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Evaluation of Cavity Collapse and Surface Crater Formation at the Norbo Underground Nuclear Test in U8c, Nevada Nuclear Security Site, and the Impact on Stability of the Ground Surface

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Purpose of Work

At the request of Jerry Sweeney, the Lawrence Livermore National Laboratory (LLNL) Containment Program performed a review of nuclear test-related data for the Norbo underground nuclear test in U8c to assist in evaluating this legacy site as a test bed for application technologies for use in On-Site Inspections (OSI) under the Comprehensive Nuclear Test Ban Treaty. This request is similar to one made for the Salut site in U8c (Pawloski, 2012b). Review of the Norbo site is complicated because the test first exhibited subsurface collapse, which was not unusual, but it then collapsed to the surface over one year later, which was unusual. Of particular interest is the stability of the ground surface above the Norbo detonation point. Proposed methods for on-site verification include radiological signatures, artifacts from nuclear testing activities, and imaging to identify alteration to the subsurface hydrogeology due to the nuclear detonation. Aviva Sussman from the Los Alamos National Laboratory (LANL) has also proposed work at this site. Both proposals require physical access at or near the ground surface of specific underground nuclear test locations at the Nevada Nuclear Security Site (NNSS), formerly the Nevada Test Site (NTS), and focus on possible activities such as visual observation, multispectral measurements, and shallow and deep geophysical surveys.

The Containment Evaluation

The Containment Program utilized subject matter experts who participated in weapons testing activities to perform this evaluation, and focused on the pre-test hydrogeologic setting and the effects of the nuclear explosion on that setting, commonly called containment phenomenology. 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 estimates, ground motion, and radiological release information. Both classified and unclassified data were reviewed. Various amounts of information are available for the tests included in this review, depending on the age and the associated activities that took place when the test occurred. Lack of data can hamper evaluations and introduce uncertaitny. No attempt has been made to address this uncertainty.

The pre-test containment evaluation requires definition of test specifics, characterization of the geologic setting, and prediction of the shock waves from the explosion and their interactions with the geologic layers. Because there are many variables related to the phenomenology and uncertainty is unquantified, common practice involved comparison of many aspects of a proposed test to past experience; we expect this would be standard protocol in the future also. Guidelines assisting containment evaluation were developed over time, and Cliff Olsen documented general rules of thumb for site selection and containment evaluation (Olsen, 1993). These rules of thumb are derived from years of experience, and are based on data from successful and unsuccessful containment, statistical analysis of data, and pre- and post-test hydrodynamic modeling.

The work proposals at the Norbo site include the possibility of performing work at the ground surface above a cavity and chimney that collapsed much later than expected – over one year after detonation. Containment rules of thumb related to collapse were helpful in the evaluation of ground stability near U8c. One rule of thumb relates depth of burial (also called the working point or WP) and yield – regardless of subsurface geology – where a dividing line between surface crater formation and subsurface collapse at Yucca Flat is at a scale depth of burial (SDOB) of 165 m/kt$^{1/3}$. Olsen notes that there is a broad zone in which collapse to the surface is uncertain. A transition zone exists above and below this value and is dependent on the site-specific setting. Another Containment rule of thumb generalizes that chimney height is 5.5 +/- 2.0 cavity radii (Rc). Chimney collapse is the upward propogation of the cavity void volume as a result of the cavity being unable to support itself. Strong layers can terminate the collapse, leaving a void below, or the collapse may terminate if bulking of the collapsed material fills the void space.

Review Limitations

1. By request, the review was limited to utilizing unclassified data. The specific yield of the Norbo test is not announced. The report *United States Nuclear Tests July 1945 through September 1992* (USDOE, 2000) identifies yields for US nuclear tests. The Norbo test yield is anounced as <20 kt. Classification guidance does not permit associating other yields for a given test. Agreement with the Department of Energy (DOE)/National Nuclear Security Administration (NNSA) Nevada Site Office (NSO) Classification Office permits using the maximum of the announced yield range. While this is insightful, utilizing the larger yield gives a larger cavity radius, and this can skew interpretations. Clarifying discussion is not permitted in an unclassified environment.
2. Ten underground nuclear tests were conducted in Area 8. Six collapsed to the surface, and four experienced subsurface collapse. Norbo collapsed to the ground surface, but over a year after detonation – which is unusual. For subsurface collapse, there is limited data to infer how high a collapse proceeded after detonation. Interpretation of subsurface collapse height is complicated in this review by using the maximum of the announced yield range to calculate a cavity radius and attempt to apply scaled values and rules of thumb. Using maximum yields and scaled values introduces uncertainty, and no expressions of correlation are discussed.
3. While we consider the impact of ground motion from subsequent tests on surface stability above uncollapsed cavity-chimney systems, we do not consider later erosional effects that may modify collapse craters over time or impacts from recent tectonic movements. We also do not address possible radiation dangers that may currently be present.
4. LLNL does not make decisions concerning safety issues related to activities near a potential (uncollapsed) surface crater area or areas where collapse may not be complete. We rely on Nevada National Security Technologics, LLC (NSTec) and the DOE/NNSA/NSO to make decisions concerning safety issues related to activities near potential and actual crater areas.

Underground Nuclear Testing in Area 8

A brief description of the geologic setting of Area 8 is given, along with a summary of underground nuclear testing, to assist in evaluating the stability of the ground surface near the Norbo site in U8c.

Area 8 is located in the northwestern portion of the Yucca Flat basin (Figure 1). The geologic setting is complex. The structural history consists of pre-Tertiary contractional deformation that was overprinted by more recent extensional deformation. Drill holes in the area show that the depth to basement rock (i.e. Paleozoic carbonate rocks) varies widely due to faulting, and ranges from about 360 m to 740 m depth. Extra caldera Tertiary volcanic ash falls, ash flows, and bedded tuffs filled in an irregular topography on top of the Paleozoic rocks. Tuff layers near the Paleozoic surface altered to clays soon after deposition, and there are also locations of stratigraphic alteration that form “pods” with high clay content. (Clays can cause a containment concern because they are a “weak” unit, especially if they are saturated.) Above the tuffs, alluvial deposits originated mainly from the north and west and range from 85 m to 380 m thick.

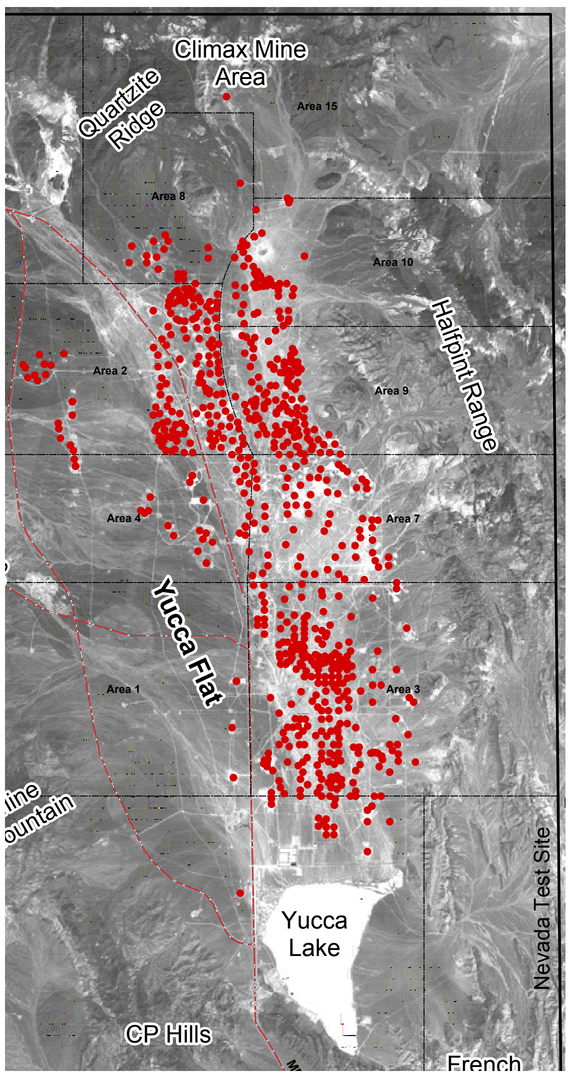

Figure 1. Location of Area 8 in northwestern Yucca Flat, NNSS (Bechtel Nevada, 2006). Red dots are locations of underground nuclear tests.

Many people in the containment community have concerns about underground nuclear testing in Area 8, and those concerns stem from the Baneberry release. Baneberry was conducted in U8d in 1970, and an unexpected accidental release of radioactivity occurred that was detected offsite (USDOE, 2000). Prompt venting occurred from a fissure near surface ground zero 3.5 minutes after detonation (Figure 2). The effluent rate steadily decreased with time, but visible vapor continued for 24 hours after the detonation (USDOE, 1996). 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 NTS until it reviewed Baneberry in detail and was convinced that every reasonable precaution was initiated to minimize the probability of a future occurrence. Due to the stigma associated with the Baneberry venting, subsequent tests proposed for Area 8 required significant characterization and comparisons to Baneberry, and containment reviews were carried out in detail. Significant efforts were applied to site characterization and improvments in predicting the phenomenology of proposed tests, with particular focus on alteration of volcanic units to clays, distance from faults and the Tertiary-Paleozoic surface, and measurement of material properties.

There were 659 underground nuclear tests (747 detonations) in Yucca Flat (Figure 1). Ten of these were conducted in Area 8 from 1966 through 1988 (Figure 3). They include: Discus Thrower in U8a on May 27, 1966; Cyathus in U8b on March 6, 1970; Baneberry in U8d on December 18, 1970; simultaneous same hole tests 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 U8, on September 23, 1982; Cottage in U8j on March 23, 1985; and simultaneous same hole tests Kawich A-Blue and Kawich A-White in U8n on December 9, 1988.

Figure 2. The Baneberry release.

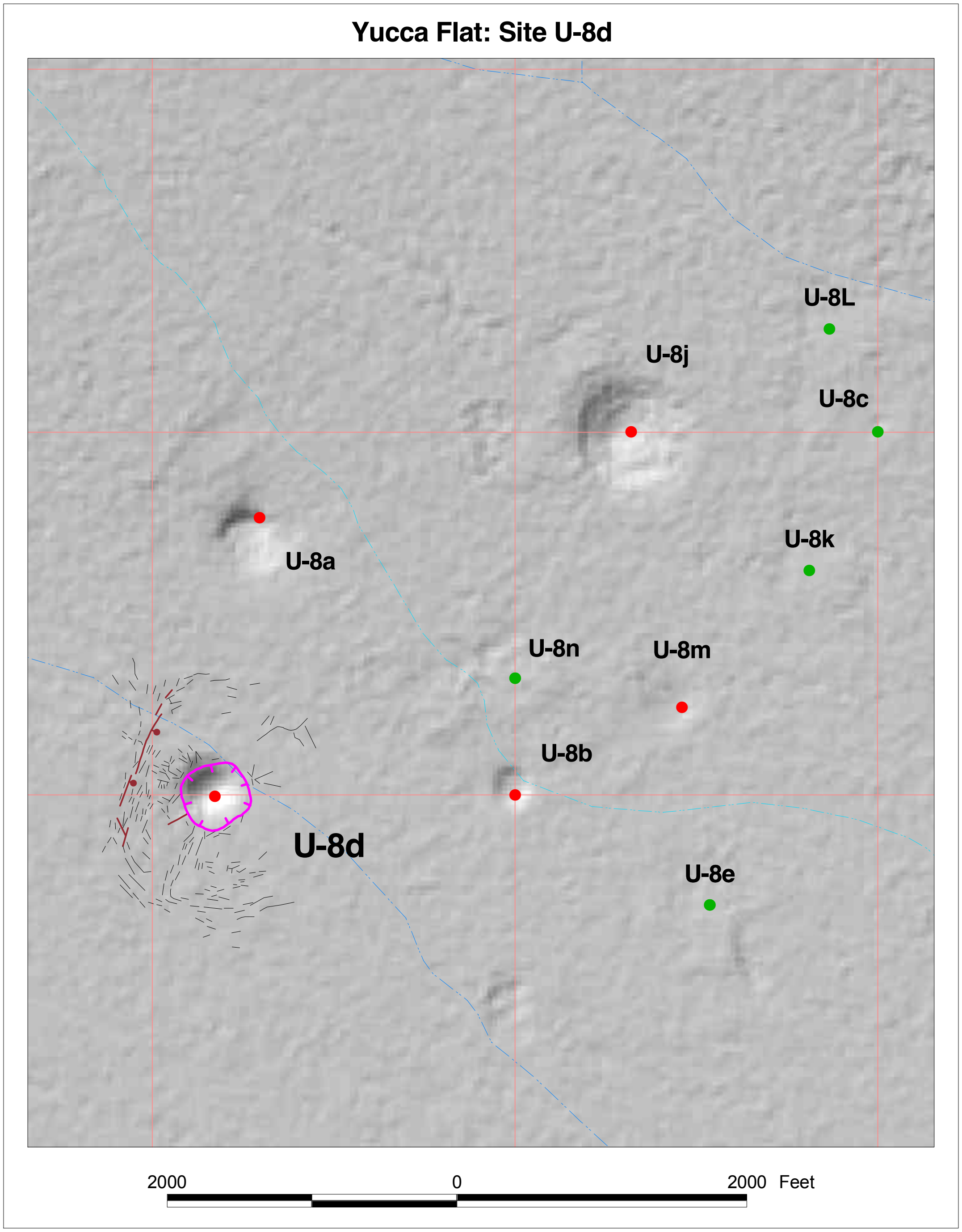

Figure 3. Locations of underground nuclear tests in Area 8, using the surface effects map from Baneberry in U8d (Grasso, 2003). Other tests include Discus Thrower (U8a); Cyathus (U8b); Norbo (U8c); Cremino and Cremino-Caerphilly (U8e); Cottage (U8j); Vide (U8k); Seco (U8l); Frisco (U8m); and Kawich A-Blue and Kawich A-White (U8n). Red dots indicate a test with mapped surface effects, and green dots indicate that either no surface effects were produced or none were mapped.

Figure 4 was taken from the U8j site characteristic summary report (Wagoner and Howard, 1984), and is included to show general features of Area 8. This includes locations of test emplacement holes, instrument and exploratory holes, seismic lines to determine the depth to the Paleozoic surface near Norbo in U8c (1979) and a later line to determine the depth of the Paleozoic surface to the southwest (1982), inferred faults on the Paleozoic surface, and lines suporting a magnetic survey for surface elevation changes at the time of Cottage in U8j.

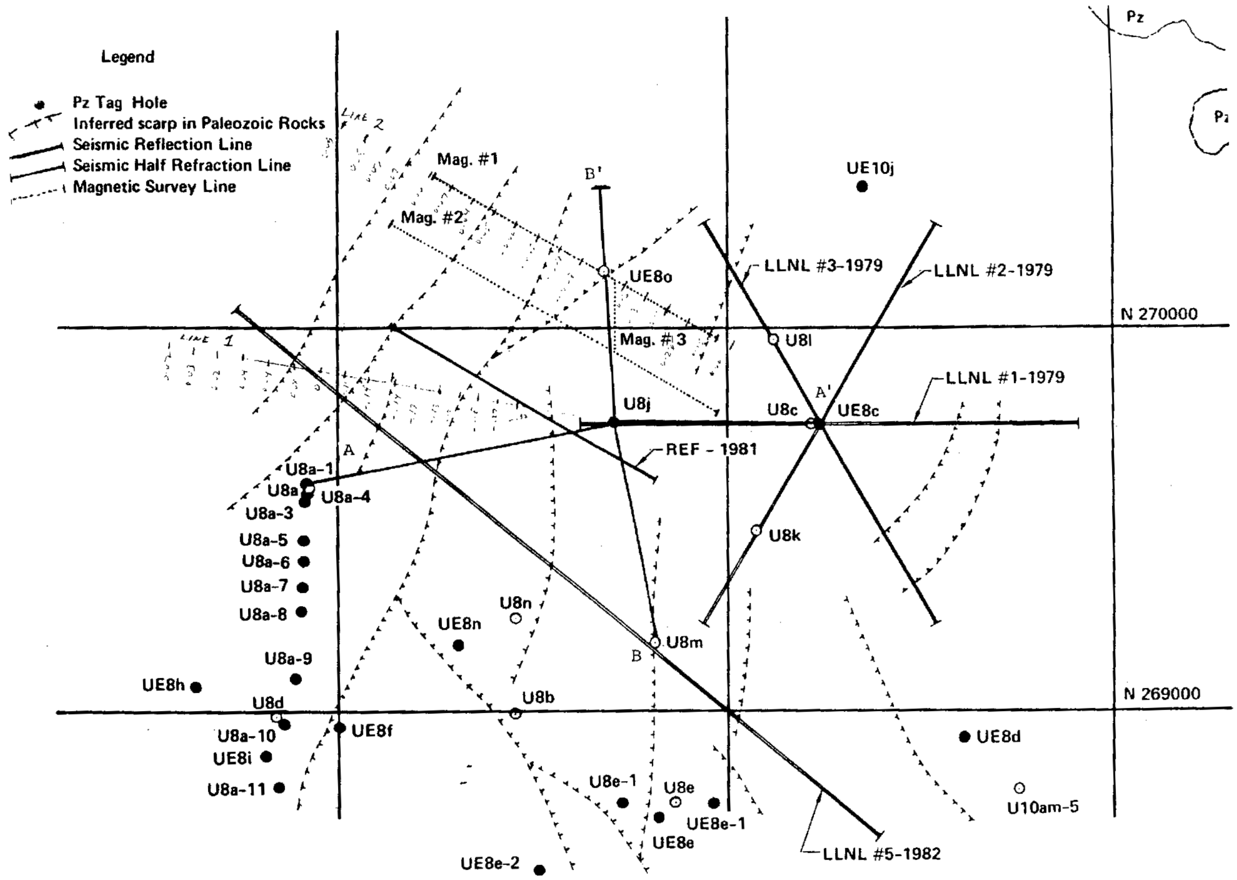

Figure 4. Locations of drill holes in Area 8, seismic and magnetic survey lines, and inferred fault locations at the Paleozoic surface determined form drill hole penetrations and seismic data interpretations.

The next several paragraphs provide a chronological summary of underground nuclear testing in Area 8. Table 1 shows test information, Table 2 shows collapse information, and Table 3 shows release information for these ten tests.

Underground nuclear testing began in Area 8 with the Discus Thrower test (U8a) sponsored by LANL in 1966. A number of exploratory holes were drilled nearby to understand geologic setting, in particluar the location of the Paleozoic surface. These holes were then instrumented to collect data from the test. Discus Thrower was detonated at a WP of 337 m below the surface in bedded tuff and had an announced yield of 22 kt (USDOE, 2000). As shown in the upper left of Figure 7, the test produced a number of surface effects when it collapsed to the surface about 53 minutes after detonation.

Subsequent to Discus Thrower, LLNL became the sponsor of Area 8 tests.

The Cyathus test in 1970 was detonated at a WP of 293 m depth in ash-fall tuffs and had an anounced yield of 8.7 kt (USDOE, 2000). As shown in the upper right of Figure 7, Cyathus produced few surface effects besides the crater when it collapsed to the surface about 26 minutes after detonation. While completely contained, Cyathus released radioactivity from the drilling platform during drillback operations (USDOE, 1996).

Baneberry was the second test in Area 8 in 1970. The WP at 278 m was in bedded tuff. Drilling of U8d encountered difficulties with sloughing attributed to montmorillonite clays, and at least eight successive cementing and re-drilling sequences were necessary to complete the emplacement hole. It was detonated at a WP of 278 m below the surface in bedded tuff and had an announced yield of 10 kt. Program operations for the Baneberry test proceeded normally until about 3.5 minutes after detonation, when a release of radioactivity detected offsite (USDOE, 2000) occurred from a surface fissure southwest of 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 H+2 hours, after which only a cloud of vapor could be seen drifting up from the portion of the fissure outside of the crater. This continued for nearly 24 hours. 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. A number of exploratory holes were drilled after the test, and significant hydrodynamic modeling was performed to understand the interaction of the shock wave with the geologic setting. The Baneberry venting was attributed to stronger coupling of energy into the ground than is normal for tests buried at that depth in Yucca Flat; the stronger coupling was due to high water content at shallow depth, which resulted from a unique, localized geologic environment. The AEC "Baneberry Summary Report" describes the analysis and conclusions of this study. Pawloski (2012a) provides a summary of activities related to the Baneberry release.

On September 27, 1978, eight years after Baneberry, Cremino and Cremino-Caerphilly were detonated simultaneously in U8e. Cremino had a WP of 210 m depth in alluvium and Cremino-Caerphilly had a WP of 420 m depth in bedded tuff. Each of these detonations had an announced yield of <20 kt (USDOE, 2000). A subsurface collapse to about 80 m occurred in about 30 minutes, terminating in alluvium. No surface effects were produced from these detonations.

Norbo was detonated in 1980 in ash-fall and bedded tuffs at a working point of 271 m below the surface. The test had an announced yield of <20 kt (USDOE, 2000). Emplacement hole U8c was originally drilled to 229 m depth in 1970, and deepened to 279 m in 1979. Nearby exploratory hole UE8c was drilled in 1976 to tag Paleozoic rock. LLNL's first seismic survey was undertaken at this site to better characterize the Paleozoic surface. Reflection and refraction data were collected on three radial lines centered on UE8c (Figure 4), and provided more confidence on the structural setting than in the past. Cross sections for this location are shown in Figures 5 and 6. Norbo experienced a subsurface collapse about 54 minutes after detonation. CLIPER data indicated the collapse probably proceeded to a depth of about 120 m, in alluvium, just above the lower rigid plug composed of coal tar epoxy (CTE). D-cable data indicate there was no stemming in the emplacement hole to a depth of 24 m. A CTE plug in the surface casing failed, probably within hours of the test, causing a release attributed to the prompt gas sampling system (USDOE, 1996). About 408 days after detonation, collapse to the surface was noted.

Seco was detonated in U8l on February 25, 1981. The WP was at 200 m depth in altered bedded tuff. The announced yield was <20 kt (USDOE, 2000). Seco experienced a subsurface collapse. No CLIPER data was available, and D-cable data was not processed because it was clear that no containment problems occurred. Lack of motion seen on instrumentation near the bottom rigid plug indicates subsurface collapse could not have proceeded above 120 m (bedded tuff). It is interesting to note that the Seco prospectus shows that the top of the Norbo chimney was at 67 m depth.

Vide was detonated in U8k on April 30, 1980, about two months after Seco. The WP was at 323 m depth in bedded tuff, and the announced yield was <20 kt (USDOE, 2000). CLIPER data indicate that a subsurface collapse to about 250 m occurred in about 54 minutes, terminating in bedded tuff. This depth is below the rigid bottom plug. Downhole pressure histories indicate a stemming fall to about 188 m depth. No surface effects were produced from this detonation. The Vide explosion served as a "seismic source" for a motion study at the ground surface, where numerous instruments were fielded to help define the Paleozoic surface. While completely contained, Vide released radioactivity from gas sampling operations (USDOE, 1996). The Vide prospectus states that Norbo did not collapse to the surface and that instrumentation in UE8c show subsurface collapse height to about 67 m depth.

Norbo collapsed to the surface 408 days after detonation. This correlates to a May 7, 1981 date. Other than a database entry, no records were found to describe this activity. A date of May 7 does not correlate with any detonation in Area 8, or any detonation at the NNSS. Aligote in U7bg on May 29, 1981 is the next test after the Norbo collapse date.

Frisco was detonated in U8m on September 23, 1982. The WP was at 323 m depth in bedded tuff, and the announced yield was 20-150 kt (USDOE, 2000). As shown in the lower right of Figure 7, the only surface effects the test produced was a surface crater when it collapsed about 30 minutes after detonation. While completely contained, Frisco released radioactivity from drillback activities (USDOE, 1996). The Frisco prospectus states that Norbo did not collapse to the surface.

Cottage was detonated in U8j on March 23, 1985 after a lengthy review process. It was detonated at a WP of 515 m depth in non-welded ash-flow tuff at an announced yield of 20-150 kt

(USDOE, 2000). As shown in the lower left of Figure 7, Cottage produced a number of surface effects when it collapsed to the surface in about 18 minutes.

The Kawich A test was detonated in U8n on December 9, 1988. This was the last underground nuclear test in Area 8. Simultaneous, same hole detonations Kawich A-Blue had a WP pf 369 m depth in bedded tuff and Kawich A-White had a WP of 384 m depth, also in bedded tuff. Both of these were safety tests, and each had an announced yield of <20 kt (USDOE, 2000). No collapse to the surface occurred, and no surface effects were produced from these detonations.

Table 1. Selected information for tests located near Norbo in U8c.

Hole Name	**U8a**	**U8b**	**U8d**	**U8e**	**U8c**	**U8l**	**U8k**	**U8m**	**U8j**	**U8n**
Test Name	**Discus Thrower**	**Cyathus**	**Baneberry**	**Cremino, Cremino-Caerphilly**	**Norbo**	**Seco**	**Vide**	**Frisco**	**Cottage**	**Kawich A-Blue, Kawich A-White**
Test Date[a]	5/27/66	3/6/70	12/18/70	9/27/78	3/8/80	2/25/81	4/30/81	9/23/82	3/23/85	12/9/88
WP Depth (m)	337	293	278	210, 420	271	200	323	451	515	369, 384
WP Rock	Bedded Tuff	Ash-fall Tuff	Bedded Tuff	Alluvium, Bedded Tuff	Ash-fall and Bedded Tuff	Altered Bedded Tuff	Bedded Tuff	Zeolitized Ash-flow Tuff	Non-welded ash-flow Tuff	Bedded Tuff, Bedded Tuff
Announced Yield (kt)[a]	22	8.7	10	<20, <20	<20	<20	<20	20-150	20-150	<20, <20
SDOB ($m/kt^{1/3}$)[b]	120	142	129	77, 155	100	74	119	85	97	136, 141
Calculated Cavity Radius (m)[c]	39	30	32	43, 36	40	44	39	70	67	38, 37
Hole Depth (m)	360	314	299	610	279	233	367	518	610	577
Water Level Depth (m)	661	611	649	588	639	646	635	583	627	540
Associated Holes	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, PS1A, PS1D, PS2D	PS1A, PS1AA	UE8d, PS1A, PS1AA, PS1AB, PS2A, PS2AA, PS2AC, PS2AD, PS2AE, PS3A, PS3AA, PS3AB, PS3ABC, PS3AD, PS5A, PS5AA	U8e#1, UE8e/Inst, UE8e #1, UE8e #1S, UE8e #2, PPS1A, PS2A, PS2AA	UE8c, PS1A, PS1AA		PS1A, PS2A	PS1A, PS1AA, PS1AB		UE8n
Site Characteristics Summary?	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Containment Data Report?	No	No	No	Yes	Yes	Yes	Yes	Yes	No	Yes

[a] USDOE, 2000
[b] Assuming the maximum of the announced yield range in USDOE (2000)
[c] Assuming the maximum of the announced yield range in USDOE (2000) and using the equation in Pawloski (1999)

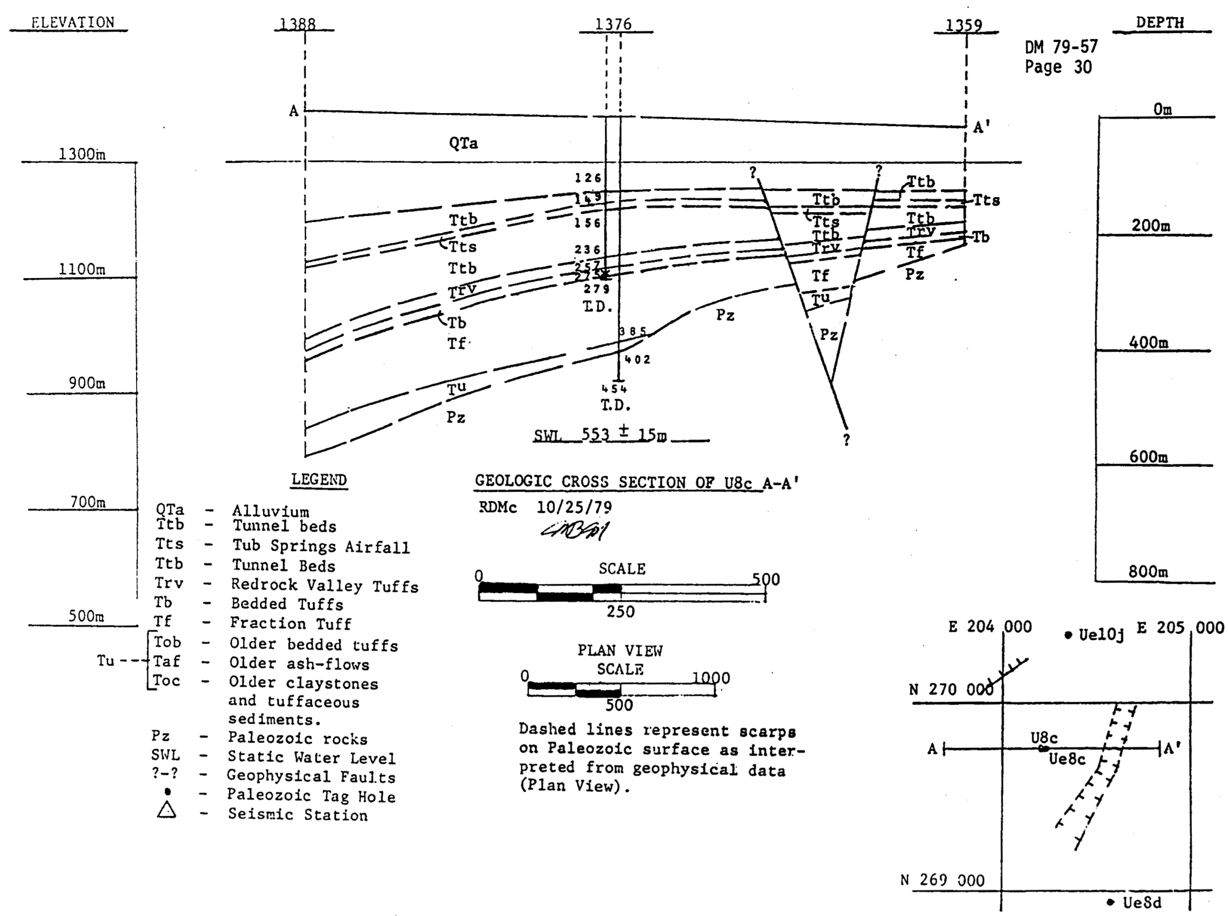

Figure 5. West-east cross section of the U8c site (Howard, 1979). Note that the stratigraphic nomenclature for the NNSS has been updated since this report was published.

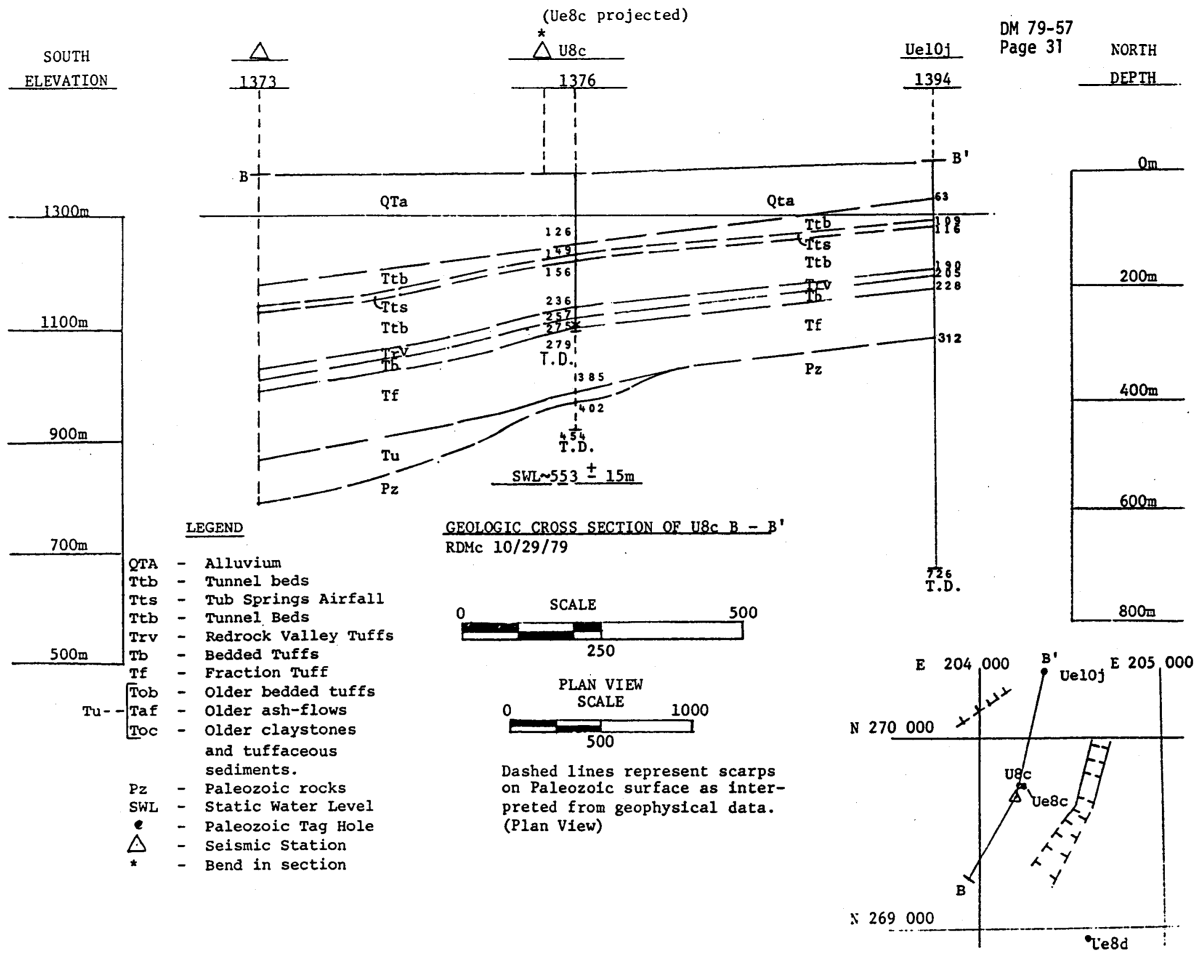

Figure 6. Southeast-north cross section of the U8c site (Howard, 1979). Note that the stratigraphic nomenclature for the NNSS has been updated since this report was published.

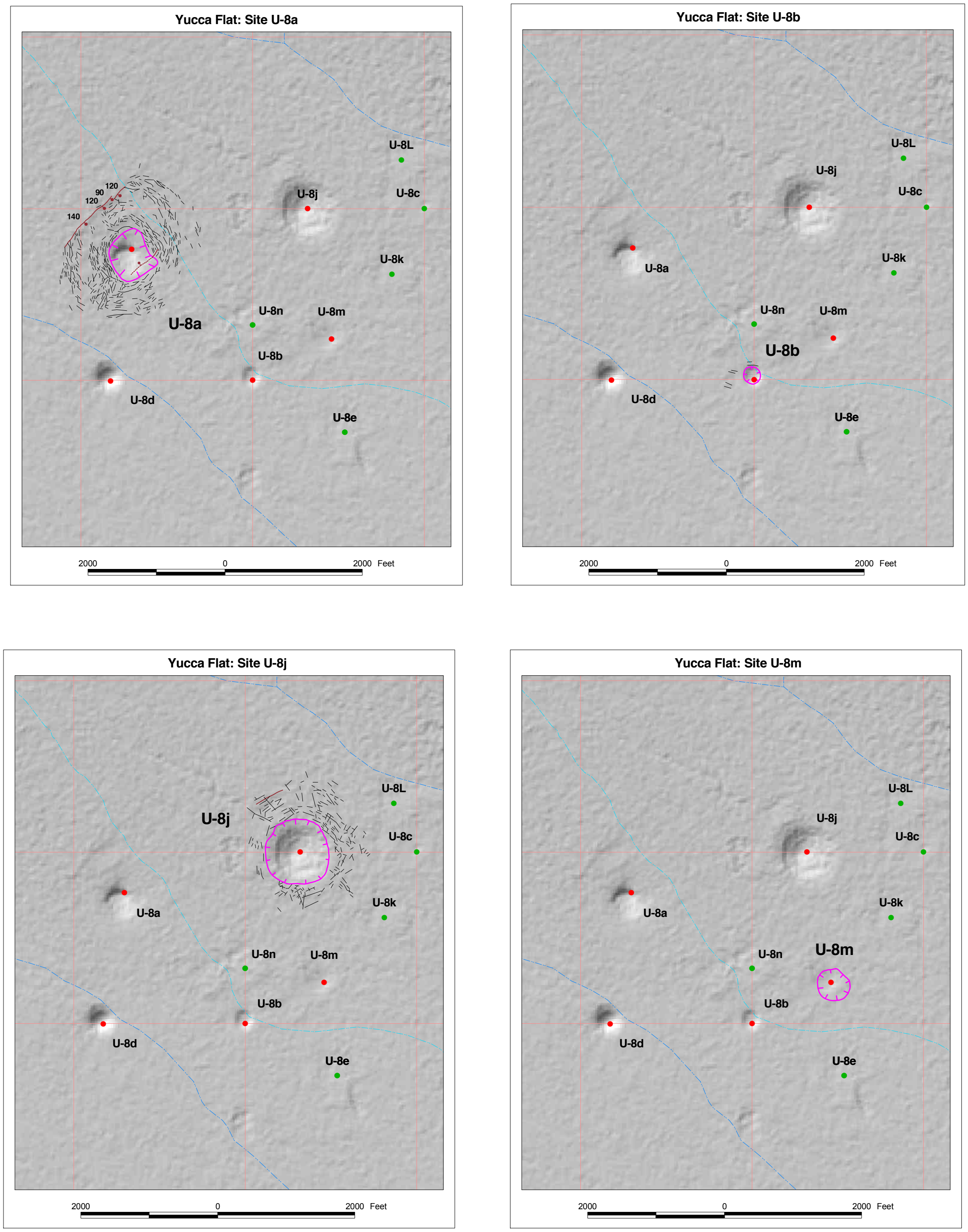

Figure 7. Surface effects from tests located near Norbo in U8c: Discus Thrower in U8a, Cyathus in U8b, Cottage in U8j and Frisco in U8m. Baneberry in U8d is shown in Figure 3. Norbo in U8c, Cremino and Cremino-Caerphilly in U8e, Vide in U8k, Seco in U8l, and Kawich A-Blue and Kawich A-White in U8n did not produce surface effects.

Evaluating Collapse of Tests in Area 8 and Implications for Ground Surface Stabillity

Why did six of ten tests in Area 8 collapse to the surface? And, why did Norbo in U8c proceed from what would have been considered a stable subsurface collapse to a surface collapse over a year after detonation?

- The SDOB rule of thumb for Yucca Flat states that tests with a SDOB below 165 $m/kt^{1/3}$ should collapse to the surface. As seen in Table 1, SDOBs for tests in Area 8 range from 74 to 155 $m/kt^{1/3}$, implying that every detonation should have collapsed to the surface. Collapse to the surface would have been predicted for Norbo with a SDOB of 100 $m/kt^{1/3}$. Olsen notes that there is a broad range associated with this rule of thumb. It is important to keep in mind that applying unclassified data is a known limitation, specifically using the maximum of the announced value, which can result in the possibility of skewing interpretations using the maximum announced yield.
- Another rule of thumb states that subsurface collapse has a chimney height of 5.5 Rc, +/- 2.0 Rc above the WP. Table 2 shows that all six tests that collapsed to the surface had values above 6.5 Rc. The three tests experiencing subsurface collapse all had low values (Kawich A detonations had no subsurface collapse height data) - Seco and Vide had very low collapse height values (1.8 Rc for both), and Cremino had values near 3-3.5 Rc. Collapse to the surface would have been predicted for Norbo using this rule of thumb. Again, it is important to keep in mind the known limitation of using the maximum of the announced yield value.
- Did site-specific geology affect collapse at these ten sites? Are there any layers that could be considered strong and possibly impede collapse to the surface? Figure 8 is a schematic correlating lithology at the ten tests sites in Area 8. Lithologies include alluvium (yellow), vitric and devitrified tuffs (green), altered tuffs (orange), and Paleozoic carbonate rocks (blue). WPs are labeled in red, collapse heights (as depth) in black, and predicted collapse heights, calculated at 5.5Rc, are shown as asterisks. It is important to note that tuffs in Area 8 are typically extra caldera ash-flow, ash-fall, and bedded tuffs. Welded tuffs are present only in a few holes where faulting has dropped younger stratigraphic units downward (a graben near U8n, U8m and U8e). If welded tuffs are present they are typically thin – less than 20 m thick. A review of bulk density logs from drill holes indicates that the bulk densities of tuffs above these WPs range from 1.45 to 1.8 Mg/m^3, and log character does not change rapidly. One can infer from this that no strong layers are present in the tuff section to terminate collapse based solely on rock density, which is assumed to correlate to rock strength. Alluvium in Area 8 displays a relatively high bulk density, ranging from 1.95 to 2.2 Mg/m^3. This density is relatively high, and could indicate strength in the alluviual units. Log character does not vary significantly over the alluvium, and when sample spacing is included, it is difficult to infer if strong layers are present. There are no records to determine if calcite cementation is present. Predicted collapse following the 5.5Rc rule of thumb shows that two tests would have collapsed to the surface (Cremino and Cremino-Caerphilly in U8e and Seco in U8l). Collapse for six of the ten tests would have terminated in alluvium (Baneberry in U8d, Discus Thrower in U8a, Cyathus in U8b, Frisco in U8m, Vide in U8k, and Norbo in

U8c). The remaining two would teminate in tuff (Kawich A-Blue and Kawich A-White in U8n and Cottage in U8j).

It is important to note that while there is confidence in making generalizations about the extent of the stratigraphic and lithologic units from the WP to the surface, we do not know much about the spatial variability of smaller scale features found within the drill holes, nor their continuity outside the drill holes.

- Can comparison of cavity diameter to collapse crater diameter indicate that collapse to the surface is complete? One might think that the cavity diameter should be the minimum collapse crater diameter at the surface, assuming the chimney connecting the cavity and crater would have straight sides from the WP depth to the ground surface. For the six tests that collapsed to the surface, five have crater diameters that are equal to or larger than the cavity diameter (Discus Thrower, Cyanthus, Baneberry, Frisco, and Cottage). Only Norbo has a smaller crater diameter when compared to cavity diameter.
- Does the relationship of collapse crater diameter to depth offer information about completeness of collapse? It is well known that collapse shapes vary – shallow bowls with sloping sides and cookie cutter shapes with steep sides tend to be the most common, particularly when alluvium is present. For the six tests that collapsed to the surface, the lowest crater diameter-to-depth ratio belongs to Norbo (3.0) when compared to Discus Thrower at 10, Cyathus at 8.3, Baneberry at 6.7, Frisco at 46, and Cottage at 7.2.

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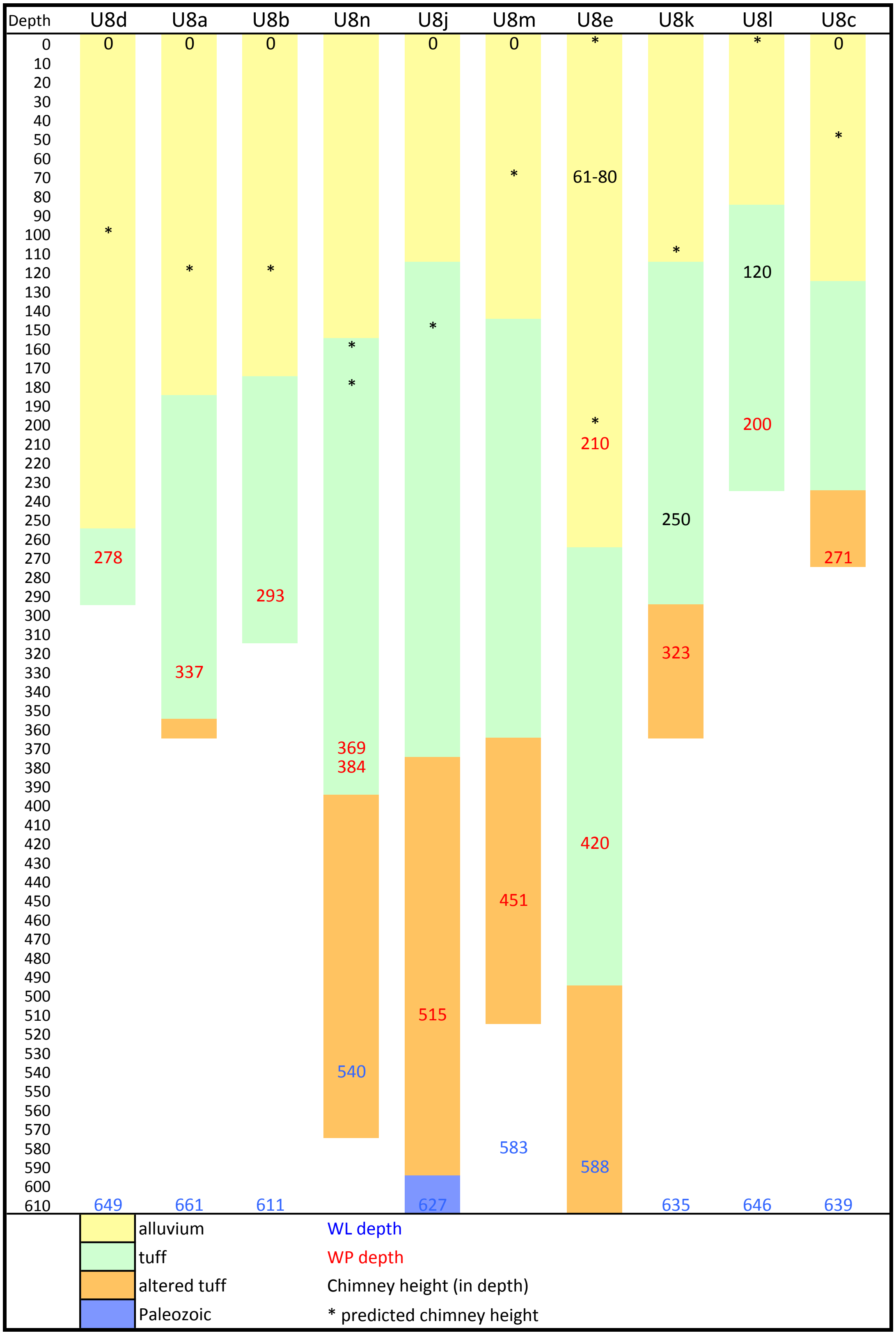

Figure 8. Schematic correlating lithology for the ten tests near Norbo in U8c.

Potential Issues at the Ground Surface

Five of the ten tests in Area 8 had releases associated with them, identified in *Radiological Effluents Released from U.S. Continental Tests 1961 through 1992* (USDOE, 1996), and shown in Table 3. Norbo had a release from the gas sampling system. Care should be taken to evaluate if any lingering effects are still present at the surface before surface work is initiated.

Conclusions

It is difficult to determine if the ground surface above the Norbo test in U8c is stable.

- Comparison of the calculated SDOB of 100 m/kt$^{1/3}$ to the SDOB rule of thumb (165 m/kt$^{1/3}$) using the maximum of the announced yield range indicates Norbo should have collapsed to the surface.
- Using the 5.5 Rc chimney height rule of thumb indicates Norbo should have experienced a subsurface collapse to 51 m, which is shallower than the initial subsurface collapse height measured at about 120 m depth.
- Norbo experienced a subsurface collapse, terminating in alluvium. It was stable for 408 days, even with two tests being detonated nearby (Vide and Seco).
- Eight tests in Area 8 that had collapse times measured indicate that collapse, both subsurface and to the surface, proceeded quickly after detonation. The maximum time is 54 minutes, and six of the eight collapsed within 30 minutes. This includes the initial Norbo subsurface collapse time (54 minutes).
- There is no correlation to any other underground nuclear test or other significant activity to explain why Norbo collapsed to the surface a little over one year later.

From a Containment point of view, it is clear that the dynamics of cavity collapse are complete at all ten of these tests. It seems likely that the possibility of collapse to the surface is complete. It seems reasonable that the current subsurface and surface collapse area configurations should be considered stable. The ground surface above all of these tests has not changed over time, so it seems reasonable to conclude that the current configurations are stable. However, we find it hard to explain why Norbo experienced a subsurface collapse, and then collapse continued to the surface a little over a year later, with no apparent cause. The secondary collapse behavior at Norbo is different from other tests in Area 8, and different from almost all tests at the NNSS. Few underground nuclear tests exhibit such late surface collapse activity.

Significant ground motion has occurred due to underground nuclear testing subsequent to Norbo in 1980. It has been 24 years since any nuclear testing in Area 8, and 20 years since any nuclear testing at the NNSS. One might think that the current configuration is sufficiently stable to permit access to the ground surface near U8c. However, we have much less confidence in this evaluation than normal. We have evaluated crater stability produced from cavity collapse, and have not considered later erosion effects. We rely on NSTec and DOE/NNSA/NSO to make decisions concerning safety issues related to reentering the area above Norbo.

Table 2. Selected collapse information for tests near Norbo in U8c.

Hole Name	U8a	U8b	U8d	U8e	U8c	U8l	U8k	U8m	U8j	U8n
Test Name	**Discus Thrower**	**Cyathus**	**Baneberry**	**Cremino, Cremino-Caerphilly**	**Norbo**	**Seco**	**Vide**	**Frisco**	**Cottage**	**Kawich A-Blue, Kawich A-White**
Test Date[a]	5/27/66	3/6/70	12/18/70	9/27/78	3/8/80	2/25/81	4/30/81	9/23/82	3/23/85	12/9/88
WP Depth (m)	337	293	278	210, 420	271	200	323	451	515	369, 384
WP Rock	Bedded Tuff	Ash-fall Tuff	Bedded Tuff	Bedded Tuff, Bedded Tuff	Ash-fall and Bedded Tuff	Altered Bedded Tuff	Bedded Tuff	Zeolitized Ash-flow Tuff	Non-welded Ash-flow Tuff	Bedded Tuff, Bedded Tuff
Announced Yield (kt)[a]	22	8.7	10	<20, <20	<20	<20	<20	20-150	20-150	<20, <20
SDOB ($m/kt^{1/3}$)[b]	120	142	129	77, 155	100	74	119	85	97	136, 141
Calculated Cavity Radius (m)[c]	39	30	32	43, 36	40	44	39	70	67	38, 37
Collapse Type	Surface	Surface	Surface	Subsurface	Surface	Subsurface	Subsubsurface	Surface	Surface	Subsurface
Collapse Height (m depth)	0	0	0	61-80	0	120	250	0	0	No data
Collapse Height (Rc)	8.6	9.8	8.7	61 m-3.5, 10.0; 80 m-3.0, 9.4	6.8	1.8	1.9	6.5	7.7	
Collapse Height at 5.5 Rc (m depth)	122	128	102	0, 222	51	0	108	66	146	160, 180
Collapse Time (min)	52.6	26.0	16.5	29.7	587,520		53.5	30.0	18.2	
Surface Collapse Crater Diameter (m)	200	75	142		19			139	273	
Surface Collapse Crater Depth (m)	20	9	23		6			5	38	

[a] USDOE, 2000
[b] Assuming the maximum of the announced yield range in USDOE (2000)
[c] Assuming the maximum of the announced yield range in USDOE (2000) and using the equation in Pawloski (1999)

Table 3. Selected release information for tests near Norbo in U8c.

Hole Name	**U8a**	**U8b**	**U8d**	**U8e**	**U8c**	**U8l**	**U8k**	**U8m**	**U8j**	**U8n**
Test Name	**Discus Thrower**	**Cyathus**	**Baneberry**	**Cremino, Cremino-Caerphilly**	**Norbo**	**Seco**	**Vide**	**Frisco**	**Cottage**	**Kawich A-Blue, Kawich A-White**
Test Date[a]	5/27/66	3/6/70	12/18/70	9/27/78	3/8/80	2/25/81	4/30/81	9/23/82	3/23/85	12/9/88
WP Depth (m)	337	293	278	210, 420	271	200	323	451	515	369, 384
WP Rock	Bedded Tuff	Ash-fall Tuff	Bedded Tuff	Bedded Tuff, Bedded Tuff	Ash-fall and Bedded Tuff	Altered Bedded Tuff	Bedded Tuff	Zeolitized Ash-flow Tuff	Non-welded Ash-flow Tuff	Bedded Tuff, Bedded Tuff
Announced Yield (kt)[a]	22	8.7	10	<20, <20	<20	<20	<20	20-150	20-150	<20, <20
SDOB ($m/kt^{1/3}$)[b]	120	142	129	77, 155	100	74	119	85	97	136, 141
Release Detected[c]	No	Onsite only	Onsite only	No	Onsite only	No	Onsite only	Onsite only	No	No
Species[c]		I, Xe	Xe, H, Kr, I, tritiated water		H, Kr		Xe, H, Kr, Cs	Xe		
Comments[c]		Drillback release from the drilling platform	Drillback releases from the postshot ventilation line		Test release from gas sampling system; controlled gas sampling containment tank release		Release during gas sampling operations; second gas sampling release from containment task	Fourteen intermittent releases from drillback activities		

[a] USDOE, 2000
[b] Assuming the maximum of the announced yield range in USDOE (2000)
[c] USDOE, 1996

References

Bechtel Nevada, 2006, *A Hydrostratigraphic Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Correction Action Unit 97: Yucca Flat-Climax Mine, Lincoln and Nye Counties, Nevada*, Bechtel Nevada, Las Vegas, Nevada, DOE/NV/11718-1119.

Fernald, A.T., 1973, *Some Alluvium Characteristics, Northwest Yucca Flat, Nevada Test Site*, United States Geologic Survey, Denver, CO, Informal Letter Report November 13, 1873.

Grasso, D., 2003. *GIS Surface Effects Map Archive*, Nevada Test Site, Nevada, USGS OFR-03-051 (searchable database at http://pubs.usgs.gov/of/2003/151/Archive/Start.htm).

Hearst J. R and J.L. Wagoner, 1988, *U8n Site Characteristics Report*, Lawrence Livermore National Laboratory, Livermore, CA, CP 88-101.

Heinle, R. and T. Stubbs, 1994, *Kawich-A Containment Data Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-120477.

Howard, N.L., 1980 and 1981, *U8k Preliminary Site Characteristics Summary*, Lawrence Livermore National Laboratory, Livermore, CA, DM 80-59 and DM-81-9.

Howard, N.W., 1980, *U8l Preliminary Site Characteristics Summary*, Lawrence Livermore National Laboratory, Livermore CA, DM 80-60.

Olsen, C.W., 1993, *Site Selection and Containment Evaluation for LLNL Nuclear Events*, Lawrence Livermore National Laboratory, Livermore CA, UCRL-JC-113334.

Pawloski, G.A., 1999, *Development of Phenomenological Models of Underground Nuclear Tests on Pahute Mesa, Nevada Test Site – Benham and Tybo*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-136033.

Pawloski, G.A., 2012a, *Evaluation of Cavity Collapse and Surface Crater Formation for Selected Lawrence Livermore National Laboratory Underground Nuclear Tests – 2011, Part 2*, Lawrence Livermore National Laboratory, Livermore, CA, LLNL-TR-525400.

Pawloski, G.A., 2012b, *Evaluation of Cavity Collapse and Surface Crater Formation at the Salut Underground Nuclear Test in U20ak, Nevada Test Site, and the Impact of Stability of the Ground Surface*, Lawrence Livermore National Laboratory, Livermore, CA, LLNL-TR-553813.

Stubbs, T. and R. Heinle, 1995, *Norbo Containment Data Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-123238.

Stubbs, T. and R. Heinle, 1996, *Frisco Containment Data Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-125016.

Stubbs, T. and R. Heinle, 1996, *Vide Containment Data Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-125022.

Stubbs, T. and R. Heinle, 1998, *Cremino Containment Data Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-131714.

Stubbs, T. and R. Heinle, 1995, *Norbo Containment Data Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-123238.

United States Atomic Energy Commission, *Baneberry Summary Report*, May 1971.

USDOE (U.S. Department of Energy), 2000, *United States Nuclear Tests July 1945 through September 1992*, U.S. Department of Energy, Nevada Operations Office, Las Vegas, NV, DOE/NV-209, Rev 15.

USDOE (U.S. Department of Energy), 1996, *Radiological Effluents Released from U.S. Continental Tests 1961 through 1992*, U.S. Department of Energy, Nevada Operations Office, Las Vegas, NV, DOE/NV-317, Rev 1.

Wagoner, J.L. and N.W. Howard, 1984, *U8j Preliminary Site Characteristics Summary*, Lawrence Livermore National Laboratory, Livermore, CA, CP 84-117.

Wagoner, J.L., 1982, *U8m Preliminary Site Characteristics Summary*, Lawrence Livermore National Laboratory, Livermore, CA, DM 82-32.

Wagoner, J.L., 1985, *Geology of the U8n Emplacement Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20344.