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**SURVEY OF PILEDRIVER RESULTS
AND PRELIMINARY INTERPRETATION OF THREE
POSTSHOT CORES IN AND NEAR THE CAVITY**

I. Y. Borg

April 29, 1970

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SURVEY OF PILEDRIVER RESULTS AND PRELIMINARY INTERPRETATION OF THREE POSTSHOT CORES IN AND NEAR THE CAVITY

Abstract

A summary of measured data collected by numerous agencies cooperating in the Piledriver event (61 ± 10 kt in granodiorite, June 2, 1966) is presented together with calculations based on empirical relations deduced from past events in comparable media. Highlights include the following: peak measured radial pressure experienced by surviving rock was 250-270 kb; at 350 m from the present cavity edge the radial pressure was <1 kb; radius of the spherical mass of rock vaporized and melted is 15.6 m; the displacement ("heave") is at a maximum at the cavity edge, 24.5 m, and is less than 0.3 m at 305 m from the shot point; measured cavity radius is 40.1 m. Of nine relations that have been proposed to predict cavity radius, five result in radii accurate to $<3.5\%$. The remainder are off by about 10-18%.

The shape of the Piledriver chimney is known to depart from that of a cylinder with semihemispherical ends. The 13° cant measured on the SW wall is probably due to collapse and shearing along pre-existing planes of weakness which are part of a regional pattern. By analogy with information from the Hardhat chimney exploration in the same igneous body, the Piledriver chimney may in fact have nearly vertical walls on the unexplored NE side

and thus be axially asymmetric. It is possible that further exploration in the Hardhat chimney would reveal a similar asymmetry.

Three postshot recovered cores (U-15.01 PS-1, -2, -3) have been examined on a gross scale prior to extensive detailed sampling for laboratory tests. The positions of injected glass seams, radioactivity, and shear zones were recorded. The orientation of several thousand core fractures was measured with respect to the core axes and distance from the shot point. Although cores and the fractures they contain cannot be uniquely oriented in space, it can be demonstrated that the fractures are not randomly oriented with respect to the shot point and that they have attitudes consistent with failure along the four major and several minor preexisting fracture and/or joint sets. In general their positions are not consistent with radial or tangential fracturing. The test for shear failure cannot be applied satisfactorily to the data at hand. Taking all observations into account, phenomena related to failure of rock in the Piledriver event are closely related to preexisting weaknesses and inhomogeneities.

Introduction

The Piledriver event in 1966 was a 61-kt contained nuclear shot in granodiorite. Of interest to the Plowshare program were the effects produced in the medium by the explosion—for example, cavity size, chimney shape and dimensions, displacements, pressures, and so forth. Table 1 summarizes these aspects of the experiment and the principal results obtained to date.

The purpose of this report is twofold: (1) to compile information pertinent to the study of the effects of the Piledriver nuclear explosion in granodiorite, and (2) to describe macroscopic phenomena observed in three recovered postshot cores.

The compiled information constitutes background material for further study of permeability, compressibility, phase transformations, micro-deformational

features, etc. It derives from technical letters and reports of various agencies that have been involved in both the Hard-hat and Piledriver experiments: e.g., USGS, NTS, DASA, U.S. Army Corp of Engineers, and their subcontractors. The data are presented in abbreviated form, primarily as appendices. Because the number of reports covering Piledriver effects is already quite large and because they infrequently refer to each other, it was decided to cite all sources. In this way it is hoped that this summary will be useful to the various groups working on postshot effects. Interested parties can thus readily locate additional information or details if desired.

The second aim was to retrieve as much information as possible from the cores before they were subjected to

Table 1. Summary of principal data on Piledriver event.

Date shot	June 2, 1966.
Yield	61 ± 10 kt, based on LASL determination on injected glass encountered in reentry tunnel 300 ft from shot point, 14 months after shot. ^{1,2}
Shot depth	1518 ft (462.8m) below surface (3572 ft above MSL).
Cavity radius	131.5 ft (40.1 m), measured in drill hole which intersected cavity wall at a point 34 ft (10.4 m) below shot level. ³
Chimney height	910 ft (277.4 m) above shot level. ²
Chimney width	160 ft (48.8 m), measured in reentry tunnel at a point 103 ft (31.4 m) above shot level.
Chimney volume	$6.69 \times 10^7 \text{ ft}^3$ ($19.0 \times 10^5 \text{ m}^3$), or >29.4 r ³ .
Pressure of overburden at shot point	1751 psi (121 bars), calculated on basis of average density of 2.66 g/cc.
Apical void ^a	2 ft high. ²
Time of cavity collapse	Within 14 sec after the shot. ¹
Maximum vertical extent of increased permeability	$1032 \pm 36 \text{ ft}$ ($314.6 \pm 11.0 \text{ m}$) ² above shot level.

^a Empty space between top of chimney fill material and chimney ceiling.

extensive sampling. To this end all three cores were photographed in their entirety and the photographs are reproduced here. The attitudes of all throughgoing fractures

in the cores (>2000) were determined with respect to the core axes. Positions of radioactive glasses, shear zones, and petrological discontinuities were noted.

Description of the Piledriver Site

Both the Hardhat and Piledriver experiments were carried out within the granitic Climax stock of Area 15, NTS (Figs. 1 and 2). In both instances a heavily in-

strumented underground tunnel/drift complex was designed to monitor shock phenomena. Names of the projects, outside cooperating agencies, principal

Fig. 1. Piledriver and Hardhat sites in Area 15, NTS.⁴ Contours show surface elevation in feet above sea level. WP marks shot point.

Fig. 2. Piledriver tunnel and drift complex, showing locations of instrumented boreholes at shot time. Stations indicated on Elevation (e.g., 5+06) are referenced to 15.01 shaft (0+00) which is off diagram. (Modified from drawing by K. Willits, Fenix and Scisson, Inc., Project Engineer, 1968, Piledriver Project Sta 15.01, Drawing No. MER-M2 14d-1501, USAEC Nevada Operations Office.)

investigators, and report numbers for the Piledriver event are listed in Appendix 1.

The area of the Climax stock exposed at the surface is 1.3 square miles; however, the rock mass broadens to a diameter of 6 miles at a depth of 13,000 ft.⁵ Adjacent marble, tactite, and sedimentary sequences are well removed from the Piledriver shot point. The stock consists of two petrological types: granodiorite and a younger porphyritic quartz monzonite (230 ± 25 million years).⁶ Figure 1

shows the indurated, nearly vertical contact between the two. Although much of the instrumentation surrounding both Hardhat and Piledriver was placed in the quartz monzonite portion of the intrusive, the shot points are located well within the granodiorite. Similarly the three post-shot Piledriver holes were cored within the granodiorite.

The two igneous rock types are differentiated on the basis of large, pink K-feldspar crystals (up to 5 cm) which occur in the quartz monzonite but not in

the granodiorite. The two rocks are nonetheless similar in chemical composition. Chemical analyses of nine samples are given in Appendix 2. Modal analyses of the volume occupied by the various mineral constituents in a large number of samples (Appendix 3) suggest that there is a wider variation of rock types within the stock than is indicated by the chemical analyses. While it is possible that the chemical analyses available are not representative of the whole stock, it seems more likely that the modal analyses reflect sampling problems connected with the medium coarse grained (1-4 mm), sometimes porphyritic texture of the rocks. Initial porosity, bulk grain and powder densities, water content of pores, and sonic velocities are given in Appendix 4 for 26 samples from the U-15a preshot borehole at the Hardhat site (Fig. 1).

The amount of water in the stock is of considerable importance in the interpretation of shock effects. The ~1 wt% H_2O recorded in chemical analyses (Appendix 2) is so-called combined water: H_2O in the form of $(OH)^-$ tied to hydrous phases such as micas, hornblende, sphene, and alteration products. Another 2% is estimated to be localized in small scale fractures and pores.⁷ The device was emplaced below the water table which is encountered at about 4500 ft MSL⁸; however, perched water was encountered at variable depths (80-687 ft) during preshot drilling and tunneling operations, suggesting that it is localized by the major fracture and shear zones.⁷ During emplacement of the Piledriver device a local saturated shear zone was encountered which gave rise to substantial downhole flow.⁹

In Situ Stress Measurements

In addition to instrumentation in the drifts and associated slant holes,¹⁰ five close-in radial bore holes were fitted with stress gages^{11, 12} (Fig. 2, holes A-F) by outside contracting agencies. The group from Illinois Institute of Technology used electrolytic chamber gages (CCl_4 , paraffin, and NH_4OH); the group from Stanford Research Institute used manganin gages, many of which failed before arrival of the peak radial stress. Data from all reliable gages are plotted in Fig. 3 as a function of distance from the shot point. Also included are peak radial stresses calculated from peak particle velocities.¹⁰ In at least one instance the calculated stress (3.9 kb) is higher than the observed peak stress (1.2 kb) at that point.¹⁰ In this case calculated stress is believed to be more reliable. Stress data at various stations are included in Appendix 5. Comparable calculated data (SOC code) have been given by Cherry and Rapp.¹³

Fig. 3. Measured peak radial stress vs pre- and post-shot distance from Piledriver shot point.

Displacements

The expansion and heave of the cavity following passage of the main shock wave result in displacements of the surrounding rock which diminish in magnitude with distance from the shot point. In order to correlate data such as peak pressures measured within 100 msec of the time of detonation with observed phenomena in postshot cores and reentered drifts, an estimate of the real displacements must

be made. There are numerous ways to do this. One way is to compare positions of surviving surveyed markers in the access tunnel and drifts before and after. This is somewhat unsatisfactory because the portions of the tunnel and drifts have undergone local gross movement on pre-existing joints and faults.

Yet another guide to displacements is the so-called "residual radial displacement"

calculated by single integration of particle velocity or double integration of acceleration curves. Displacements so calculated are strongly affected by base line errors in the initial data and characteristically show great scatter (see Fig. 2.3, Ref. 14).

Data of these sorts are plotted as a function of preshot distance in Fig. 4 together with displacements calculated from the SOC code.¹³ Also plotted is a calculated point based on the difference between the observed cavity radius and the radius of melted and vaporized rock. It is assumed that the cavity wall which was intersected below the shot point in postshot drilling (core 3) is the true boundary between melted and unmelted rock; i.e., has not been affected by late spall. The argument is as follows:

Cavity development is a continuous process, but it is convenient to describe it as a discontinuous process involving shock vaporization, shock melting, and vapor-solid interactions. The latter involve thermal conduction and exothermic condensation of ionized-vaporized elements on solid rock interfaces exposed by gravity removal of the shock-melted zone.

Butkovich^{19,20} has estimated the amount of granitic rock involved in the three types of transformation:

Shock-vaporized 70×10^6 g/kt

Shock-melted 350×10^6 g/kt
Melted by solid-vapor interactions $250-300 \times 10^6$ g/kt

The volume of rock affected can be calculated and the radii of the concentric zones determined (Table 2). The difference between the final cavity radius 40.1 m (131.5 ft) and that of the cavity void calculated above, 15.6 m (51.2 ft), represents the distance rock at the cavity wall has been transported by gas expansion, 24.5 m (80.3 ft).

Agreement between measured and calculated displacements is reasonably good where they can be compared, indicating that the SOC calculation can be used to estimate displacements fairly accurately over the whole range. In the linear portions of the displacement-vs-distance curve (elastic regime?), underground displacements are proportional to the inverse of the square of radial distance. A similar relationship was established from permanent particle displacements at depth in the Hardhat and Shoal tests in granite despite greater scatter in the data.¹⁴

Figure 5 and Table 3 show preshot and postshot radial distances from the shot point derived from displacement data for the Piledriver event.

Table 2. Calculated amounts of rock vaporized and melted by Piledriver explosion.

Process	Amount of rock affected		Zone limits (radial preshot distance from shot point)	
	Weight (10^7 g)	Volume (10^7 cc)	Meters	Feet
Shock vaporization	427	160	0 - 7.26	0 - 23.8
Shock melting	2135	800	7.26 - 13.2	23.8 - 43.3
Melting by solid-vapor interactions	1678	628	13.2 - 15.6	43.3 - 51.2

Fig. 4. Measured and calculated displacements as a function of preshot distance from shot point.

Table 3. Preshot vs postshot radial distances from shot point for displaced rock in Piledriver event.

Preshot distance (feet)	Displacement (feet)	Postshot distance (feet)
51.2	80.3	131.5
60	73	133
70	65	135
80	58	138
90	53	143
100	48	148
120	41	161
140	35	175
160	30.5	190.5
180	26.5	206.5
200	24	224
300	10.5	310.5
400	5.6	405.6
500	3.6	503.6
600	2.45	602.5
700	1.75	701.75
1000	0.86	1000.86
1500	0.38	1500.38
2000	0.205	2000.21
3000	~0	3000

Fig. 5. Displacement of surrounding rock by Piledriver explosion, shown by plot of postshot vs pre-shot distances from shot point.

Cavity Size Measurements and Predictions

Prior to postshot drilling of three core holes, various estimates were made of the cavity size to be expected. Table 4 lists these estimates and the methods used

to make them. It is of interest to compare these values with the most probable cavity radius of 131.5 ft (40.1 m) determined by the core drilling.

Table 4. Predictions of Piledriver cavity radius.

Predicted radius		Prediction method ^a
m	ft	
32.7	108	SOC calculation assuming constant overburden and no free surface. ¹³
36.4	119	$r_c = 21.0 \left[\frac{W^{0.306} E^{0.514}}{\rho^{0.244} \mu^{0.576} h^{0.161}} \right]$, Closmann. ²¹
40.1	131.5	$r_c = \frac{CW^{1/3}}{(\text{ph})^\alpha}$ where C = 103 (granodiorite), $\alpha = 0.32$ (2% H ₂ O), Higgins and Butkovich. ²²
40.1	131.5	Measured value, accepted as <u>most probable cavity radius on basis of gamma and caliper logs of core hole PS-3 which intersected cavity below level of shot point, Sterrett.</u> ³
40.1 ⁺	131.7	
		Assuming adiabatic expansion of cavity gas to twice overburden pressure (Fig. 2, granite), Chapin. ²³
40.9	134	$r_c = C \frac{W^{1/3}}{(\text{ph})^{1/4}}$ where C = 61.6 (granite), Boardman. ²
41.2	135	$r_c = 16.3 \frac{W^{0.29} E^{0.62}}{h^{0.11} \rho^{0.24} \mu^{0.67}}$, Heard and Ackerman. ²⁴
41.6	136	$r_c = 52 \frac{\alpha^{1/3} W^{1/3}}{(\rho gh + Cs)^{1/3} \gamma}$ where Cs = 30 bars (granite), $\gamma = 1.05$ (granite with 2.5% H ₂ O), ²⁵ Michaud. ²⁶
44.5	146	Calculated from void volume of the chimney determined from chimney pressurization tests, Boardman. ²
45.1	148	$r_c = (3R^2 \Delta s)^{1/3}$ from corrected residual particle displacements at slant holes (668 ft and 1543 ft radial distance), Perrett. ¹⁰
45.7	>150	SOC calculation assuming variable overburden and rarefaction at a free surface. ¹³

^aThe symbols used here are defined as follows:

r_c = cavity radius,

W = yield (kt),

E = Young's modulus (Mb),

ρ = density of rock (g/cc),

μ = shear modulus (Mb),

h = depth of burst (m),

α (Higgins and Butkovich) = $\frac{1}{3} \gamma$,

γ = coefficient of adiabatic expansion,

α (Michaud) = 1.0 (coefficient related to size of the shot chamber),

Cs = coefficient related to the "constraints of the structure,"

R = radial range (m),

Δs = residual displacement (m).

Preexisting Joints and Fractures

The Climax stock is everywhere broken by fractures, faults, and shear zones most of which are healed (i.e., cemented

by minerals of later origin). The old fractures are conspicuous on all scales, microscopic and macroscopic. Blocks 1

cubic foot or larger in size are rarely observed without macroscopic fracturing of some sort.²⁷ The consensus among geologists who have mapped the fracture systems is that the joints and fractures are short-lived (i.e. terminate within a few yards), and that extrapolation of frequency or attitudes any distance is tenuous.^{4,27} Particle size analysis of Piledriver chimney material indicates that the rubble is somewhat smaller than might be expected from a "typical hard rock." The Hardhat rubble conforms more nearly to the expected distribution. The difference is attributed to the proximity of the Piledriver chimney rubble samples to a preexisting shear zone which now forms the SW chimney wall.⁹ There is no evidence that preshot fractures and joints at the two sites differed significantly in number or spacing.

ORIENTATION

Preshot fracture and joint studies were carried out by a number of agencies and geologists.^{1,4,7,27-30} As many as eleven sets of joints and fractures have been recorded along the Hardhat 1500 tunnel²⁸

and nine sets within approximately 220 ft of the Piledriver CR drift.²⁹ (See Appendix 6 for an example of the amount of variation in attitude recorded within the sets.)

Table 5 lists the most prominent sets observed in the stock. Most of the data from the Piledriver site were collected within the quartz monzonite phase of the intrusive (CR and DL drifts and within the tunnel from the access shaft to the Station 9 + 35); however, there is no evidence suggesting they are oriented differently within the granodiorite surrounding the shot point.

A preexisting fracture-joint set makes a constant angle with the core axis in a given hole, assuming that the bearing of the hole remains constant along its length. These angles are also recorded in Table 5 for all three core holes.

INFLUENCE ON CHIMNEY SHAPE

Figure 6 contains stereographic projections of the various fracture sets recorded in the Piledriver drifts together with the orientation of the three postshot cores and the main access tunnel. The

Table 5. Orientation of preexisting joints and fractures in the Climax stock.

	Hardhat ^{7,27,28,30}		Piledriver ^{4,29}		Angle, core axis to fracture set		
	Strike	Dip	Strike	Dip	Core 1	Core 2	Core 3
Major sets	N45-53°W	80SW-83°NE	N50-53°W	29-34°NE	77-83°	14-20°	84-90°
	N20-36°W	22-30°NE	N45-50°W	83SW-79°NE	41-59°	32-50°	30-48°
	N40-62°E	78SE-78°NW	N73-79°W	78SW-79°NE	42-63°	35-57°	32-83°
	—	—	N36-41°E	73-79°SE	77-83°	80-83°	80-83°
Minor sets	N15°E	77SE-78°NW	N39-49°E	52-59°NW	68°	64°	74°
	N24-36°W	83NE-83°SW	N65-67°W	86-87°NE	53°	40°	43°
	N75-84°W	82NE-80°SW	N12°E	68°NW	78°	39°	70°
	B31-34°E	85NW-75°SE	N28°E	75°NW	38°	62°	21°
	And others		And others				

value of the strike of the fracture sets is an average value. The variation is on the order of $\pm 7^\circ$ about this value (Table 5). The range in the value of the dip (shaded areas of Fig. 6(a)) is only approximately known and is probably of the same order of magnitude as that of the strike. Average values for both strike and dip are plotted for minor fracture sets in Fig. 6(b). Also plotted in Fig. 6(a) is a line (point c) joining the two locations at which the chimney was encountered in postshot explorations—in the tunnel and during coring of hole 3. The line falls near the intersection of the two major steeply dipping fracture sets. Thus one or both of these sets of preexisting fractures probably influenced the spall and chimney shape on the SW side as pointed out by Sterrett.³

Assuming that the other sets are equally well developed and just as influential in determining chimney shape, one

might anticipate the same cup-shape on the NW side of the chimney (Fig. 7(a)). The development of NE and SE walls appears to lack structural control, and they would be expected to be nearly vertical up to the roof. Of the four major fracture systems, the fourth, which dips 31° NE, is in the best position to affect the shape of the chimney roof, especially on the NE side. It would be expected to expedite collapse of an apical void if one formed. No appreciable void was detected during exploration into the top of the chimney.²

The Hardhat event (February 15, 1962) occurred approximately 1/4 mile away in the granodiorite of the same (Climax) igneous body. Postshot exploration of the Hardhat chimney (Fig. 7(b)) indicates the walls are nearly vertical, at least in the plane of the sketch which contains all drill holes and the tunnel. If it is assumed that the shape of the Piledriver and Hard-

Fig. 6. Stereographic projections of major (a) and minor (b) fracture-joint systems within the Climax Stock. 1, 2, and 3 are locations of postshot drill holes; C is line connecting two points (in tunnel and in core 3) where chimney-granodiorite contact was observed—i.e., a line in the chimney wall.

Fig. 7(a). Chimney shape resulting from Piledriver event.

Fig. 7(b). Chimney shape resulting from Hardhat event.

hat chimneys are similar, the only way to reconcile the results of postshot

exploration at the two sites is by proposing an axially asymmetric shape.

Thus by analogy with the Hardhat experience, a cross section with vertical walls may exist in the Piledriver chimney.

Conversely at least one wall of the unexplored portions of the Hardhat chimney may depart from the vertical.

Fracturing Produced by the Explosion

No one has yet made a thorough study of the attitude of shock-induced fractures in an isotropic medium surrounding an underground explosion source.* However, it is generally assumed that their orientations are related to the direction of propagation of the shock wave and that they can be described as radial, tangential, or shear fractures. By analogy with static loading tests, shear fracturing at angles of 25-45° to the direction of maximum principal stress (σ_1) occurs at high mean compressive stresses. This shear fracturing is in large part responsible for the intense fracturing and disaggregation of rock immediately surrounding a cavity produced by a nuclear explosion. At greater distances from the source, compressive failure probably more closely resembles "extension" failure of static tests.^{32,33} Specifically, breaks occur parallel to the direction of peak pressure which may (but not necessarily) coincide with a radial direction. Rarefaction of the shock at a gross discontinuity—e.g., the surface of a tunnel—can potentially produce fracturing at right angles to this second type, thereby approximating tangentially oriented breaks.

*There have, however, been several investigations of local effects. For example, Houser and Emerick³¹ measured the orientation of large-scale "explosion-produced" fractures within a 100-ft interval of the 1500 tunnel adjacent to the Hardhat chimney.

These fractures are directly related to the passage of the shock wave. At close-in locations another series of fractures develops as a consequence of the later expansion of the cavity formed by melt and vaporization of the rock. This is gross displacement (heave) of adjacent unmelted or unvaporized rock. By analogy with the surface of an expanding balloon, radial breaks are likely.

In practice, fielding of an experiment in an isotropic medium is highly unlikely because of the ubiquitous joints, bedding, layering, etc. of most rocks. In the Piledriver experiment, such preexisting discontinuities have dissipated the peak radial pressure by at least 20% as judged by the magnitude of the tangential component¹⁰ of measured pulses. Under such circumstances, it is questionable whether any fracture pattern symmetrically related to the shot point can be recognized. However, it is one of the problems addressed by the core fracture study described later.

POSTSHOT CORE DRILLING TO STUDY FRACTURING

The drilling of three postshot cores has been described by Sterrett.³ He obtained gamma, caliper, and temperature logs of core 3 which penetrates the cavity, thereby fixing the cavity radius at $r_c = 131.5$ ft. All three recovered cores were photographed in their entirety prior to sampling (Appendices 7-9). The

information noted alongside the individual photographed core boxes derives largely from inspection. "Shear zone" labels were assigned on the basis of the condition of the core, the percent recovery in that interval, and whether there was a loss of drilling fluid circulation at that point. By extrapolation between cores 1 and 3 the trend of the zones so recognized (Fig. 7(a)) can be established as parallel to regional structure. Furthermore, they are parallel to the one line known to be contained by the SW chimney wall.

Core 1 approaches within 160 ft of the shot point. There is a clear disparity in the condition of the core on either side of this point (288 ft slant hole distance). From the photographs as well as from the amount of core recovered on either side of the point of closest approach, it can be seen that the amount of fracturing at a given distance from the shot point can vary. In this instance there is more fracturing in the vicinity of the chimney walls than in rock more nearly under the cavity void.

Core 3 is in the poorest condition of the three and has the lowest recovery record (Fig. 8). This is primarily due to a change in drilling technique.³ Spikes in the gamma log of the hole do not always have radioactive counterparts in the recovered core. Combined beta and gamma counts (measured in the cores rather than in the core hole) are recorded alongside the photographs to indicate location of high level radiation, glass seams, and position of the spikes in the gamma log whether or not the source of the radioactivity was recovered. Most of the readings were taken as the rock was removed from the core barrel. A few were made later, e.g., on small glass seams, and they should be interpreted with the recorded data in mind.

Narrow glass seams (Fig. 9) were first encountered at 164 ft SHD (slant hole distance), which is 182 ft from the shot point. They become increasingly abundant with approach to the chimney (at 181, 210, 214, 219, 223, 226, 229,

Fig. 8. Amount of core recovered in the three postshot exploratory holes.

232 ft

226 ft

Fig. 9. Sections of core from hole 3, showing glass seams filling fractures (upper and lower left) and contact between granodiorite and cavity debris (right).

230, and 232 ft SHD). The glass fills well-developed fractures that appear to be preexisting. At the nominal chimney/country-rock intersection, black vesicular

rock in a glassy matrix makes its appearance (Figs. 9,10). It can be quite coherent and the core fragments are commonly bounded by flat throughgoing surfaces

Fig. 10. Sections of core from hole 3 at depth of 233.5 ft, showing vesicular, glassy debris within cavity

(fractures) similar to those observed throughout all three cores (Fig. 11). The chimney rubble beyond this point consists of glassy vesicular debris to-

gether with melted and highly fractured granite. It becomes generally more glassy along the core, but partially melted granitic spall occurs as well.

258 ft

260 ft

Fig. 11. Sections of core from hole 3. Core fracture (left) is coated with dull material that is presumably low-silicon glass. Sharp, planar fracturing is evident in vesicular, partially melted rock within cavity (right).

246 ft

241 ft

Fig. 12. Sections of core from hole 3, showing (left) spall in vesicular, glassy matrix within cavity, and (right) partially melted phenocrysts.

There are numerous examples of partially absorbed spall within the solidified vesicular glassy debris (Fig. 12).

AMOUNT OF MACROSCOPIC FRACTURING IN THE CORES

In cores 1 and 2 fractures are 1-6 in. apart. Almost certainly many of these open breaks are produced during the drilling and coring process, as stress relief cracks. The tacit assumption in analysis of core fracturing is that the measurable breaks comprise (1) shock-induced fractures, (2) "open" preexisting fractures and joints, (3) breaks produced during the coring process which are parallel to the planes of weakness (either shock-produced or preexistent), for example, healed fractures.

The amount of core in which fractures can be measured depends on the amount recovered (89, 86, and 61% in holes 1, 2, 3, respectively). This in turn depends on local vagaries such as intersection with preexisting fault and shear zones as well as drilling and recovery techniques. For example, sampling and recovery was poor within a 28-ft-wide shear zone encountered in hole 2. For the purposes of study of fracture orientation or frequency, core 3 is considered almost a total loss because of its poor condition. This is believed to be a consequence of intersection of a wide shear zone at a considerable distance from the shot point as well as recovery techniques inferior to those used for the other two cores.³ Measurement of fracture orientation in such rubble is difficult and only a few fractures out of the total present are represented in the compilations that follow. Thus the actual number of fractures re-

corded within any particular interval in a core is often meaningless. A comparatively low number per foot of core can indicate either that fracturing has been minimal or that fracturing of either pre- or post-shot origin has been so extensive as to affect the amount of core recovered and/or the number of fractures whose orientation relative to the core axis can be determined.

ORIENTATION OF FRACTURE PLANES IN THE CORES

Detailed postshot examination of failure in the CR and DL drifts,²⁹ 256 and 287 m respectively from the shot point, indicates that partial collapse of these drifts was controlled by movement and dilation of preexisting fractures and faults. There is good evidence that the shape of the chimney, at least in the section which was subject to postshot examination, was also influenced by the presence of one or more pervasive fracture sets. One of the problems to be addressed is to what extent the fracturing throughout the shocked body of granite is similarly influenced.

Lacking oriented core, i.e., core whose original orientation with respect to the shot point is uniquely determined, the orientation of fractures cannot be unambiguously determined. Accordingly, fracture orientation has not been attempted in any previous core study.^{34,35} However, some information can be gained by recording the angle ϕ between the core axis and the fracture planes along the whole length of a core. For example, it is possible to determine whether or not the data are consistent with the following possibilities and hypotheses:

1. Randomness of ϕ in the whole core as well as within particular core intervals. A random distribution of ϕ which is non-Gaussian* is shown in Fig. 13 for 1500 hypothetical core fractures. A random distribution of ϕ does not necessarily equate with a random orientation of fractures with respect to the shot point. Fractures of the shear type taken as a group in the core might produce a nearly random distribution of ϕ angles in cores whose axes do not coincide or nearly coincide with a radial line from shot point. A nonrandom distribution of ϕ , on the other hand, is definitive whether measured over the whole core or within a given core interval. Assuming adequate sampling it can be correlated with nonrandom fracture orientation.

2. Coincidence of core fractures with preexisting sets. Because preexisting sets make a constant angle with any core axis or radial line to shot point, foreknowledge of their attitude permits recognition of their control over the observed postshot fracture pattern if it is strong. If instead new fractures are geometrically related to the main direction of propagation of the shock wave, e.g., as shear fractures, a weak structural control on

* A random (isotropic) distribution of this type of measurement is sinusoidal. Within any class interval defined by θ_1 and θ_2 , the percentage of points is given by

$$P = 100 \int_{\theta_1}^{\theta_2} \sin \theta d\theta = 100(\cos \theta_1 - \cos \theta_2) \text{ for angles between lines}^{36}$$

$$= 100 \int_{\theta_1}^{\theta_2} \sin (90^\circ - \theta) d\theta = 100 (\sin \theta_2 - \sin \theta_1) \text{ for minimum angles between a line and planes.}$$

Fig. 13. Isotropic (random) distribution of ϕ -angles between a core axis and 1500 fracture planes calculated in 10° increments.

the orientation of core fractures could not be recognized.

3. Coincidence of the core fractures with sets either tangentially or radially oriented with respect to shot point. The angle such fractures make with the core is variable from place to place along the length of the core. It is, however, uniquely defined at any particular position. Thus, given the core bearing and the position within the core, the angle ϕ for tangential and radial fractures at that point can be computed and compared with the observed angle(s). Figure 14 shows the variation in position that hypothetical tangential (T) and radial (R) fractures have along the lengths of the three cores.

4. Coincidence of core fractures with planes of potential shear failure. Most of the fractures within about 100 m of the shot point would be expected to arise during failure in compression, e.g., as shear fractures. If the mean peak pressure is sufficiently high, their orientation is not as likely to be influenced by

Fig. 14. Variation in ϕ for radial, tangential, and shear (45° to σ_1) fractures along the three core lengths from holes PS-1, -2, and -3. Radial and tangential fractures make unique angles to core axes; a wide range of ϕ is consistent with shear failure.

preexisting planar weaknesses as by the position of the principal stresses.³⁷ For isotropic material in which $\sigma_2 = \sigma_3$, the locus of shear fractures is a cone whose axis is in the direction of propagation of the main shock wave and whose semiapex is $30-45^\circ$ depending on the physical properties of the material. At any point in a core with random bearing with respect to the shot point, potential fractures tangent to the cone occur within definable angular limits.* Since the angular range is generally large (Fig. 14), a test for consistency of a shear interpretation at any

point in a core is possible but not useful. Exceptions occur where a core axis is either parallel or perpendicular to a radial line from the shot point. In these two instances shear fractures make angles of about $30-45^\circ$ and $45-60^\circ$ respectively with the core axis. In the more general case, a second spherical coordinate in addition to the ϕ angle is needed to

*Limits on ϕ are determined from projections or drawings in the plane defined by the core axis and the shot point. In the present instance, this coincides with the plane of Fig. 7 for all cores.

Fig. 14. (Continued)

Fig. 14. (Continued)

determine whether the fracture fits the chosen shear criteria.

In summary then, the data available, namely measurements of the angle ϕ , can only test whether or not the observations are consistent with the various possibilities. Inconsistency constitutes good reason for disregarding the hypothetical relation. Consistency, on the other hand, does not verify the model.

Some preshot joints and fractures are sites of alteration and mineralization and are readily recognized as such. Core fractures of this sort thus provide a check on the orientation of preshot fractures with respect to the core axis as deduced from field studies shown in Fig. 15. The exact shape of the distribution to be expected is contingent on a knowledge of the relative degree of development of each of the sets recognized in the stock

Fig. 15. Calculated angle (ϕ) between core axes and various pre-existing fracture and joint sets in Climax stock.

Fig. 16. Measured ϕ for 1458 macroscopic core fractures in core 1.

at any point along the core length (Table 5). As this information is lacking, Fig. 15 is only a qualitative guide. The top histogram of Figs. 16, 17, and 18 shows

the comparable data from measurement of altered and mineralized fractures in the cores. Data from cores 2 and 3 are probably too sparse for comparison with

Fig. 16. (Continued)

the estimated distribution shown in Fig. 15; however, data from core 1 show general agreement in that most preshot fractures make angles of 30-53° with the core axis.

Fractures represented in the 80-90° range (Fig. 15) are either unmineralized or poorly developed in the area cut by the core. Comparison of these data with

Fig. 17. Measured ϕ for 256 macroscopic core fractures in core 2.

Fig. 18. Measured ϕ for 287 macroscopic core fractures in core 3.

those of Fig. 13 further emphasizes the nonrandomness of preexisting fractures.

Figures 16, 17, and 18 show the angular relation of observed fractures to the core

axes in approximately 50-ft sections of the cores. Fractures that can be recognized as preexisting are not included. Each histogram contains the range of

angles that tangential (T), radial (R), and shear (S) fractures would make with the core axis within that 50-ft interval.

The final histogram shows the distribution of ϕ for all fractures measured in each of the three cores. Such an accumulative plot is only meaningful if the orientation of observed fractures is largely controlled by preexisting discontinuities. Presumably such a plot would be nearly random if the orientation of observed fractures were symmetrically related to a point source.

IMPLICATIONS OF OBSERVED ORIENTATIONS OF FRACTURE PLANES

The observed macroscopic fractures in postshot cores are not randomly oriented. As a whole their departure from randomness is in directions consistent with their interpretation as loci of preshot planes of weakness—fractures and/or joints. In general there is no local correlation between measured ϕ and calculated ϕ for tangential and radial fractures. The consistency test for shear fracturing is poor over most of the core

lengths; however, where it can be used, the ϕ angles are inconsistent with shear fracturing.

In only one core (core 2) is there any suggestion that fractures might be symmetrically related to a point. Specifically, in the first 50 ft along the core, fractures are possibly tangential; and in the slant hole interval from 69 to 100 ft (117–123 m from the shot point) they are consistent with the positions of radial fractures. It can be readily shown that the first group of fractures in the 0–50 ft interval are also geometrically consistent with radial fracturing associated with a reflected shock wave from the adjacent interface formed by the 10-ft-diam access tunnel.

At this distance (117–123 m) from the shot point, radial fracturing is consistent with failure in compression at low stress levels. The SOC calculation¹³ predicts onset of "release fractures" approximately 170 m from the shot point. Thus the observations are consistent with the models; however, the relatively few fractures measured in the interval make the interpretations tenuous.

Summary and Conclusions

The foregoing constitutes a summary of a large body of information dealing with the Piledriver event in granodiorite. From measured data reported by cooperating agencies, the peak radial stress seen by surviving rock at the cavity edge is 250–270 kb. Rock presently at a distance of 1148 ft (350 m) from the shot point saw less than 1 kb radial pressure. The radius of the vaporized and melted fraction is 51.2 ft (15.6 m) as calculated

from Butkovich's estimates of the weight of rock per kiloton involved in the various vaporization and melting processes. From the final cavity radius of 131.5 ft (40.1 m) a maximum displacement or "heave" of 80.3 ft (24.5 m) can be computed for rock at the present cavity edge. At 1000 ft (305 m) from the shot point the radial displacement was less than 1 ft. Clearly, local conditions can alter these estimates, especially in the vicinity of

the tunnel void that existed as a discontinuity at shot time.

Nine predictions of the radius of the cavity have been compared. The equations of Higgins and Butkovich, Chapin (based on adiabatic expansion of cavity gases to twice overburden pressure), Boardman, Heard and Ackerman, and Michaud result in predictions that are within 0-4.5 ft of the value determined from field measurements. The remaining four estimates are within 12.5 to 23.5 ft of the accepted value and represent a maximum error of 18%. Four of the five predictions made by LRL scientists are in error by less than 5%. Thus cavity radii can be predicted with some confidence, given appropriate physical parameters of the surrounding rock.

The volume occupied by the chimney is not so predictable. The Piledriver chimney is not shaped like a cylinder with semihemispherical ends, as one might expect. Sterrett was the first to note that at least the SW wall is canted 13° from the vertical due to collapse and shearing along preexisting fractures and/or joint systems. The survey of preshot fracture and joint systems measured within the stock (Table 5) shows that these local shear zones are part of the regional pattern. As there are at least four major fracture and/or joint sets recognized, it is likely that they have similarly influenced the configuration in portions of the chimney as yet unexplored. Furthermore, it is possible that the shape of the Hardhat chimney 1/4 mile away within the same granodiorite is similarly influenced by preexisting fractures and shear zones. Hardhat chimney explora-

tion was not extensive enough to test the hypothesis. Assuming that the preexisting discontinuities in the stock govern the attitude of chimney walls, more than one-half of the Piledriver chimney would be expected to be cup-shaped (walls slanting outward about 13° from the vertical), and the remainder to have walls departing only slightly from the vertical as was found in the portion of the Hardhat chimney explored to date.

A thorough knowledge of chimney volume and hence chimney shape is of great importance in most economic plans designed to utilize the broken rock—e.g., recovery of oil from oil shale and ore winning.³⁸ For a given cavity radius, r_c , the volume of a chimney can vary by several factors. For example, the volume of the French chimney model, an egg-shaped unit approaching the shape of a prolate spheroid, is $19.3r_c^3$ as compared to $12.6r_c^3$ for an axially symmetric, straight-walled chimney patterned after the one explored planar section through the Hardhat rubble shown in Fig. 7(b).

Three drill cores (U-15.01 PS-1, -2, and -3) recovered from rock both outside and inside the chimney have been visually examined before being subjected to extensive sampling for laboratory tests. The attitudes of several thousand macroscopic fractures were determined with respect to the core axes and distance from the shot point. All three cores were photographed in their entirety. The positions of injected glass seams, radioactivity, and gross recognizable shear zones were noted.

Core fractures cannot be uniquely oriented with respect to the shot point; however, they are demonstrably nonrandomly

oriented. Their positions are consistent with failure along preexisting regional joints, fractures, and shear zones. With one possible exception, in no core interval are their positions consistent with fracturing parallel or perpendicular to the direction radially outward from the shot point. With the core information available, the test for shear failure at any point or core interval is not sufficiently precise to determine whether or not the orientation of the observed fractures are also consistent with an origin through shear.

The amount of fracturing observed in a recovered core cannot be used as a reliable guide to the amount of shock-induced fracturing in the rock the core came from, because in general highly fractured rock is not recovered. The

amount of core recovered is in addition influenced by preexisting shear zones, by slightly different drilling techniques used for the several cores, and by temporary drilling problems within individual drill holes. Nonetheless, taking all uncertainties into account, there is evidence that at the same radial distances from the shot point the amount of fracturing is variable. Specifically in core 1 there is more fracturing near the chimney wall than beneath the cavity within core intervals equidistance from the shot point. The phenomenon is most likely related to local, well-developed, pre-existent fracture systems in the granitic stock. Comparable inhomogeneities might be expected to be the rule rather than the exception in most underground tests.

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Appendix 1

Summary of Projects Included in Piledriver Event

Table 1.1 gives basic information on the projects conducted as part of the Piledriver event.

Table 1.1 Summary of Piledriver projects.¹⁴

Project No.	Project title	Agency	Project officers	Report No.
1.1	Surface Motion	Stanford Research Institute (SRI)	W. M. Wells, F. M. Sauer	POR 4000
1.2a	Free-Field Motion	Sandia Corp.	D. G. Palmer, H. R. Holmes, W. R. Perret	POR 4001
1.3a	Close-In Stress	Illinois Institute of Technology Research Inst. (IITRI)	P. Lieberman	POR 4002
1.3b	Close-In Stress	SRI	C. T. Vincent	POR 4003
1.4	Strong Motion Seismic	USCGS	T. H. Pierce	Cancelled by ARPA 8/31/65
1.5a	In Situ Stress in Granite	US Bureau of Mines	L. Obert	—
1.5b	In Situ Stress in Granite	Lucius Pitkin, Inc.	F. H. Wright	POR 4005
1.6	Seismic Studies in Granite	USGS	J. H. Scott	USGS Technical Letter Piledriver—1
3.1	Tunnel Liner Response	Omaha Dist., CE (U.S. Army Corps of Engineers)	C. T. Flanigan, W. P. Moore, K. C. Fox, C. J. Distefano	POR 4010, Vol. 1
3.2a	Instrumentation of Tunnel Liners	SRI	W. M. Wells, F. M. Sauer	POR 4010, Vol. 2
3.2b	Instrumentation of Tunnel Liners	Sandia	D. G. Palmer, H. R. Holmes	POR 4010, Vol. 3
3.2c	Instrumentation of Tunnel Liners	Omaha Dist., CE	See Project 3.1	POR 4010, Vol. 4
3.3	Shock Spectra	TRW Systems	F. A. Pieper, F. W. Galbraith	POR 4011
3.4	Motion Photography	Edgerton, Germeshausen & Grier (EG&G)	H. L. Smith	POR 4012
3.5	Grouting and Materials Control	Waterways Expt. Sta., CE	J. M. Polatty	POR 4013
3.6	Microwave Doppler	EG&G	R. A. Shunk	POR 4014
3.7	Experiments in Rock Bolting	Omaha Dist., CE	See Project 3.1	POR 4015

Table 1.1 (Contd.)

Project No.	Project title	Agency	Project officers	Report No.
3.8	Cable Vulnerability Studies	DCA/Bell Tel. Labs.	H. A. Wells, A. H. Williamson, E. F. Witt	POR 4016
4.1	Acoustical Measurements	EG&G	A. E. Villaire	None
6.1	Electromagnetic Pulse Measurements	Air Force Weapons Lab.	W. D. Henderson	Deleted 1/11/66
9.3a	Design and Engineering	Holmes and Narver, Inc. (H & N)	H. F. Haller, W. H. Wisniski	None
9.3b	Design and Engineering	EG&G	R. A. Shunk	None
9.3c	Design and Engineering	Fenix and Scisson, Inc.	J. Dowling	None
9.3d	Technical Direction	University of Illinois	J. L. Merritt	POR 4017
9.3e	Conceptual Development	Newmark, Hansen and Associates	—	DASA 1399
9.4	Construction and Field Support	Reynolds Electrical and Engineering Co. (REECo)	W. M. Flangas, G. L. Clayton	None
9.7	Documentary Photography	Photo Section, TC/DASA	J. M. Hartnett	None
9.8	Motion Picture Film Reports	USAF, Lookout Mtn. AF Station	S. J. Williams	"Quick Look" and "Class A" Documentary Films
9.9	Reports	Oak Ridge National Lab.	—	—
9.10	Survey Control	H & N	See Project 9.3a	—
9.11	Timing and Firing	EG&G	J. Tsitouras	—
9.12	Arming and Device Support	Sandia	R. J. Burton, H. L. Miller, M. L. Merritt	Sandia, SC-RR-68-173
9.13	Reentry Construction	REECo	G. L. Clayton	None
9.14	Instrumentation Timing	EG&G	J. Tsitouras	None
9.15	Reentry Safety	Sandia	H. L. Rarrick	None
—	Chimney Exploration	Lawrence Radiation Laboratory (LRL)	C. R. Boardman	UCRL-50385 (TID 4500, UC-35)

Appendix 2

Chemical Analyses of Samples from Climax Stock

Table 2.1 gives chemical analyses of four samples from the Climax stock, and Table 2.2 gives chemical and mineral compositions of material included in spheres of various radii centered at the shot point.

Table 2.1 Chemical analyses^a of samples from southwest part of Climax intrusive, Nye County, Nevada.³⁹

Sample No. ^b	HG-7	HG-8	FP-62	FP-63
Sample material	Granodiorite	Granodiorite	Granodiorite	Quartz monzonite
Analysis, wt%:				
SiO ₂	68.6	68.2	67.5	70.8
Al ₂ O ₃	15.6	16.1	16.2	15.9
Fe ₂ O ₃	1.7	1.7	1.9	0.6
FeO	1.7	1.5	1.7	0.34
MgO	0.64	0.52	0.70	0.16
CaO	3.6	3.3	3.9	1.8
Na ₂ O	3.1	3.1	3.2	3.0
K ₂ O	3.3	3.5	3.4	5.1
H ₂ O	0.70	0.80	0.83	1.1
TiO ₂	0.38	0.40	0.46	0.22
P ₂ O ₅	0.18	0.18	0.18	0.13
MnO	0.06	0.04	0.07	0.02
CO ₂	0.08	0.06	0.08	0.04

^aRapid rock analysis by Paul L. D. Elmore, Ivan H. Barlow, Marvin D. Mack, and Samuel D. Botts, Rept. No. IRC-354 (Jan. 19, 1959).

^bSamples HG-7 and FP-62 are very light gray medium-to-coarse-grained equigranular rocks. Sample HG-8 is a light gray fine-to-medium-grained porphyritic rock containing feldspar phenocrysts up to 5 cm long. Sample FP-63 is similar to FP-62; however, it is a porphyritic rock containing feldspar phenocrysts up to 4 cm long.

Table 2.2 Bulk mineral and chemical compositions for spheres of rock of selected radii about the Hardhat shot point.⁷ The granodiorite data are based on 19 modal analyses.

Sphere radius (ft)	50	100	150	200	300
Percent of sphere within granodiorite intrusive	100	100	97.5	89.7	79
Principal minerals (vol%):					
Quartz	28	28	28	27.5	27.5
Potassium feldspar	16	16	16	15.0	16.5
Plagioclase	45	45	45	45.5	45
Biotite	9	9	9	9	9
Hornblende	Trace	Trace	Trace	Trace	Trace
Chemical analysis (wt%):					
SiO ₂	67.6	67.6	67.8	66.6	67.8
Al ₂ O ₃	15.8	15.8	15.9	15.8	15.9
Fe ₂ O ₃	1.8	1.8	1.8	1.7	1.7
FeO	1.6	1.6	1.6	1.5	1.6
MgO	0.82	0.82	0.81	0.81	0.80
CaO	3.7	3.7	3.7	3.7	3.6
Na ₂ O	3.1	3.1	3.1	3.1	3.1
K ₂ O	3.5	3.5	3.5	3.5	3.6
H ₂ O	1.0	1.0	1.0	1.0	1.0
TiO ₂	0.39	0.39	0.39	0.4	0.39
P ₂ O ₅	0.18	0.18	0.18	0.18	0.18
MnO	0.07	0.07	0.07	0.07	0.07
CO ₂	0.20	0.20	0.20	0.19	0.18

Appendix 3

Modal Analyses of Mineral Content of Samples from Climax Stock

Table 3.1 gives the results of modal analyses made on 17 samples from various depths in the U-15a exploration borehole.⁴⁰

Table 3.1 Modal analyses of samples from the U-15a exploration hole in the Climax stock.

Sample depth (ft)	63	160	236	277	321	374	414	477	555	693	739	800	812	833	854	900	1000
Rock type	QM ^a	G ^b	G	G	G	G	QM	QM	G	G	QM	G	G	QM	G	G	G
Minerals (vol%):																	
Plagioclase feldspar An ₃₆ ^c	50	48	45	47	54	45	39	37	46	40	43	48	49	41	40	54	46
Potassium feldspar	27	17	16	17	14	20	26	24	21	19	22	21	19	25	18	19	17
Quartz	15	25	27	25	21	26	25	25	20	30	27	22	25	26	31	20	27
Biotite	5	8	9	8	7	4	7	11	9	9	5	6	5	6	8	4	7
Chlorite	2	1	2	2	2	4	1	2	2	Tr.	2	1	1	1	Tr.	1	2
Hornblende	Tr. ^d	Tr.	Tr.	Tr.	—	Tr.	Tr.	Tr.	Tr.	1	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Allanite	Tr.	—	Tr.	Tr.	—	Tr.	—	—	—	Tr.	—	—	—	Tr.	—	—	Tr.
Pyrite	—	Tr.	Tr.	Tr.	Tr.	Tr.	—	—	Tr.	—	—	—	—	—	—	Tr.	—
Hydrous iron oxide	—	Tr.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sphene	Each of these constituents occurs in trace amounts (<1%) in all thin sections																
Apatite																	
Zircon																	
Magnetite																	
Myrmekite																	
Sericite																	
Calcite																	
Clinozoisite																	
Epidote																	
Clay (unidentified)																	

^aQM = quartz monzonite.

^bG = granodiorite.

^cDetermined by flat-stage extinction angles.

^dTr. = trace.

Appendix 4

Porosity, Density, Water Content, and Sonic Velocity of Samples from Climax Stock at Various Depths

Table 4.1 gives a statistical summary of porosity and density for samples in the Climax stock. Table 4.2 gives porosity, water content, and sonic velocity for the more electrically resistive zones in various holes in the Climax stock.

Table 4.1 Statistical summary of porosity and density of 26 Climax granite samples from the U-15a borehole, Area 15, Nye County, Nevada.⁴⁰

Percent porosity:		
Arithmetic mean		0.9
1 standard deviation		± 0.9
2 standard errors of mean		± 0.3
Density, bulk (g/cc):		
Arithmetic mean		2.67
1 standard deviation		± 0.02
2 standard errors of mean		± 0.02
Density, grain (g/cc):		
Arithmetic mean		2.69
1 standard deviation		± 0.02
2 standard errors of mean		± 0.02
Density, powder (g/cc):		
Arithmetic mean		2.69
1 standard deviation		± 0.01
2 standard errors of mean		± 0.005

Table 4.2 Porosity and water content (both derived from electrical resistivity) and sonic velocity for the more electrically resistive zones of various drill holes in granite at the Nevada Test Site, Nye County, Nevada.⁷ (Interpretations by G. E. Manger of USGS.)

Hole No.	Depth interval (ft)	Porosity, ^a (%)	Water content of pores, ^b (%)	Sonic velocity (ft/sec)
33	90 - 114	17.8	109 (59) ^c	16,350
	461 - 520	9.5	100 (25) ^c	18,360
	720 - 760	12.8	109	17,630
	793 - 853	12.7	101	17,930
34	105 - 149	10.6	110	17,010
	154 - 178	6.4	105	18,370
	286 - 314	8.5	98	18,290
	400 - 424	6.6	96	18,640
	735 - 778	8.5	98	17,990
	869 - 908	5.4	84	19,020
35	335 - 377	1.4-	80+	18,890
	468 - 510	2.3	77	18,930
	603 - 627	1.7	73	18,430
	770 - 798	1.7	100	— ^d
37	255 - 279	3.9	57	19,080
	316 - 340	4.1	53	18,820
	460 - 498	2.2	88	18,100
38	194 - 217	9.0	89	18,150
	266 - 309	7.6	80	18,360
	323 - 363	4.3	60	18,950
	374 - 399	2.9	78	18,960
	442 - 487	3.4	77	18,800
	590 - 614	4.9	91	18,700
	800 - 854	2.9	69	18,800
	862 - 913	2.0	74	18,890
	972 - 1020	1.9	80	19,150
	1118 - 1143	3.2	49	18,710
	1170 - 1211	2.2	68	18,800
	1280 - 1333	2.4	61	18,840
	1376 - 1414	2.6	53	18,850
	1451 - 1493	2.7	46	18,830
	1515 - 1554	2.7	65	18,340
	1578 - 1606	2.1	78	18,520
	1660 - 1697	2.7	78	18,500
31	1711 - 1751	3.2	68	18,900
	1770 - 1820	3.2	61	18,520
	1845 - 1913	2.4	73	18,530
	275 - 320	1.05	— ^d	20,400 ^e
	1060 - 1075	0.7 (?)	— ^d	— ^d

Average sonic velocity of the more resistive zones from 450 to 940 ft in drill hole U-15a is by inspection 20,800 ft/sec. Corresponding porosity obtained from cores is probably 0.9%.

^aDerived from the 16-in. normal resistivity.

^bDerived from the resistivity of the 16-in. normal log and 19-ft lateral log.

^cDerived from the SP log.

^dNot determined.

^eBy inspection.

Appendix 5

Stress Measurements from Piledriver Event

Table 5.1 gives calculated and observed stresses and strains at various stations for the Piledriver event. Figure 5.1 shows peak radial stresses measured in holes A-E. (See Fig. 2 for layout of stations and holes in Piledriver event.)

Table 5.1 Radial stresses and strains calculated and observed for Piledriver event.¹⁰

Station	Slant range		Stress (kb)		Strain (%)	
	(ft)	(m)	Calc.	Obs.	Calc.	Obs.
Y-SL	386	117.7	7.7	—	1.5	—
A-SL	473	144.2	4.1	—	0.8	—
B-SL	668	203.6	3.9	1.2	0.76	0.24
D-SL	833	253.9	1.8	—	0.35	—
C-SL	932	284.1	1.3	—	0.26	—
16-SL	1543	470.4	0.59	—	0.11	—

Fig. 5.1. Measured shock pressure vs distance from shot point for Piledriver event.¹²

Appendix 6

Strikes and Dips of Preexisting Joint Sets in the CR Drift

Table 6.1 gives the orientation and number of fractures and/or joints in the CR lateral drift. Table 6.2 gives similar information for the CR north drift.

Table 6.1 Strikes and dips of joint sets in the CR lateral drift²⁹ (see Fig. 2 for location). For each station and joint set, the upper value is average strike and the lower value is average dip. The number of measurements included in the average is shown in parentheses.

Station	Strikes and dips of joint sets A through I								
	A	B	C	D	E	F	G	H	I
0 + 20	N53W(12) 27NE(12)	N62W(13) 88SW(13)	N32E(4) 77NW(4)	N72E(2) 62SE(2)	— —	— —	— —	— —	N40W(1) Vert (1)
0 + 30	N50W(5) 28NE(5)	N68W(7) 83SW(7)	N31E(3) 62NW(3)	N72E(3) 64SE(3)	N55E(1) 46NW(1)	— —	— —	— —	N41W(4) 89NE(1)
0 + 40	N50W(5) 29NE(5)	N67W(5) Vert(5)	N19E(4) 66NW(4)	N82E(1) 69SE(4)	N50E(6) 57NW(6)	— —	— —	— —	N41W(3) 89NE(3)
0 + 50	N44W(3) 32NE(3)	N75W(3) 85NE(3)	N19E(1) 66NW(1)	— —	N46E(6) 57NW(2)	N38W(1) —	— —	— —	N29W(1) 80SW(1)
0 + 60	N50W(8) 26NE(8)	N78W(4) 79SW(4)	N21E(3) 76NW(3)	N85E(3) 74SE(3)	N46E(6) 61NW(6)	N38W(1) 48NE(1)	— —	— —	N8W(1) 77SW(1)
0 + 70	N48W(7) 29NE(7)	N79W(4) 78SW(4)	N13E(5) 68NW(5)	N80E(1) 71SE(1)	N49E(9) 56NW(9)	N38W(1) 48NE(1)	— 65SE(8)	— —	— —
0 + 80	N48W(5) 29NE(5)	N73W(7) 84SW(7)	N13E(3) 66NW(3)	— —	N45E(5) 55NW(5)	— —	N35E(14) 67SE(14)	— —	— —
0 + 90	N50W(5) 30NE(5)	N73W(10) 88SW(10)	— —	— —	N44E(8) 55NW(8)	— —	— —	— —	— —
1 + 00	N53W(7) 29NE(7)	N74W(2) Vert(2)	N10E(5) 74NW(5)	— —	N45E(2) 55NW(2)	— —	N41E(2) 84SE(2)	— —	— —
1 + 10	N49W(8) 31NE(8)	N80W(2) Vert(2)	N12E(12) 75NW(12)	— —	— —	— —	— —	— —	— —
1 + 20	N61W(10) 25NE(10)	N81W(16) 89SW(16)	N10E(9) 67NW(9)	— —	— —	— —	N41E(2) 75SE(2)	— —	N22W(2) 74SW(2)
1 + 30	N49W(4) 39NE(4)	N83W(1) Vert(1)	— —	— —	— —	— —	— —	— —	N27W(3) 79SW(3)
1 + 40	N49W(7) 30NE(7)	N79W(3) Vert(3)	N13E(1) 59NW(1)	— —	— —	— —	N33E(1) 65SE(1)	— —	— —
1 + 50	N49W(5) 30NE(5)	N72W(1) 88NE(1)	— —	— —	— —	— —	— —	— —	— —
1 + 60	N51W(7) 31NE(7)	N76W(7) 87NE(7)	— —	N54E(1) 73SE(1)	— —	— —	N26E(1) 65SE(1)	N53W(1) 65SE(1)	N23W(2) 85SW(2)
1 + 70	N52W(6) 31NE(6)	N70W(10) 84NE(10)	— —	— —	— —	— —	N52E(9) 68SE(9)	— —	— —
1 + 80	N51W(3) 27NE(3)	N65W(9) Vert(9)	— —	— —	N55E(2) 54NW(2)	— —	N48W(5) 55SE(5)	— —	— —
1 + 90	N49W(4) 28NE(4)	N64W(8) 88NE(8)	N12E(3) 48NW(3)	— —	— —	— —	N46E(4) 51SE(4)	— —	— —
2 + 00	N52W(1) 24NE(1)	N61W(3) Vert(3)	N9E(2) 50NW(2)	— —	— —	— —	N42E(3) 60SE(3)	N75W(1) 65NE(1)	— —
2 + 10	N48W(5) 30NE(5)	N71W(6) 79SW(6)	N30E(1) 46NW(1)	— —	N60E(1) 35NW(1)	N43W(4) 59NE(4)	— —	N87W(1) 59NE(1)	— —
2 + 19	N47W(4) 30NE(4)	N73W(4) 88SW(4)	— —	— —	N30E(1) 46NW(1)	— —	N42E(1) 59SE(1)	N87W(1) 59NE(1)	N47W(1) 89SW(1)
Mean values	N50W(121) 29NE(121)	N73W(125) 89SW(125)	N12E(56) 68NW(56)	N80E(11) 69SE(15)	N46E(47) 56NW(47)	— (7) — (7)	N42E(42) 65SE(50)	— (4) — (4)	— (18) — (18)

Table 6.2 Strikes and dips of joint sets in the CR north drift²⁹ (see Fig. 2 for location). For each station and joint set, the upper value is average strike and the lower value is average dip. The number of measurements included in the average is shown in parentheses.

Station	Strikes and dips of joint sets A through I								
	A	B	C	D	E	F	G	H	I
0 + 60	N41W(3) 34NE(3)	N68W(4) 86NE(4)	N22E(3) 89SE(3)	— —	N35E(3) 62NW(3)	— —	N35E(3) 63SE(3)	— —	— —
1 + 70	N41W(4) 34NE(4)	N70W(2) 86NE(2)	— —	— —	N41E(5) 58NW(5)	— —	N39E(3) 86SE(3)	— —	N15W(2) 85SW(2)
1 + 80	N54W(7) 31NE(7)	N55W(1) Vert(1)	— —	— —	N57E(1) 80NW(1)	— —	N36E(8) Vert(8)	— —	— —
1 + 90	N53W(7) 31NE(7)	N62W(5) 88NE(5)	— —	— —	— —	— —	N40E(16) 88SE(16)	— —	N41W(2) 83SW(2)
2 + 00	N50W(7) 31NE(7)	— —	— —	— —	N50E(1) 51NW(1)	— —	N35E(2) 79SE(2)	— —	N49W(1) 84SW(1)
2 + 10	N53W(8) 31NE(8)	— —	N30E(1) 50NW(1)	— —	N48E(4) 54NW(4)	— —	N42E(3) 74SE(3)	— —	N16W(3) 78NE(3)
2 + 20	N51W(6) 35NE(6)	— —	— —	N84E(5) 85SE(5)	N50E(3) 58NW(3)	— —	N44E(1) 87SE(1)	— —	N10W(1) 87NW(1)
2 + 30	N54W(1) 30NE(10)	— —	— —	N88E(4) 86SE(4)	N50E(4) 58NW(4)	N21W(1) 52NE(1)	N30E(1) 85NE(1)	— —	N7W(10) 85SW(10)
2 + 38	N54W(6) 31NE(6)	— —	— —	— —	— —	— —	— —	— —	N9W(15) 87SW(15)
Mean values	N51.3W(58) 31.5NE(58)	N64.7W(12) 87.1NE(12)	N22E(4) 89SE(4)	N86E(9) 85SE(9)	N45.6E(21) 59NW(21)	— (1) — (1)	N38.1E(37) 84.5SE(37)	— —	N9.4W, N46W 87.6SW, 83SW

Appendix 7
Photographs of Cores from Hole U-15.01 PS-1

Total depth 423.8 ft.

Overall core recovery 89.4%.

PS-1

Depth in hole: 0-53.4 ft

Distance from shot point: 287-328 ft

37-43' Shear zone, core recovery 69%

PS-1

Depth in hole: 53.4-95.3 ft

Distance from shot point: 250-287 ft

PS-1

Depth in hole: 95.3-141.2 ft

Distance from shot point: 218-250 ft

PS-1

Depth in hole: 141.2-189.7 ft

Distance from shot point: 188-218 ft

PS-1

Depth in hole: 189.7-234.3 ft

Distance from shot point: 167-188 ft

PS-1

Depth in hole: 234.3-283.5 ft

Distance from shot point: 160-167 ft

247-254' Core recovery 96%

254-266' Core recovery 65%

266-274' Core recovery 91%

274-287' Core recovery 63%

PS-1

Depth in hole: 283.5-326.2 ft

Distance from shot point: 160-168 ft

287.5' Closest approach to shot point.
D = 160' postshot or 120' preshot

287-297' Core recovery 96%

297-308' Core recovery 81%

308-319' Core recovery 86%

319-329' Core recovery 86%

PS-1

Depth in hole: 326.2-365.2 ft

Distance from shot point: 168-183 ft

329-338' Core recovery 97%

PS-1

Depth in hole: 365.2-410.4 ft

Distance from shot point: 183-203 ft

← 376' Temporary loss of drilling fluid circulation

PS-1

Depth in hole: 410.4-423.8 ft

Distance from shot point: 203-213 ft

Appendix 8
Photographs of Cores from Hole U-15.01 PS-2

Total depth 154.6 ft.

Overall core recovery 86.2%.

PS-2

Depth in hole: 0-57 ft

Distance from shot point: 340-374 ft

← 41' Beginning of shear zone

PS-2

Depth in hole: 59.5-105.0 ft

Distance from shot point: 375-405 ft

← 69' End of shear zone

PS-2

Depth in hole: 105-150 ft

Distance from shot point: 405-438 ft

PS-2

Depth in hole: 150-154.6 ft

Distance from shot point: 438-440 ft

Appendix 9
Photographs of Cores from Hole U-15.01 PS-3

Total depth 274.4 ft.

Overall core recovery 61.4%.

PS-3

Depth in hole: 0-86.0 ft

Distance from shot point: 250-330 ft

15-35' Shear zone core recovery, 41%

PS-3

Depth in hole: 86.0-152.0 ft

Distance from shot point: 194-250 ft

← 115' Temporary loss of drilling fluid circulation

← 110-123' Shear zone. First detection of radioactivity (0.6mR, $\beta + \gamma$, 8-5-69). Core recovery ~20%

← 135' Permanent loss of drill fluid circulation. Spike in gamma log ($<0.02\text{mR}$, $\beta + \gamma$, 2-27-70)

PS-3

Depth in hole: 152.0-191.0 ft

Distance from shot point: 165-194 ft

← 162' $T = 150^{\circ}\text{C}$, 8-19-69

← 164' First glass encountered (90mR, $\beta + \gamma$, 8-6-69)

← 178-180.5' Granulation due to recovery technique (?)

← 181' $T = 175^{\circ}\text{C}$, 8-19-69. Glass seams (0.3mR, $\beta + \gamma$, 2-28-70)

Discoloration (brown) from drilling mud

PS-3

Depth in hole: 191.0-235.8 ft

Distance from shot point: 131-165 ft

← 197' T = 200°C, 8-19-69

Discoloration (brown) from drilling mud

← 200' Spike in gamma log (0.5mR, $\beta + \gamma$, 2-27-70)

← 210' T = 204°C, 8-19-69. Beginning of temperature plateau. Radioactive glass in fractures (20mR, $\beta + \gamma$, 9-69)

← 214' Glass seam (0.8mR, $\beta + \gamma$, 8-11-69)

← 219' Radioactive "sand" (80mR, $\beta + \gamma$, 8-11-69)

← 223' Glass seam (0.1mR, $\beta + \gamma$, 2-27-70)

← 226' Glass seam

← 229' Onset of appreciable increase in radioactivity

229 | Glass seams, 150mR, $\beta + \gamma$, 8-11-69

230 |

232 | Chimney boundary, 200mR, $\beta + \gamma$, 8-11-69. Vesicular, glassy matrix

PS-3

Depth in hole: 235.8-274.4 ft

Distance from shot point: 112-131 ft

- ← 237' Aplite dike (3mR, $\beta + \gamma$, 8-11-69).
Dull black rock, not glassy, partially absorbed spall
- ← 241-247' 190mR, $\beta + \gamma$, 8-11-69
- ← 246' Partially absorbed spall in black, vesicular, glassy matrix
- ← 253' Vesicular, glassy (150mR, $\beta + \gamma$, 8-11-69)

- ← 253-263' Glassy seams in slightly vesicular matrix (200mR, $\beta + \gamma$, 8-12-69)
- ← 258' Vesicular, dull, low-Si melt (?)
- ← 263-270' Partially absorbed spall Epidote (?) (160mR, $\beta + \gamma$, 8-12-69)
- ← 270' Glassy, vesicular (150mR, $\beta + \gamma$, 8-12-69)

(All $\beta + \gamma$ readings are on contact)

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