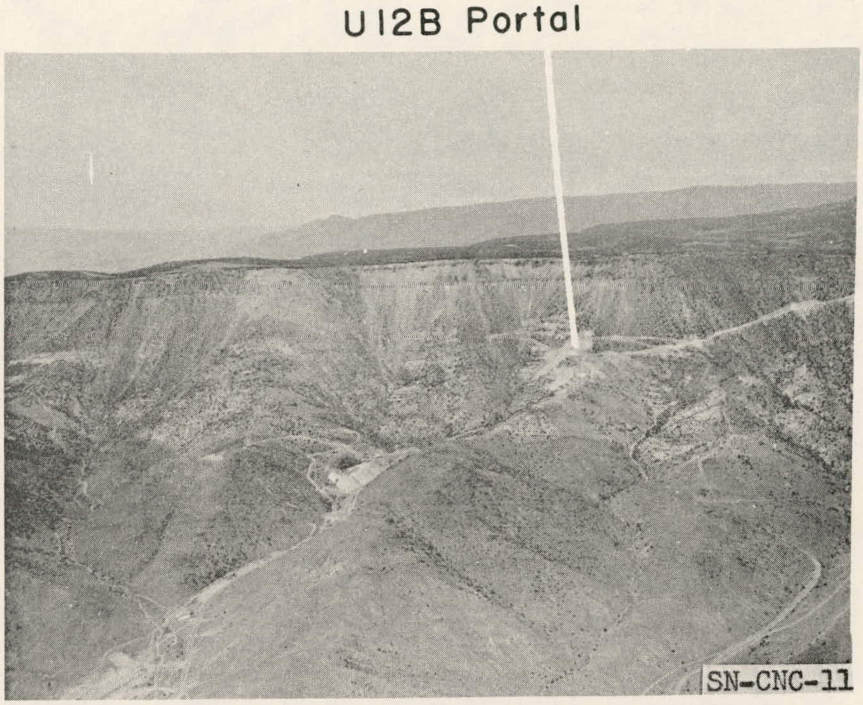
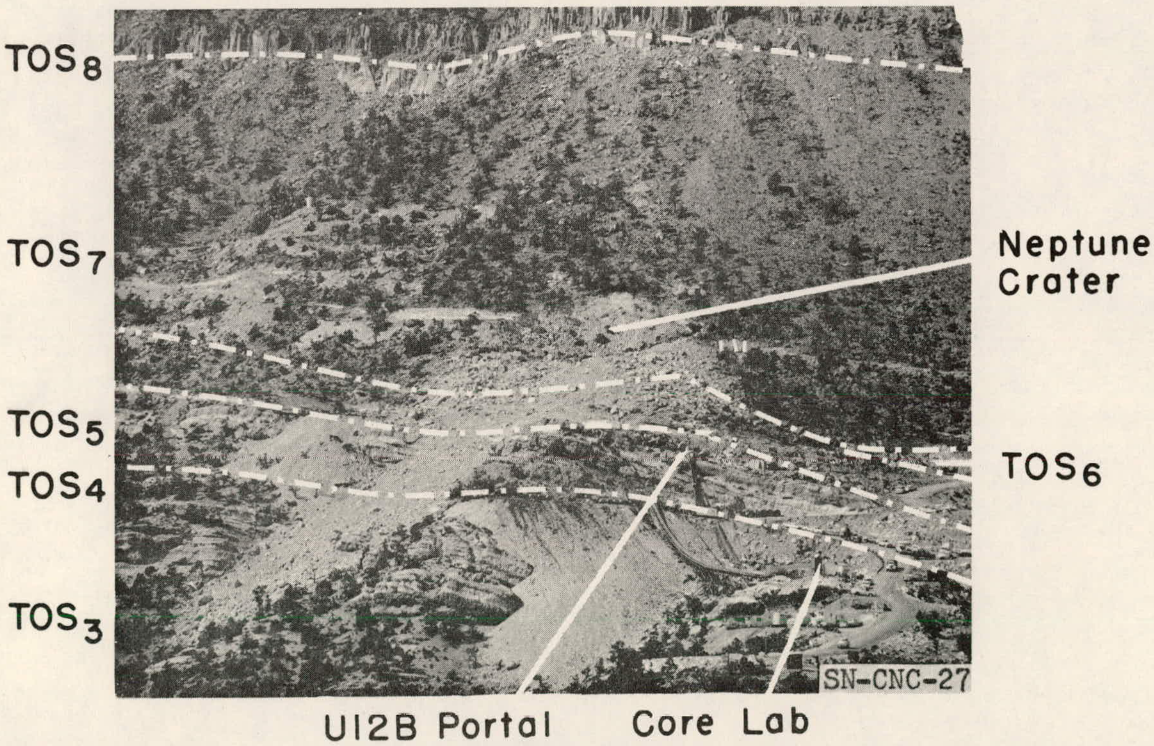
FINAL REPORT

Thomas L. Thompson and John B. Misz

October 28, 1959





Frontispiece. Above, Aerial View of Rainier Mesa. Below, Neptune Crater, U12-B Tunnel Portal, Core Laboratory, etc.

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GEOLOGIC STUDIES OF UNDERGROUND NUCLEAR EXPLOSIONS RAINIER AND NEPTUNE

Thomas L. Thompson* and John B. Misz**

I. INTRODUCTION

This report is an analysis of rock changes and displacements resulting from underground nuclear explosions Neptune and Rainier.

A. Background Information

Rainier and Neptune were exploded at the end of tunnels driven into the side of Rainier Mesa. (See Figs. 1 and 2.) The mesa is capped by 250 feet of hard, brittle, welded tuff (TOS_8). This welded tuff is underlaid by a 500-foot sequence (TOS_7) of pyroclastic materials, which range, generally, from structurally weak, friable materials in the upper two-thirds to compact, hard materials in the lower one-third. This in turn is underlaid by welded tuff (TOS_6) which varies in thickness from 10 feet on the surface near Neptune to 85 feet under Rainier. Beneath TOS_6 is another 600 to 800 feet of bedded tuff which is generally well-cemented and hard. This pyroclastic sequence rests on Paleozoic limestone and dolemite.

The Rainier explosion took place in a 6 × 6 × 7 foot room, 90 feet above the base of TOS_7 and in the bottom of a shallow east-northeast trending syncline. The vertical depth of burial was 900 feet and the distance to the nearest point on the sloping surface of the mesa was 790 feet.

The Neptune shot room measured 12 × 17 × 10 feet high. The shot was located 10 feet above the base of TOS_7 which dips 15 to 25 degrees to the northwest. The vertical depth of burial was 110 feet and the nearest point to the surface was 100 feet.

The total energy release was equivalent to 90 ± 20 tons of high explosives for Neptune and 1700 tons of high explosives for Rainier. One ton is defined as 10^9 calories of energy.

The Neptune explosion broke out to the surface with some venting of radioactive material. Documentary films show the sudden bulging of the mountain side over the detonation point. This bulge expanded and rose to

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a height of 25 to 35 feet at which time the explosion burst out on the downhill side from under the domed mass, and great volumes of rock were blasted some 80 feet into the air and down the mountain side. Sequentially the domed mass settled back into the void with the result that a crater was formed which measures 200 feet wide and 50 feet deep. Open fractures are observed on the surface to a radius of about 150 feet.

The Rainier explosion was completely contained.[1] The main tunnel collapsed to a radial distance of 200 feet from ground zero and spalling was observed to about 400 feet. At 1100 feet from the center of detonation, there was a shift along a bedding plane of about 4 inches. A 9-inch vertical displacement was observed at the ground surface 350 microseconds after the explosion. Rocks were shaken loose from the cap rock (TOS_8) for distances of about one-half mile on each side of the detonation point.

The sequence of events immediately following the explosion as reconstructed by previous workers[1] is as follows:

At the time the energy was released in the shot room, the temperature was about 1,000,000°K, and the pressure 7,000,000 bars. (1 Bar = 1 atmosphere.) The shock for about the first three feet was sufficiently strong to vaporize the rock, and to melt it to a radius of 15 feet. The rock was crushed to a radius of about 130 feet.

As the shock moved outward, the room expanded spherically and reached a radius of 62 feet in several milliseconds. At this time, the cavity was lined with about 4 inches of melted rock (that was initially contained in a sphere of radius 15 feet about the center of detonation), at a temperature of 1200°C to 1500°C. The cavity when first formed was filled with steam at a pressure of 40 atmospheres, which is approximately the lithostatic pressure. The cavity stood long enough, between 30 seconds and 2 minutes, for much of the fluid rock to flow down the sides and to drip from the roof. At this time the cavity began to collapse and cool rapidly due to expansion of the steam which quenched some of the droplets of rock in free fall, as well as some of the "icicles" as they hung from the cavity roof. The cavity was filled with broken rock from the collapse, and the caving progressed vertically to a distance of 388 feet above the point of detonation. Because of the presence of water and the large permeable region produced by the collapsed cavity, the melted rock rapidly cooled to the temperature of boiling water, 93°C (at elevation 6600 feet). All of the rock which was initially melted converted to a glass on cooling. The glass was found to contain all of the radioactive fission products except some of the rare gases.

The model just described is based on data from one hole (R-6) drilled from the surface vertically downward through the point of the detonation, and from three cored holes (B, C, and D) drilled from within the tunnel. (See Plate V.) Drilling vertically downward revealed no radioactivity until the drill broke into a 25 foot high cavity at depth 513 feet. From this point down to the center of detonation, the rock was broken and permeable as indicated by the failure to recover cores and by the loss of drilling fluid. Drill holes B, C, and D revealed a crushed region within a 62-foot radius from ground zero.

For further details of the phenomena and geologic effects of underground nuclear explosions as understood previously, the reader is referred to reports by Johnson and Violet[1] and Diment et al.[2]

B. Present Study

The principal objectives of the current study are:

1. To determine the present physical distribution and condition of rock materials.
2. To establish the original position of displaced rock materials.
3. To extend the knowledge of the results of detonation of Rainier and Neptune.
4. To establish criteria by which data pertinent to the understanding of the explosions can most readily be derived and described.
5. To relate these studies to practical engineering and mining application.

The method of approach has been to utilize elementary geologic observation of lithologic and structural details and stratigraphic correlation. The data are derived primarily by hand-lens examination of drill core from some 5,000 feet of drilled depth, from surface mapping in Neptune area, and from underground mapping of two 400-foot exploratory drifts in the Rainier area.

The physical and lithologic properties of the rocks in the different stratigraphic units are discussed in detail in Section IV because this information composes the principal factual data upon which this report is based. The interpretations discussed in the text and shown on the illustrations are based upon factual data and application of the theory of rock deformation. The results of the investigation are illustrated by plans and cross sections (Plates I through VI). The main text is principally a discussion of these illustrations with brief excursions into theoretical aspects and discussion of possible practical application.

II. SUMMARY AND CONCLUSIONS

The approximate physical distribution and condition of displaced and ruptured rock materials in the Rainier and Neptune areas have been established by geologic observation of structural and lithologic details, and stratigraphic correlations. The effects of the detonations are found to be related to the rock types considered from the standpoint of engineering materials as well as to their structural positioning. Gross displacements and fracturing are in apparent accord with Mohr theory of rupture stress orientation. Factual data find explanation on the fundamental basis of primary (blast) and secondary (gravity) induced principal stresses.

The 90 ± 20-ton Neptune explosion disaggregated and displaced rock materials to a radial distance which ranged between 45 and 100 feet from ground zero depending on the orientation of bedding plane weaknesses and proximity of the ground surface to the point of detonation. Primary fracturing extended from ground zero to a radial distance which ranged from 55 feet to an estimated 145 feet depending on the favorable distribution of geologic structural weaknesses. Neptune was found to exhibit primary (blast) and secondary (gravity) rupture features which are fundamentally the same as those found in the Rainier area.

The 1700-ton Rainier shot initially formed a fused-rock-lined cavity of an average 62 ± 10-foot radius below ground zero and an undetermined radius above ground zero. Gross primary rock displacement and grain disaggregation took place to a radial distance of from 80 to 130 feet from ground zero. Visible primary fracturing extended to a radial distance which ranges between 150 and 220 feet depending on the proximity of hard brittle rock (welded tuff) which, it is concluded, transmitted rupture stresses to a much greater distance than the "punky" granular tuff. Collapse of rock material into the initial cavity was favored by primary shear fractures, which developed prominently to a radius of 150 feet from ground zero. The collapsed rock defines a 100-foot-diameter cylindrical zone. This zone is presumed to extend for 388 feet upward from ground zero. A dome-shaped top is postulated on the basis of Mohr stress theory.[11] It should be noted that, with the exception of drill hole G, there has been no drilling or underground working above the "Raise" Drift. Cavities, distributed around the perimeter of the cylinder, are attributed to variations in the coherence of the rock strata which were disrupted during collapse. The collapse block has remained essentially intact. This fact, coupled with the virtual absence of radioactive fission products above ground zero and nearly complete pulverization of the central collapse block, leads to the conclusion that underground nuclear explosions are applicable to mining by block-caving methods. Furthermore, material within the crushed zone should be mineable without the use of additional explosives. The mineability of material within the fracture limit is a question that is difficult to answer at present, as the degree of fracturing has not been established. Perhaps the direct approach of experimental excavation would be the best solution to the problem.

The conclusions enumerated above should be considered as hypotheses awating verification. There is still much to be learned from the Rainier explosion.

III. WORK PROCEDURES AND FACTUAL DATA

Methods of analysis are discussed in relatively great detail for the possible benefit of other persons who may be engaged in this type of work. As the methods of core logging and data presentation to-date are in the developmental stage, minor inconsistencies are to be expected. All maps, graphic core logs, plans and cross sections have been completed at the same scale (1 inch: 20 feet) to allow convenient analysis. Observed details are given on field maps and in written descriptions of field observations and core analysis. Core logging data are in graphic form to aid interpretation. Plans and cross sections have been developed from and concurrent with the collection of basic data.

A. Surface Mapping

Surface geologic and topographic maps were prepared in the Neptune area using plane table and alidade methods. All rod stations were located directly from the same instrument station, 125 feet east of ground zero.

The reader is referred to Plate I for details of the mapping. Large boulders within the boundaries of the rubble area are drawn to scale.

B. Tunnel Mapping

With the exception of a brief examination of U12.03-C drift, the authors' tunnel mapping was confined to the Rainier area. Plan mapping was carried out at waist level with steel tape measurements between surveyed drift station numbers. Cross sections of the walls were mapped where significant details were not found in plan.

In U12-B "Raise" Drift, mapping was conducted concurrently with mining activity by daily or twice daily trips to the heading. This procedure was considered essential for adequate mapping of the drift as wall lagging and overhead spiling have since concealed many of the pertinent geologic details.

The U12-B Exploratory Drift was mapped for obvious geologic features and some further geologic detail was obtained from USGS-TEI Report 355.[2]

C. Core and Core Hole Analysis

Core and core hole investigation included analysis of radiation measurements, drilling data, rock fracturing, petrographic descriptions, and other pertinent observations.

Cores were examined from 13 drill holes totaling 3100 feet of drilled depth in Rainier area, and 11 drill holes totaling 1800 feet of drilled depth in Neptune area.

1. Rock Descriptions.

Petrographic descriptions were by hand lens examination with basic reference to color, structure, hardness, and texture. Structure is referenced with terms such as massive, thick-bedded, etc.

An arbitrary hardness scale was set up on the basis of numbers from 1 to 5. The numbers in sequence refer to the rock as (1) loose or slightly cemented grains; (2) friable when the rock can be readily disintegrated by hand; (3) slightly friable when grains may be rubbed off with the fingers but the material does not disintegrate; (4) hard when the material is broken by hand with difficulty; (5) very hard when the material is silicified or cherty.

Texture refers to size, shape, percentage, and distribution of mineral and rock particles. Colors represent the general color of samples rather than the color of individual particles or fragments, which are specifically described. In some instances, colors have been keyed to the rock color chart as developed by the Geological Society of America (1951).[14]

Rock names for pyroclastic rocks are based on the dominant particle size. The Wentworth scale as presented by Wahlstrom[3] is used with the exception that the term medium tuff is added. The terminology is presented as follows:

Fragment type	Size	Rock type
Block, bomb	Over 32 mm	Volcanic breccia or agglomerate
Lapilli	4 to 32 mm	Lapilli tuff
Coarse ash	2 to 4 mm	Coarse tuff
Medium ash	1/2 to 2 mm	Medium tuff
Fine ash	Less than 1/4 mm	Fine tuff

2. Core Examination.

Core descriptions are as described from wet samples. Preliminary examination of cores was made at the drill site when possible. Subsequently, the core for the entire drilled depth was laid out in sequence in the laboratory. A cursory examination was made by breaking and wetting the core and leaving the freshly broken end face-upward in the core box. Stratigraphic contacts were picked and general notes made on such things as fused fragments, wood debris, crushed materials, and the degree and type of fracturing. The angle between bedding and core axis was determined by protractor with the core held parallel to the core box. Representative samples were selected of the different lithologies and the samples were examined with a hand lens to obtain petrographic details. These samples were subsequently cleaned and coated with clear plastic to simulate wetting. The samples are kept on file for correlation and reference purposes.

3. Data Analysis.

Factual observation and interpretation were initially recorded in long hand. Subsequently, the data on core logging, drilling, and radiation were combined on graphic logs at a scale of 1 inch: 20 feet. At the top of each page the map coordinates, elevation, inclination, and bearing are given for the beginning of each one hundred feet of drilled depth. The common parameter, hole depth, allows ready comparison of the various types of data.

D. Illustrations

Basic data, as discussed in preceding paragraphs, have been plotted to scale (1 inch: 20 feet) in plan view and in two cross sections for each explosion area. Symbolic representation of basic data is used to conserve space and make interpretation easier. The legend included with each illustration explains the various symbols. Lithologies are represented both for stratigraphic analysis and for evaluation as engineering materials.

IV. STRATIGRAPHY AND ENGINEERING MATERIALS

Neptune and Rainier were exploded within a 2000-foot sequence of moderately folded (maximum dip 35°) and faulted Tertiary pyroclastic rocks which overlie Paleozoic limestones and dolomites.

The pyroclastic sequence, which is referred to as the Oak Springs Tuff (TOS) by Johnson and Hibbard,[4] has been divided by Hansen and Lemke[5] into eight units referred to as TOS_1, TOS_2, etc. These units have, in part, been divided into subunits which have been given letter designations by Gibbons[6] in the Rainier area. These letter designations for TOS_6 and TOS_7 have been maintained by Diment et al.[2] in their analysis of the Rainier event. The letter "Z" was used for the highest stratigraphic unit exposed in the Rainier underground workings. It is apparent that, in order to extend the subunit designation stratigraphically upward, a new system must be adopted. Accordingly, subunits in each area are given number designations beginning with 1 at the base of each TOS unit. Since lithologies vary considerably from area to area, a small letter suffix (denoting the area) is included with each subunit number. Thus the basal subunit of TOS_7 in the Neptune area is referred to as TOS_{7-1n}. In the Rainier area, a capital letter is included in parentheses to reference the U. S. Geological Survey letter system.

A. Neptune Stratigraphy

Dips of bedding in the Neptune area vary from 35° to 10° (Plate III). Lithologic units TOS_5, TOS_6, and the lower part of TOS_7 are pertinent to an understanding of the explosion effects. In section A-A' (Plate II), the preshot stratigraphic contacts have been reconstructed from core data obtained from apparently undisplaced rock.

The basal 230 feet of TOS_7 is included in a stratigraphic sequence which was measured, sampled, and described on the surface west of Neptune crater. Tape and compass were used for detailed measurements with thickness control by plane-table and alidade. Sample stations are located by number on Plate I. This 230-foot sequence was divided into 10 subunits designated as TOS_{7-1n}, TOS_{7-2n}, etc. These units were projected along strike to the line of Neptune cross section B-B' (Plate III). Preshot stratigraphic contacts in this section were then reconstructed on the basis of the projected surface contacts, cross section A-A' preshot contacts, and data from core holes in the vertical plane of cross section B-B'. Lithologic units thus established were measured for thickness, and a composite stratigraphic column was described on the basis of core analysis and surface sample description. Likewise, the upper part of TOS_{5n} and TOS_{6n} were defined. A description of these units is included in subsequent paragraphs and in brief on Plate I. U. S. Geological Survey descriptions were adopted for TOS_{4n} and the lower part of TOS_{5n}.

Unit TOS_{5n} (thickness 100 to 125 feet), is greenish gray, yellowish gray, olive green, and brown; fine-to coarse-grained; slightly friable to very hard lapilli tuff, which generally forms ledges at the ground surface. Pumice fragments are typically elongated and flattened, while lithic and obsidian fragments up to 15 mm in diameter are scattered throughout the section. The upper 15 feet of the unit are composed of greenish orange, massive, slightly friable; low density; porous lapilli tuff. Greenish gray and orange pumice lapilli range in size from 5 to 15 mm in diameter. Dark green to black, low density, brittle, devitrified obsidian lapilli commonly compose 5% of the rock. 4- to 10-inch interbeds of coarse sandstone make up about 10% of this interval. The top few feet are commonly white to light gray, fine, earthy material believed to be the result of baking during deposition of the overlying welded tuff.

Unit TOS_{6n} is composed of dark purple, yellowish green and brown, very hard, fine tuff and agglomerate with 5 to 20% dark lithic fragments from 1 to 15 mm in diameter, and with a few percent of large (4 to 20 mm), partly flattened pumice lapilli. The top few feet of the unit are typically orange brown to hematite red, fine, earthy material. Examination of Plate III reveals that this unit thickens northwestward from 10 feet to 40 feet in a horizontal distance of about 300 feet.

Subunit TOS_{7-1n} (thickness 1 to 3 feet) is light yellowish green, wavy bedded, slightly friable, lapilli tuff with 5 to 30% dark angular lithic fragments

5 to 20 mm in diameter. The upper contact of the subunit is gradational with the overlying sandstone.

Subunit TOS_{7-2n} (thickness 12 to 15 feet) is primarily a brown, cross-bedded, hard to slightly friable, fine-grained sandstone. The lower few feet of the unit typically contain 1/4 to 3-inch interbeds of yellowish white lapilli tuff (gradational into underlying unit) and lavender brown claystone with 30% light greenish yellow pumice fragments 1 - 3 mm in diameter. The unit grades over a 3-foot zone into overlying subunit TOS_{7-3n}.

Subunit TOS_{7-3n} (thickness 8 to 12 feet) is a buff to light brown, massive, hard to slightly friable, coarse tuff with 5 to 10% yellowish gray to pink tuff lapilli from 4 to 15 mm in diameter. The subunit is gradational into underlying subunit TOS_{7-2n}, the contact being picked where volcanic material predominates over fine sand. Irregular (scalloped) patches of reddish orange porcellanite are common near the base. The upper part of the subunit generally is porcellanite (commonly with faint outlines of lapilli-size fragments), but varies in color from chalky white to brick red or reddish brown.

Subunit TOS_{7-4n} (thickness 20 to 25 feet) is composed of light gray, greenish gray and yellowish gray pumice lapilli (4 to 20 mm in diameter) which form a massive, hard to slightly friable, low density, porous rock with 0 to 5% of dark, angular lithic fragments. This subunit commonly contains interbeds (up to a few feet thick) of brown, sandy tuff typical of subunit TOS_{7-5n}; however, a distinction can be made on the basis of associated pumice lapilli which are gray and gray green in TOS_{7-4n} and white or pink in TOS_{7-5n}.

Subunit TOS_{7-5n} (thickness 20 to 25 feet) is brown, massive, hard to slightly friable, fine to medium grained, sandy tuff with 5 to 15% light yellow to white pumice lapilli from 4 to 15 mm in diameter. The upper few feet commonly show conspicuous fine red specks.

Subunit TOS_{7-6n} (thickness 10 to 15 feet) is typically composed of gray and brown, hard to very hard (silicified), medium-grained sandy tuff. The interbeds seem to vary in thickness along strike. The following sequence was measured and described on the ground surface northwest of Neptune crater (see Plate I).

Bottom: 4 feet (sample 9) of gray, massive, hard, medium-grained, sandy tuff with conspicuous (15%) black mineral fragments (biotite and hornblende).

4 feet (sample 10) of brown, massive, hard, fine-grained, sandy tuff.

Top: 2 feet (sample 11) of mottled gray, very hard (silicified), lapilli tuff.

Total thickness - 10 feet (approximately).

Subunit TOS_{7-7n} (thickness 50 to 60 feet) is slightly friable to friable, thick bedded (1 to 7 feet), medium-grained tuff. Massive beds grade from gray at the bottom to light brown at the top. Two feet from the top of the unit a 6-inch interval is dominated by bluish gray pumice lapilli (4 to 15 mm in diameter). The following sequence was measured northwest of Neptune crater.

Bottom: 18 feet covered.

8 feet (sample 12) of thick beds (2 to 4 feet) which grade from gray, friable tuff at the bottom to light brown, friable tuff at the top. The interval contains occasional 4-inch-diameter, brown, silicified, "rock-ball" concretions. (See Fig. 3.)

6 feet (sample 13) of massive, medium-grained tuff, which grades from gray at the bottom to brown at the top.

6 feet (sample 14) of friable, medium-grained, sandy tuff in 1- to 2-foot beds which grade from gray at the bottom to brown at the top.

7 feet (sample 15) of gray to brown, poorly bedded, friable tuff, with some pink lapilli and a 6-inch fine, lightweight tuff bed at the base.

4 feet (sample 16) of brown, massive, friable tuff. The interval is gray in the bottom half, with an irregular distribution of pink lapilli. Two feet from the top of the sequence bluish gray lapilli and 10% lithic fragments dominate a 6-inch thickness.

Top: 1 foot (sample 17) of gray, friable, lapilli tuff with a dominant pink color at the top.

Total thickness - 50 feet (approximately).

Subunit TOS_{7-8n} (thickness 20 to 25 feet) is brown, massive, slightly friable to friable, medium- to coarse-grained, tuffaceous sandstone and sandy tuff with 0 to 5% white pumice fragments (3 to 10 mm). The base of this unit is recognized by a 30-inch interbedded (4 to 8 inch) sequence of: (1) Lavender brown, faintly bedded, hard, fine-grained tuff (sample 18-1) with 0 to 5% white pumice fragments (1 to 10 mm). (2) Mottled brown, friable, medium tuffaceous sandstone (sample 18-2) with 10% white to blue-gray pumice lapilli (4 to 20 mm).

Subunit TOS_{7-9n} (thickness 20 to 25 feet) is massive, friable, fine- to medium-grained tuff in 2- to 6-foot beds which grade from gray at the bottom to light brown at the top.

Subunit TOS_{7-10n} (thickness approximately 30 feet) is gray to buff, poorly bedded (6 inch to 3 feet), hard, fine- to medium-grained tuffaceous sandstone.

B. Rainier Stratigraphy

The Rainier shot chamber was in the bottom of a shallow east-northeast trending syncline in which the dip within the area of study approaches a maximum of 12 degrees on the south flank. Although an approximate correlation is apparent between the Neptune and Rainier areas, the variations are sufficient to warrant separate descriptions. Descriptions by the U. S. Geological Survey have been incorporated and extended.

In contrast to the Neptune area, drill holes below Rainier ground zero reveal TOS_{5r} as a hard, brittle tuff, while TOS_{6r} is a massive, 85-foot thick, hard, welded tuff with 20 feet of black obsidian at the base. (See Fig.2.) It seems probable that the light-weight, porous lapilli tuff, typical of the Neptune area, has been baked by the deposition of TOS_{6r} and considerably compacted by this and overlying materials. The change in thickness of TOS_6 from 20 feet in the Neptune area to 85 feet in the Rainier area (a horizontal distance of 1200 feet) is not so surprising if one considers that this material originated as a fluidized mass of incandescent gas and ash moving swiftly out from its source. The "lens" of black obsidian at the base of TOS_{6r} perhaps represents a rapidly cooled "forerunner" to the welded tuff.

Subunit TOS_{7-1r} (Q) is as described for Neptune area.

Subunit TOS_{7-2r} (R) persists as a cross-bedded sandstone, but thickens to a maximum of 40 to 50 feet in the Rainier area.

Subunit TOS_{7-3r} (S), (thickness 10 to 13 feet), is buff, massive, friable to slightly friable, coarse tuff. Light gray and yellowish gray to pink lapilli (4 - 15 mm diameter) constitute approximately 10% of the unit. The base is recognized by the presence of irregular, "scalloped" patches of reddish orange porcellanite.

Subunit TOS_{7-4r} (T, U, V_1, V_2), (thickness 18 to 20 feet), is typically gray to greenish and yellowish gray, slightly friable, lightweight, porous, lapilli tuff with 5% dark angular lithic fragments (4 to 20 mm in diameter) and occasional 6-inch to 1-foot interbeds of reddish brown, sandy tuff. The basal few feet (up to 8 feet) of this unit are usually composed of chalky white silt and clay size material believed to result from devitrification of lapilli tuff. Lapilli-size grain outlines are commonly observed on close examination. About 3 feet from the top of the subunit is a 6-inch interbed of hard, conglomeratic porcellanite which persists as a "marker" bed throughout the U12-B tunnel area. In the U. S. Geological Survey system, this bed marks the base of subunit V; however, the overlying 3 feet of greenish gray pumice lapilli tuff are lithologically similar to subunit U but in sharp contrast to subunit V. The contact between TOS_{5-4r} and TOS_{5-5r} is therefore placed at the top of the greenish gray lapilli tuff.

Subunit TOS_{7-5r} (V_3), (thickness 25 to 30 feet), is brown to pinkish brown, massive, hard, fine, sandy tuff, with 5 to 15% (locally 30%) pale yellow to greenish yellow pumice fragments 4 to 12 mm in diameter.

Subunit TOS_{7-6r} (W_1, X, Y, and Z), (thickness 10 to 15 feet), is composed of 1- to 4-foot interbeds of: (1) Greenish to dirty-gray, massive, hard, sandy tuff with up to 30% lithic and mineral fragments. (2) Brown, hard, fine, sandy tuff, which has up to 10% light yellow tuff fragments.

Subunit TOS_{7-7r} (thickness 70 feet) in cores from drill holes G and R is predominantly light brown to grayish brown, massive, hard, fine- to medium-grained, sandy tuff with 10% of 1- to 3-mm diameter white tuff fragments and occasional 1- to 2-foot interbeds of silicified material which contains up to 80% pumice lapilli. Gray, fine- and medium-grained tuff interbeds make up about 10% of the subunit. In the upper few feet, the sequence grades to a brown, slightly friable sandy tuff which has occasional mottled green porcellanite nodules up to 2 feet long and 6 inches thick.

Subunit TOS_{7-8r} (thickness 40 feet) is typically friable to slightly friable, medium-grained, sandy tuff with 2- to 7-foot beds which grade in color from gray at the bottom to brown at the top. White and pink pumice lapilli compose 5 to 30% of the rock with local concentrations as high as 50%. The unit typically contains 6-inch to 1-foot-thick porcellanite lenses from a few feet to 30 feet in length. These lenses grade laterally to lapilli tuff and are believed to be the result of silica deposition by groundwater percolating through the porous beds. "Rock-ball" concretions from 3 to 9 inches in diameter are also typical of this interval. At the top of the subunit is a 10-foot-thick, pale olive to pinkish tan, massive, slightly friable, fine tuff which contains from 10% to 50% pink, blue-gray, and white pumice lapilli. This unit is recognized in drill holes I-2, J-2, and K and is present in large collapse blocks between stations 3 + 35 and 3 + 45 in the "Raise" Drift.

Subunit TOS_{7-9r} is at least 55 feet thick as observed from I-2 drill cores. The lower 30 feet of the unit is brown, thick-bedded to massive, friable, sandy tuff or tuffaceous sandstone. Above this is a 25-foot-thick interbedded (2 to 5 feet) sequence of light greenish gray, slightly friable, lapilli tuff; and medium to coarse, yellowish brown, massive, friable tuffaceous sandstone. The subunit, as described above, is correlated with materials exposed in the "Raise" Drift between stations 2 + 00 and 3 + 30. However, the light colored interbeds here are light gray to chalky white, fine tuff. The conclusion is reached that the lapilli-size fragments as observed in core from the I-2 hole have been pulverized during collapse of the material from 70 feet above. Distortions of this material as shown in Figs. 17 and 18 are offered as concluding evidence for pulverization. The basal few feet of the sequence, as exposed in the Exploratory Drift, are light tan, thin-bedded to massive, fine tuff, which, between station 3 + 20 and 3 + 30, contain up to 50% dark angular chert (volcanic) gravel. This gravel was also recognized in material recovered from drill hole K-2.

The base of subunit TOS_{7-10r} is seen at station 2 + 60 in the "Raise" Drift where large blocks (up to 3 feet in diameter) of brown, massive, slightly friable, very coarse, pebbly, tuffaceous sandstone are exposed. The rock has 5% of white pumice lapilli (5 - 15 mm in diameter). Brown sandy tuff and tuffaceous sandstone answering this description is observed in G hole cores from a depth of 221 to the total depth of 551.8 feet. Four-foot interbeds at depths of 400 and 418 feet are light bluish to greenish gray, massive, lightweight, friable, fine to lapilli tuff. The thickness of subunit TOS_{7-10r} has not been defined.

C. Engineering Materials

The rocks described in the preceding paragraphs may, from a geological engineering standpoint, be divided into four types as follows: (1) Hard, brittle rock, which would include welded tuff, porcellanite (silicified or devitrified tuff) and such very hard granular tuffs as TOS_{5r} and TOS_{7-7r}.

(2) Compact to friable rock, which would include the indurated granular tuffs in the lower part of TOS_7; units TOS_1, TOS_2, TOS_3; and sandstones such as TOS_{7-2}. (3) Structurally weak rock which would include the friable, granular tuffs which extend stratigraphically above TOS_{7-6r} and TOS_{7-7r} to the base of TOS_8. (4) Porous, compressible rock, which is typified by the lightweight lapilli tuffs of TOS_{5n} and TOS_{7-4n}, and to some extent by TOS_{7-4r}.

For more detailed and varied discussion of the Oak Springs Tuff relative to its engineering properties, the reader is referred to report UCRL-5542 by Warner and Violet.[7]

V. DISCUSSION AND INTERPRETATION

From a structural geologist's point of view, the effects of underground nuclear explosions may be thought of in terms of the stress origin. On this basis, effects are divided into primary (blast) and secondary (collapse) features, depending on whether the explosion or the force of gravity imparted the dominant stress.

The blast (primary) features may be categorized in terms of an initial cavity, a crushed zone and a fractured zone. Secondary (collapse) features are referred to in terms of fracture limit and central collapse block. Both explosion and collapse stresses are considered in the concept of a main shear zone.

A. The Initial Cavity

The Rainier shot obviously had an initial cavity which was lined by fused rock. Dark green to black and brown, highly radioactive, vesicular fused material was observed continuously in cores over drilled distances which range from 3 to 10 feet in holes B, C, H, I, J, K, and T-11. This material is distributed in a hemispherical shell below ground zero at an outside radial distance which ranges between 55 and 75 feet (see Plate V). An average 62 $\pm$ 10-foot radius for the initial cavity is evident. The thickest concentration of glass was along the bottom of the cavity, as indicated in drill holes H and T-11. Light brown tuff immediately overlying the fused core is part of the lithologic subunit TOS_{7-7r}, which existed above the shot chamber prior to detonation. Little or no fused core was observed in holes I-2, J-2, and K-2 which were drilled up from the Exploratory Drift alcove. A fused fragment at a depth of 75 feet in I-2 (65 feet from ground zero) appears to be near the former cavity boundary. Fused fragments, as shown in Figs. 3 and 4, are distributed through TOS_{7-7r} adjacent to the fused core and also in sections of drill hole D (see Plate V). These are presumed to have been emplaced in the rock which formed the ceiling of the cavity.

The hemisphere of fused glass in Rainier, according to Kennedy and Higgins,[8] has resulted from direct melting plus additions by flow down the sides of an initial cavity. Flow structures observed by Donald Rawson (personal communication, November 24, 1959), in a study of thin-sections, tend to support this conclusion. Nevertheless, the positioning of the fused material as shown in Plate V suggests that some of this glass concentration may be attributed to preferential melting of a specific rock type, (in this case TOS_{7-6}). This possibility could be easily evaluated by laboratory tests.

B. The Crushed Zone

A crushed zone is defined by the limit of obvious grain disaggregation and gross primary displacement of rock materials. Wood fragments and the pulverized and crushed appearance of drill cores offer clues to the extent of the crushed zone. Physical displacement and obvious thinning of stratigraphic units are apparent in both the Neptune and Rainier areas.

The crushed zone thus defined is observed to extend (in the Rainier area) for a radial distance of some 80 to 100 feet, with a maximum extent of 130 feet, southeastward from the shot point. The anomalous extent of crushing in this direction probably can be attributed to the fact that the preshot drift extended in this direction. As noted in the Introduction, this drift collapsed to a radial distance of 200 feet. The disturbed and jumbled materials observed on the northeast wall of the Exploratory Drift at stations 16 + 25 (Fig. 7) and 17 + 50 are tentatively assigned to TOS_{7-6}. Radiation measurements made on both sides of the fused stringer (Fig. 7) showed high radiation in the direction away from the shot point (right) but low radiation toward the shot point. The conclusion was reached that the stringer marked the boundary between collapse material on the ground zero side and crushed material on the side away from ground zero.

Measurements of bulk density, grain density, porosity, permeability and compressive strength as quoted by Warner and Violet[7] from work by Diment et al.,[15] and measured along the Exploratory Drift, show anomalies which appear to be related to the crushed zone (Plate V). Measurements of compressive strength suggest that crushing extended to a radial distance of 100 feet from ground zero. Permeability increases toward ground zero abruptly at station 16 + 00 (80 feet from ground zero) from about 1.5 millidarcies to more than 14 millidarcies. At station 16 + 30 (60 feet from ground zero), bulk density decreases from about 2.2 to 1.8 g/cm^3, and porosity increases from 20-30% to 30-44%. A comparison of postshot measurements with preshot measurements indicates that the grain density of subunit TOS_{7-5r} (V) has been reduced. Apparently grain disaggregation has resulted in a looser packing. Dry bulk density determinations tend to support this conclusion. Analysis of thin-sections as described in a subsequent paragraph relative to the properties of the fractured zone also tend to delineate the limit of crushing.

Drilling above ground zero in the Rainier area has not been designed to delimit the extent of crushing. Furthermore, analysis of crushing in this direction is complicated by secondary (collapse) features.

In the Neptune area, crushing extends downward about 40 feet and laterally about 50 feet, except in the southeast direction (Plate III) where crushing effects are observed to a radius of at least 80 feet. A peculiar wave structure is shown in the distribution of TOS_6, TOS_{7-1} and TOS_{7-2} in drill holes A, I, and K. A piece of wood core from a depth of 97 feet in hole K is presumed to have come from the drift which crossed the line of fire at a radial distance of 45 feet. The anomalous extent of crushing apparently was favored by bedding plane weaknesses.

C. The Fractured Zone

Fracture limits include primary as well as secondary effects. A variety of criteria have been used to define the limits as depicted in Plates I through VI. In general, these limits are consistent with marked changes in drill fluid loss, core recovery, or degree of fracturing as interpreted from the graphic logs of the core hole analysis.

Interpretation from cores is immediately confronted with the problem of separating explosion fracturing from preshot and drilling effects. Preshot fracturing can normally be distinguished by some degree of weathering or cementation, but separating explosion fracturing from drilling effects is more difficult.

The peculiar type of irregular longitudinal fracture pictured in Fig. 8 is believed to be a primary (blast) feature. The irregular nature of these fractures leads to the conclusion that they are the result of tensional stresses. It is difficult to visualize how tensional stresses could be thus developed by drilling operations. Such fractures are interpreted as tension cracks resulting from primary stresses directed radially from ground zero.

In the Rainier area, a pronounced bulge in the fracture limit to the southeast is defined by data from drill holes B, C and D (Plate V). This is consistent with the anomaly in the crushed zone and here again is attributed to the location of the Rainier main drift. Support for this fracture limit is found in studies reported by Warner and Violet:[7]

"In specimens from the first 95 feet (stations 14 + 65 to 15 + 60) of the exploratory tunnel, the effect of the explosion is indicated by the closer spacing of the joints in the rock. From 15 + 60 (120 feet radially from the chamber) toward the face, the rock becomes progressively more friable and much of it can be crushed easily in the hand. On drying in air it becomes somewhat more coherent but disintegrates rapidly upon contact with water. A series of half-inch pieces of the brownish tuff from the samples collected along the tunnel were dried in air and then placed in water. Those pieces from samples obtained between 140 and 210 feet from the chamber showed selective disintegration of small masses of white material that apparently are richer in clay minerals. Those pieces from 75 to 120 feet from the chamber showed progressively more disintegration, and those from 65 to 75 feet disintegrated completely within a few minutes to heaps of granular material, mostly smaller than 1-mm diameter. Similar pieces of air-dried lumps of the white tuff from about 140 feet radially from the chamber all disintegrated rapidly in water, possibly due to high content of clay."

Thin-section studies[2] (as quoted by Warner and Violet[7]) further define the fracture zone:

"Under the microscope, thin-sections of the samples from the interval 140 to 210 feet radially from the chamber do not appear noticeably different from the normal preshot tuff of this portion of the Oak Springs formation. A sample at 15 + 50 (130 feet from the shot chamber), however, shows a few short irregular hairlike fractures filled with fine-grained, opaque material. Specimens taken at points further down the exploratory tunnel contain similar hairlike cracks in progressively greater abundance, and about 75 feet from the chamber they form a fine anastomosing network. In many specimens these cracks show random orientation, in others a single direction may be dominant. Autoradiographs did not show these fracture networks to be appreciably more radioactive than the intervening rock material. In addition to the hairlike fractures, there are scattered thicker masses of this opaque material in the rock in and near the heading of June 6, 1958 (16 + 30). These masses are generally wormlike, up to 1 mm thick, and have blunt or tapering ends. Further investigation of these features are necessary."

To the northwest, the fracture limit is placed near the end of the Exploratory Drift since fractures observed in the walls of the drift seem to die out at about this point. The lateral extent of the fracture limit in Plate VI is largely hypothetical as control data is scanty.

The extension of the fracture limit to a radial distance of 220 feet below the point of detonation is based primarily on the observation of tension fractures in core from hole H (see Fig. 8). Perhaps the greater extension of fracturing in this direction finds explanation in the proximity of the hard, brittle rocks of TOS_{6r} and TOS_{5r}. These rocks, as might be expected, apparently were able to transmit the shock waves to a much greater distance. This conclusion, if verified, could have tremendous practical significance in the planning of future underground detonations in other materials, such as limestone, dolomite, or granite, for these rock types should be expected to behave in a similar way.

In the "Raise" Drift, fractures at station 1 + 85 and between stations 3 + 30 and 3 + 85 as shown on Figs. 9 through 15 are attributed to primary shear. There is little doubt that the most recent movement has been due to collapse of material into the primary (blast) cavity. Nevertheless, the exactness with which these fractures are consistent with expectable shear fractures resulting from radial projection of stress from the explosion point forces the conclusion that they are primary features. In accordance with stress ellipsoid theory, the fractures are inclined at an angle of less than 45° to the principle stress. For strict correspondence with observation, a coefficient of internal friction (ϕ angle) of 40° is postulated and represented in the stress ellipsoids shown on Plates V and VI. Perhaps this ϕ angle value may seem too high; however, under the extreme temperatures and pressures expectable in these regions, the material may well be expected to behave other than as in the laboratory. It is also observed that the postshot joints between stations 1 + 50 and 1 + 55 are consistent with the postulate.

The fracture limit above the "Raise" Drift in the Rainier area is believed to be defined by the boundary of collapse of material into the central cavity. The boundaries as shown on Plates V and VI are consistent with analysis of core and drilling data from holes G, I-2 and J-2. Bedding dips consistent with preshot structure are particularly conclusive in fixing the approximate limit. Fractures on top of Rainier Mesa as illustrated in Figs. 21 and 22, and located in Fig. 23, are attributed to slumping toward the mountain front along a preexisting gravity shear zone which was reactivated by explosion shock waves. This shear zone forms a 50-foot-wide topographic low in which the soil cover is observed, in the field, to have settled a foot or two below the large rock masses. The former position of the soil mantle relative to the rock masses is shown by a well-defined line below which the rocks were buried.

On the ground surface over the detonation point no fractures were found which could be attributed to collapse into the initial cavity.

In the Neptune area, the fracture limit below the elevation of ground zero is defined principally on the basis of fracturing observed in core analysis. Above the elevation of ground zero, the fracture limit is, in part, related to primary (blast) effects and in part to secondary (gravity) effects.

In the southeast direction (Plate III), primary fracturing is believed to have propagated all the way to the ground surface along the lithologic contact between TOS_5 and TOS_6. As shown in Fig. 25, the hard, brittle TOS_6 unit has been shattered while the compressible, "punky" TOS_5 has remained intact.

Primary breakthrough to the ground surface in the southeast direction, as shown by the documentary film described in the Introduction, probably is related to the favorable dip of the bedding and to the proximity of the detonation to the ground surface. The dominance of rock rubble from TOS_7 subunits 4n, 5n, and 6n as shown on Plate I confirms the positioning of the breakthrough.

The fracture limit to the northwest and southwest of the shot point, as defined by open surface fractures, is believed to be the result of normal faulting toward the crater created by the blast. Displacements, slickensides, and dips on faults southwest of the shot point (exposed in road cut) are consistent with shearing due to a vertical principal stress (force of gravity).

Northeast of the Neptune shot point, the origin of the fracture limit is confounded by the transition from primary (blast) fracturing to secondary (collapse) fracturing.

D. The Central Collapse Block

There is no doubt that a large mass of rock material was moved by the force of gravity to fill an initial cavity formed by Rainier explosion. The manner of this movement and the source of present distribution of displaced materials will now be discussed.

Perhaps, intuitively, one may picture a jumbled mass of rock types in the central collapse zone. Additional thought should lead to the conclusion that each particle of rock is under the influence of the same force of gravity and should thus be accelerated at the same rate, barring boundary effects. From a theoretical point of view, then, one should expect gravity-displaced rock masses to remain essentially intact at least in the gross sense. This prediction has been conclusively borne out by factual observations.

A brief excursion through the Rainier Exploratory Drift discloses the fact, with one exception, that the material is all of the same lithologic type. Fracturing and somewhat erratic tilting of bedding planes (recognized by textural variations) as shown in Figs. 5 and 6 are observed, but even here, the dips, in general, are toward ground zero.

An apparently anomalous block of rock about 10 feet square rests adjacent to the drilling alcove at station 16 + 84. (See Plate IV.) Well defined bedding strikes N 25° E and dips 30° NW. The block is composed of massive, gray, slightly friable sandy tuff with 1- to 6-inch interbeds of silicified, brown lapilli tuff. The block is apparently surrounded by massive, very light brown, friable, fine tuff which is correlated with the similar but harder materials of TOS_{7-7n} as observed in cores from the drill holes R and G. The lithology of the foreign block is similar to that observed near the base of TOS_{7-8n} as exposed in the "Raise" Drift. The conclusion is reached that this block has been displaced about 100 feet by gravity collapse. Its silicification apparently allowed it to remain intact and to be engulfed by the pulverized materials of TOS_{7-7n}.

The approximate position of the displaced contact between TOS_{7-7n} and TOS_{7-8n} is delimited by pieces of silicified lapilli tuff recovered from drill holes I-2, H-2 and K-2.

By careful mapping and observation in the "Raise" Drift, it has been possible to correlate lithologies from one side to the other of the central collapse block. Figures 9 through 19 show that the originally flat-lying strata have been tilted to high angles and made to flow and slip. Still, only minor mixing is observed. Blocks of coarse, pebbly, tuffaceous sandstone, as observed at station 2 + 60 (directly over ground zero), have been recognized nowhere else except above the "Raise" Drift in drill hole G. It is concluded that here again the rock has collapsed essentially as a unit.

Cavities have been observed, as depicted on Plate V, over the Rainier "Raise" Drift at stations 2 + 00 and 2 + 60. A percussion probe hole (see Fig. 20) defined a void at least 10 feet in diameter 35 feet above the drift at station 3 + 10. A cavity at elevation 7002 feet had previously been encountered by drilling (hole R-6) vertically down from the surface.

Although not conclusive (because of the small number of observations), the positioning of these cavities suggests that more of them may be distributed around the perimeter of a vertical cylinder with a 50- or 60-foot radius. Perhaps such positioning of voids may be attributed to boundary effects of the central collapse block shearing away from the solid rock wall.

A distribution of cavities vertically over ground zero is also indicated. This positioning of cavities, perhaps, is to be expected since it is in the location of maximum subsidence.

The height of collapse above ground zero is a question deserving consideration. The hypothesis is advanced that collapse would progress upward until such time as enough cavities and sufficient increase in bulk porosity had been produced to account for the initial void created by the explosion. It seems self-evident that the bigger the initial cavity the higher would be the collapse. The only factual evidence to date would place the collapse limit (fracture limit) at the top of the cavity detected at the 7002-foot elevation. The dome shape at the top of the collapse limit is predicted on the basis of expectable distribution of principal stresses. It is interesting to draw an analogy to stress distributions as predicted by Anderson and Jeffreys[9] in their analysis of the stress conditions which prevail in the formation of certain natural geologic features (cone sheets, ring dykes, and caldron subsidence). Billings[10] also has developed theories along these lines.

The strength of materials in and above the central collapse block is pertinent to block caving considerations. The flow features shown in Figs. 17 and 18 certainly indicate that this material is not strong structurally and should be expected to collapse under its own weight with very little agitation. That the material in the collapse block is unstable is supported by the fact that solid roof spiling and wall lagging were required through the total traverse of the central collapse block in the Rainier "Raise" Drift. There was serious doubt as to whether the drift was feasible when pulverized rock engulfed the heading at station 2 + 00. Without the benefit of expert mining techniques, the drift could not have been completed.

The instability of the material overhead was continually in evidence by the sound of overhead caving, which proceeded in spite of the fact that the heading was advanced without the use of dynamite but entirely by digging. Breast-boarding was required through much of the operation.

Relative to the materials observed in the "Rise " Drift, the rocks of the collapse block exposed in the Exploratory Drift are compact. This, at least in part, may be attributed to compaction on initial collapse, but it would appear that the high temperature and humidity encountered in this drift may cause a healing effect on these materials. Nevertheless, there is little doubt that somewhere between the Exploratory Drift and the "Raise" Drift the material could be made to flow.

The authors' opinion is that if material were continuously drawn out by mining at the "Raise" Drift level, the rock above would collapse under its own weight and caving would proceed upward to the ground surface. Probably the only conclusive way to evaluate this opinion is through an actual block-caving test. Such caving might be hindered to some extent by jamming of finger raises with massive blocks like the one described in the Exploratory Drift, but otherwise no obstacle is apparent that would seriously hinder a successful block-caving operation.

Three points emerge which could have practical importance from a mining point of view:

In the first place, it is apparent that huge quantities of rock could be removed by block-caving methods from a single draw level (for discussion of these methods and further details of mining conditions encountered and mining methods used in the driving of the Exploratory and "Raise" Drifts, the reader is referred to a report being prepared by William G. Flangas and L. E. Shaffer[16]). The unstable material as presently outlined above ground zero has been estimated at 600,000 cubic yards. If caving should be continued to the ground surface, this volume would be at least doubled.

Of equal significance from the mining point of view is the fact that, in the gross sense, the caved materials remained intact. If the sought-after ore were distributed in small pockets, as is frequently the case, these could be removed directly to the mill without the necessity of sorting the ore from the worthless country rock as would be necessary if mixing were extensive. Furthermore, pulverization due to collapse may eliminate the necessity of some grinding operations in the milling process.

Another significant fact is that no anomalous radioactivity was encountered in the Rainier "Raise" Drift. In a mining operation, the initial blast could be detonated at the bottom of a winze or incline designed in such a way that re-entry at the level of the main drift would allow complete elimination of radiation as a mining hazard.

In the Neptune area, definition of a central collapse block is complicated to some extent by the initial upward displacement of the domed mass as described in the Introduction and the fact that primary shearing broke through to the surface with expulsion of large amounts of rock materials. Nevertheless, the stratigraphic units as defined can still be recognized from drill core, and in the gross sense the different lithologic types are found to be distributed in an essentially unmixed condition. Certainly, there has been extensive fracturing and a limited amount of mixing is apparent. For example, hard porcellanic rock, typical of the upper and lower parts of TOS_{7-3n}, are commonly found intermixed with materials of the adjacent TOS_{7-4n} and TOS_{7-2n} as if they had been propelled like bullets into the less coherent sandstone (TOS_{7-2n}) and lapilli tuff (TOS_{7-4n}). TOS_{7-4n} is noticeably compressed but still intact. Mixing is observed between subunits TOS_{7-6n} and TOS_{7-7n} and between the upper part of TOS_{7-5n} and TOS_{7-6n}. Such mixing might be expected for at least two reasons. In the first place, large blocks have been heaved to the surface where they are observed as rubble strewn down the mountainside. In the second place, these upper units were not confined by overlying strata during the blast to the extent that the lower units were.

The boundary of the central collapse block to the northwest and southwest of ground zero is fairly definitely fixed by a marked shear zone which is believed to be primarily a collapse feature. However, to the northeast and particularly to the southeast, definition of a boundary is complicated by primary shear and removal of material.

E. The Main Shear Zone

The concept of a main shear zone was first considered during the driving of the Rainier "Raise" Drift. Essentially undisturbed, flat-lying strata were mapped to station 1 + 85 (see Plate V), where they are abruptly terminated by closely spaced, nearly vertical, open fractures as shown in Fig. 9. This breakoff is extended downward by analysis of drilling and core data from G hole.

Between stations 1 + 90 and 2 + 10 in the Rainier "Raise" Drift, only fine pulverized sand with a few coherent blocks up to 1 or 2 feet in diameter were encountered. At this position, the presence of a large (estimated 1100 cubic yards) cavity became apparent after the pouring of large quantities of pulverized rock into the drift. An estimated 80 cubic yards of muck were removed before the cavity could be observed by peering up between the spiling. The cavity was estimated to be about 40 feet high and roughly cylindrical in shape with a 15-foot radius. This pulverized zone extended to about station 2 + 10 where steeply dipping (70°) bedding was measured. Observations, as the heading was advanced, showed that the bedding was progressively flatter until it was 45° over ground zero. The dip is 55° at station 2 + 90 and finally 22° at station 3 + 30 where it is abruptly terminated by the steeply dipping fault shown in Fig. 10. From this point on to station 3 + 58 the rock breakage is characterized by great slabs of rock (3 to 6 feet thick) which are successively displace downward as one progresses toward the center of the collapse block. These massive blocks remained intact and show prominent slickensides on fault surfaces, as shown in Figs. 11 and 12, while adjacent granular materials are sheared to a loose, friable material. It is interesting to note that open fractures, as observed in Figs. 11 and 12, curve and are closed in their extension into the more friable materials. This observation finds explanation in the expected variations in coefficient of internal friction (ϕ angle) in these two rock types.

The closely spaced faults exposed between stations 3 + 47 and 3 + 58 as shown in Fig. 14 are interpreted as shear fractures resulting from a vertical (gravity) principal stress. A stress ellipsoid is included above station 3 + 50 on Plate V in order to illustrate this point.

In Rainier cross section B-B' (Plate VI), material recovered from drill holes I-2 and J-2 is observed to be particularly pulverized between depths 78 and 109 feet in I-2 and depths 55 to 84 feet in J-2. This pulverization is believed to be the result of a concentration of shear slippage in these zones.

As pointed out in previous paragraphs, this zone of pulverization may be, at least in part, attributed to primary (blast) shear stresses. One should expect that these primary stresses should project out from ground zero until the energy is dissipated in the form of heat, massive displacements or shock waves. Relative to the case at point (Rainier), visible effects are described in the discussion of fracturing where it was concluded that the open fractures observed in the "Raise" Drift originated as primary shear fractures that subsequently acted as planes of weakness which favored the collapse of material into the cavity. A thin-section analysis of field oriented samples of rocks adjacent to these fractures should help to verify this hypothesis.

The main shear zone in the Neptune area, as in the Rainier area, is defined on the basis of a particularly pulverized zone encountered in drill holes. This zone is characterized by lack of whole core and by high drill-fluid losses. It should be apparent from preceding discussions of fracturing and collapse that the pulverized zone is due to primary (blast) stresses as well as collapse (gravity) shear. The blast effects were dominant in the southeast direction where the explosion broke through to the surface, while collapse shearing is dominant on the southwest and northwest where the existence of a steep free-face favored shearing by the force of gravity. The shear zone defined on the northeast end of Neptune section A-A' (Plate II) is believed to be a transitional case in which both primary and secondary shear were of importance.

VI. RECOMMENDATIONS FOR FUTURE WORK

Initially it is suggested that the Rainier Event be analyzed in the detail necessary to definitely verify or disprove the hypotheses advanced in this report; and further, that basic criteria be established by which the initial cavity, the crushed zone, the fractured zone, etc., can be most readily defined. Once fundamental hypotheses have been conclusively verified and basic criteria established for their recognition, then short cuts to the analysis of other shots should become evident, at least for those detonations in layered pyroclastic rocks.

Stratigraphic Correlations. Rock distributions as depicted in Plates I through VI should be checked by thin-section analysis. A few of the pertinent correlation which should be checked are as follows:

1. Samples from the jumbled materials on the northeast wall of the Rainier Exploratory Drift at stations 16 + 25 and 17 + 50 should be compared with undisturbed samples of TOS_{7-6r} obtained from drill holes R and G, care being taken to select similar lithologies. According to Warner and Violet[7] "a lineation is visible as a fine fibrous material in plain light and as an oriented birefringence under crossed nicols. Such linear structures have also been observed in the preshot rocks." No mention is made of what preshot rocks, but in any case such a feature should have correlative value.

2. The large block of rock (TOS_{7-8r} ?) adjacent to the drilling alcove at station 16 + 84 in the Exploratory Drift should be compared with samples of TOS_{7-8r} from the "Raise" Drift.

3. TOS_{7-8r} should be further checked by studying the ten-foot massive unit at its top as observed in drill holes I-2, U-2, R-2, and K, and in the large collapse blocks between stations 3 + 35 and 3 + 45 in the "Raise" Drift. At the same time an effort should be made to establish a precise correlation between undisturbed rock adjacent to the central collapse block at opposite ends of the "Raise" Drift. This may require further drilling above and below the drift in order to encounter correlative sequences.

Additional drilling is certainly needed, particularly northwest of the shot point and above the "Raise" Drift, to more accurately locate other subunit contacts. As the reconnaissance examination progresses, other problems of correlation will become evident and these problems should be worked out as they are recognized.

The main item that should be kept in mind in selecting specimens for thin-section analysis or for any other measurement is that comparisons should be made at the same stratigraphic horizon. This requisite is imperative, even to different samples taken from the same subunit, since the latter are themselves composed of varied lithologies.

The Initial Cavity. Laboratory melting tests and chemical analysis of specimens (preshot) from rock unit TOS_{7-6r} and adjacent subunits should prove or disprove the suggestion that certain lithologies are particularly susceptible to fusion.

The Crushed Zone. Measurements, on removed samples, of bulk density, grain density, porosity, permeability and compressive strength provide useful empirical data. Additional measurements appear to be warranted.

Fractures in the "Raise" Drift. The postulate that the open fractures at station 1 + 85 and between stations 3 + 30 and 3 + 85 in the Rainier "Raise" Drift (see Figs. 9 through 15) are the result of primary (blast) shear with secondary (collapse) movement perhaps can be studied effectively with thin-sections. Oriented samples of slip surfaces are suggested as a starting point. This study can be expanded to include the joints between stations 1 + 50 and 1 + 55 in the "Raise" Drift as well as the many fractures observed in the Exploratory Drift.

Variations in fracturing due to rock type can probably best be evaluated in situ after definite criteria have been established for the recognition of blast fracturing. Analyses of explosions in rock types other than pyroclastic material will certainly be necessary to arrive at a useful conclusion relative to mining practice.

Tension Fractures. Fractures like those pictured in Fig. 8 of this report should be studied with the purpose of definitely establishing their origin as preshot, blast effect, or drilling effect. A search of the literature is suggested as a starting point since much research has been conducted by various drilling, petroleum, and mining companies relative to rock breakage by core drilling. Thin-section studies of such cracks observed in the Rainier area may also be instructive.

Properties of the Central Collapse Block. The generally incoherent nature of rock materials in the central collapse block make difficult the application of the standard methods for measurement of porosity, permeability, density, strength, and elastic properties. Experiments could be designed to test the healing effect of high temperature and humidity on pulverized rock materials like those exposed in the Exploratory Drift.

A drop cone might be used as an empirical means of defining the relative hardness of materials, as is done in soil mechanics.

Thin-section comparison of collapse materials with stratigraphically equivalent rocks which have not been disturbed should reveal changes in rock fabric.

More exploration is certainly needed above the "Raise" Drift level to delimit the extent of the central collapse block. The pictorial and descriptive approach as applied in the present report perhaps will be as productive as any. An effort should be made to determine the size and distribution of cavities. Probably the most practical test (to be applied after all other analyses are complete) would be an actual block-caving operation.

Measurement of Strength and Elastic Properties. The strength and elasticity of the test medium is certainly fundamental to evaluating the effects which will result from nuclear detonation. Accurate measurement of these properties is a difficult problem. The scale factor as discussed by Hubbert[11, 12] must be taken into consideration as is the practice in a model study of geologic phenomena. Two important factors of consolation in evaluating nuclear tests are that the time factor is not a problem and that the origin of maximum principal stress is known. Nevertheless, a mountain of rock should be expected to have strength and elastic properties which differ from a small test sample of the same rock, even if discontinuities such as stratification and joints are ignored. The great importance of fluid pressures in determining rock strength has recently been discussed by Hubbert and Rubey.[13]

Static tests under fluid confining pressure is probably an improvement over tests on unconfined specimens. Equation of state measurements allow a degree of dynamic similarity. Perhaps instrumentation could be devised which would measure in situ such properties as fluid pressure, shock, particle velocity, etc., during actual explosions. The results of such measurements, if successful, would certainly be of tremendous significance in the fundamental understanding of explosion effects.

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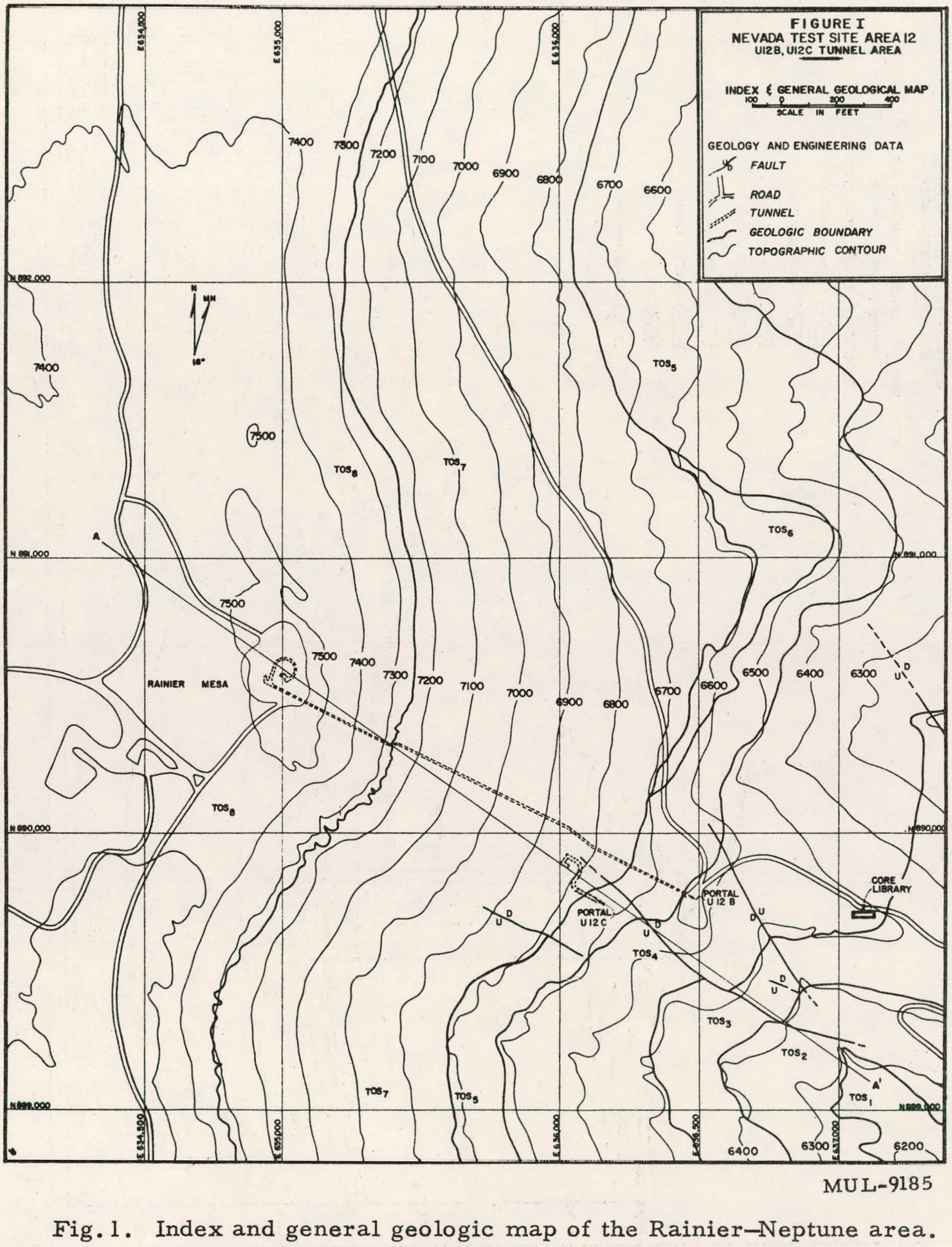

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Fig. 1. Index and general geologic map of the Rainier—Neptune area.

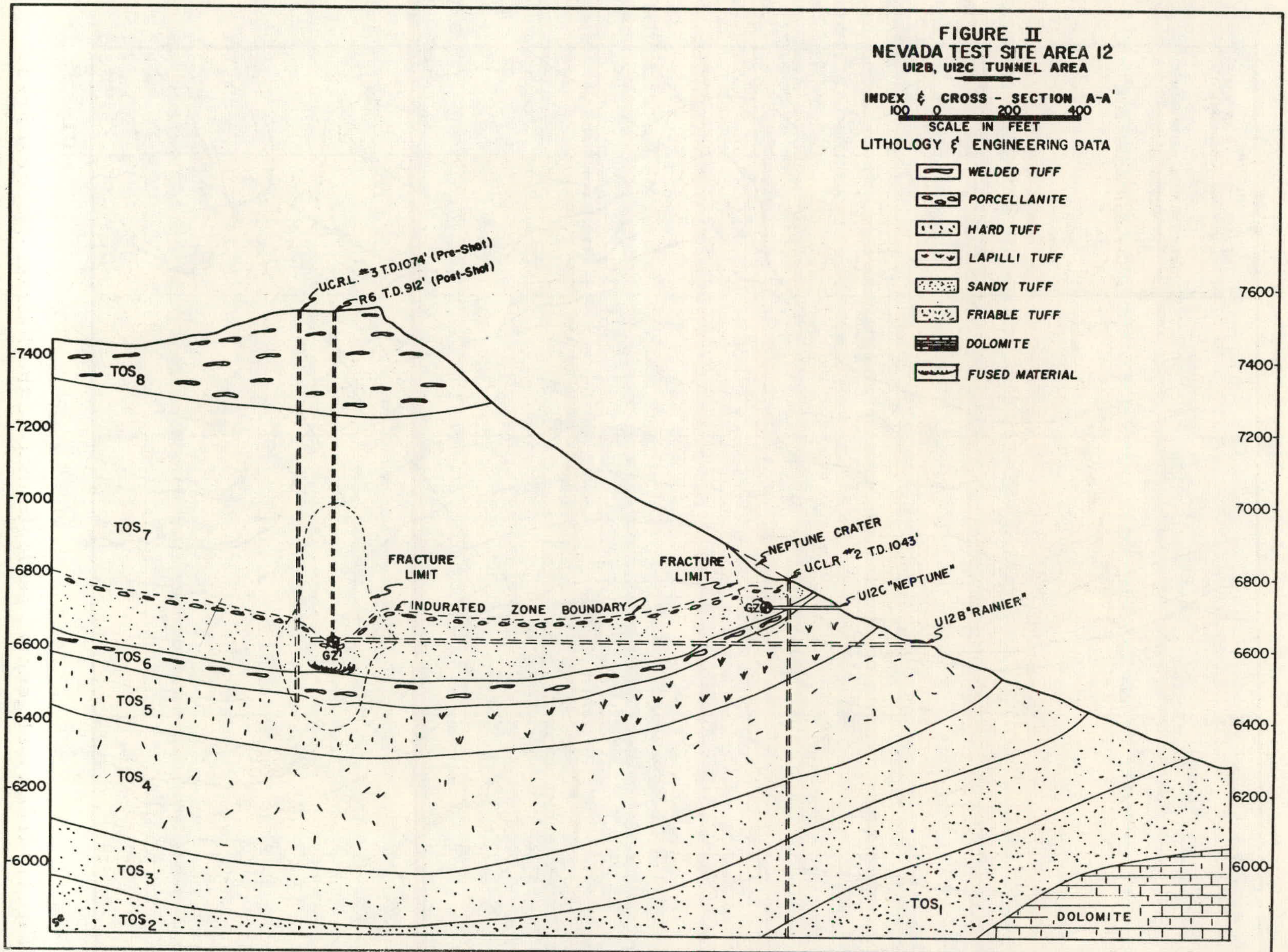

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Fig. 2. Geologic cross section through Rainier and Neptune areas.

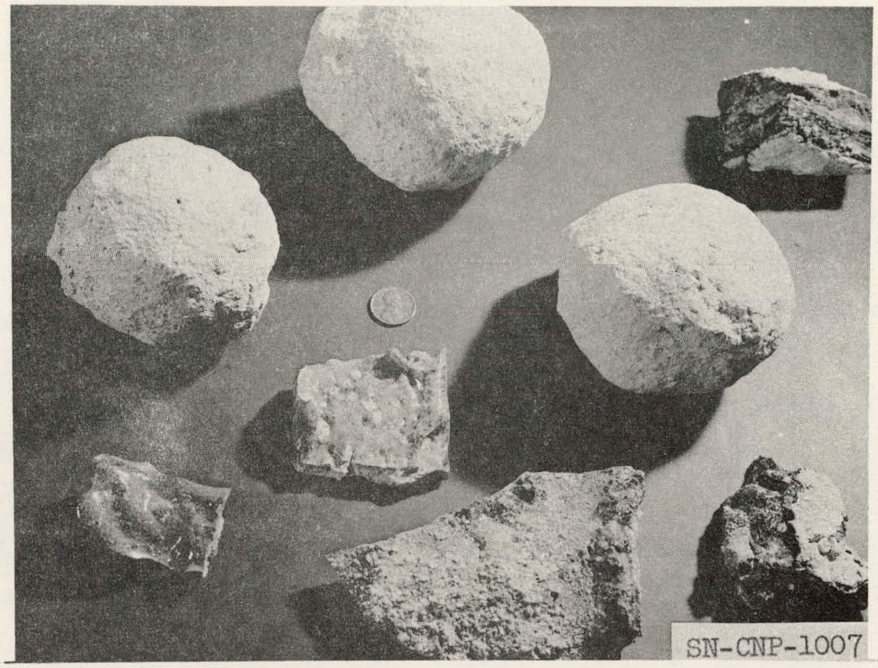

Fig. 3. Rock-ball concretions and fused rock fragments found in Rainier Exploratory Drift.

Fig. 4. Fused material in U12-B Exploratory Drift.

Fig. 5. Collapsed TOS_{7-7r} showing shear plane in U12-B Exploratory Drift.

Fig. 6. Pulverized rock (TOS_{7-7r}) in central collapse block U12-B Exploratory Drift.

Fig. 7. Stringer of fused rock and adjacent crushed TOS_{7-6r} (right) and collapsed TOS_{7-7r} (left) at station 16+25 in U12-B Exploratory Drift.

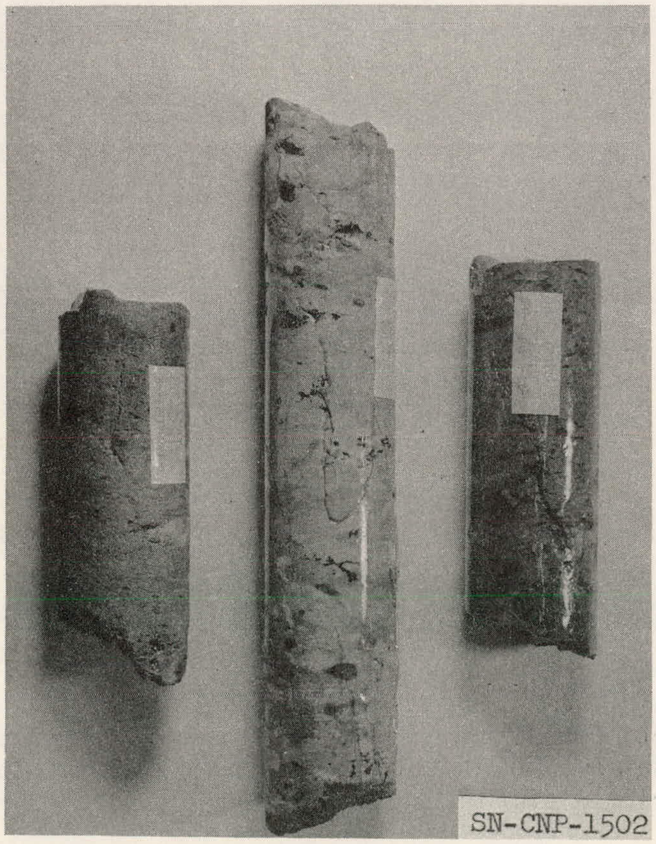

Fig. 8. Primary (blast) tension fractures in core from U12-B Rainier hole H.

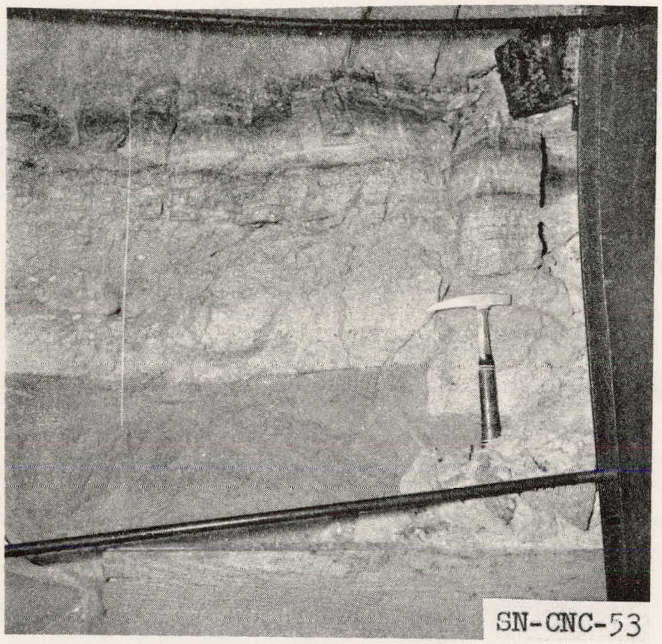

Fig. 9. Limit of Rainier collapse zone showing near vertical fractures with slight gravity displacement at station 1+85 in "Raise" Drift.

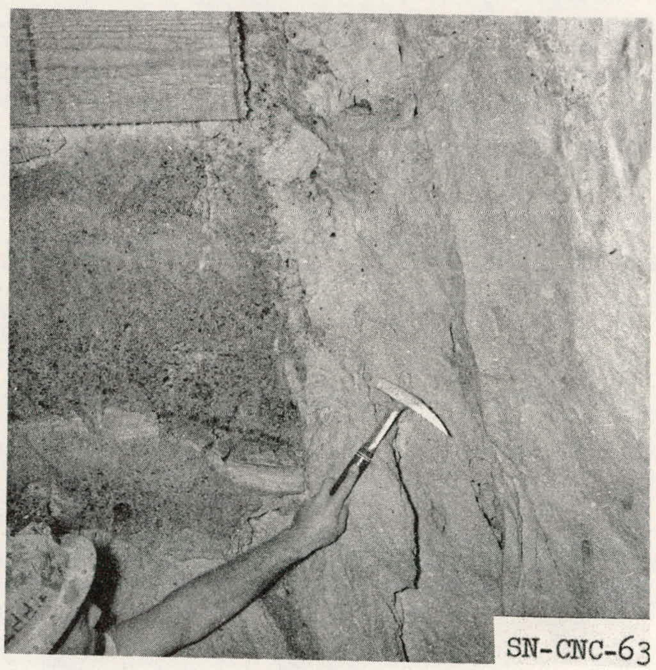

Fig. 10. Loose volcanic gravel in fault contact with sheared blocks of massive lapilli tuff on the southwest wall of U12-B "Raise" Drift at station 3+34.

Fig. 11. U12-B "Raise" Drift at station 3+35 showing vertical slickensides on heading block of massive tuff and open fractures (Strike N-10°-E) in downdrop fault block.

Fig. 12. U12-B "Raise" Drift (station 3+31 to 3+35). Open fractures in the massive lapilli tuff (TOS_{7-8r}) are closed and curved on projection through the loose pebbly tuff (TOS_{7-9r}).

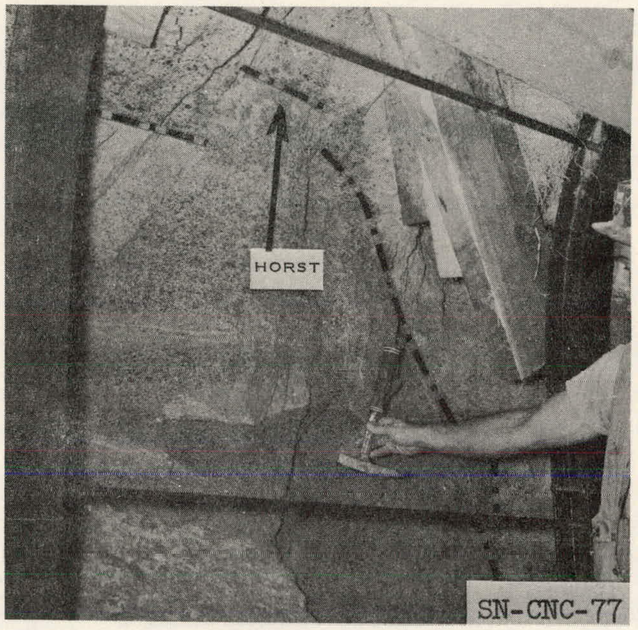

Fig. 13. Pebbly volcanic tuff showing a horst bounded by normal (gravity) faults on northeast wall of U12-B "Raise" Drift at station 3+65.

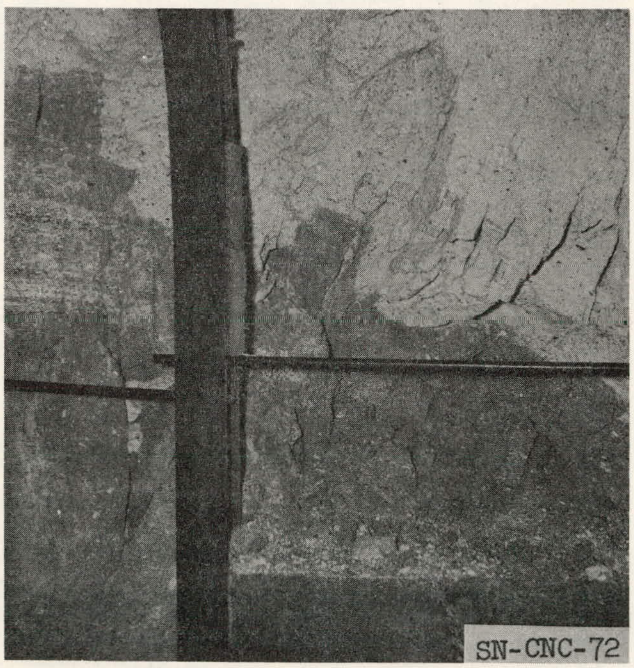

Fig. 14. Secondary (gravity) faults are illustrated by displaced stratigraphic contact between brown tuffaceous sandstone below and white sandy tuff above. (Northeast wall between stations 3+50 and 3+55 in U12-B "Raise" Drift.)

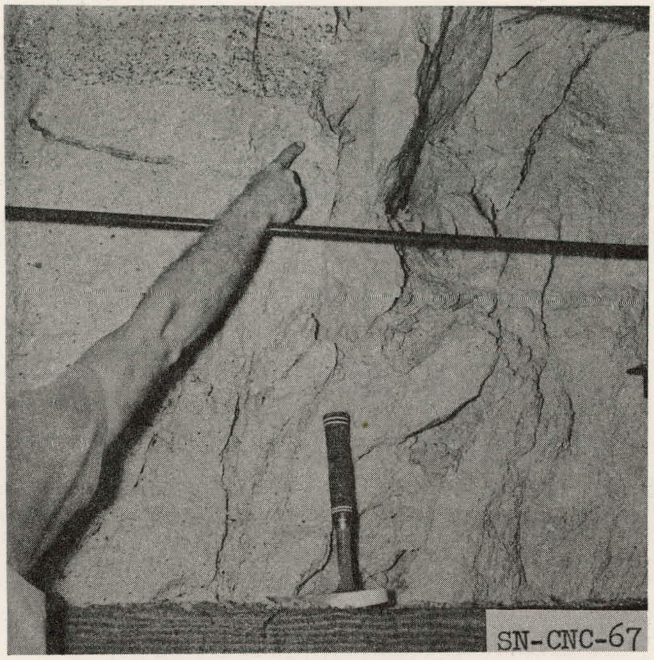

Fig. 15. Vertical fault shown by down-dropped massive brown tuff adjacent to bedded white tuff. (U12-B "Raise" Drift at station 3+47.)

Fig. 16. Heading at station 3+48 in U12-B "Raise" Drift. Note the displacement of the lapilli tuff bed.

Fig. 17. Slump structures in bedded tuff of Rainier central collapse block at heading station 2+55 in U12-B "Raise" Drift.

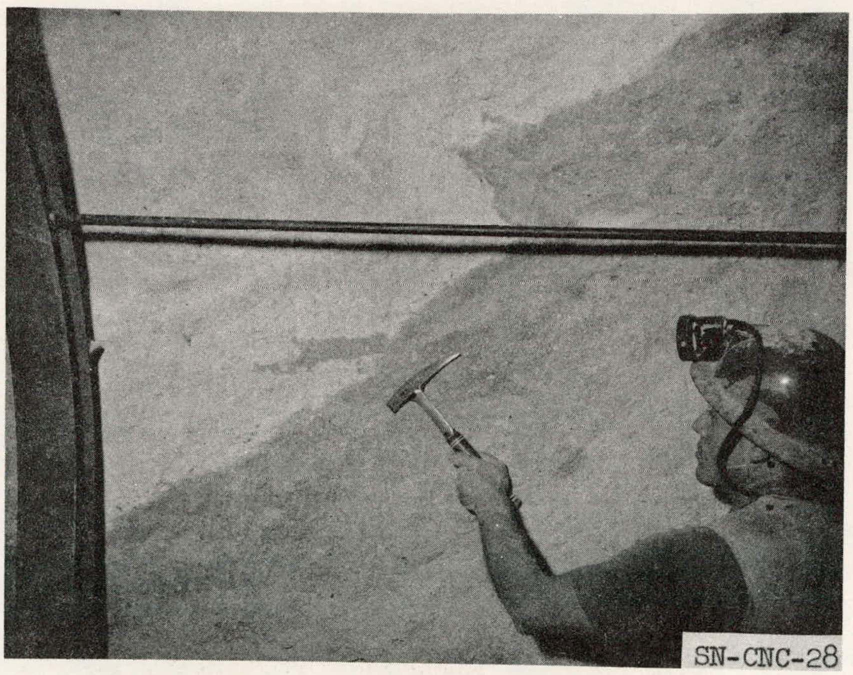

Fig. 18. Slump structures in bedded tuff of Rainier central collapse block between stations 2+50 and 2+55 along the northeast wall of U12-B "Raise" Drift.

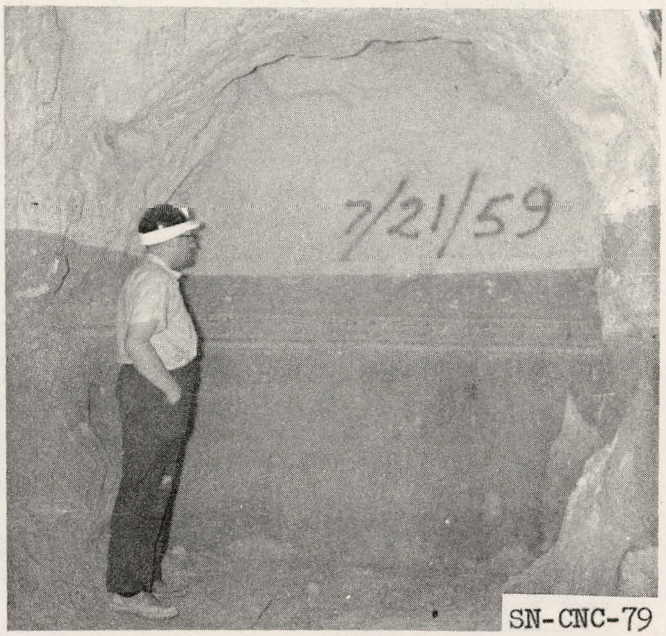

Fig. 19. Undisturbed rock at U12-B "Raise" Drift heading station 3+76.

Fig. 20. Cavity probe operation over station 3+20 in U12-B "Raise" Drift.

Fig. 21. Surface fracture adjacent to cliff face above U12-B Rainier detonation point. (See Fig. 23 for location.)

Fig. 22. Surface fracture adjacent to cliff face above U12-B Rainier detonation point. (See Fig. 23 for location.)

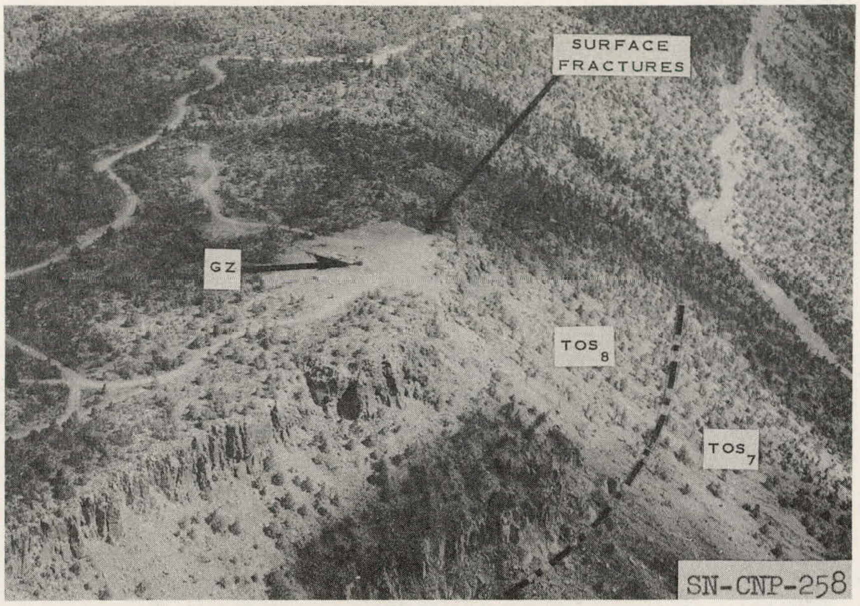

Fig. 23. Aerial photo of Rainier Mesa above U12-B Rainier shot point showing location of fractures illustrated in Figs. 21 and 22.

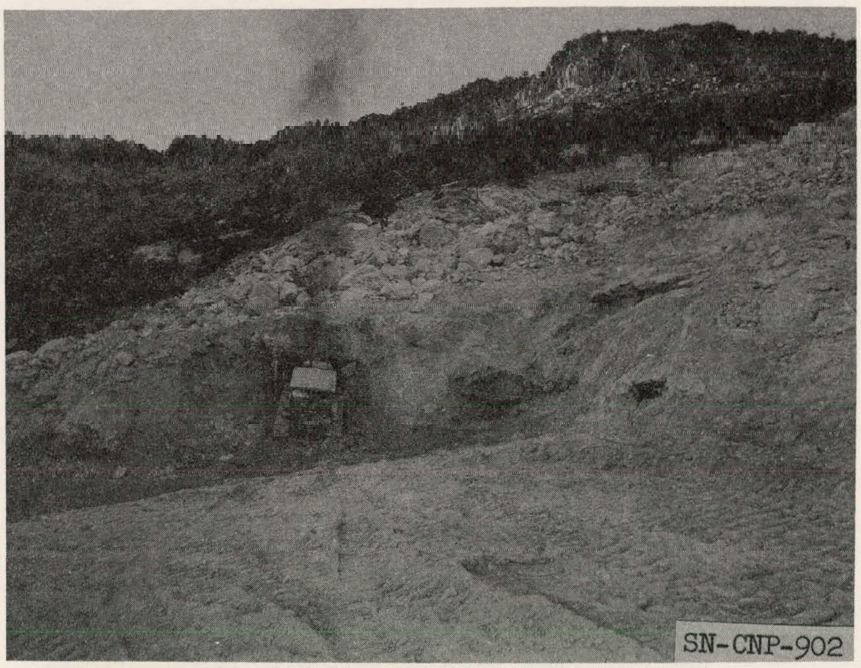

Fig. 24. Surface rubble below Neptune crater.

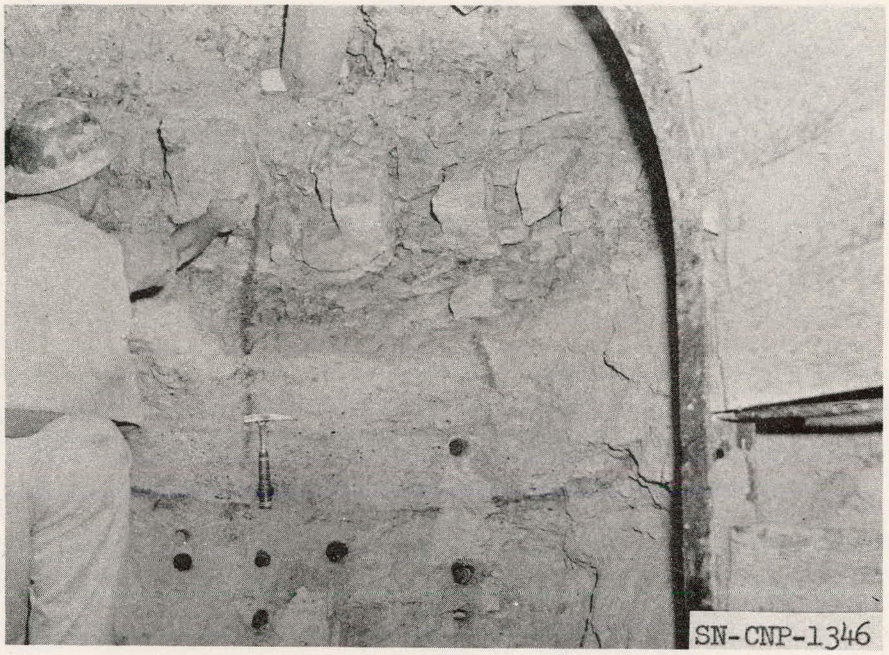

Fig. 25. Fractured welded tuff (TOS_6) overlying undisturbed lapilli tuff (TOS_5) at station 0+40 in U12-C Neptune Exploratory Drift.

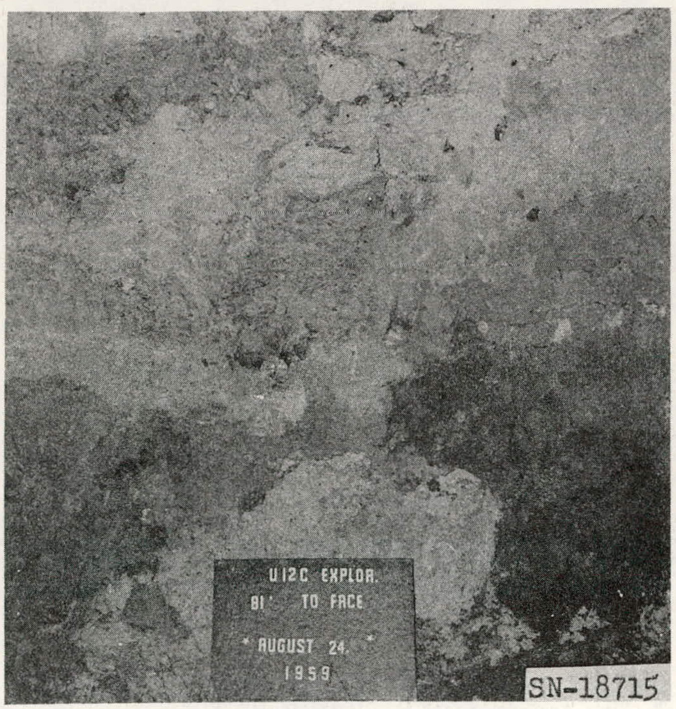

Fig. 26. Blast mixed lithologies TOS_{7-2n} and TOS_{7-3n} at station 0+96 in U12-C Neptune Exploratory Drift.

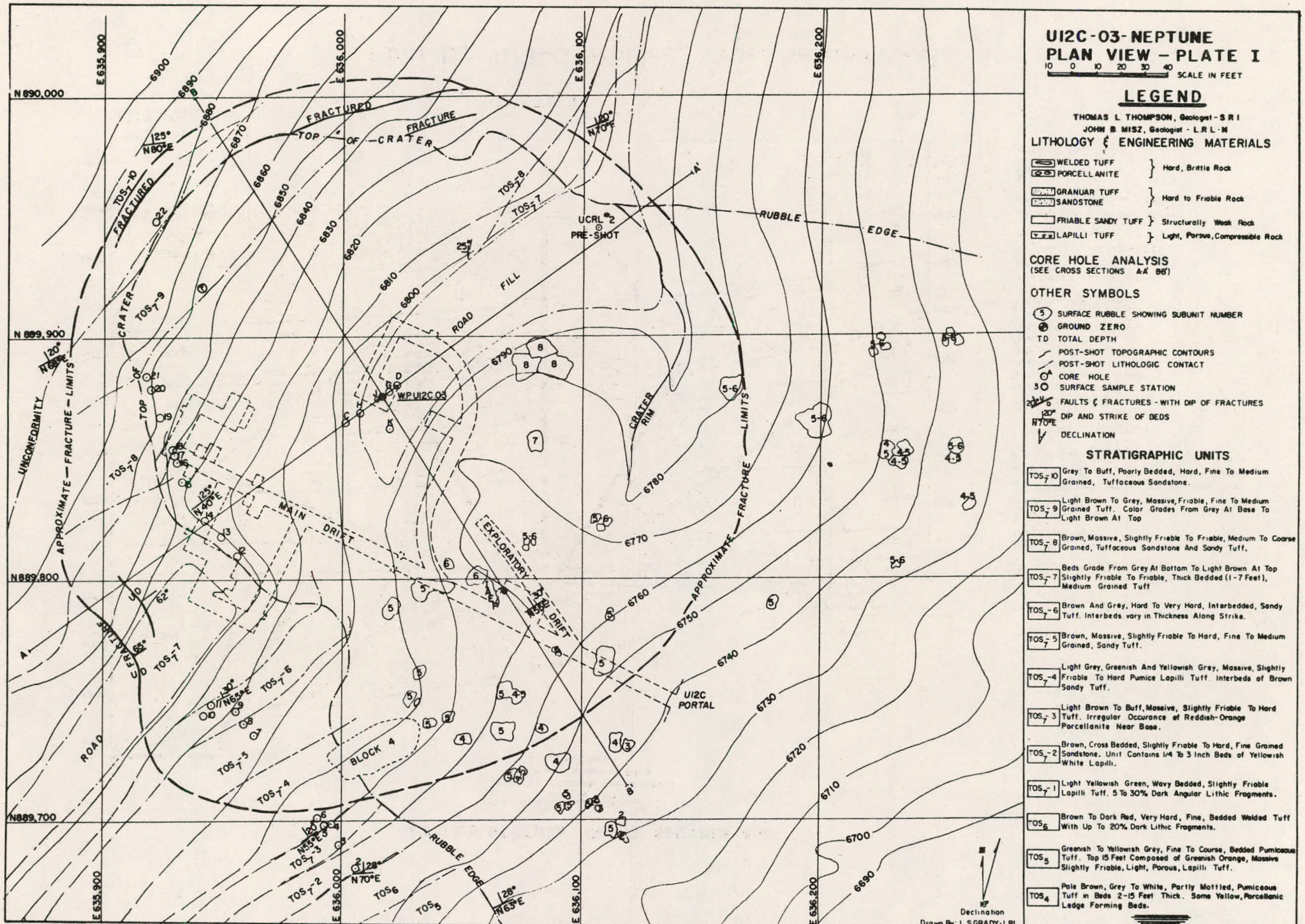

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Plate I. U12-C Neptune Plan.

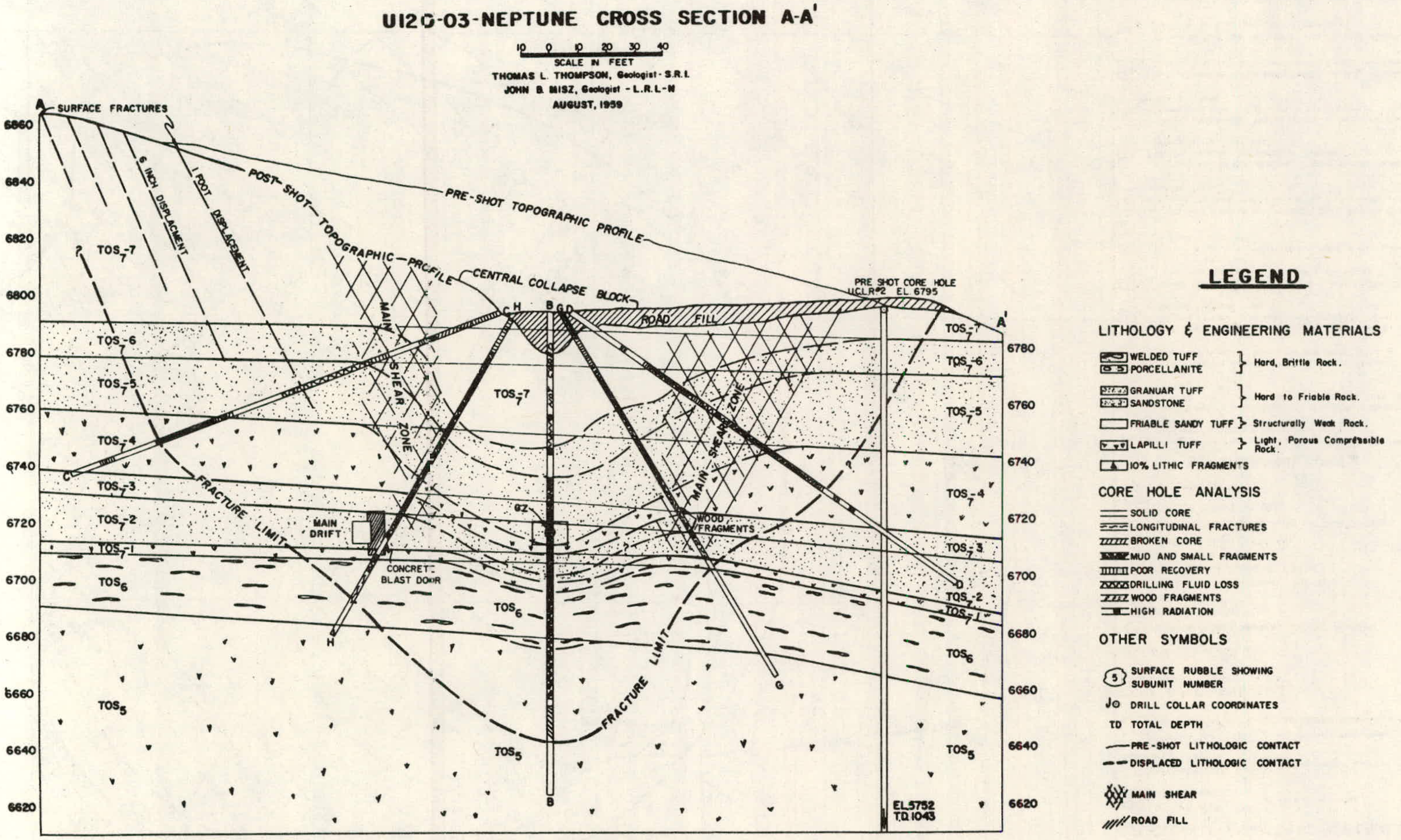

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PLATE II

Plate II. U12-C Neptune, Cross Section A-A'.

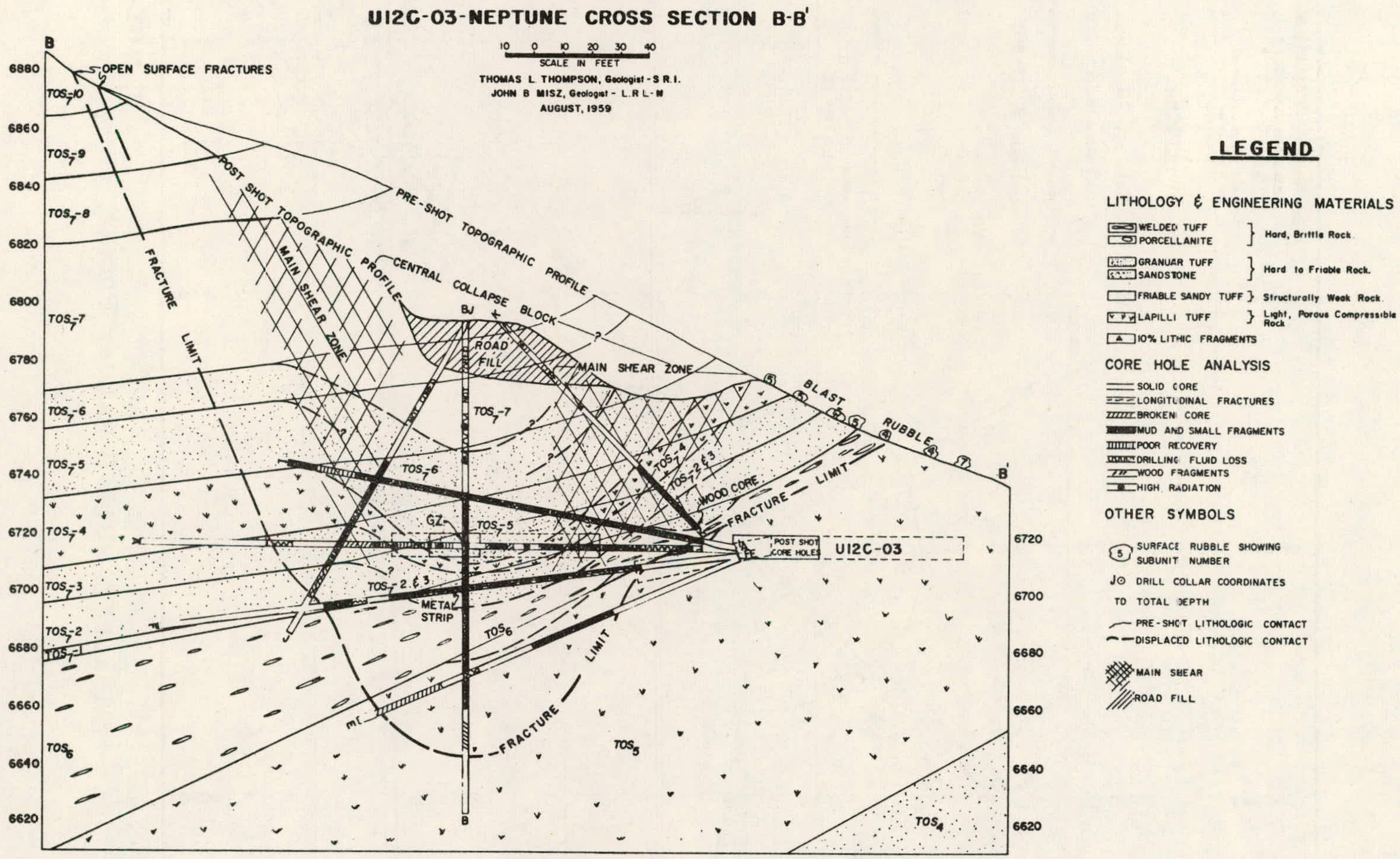

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PLATE III

Plate III. U12-C Neptune, Cross Section B-B'.

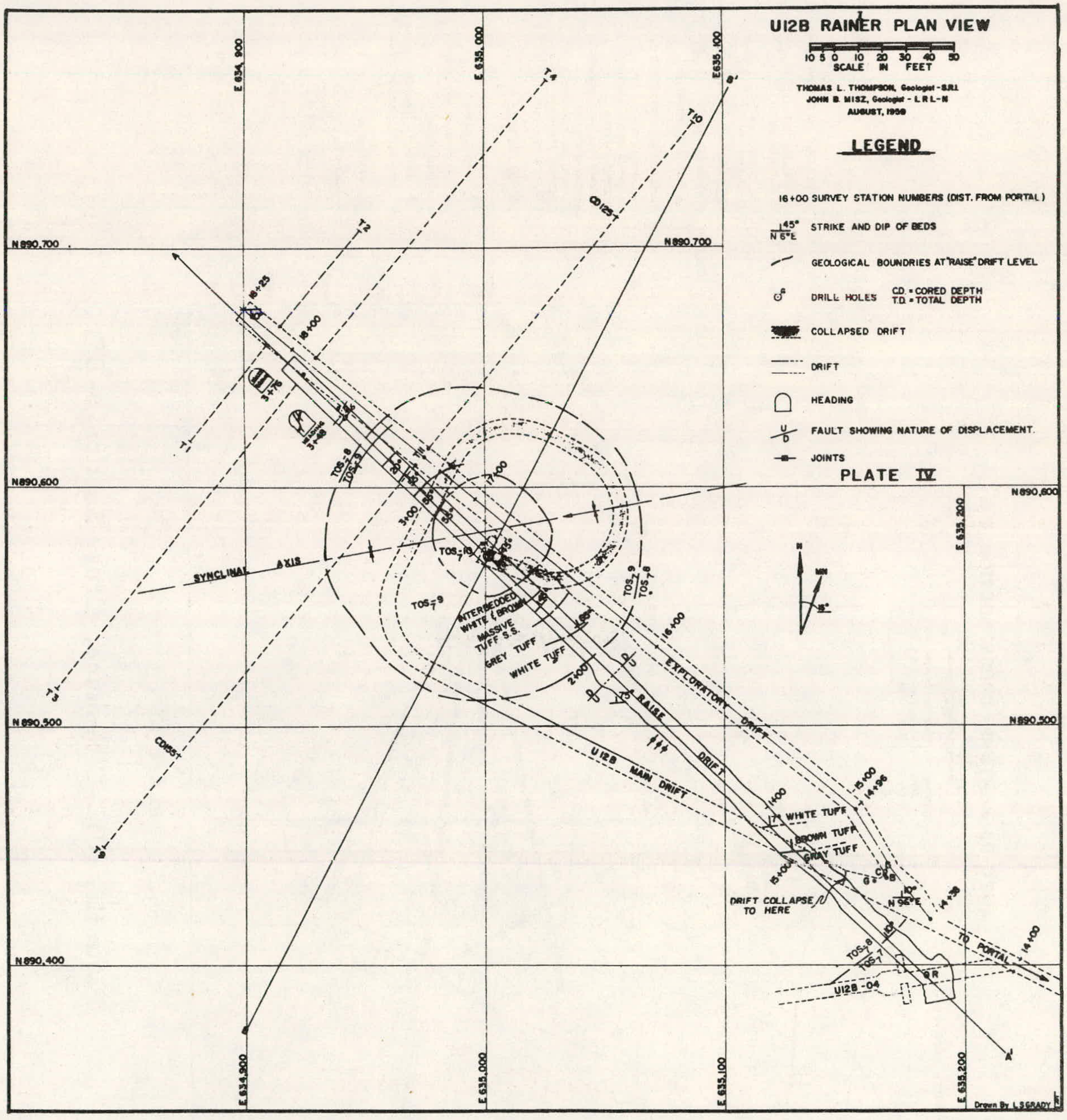

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Plate IV. U12-B Rainier Plan.

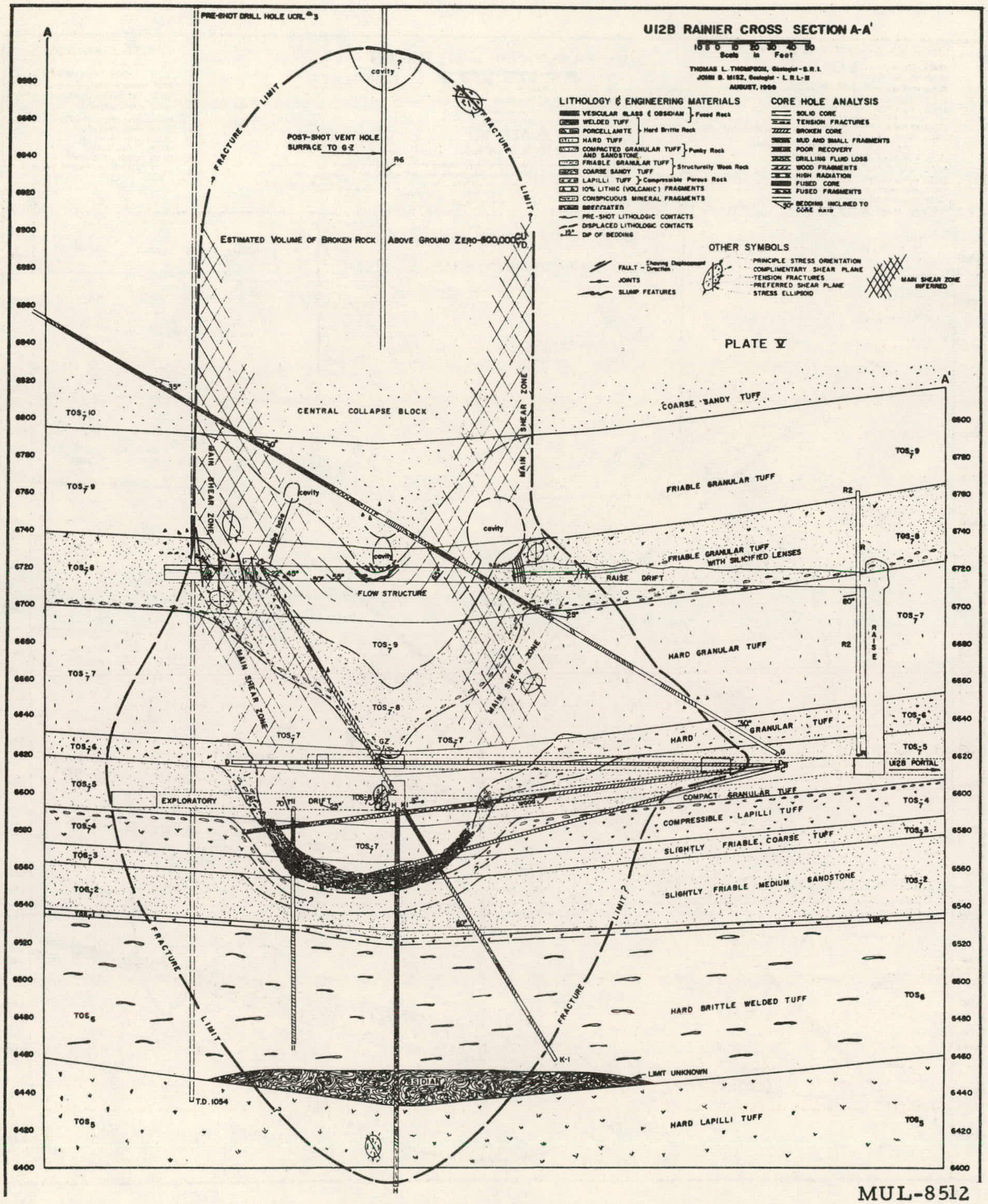

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Plate V. U12-B Rainier, Cross Section A-A'.

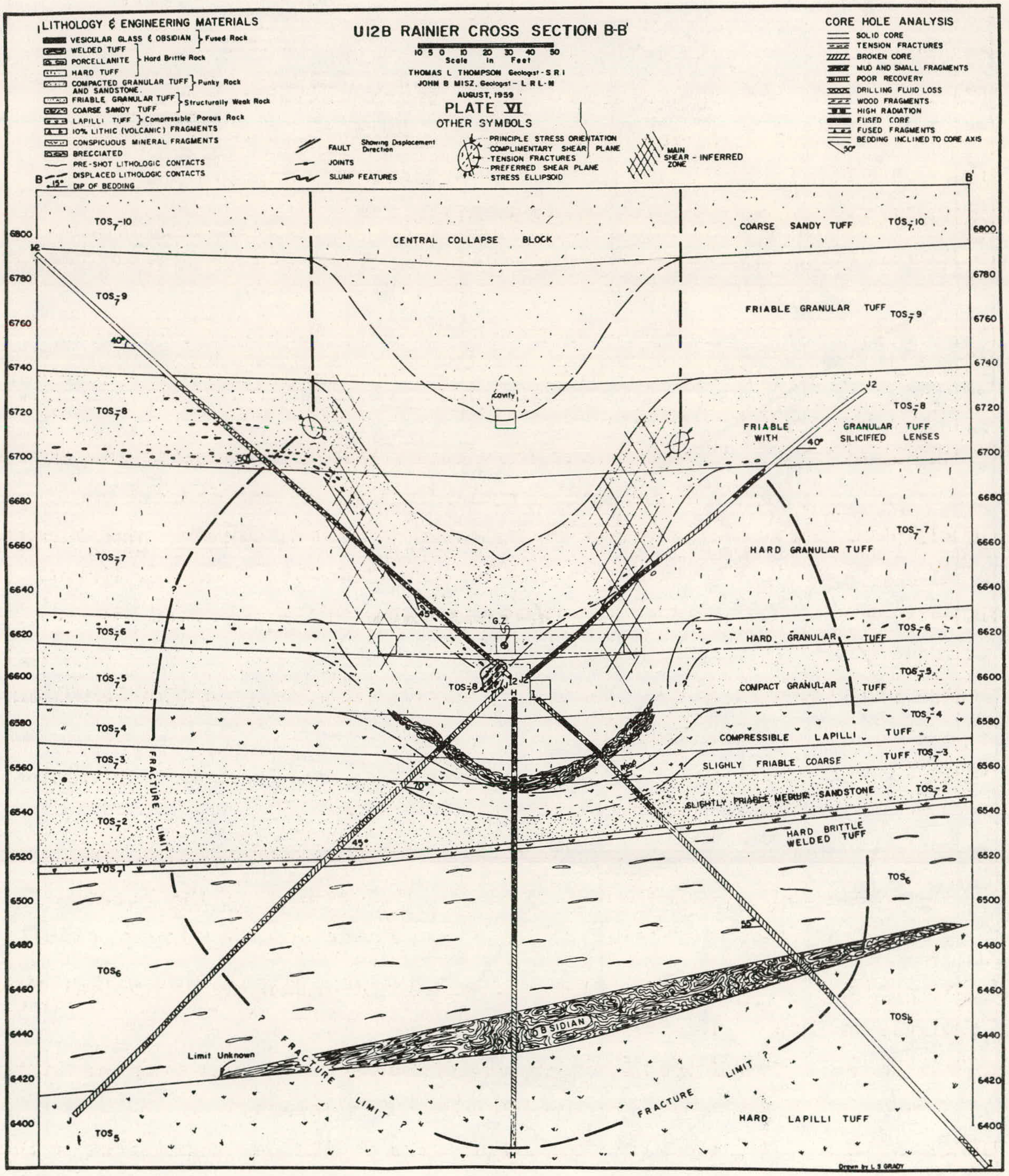

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Plate VI. U12-B Rainier, Cross Section B-B'.

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UCRL-5026	Non-Military Uses of Nuclear Explosions.
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UCRL-5253	Industrial Uses of Nuclear Explosives.
UCRL-5257, Rev.	Peaceful Uses of Fusion.
UCRL-5281	Temperatures and Pressures Associated with the Cavity Produced by the Rainier Event.
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Plowshare Series: Report No. 2. Proceedings of the Second Plowshare Symposium (Held at San Francisco May 13-15, 1959):

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UCRL-5676	Part II : Excavation.
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