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Evaluation of Cavity Collapse and Surface Crater Formation for Selected Lawrence Livermore National Laboratory Underground Nuclear Tests – 2011, Part 2

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Auspices Statement

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This report evaluates collapse evolution for selected Lawrence Livermore National Laboratory (LLNL) underground nuclear tests at the Nevada National Security Site (NNSS, formerly called the Nevada Test Site). The work is being done to support several different programs that desire access to the ground surface above expended underground nuclear tests. The programs include: the Borehole Management Program, the Environmental Restoration Program, and the National Center for Nuclear Security Gas-Migration Experiment. Safety decisions must be made before a crater area, or potential crater area, can be reentered for any work. Evaluation of cavity collapse and crater formation is input into the safety decisions.

Subject matter experts from the LLNL Containment Program who participated in weapons testing activities perform these evaluations. Information used included drilling and hole construction, emplacement and stemming, timing and sequence of the selected test and nearby tests, geology, yield, depth of burial, collapse times, surface crater sizes, cavity and crater volume estimations, ground motion, and radiological release information. Both classified and unclassified data were reviewed. The evaluations do not include the effects of erosion that may modify the collapse craters over time. They also do not address possible radiation dangers that may be present. Various amounts of information are available for these tests, depending on their age and other associated activities. Lack of data can hamper evaluations and introduce uncertainty. We make no attempt to quantify this uncertainty.

Evaluation of Cavity Collapse and Surface Crater Formation for Selected Lawrence Livermore National Laboratory Underground Nuclear Tests – 2011 was published on March 2, 2011. This report, considered Part 2 of work undertaken in calendar year 2011, compiles evaluations requested after the March report.

The following unclassified summary statements describe collapse evolution and crater stability in response to a recent request to review 6 LLNL test locations in Yucca Flat, Rainier Mesa, and Pahute Mesa. They include: Baneberry in U8d; Clearwater in U12q; Wineskin in U12r, Buteo in U20a and Duryea in nearby U20a1; and Barnwell in U20az.

Baneberry
U8d

The LLNL sponsored Baneberry test was detonated in uncased hole U8d on December 18, 1970. Baneberry had an announced yield of 10 kt (USDOE, 2000). It was detonated in tuff at a working point of 278 m below the surface. U8d is located in a small structural basin in southwestern Area 8 in northern Yucca Flat, west of Yucca Fault.

The first test in this area was the LANL-sponsored test Discus Thrower in U8a on May 27, 1966, with an announced yield of 22 kt (USDOE, 2000). This test had a large number of satellite holes associated with it, many of which were instrumented for the test. Discus Thrower was followed by Cyanthus in U8b on March 6, 1970. (All tests in Area 8 after Discus Thrower were sponsored by LLNL.) Surface effects from Discus Thrower are shown in Figure 1.

Baneberry in U8d was sited near U8a #9, #10, and #11, instrument holes for Discus Thrower. Drilling of U8d proceeded normally until about 213 m, when continued sloughing and re-drilling affected progress. At least eight successive cementing and re-drilling sequences were necessary to complete the hole to its final depth of 287 m. Problems completing the hole were attributed to high montmorillonite clay content below 213 m. Similar problems were encountered while drilling some of the Discus Thrower satellite holes, in particular U8a #9, #10, and #11, which bracket the Baneberry site. The amount of difficulty in drilling U8d was not a unique NNSS experience.

Program operations for the Baneberry test execution proceeded normally until about 3.5 minutes after detonation, when a release of radioactivity began about 91 m S60˚W from the emplacement hole. Examination of aerial photography indicates that the surface expression of the Baneberry fault and the vent fissure formed within 2 seconds after detonation. The initial point of release elongated rapidly until radioactivity was issuing from a fissure oriented radially from surface ground zero. The release occurred over a distance of 96 m, from 18 m from SGZ to 114 m. The release (“Baneberry vent”) continued even after surface collapse occurred at 16.5 minutes after detonation. The collapse was normal and expected. Fairly rapid venting of steam continued until about two hours after detonation, after which only a cloud of vapor could be seen drifting up from the portion of the fissure outside the crater. This continued for nearly 24 hours. Release from the Baneberry test was detected offsite (USDOE, 1996). Previous ventings through emplacement holes or fissures were reduced or stopped entirely with surface collapse. Initial thoughts were that a large portion of the release path was external to the chimney region and therefore not related to cavity collapse, chimney formation, and surface collapse. Surface effects from Baneberry are shown in Figure 2. A map of the Baneberry fissure is shown in Figure 3.

Baneberry had a profound affect on the nuclear testing program and containment activities. Because the phenomena which led to the release of radioactivity from Baneberry was not immediately evident, the United States Atomic Energy Commission (AEC) suspended weapons tests at the NNSS until it reviewed Baneberry in detail and was convinced that every reasonable precaution was initiated to minimize the probability of a future occurrence. The Baneberry venting was attributed to stronger coupling of energy into the ground than was normal for tests buried at that depth in Yucca Flat, and that the stronger coupling was due to high water content at shallow depth, which resulted from a unique, localized geologic environment. The "Baneberry Summary Report" describes the analysis and conclusions of this study (USAEC, 1971).

Baneberry had a line-of-site (LOS) pipe equipped with fast closure systems running vertically from near the explosive device to the surface. The hole outside the LOS pipe was stemmed to the surface with sand, gravel and plastic stemming materials. The Baneberry site was intentionally selected to provide high seismic velocities in the first 61 m above the detonation point to assist with closure of the LOS pipe. Data extracted soon after the test showed that the LOS pipe and stemming were not part of the initial vent path and did not contribute to the eventual release.

There were numerous holes that supported characterization of the Baneberry site. Pre-test holes included the nearby U8a #9, #10, and #11. Four post-test holes were drilled for Baneberry, and each had several sidetracks at various depths. Nearby exploratory holes UE8f, UE8h, and UE8i were drilled in 1971-1973 as part of Baneberry evaluation activities.

At the time of the Baneberry test, the nearest known fault was near Discus Thrower in U8a (see Figure 1). The Baneberry fault associated with the release was not known to exist pretest. Post-test data indicate it bounds the west side of the basin and has displaced the Paleozoic surface approximately 300 m. The closest approach of the fault to the working point was 1.3 cavity radii. In addition to relatively large displacements of lithologic units across the fault, clay was also found along it. This is significant because it reduces frictional forces that would normally retard differential motion across the fault. In addition, post-test drilling identified a second fault west of the Baneberry fault. The United States Geological Survey hypothesized that there was a zone of closely spaced shear faults that permitted channeling of water and was the principal mechanism for the alteration of alluvium and tuff to clays near the working point (USGS, 1974). The clay zone, while localized, was more pervasive than a simple stratigraphic horizon.

Discus Thrower satellite holes and U8d show high velocities, high clay content, and high water content. The underlying Paleozoic rock near the Baneberry site changes from carbonate rock to the east to quartzite to the west. The upper 213 m of alluvium at U8d was relatively well cemented, with densities and sonic velocities higher than that normally associated with alluvium found near the center of Yucca Flat. The Baneberry test caused surface faulting and cracking. While similar faulting occurred with Discus Thrower, the magnitude of faulting is unusual for a test of the Baneberry yield. The motion and faulting were consistent with the regional stress pattern, implying a low stress in the northwest-southeast direction. The radial nature of the fissure indicates it may have been generated by the ground shock and doming of the ground above the cavity with its azimuth being determined by the minimal principal stress orientation.

Complex geology of the Baneberry site had several features that contributed to the vent: (1) a clay-rich zone near the working point which reduced the strength of the tuff to below normal and created an impedance mismatch with material above it; (2) a double fault system west of the working point; and (3) a high Paleozoic scarp below and to the west of the working point. With the exception of the low strength caused by the clay, each of these features had been present in successfully contained tests with larger yields and deeper depths of burials. On occasion, two or more of these features have been present and successful containment has still occurred. The Baneberry site was unique only because all of these features appeared at a shallower depth than is normally found at the NNSS.

Conclusions drawn from shock wave modeling (described in Terhune et al., 1977, and updated in Glenn et al., 1981) indicated that it was questionable if a good containment cage formed. (A containment cage is thought to be a stress-related feature that holds pressure and radioactivity within 1-2 cavity radii until the cavity collapses.) All three undesirable features contributed to the establishment of the vent path from the cavity to the ground surface. Modeling showed that the shock wave in the direction of the surface was composed of the main shock front, induced by cavity expansion, and of the Paleozoic reflection. The Paleozoic reflection contributed primarily to the main shock front, partially to the peak, and also to horizontal rebound. Tensile reflection off the saturated interface and partially saturated tuff interface of the second fault resulted in an open fracture path to the first fault. Motion along the weak Baneberry fault provided an open fracture to the spall zone. Focusing the shock wave across the saturated interface above the cavity resulted in less shock attenuation than might be expected. As a consequence, the highly fractured spall region penetrated much farther below the surface than might normally be expected. Finally, surface motion produced an open fissure near the ground surface at emplacement site constituted the final segment of the vent path. It is important to note that all of these features happen more or less simultaneously.

NNSS underground nuclear testing resumed in June 1971. Area 8 saw limited use: simultaneous, same hole Cremino and Cremino-Caerphilly in U8e on September 27, 1978; Norbo in U8c on March 8, 1980; Seco in U8l on February 25, 1981; Vide in U8k on April 30, 1981, Frisco in U8m on September 23, 1982; Cottage in U8j on March 23, 1985; and simultaneous, same hole Kawich A-Blue and Kawich A-White in U8n on December 9, 1988. Due to the stigma associated with the Baneberry venting, tests proposed for Area 8 included significant characterization and comparisons to Baneberry, and containment reviews were carried out in detail. The Cottage test is an example of a lengthy evaluation and review process to demonstrate adequate containment planning.

In order to evaluate cavity collapse and surface crater formation, it has been necessary to understand the geologic setting of the Baneberry site and the cause of the release. Undesirable geologic features linked together to contribute to the venting. The question is – could any of these features cause a possible instability in the ground surface now?

- The venting path from the cavity to the ground surface required shock wave interactions specific to the local setting, a fault path, and weak material properties.

The shock waves occurred only during the dynamic timeframe related to the nuclear explosion. Cavity collapse, chimney formation, and surface collapse are related to the dynamic timeframe and are most likely completed. The faults and the material properties are inherent to the local setting and still exist.

- Many activities took place soon after Baneberry that affected the local area, including post-test drilling, exploratory drilling to investigate the cause of the venting, and later drilling of emplacement holes.

- Ground motion occurred from nine nuclear detonations in Area 8 subsequent to Baneberry. Many subsequent tests in Yucca Flat, Rainier Mesa, and Pahute Mesa also caused ground motion. It seems that if any additional collapse were to occur at the Baneberry site, for any reason, it should have occurred by now.

- A seismic survey was done in 1979 to support characterization for the Norbo test in U8c. However, the energy supplied for this work was small when compared to underground nuclear tests and probably did not affect subsequent collapse or earth motion.

We have reviewed geology and test-related data for a number of tests in the locality of U8d. We believe that the Baneberry test displayed complete collapse soon after detonation. Ground motion caused by later nuclear tests gives us comfort that cavity collapse and crater formation for Baneberry should be complete. In general, the ground surface above the U8d site has not changed over time, so it seems reasonable to conclude that the current configuration is stable. We have evaluated crater stability produced from cavity collapse, and have not considered later erosion effects, nor the relationship of the vent fissure to the collapse crater. We rely on Nevada Security Technologies, LLC (NSTec) and Department of Energy (DOE) National Nuclear Security Administration (NNSA) Nevada Site Office (NSO) to make decisions concerning safety issues related to activities near the crater area.

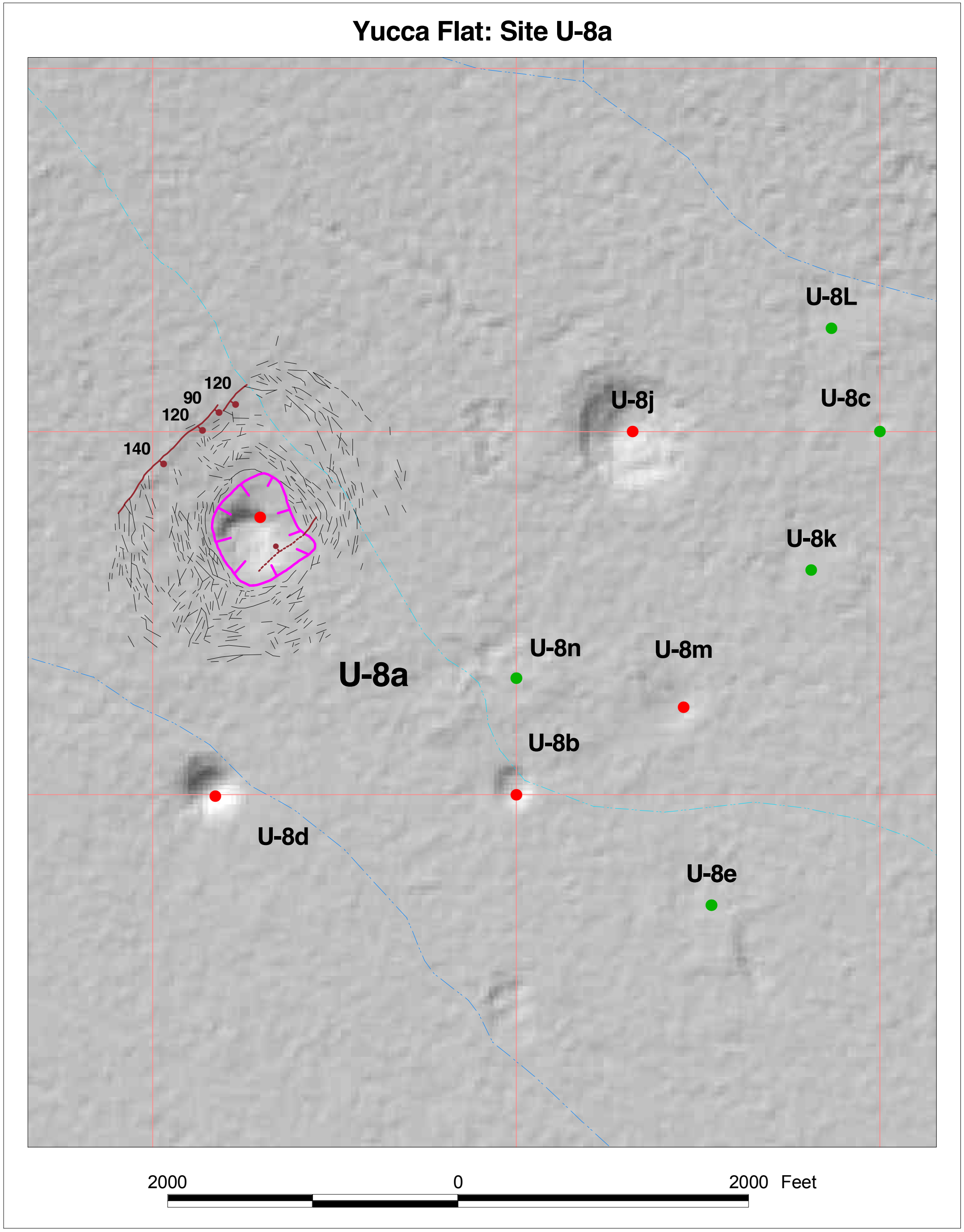

Figure 1. Surface effects map of Discus Thrower in U8a (Grasso, 2003). Surface expression of the Discus Thrower fault is shown to the northwest of the collapse crater, with numbers showing displacement in centimeters.

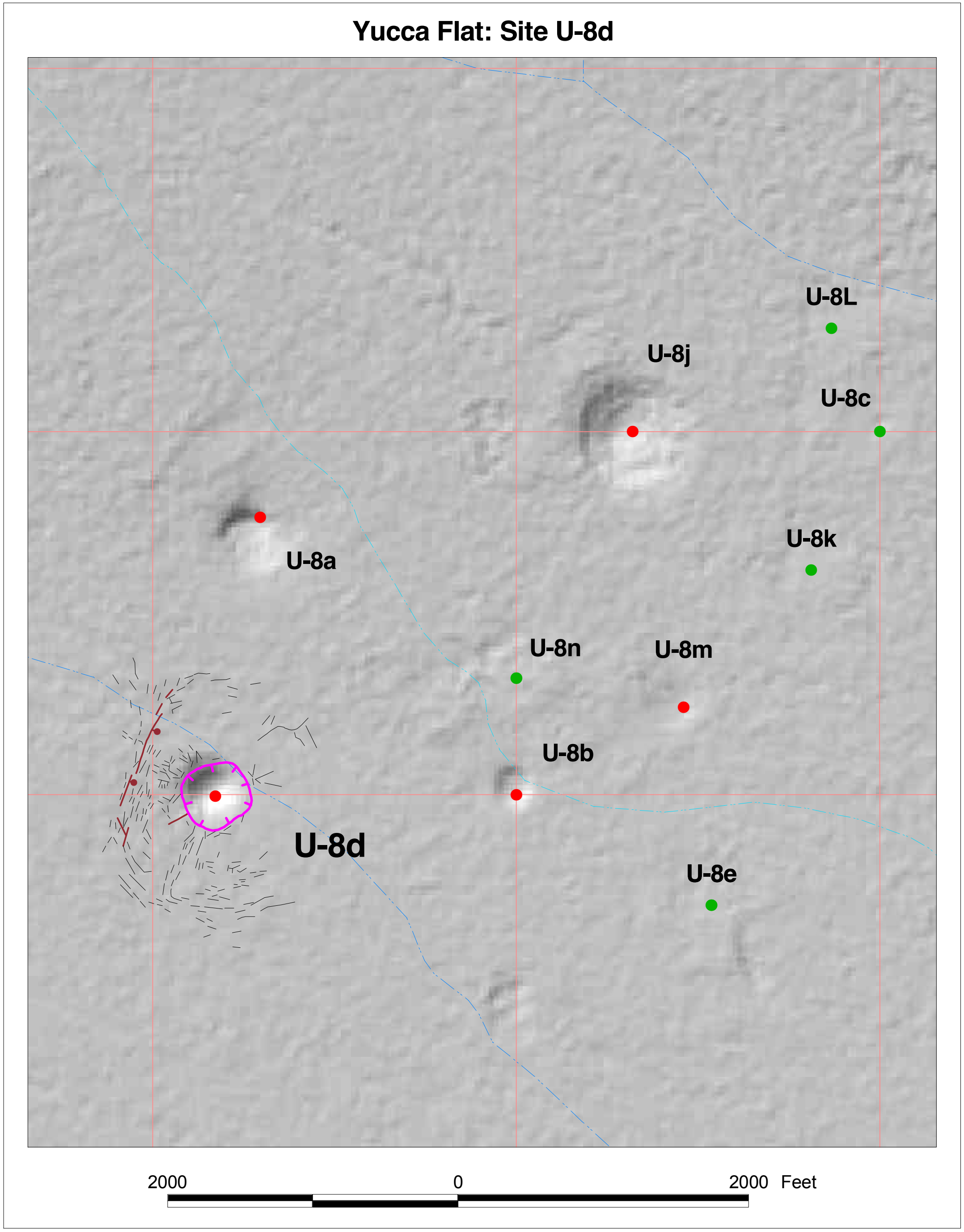

Figure 2. Surface effects map of Baneberry in U8d (Grasso, 2003). Surface expression of the Baneberry fault is shown to the northwest of the collapse crater, where the ball (of the bar and ball) is on the downthrown side of the fault. The brown line near the surface crater is the fissure that vented.

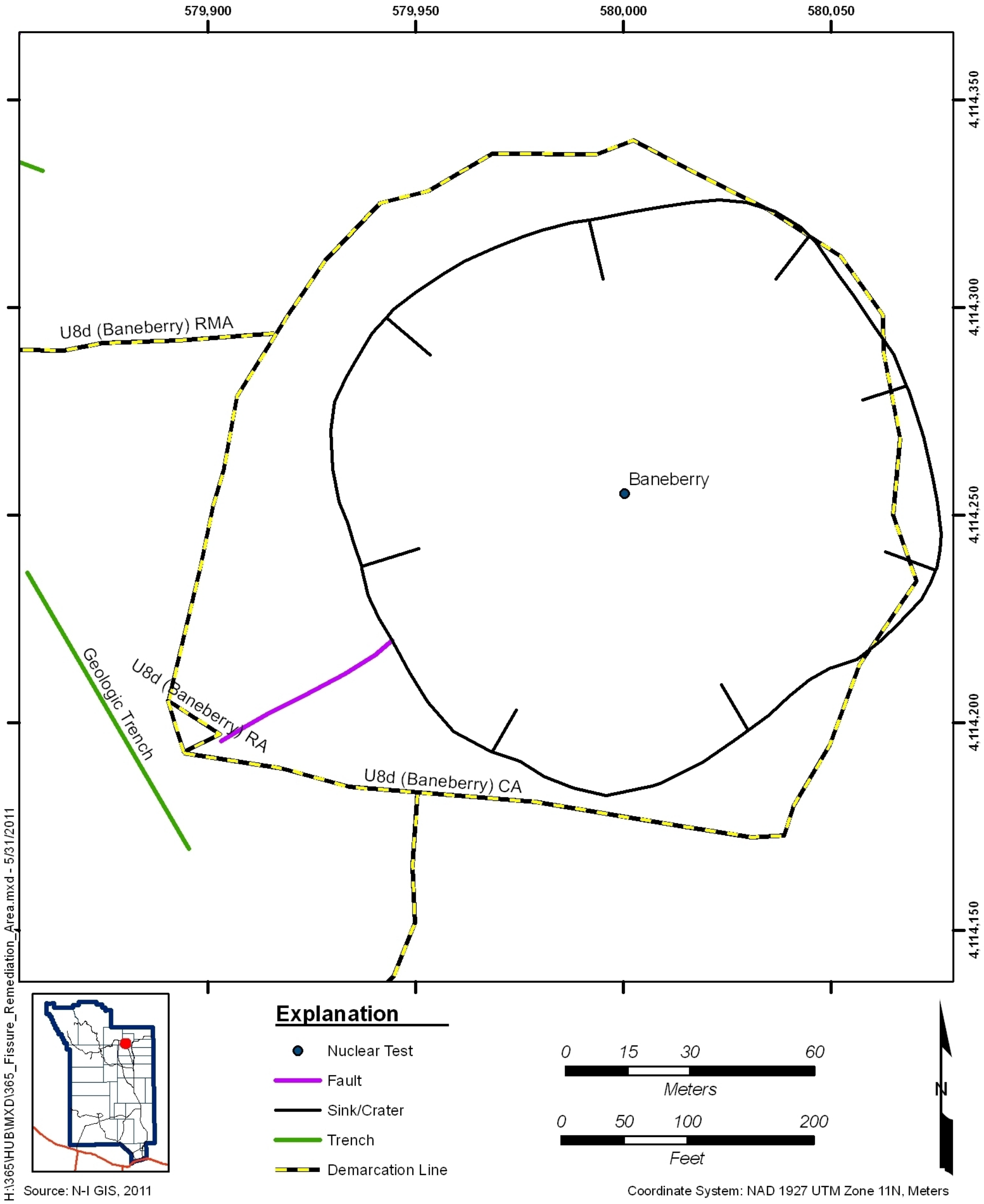

Figure 3. Map of surface collapse crater and venting fault (from NSTec, 2011).

Clearwater
U12q

The LLNL-sponsored Clearwater test was detonated in U12q on October 16, 1963. It was one of two shaft (vertical drill hole) tests on Rainier Mesa, where most underground nuclear tests were conducted in horizontal tunnels. Clearwater, a weapons-related test, had an "intermediate" yield, which equates to 20-200 kt, (USDOE, 2000).

Emplacement hole U12q is located on Rainier Mesa west of N Tunnel (Figure 4). The hole was sited to be equidistant from tests in maximum extents of N, B, and E tunnels. Nearby tests include Diana Mist in U12n.06 on February 11, 1970; Husky Ace in U12n.07 on October 12, 1973; and Misty Rain in U12n.17 on April 6, 1985. The other vertical test on Rainier Mesa, Wineskin in U12r, detonated on January 15, 1969, is located about 2 km northeast of U12q.

U12q was drilled to 653 m in 1962. Water was produced in the hole while drilling, causing a decision to terminate the hole above the planned total depth of 762 m. Four years later a 10.7 m long by 5.5 m wide by 10.6 m high room was mined in the drill hole. The working point, at 545 m depth in tuff, was located near the floor of the room. Two drifts were mined off the working point area for experiments.

Clearwater did not collapse to the surface. No information on cavity collapse or subsurface chimney height was found. Clearwater was the 19th detonation on Rainier Mesa, and there were 43 detonations on Rainier Mesa that caused subsequent ground motion.

There were six post-test holes and 1 cable hole associated with Clearwater. Four post-test holes were abandoned while drilling (PS #1, PS #2, PS #6, and PS #7). U12q PS #5 was drilled to 631 m. U12q PS #8 was drilled to 617 m. Neither appears to be plugged. Cable hole U12q CH #3 was drilled to 549 m, and does not appear to be plugged.

We have reviewed geology and test-related data, including information and believe that complete collapse occurred soon after detonation. The number of subsequent tests on Rainier Mesa, and the entire NNSS, gives us comfort that cavity collapse and potential for crater formation should be complete. The ground surface above the U12q site has not changed over time, so it seems reasonable to conclude that the current configuration is stable. Because there are only two vertical tests on Rainier Mesa to infer collapse history from, LLNL is less confident making a statement on completeness of collapse. We have evaluated crater stability produced from cavity collapse, and have not considered later erosional effects. We rely on NSTec and DOE/NNSA/NSO to make decisions concerning safety issues related to reentering the crater area.

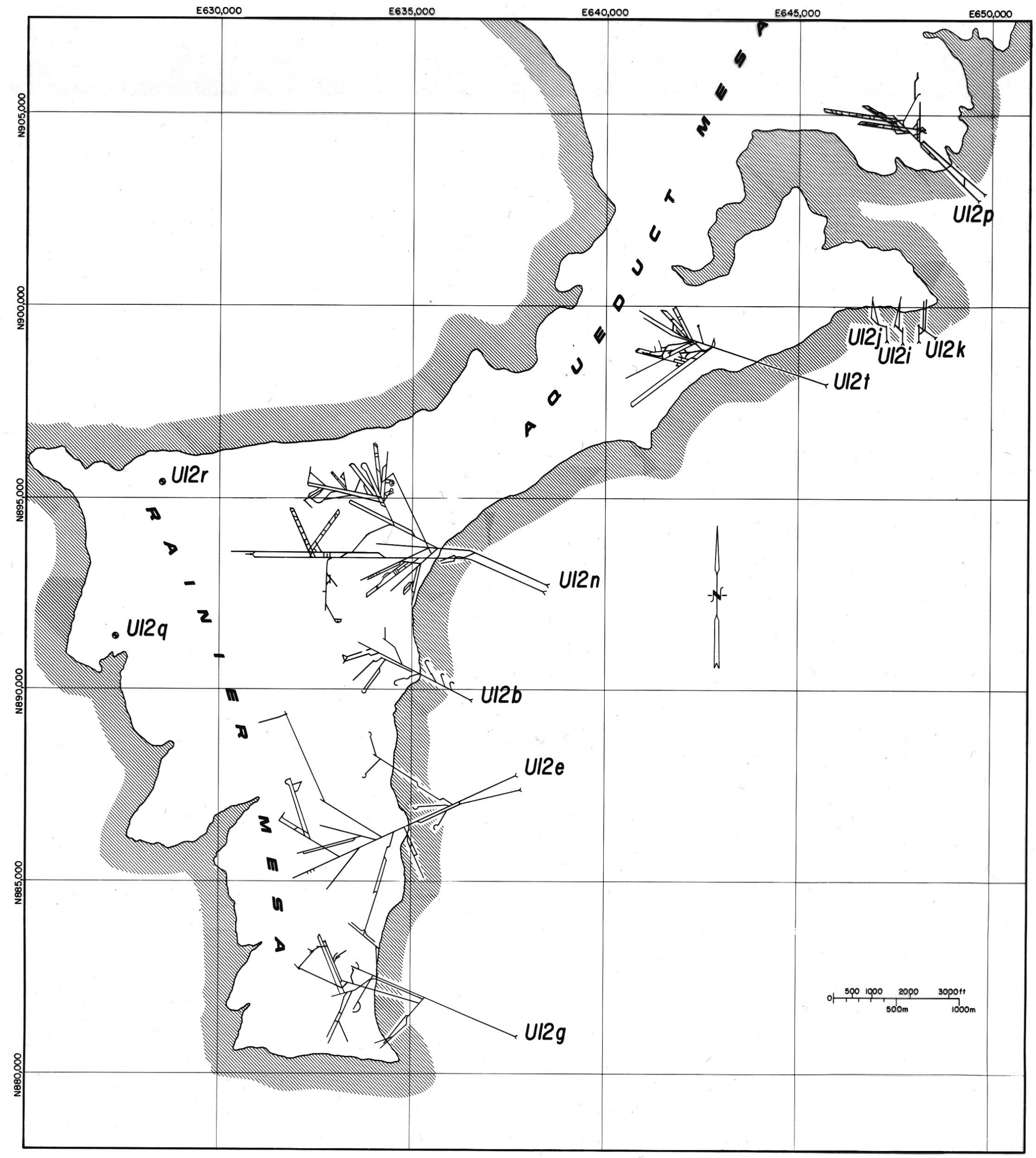

Figure 4. Location map for U12q and U12r on Aqueduct Mesa, NNSA.

Wineskin
U12r

The LLNL-sponsored Wineskin test was detonated in cased hole U12r on January 15, 1969. It was one of two shaft (vertical drill hole) tests on Rainier Mesa, where most underground nuclear tests were conducted in horizontal tunnels. Wineskin, a weapons-related test, had an announced yield of 20-200 kt, (USDOE, 2000).

U12r is located on Rainier Mesa west of N Tunnel (Figure 4). Nearby tunnel tests include Mighty Epic on May 12, 1976 in U12n.10 and the simultaneous, separate drifts Mineral Quarry (in U12n.22) and Randsburg (in U12n.22a) on July 25, 1990. The other vertical test on Rainier Mesa, Clearwater in U12q, detonated on October 16, 1963, is located about 2 km southwest of U12r.

Emplacement hole U12r was drilled to 768 m in 1962, and four years later a 4.9 m diameter by 6.1 m high room was mined from about 515.1 m to 521.2 m depth. The Wineskin working point was at 518 m depth in tuff.

Wineskin collapsed to the surface about 45 minutes after detonation (Figure 5). The surface terrain was gently altered, not in the form of a classical collapse crater (Figures 5 and 6). Figure 7 shows the pre-test layout configuration. Some reports noted that this was a subsurface collapse (as opposed to surface collapse) because no discernable surface features were found. No measurements of the collapse crater dimensions have been located, possibly because none were made due to the lack of a distinct collapse shape. There are indications that the stemming in the main casing dropped by about 10 m.

There was one slant post-test hole associated with Wineskin, and one hole was sidetracked off of it. U12r PS#1A was located about 183 m southwest of U12r, probably just outside the “surface collapse crater”.

Wineskin was the 25th detonation on Rainier Mesa, and there were 37 detonations on Rainier Mesa that caused subsequent ground motion. There were also a significant number of subsequent tests at nearby Pahute Mesa and Yucca Flat that caused ground motion after the detonation of Wineskin.

We have reviewed geology and test-related data, including information on the cavity and surface subsidence crater, and believe that complete collapse occurred soon after detonation. The number of subsequent tests on Rainier Mesa, and the entire NNSS, gives us comfort that cavity collapse and surface crater formation should be complete. The ground surface above the U12r site has not changed over time, so it seems reasonable to conclude that the current configuration is stable. Because there are only two vertical tests on Rainier Mesa to infer collapse history from, LLNL is less confident making a statement on completeness of collapse. We have evaluated crater stability produced from cavity collapse, and have not considered later erosional effects. We rely on NSTec and DOE/NNSA/NSO to make decisions concerning safety issues related to reentering the crater area.

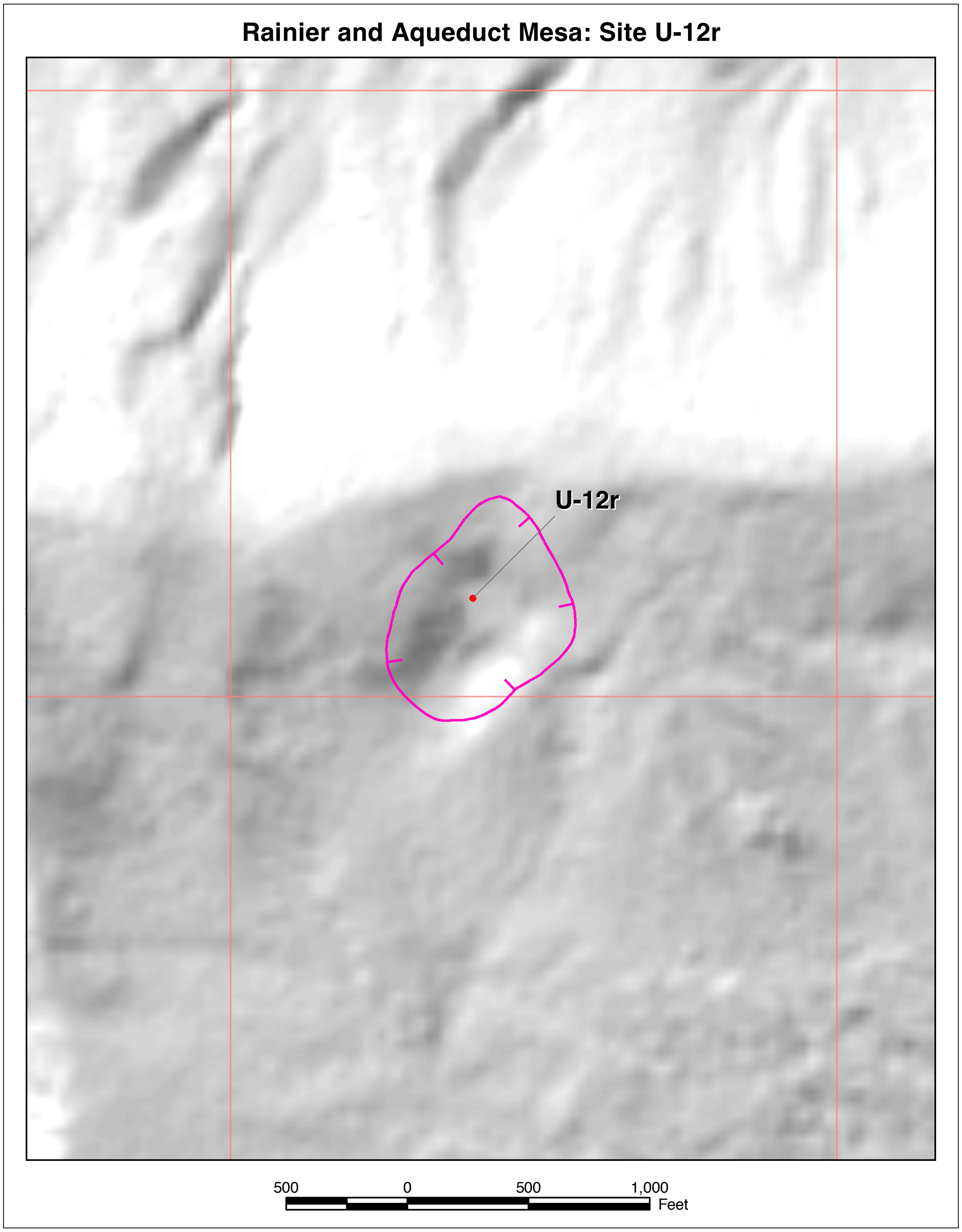

Figure 5. Surface effects map of Wineskin in U12r (Grasso, 2003).

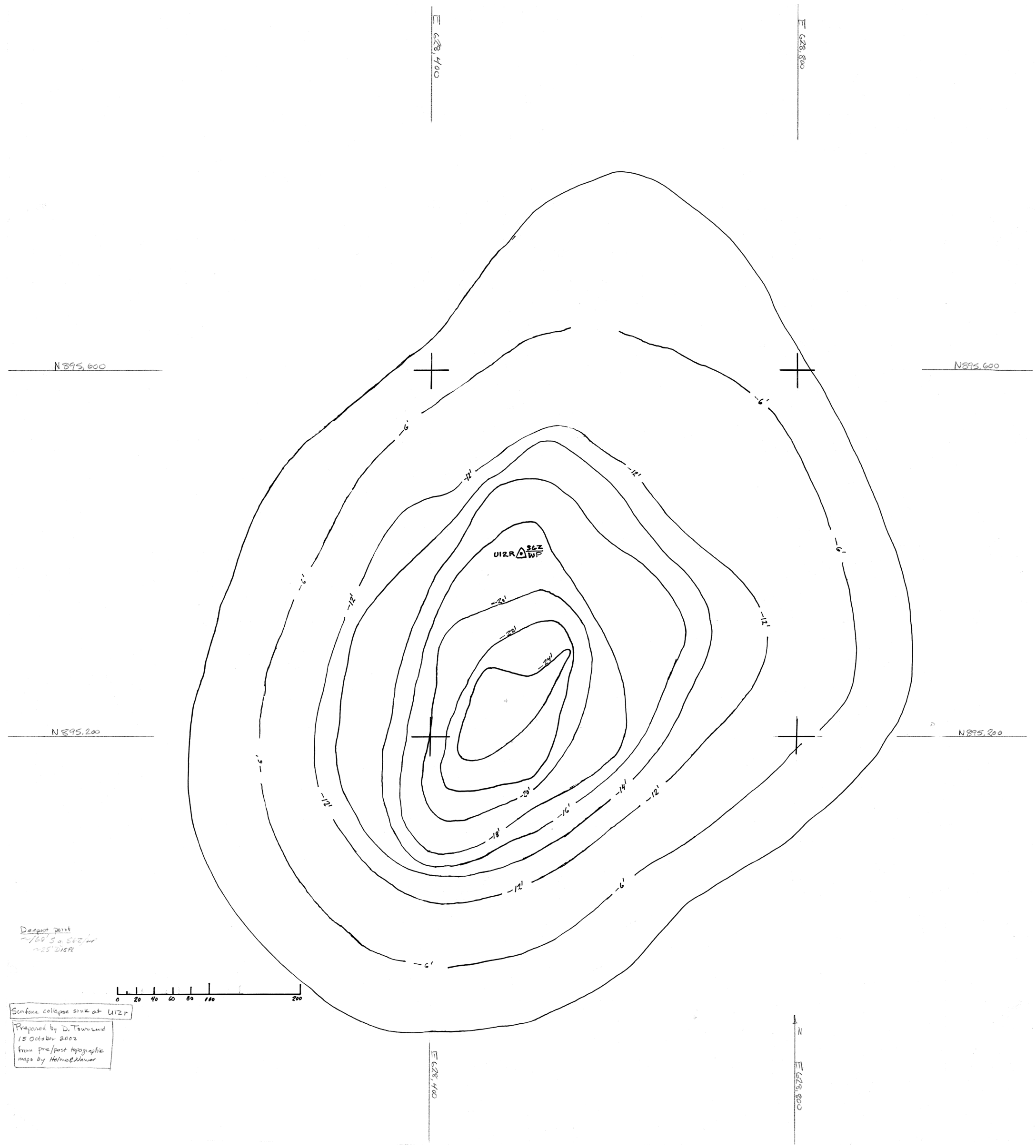

Figure 6. Contour map of surface collapse for Wineskin in U12r.

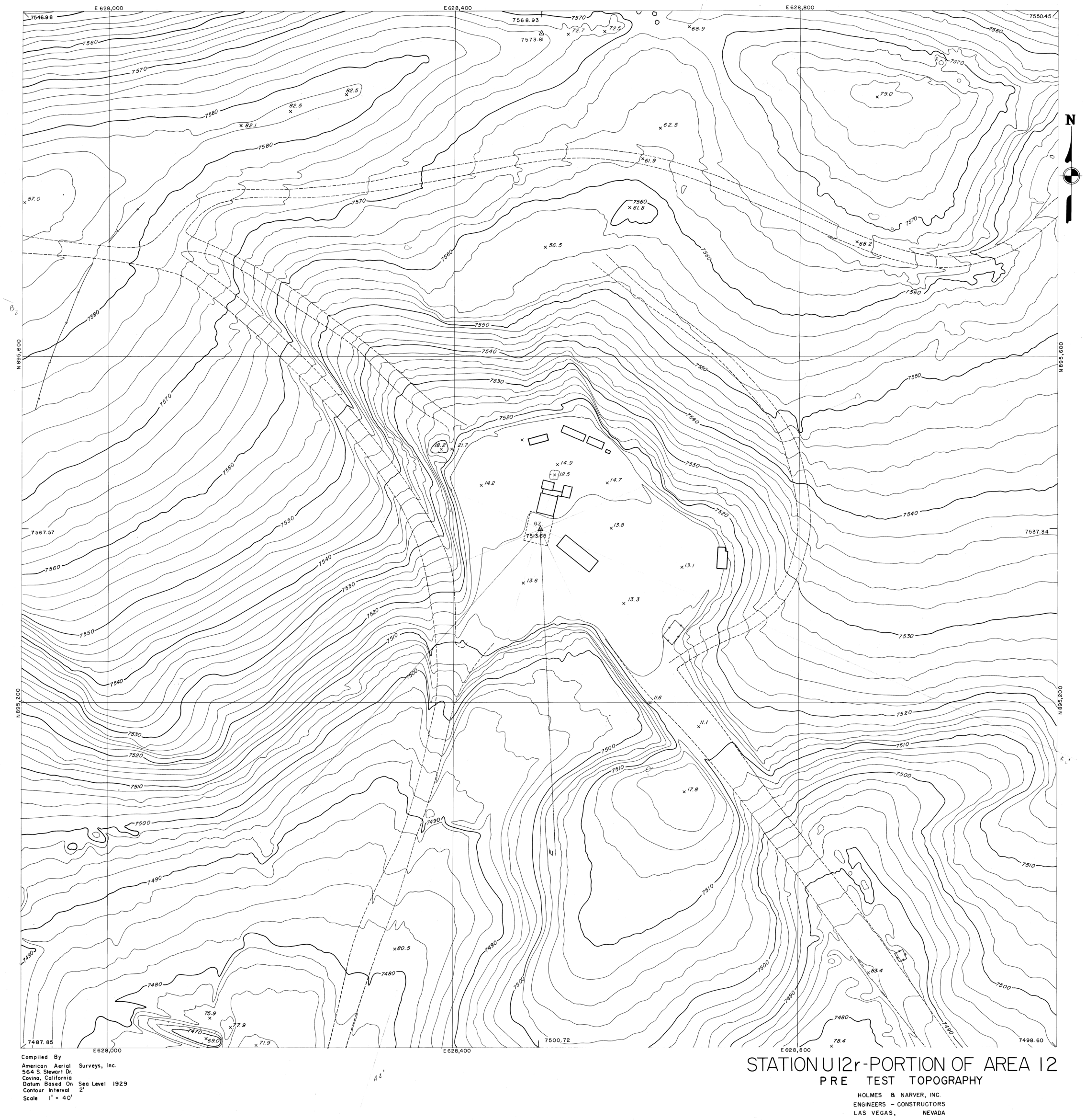

Figure 7. Pre-test location map of Wineskin in U12r, showing topography and equipment layout.

Buteo in U20a
Duryea in U20a1

Buteo and Duryea were detonated in the same hole about 1 year apart.

U20a is located in Area 20, southwestern Pahute Mesa, between the Boxcar Fault to the west and the West Greeley Fault to the east. Nearby tests include Cheshire in U20n on February 14, 1976; Colwick in U20ac on April 26, 1980; Hardin in U20av on April 30, 1987; and Montello in U20bf on April 16, 1991. Water Well 20 (U20WW) is located about 9500 m to the north of U20a.

The LANL-sponsored Buteo test was the first underground nuclear test on Pahute Mesa. It was detonated in cased hole U20a on May 12, 1965. U20a was originally drilled to 774 m depth, then backfilled with gravel and cement between 567 to 765 m. The Buteo working point was at about 695 m depth in zeolitized bedded tuff. This was a weapons-related test with an announced yield of <20 kt, (USDOE, 2000).

There were a number of drill holes associated with Buteo including instrument holes, vent holes, and post-test holes. Some holes were specifically used for the Buteo test, some were partially constructed and suspended during the Buteo execution, and then recompleted for Duryea.

Instrument holes U20a #1, U20a #2 and U20a #3 were located northeast of U20a, at roughly 100, 200 and 300 m respectively. These holes were drilled and instrumented for the Buteo test. They were stemmed with sand and gravel and plugged with cement at the surface prior to the detonation.

U20a PS #1V, located about 240 m north of U20a, was drilled to 457 m, stemmed, and suspended before Buteo was detonated. It was then recompleted to 726 m depth as a post-test hole, and afterwards plugged with sand, gravel and cement from about 600 m depth to the surface.

U20a PS #2V is located about 240 m south of U20a. U20a PS #2V Hole 1 was drilled to 458 m, plugged and stemmed. U20a PS #2V Hole 2 developed as the plug in Hole 1 was drilled out and the hole sidetracked. Hole 2 was drilled to 244 m and plugged. After the detonation Hole 1 was cleaned out, drilled to 720 m as a post-test hole and sampled. Reentry work several months later cleaned, stemmed and plugged the hole.

Buteo did not collapse to the surface. No records were found to indicate any surface effects were created by this test. At the working point depth of 695 m and the relatively small yield of <20 kt, collapse to the surface would not be expected.

Duryea was detonated at a working point depth of about 544 m in U20a, above the expended Buteo test. Duryea was a weapons related test and had an announced yield of 70 kt (USDOE, 2000).

Duryea was emplaced and stemmed when some cables began to fail before detonation. A remedial plan to repair the cables was designed and executed. A new drill hole, U20a1 (also called the U20a reentry shaft), sited about 18 m southwest of U20a, was drilled to 149 m and cased. A tunnel was constructed between the new and old holes, cables were repaired and Duryea was detonated on April 14, 1966.

U20a PS #2V, drilled for the Buteo test, was reentered and sidetracked at 279 m depth to form U20a PS #1D. This hole was then sidetracked at 533 m depth to become U20a PS #1DS, and PS #1D was sidetracked at 451 m to become U20a PS #1DSS. U20a PS #2V (and all sidetracked holes) was plugged from 542 to 184 m with cement, sand and gravel.

Duryea did not collapse to the surface. Figure 8 shows that only very minor surface effects (cracks) were caused by Duryea. Given the working point of 544 m depth and yield of 70 kt yield for this test, surface collapse would not be expected, based on scaled depth of burial (SDOB) guidelines used today. No information on cavity collapse or subsurface chimney height for Duryea was found.

Buteo was the first underground nuclear test at Pahute Mesa and Duryea was the fourth. There was a total of 82 underground nuclear tests at Pahute Mesa, including 19 high yield tests. All Pahute Mesa tests, and many others at the NNSS, caused ground motion that would have affected the U20a site.

We have reviewed geology and test-related data, including information on the cavity collapse and potential for subsurface collapse. We have no data to evaluate if subsurface collapse has changed over time, or preclude that small, additional collapses have or have not occurred. Because of this there is less confidence in making a statement on completeness of collapse. The number of subsequent tests on Pahute Mesa, and the entire NNSS, gives us comfort that cavity collapse should be complete. The ground surface above the U20a site has not changed over time, so it seems reasonable to conclude that the current configuration is stable. We have evaluated crater stability produced from cavity collapse, and have not considered later erosional effects. We rely on NSTec and DOE/NNSA/NSO to make decisions concerning safety issues related to reentering the crater area.

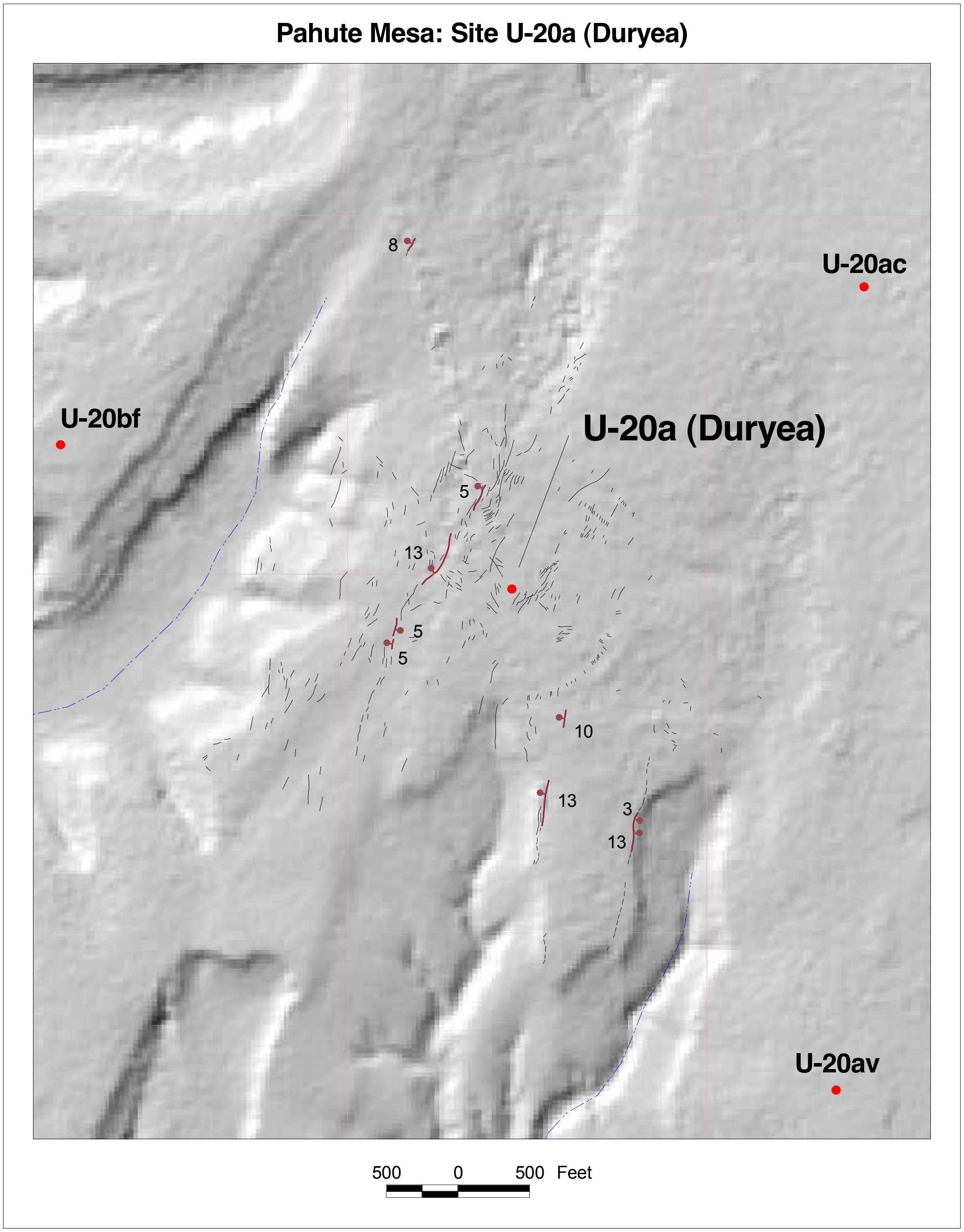

Figure 8. Surface effects map of Duryea in U20a. (Grasso, 2003).

Barnwell
U20az

The LLNL-sponsored Barnwell test was detonated in U20az on December 8, 1989. Barnwell, with an announced yield of 20-150 kt (USDOE, 2000), was detonated in zeolitized ash-flow tuff at a working point of 601 m below the surface. U20az is located in southeast Area 20 on Pahute Mesa, between the West Greeley Fault to the west and the East Greeley Fault to the east. Barnwell in U20az is at the southern extent of underground testing in this structural block. Bodie, in U20ap on December 13, 1986, to the north is the closest test in the same structural block. Nearby tests to the west across the West Greeley Fault include: Cheshire in U20n on February 14, 1976; Hardin in U20av on April 30, 1987; and Hoya in U20be on September 14, 1991. Tests to the east (in Area 19) are more than 3 km distant.

We have reviewed geology and test-related data for Barnwell.

- Barnwell did not collapse to the surface. Figure 9 shows surface effects caused by the Barnwell test. Based on scaled depth of burial (SDOB) guidelines used today, collapse to the surface would not be expected at the minimum announced yield, and uncertain at the maximum announced yield. At the minimum announced yield of 20 kt, the SDOB would be about 221 $m/k^{1/3}$. At the maximum announced yield range of 150 kt, the SDOB would be about 113 $m/kt^{1/3}$. Generally speaking, tests with smaller SDOBs are more likely to collapse to the surface after detonation.

- Barnwell exhibited a staged subsurface collapse (Hudson et al.). First signs of collapse occurred about 4 minutes after detonation and collapse extended to about 360 m depth as measured by EXCOR. At 120 minutes after detonation a second collapse event occurred, with collapse height increasing to about 176 m in depth. A final instrument station was lost in the hole at about 317 minutes, but it appears that collapse height did not increase above 176 m depth.

- Rainier Mesa Tuff overlies this depth and consists of partially to moderately welded tuff from 0-28 m, densely welded tuff from 28-152 m, vitrophyre from 152-157 m, and nonwelded ash-flow tuff from 157-166 m. High density, high velocity tuff occurs from about 25-52 m and again at 82-150 m. If collapse extended to these regions the rock strength may be sufficient to terminate collapse and provide a stable setting.

- A seep of radioactive gas occurred from surface cracks at the Barnwell site about eight days after detonation (described in Hudson et al.). DOE/NV-317 (USDOE, 1996) indicates that the seepage, about 47 Curies of Xe and Kr, began on December 17, 1989 and continued until March 7, 1990. Hudson et al. postulated that atmospheric pressure was the driving force for this late-time seepage, and although the seep location suggests a relation with the post-test hole, both past experience and a lack of direct evidence imply no causal relationship exists between the seep and the post-test hole. Breathing, or the late-time seepage of noble gases, has been correlated with tests associated with the presence of the Timber Mountain Group at the ground surface (the Rainier Mesa Tuff is part of the Timber Mountain Group).

- The ground surface at the U20az site has not changed over time since the test. There were seven tests on Pahute Mesa after Barnwell that caused subsequent ground motion.

We have reviewed geology and test-related data, including information on the cavity collapse and potential for subsurface collapse. We have no data to evaluate if subsurface collapse has changed over time, or preclude that small, additional collapses have or have not occurred. However, known stratigraphy and lithology seems to indicate that subsurface collapse could be stable into the future. Since the ground surface above the U20az site has not changed over time with shaking from subsequent tests, it seems reasonable to conclude that the current configuration should be stable. However, LLNL has much less confidence than normal in making this statement. We rely on DOE/NNSA/NSO to make decisions concerning safety issues related to reentering potential crater areas.

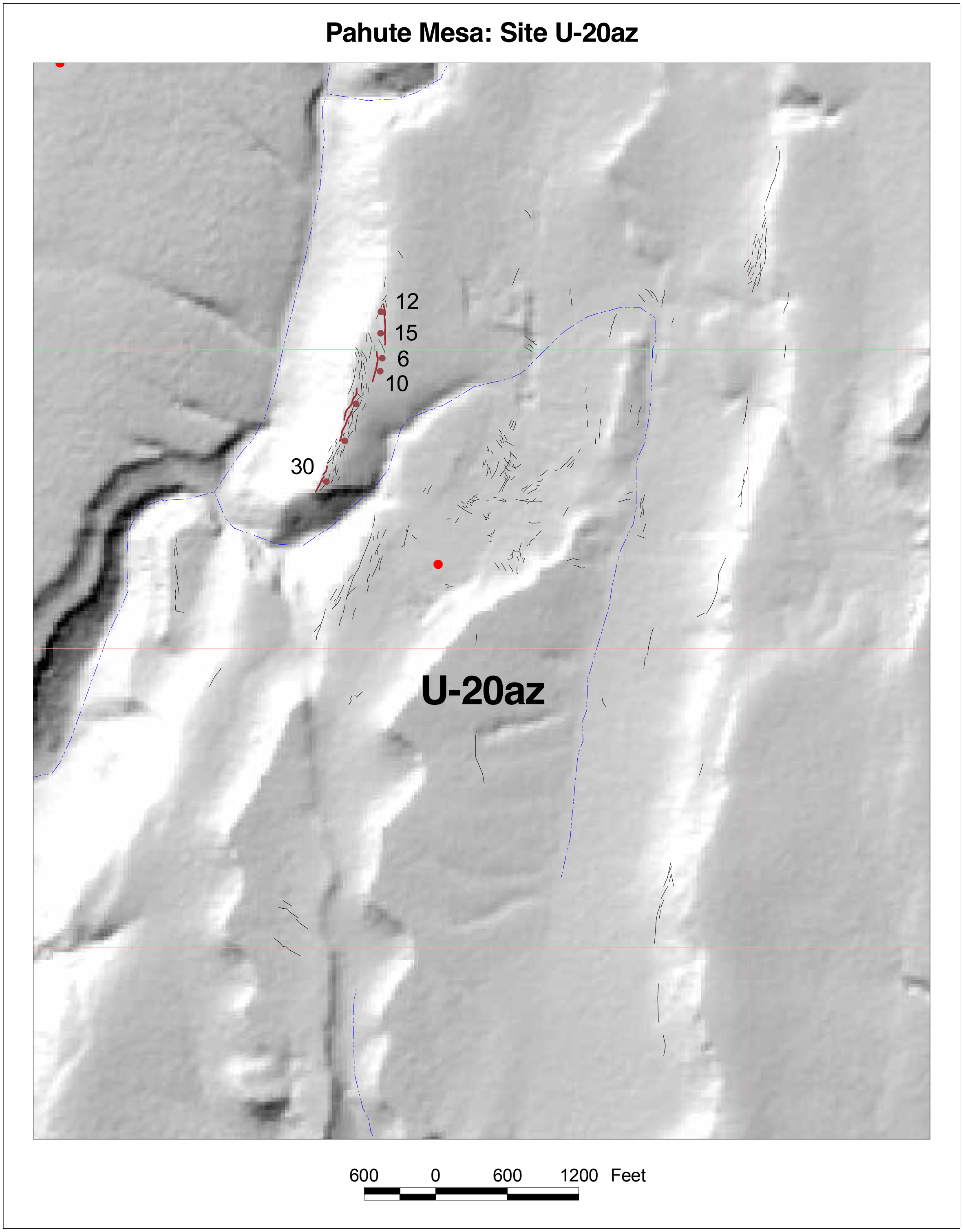

Figure 9. Surface effects map of Barnwell in U20az (Grasso, 2003).

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