TID-4500, UC-35
Nuclear Explosions—
Peaceful Applications

Lawrence Radiation Laboratory
UNIVERSITY OF CALIFORNIA
LIVERMORE

UCRL-50979

**RESULTS OF POSTSHOT EXPLORATION
OF THE GREELEY EVENT**

D. E. Rawson
I. Y. Borg

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

P9214

Contents

Abstract	1
Introduction	1
Geological Setting	2
Results of Postshot Drilling	4
Drilling Rate	6
Directional Survey	9
γ -Radiation and Temperature Logs	9
Hydrology	13
Cracking Radius	16
Comparison of Observed and Predicted Cavity and Chimney Size	17
Surface Effects at the Greeley Site	18
Chimney Development and Surface Subsidence	18
Enlargement of the Crater	22
Conclusions	24
Acknowledgments	24
References	25
Appendix A: Physical Properties of Samples from U20g Satellite 1 (Preshot)	27
Appendix B: GORBAG Runs on Greeley Postshot Holes 1D and 1DS	29

RESULTS OF POSTSHOT EXPLORATION OF THE GREELEY EVENT

Abstract

Temperature and radiation logs made in a postshot drill hole (U20g PS-1D), which penetrates the Greeley chimney-cavity on Pahute Mesa, Nevada Test Site, indicate that the cavity radius is 224 to 265 ft. The chimney height immediately after the event was about 1640 ft above the shot point. Propagation of the chimney to the surface occurred periodically following the event until a surface subsidence crater formed two to eight months later. Enlargement of the crater continued for several years in response to other Pahute Mesa events and natural earthquakes. As of April 26, 1968

(D + 1.35 years), the volume of the crater was 8.5% of that of the cavity, and the void space in the chimney was estimated to be 7.6% of the total chimney volume. The most distant fracturing, as evidenced by increased γ radiation in the postshot hole, occurs 2091 ft from the shot point. Extensive fracturing, permitting rapid inflow of displaced ground water, occurs 1100 ft and perhaps as far as 1700 ft from the shot point. The rate of inflow into the chimney area during the first year was about 2.4×10^2 gal/min. Two years after the shot, the water level was within 17 ft of the preshot level.

Introduction

The Greeley Event was an 800- to 900-kt underground explosion in bedded zeolitized ash-flow tuff on Pahute Mesa, Nevada Test Site (Area 20). Data pertinent to the experiment are given in Table 1.

Results of studies in holes drilled into the cavity following the shot are of particular interest since the shot was several thousands of feet below the static water level on the Mesa. In addition, the collapse to the surface many months after the detonation is unique and has been fol-

lowed up to the present time. For about three years after the shot, there was continuing enlargement of the subsidence crater.

Information on postshot effects can be found in numerous reports and memoranda. In order to produce a comprehensive report, this information is reproduced here together with a large body of data collected in conjunction with the postshot drilling program and monitoring of the delayed collapse of the chimney in subsequent years.

Table 1. Summary of principal data on the Greeley Event.

Date of explosion:	December 20, 1966
Yield:	825 kt (announced)
Depth of burst:	3991 $\pm$ 6 ft
Medium:	Zeolitized, nonwelded ash-flow tuff [ρ = 2.16 g/cc (Ref. 1), porosity = 29% (Ref. 1), permeability = 2.5 mD at overburden pressure (Ref. 1), water content = 11 to 15% (Ref. 2)]
Top of water table:	4455 ft above mean sea level (MSL), 2015 ft below ground surface of hole U20g at elevation 6470 ft (Ref. 1)
Time of subsidence to surface:	Between D + 53 and D + 241 days, and possibly between D + 150 and D + 157 days

Geological Setting

Structure and lithology of the Pahute Mesa and the Greeley site in particular (Figs. 1 and 2) have been described by

Byers and Orkild; Orkild; Schnabel; and Snyder of the USGS.³⁻⁶ These data were amplified and corroborated by Meyer and

Fig. 1. Location of Greeley site on Pahute Mesa, Area 20, Nevada Test Site.

Fig. 2. Map of major geological structures in the vicinity of Greeley emplacement (U20g PS-1D).

Rambo¹ with logs of temperature, density, resistivity, caliper, and compressional and shear wave velocities in preshot holes,

U20g (emplacement), and U20g Satellite 1 (approximately 80 ft east of U20g). The Mesa consists of Tertiary volcanic rock

in interfingered and alternating nearly horizontal layers. The units recognized include welded tuffs, rhyolite lava flows, zeolitized bedded tuffs and sandstones, and zeolitized bedded nonwelded ash-flow tuffs. The latter, immediately surrounding the shot point, comprise rock whose in situ properties are given in Table 1.

Results of Postshot Drilling

Drilling and logging at U20g PS-1D was done during the period from January 3, 1967 to February 11, 1967. At that time, the chimney had not propagated to the ground surface, although shocks were felt and recorded on geophones throughout the drilling period. Major structural features at the Greeley site are shown in Fig. 3, which is a vertical section through the cavity and chimney, parallel to AA' of Fig. 2. The geological setting is deduced from a consideration of both preshot and postshot drilling data. The deduction is necessarily somewhat subjective, since assessment of the amount of movement on the major faults depends on an exact knowledge of the arching of the tuffs over a monoclinical axis normal to the plane of the drawing. Interpretation of the available data is further complicated by lateral variation in thickness and the character of the various rock units.

Specific details from the drilling are summarized in Table 2. Caliper and density logs are given in Fig. 4 for the interval 0 to 1600 ft slant hole distance (SHD) in U20g PS-1D. In regions where Birdwell proximity logs (tool-to-bore separation) exceeds 0.25 in., the density data are probably too high.¹

Additional measurements on core samples from depths of 3401 to 4015 ft in U20g Satellite 1, made by Somerton, Pye, and Singhal² (Appendix A), are consistent with the in situ measurements and indicate that the rock at the shot point contained 11 to 15% water

Figure 5 shows the following additional logs for the 1600 to 2900-ft interval: electrical logs, including spontaneous potential (record of plus and minus anomalies in the electrical potential—primarily a correlation tool) and resistivity; and P-wave (compressional) and S-wave (shear) velocity logs. Below 1700 ft SHD the hole was logged in mud. However, that level is not believed to correspond to the postshot water surface, but rather to a local accumulation in the hole due to plugging of lower permeable zones by drilling debris and mud. Densities and P-wave and S-wave velocities are tabulated in Table 3. In lower reaches of the hole where adequate comparison with preshot data can be made, the general characters of the logs compare well. The lower unit recognized, ash-flow tuff 2850 to 3000 ft below ground zero (GZ) (2647- to 2848-ft SHD interval), has an average density and P-wave and S-wave^{*} velocities of 2.05 g/cc, 2550 m/sec, and 1350 m/sec, respectively.

^{*}Measured values of S-wave velocity are based on time-of-arrival data from 3-D velocity logs. The remainder of the S-wave log was computed from P-wave and density logs.

Fig. 3. Vertical section (A-A', Fig. 2) through Greeley site. (Lettered points in U20g PS-1D are explained in Hydrology section of text, which begins on p. 13.)

Table 2. Results from drill holes U20g PS-1D and PS-1DS.

Date of drilling and logging: January 3 to February 11, 1967

Location of collar: N928897.25; E573555.02

6107 ft (MSL)

Drilling media: Air and foam until circulation lost, then mud

Casing: 10-3/4-in. casing to 2916 ft slant hole distance (SHD)⁷

Sidetracked (hole U20g PS-1DS): 3850 ft (SHD)

Observation	Slant-hole distance (ft.)	Radial distance to shot point (ft)	Interpretation
Increased drilling rate ^a	1750-1800	2372-2324	Major pre-existing fault zone
First detected γ radiation (spikes)	2040	2091	Horizon of chimney top, 1640 ft above SP horizon
Drilling circulation loss	2764	1376	Approximate location of water table at D + 34 days
Increased γ radiation and cold water entrance into hole	3050	1090	Interconnected fractures to chimney and to saturated fault zone to the west
Hot water entrance into hole	3620-3730	425-533	Intense fracturing adjacent to chimney
Increase in temperature, PS-1D (spikes)	3876 and 3896	285 and 265	Intersection with chimney wall; 150 and 136 ft above SP horizon
Increase in γ radiation and temperature PS-1D and PS-1DS	4600 (PS-1D) 3991 (PS-1DS)	168 188	First glass, 61 and 52 ft above SP horizon, respectively
Decrease in γ radiation in PS-1D and PS-1DS	4352 (PS-1D) 4349 (PS-1DS)	224 265 ^a	Bottom of cavity

^aConsidered more reliable; see text, p. 11.

These values are to be compared with preshot averages of 2.16 g/cc, 3094 m/sec, and 1427 m/sec in the 3600- to 4200-ft depth interval. It is not possible to determine whether the differences are due to lateral and vertical variation within the ash-flow tuff unit, differences in calibration of the logging instruments, or explosion effects such as fracturing and changes in water content.

DRILLING RATE

Aron and Randolph⁸ have shown that drilling rate can be useful in locating zones of friable and fractured rock. Their compilation of data from the Greeley postshot exploratory drilling program is reproduced here in modified form (Fig. 6). Various rock types encountered are indicated, together with

Fig. 4. Proximity, corrected density, and caliper logs from 100 to 1600 ft (slant hole distance) in postshot hole U20g PS-1D. (See Fig. 3 for rock-type symbols.)

Fig. 5. Proximity, corrected density, caliper, electrical, and velocity logs from 1600 to 2900 ft (slant hole distance) in postshot hole U20g PS-1D. (See Fig. 3 for rock-type symbols.)

2

Table 3. Summary of average density and velocity data obtained from geophysical logs, hole U20g PS-1D.

Depth (ft SHD)	Rock type	Density (g/cc)	P-wave (compressional) velocity (m/sec)		S-wave (shear) velocity (m/sec)	
			Aver- age	Range	Aver- age	Range
100-632	Caprock	2.06 (av)	No data		No data	
632-1001	Bedded tuff	1.82	↓	↓	↓	↓
1001-1158	Lava flow	2.06				
1158-1335	Bedded tuff	1.74				
1335-1417	Lava flow	1.94				
1417-1825	Bedded tuff	1.83				
1825-1856	Lava flow (in fault zone)	2.27	4500	2850-5300	2000	1400-2400
1856-2033	Bedded tuff	1.98	3250	2850-4000	1600	1300-2100
2033-2300	Lava flow	2.06	3500	2100-6000	1900	1000-3400
2300-2647	Tuff sandstone	1.96	3100	2150-4200	1550	1000-2200
2647-2848	Ash-flow tuff	2.05	2550	2150-3300	1350	1080-1820

information inferred from the logs and observations made during drilling. In some instances these differ from those reported by Aron and Randolph. For example, they have indicated the loss of circulation of drilling lubricant to have occurred at 3050 ft SHD. This depth, rather, corresponds to entrance of cold water into the hole. Circulation was lost at about 2764 ft SHD.

DIRECTIONAL SURVEY

A series of Sperry-Sun directional surveys were made at the conclusion of the drilling. In addition, Reynolds Electrical and Engineering ran single-shot surveys at the bottom of the PS-1D and PS-1DS holes. All of these data were combined in a calculation of the slant hole distance versus radial distance (GORBAG), shown in Fig. 7. The cavity

and chimney dimensions have been taken from these calculations. Details concerning the surveys and the GORBAG calculations are given in a memorandum by J. Rambo, which is included as Appendix B of this report. In view of the depth of the holes, data at the bottom are less reliable than those at the top. The amount of error is unknown, but radial distances in the vicinity of the cavity may be in error by 10 to 20 ft. Errors of 50 ft, although possible, are considered unlikely.

γ-RADIATION AND TEMPERATURE LOGS

Both γ-radiation and temperature logs were run in the drill string. The data are primarily useful for purposes of comparison. Very low-level γ radiation was detected as high as 2040 ft (SHD) in the postshot exploration hole (Fig. 8), approximately 2100 ft distant from the shot point.

Fig. 6. Drilling rate versus slant-hole distance in postshot holes U20g PS-1D and PS-1DS (modified from Ref. 8; note change in scales at 2500 ft).

Fig. 7. Slant hole distance in postshot holes U20g PS-1D and PS-1DS versus radial distance from shot point.

It is possible that these small spikes in the γ log are due to radiation originating from the explosion, which has migrated horizontally along bedding planes and fractures. If so, the height of the chimney can be crudely set at 1641 ft above the shot point (SP) three months after the explosion. This point corresponds to the boundary of a rhyolitic flow and overlying bedded tuff (Fig. 3). Alternatively, it is possible that the spikes represent variation in the natural background, although preshot logs are not available for comparison. The background indicated in Fig. 8 is based on γ logs from other holes in Pahute Mesa. A much larger increase in radiation over background occurs over a 200-ft interval below a depth of 3050 ft SHD (about 1100 ft radial distance from the SP) and is almost certainly due to the explosion. At this point a major influx of cold water into the hole also occurred,

which accounts for the stabilization of the temperature record (Fig. 8) over the next 550 ft.

Below 3250 ft SHD, increased radioactivity and temperature were not encountered until a depth of 3620 ft SHD (535 ft from SP). (Note the change in the scale of the γ log at 3300 ft.) The increase in temperature in the interval from 3620 to 3730 ft SHD is interpreted as a zone of hot water entry into the drill hole from the chimney. This, in turn, may reflect a zone of intense fracturing adjacent to the chimney wall or intersection of a fault zone (Fig. 3).

Using the temperature log (Fig. 8) as a guide, the drill hole is believed to have intersected the chimney edge at either 3896 or 3876 ft SHD. This corresponds to a distance of 285 or 265 ft from the SP. Note that there is no recorded increase in radiation at this point in either U20g PS-1D or the sidetracked hole, U20g PS-1DS. Of the two possible points of intersection, the one corresponding to a 265-ft distance is considered the more likely.

The high levels of radioactivity and increase in temperature at 3990 to 4000 ft SHD define the first appreciable amount of glass encountered at the top of the "puddle." The lower cavity edge, by similar criteria, occurs at 4352 ft SHD in U20g PS-1D and at 4349 ft in U20g PS-1DS. These depths correspond to cavity radii of 224 and 265 ft, respectively. The values, of course, are subject to errors due to inaccuracies in the directional survey of the slant hole and uncertainties in interpretation of the radiation and temperature logs. Inspection of the directional-survey data suggests that the single-shot data from the bottom of

Fig. 8. Temperature and radiation logs from 2000 to 4450 ft (slant hole distance) in postshot holes U20g PS-1D and PS-1DS. Note apparent calibration shift between Run 1 and Run 2 of the PS-1DS radiation log.

PS-1DS are more reliable than those from the bottom of PS-1D.

HYDROLOGY

Preshot Information

The static water level defined by pre-shot drilling of U20g and U20g Satellite 1 was 2015 ft below the surface.¹ Water entries were determined to occur at three locations ("mobile water zones" of Fig. 3). The first and qualitatively least important* is a zone at a depth of 2040 to 2090 ft in an ash-flow unit. The second is within a rhyolitic lava flow. At 2500 ft, water was injected into this zone at the rate of 40 gal/min; between 2580 and 2590 ft, 89 gal/min was accepted. The third entry was also in a rhyolitic flow at 3030 to 3050 ft. Presumably the water entries are associated with local fractures, and injection rates reflect the spacing and size of the fractures rather than the general hydrologic characteristics of the geologic section as a whole.

Postshot Information

During drilling of U20g PS-1D, major fluctuations in mud and water levels occurred which, together with the rate of flow, were monitored regularly.[†] Collectively the data have been evaluated so as to construct the water pressure surface as it existed during the period of postshot

drilling. Information was collected when drilling had progressed as far as points B, C, D, E, and F (Fig. 3). B (2764 ft SHD) is the point at which circulation was first lost. Mud levels measured at this point and at 2912 ft SHD (top portion of Fig. 9) are not believed to reflect the postshot water pressure surfaces at that time but rather local equilibrium levels established after drilling debris had restricted outward migration of mud from the hole. After these mud levels were measured, the hole was cased to a depth of 2916 ft SHD. C (3050 ft SHD) is the point of cold water entry into the hole. D (3914 ft SHD) is near the chimney wall. At D the water in the hole was pumped out and the inflow was measured. It stabilized at about 2200 ft SHD (D', Figs. 3, 9, and 10) which is taken to be the piezometric surface at that point in the drilling history. E and F are at the bottom of the cavity-chimney; mud levels associated with these measurements, made some 12 days apart, are indicated as E' and F'. Point E' (2736 ft SHD) is considered to be a measure of the water level in the chimney (E'', Fig. 3), since the drill hole was open and permitted a U-shaped connection to the chimney. E' nearly coincides with B (2764 ft SHD), the point at which drilling foam had been cut 17 days earlier (D + 34 days). Thus it is likely that the piezometric surface was first penetrated at B. A measurement 12 days after drilling had reached point E-F indicated that water had risen in the hole to F' (2150 ft SHD). The measured rate of continuing rise was 1.4 ft/day, insufficient to explain the large observed change between E' and F'. It is likely that the hole had caved above D soon after E had been reached and before

*Observation by T. Carter, Felix and Scission, Mercury, Nevada, 1968.

†Measurements were made by R. D. Clark, Birdwell, Las Vegas, initially using a water locator on a wire-line. After the drilling ceased, a pressure transducer was placed in the hole ~2 ft under the fluid and pulled up every few days after readings were made.

Fig. 9. Measurement of short-term water and mud fluctuations as a function of time in postshot hole U20g PS-1D. Points B, D, and D' are identified in text and on Fig. 3.

the F' measurement; this F' reflects water entering at C rather than at points from within the chimney. Continued surveillance of water levels beyond F' in time are shown in Fig. 10. In support of this analysis, i.e., collapse of lower portions of the hole, is the observation that these data can be projected back to D', a measurement made before a complete connection had been made with the water level in the chimney.

The postshot water level history at Greeley has been reconstructed by Korver,

using the T-WAVE code.^{9,10} The water surface at D + 51 days was considered to be defined by points E'' and G (Fig. 3). Taking F' and subsequent measurements into account (Fig. 10), G is the most likely position of the water table at D + 51 days. By assuming porosities and permeabilities for rock surrounding the shot point, it is possible to match the well history recorded in Fig. 10 for the period after D + 51 days. This corresponds to an average flow rate into the chimney area of 2.4×10^2 gal/min. By December 1966

Fig. 10. Measured and calculated water levels as a function of time in postshot hole U20g PS-1D. Lettered points are identified in text and on Fig. 3.

the water level in PS-1DS had reached 1698 ft SHD, or 17 ft below the preshot level of 2015 ft. This is in very good agreement with projection of the data and calculations (solid line) of Fig. 10.

Conversely, it is possible to extrapolate back in time to D + 34 days, when drilling circulation was lost (B, Figs. 3 and 10). At that point the level in the chimney is calculated to have been at point H (Figs. 3 and 10).

CRACKING RADIUS

The SOC calculation¹¹ used to predict the cavity radius (Table 4) estimates shear cracking to a radial distance of 1040 ft and tensile failure to a distance of 2440 ft. These distances equate to slant hole distances of about 3100 and 1675 ft, respectively. From information shown in

Figs. 3 and 6 and summarized in Table 2, a radial distance of 1040 ft is near the point (C, Fig. 3) where fracturing was first observed to have been sufficiently extensive to permit upward and lateral migration of radioactive material from the chimney-cavity during early phases of the explosion and lateral and downward migration of ground water during later times. The limit of predicted tensile fracturing, 2440 ft radial distance, nearly coincides with the pre-existing fault zone intercepted by the drill holes, and hence is difficult to recognize in drilling-rate data (Fig. 6). The horizon of the top of the chimney, which was judged to be 1640 ft above the shot point, is well within this radius. With the limited information afforded by the single drill hole, the farthest point at which fracture can be recognized would be

Table 4. Comparison of different methods of predicting cavity radii.

Method	Assumed yield (kt)	Cavity radius (ft)	Chimney height ^a (ft)
Heard and Ackerman ¹² calculation using measured <u>in situ</u> parameters ($\rho = 2.16$; $V_p = 3094$ m/sec; $V_s = 1427$ m/sec) from Meyer and Rambo U20g logs	825	310	—
Butkovich and Lewis calculation ¹³ assuming average overburden density of 2.07 g/cc and 11% water content; α (calculated) = 0.301; bulking porosity = 8.2%	780	286	4557
	825	292	4643
	870	297	4726
Cherry SOC calculation ¹¹	780	279	—
Measured here		224-265	

^aHeight above shot point.

set at about 2090 ft radial distance (Table 2). This radius is consistent

with preshot estimates of the limit of tensile failure.

Comparison of Observed and Predicted Cavity and Chimney Size

Almost all calculations of the radius of the cavity produced by the explosion are larger than the values reported here. Results of the more sophisticated calculations, which take into account either the in situ water content or measured properties effected by the water content, are summarized in Table 4. The first two methods are based on empirical data collected at the Nevada Test Site over a period of years. In the Butkovich and Lewis calculation,¹³ some estimate must

be made of the weight-percent of H_2O present in the rock surrounding the explosion. It can be shown that a bulk density of 2.155 g/cc^1 in the area surrounding the SP, and a grain density of 2.5 g/cc , are consistent with 11% H_2O in a fully saturated rock. This value is in keeping with measured water content in core samples (Appendix A) and is assumed to be a reasonable estimate. The effect of various water contents and yields on calculated cavity radius is shown in Fig. 11. Taking

Fig. 11. Cavity radius as a function of yield and water content. $\rho = 2.07$ (av); α is calculated exponent of ρ in the Butkovich and Lewis equation (Ref. 13).

all uncertainties into account, it would appear that a yield of 825 kt is too high.

The chimney height calculated by Butkovich and Lewis exceeds the depth of burial and thus predicts collapse to the surface, which occurred some months after the shot. The calculation of chimney height is sensitive to the bulking porosity

(B). Assuming a cylindrical chimney with hemispherical ends, likely values of B are in the range of 8 to 10%. For B = 10%, W = 870 kt, H_2O = 11%, and ρ = 2.07 g/cc (average of overburden), the chimney would be approximately 3980 ft high and almost reach the surface (DOB = 3991 ft).

Surface Effects at the Greeley Site

Surface motion was studied by Rawson and Rohrer¹⁴ at the Greeley site by photographing a series of targets in the GZ area and in the valley below the Mesa. The targets are visible in the photographs of the collapse crater (Fig. 12). Maximum vertical displacements of 12 to 14 ft and surface velocities of 20 to 25 ft/sec were recorded for targets within 550 ft of GZ. No differential displacement was observed across minor faults near GZ.

Within a few weeks of the Greeley Event, USGS geologists mapped surface fracture and spall in the vicinity. They

report, "The geologic effects of the Greeley Event are more conspicuously controlled by preexplosion natural fractures than any prior event detonated at the Test Site. . . . Explosion-produced fractures correlate closely to natural fractures and occur as far as about three miles from ground zero. Though fracturing was intense at many places along natural faults, the ground between them has surprisingly few fractures."¹⁵ The area immediately surrounding GZ was not examined in detail; however, two of the three concrete pads at the site (Fig. 12) were unfractured.

Chimney Development and Surface Subsidence

The collapse of the cavity and chimney was detected by geophones^{*} and was recorded as aftershocks by seismic stations (Fig. 13) for several months after the explosion. Judging from small spikes in the γ logs in the postshot drill hole (2040 ft SHD or at a horizon 1640 ft above the SP), the chimney had developed to a

point approximately 2350 ft below GZ immediately after the explosion. The uppermost break in the cliper cable also occurs in this vicinity (2415 ft below GZ).[†] This horizon is in zeolitized bedded tuff

^{*}Because of power failure, the data from the first few minutes were lost.

[†]Measurement in U20g Satellite 1 hole, which at that point (downhole) is 70 to 80 ft from U20g emplacement hole. The cliper break was recorded within one-half second of the detonation. The break occurred approximately 20 ft below the bottom of the casing in the hole.¹⁶

Fig. 12. Photographs of progressive development of Greeley subsidence crater. A: September 11, 1967.
B: September 27, 1967.

Fig. 12 (continued). C: April 23, 1968. D: April 26, 1968.

Fig. 13. Geophone and seismic activity at the Greeley site following the explosion. Topped bars correlate with seismic events recorded at the Tonto Forest Station, Arizona (H. Krivoy, USGS). Untopped bars are geophone data; seismic correlation was not attempted. (Modified from Ref. 14.)

and lies immediately above one of the jointed and fractured rhyolitic lava flows which was interpreted as a mobile water zone in preshot drilling and logging (Fig. 3).

The time of formation of a subsidence crater at the surface is not exactly known. The crater was first observed September 7, 1967, from the air.¹⁷ Examination of water-level measurements made periodically in PS-1D (Fig. 10) shows that there had been a rapid rise and fall in the water level on several occasions during the preceding spring and summer. None of these fluctuations can be correlated with explosions on the Mesa, and they probably represent stages in the chimney propagation to the surface and enlargement of the surface crater once formed. The last fluctuation, in late September 1967 (D + 274 to 378 days, Fig. 10), may be associated with the enlargement of the crater that occurred sometime between September 11 and 27 (Figs. 12A and B). The fluctuation recorded in August (D + 243 to 254 days) was not observed by the Berkeley seismic net, and it is

believed from past experience that the Greeley collapse to the surface would have been well above the Berkeley net threshold.¹⁸ No fluctuation in water level in U20g PS-1D was associated with the Benham Event (three miles away on December 19, 1968), although water in other holes, e.g. UE20f (Fig. 1), was grossly affected.¹⁹

Records at the Nevada Test Site indicate that collapse (partial or complete) of Greeley preceded the Commodore Event on Yucca Flat (May 20, 1967, D + 151 days). It is not known whether the inference from seismometers operating at that time at the Test Site was visually checked out.²¹ The Scotch (May 23, 1967, 150 kt) and Knickerbocker (May 26, 1967, 76 kt) Events on Pahute Mesa are more likely to have been instrumental in causing the Greeley collapse and/or crater enlargement. Scotch was exploded within a few

²¹ According to W. King at NTS, a guard saw dust over the Mesa and people in the area at the time felt that something had happened.²⁰

miles of Greeley (Fig. 1). It is questionable whether the Greeley collapse could have been recognized in seismic records collected within seconds of any Pahute Mesa event; however, Scotch, which did not collapse to the surface, was associated with five or more relatively large (magnitude 2.8 to 3.7) unidentified after-events which were picked up by the Berkeley seismic net. "All of these events occurred 2-6 hours after the explosion of Scotch (magnitude 5.6). These events could be considered as afterevents of Scotch. If this interpretation is accepted, then one must conclude that the spectral behavior of these Scotch after-events is different from that of the after-events of the larger explosions Boxcar, Jorum, and Benham."²¹ All three explosions were on Pahute Mesa; the first two formed surface subsidence craters within hours after the shot. Unfortunately, water levels in PS-1D were not monitored during

the period from May 21 to June 14, 1967* (D + 152 to D + 174 days, Fig. 10), so major fluctuations, if they occurred, were not recorded. Furthermore, the present surface crater at Greeley is several hundred feet above the collar at PS-1DS, and GZ could not be readily inspected when measurements were resumed in mid-June. Thus the most that can be said is that the collapse to the surface occurred sometime between February 11, 1967, the end of drilling, and August 18, 1967, a date set by observations of the Berkeley seismic station.

* According to R. D. Clarke, who was recording water levels, the water transducer was damaged on May 14. Readings indicated that water had risen about 40 ft in 5 days; a depth of 20 ft of water over the transducer is potentially damaging. Whether a fluctuation in water level of that magnitude had actually occurred was not certainly established, and the readings were considered anomalous. The water level was measured on May 20 using a water locator and proved to be "normal."

Enlargement of the Crater

Enlargement of the Greeley subsidence crater has occurred periodically since it was formed. Explosions on the Mesa have probably been responsible to a large measure. The airborne dust in the bottom of the crater seen in Fig. 12D is related to spall following the Boxcar Event (Fig. 1), which occurred earlier in the morning of the same day that the photograph was taken, April 26, 1968. The line of 16-ft-high targets used in surface-motion studies is visible in Fig. 12A, taken 4 days after the crater was first sighted. The marker nearest to the edge of the crater had fallen in by April 23, 1968, and the

next marker in line is near the edge by April 26. When first measured by J. Shipman, LRL Nevada, the crater had an elliptical outline with minimum dimensions of 140 and 180 ft and a depth of 170 ft¹⁷ (inner outline in Fig. 14). The outline was not symmetrical about GZ, and subsequent enlargement has preserved the skew toward the northwest. It appears from Fig. 2 that the migration to the surface was influenced by the local dip of the layered rocks.

Just before the Benham Event on the Mesa (December 19, 1968), a battery-operated clock was installed about 200 ft

Fig. 14. Enlargement of the Greeley subsidence crater.

from the Greeley crater by D. Rawson and P. Turner. It is linked by cables to three spots on the crater walls and is automatically stopped by slumping or caving. According to records kept by L. Ramspott, it was stopped by enlargement at the time of Benham, Purse (May 7, 1969), and Pipkin (October 8, 1969). It was not running at the time of the Jorum Event (September 16, 1969), and was running but did not stop at the time of Handley (March 26, 1970).

The cross section and plan of the sub-

sidence crater as of April 26, 1968, are shown as outer boundaries in Fig. 14.

The volume of the crater, about $6.3 \times 10^6 \text{ cu ft}$, estimated from its topography, is probably accurate to 15%. Assuming a cavity radius of 260 ft, a straight-walled chimney to the surface has a volume of $884 \times 10^6 \text{ cu ft}$. The void space distributed in the chimney can be obtained by subtracting the estimated crater volume from the cavity volume. This constitutes $67 \times 10^6 \text{ cu ft}$ or 7.6% of the chimney volume.

Conclusions

The Greeley cavity radius was measured to be in the range of 224 to 265 ft in two postshot holes. The upper value is believed to be more reliable. The maximum error in the radius measurement is estimated to be 20 ft. Calculated values based on yields of 780 to 370 kt and 11% water content are in the range of 279 to 310 ft. The two sets of results can be reconciled either by assuming low (albeit unrealistic) water content for the rock surrounding the shot point or by using lower yields in the calculations.

Extensive fracturing, as evidenced by flow of water into the drill hole (presumably by lateral migration from a more distant saturated pre-existing fault zone) occurs 1100 ft and perhaps as far as 1700 ft from SP. The most distant radiation encountered is 2091 ft from SP and is the outer limit of shock-induced fracturing that can be recognized. It is likely, and consistent with preshot predictions made with the SOC code, that distant fracturing (more than 1100 ft from SP) is confined to dilation on pre-existing weakness such as jointing and bedding.

It is judged that the chimney collapsed in the first few minutes to a height in excess of 1600 ft above SP. Geophone and seismic activity at the site continued for

several months after the event, indicating that the chimney was propagating toward the surface. Nearly vertical jointing and preexisting faults may have aided the upward migration. The ultimate development of a surface crater could have been predicted with some certainty by methods developed by either Butkovich and Lewis¹³ or Ramspott.²² The exact time of the surface expression of the chimney is not known, but it was almost certainly between two and eight months after the explosion. As of April 26, 1968, the estimated volume of the crater was 6.3×10^6 cu ft, or 8.5% of the cavity volume (73.6×10^6 cu ft). The void space distributed throughout the existing chimney was 67.3×10^6 cu ft, or 7.6% of the chimney volume.

Enlargement of the crater has occurred periodically since the crater was first sighted. The crater has more than doubled in size; nuclear explosions and natural earthquakes are largely responsible.

Measurements of water levels in the postshot hole indicate that the average rate of inflow of water into the chimney and surrounding rock during the first year was approximately 2.4×10^2 gal/min. By December 1968, two years after the shot, the water level in the postshot hole was within 17 ft of the preshot level.

Acknowledgments

The authors wish to acknowledge the cooperation of Ken Oswald and his staff during postshot drilling. John Rambo and R. Carlson were responsible for much of the data reduction from geophysical logs. Bud Ault and Robert Clarke of the Birdwell

Corporation obtained the geophysical logs and made the water level measurements. L. Ramspott, D. Emerson, and D. Rabb have been helpful in bringing the data up to date. P. L. Randolph, G. H. Higgins, and M. D. Nordyke gave support to the effort.

References

1. G. L. Meyer and J. Rambo, Lithology and Geophysical Properties of the "Greeley" Medium, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50142 (1966).
2. W. H. Somerton, S. D. Pye, and A. Singhal, Physical Properties of U20g Sat. #1 Samples, University of California, Petroleum Engineering Laboratories, Rept. UCL-2361 (1966).
3. F. M. Byers and P. P. Orkild, "Minor Fault-Fold Structures in the Vicinity of Pahute Mesa Sites U19a-s, U19b, and U20g," U.S. Geological Survey Tech. Letter Special Studies I-29 (1964).
4. P. R. Orkild, "Report of Exploration Progress, Pahute Mesa, Period Oct. 30, 1965—July 31, 1966," U.S. Geological Survey Tech. Letter Special Studies I-23 (1966).
5. R. W. Schnabel, "Geologic Appraisal of the U20g Site, Pahute Mesa, Nevada Test Site," U.S. Geological Survey Tech. Letter Special Studies I-15 (1964).
6. R. P. Snyder, "Preliminary Report on the Lithology of the U20g Drill Hole, Pahute Mesa, Nevada Test Site," U.S. Geological Survey Tech. Letter Special Studies I-32 (1965).
7. K. Oswald, Lawrence Radiation Laboratory, Livermore, private communication (October 1970).
8. F. W. Aron and P. L. Randolph, Use of the Drill Penetration Rate of Post-Shot Holes in Examining the Phenomenology of Containment, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50378 (1968).
9. J. Korver, "Analysis of the Postshot Hydrologic Conditions Near the Greeley Event," Lawrence Radiation Laboratory, Livermore, internal document SDK 69-12 (1969).
10. J. Korver, T-Wave, A Computer Code for Analyzing the Nonsteady Gravity Decay of a Ground-Water Anomaly, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50830 (1970).
11. J. T. Cherry, Lawrence Radiation Laboratory, Livermore, private communication (1968).
12. H. C. Heard and F. J. Ackerman, Prediction of Cavity Radii from Underground Nuclear Explosions, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50324 (1967).
13. T. Butkovich and A. E. Lewis, Aids for Estimating Effects of Underground Nuclear Explosions, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50929 (1970).
14. D. Rawson and R. F. Rohrer, Surface Motion and Subsidence Study of the Dumont, Vulcan, and Greeley Events, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50432 (1968).

15. D. D. Dickey, E. C. Jenkins, F. A. McKeown, and W. H. Lee, "Geologic Effects of the Greeley Event, Nevada Test Site," U.S. Geological Survey Tech. Letter NTS-196 (1967).
16. C. Sisemore, Lawrence Radiation Laboratory, Livermore, private communication (1970).
17. C. Boardman, "Recent Earth Movements in Vicinity of Greeley," Lawrence Radiation Laboratory, Livermore, internal document UOPKC 67-104 (1967).
18. D. Springer, "Greeley Collapse Time (Seismic observations 8-18-67 through 9-7-67)," Lawrence Radiation Laboratory, Livermore, internal document UOPKB 67-126 (1967).
19. R. N. McArthur, Lawrence Radiation Laboratory, Nevada, private communication (1968).
20. W. King, Lawrence Radiation Laboratory, Nevada, private communication to D. Raab, LRL Livermore (1970).
21. W. H. Bakun and L. R. Johnson, The Spectral Ratio of Pg as a Discriminant for Explosions in Spectral Identification Criteria for Small Earthquakes, ARPA Rept. 1783 (October 1969-June 1970).
22. L. D. Ramspott, An Empirical Analysis of the Probability of Formation of a Collapse Crater by an Underground Nuclear Explosion, Lawrence Radiation Laboratory, Livermore, Rept. UCRL-50883 (1970).

Appendix A

Physical Properties of Samples from U20g Satellite 1 (Preshot)

(From W. H. Somerton, S. D. Pye, and A. Singhal, University of California, Department of Mechanical Engineering, Petroleum Engineering Laboratories, Rept. UCX 2361, June 30, 1966.)

METHODS

Dry bulk density and porosity—from mercury pycnometer and Boyle's Law porosimeter measurements made on dried samples.

Wet bulk density—calculated from weights of sample as received; paraffin-coated sample was weighed in air and in water.

Water content—calculated from weights of sample as received and sample dried at $110 \pm 5^\circ\text{C}$ for 24 hr.

Grain densities—measurements using a La Chatelier flask.

Sonic velocities—measurements using apparatus described by King¹ and modified by Mossahebi.² A spring force of 100 lb was applied to samples and transducers. The second set of dry velocities are redeterminations on samples dried after the "resaturated" runs (resaturation with dilute NaCl solution for 24 hr).

Table A1. Density and pore properties.

Sample ^a	Depth (ft SHD)	Bulk density (g/cc)		Grain density (g/cc)	Water content (wt%)	Effective porosity ^b (volume fraction)
		Wet	Dry ^b			
1	3402	2.26	1.90	—	6.28	0.245
2	3519.5	2.05	1.61	2.497	15.5	.297
3	3600.5	2.04	1.76	—	14.4	.263
4	3717.7	2.12	1.67	—	13.8	.285
6	3830	2.08	1.68	—	19.9	.274
7	3874	2.08	1.86	—	14.9	.263
10A	3985	2.07	1.75	—	14.2	.260
10B	4014	2.06	1.72	2.496	13.2	0.274

^aZeolitized, bedded, nonwelded ash-flow tuff.

^bAverage of five samples.

¹M. S. King, "Wave Velocities in Rocks as a Function of Changes in Overburden Pressure and Pore Fluid Saturants," Geophysics XXXI, 1 (February 1966).

²M. Mossahebi, Thermal Conductivity of Rocks by a Ring Source Device, M.S. thesis, University of California, Berkeley (January 1956).

Table A2. Sonic velocities.

Sample	Depth (ft SHD)	Dilatational velocity (ft/sec)				Shear velocity (ft/sec)			
		Wet	Dry	Resat- urated	Dry	Wet	Dry	Resat- urated	Dry
1	3402	9560	9,340	9,330	9,480	6400	4620 ^a	6740	6510
2	3519.5	9150	10,400	—	10,400	7460	4930 ^a	7710	6740
3	3600.5	9900	9,730	10,000	10,100	7170	6850	7170	6810
4	3717.7	9260	9,180	9,340	9,330	6350	4920 ^a	6350	6280
6	3830	9300	9,550	9,230	9,530	6940	6940	6930	6740
7	3874	9780	9,550	9,780	9,780	6810	6970	7060	6850
10A	3985	9400	9,820	9,650	10,100	6320	6710	6830	6700
10B	4014	9460	9,550	9,460	9,780	6690	7060	7020	6800

^aResults probably in error.

Appendix B

GORBAG Runs on Greeley Postshot Holes 1D and 1DS *

Two separate runs on GORBAG were run to check cavity radius calculations. In a case where the hole changes declination at 1 $\frac{1}{2}$ /25 ft course length, the radius of curvature method is probably superior to the tangential method used by Sperry Sun. Some cases of 4 $\frac{1}{2}$ /100 ft course length will probably result in substantial errors regardless of the method used.

The coordinates used are shown in the following table:

<u>Hole</u>	<u>North</u>	<u>East</u>	<u>Elevation (ft)</u>
U20g emplacement surface	929043.35	575148.13	6470.10
U20g emplacement work point	929043.89	575147.42	2479.1
U20g postshot 1D surface	928897.25	573555.02	6107.4

The DOB used was 3991 ft.

Sperry Sun surveys used:

<u>Depth (ft)</u>	
0-1000	In Run 1, 151-SU3-067
1000-2850	In Run 2, 151-SU3-068
2850-4420 (1D)	In Run with single shots, 151-SU3-070 + 069
2850-4421 (1DS)	In Run with single shots, 151-SU3-070 + 071

The survey at 2850 ft shows 4.67-ft error in the north-south direction and 2.06 ft in the east-west direction. It is at least ± 8 ft off in the north-south direction and ± 3.5 ft off in the east-west direction at 4430 ft.

* J. Rambo, Lawrence Radiation Laboratory, Livermore, internal document UOPKB-70-106 (October 9, 1970).

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

**Printed in USA. Available from the National Technical
Information Center, National Bureau of Standards,
U. S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65.**