The Silent Canyon Caldera— A Three–Dimensional Model as part of a Pahute Mesa – Oasis Valley, Nevada, Hydrogeologic Model

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Open-File Report 01-297
Version 1.0

http://geopubs.wr.usgs.gov/open-file/of01-297/

2001

Manuscript approved August 29, 2001

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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Abstract

A 3-dimensional caldera model based on gravity inversion, drill hole data and geologic mapping offers the framework for a hydrogeologic evaluation of the Silent Canyon caldera in the central part of Pahute Mesa, Nevada.

It has been recognized for several decades that the central part of Pahute Mesa is the site of a buried caldera called the Silent Canyon caldera. Conceptually the structural framework of the Silent Canyon caldera is based on the idea of collapse of the caldera roof over a shallow magma chamber to form a structural basin following violent volcanic eruptions. Calderas are common in certain volcanic regions of the world and most well exposed calderas are broadly similar to each other, particularly the arcuate or circular shape of their collapse depression. There are other reasons for modeling the Silent Canyon caldera as a circular feature in addition to knowledge that calderas throughout the world are generally circular features. The Silent Canyon caldera is the site of one of the largest gravity lows in the Western United States, indicating a thick accumulation of low density rocks such as lavas and tuffs - a fact confirmed by drilling on Pahute Mesa. This gravity low is bowl-shaped and the uppermost volcanic units on Pahute Mesa form a circular outcrop pattern of inward dipping tuff interpreted to be the result of their filling the upper part of the bowl-shaped depression. Together these features are consistent with, and indicative of, a circular collapse structural model for the Silent Canyon caldera. The collapse depression of the Silent Canyon caldera, bounded by arcuate faults, is filled with as much as 6 km (19,800 ft.) of volcanic and sedimentary rocks that are considerably less dense than the underlying and surrounding basement rocks. The boundary surface between less dense caldera fill and more dense basement is modeled as the caldera ring fault. Rocks in the upper part of the caldera fill are penetrated by drilling and the drill hole data are the basis for 3-dimensional computer modeling of the thickness and distribution of the rock units. The displacement on younger N-S faults that cut the caldera is also determined by offset of the computer derived surfaces defined by the drill hole intercepts of stratigraphic units.

Silent Canyon caldera

Basis for 3-dimensional model

It has been recognized for several decades that the central part of Pahute Mesa is the site of a buried caldera called the Silent Canyon caldera (Noble et al., 1968; Orkild et al., 1968; Healey.1968; and Orkild et al., 1969). Conceptually the structural framework of the Silent Canyon caldera (SCC) is based on the idea of a structural collapse of the caldera roof over a shallow magma chamber to form a collapse basin following violent volcanic eruptions. Calderas are common in certain volcanic regions of the world and most well exposed calderas are broadly similar to each other, particularly the arcuate or circular shape of their collapse depression.

Calderas form above shallow cupolas of magma that rise above the tops of a batholithic complex. Where the cupola intrudes near the surface, a violent eruption occurs and the roof of the evacuated magma chamber collapses. The original shape of the roof failure is defined by arcuate ring faults that dip steeply into the underlying cupola. These ring faults define the structural margin of the caldera and rocks inside the ring fault subside in a piston-like manner to form a circular basin. Some variations in caldera geometries have been summarized by Lipman (1997) but arcuate faults form around all or parts of the collapse structure in all calderas.

There are other reasons for modeling the Silent Canyon caldera (SCC) as a circular feature in addition to knowledge that calderas throughout the world are generally circular features. The SCC is the site of one of the largest gravity lows in the Western United States, indicating a thick accumulation of low density rocks such as lavas and tuffs – a fact confirmed by drilling on Pahute Mesa. This gravity low is bowl-shaped (fig. 1a) and the uppermost SCC volcanic units on Pahute Mesa form a circular outcrop pattern of inward dipping tuff (fig. 2) interpreted to be the result of their filling the upper part of the bowl-shaped depression (Orkild et al., 1969 ; Byers et al.,1976). Together these features are consistent with, and indicative of, a circular collapse structural model for the SCC.

Basement surface

The isostatic residual gravity field of the region shown in figure 1a is based on about 4,000 gravity measurements (Mankinen et al., 1999). The overall distribution of gravity stations is roughly one station within 0.7 km^2 on the average, although denser coverage exists within the area of the SCC. Mankinen et al., (1999) described the data reduction process to obtain the Bouguer gravity anomaly. The isostatic residual anomaly was calculated using a reduction density of 2,670 kg/m^3, crustal thickness of 30 km, and a mantle-crust density contrast of 350 kg/m^3 (see Simpson et al., 1986). All data were gridded at a spacing of 1 km using a minimum curvature algorithm of Webring (1981).

To the first order, the isostatic residual gravity field reflects the pronounced contrast between dense basement rocks (about 2,670 kg/m^3) and significantly less dense (generally < 2,500 kg/m^3) younger volcanic and sedimentary rocks. The prominent gravity low (fig. 1a) over the SCC delineates the thick, anomalously low-density volcanic caldera fill (Healey, 1968; Ferguson et al., 1994; Grauch et al., 1997; Hildenbrand et al., 1999). In contrast, granitic resurgent domes (density about 2670 kg/m^3) under Timber Mountain and Black Mountain appear to produce gravity highs (Kane et al., 1981; Grauch et al., 1997). Using the gravity inversion method derived by Jachens and Moring (1990; modified to include drill hole data), the isostatic residual anomaly is separated into a basin field and a basement field. The basin gravity field reflects variations in thickness and density of low-density Tertiary volcanic and sedimentary rocks. The basement gravity field reflects changes in density related to lithologic variations within the denser pre-Tertiary rocks or dense Tertiary granitic intrusions. In the gravity inversion process, the density of basement varies horizontally but the density of basin-filling deposits is fixed using a representative density versus depth relationship. Knowledge of the thickness of low density rocks (outside the SCC) and of basement rock types and densities based on drill hole information constrains the calculations. Refer to Hildenbrand et al., (1999) for details on the generation and constraints of the basin thickness data shown in figure 1a.

In general, basement is shallower outside the caldera complex along the western and southern parts of the study area. The basement descends to great depths beneath the SCC.

Density-depth functions

The accuracy of the thickness calculation of the basin filling rocks depends primarily on how accurately the modeled rock densities match the actual rock densities. The Tertiary rocks are almost entirely of volcanic origin (although thin sedimentary deposits are found at many places in the caldera). Complicating the task of selecting representative densities at a particular depth is the significant variation in density related to compaction, degree of welding and alteration of the ash-flow tuffs, to structure, and to water saturation. Because density generally increases with depth due to compaction, a layered density model is assumed for the Cenozoic deposits, although the lenticular nature of the volcanic rocks is acknowledged.

Based on deep-drill hole gravimeter studies and drill hole density logs from moderately deep and deep drill holes in the region of the Southwestern Nevada Volcanic Field (SWNVF), Hildenbrand et al., (1999) used a density-depth relation for the Cenozoic basin fill and basement shown as model A (table 1) to derive the basement depths in figure 3. Although this relationship may be a reasonable approximation for the large region shown in figure 1a, it may lead to significant errors in more local areas. For example, anomalously low-density tuff bodies are observed beneath Pahute Mesa. Drill hole gravimeter measurements in the SCC (Ferguson et al., 1994; R.G.Warren, personal communication, 1999) indicate densities of 2100 kg/m^3 extending in many areas to depths of over 3,300 ft (1,000 m). In such situations calculated basement depths in figure 1b will be overestimated. Thus for this study a different density-depth relation for the SCC area was necessary. Several models were considered and are shown in table 1.

A careful analysis of deep drill hole data outside the SCC (Hildenbrand et al.,1999) and of a large drill hole data base of density values from R.G.Warren (personal communication, 1999) for the SCC area results in using the same density-depth relationship to depths of 1,980ft (600 m) for all models (table 1). Below 1,980 ft (600 m) the basin fill within the SCC is likely greater than, or equal to, 2100 kg/m^3, although less dense than the rocks outside the caldera (assumed to be represented by model A). Models B through E are considered representative of the possible range of general density distributions for rocks within the SCC. To understand the sensitivity of the basement depths to changes in the depth-density function, maximum depth to basement and apparent basement depth at drill hole Ue20f (fig. 3) were determined for all models and are shown in table 1. At a depth of about 13,743 ft (4.2 km) Ue20f bottomed in relatively low density volcanic rocks.

General comments on the depth results shown in table 1 are: (1) basement depths are sensitive to the densities assumed below 1,980 ft (0.6 km) where our knowledge is limited, (2) models B and E provide reasonable basement depths at Ue20f, which bottomed in volcanic rock at 13,743 ft (4.2 km) and (3) a viable density-depth function can only be derived intuitively by our knowledge of rock types and densities inside and outside the caldera that are predicted at depth within the SCC.

Our knowledge of rock densities at depth (> 6,600 ft or 2 km) is based on limited data from deep drill holes (e.g., Hildenbrand et al., 1999; R.G. Warren, personal communication, 1999). Based on these data and due to expected high pressures and temperatures at depth, one would not expect substantial volumes of low density volcanic rocks (< 2450 kg/m^3) at depths greater than 6,600 ft (2 km). A density-depth function depicting volcanic rock of density of about 2100 kg/m^3 extending to depths of 6,600 ft (2 km) is also unlikely (because such a large volume of these unusually low density rocks has not been observed in any drill hole in southern Nevada). Thus models C and D are considered unrealistic. Moreover, models C and D lead to calculated basement depths at Ue20f much shallower than the known depth of volcanic rocks. Both models B and E lead to similar, reasonable solutions and possess densities that are defensible based on drill hole density data. Models A and E were chosen to represent the density distributions outside and within the SCC, respectively.

Table 1. Density-depth functions used to determine the thickness of basin-filling deposits and calculated depths near and at drill hole Ue20f.

Depth Range	Density (kg/m^3) for 5 models				
	A	B	C	D	E
0.0–0.2 km (0.0-660 ft)	1900	1900	1900	1900	1900
0.2–0.6 km (660-2000 ft)	2100	2100	2100	2100	2100
0.6–1.2 km (2000-4000 ft)	2300	2100	2100	2100	2100
1.2–1.5 km (4000-5000 ft)	2450	2300	2100	2100	2100
1.5–2.0 km (5000-6600 ft)	2450	2300	2100	2100	2300
>2.0 km (>6600 ft)	2450	2450	2450	2300	2450
Max. Depth	8.9 km (29,370 ft)	6.6 km (21,780 ft)	5.4 km (16,830 ft)	3.8 km (12,540 ft)	6.2 km (20,469 ft)
Ue20f depth	6.8km (22,440 ft)	4.5 km (14,850 ft)	3.3km (10,890 ft)	2.7 km (8,910 ft)	4.3 km (14,190 ft)

Basin geometry

The basement surface in the region of the SCC (figure 3) was derived using the two density-depth models (models A and E, table 1). To successfully merge the two depth data it was necessary to define a zone dividing regions outside and inside the caldera where no depth values were assigned. Depth values were calculated using a minimum curvature algorithm that utilized the depths based on the low-density model E inside the zone of no depth values (inside the caldera) and depth values from the high-density model A were used outside the zone of no depth values (outside the caldera).

The resulting basement surface in figure 3 indicates that the estimated average thickness of the basin fill is about 4.5 km (14,850 ft.) and that the maximum thickness may exceed 6 km (19,800 ft.).

Caldera fault

Ring faults of the SCC are deeply buried by younger volcanic units that lap over the caldera collapse structure and fill the topographic depression formed by collapse (fig. 4). However, the general area of subsidence is well documented by the drill holes that penetrate caldera-filling rocks within this subsidence basin. The outline of the topographic basin is indicated by the circular outcrop pattern of the Timber mountain Group tuffs (fig. 2). The SCC margin on the west is completely buried by Thirsty Canyon Group tuffs, the youngest rocks in the area. The structural margin (ring faults) of the caldera, thus, must be determined by indirect means.

Geologic studies indicate that where caldera outlines are well expressed by geologic features, gravity profiles usually reveal the structural margins of the caldera as the boundary between lower density caldera fill and higher density basement, or country rock (Hildenbrand et al., 1999). The location and approximate geometry of the SCC caldera margin can be determined by such indirect geophysical methods.

Gravity analyses estimate the location of the structural margin, slope of the margin, and depth of the basin beneath the nearly horizontal upper welded tuffs that fill the topographic basin above the caldera ring fractures (fig. 2). Extrapolation of this gravity surface upward toward the outer topographic edge of the basin, as defined by the outcrop pattern of the Timber Mountain

Group tuffs, defines the upper part of the collapse structure. The SCC ring fault extends upward above the gravity interface several thousand meters to the level of the Bullfrog Tuff, the youngest unit erupted from the Silent Canyon caldera (SCC). Tuffs older than the ring fault (Bullfrog Tuff and older units) partially fill the caldera and are overlain by younger caldera-filling rocks from sources other than the SCC. The older tuffs outcrop outside the extrapolated upper edge of the caldera ring fault at a number of places in the SWNVF. The crenulated, steeply dipping, oval- shaped surface between high- and low- density rocks is assumed to be the youngest ring fault at the margin of the caldera (fig. 5). Older caldera faults within the SCC that are partially or completely destroyed are not clearly revealed by the gravity inversion analysis. Because of the great depth of the high/low density surface (>10,000 ft; [3,000 m]), the inverted gravity data will likely be unable to resolve the many individual fault surfaces that collectively form the ring fault structure and subsequently,the caldera ring fault is modeled as a single, smooth, continuous surface (fig. 5).

North - South trending faults

More than 80 mapped faults with surface traces greater than 1/2 mile (800 m) cut volcanic rocks in the central part of Pahute Mesa (fig.2). All of these faults are N-S trending, high-angle-normal- faults and about two-thirds of them are down-dropped to the west. Twelve major faults with the greatest offset were selected for use in the 3-D caldera model of the SCC (fig. 6). Of the twelve faults several have measured offset of as much as 500 ft. (150 m), but most of them have less than half this amount (Orkild et al., 1969; Blankennagel and Weir, 1973). All are normal faults down-dropped on the west. The twelve faults, from west to east are:

NAME	AMOUNT OF OFFSET AT THE SURFACE
Handley	~ 100 ft. (30m)
West Purse	~ 100 ft. (30 m)
Purse	~ 100 ft. (30m)
West Boxcar	~ 200 ft. (60m)
Boxcar	~ 200 ft. (60 m)
West Greeley	~ 500 ft. (150 m)
East Greeley	~ 100 ft. (30 m)
unnamed fault (fault A, fig. 6)	~100 ft. (30 m)
East Estuary	~ 200 ft. (60 m)
Almendro	~ 500 ft. (150 m)
Scrughan Peak	~ 500 ft. (150m)
Split Ridge	~ 100 ft. (30 m)

The surface traces of these faults, digitized from the geologic map of Wahl et al. (1997), were extended downward and are shown to dip 80^0 to the west. The depth to which these faults extend was determined by a three step process: (1) extending all of the faults to the base of the model (5 km), (2) fitting horizon surfaces to the data points (drill hole intercepts) of each hydrostratigraphic unit and, (3) terminating the faults at the depths where unit horizon surfaces on either side of the fault showed no offset or offset in the opposite sense of the known slip-direction. The drill hole intercept points were fitted for each horizon (hydrostratigraphic surface) on either side of the fault, and the offsets produced by the extrapolation of the data to the fault were examined. Fault offsets were evaluated for magnitude, direction, and consistency with depth. Faults were terminated where offsets decreased to negligible values at depth or where offsets produced the incorrect sense of motion as determined by surface offset. Most of the faults showed no offset or inconsistent offset at depth. Only the West Greeley fault is warranted by stratigraphic offset to be as deep as the Pre-Belted Range composite unit, the deepest unit reached by drilling.

Hydrostratigraphy

The Tertiary rocks in and near the Nevada Test Site (NTS) are classified hydrologically on the basis of their lithologic properties including degree of crystallization, grain size and sorting, compaction, welding (for tuffs), secondary mineralization, and fracturing. A comprehensive evaluation of the hydrologic characteristics of these rocks is in Laczniak et al.(1996) and Drellack and Prothro (1997). For the SCC hydrogeologic 3-D model, 47 Quaternary and Tertiary stratigraphic units shown on the geologic map of Wahl et al.(1997) or encountered in drill holes on Pahute Mesa, and classified by Warren et al.(1999), are combined or split according to their hydrologic properties into three hydrostratigraphic types- - aquifers, confining units, and composite units (table 2). The composite unit, a name first used by Drellack and Prothro (1997) contains both aquifers and confining units that are local in extent and are too small or limited to separate on the scale of the model. In the SCC some units are categorized as composite units because they change from aquifer to confining unit or visa versa, due to compaction, welding, alteration or other hydrologic altering processes across relatively short distances within the caldera.

Table 2 lists the 12 hydrostratigraphic units used in the 3-D model of the SCC and the stratigraphic or rock units from which they are derived. These rocks comprise the less dense (< 2.45 kg/m^3) caldera-fill as defined by gravity measurements (see density-depth functions, table 1). The more dense basement (2.67 kg/m^3) beneath the caldera is modeled as a subvolcanic intrusive dome with inliers of Paleozoic and Proterozoic rock and is considered to be a single hydrostratigraphic confining unit.

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Table 2 Stratigraphic and hydrostratigraphic units used in the 3-D model of the Silent Canyon caldera (SCC). A is aquifer, CU is confining unit, and CM is composite unit. Unit identifications are from Warren et al., 1999.

ABOVE BASEMENT

Stratigraphic unit	Source	Hydrostratigraphic unit
Alluvium	local sources	
Thirsty Canyon Group	Black Mountain caldera	
Trail Ridge Tuff		
Pahute Mesa Tuff		
Rocket Wash Tuff		
comendite of Ribbon Cliff		
Volcanics of Fortymile Canyon	local sources	
Beatty Wash Formation		
tuff of Scotch		Younger volcanics composite unit
rhyolite of Beatty Wash		YVCM
rhyolite of Chucar Canyon		
Timber Mountain Group	Timber Mountain caldera	
Ammonia Tanks Tuff		
tuff of Crooked Canyon		
rhyolites of Tannenbaum Hill		
Rainier Mesa Tuff		
andesite tephra		
rhyolite of Fluorspar Canyon		
tuff of Holmes Road		
dacite tephra		
basalt of Tierra		
rhyolite of Windy Wash		
Paintbrush Group	Claim Canyon caldera	
rhyolite of Benham		Benham aquifer BA
Tiva Canyon Tuff		
rhyolite of Delirium Canyon		Tiva Canyon aquifer TCA
rhyolite of Echo Peak		Lower Paintbrush confining unit
rhyolite of Silent Canyon		LPCU
Topopah Spring Tuff		Topopah Spring aquifer TSA
Calico Hills Formation		Calico Hills tuff and lava composite unit CHCM

Crater Flat Group		
rhyolite of Inlet		Inlet aquifer IA
tuff of Pool tuff of Jorum rhyolite of Sled rhyolite of Kearsarge latite of Grimy Gulch		Crater Flat tuff and lava composite unit CFCM
Bullfrog Tuff Tram Tuff	Silent Canyon caldera complex	Bullfrog Tuff confining unit BFCU
Belted Range Group Dead Horse Flat Formation Grouse Canyon Tuff	Silent Canyon caldera complex (?)	Belted Range lava and tuff aquifer BRA
comendite of Split Ridge comendite of Quartet Dome	Silent Canyon caldera complex (?)	
Tram Ridge Group rhyolite of Picture Rock Tunnel Formation dacite of Mount Helen volcanics of Oak Spring Butte Redrock Valley Tuff tuff of Twin Peaks tuff of Argillite Wash rhyolite of the Hump	local sources	Belted Range and pre-Belted Range volcanic and sedimentary rock composite unit PBRCM
BASEMENT		
Silent Canyon caldera complex intrusive		Silent Canyon caldera complex intrusive rock confining unit SCICU

Figure 1. (a) Isostatic residual gravity anomaly of the central part of the SW Nevada volcanic field (SWNVF) from Hildenbrand and others (1999). Anomalies express to first order the average density of the middle and upper crust. Small crosses represent locations of gravity stations. Letters denote: TMCC–Timber Mountain caldera, SCC–Silent Canyon caldera , and the BMC–Black Mountain caldera.
(b) 3D view of the basement surface beneath the central part of the SNVF (from Hildenbrand and others, 1999). Note the deep ovoid basin beneath the Silent Canyon caldera (highlighted by the white arrow). No vertical exaggeration.

Figure 2. Geologic map of the central part of Pahute Mesa; centrally located in this area is the Silent Canyon caldera.

Figure 3. Basement surface beneath the central part of Pahute Mesa based on the gravity inversion model. The Silent Canyon caldera complex shows as the oval-shaped basin outlined by the yellow to red contours. The steepest gradient along the rim of the basin is used to create the Silent Canyon caldera fault surf

Figure 4. East-west cross section across the Silent Canyon caldera. No vertical exaggeration. Caldera faults (ring faults) are heavy red lines. Green is the dense basement; yellow, pink, and gray is less dense caldera fill and caldera overlap volcanic rock.

Figure 5 . The Silent Canyon caldera fault surface from the "EarthVision" 3-D model. No vertical exaggeration. Looking north.

Figure 6. The major faults mapped at the surface of Pahute Mesa. These faults are mostly within the surface trace of the buried Silent Canyon caldera.