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Field-Based Description of Rhyolite Lava Flows of the Calico Hills Formation, Nevada National Security Site, Nevada

Scientific Investigations Report 2015–5022

U.S. Department of the Interior
U.S. Geological Survey

Cover. Looking northeast across Fortymile Wash to the Calico Hills and Shoshone Mountain. All rocks in the center part of photograph are volcanic rocks of the Calico Hills Formation. Photograph taken by Wayne R. Belcher, U.S. Geological Survey, June 9, 2014.

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Suggested citation:
Sweetkind, D.S., and Bova, S.C., 2015, Field-based description of rhyolite lava flows of the Calico Hills Formation, Nevada National Security Site, Nevada: U.S. Geological Survey Scientific Investigations Report 2015–5022, 36 p., http://dx.doi.org/10.3133/sir20155022.

ISSN 2328-0328 (online)

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
cubic mile (mi^3)	4.168	cubic kilometer (km^3)

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Abstract

Contaminants introduced into the subsurface of Pahute Mesa, Nevada National Security Site, by underground nuclear testing are of concern to the U.S. Department of Energy and regulators responsible for protecting human health and safety. The potential for contaminant movement away from the underground test areas at Pahute Mesa and into the accessible environment is greatest by groundwater transport through fractured volcanic rocks. The 12.9 Ma (mega-annums, million years) Calico Hills Formation, which consists of a mixture of rhyolite lava flows and intercalated nonwelded and bedded tuff and pyroclastic flow deposits, occurs in two areas of the Nevada National Security Site. One area is north of the Rainier Mesa caldera, buried beneath Pahute Mesa, and serves as a heterogeneous volcanic-rock aquifer but is only available to study through drilling and is not described in this report. A second accumulation of the formation is south of the Rainier Mesa caldera and is exposed in outcrop along the western boundary of the Nevada National Security Site at the Calico Hills near Yucca Mountain. These outcrops expose in three dimensions an interlayered sequence of tuff and lava flows similar to those intercepted in the subsurface beneath Pahute Mesa. Field description and geologic mapping of these exposures described lithostratigraphic variations within lava flows and assisted in, or at least corroborated, conceptualization of the rhyolite lava-bearing parts of the formation.

In the area south of the Rainier Mesa caldera, surface exposures and nearby subsurface equivalents were studied through compilation of geologic maps, new field mapping, subsurface information from boreholes, and data extracted from three-dimensional geologic framework models. Rhyolite lava flows within the Calico Hills Formation are described in terms of lithostratigraphic variations established for rhyolite lava flows in other volcanic fields. In general, the flows consist of a core of crystallized, flow-banded rhyolite lava, surrounded by a carapace of obsidian, commonly mantled by blocky, pumiceous rhyolite lava and flow breccia. Rhyolite lava flows were correlated and mapped on the basis of distinctive appearance in outcrop, stratigraphic sequence, and the presence of stratigraphic markers. Pyroclastic deposits that are spatially, temporally, and genetically related to the rhyolite lava flows consist of a series of intercalated pyroclastic flows, bedded ash-fall, and reworked tuff that have varying amounts of pumice and volcanic rock clasts.

In the area south of the Rainier Mesa caldera, surface and subsurface geologic data are combined to interpret the overall thickness of the Calico Hills Formation and the proportion of lava flow lithology across the study area. The formation is at least 500 meters (m) thick and contains the greatest proportion of rhyolite lava flow to the northeast of Yucca Mountain in the lower part of Fortymile Canyon. The formation thins to the south and southwest where it is between 50 and 200 m thick beneath Yucca Mountain and contains no rhyolite lavas. Geologic mapping and field-based correlation of individual lava flows allow for the interpretation of the thickness and extent of specific flows and the location of their source areas. The most extensive flows have widths from 2 to 3 kilometers (km) and lengths of at least 5–6 km. Lava flow thickness varies from 150 to 250 m above interpreted source vents to between 30 and 80 m in more distal locations. Rhyolite lavas have length-to-height ratios of 10:1 or greater and, in one instance, a length-to-width ratio of 2:1 or greater, implying a tongue-shaped geometry instead of circular domes or tabular bodies. Although geologic mapping did not identify any physical feature that could be positively identified as a vent, lava flow thickness and the size of clasts in subjacent pyroclastic deposits suggest that primary vent areas for at least some of the flows in the study area are on the east side of Fortymile Canyon, to the northeast of Yucca Mountain.

Introduction

Pahute Mesa, an area in the northwestern part of the Nevada National Security Site (NNSS) in southern Nevada, was the site of 85 underground nuclear tests during the period 1951–1992 (U.S. Department of Energy, 2000; fig. 1). Many of these tests, conducted in the volcanic-rock section beneath Pahute Mesa, likely introduced radionuclide contaminants

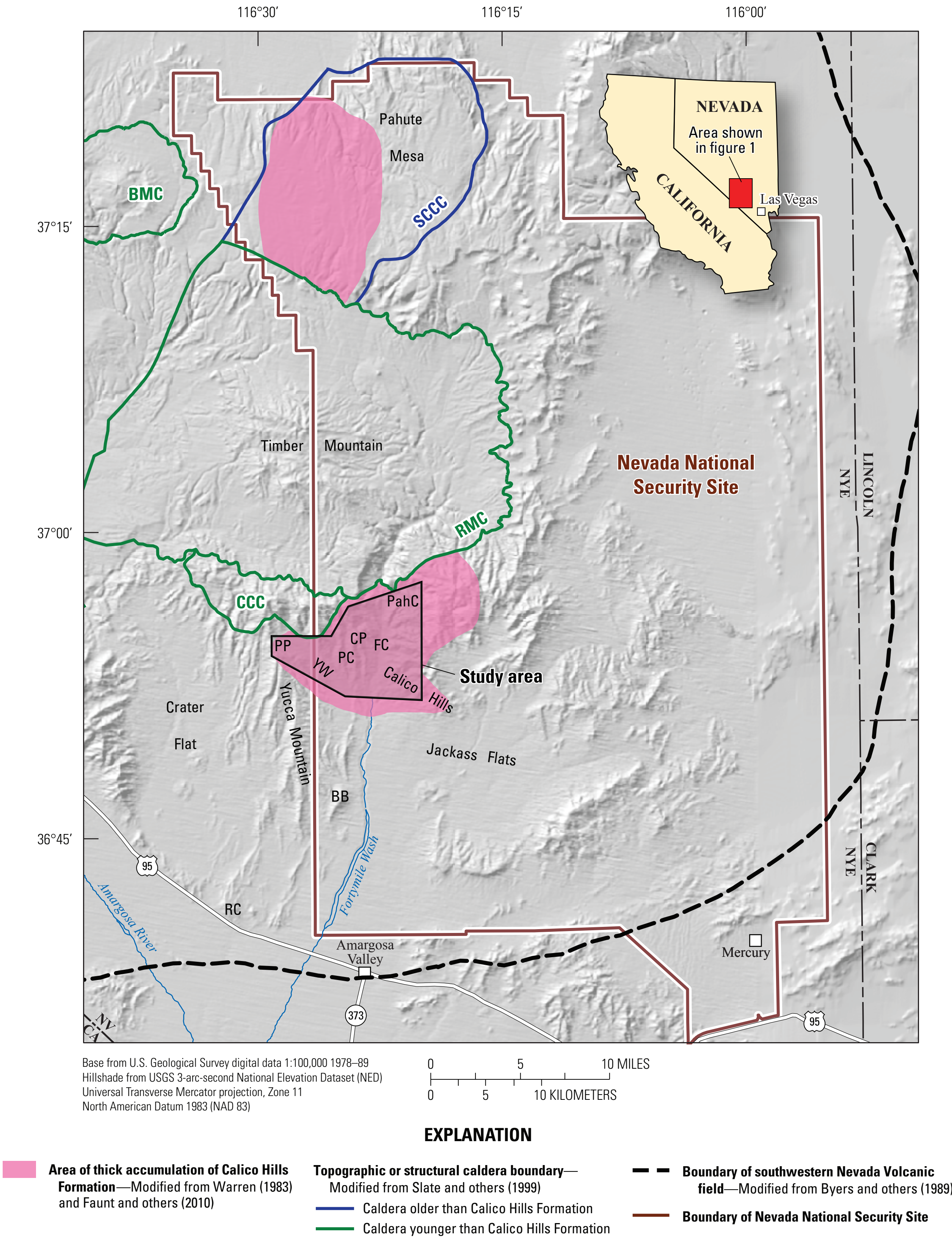


Figure 1. Geographic and geologic features near the Calico Hills, Nevada National Security Site. BB, Busted Butte; CCC, Claim Canyon caldera; CP, Comb Peak; FC, Fortymile Canyon; PC, Paintbrush Canyon; PahC, Pah Canyon; PP, Prow Pass; RC, Raven Canyon; YW, Yucca Wash, RMC; Rainier Mesa caldera; SCCC, Silent Canyon caldera complex; BMC, Black Mountain caldera.

into the groundwater (Laczniak and others, 1996, table 4). The potential for subsurface transport of radionuclides away from Pahute Mesa to the accessible environment is of concern to the U.S. Department of Energy and to other regulatory Federal and state agencies (State of Nevada and others, 1996; U.S. Department of Energy, 2009).

In the upper part of the saturated section beneath the western part of Pahute Mesa, volcanic rocks of the Calico Hills Formation locally form a volcanic-rock aquifer as much as 1,200 meters (m) thick (Laczniak and others, 1996, plate 4; Prothro and Drellack, 1997). The formation is a stratigraphically complex assemblage of multiple, lithologically heterogeneous, rhyolite lava flows and bedded and nonwelded tuff that is difficult to characterize and correlate on the basis of borehole data (Prothro and Drellack, 1997; U.S. Department of Energy, 2004, 2011). In previous three-dimensional (3D) hydrostratigraphic framework models and conceptualizations of Pahute Mesa, the Calico Hills Formation was treated as a composite unit, not specifically as an aquifer or confining unit, because of its stratigraphic complexity (Bechtel Nevada, 2002; Prothro and others, 2009).

A second volcanic accumulation of the Calico Hills Formation is exposed in outcrop and present in boreholes near Calico Hills and Yucca Mountain (fig. 1; Warren, 1983; Sawyer and others, 1994; Buesch and others, 1996). These outcrops expose in three dimensions an interlayered sequence of tuff and lava flows (Christiansen and Lipman, 1965; Orkild and O’Connor, 1970) similar to those intercepted in the subsurface beneath Pahute Mesa (for example, U.S. Department of Energy, 2004, 2011). Outcrop exposures of lava flows and tuff allow for detailed examination of lithostratigraphic variations within lava flows and the possibility of direct stratigraphic correlation of units. This report provides a description of these outcrop exposures with the intent of providing a surface analog to the lava-bearing Calico Hills Formation beneath Pahute Mesa.

Purpose and Scope

The purpose of this report is to describe the lithologic variability of the Calico Hills Formation based on geologic mapping of surface outcrops near the Calico Hills and Yucca Mountain (fig. 1). Map data and outcrop descriptions are used to develop information on the individual rhyolite lava flows within the Calico Hills Formation, including their lateral extent and continuity, thickness, and field-based criteria useful in stratigraphic correlation. Geologic mapping results are used to define the stratigraphic succession of tuffaceous deposits and lava flows within the Calico Hills Formation and the change in the proportion of nonwelded tuffaceous units and lava flows with distance from the inferred volcanic source area. The internal lithostratigraphic zonation of individual lava flows is described, documenting variations in rock type, alteration pattern, and fracture type and intensity.

The study area encompasses exposures of the Calico Hills Formation to the south of the Rainier Mesa caldera (RMC, fig. 1) and Claim Canyon caldera (CCC, fig. 1) in the western part of the Calico Hills and Shoshone Mountain and to the north of Yucca Mountain (figs. 1 and 2). Geologic mapping results come from three principal areas of exposure: (1) outcrops to the east of Fortymile Canyon on the western side of the Calico Hills and Shoshone Mountain from Pah Canyon southward to Jackass Flats; (2) outcrops that occur on the east and west flanks of Comb Peak and in Paintbrush Canyon, all on the west side of Fortymile Canyon; and (3) outcrops near Prow Pass to the north of Yucca Mountain (fig. 2). Surface geologic observations are augmented by subsurface data, mostly boreholes from the Yucca Mountain vicinity (appendix 1). Exposures in the southern part of the Calico Hills Formation affected by hydrothermal alteration (fig. 2) (Simonds, 1989) were not included in this study. Elsewhere in the study area, initially porous marginal parts of rhyolite lava flows and intercalated tuffaceous rocks are pervasively zeolitically altered (Broxton and others, 1986; 1987; Buesch and Spengler, 1999), but this alteration does not substantially affect recognition or mapping of the crystallized parts of the rhyolite lava flows.

Geologic mapping and outcrop description of the lava-bearing Calico Hills Formation are intended to provide a useful surface analog to similar rocks buried beneath Pahute Mesa. The geologic mapping results may be useful in developing, or at least corroborating, conceptual models of Calico Hills Formation lithofacies variations at Pahute Mesa. Detailed comparison among the outcrop exposures, descriptions from boreholes (appendix 1), and the results from boreholes at Pahute Mesa (for example, U.S. Department of Energy, 2004, 2011) was beyond the scope of this project, but the results from this study may provide a useful comparison to the subsurface geologic data.

Field exposures of the Calico Hills Formation are difficult to access; documentation of these exposures preserves useful geologic data. Restricted public access to the Nevada National Security Site and the remoteness of the exposures, which typically involved hikes of an hour or more over rough desert terrain, means that considerable time and energy would be spent trying to reoccupy these exposures. In order to provide “virtual access” to these exposures, this report contains many photos and descriptions of outcrops to document exposures that have rarely been visited and are unlikely to be frequently visited in the future.

Boreholes on the Nevada National Security Site (NNSS) are designated with UE (for Underground Exploratory), followed by the NNSS use area number (Area 25 in the immediate area of Yucca Mountain; for example, UE-25). For boreholes on Bureau of Land Management or Nellis Air Force Range land to the west and south of the NNSS, the prefix USW is used (for Underground, Southern Nevada, Waste). The prefix designators UE-25 and USW are not posted on figures in this report because of space limitations; on the figures, boreholes are given abbreviated designations that may still be correlated to the full borehole name listed in appendix 1.

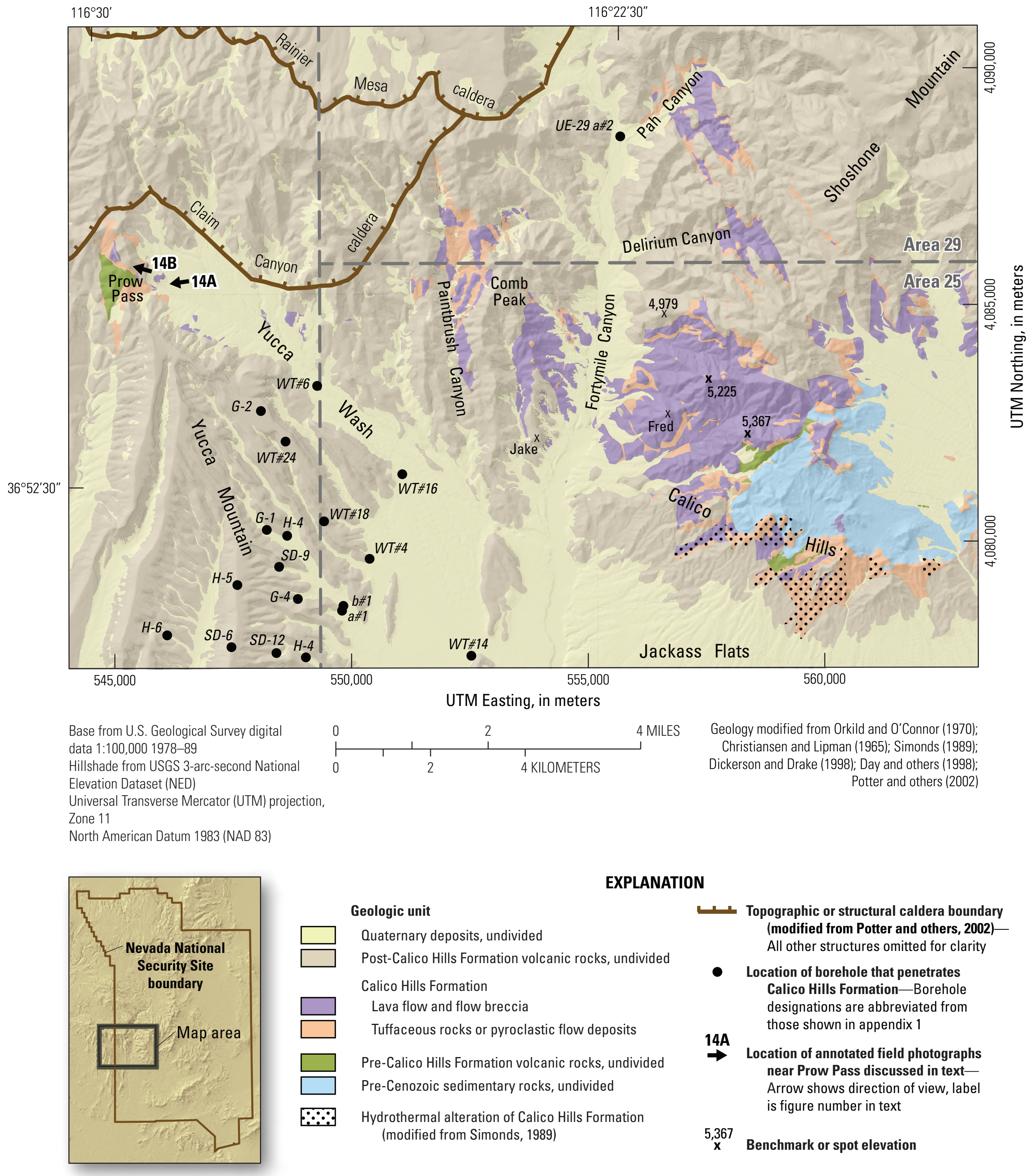


Figure 2. General geologic features and location of boreholes in the study area.

Geologic Setting

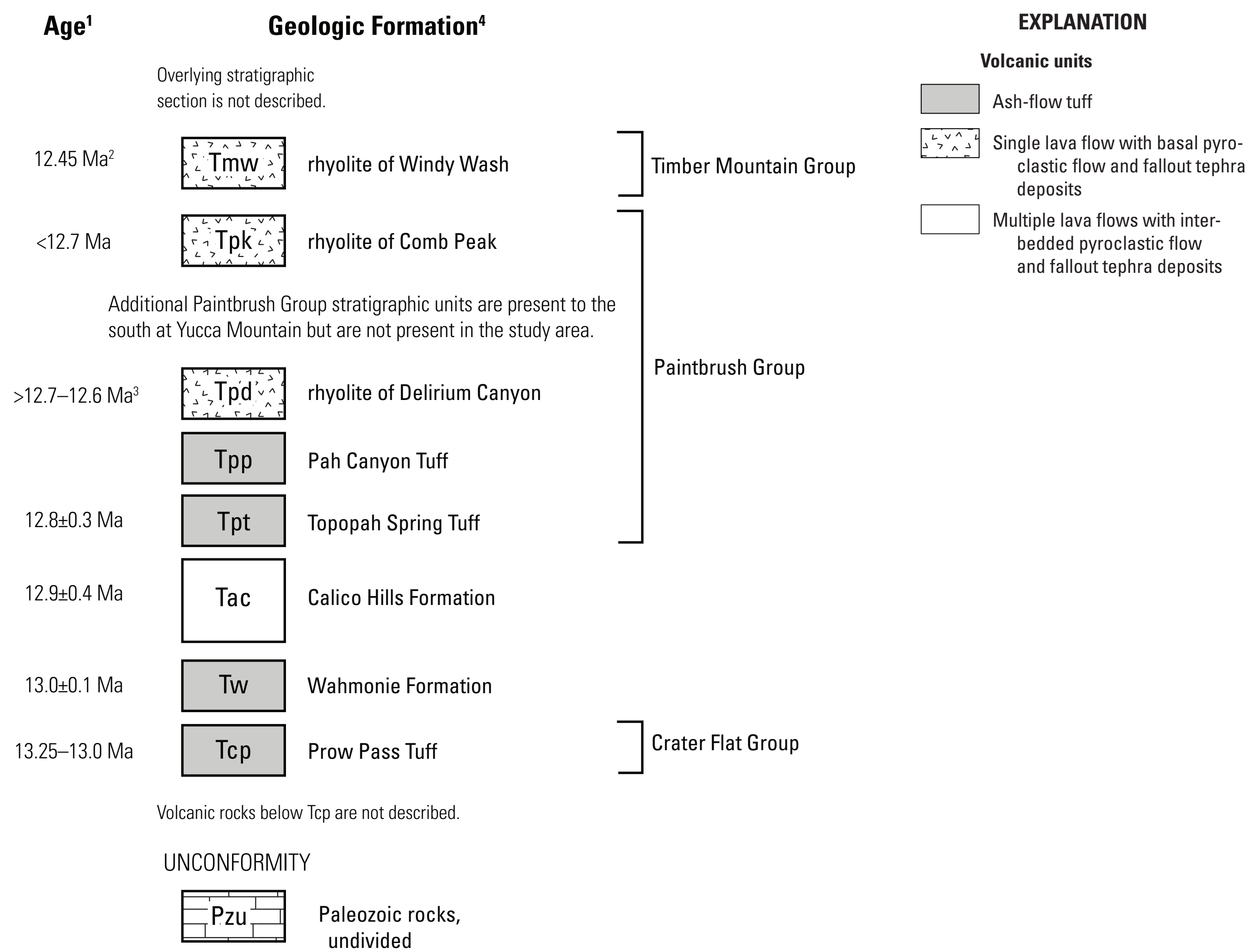
Volcanic rocks of the southwestern Nevada volcanic field (SWNVF; Byers and others, 1989) are the dominant surface exposures in the northwestern and west-central parts of the NNSS and are present in the subsurface or as more localized outcrops over most of the rest of the NNSS (fig. 1). Volcanism associated with the SWNVF occurred episodically from about 15.1 to 7.5 Ma (Byers and others, 1976; Carr and others, 1986; Sawyer and others, 1994). The volcanic rocks of the SWNVF include voluminous, regionally extensive, silicic, ash-flow tuffs formed during caldera-forming eruptions, small-volume pyroclastic deposits and silicic to mafic lava flows erupted from many small volcanic vents, fallout tephra deposits, and minor redeposited tuffaceous and epiclastic rocks (Byers and others, 1976; Carr and others, 1986; Byers and others, 1989; Ferguson and others, 1994; Sawyer and others, 1994).

The 12.9 Ma Calico Hills Formation (Sawyer and others, 1994) consists of two spatially distinct volcanic accumulations of rhyolite lava flows and intercalated nonwelded and bedded tuff and pyroclastic flow deposits where one area is north of the Rainier Mesa caldera, and the second area is south of the caldera (fig. 1). Although physically separated, the two accumulations are stratigraphically, lithologically, and petrographically equivalent (Warren, 1983; Sawyer and others, 1994). In the northern accumulation, beneath Pahute Mesa, the Calico Hills Formation volcanic rocks postdate and lie within the Silent Canyon caldera complex (SCCC, fig. 1) (Prothro and Drellack, 1997). In the southern accumulation, near the Calico Hills and Yucca Mountain, the Calico Hills Formation volcanic rocks predate and lie outside of any of the calderas of the SWNVF, including the nearby 12.7 Ma Claim Canyon caldera (Sawyer and others, 1994) (CCC, fig. 1). In both the northern and southern accumulation areas, rocks of the 12.8 to approximately 12.7 Ma Paintbrush Group were deposited on the Calico Hills Formation (Potter and others, 2002; Wood, 2009). Both accumulations are truncated and physically separated by the 11.6 Ma Rainier Mesa caldera (RMC, fig. 1) of the Timber Mountain caldera complex (Byers and others, 1976; Sawyer and others, 1994).

The general stratigraphic relations of the Calico Hills Formation are well exposed in the areas south of the Claim Canyon and Rainier Mesa calderas (figs. 2 and 3). The Calico Hills Formation unconformably overlies Paleozoic sedimentary rocks and locally overlies the volcanic rocks of 13.0 Ma Wahmonie Formation in the Calico Hills (fig. 3) (McKay and Williams, 1964; Orkild and O’Connor, 1970; Potter and others, 2002). At Prow Pass, the Calico Hills Formation disconformably overlies the 13.25–13.0 Ma Prow Pass Tuff of the Crater Flat Group (Christiansen and Lipman, 1965; Day and others, 1998). The Calico Hills Formation is overlain in the study area by volcanic rocks of the 12.8–<12.7 Ma Paintbrush Group. At Yucca Mountain, Shoshone Mountain, and the Calico Hills, the Calico Hills Formation is overlain by the 12.8 Ma Topopah Spring Tuff, the oldest regionally extensive ash-flow tuff of the Paintbrush Group (Orkild and O’Connor, 1970; Potter and others, 2002). Near Comb Peak, the Calico Hills Formation is overlain by rhyolite lava flows of the Paintbrush Group that are younger than 12.7 Ma and are spatially associated with the structural margin of the Claim Canyon caldera (Dickerson and Drake, 1998; Potter and others, 2002).

The lithology of the Calico Hills Formation is variable within the study area. Thick lava flows and intercalated tuffs of the Calico Hills Formation are exposed in the Calico Hills, Fortymile Canyon, Paintbrush Canyon, and locally exposed in Yucca Wash (fig. 2). Thick pyroclastic flow deposits overlie a rhyolite lava flow near Prow Pass, and lava flows were found in four boreholes at the north end of Yucca Mountain (WT#4, WT#6, WT#16, and WT#18, fig. 2, appendix 1). Tuffaceous pyroclastic flow deposits as much as 300 m thick and without rhyolite lava are penetrated in boreholes in the northern part of Yucca Mountain to the south and west of the four boreholes where lava flows were found (for example, G-2 and WT-24; fig. 2, appendix 1; Moyer and Geslin, 1995; Wood, 2009). The tuffaceous deposits thin to the south to less than 15 m thick at Busted Butte (Moyer and Geslin, 1995), 5 kilometers (km) to the south of the southern boundary of figure 2 (location shown on fig. 1), and are absent in Raven Canyon (RC) at the southern end of Yucca Mountain (Peterman and others, 1994; Moyer and Geslin, 1995; location shown on fig. 1).

Unaltered lava flows and intercalated tuffaceous rocks of the Calico Hills Formation are all rhyolitic in composition, having greater than 72 percent silicon dioxide (SiO_2) and approximately 7 percent total alkalis (sodium oxide and potassium oxide [Na_2O+K_2O]; weight percent, volatile-free) (Broxton and others, 1986; Broxton, Warren, and others, 1989; Warren and others, 2003; Don Sweetkind, USGS, unpub. data, July, 2014). Tuffaceous rocks of the Calico Hills Formation are pervasively zeolitically altered beneath the northern part of Yucca Mountain and in all field exposures to the north of Yucca Mountain, including Prow Pass, Yucca Wash, Paintbrush Canyon, Fortymile Wash, and the Calico Hills (Broxton and others, 1986; 1987; 1993; Broxton, Byers, and Warren, 1989; Moyer and Geslin, 1995). Zeolitic alteration results in the conversion of original volcanic glass to zeolite minerals in initially porous rocks such as nonwelded to moderately welded pyroclastic rocks and moderately vesicular to pumiceous obsidian (Broxton and others, 1986; 1987; Buesch and Spengler, 1999). Locally in the upper part of Paintbrush Canyon and in Fortymile Canyon, zeolitic alteration obscures the contact between autoclastic lava flow-breccia and blocky, zeolitized massive tuff (Dickerson and Drake, 1998). Rocks with low primary porosity, such as obsidian and dense, crystallized lava, are unaffected by zeolitization except along fracture surfaces; primary volcanic textures are preserved in these rocks (Buesch and Spengler, 1999). The intense zeolitic alteration that affects much of the Calico Hills Formation was the result of geothermal fluid circulation that may have been associated with volcanism within the moat of the Rainier Mesa caldera at approximately 10.7 Ma (Bish and Aronson, 1993). The Calico Hills Formation is hydrothermally altered in the eastern and southern part of the Calico Hills (fig. 2); the primary alteration types are argillic alteration, silicification, and pyritization (Simonds, 1989). Hydrothermal alteration in this area affected the 11.60 Ma Rainier Mesa Tuff (Sawyer and others, 1994), and two alunite samples from acid-sulfate altered rock at near-surface hot spring edifices yielded conventional potassium-argon (K-Ar) ages of 10.4±0.3 Ma (Jackson, 1988). Hydrothermal alteration is localized around and above two intrusions inferred to exist beneath the eastern part of the Calico Hills (Simonds, 1989). No significant hydrothermal alteration has occurred since approximately 10.4 Ma (Bish and Aronson, 1993).



[1] From Sawyer and others (1994), tables 1 and 3, except where otherwise noted. Ages designated as "less than" (<) indicate that unit stratigraphically overlies, and is younger than, the listed age. Age designated as "greater than" (>) indicates that unit underlies, and is older than, a unit with the listed age.

[2] As reported by Fridrich and others (1994).

[3] Age of 12.6 Ma reported by Warren and others (1988). Unit suggested to be older than 12.7 Ma based on stratigraphic relations described by Dickerson and Drake (1998, p. 7).

[4] Stratigraphic nomenclature follows that of Potter and others (2002).

Figure 3. Stratigraphic units in the study area.

Previous Studies

Geologic and hydrologic studies at the Nevada National Security Site and at Yucca Mountain have produced surface and subsurface data in which the thickness and lithologic variability of the Calico Hills Formation were described. In addition, descriptions of rhyolite lava flows from other volcanic fields provide interpretive guidelines to understand the rhyolite lava flows within the Calico Hills Formation.

Geologic Mapping of Calico Hills Formation

Lithologic units within the Calico Hills Formation were mapped at 1:24,000 scale in the western part of Calico Hills (Orkild and O'Connor, 1970), the southern part of Calico Hills (McKay and Williams, 1964), and to the north of Yucca Wash (Christiansen and Lipman, 1965). The western part of Calico Hills was subsequently mapped at 1:12,000 scale (Simonds, 1989), and the Paintbrush Canyon area mapped at 1:6,000 scale (Dickerson and Drake, 1998). Lithologic units within the Calico Hills Formation were described on each of these maps using various terms, such as tuff, nonwelded tuff, tuff breccia, lava flow, rhyolite flows and tuff breccia, and the terms used were specific to the individual mapped area. These maps portrayed lithologic variations within the Calico Hills Formation, but none defined the stratigraphic sequence of lava flows nor made stratigraphic correlations of tuff or lava flows across the map area.

Digital geologic maps that have all or parts of the study area include a 1:24,000-scale map of Yucca Mountain (Day and others, 1998) and a 1:50,000-scale map of the Yucca Mountain region (Potter and others, 2002). The scale of these maps required that the lithologic variations within the Calico Hills Formation be generalized, yet these maps provide a regional context of faulting and distribution of pre- and post-Calico Hills Formation geologic units in the study area.

Subsurface Data

Boreholes in the study area that intercept the Calico Hills Formation include borehole UE-29 a#2 in Fortymile Canyon and 18 boreholes at Yucca Mountain (fig. 2; appendix 1). Additional boreholes at Yucca Mountain intercept the Calico Hills Formation south of the study area (Moyer and Geslin, 1995; Buesch and others, 1996). Borehole data include detailed lithologic descriptions of downhole intervals based on description of cuttings, core, or video logs. Lithologic descriptions for many of the boreholes in the study area were compiled in a digital database of borehole data from the NNSS (Wood, 2009); other sources of data are listed in appendix 1.

Total thickness of the Calico Hills Formation for the southwestern part of the study area is represented within the Yucca Mountain site-scale hydrogeologic framework model (Bechtel SAIC Company, 2002), which combined borehole data with geologic map data, a digital elevation model, and geologic cross sections. Thickness of the formation in the study area is represented within the 3D hydrogeologic framework model of the Death Valley regional groundwater flow system, combining data from the Yucca Mountain site-scale model with additional geologic data (Faunt and others, 2010).

Previous Description of Rhyolite Lava Flow Lithofacies

Observations of rhyolite lava flows from other volcanic fields provide the necessary geologic context for interpreting lava-flow lithofacies variations within the Calico Hills Formation. Based on outcrop observation and limited drilling, the generalized lithofacies pattern within rhyolite lava flows is reasonably well established (Fink, 1983; Cas and Wright, 1987; Bonnichsen and Kauffman, 1987; Fink and Manley, 1987; Manley and Fink, 1987; Duffield and others, 1995) (fig. 4). Rhyolite lava flows typically have a core of crystallized rhyolite lava, surrounded by a carapace of obsidian, and are commonly mantled by pumiceous lava and flow-generated breccia. Crystallized rhyolite is typically nonvesicular and fine grained, with texture ranging from massive to prominently flow banded. The crystallized rhyolite core grades outward to dark, vitreous obsidian that is commonly blocky, although the blocks may be fully to partly annealed. At some locations the upper obsidian grades upward into finely to coarsely vesicular, pumiceous rhyolite lava (Fink and Manley, 1987) (fig. 4). Rhyolite lava flows are typically spatially, temporally, and genetically related pyroclastic deposits which form tuff cones or aprons beneath the flow or tephra deposits above the flow as a result of violent eruptions of pyroclastic material associated with the eruption of the lava flow (Heiken and Wohletz, 1987). The location of the source vent or conduit for a rhyolite flow has been inferred on the basis of alignment and shape of rhyolite domes (Fink and Pollard, 1983), orientation of flow banding (Christiansen and Lipman, 1966; Fink, 1983), and topography and distribution of marginal breccia (Duffield and others, 1995); however, in some cases the conduit may be buried by crystallized lava, making its precise location difficult to establish.

Lithostratigraphic variation in rhyolite flows is governed by several processes, including cooling rate and response of the lava to a temperature gradient; continued movement of the flow during cooling; syn- to post-motion crystallization; and movement of exsolved water vapor through the cooling rhyolite (Bonnichsen and Kauffman, 1987; Fink and Manley, 1987) (fig. 5). After eruption, quenching of the outer surface of the rhyolite flow produces a glassy carapace that breaks into blocks as the viscous, still plastic interior of the flow continues to move. The vitric blocks spall off the steep flanks and front of the advancing flow to form a talus apron or marginal breccia (Borgia and others, 1983; Bonnichsen and Kauffman, 1987). Continued advance of the flow results in the talus apron being overridden, creating a flow-generated breccia at the base of the lava flow (fig. 4; Bonnichsen and Kauffman, 1987).

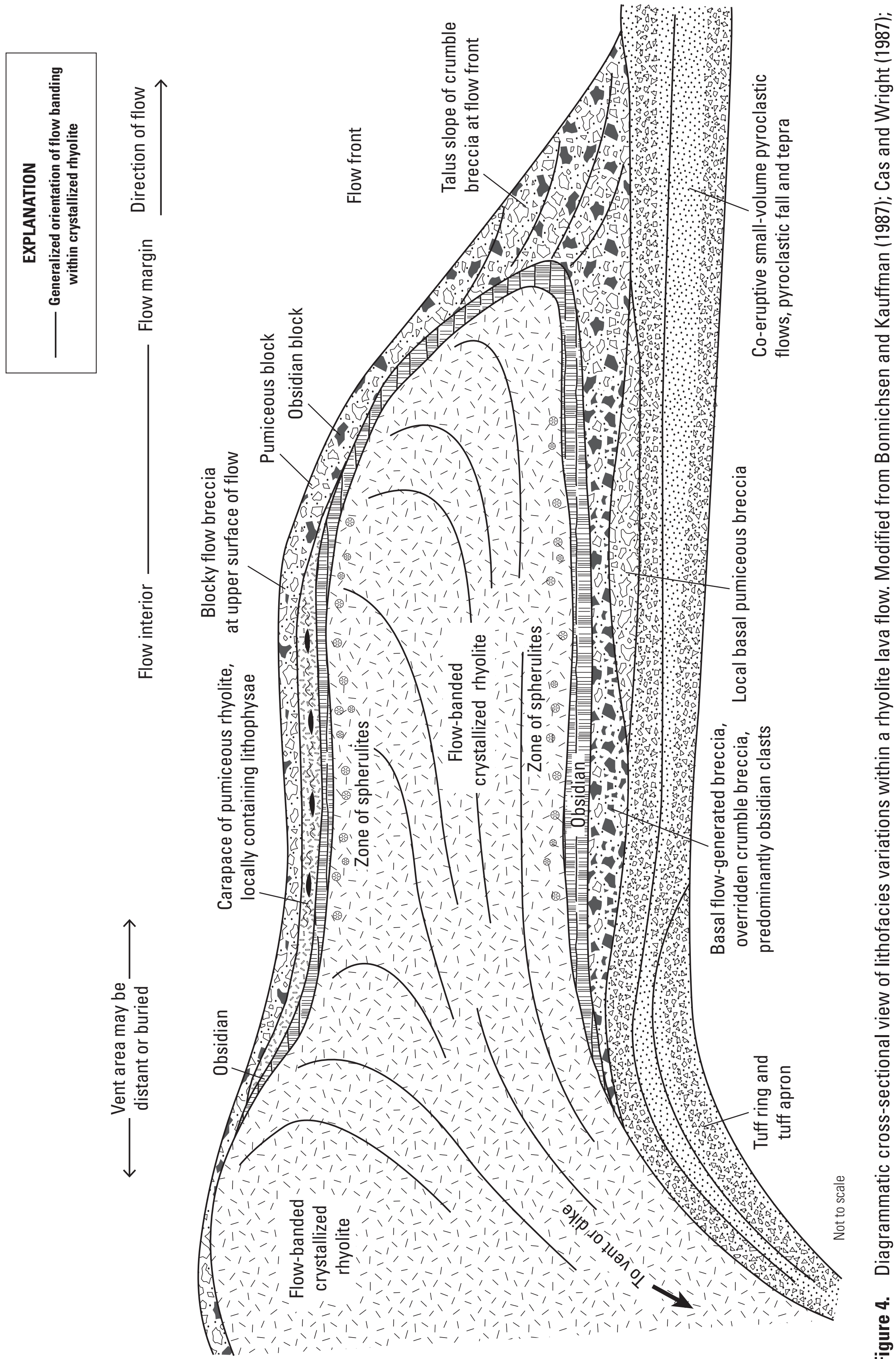


Figure 4. Diagrammatic cross-sectional view of lithofacies variations within a rhyolite lava flow. Modified from Bonnichsen and Kauffman (1987); Cas and Wright (1987); and Duffield and others (1995).

Vitric blocks below or at the top of the advancing lava flow may anneal as a result of elevated temperatures and transient compressive stresses (Christiansen and Lipman, 1966; Manley, 1992). The continued cooling of the flow results in the typical zonation of obsidian surrounding a core of crystallized rhyolitic lava (fig. 5). Crystallization causes the exsolution and movement of water vapor within the flow and results in vesiculation and development of fine pumiceous texture at the flow top and formation of lithophysae or spherulitic zones within the flow (Fink and Manley, 1987; Swanson and others, 1989; McPhie and others, 1993) (figs. 4 and 5).

Methodology

Digital geologic map compilation.—Digital geologic data were compiled for the northern part of Yucca Mountain from Day and others (1998) and the Paintbrush Canyon area from Dickerson and Drake (1998; R.M. Drake, II, USGS, written commun., January, 2013). Paper geologic maps that show lithologic variation within the Calico Hills Formation were scanned, georeferenced, and digitized within a geographic information system (GIS) from the following sources: southern part of Calico Hills, Simonds (1989) and McKay and Williams (1964); western part of Calico Hills, Orkild and O'Connor (1970); northern part of Yucca Mountain and Prow Pass, Christiansen and Lipman (1965). Additional regional-scale stratigraphic and structural data were compiled from the digital map data of Potter and others (2002).

Field mapping of outcrop exposures.—Previous geologic mapping was field checked and, where needed, additional 1:6,000-scale mapping was completed for most of the outcrop areas of the Calico Hills Formation near Fortymile Canyon, the western part of the Calico Hills, and to the north of Yucca Mountain. Field-based data collection included annotation on base maps of geologic contacts, stratigraphic relations between lithologic units, and the location of faults. In addition to the map data, site-specific geologic notes and measurements were collected, including unit thickness, lithologic and fracture character, and bedding orientation. The base maps for the field geologic mapping were spatially referenced, high-resolution imagery including black-and-white digital orthophotos of 1-m resolution (accessed January 2013, at http://keck.library.unr.edu/datasets/doq.aspx) and color orthophotos of approximately 2-m resolution (accessed January 2013 from Microsoft Bing Maps Platform within the Esri software ArcGIS).

Compilation of subsurface data.—The locations of all boreholes in the study area that penetrated the Calico Hills Formation were compiled as digital point locations within a GIS so that they could be portrayed with the geologic map data. Digital lithologic descriptions of downhole intervals (Wood, 2009) were checked against and augmented with data from the original published reports. Nondigital lithologic descriptions were transcribed (appendix 1). Modeled thickness of the Calico Hills Formation was extracted from the Death Valley regional flow system 3D hydrogeologic framework model (Faunt and others, 2010) at the centroid of the 1,500-m grid cells and from the Yucca Mountain site-scale 3D framework model (Bechtel SAIC Company, 2002) at the centroid

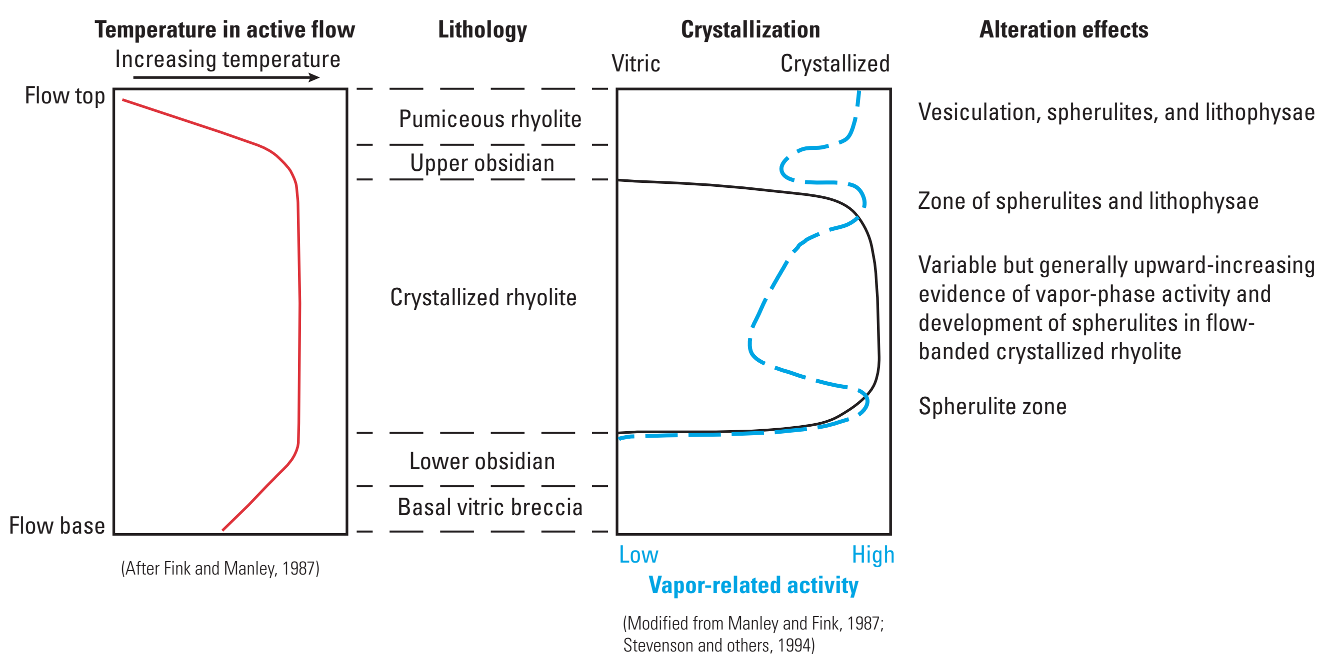


Figure 5. Generalized patterns of lithology, crystallization, and vapor-related activity within a rhyolite lava flow as a function of temperature within the flow.

of the 61-m grid cells; these point data were symbolized at a desired interval and thickness contours were digitized within a GIS.

Collection of fracture data.—Fracture data from nonwelded, zeolitized tuffaceous units of the Calico Hills Formation were collected by Donald Sweetkind, USGS, in 1997 as part of site characterization activities at Yucca Mountain from surface exposures near Prow Pass, at the northern end of Yucca Mountain, using detailed line survey (DLS) and areal fracture set survey techniques. Data collected by DLS provided a statistical sampling of the fracture network where every discontinuity longer than 1 m was measured along a horizontal datum line and the fracture attributes recorded: orientation, infillings, terminations, fracture origin, roughness, and aperture (Brady and Brown, 1993). Data collected using the areal set survey technique provide a descriptive inventory of the fracture network in the area (Throckmorton and Verbeek, 1995). Using this method, fracture sets were identified by inspection, primarily by subdividing groups of fractures on the basis of orientation and relative age, based on fracture termination relationships. Average attributes for each fracture set were measured. Fracture data from rhyolite lava flow lithology within the study area were not collected systematically but were instead recorded as notations collected at field localities during field mapping. Data collected consisted of type of fractures, number of fracture sets, and approximate length and spacing of fractures.

Results

Lithostratigraphic variations observed in vertical sections through individual lava flows are presented along with field-based criteria for the recognition of specific flows. These outcrop-specific results allowed for geologic mapping and correlation of individual flows based on physical stratigraphy. Mapped extents of the principal identified rhyolite lava flows are shown on figure 6.

Lithostratigraphic Variation within Rhyolite Lava Flows

Lithostratigraphic variation within rhyolite lava flows of the Calico Hills Formation is generally similar to rhyolite lava flows described elsewhere (Bonnichsen and Kauffman, 1987; Fink and Manley, 1987; Manley and Fink, 1987; Duffield and others, 1995; Prothro and Drellack, 1997). Lithostratigraphic variations are described for three stratigraphic columnar sections (localities SS1, SS2, and SS3; shown on fig. 6) to illustrate the characteristics of rhyolite lava flows in the study area.

Stratigraphic section 1 is a profile across the middle of three prominent lava flows in Paintbrush Canyon (here informally named the Fred lava flow, locality SS1, fig. 7). This flow is approximately 45 m thick and forms a prominent bench traceable along strike for at least 2 km (Christiansen and Lipman, 1965; Dickerson and Drake, 1998). The lava flow and underlying flow-generated obsidian breccia conformably overlie a zeolitically altered lithic tuff at the top of a thicker zeolitically altered pumiceous pyroclastic deposit (fig. 7). The base of the flow is a zone of obsidian blocks, and local pumice clasts, that probably represent an overridden marginal flow-generated breccia. The obsidian blocks become increasingly annealed upward to form a continuous outcrop band of lower obsidian (fig. 7). Vertical cooling joints that are spaced 0.5 to 1 m apart cut the obsidian and are arranged in a crude columnar pattern. The center of the flow is crystallized, flow-banded rhyolite. Flow banding occurs as bands 0.5 cm to 10 cm wide that vary in color, amount of crystallization and spherulitic development; flow bands are roughly parallel to the base of the flow, but in detail may be contorted and irregularly folded. The flow-banded rhyolite lacks continuous vertical joints, although there are many subhorizontal partings at the edges of individual bands. Vapor-related activity increases upward in the upper part of the crystallized rhyolite, primarily recorded by the development of spherulites and the deposition of minerals on flow band partings. Near the top of the flow, a dark greenish black, upper obsidian forms a prominent topographic bench; this obsidian is a blocky, brecciated flow top where the obsidian blocks have annealed to form a continuous obsidian horizon near the top of the lava flow. Above this is a thin, poorly exposed zone of vesicular pumiceous rhyolite. The lava flow is conformably overlain by a lithic-pumiceous pyroclastic flow deposit (fig. 7).

Stratigraphic section 2 is a profile through a lava flow prominently exposed beneath Point 4979 (here informally named the SS lava flow, locality SS2, fig. 2). At this location the flow is approximately 60 m thick, and it conformably overlies a 10-m-thick, lithic-rich pyroclastic flow (fig. 8). A thin (0.3 to 1 m), sintered zone occurs at the base of the lava flow where the underlying pyroclastic flow is partly fused. The base of the overlying lava flow is an overridden talus breccia of obsidian blocks without volcanic lithic clasts that transitions upward through progressive annealing of obsidian blocks into dense black glassy obsidian. The contact between obsidian breccia and overlying glassy rhyolite lava flow is obscure. Above the obsidian is a 5-m-thick zone with vapor-related activity including the common occurrence of spherulites and lithophysae. Above this interval is the central 20-m-thick crystallized part of the flow. Most of the crystallized rhyolite in this interval is structureless and has a finely crystalline equigranular texture that is not flow banded; the upper part of the crystallized zone transitions into flow-banded rhyolite. The crystallized rhyolite grades upward into a 5–10-m thick interval of zeolitically altered, vesiculated, pumiceous rhyolite that interfingers with nonvesicular obsidian. Above this interval is a 10–15-m thick zone of zeolitically altered, fragmental, pumiceous rhyolite (fig. 8).

Stratigraphic section 3 is a partial profile through the base of the SS lava flow described in section 2, but from a section approximately 2 km farther to the west where the

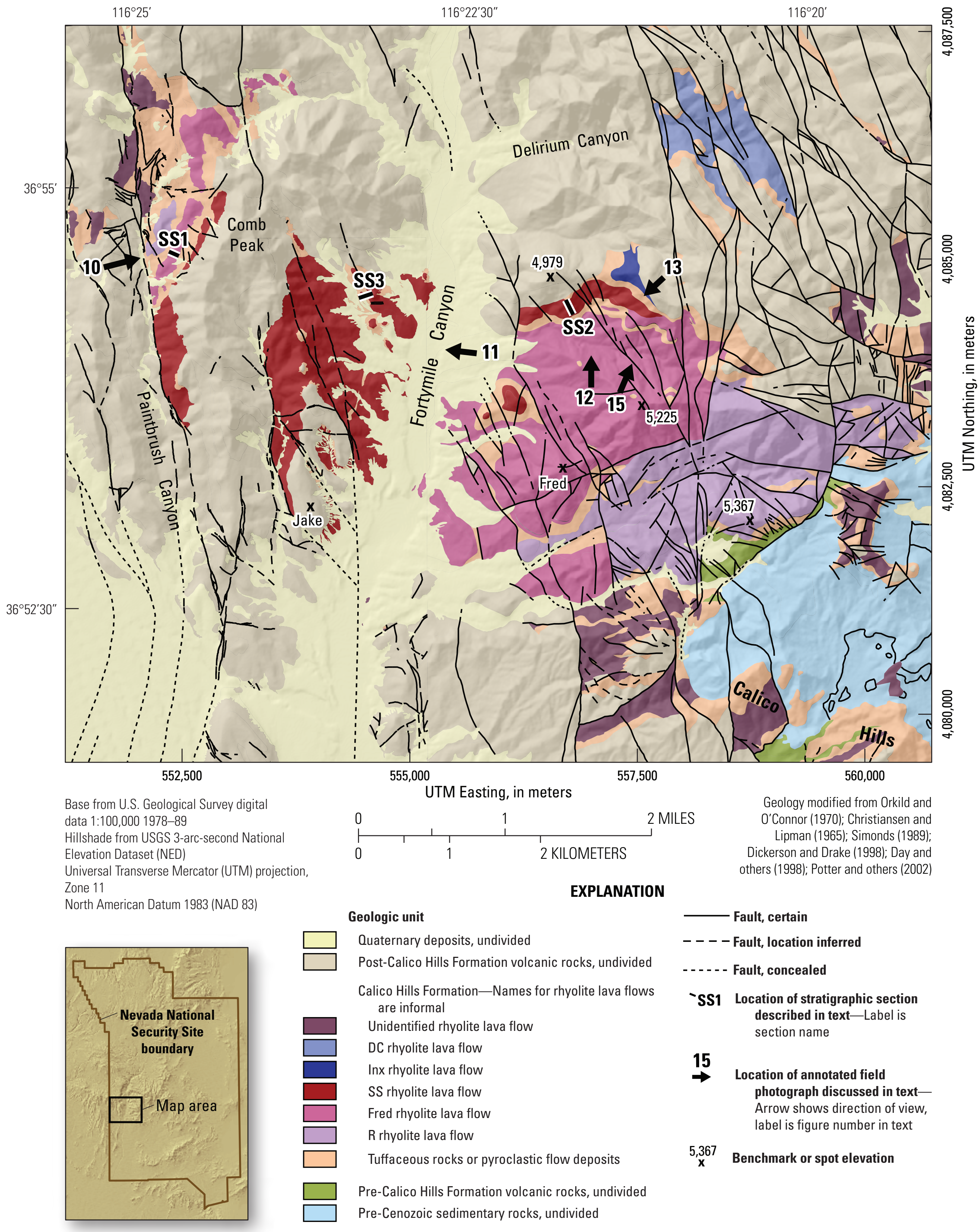


Figure 6. Principal rhyolite lava flows and locations of stratigraphic columnar sections and field photographs.

flow is markedly thicker than beneath Point 4979 (the SS lava flow, locality SS3, fig. 6). This section, modified from Dickerson and Hunter (1994), highlights the transition from a thick section of pyroclastic deposits beneath the flow upward through to the lower obsidian of the rhyolite lava flow (fig. 9). The underlying pyroclastic material consists of a thick sequence of pumiceous and lithic pyroclastic flows with minor pyroclastic fall deposits. The rhyolite lava flow is underlain by as much as 25 m of fragmental material including a pumiceous breccia that transitions upward into obsidian breccia and then to partly to totally annealed obsidian blocks at the eroded top of the section (fig. 9). Dickerson and Drake (1998) report the local presence of clasts as large as 3 to 4 m in the 25 m interval below the lava flow. The fragmental interval underlying the lava flow was previously interpreted as a welding transition in a massive tuff (Dickerson and Hunter, 1994) but is interpreted here as pumice-rich and obsidian-rich phases of a marginal flow-generated breccia that underlies a rhyolite lava flow.

Field Recognition of Specific Lava Flows

Rhyolite lava flows within the Calico Hills Formation were correlated based on distinctive characteristics of specific units in hand sample, outcrop habit, and stratigraphic sequence, and also based on the presence of stratigraphic markers such as the vitric-crystalline contact and transition from autobrecciated carapace inward to nonbrecciated core. Rhyolite lava flows within the Calico Hills Formation were given informal names on the basis of field-based correlation (table 1; fig. 6). Attempts at correlation were most successful where outcrops were continuous and a stratigraphic succession of multiple flows was present. In areas where a single flow was exposed without stratigraphic context, many stratigraphic correlations from physical criteria were not possible. Although detailed petrographic and geochemical analysis of phenocrysts has proved useful in subdividing the Calico Hills Formation at Pahute Mesa (Prothro and Warren, 2001), phenocryst type and abundance was not used for field-based discrimination of individual lava flows in this study. Phenocryst abundance was typically low (2–3 percent), only quartz was readily identified by hand lens, and phenocryst content as observed in hand sample did not appear to vary among lava flows.

The lower part of the crystallized interior of the SS flow (table 1) weathered into distinctive rounded to blocky medium brown cliffs with little internal flow banding. Typically, this unit could be recognized on sight and enabled correlation from Point 4979 westward across Fortymile Canyon to the east side of Comb Peak and to Paintbrush Canyon (fig. 6) based on physical appearance.

The upper obsidian of the Fred flow (table 1) was visually distinctive, having a dark greenish black color that contrasted with the dense black glass of most other obsidians. In addition to color, the upper obsidian of the Fred flow was typically invaded by thin gray-green veinlets and contained a few percentage white crystallites, neither of which was seen in other obsidians. Based on physical features, this obsidian was correlated from Point 4979 westward across Fortymile Canyon to the east side of Comb Peak and to Paintbrush Canyon (fig. 6) based on physical appearance.

Paintbrush Canyon.—Rhyolite lava flows and zeolitically altered interbedded pyroclastic flow and fallout deposits are exposed over a vertical interval of 275 m for approximately 3 km along strike on the west flank of Comb Peak in upper Paintbrush Canyon (Christiansen and Lipman, 1965; Dickerson and Drake, 1998) (fig. 10, location of photo shown on fig. 6). In this area, five lava-bearing horizons are exposed as an east-dipping section beneath Comb Peak (Dickerson and Drake, 1998). The top of the section is unconformably overlain by the younger rhyolite of Comb Peak (fig. 3); the lower part of the exposed section is truncated by the Paintbrush Canyon fault (fig. 10). Lava flows in these exposures are continuous along strike, but cannot be physically traced to the east face of Comb Peak. Lava flows are encapsulated in 5- to 30-m-thick, massive flow-generated breccia (Buesch and Dickerson, 1993). The crystallized interior of the SS lava flow and the upper obsidian of the Fred lava flow were recognized from physical criteria. The Fred flow forms two distinct flow lobes that are separated by an interval of nonwelded pyroclastic flow (fig. 10). The identity of the R lava flow is inferred from a similar stratigraphic sequence in the section near benchmark Fred. Stratigraphic section 1 (SS1; figs. 6 and 7) traverses the Fred lava flow near the center of figure 10.

East side of Comb Peak.—A rhyolite lava flow is exposed over a vertical interval of 275 m on the east side of Comb Peak (Christiansen and Lipman, 1965; Dickerson and Drake, 1998) (fig. 11, photo location shown on fig. 6). Exposures are of the informal SS lava flow, which dips to the east subparallel to the topographic slope, resulting in a broad areal exposure of the unit and large apparent thickness. This lava flow is continuously exposed for approximately 3 km along strike on the west side of Fortymile Canyon between benchmark “Jake” and Comb Peak (fig. 6) (Christiansen and Lipman, 1965; Dickerson and Drake, 1998). The steep northern flank of the SS lava flow is exposed beneath Comb Peak where it abuts zeolitically altered bedded tuff and pyroclastic flow deposits and is unconformably overlain by the Pah Canyon Tuff (Tpp, fig. 11) and younger volcanic rocks. The lower obsidian of the SS lava flow is exposed as four erosionally resistant knobs low on the slope below Comb Peak (lo in fig. 11). Stratigraphic section 3 (fig. 9) describes tuffaceous deposits and vitric lava near the two most prominent resistant knobs (right-center, fig. 11). These knobs have previously been interpreted as a welding transition in tuff, possibly the result of fusing by an overlying lava flow (Dickerson and Hunter, 1994; Dickerson and Drake, 1998). Recognition of the lithofacies within the SS rhyolite lava flow (fig. 11) and comparison with a more complete stratigraphic section to the east of Fortymile Canyon, suggests that these vitric knobs expose the lower obsidian

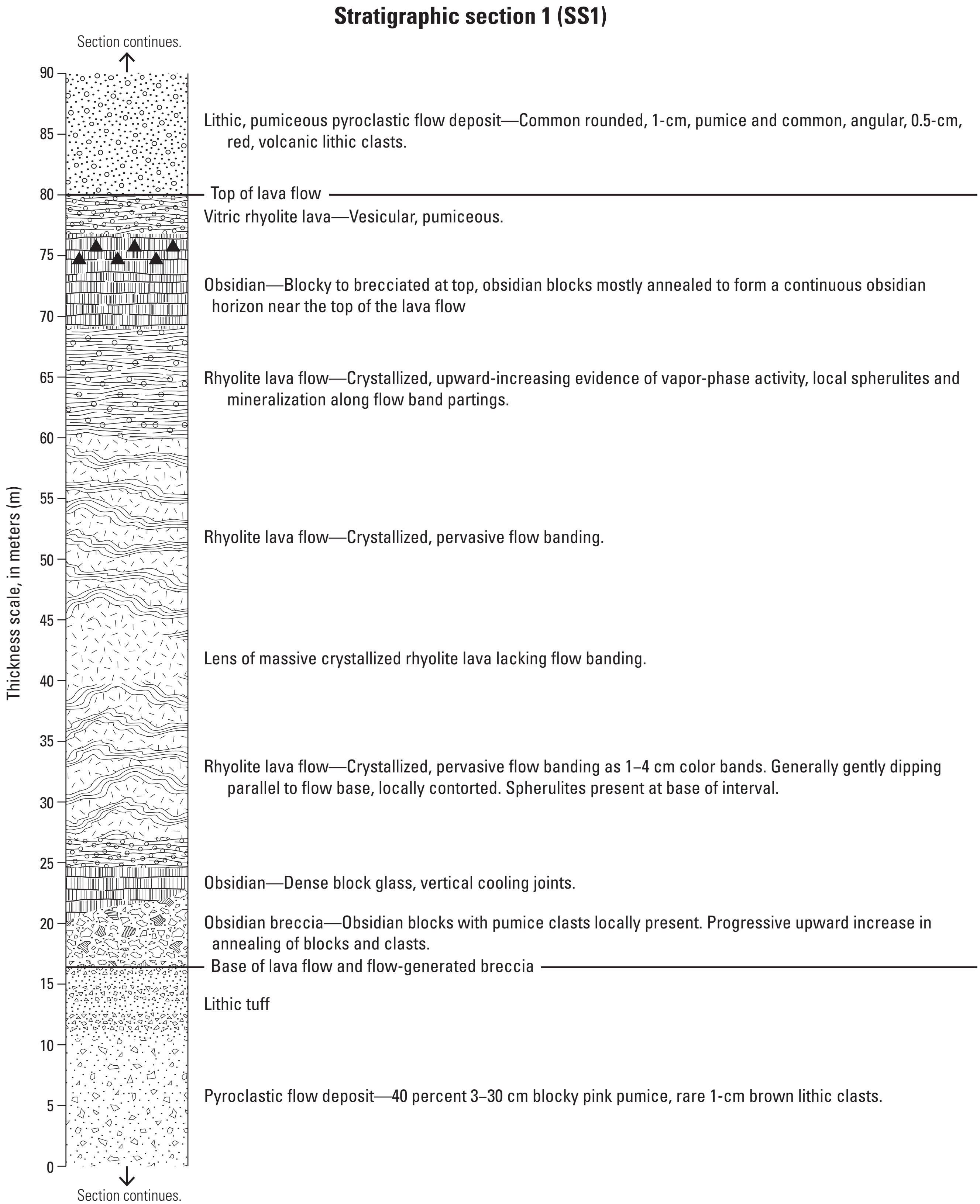


Figure 7. Stratigraphic section 1, stratigraphic columnar section through the informal Fred rhyolite lava flow of Calico Hills Formation, Paintbrush Canyon. Cm, centimeter.

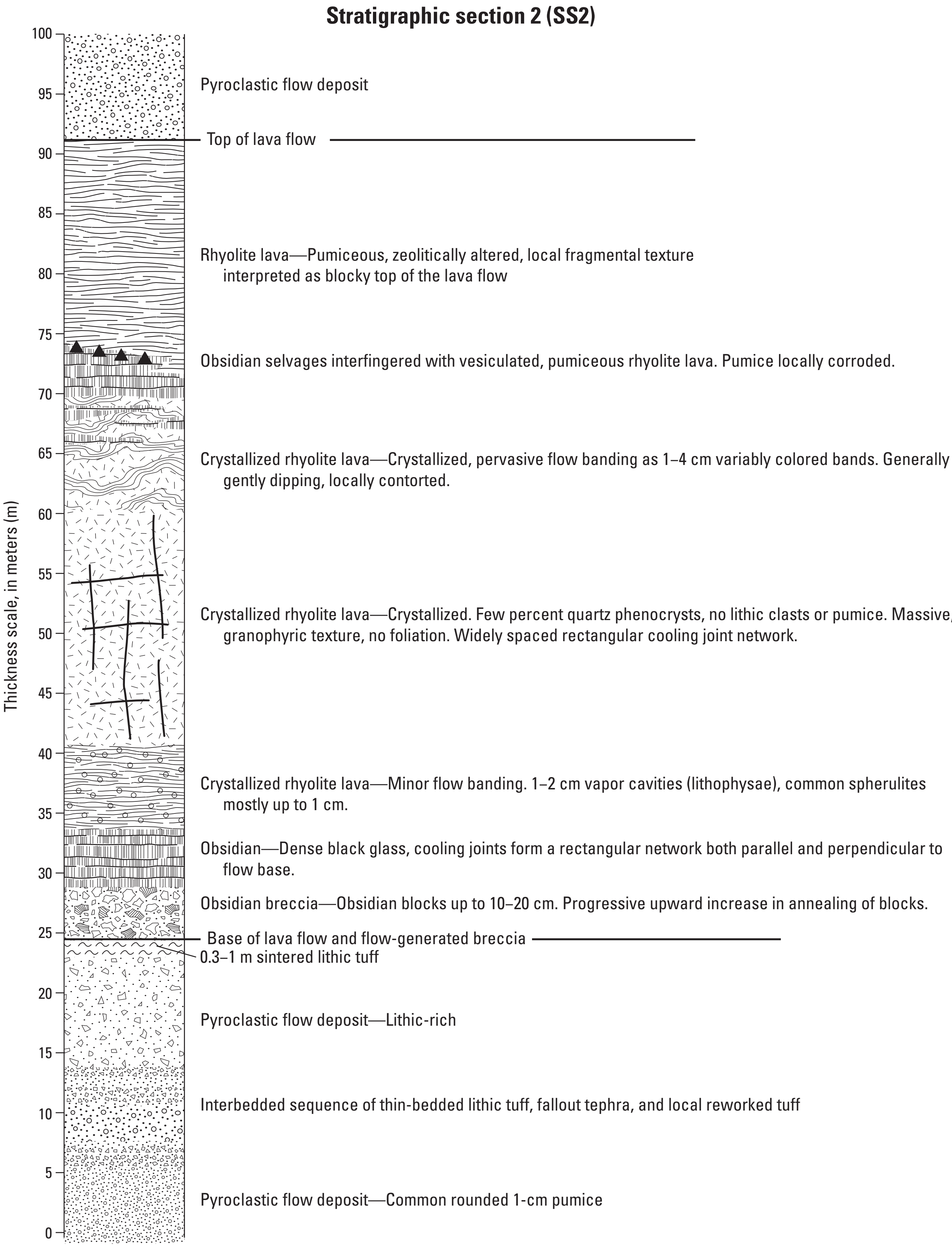


Figure 8. Stratigraphic section 2, stratigraphic columnar section through the informal SS rhyolite lava flow of Calico Hills Formation, below Point 4979. Cm, centimeter; m, meter.

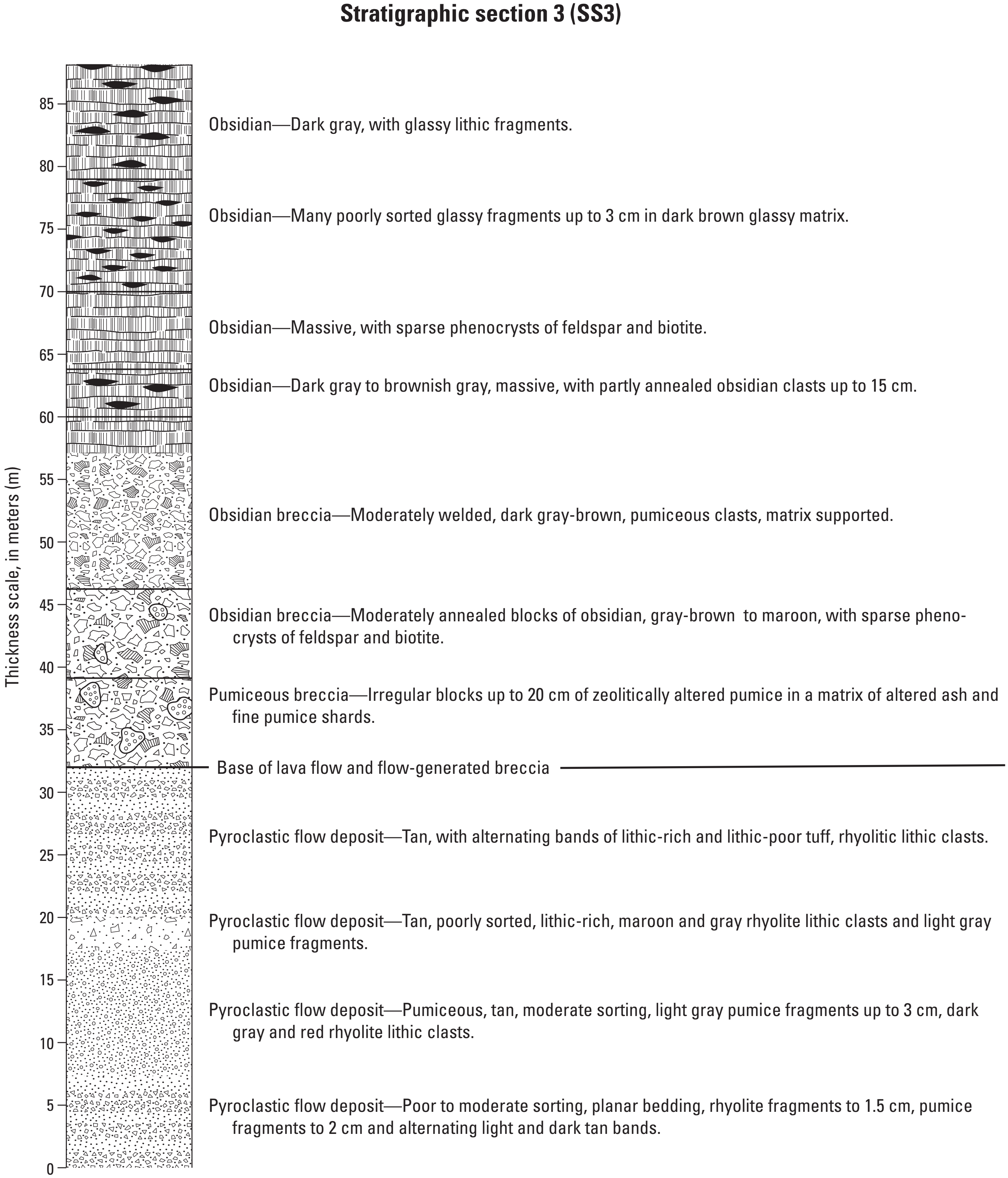


Figure 9. Stratigraphic section 3, stratigraphic columnar section through the base of informal SS rhyolite lava flow of Calico Hills Formation, Fortymile Canyon area. Modified from Dickerson and Hunter (1994). Cm, centimeter; m, meter.

Table 1. Outcrop characteristics of lava flows within Calico Hills Formation.

[Thickness reported in feet to maintain consistency with original data; thickness preceded by ">" indicates reported thickness is a minimum value because base of lava flow is not exposed; Pt, Point; m, meter; cm, centimeter]

Flow name (informal)	Location where flow is exposed[1]	Thickness (feet)	Distinguishing characteristics
Flows that form a continuous stratigraphic section			
Inx	East of Pt. 4979	200	Distinguished primarily by location; stratigraphically overlies SS flow; separated by a thick package of pyroclastic flows and deposits
SS	Pt. 4979	300	Distinctive stony interior, weathers to medium brown blocky to ledgy outcrops, lower part of crystallized lava relatively massive with little obvious flow banding.
	below Comb Peak on the east and south sides	400	
	Paintbrush Canyon	160	
Fred	Benchmark Fred	>430	Visually distinctive upper vitrophyre is dark greenish black, with few percent white crystallites, and typically shot through with millimeter-scale fine veinlets. Crystallized interior pervasively flow banded.
	Pt. 5225	>700	
	Paintbrush Canyon	120	
R	South and east of benchmark Fred	>900	Overlain by yellowish-olive-green lithic-rich pyroclastic flow, locally lithic clasts are larger than 1 m in diameter. Upper part of flow is strongly modified by vapor-phase activity, typically seen as corrosion of pumice.
	Paintbrush Canyon	100	
Isolated flows[2]			
PP	Prow Pass	120	Distinguished primarily by location; vitric lower part of flow has thin (1–2 cm) crystallized and spherulitic flow foliation bands.
DC	Delirium Canyon	200	Distinguished primarily by location; stony interior is dense, pervasively fractured, with hematite alteration along fractures.
PC	Pah Canyon	400	Distinguished primarily by location.

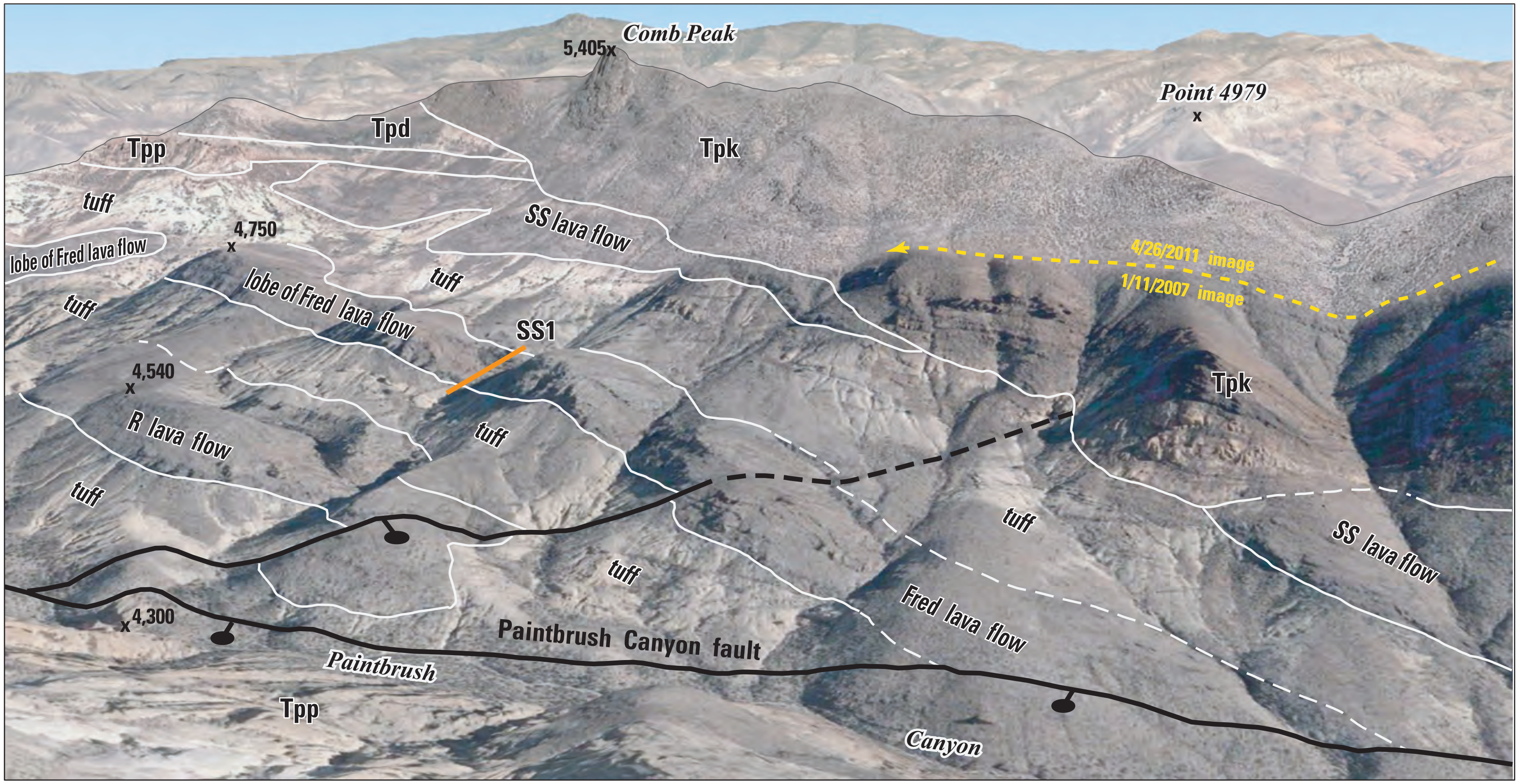
[1]Locations of flow exposures shown on map in figure 2.

[2]Based on isolated nature of exposures and lack of stratigraphic context, it is unknown whether these flows are separate flows or if they correlate to one of the flows within the continuous stratigraphic section.

of the SS lava flow and the partly annealed marginal flow-generated breccia that underlies the lava flow.

Section beneath Point 4979.—Three informal rhyolite lava flows, the Fred, SS, and Inx flows, and intervening zeolitically altered tuffaceous pyroclastic material are exposed over a vertical interval of 200 m on the south-facing canyon wall below Point 4979 (Orkild and O'Connor, 1970) (fig. 12, photo location shown on fig. 6). Stratigraphic section 2 (SS2; fig. 8) traverses the SS lava flow near the center of figure 12. This is the only location in the study area where the Inx rhyolite lava flow occurs, and it stratigraphically overlies the SS lava flow and tuffaceous deposits (figs. 6 and 12). The Inx lava flow is at least 65 m thick and has a well-developed basal lithic breccia of obsidian clasts overlain by as much as 20-m-thick obsidian which grades upward through a spherulitic zone into crystallized rhyolite lava. In this exposure, the Calico Hills Formation is unconformably overlain by the Pah Canyon Tuff (Tpp; fig. 3).

Fred and Point 5225.—Volcanic rocks exposed between benchmark Fred and Point 5225 (Orkild and O'Connor, 1970) (fig. 6) are of a single rhyolite lava flow, the informally named Fred flow. The crystallized interior of this lava flow is at least 140 m thick in this area and underlies the summits between benchmark Fred and Point 5225 (figs. 6 and 13). The base of the Fred lava flow is exposed on the south side of benchmark Fred, where continuous basal flow-generated breccia and lower obsidian overlie coarse pyroclastic flow deposits. The top of the Fred lava flow is defined by a small remnant of zeolitically altered tuffaceous rocks (fig. 13). The upper obsidian of the Fred lava flow is approximately 15 m thick and forms a visually prominent bed to the northwest of Point 5225 that dips west-northwest toward Fortymile Canyon (lithofacies uo, center of fig. 13).



Imagery: Google–Landsat; Google–Digital Globe. Upper half of image April 26, 2011; lower half of image January 11, 2007
VERTICAL EXAGGERATION ×1.1

Perspective view looking to the northeast (N69°E); eye elevation is 5,775 feet, viewing angle 13 degrees above the horizon. Scale is variable due to the effect of perspective; field of view at the lower edge of the image approximately 1 kilometer. Spot elevations, in feet, are shown with an "x" at four points near the left side of the image.

Geology modified from Christiansen and Lipman (1965) and Dickerson and Drake (1998)

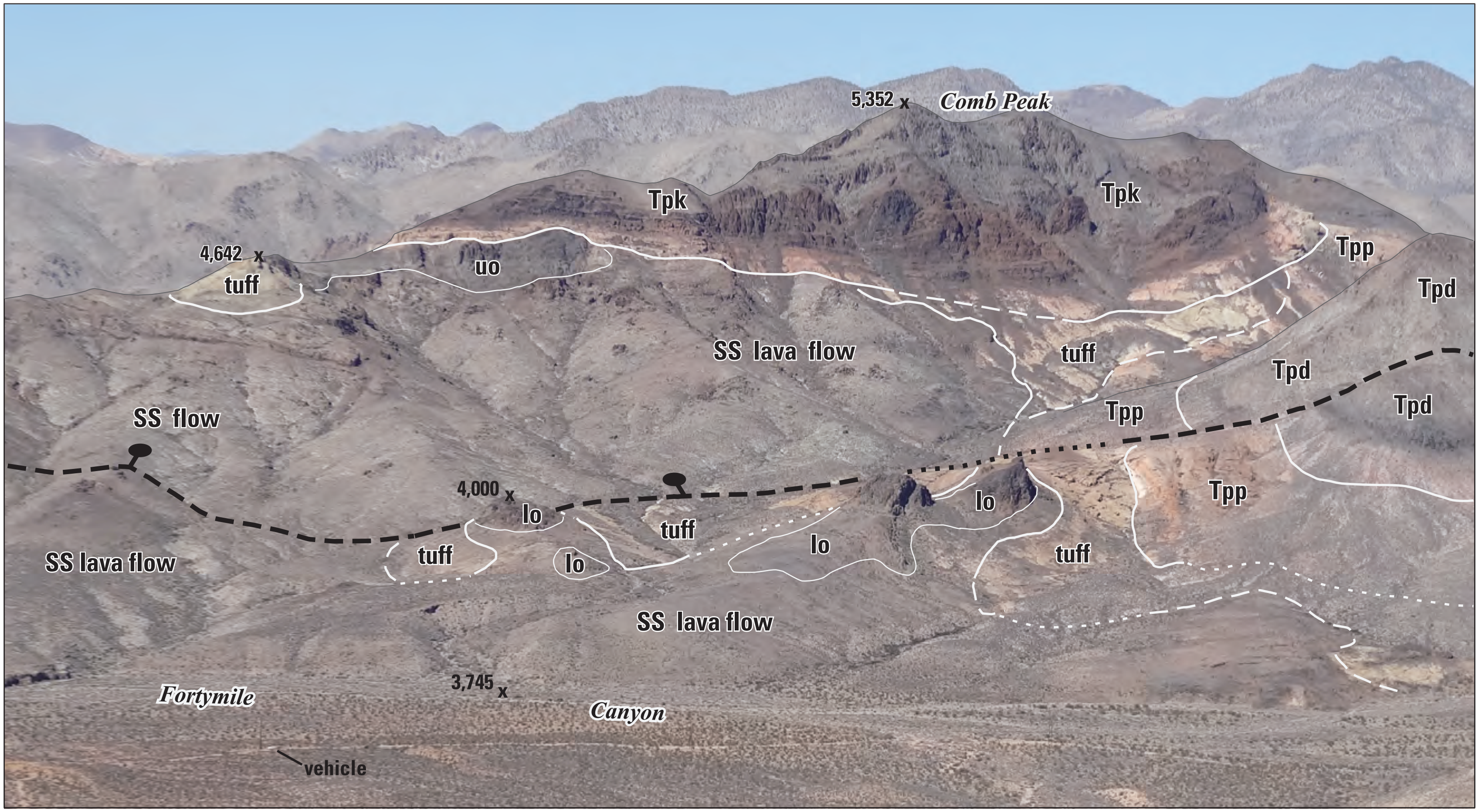
EXPLANATION

Fault—Ball-and-bar on downthrown side. Dashed where inferred

Geologic contact—Dashed where approximately located

Stratigraphic section 1 (SS1)—Shown on figure 7

Figure 10. Perspective image of rhyolite lava flows and interbedded tuffaceous deposits within the Calico Hills Formation exposed in the upper part of Paintbrush Canyon; view is to the northeast to Comb Peak across the upper part of Paintbrush Canyon. Most rock units in this view are informal units of the Calico Hills Formation; individual informally named rhyolite lava flows are labeled. Light-colored intervals between lava flows labeled "tuff" include zeolitically altered pyroclastic flow and fall deposits. Paintbrush Group rocks that overlie the Calico Hills Formation include: Tpp, Pah Canyon Tuff; Tpd, rhyolite of Delirium Canyon; and Tpk, rhyolite of Comb Peak. Dip of the Calico Hills Formation is about 30 degrees southeast, dipping away from the viewer. N, north; °, degree; E, east; SS, stratigraphic section.



Photograph taken by Wayne Belcher, U.S. Geological Survey, 2014

View looking to the west (N82°W). Scale is variable due to the effect of perspective; field of view at the lower edge of the image approximately 1 kilometer. Spot elevations, in feet, are shown with an "x" at four points on the image. Vehicle at lower left gives sense of scale. Dip of Calico Hills Formation is 14 degrees to the east, towards Fortymile Canyon.

Geology modified from Christiansen and Lipman (1965) and Dickerson and Drake (1998)

EXPLANATION

Fault—Ball-and-bar on downthrown side. Dashed where inferred. Dotted where concealed from view behind hill

Geologic contact—Dashed where approximately located. Dotted where concealed from view. Thinner white lines used for internal lithologic contacts within lava flow. Contacts appear irregular in part due to the effect of topography on outcrop pattern

Figure 11. Rhyolite lava flow and associated tuffaceous deposits within the Calico Hills Formation exposed on the west side of Fortymile Canyon; view to the west across Fortymile Canyon to Comb Peak. Most rock units in this view are informal units of the Calico Hills Formation, predominantly a single informal rhyolite lava flow labeled "SS flow." Upper and lower obsidian of this flow are labeled "uo" and "lo,"respectively. Light-colored intervals above, below, and adjacent to the flow, labeled "tuff," include zeolitically altered pyroclastic flow and fall deposits of the Calico Hills Formation. Paintbrush Group rocks that overlie the Calico Hills Formation include: Tpp, Pah Canyon Tuff; Tpd, rhyolite of Delirium Canyon; and Tpk, rhyolite of Comb Peak. N, north; W, west; °, degree; SS, stratigraphic section.

Prow Pass and Yucca Wash.—The Calico Hills Formation exposed near Prow Pass at the north end of Yucca Mountain (figs. 14*A* and 14*B*, location of photos shown on fig. 2) includes possibly two lava flows and is dominated by tuffaceous deposits that are similar in thickness and lithology to those described in boreholes beneath Yucca Mountain (Broxton and others, 1987; Moyer and Geslin, 1995). The tuffaceous rocks at Prow Pass are a sequence of intercalated zeolitized, nonwelded, pyroclastic flows and bedded ash-fall and reworked tuffs approximately 115 m thick; individual layers range from a few centimeters to 30 m in thickness (fig. 14*A*). On the east side of Prow Pass and in scattered small exposures in Yucca Wash, these tuffaceous deposits overlie rhyolite lava flows of unknown thickness (fig. 14*A*). On the west side of Prow Pass, a single 50-m-thick rhyolite lava flow occurs at the top of the Calico Hills Formation, above the tuffaceous interval (fig. 14*B*). The lava flow and the tuffaceous beds thin eastward against a pre-Calico Hills Formation topographic high of older volcanic rocks.

Delirium Canyon.—The Calico Hills Formation is exposed in a limited area in Delirium Canyon; the exposures are only traceable for approximately 1 km before being covered on all sides by younger volcanic rocks (Orkild and O'Connor, 1970) (fig. 6). Exposures consist of a single crystallized rhyolite lava, informally named the DC flow, overlain by blocky, brecciated upper obsidian and coarse pumiceous rhyolite. The base of the lava flow is not exposed. The isolated nature of these exposures and lack of stratigraphic context make it difficult to correlate these rocks with exposures farther south.

Pah Canyon.—The Calico Hills Formation crops out primarily along the south side of Pah Canyon; the exposures are only traceable for approximately 1.5 km before being covered on all sides by younger volcanic rocks (Orkild and O'Connor, 1970) (fig. 2). A single rhyolite lava flow, informally named the PC flow, is exposed, overlain by a sequence of coarse, zeolitically altered pumiceous pyroclastic flow deposits. The base of the PC flow is not exposed. Outcrops in Pah Canyon include a flow-banded crystallized rhyolite that grades upward through zone of abundant centimeter-sized spherulites to a 10-m-thick rhyolitic obsidian.

Description of Lava Flow Edges

The informal SS rhyolite lava flow is the stratigraphically highest of the three main flows to the east of Fortymile Canyon and the level of erosion provides several exposures in which edges of the lava flow may be observed. East of Point 4979, the SS lava flow is approximately 60 m thick, but it gradually thins eastward over a 1-km distance to a steep flow edge that is flanked by a talus apron of vitric clasts derived from the flow and surrounded by tuffaceous pyroclastic deposits (figs. 6 and 15). Near the edge of the lava flow, the upper and lower obsidians merge together to encase the central crystallized core of the flow (cr in fig. 15). On the east side of Comb Peak, the edge of the SS lava flow is steep and is flanked by zeolitically altered pyroclastic flow and fall deposits (fig. 11); similar relations are present at benchmark Jake (fig. 6).

Description of Pyroclastic Deposits

Geologic mapping in Paintbrush Canyon area identified five lava-bearing horizons interstratified with zeolitically altered sequences of pyroclastic flow and fallout deposits, and fluvially redeposited sediment (Buesch and Dickerson, 1993; Dickerson and Drake, 1998). Supplementing the descriptions of pyroclastic rocks from outcrops, there are many detailed descriptions from core in boreholes at Yucca Mountain (Broxton and others, 1989; Moyer and Geslin, 1995) that are appropriate to describe the tuffaceous rocks exposed north of Yucca Mountain. Using borehole data from the Yucca Mountain area, Moyer and Geslin (1995) identified five pyroclastic flows within the Calico Hills Formation based on differences in lithology, pumice content, lithic clast type and abundance, and chemistry.

Tuffaceous deposits within the Calico Hills Formation consist of a series of intercalated pyroclastic flows, fallout tephra, and reworked tuff. Pyroclastic flows are nonwelded and commonly have thin lithic-rich or ashy fallout deposits at their base (Moyer and Geslin, 1995). The pyroclastic units are typically yellow-white to pinkish tan, contain variable amounts of pumice and lithic clasts, and contain 1 to 12 percent crystal fragments of sanidine, quartz, and plagioclase, with subordinate biotite and iron-titanium (Fe-Ti) oxide minerals (Broxton and others, 1989; Moyer and Geslin, 1995). The abundance of crystal fragments is greatest in the lower deposits, as much as 25 percent in the lowermost bedded tuffs and 7 to 12 percent in the lowest pyroclastic flow, and decreases upwards to between 1 and 6 percent in overlying pyroclastic flows (Moyer and Geslin, 1995). Pumice in the pyroclastic flow deposits varies in size and composition and ranges from 10 to 30 percent of the unit. In Pah Canyon, Paintbrush Canyon, and Yucca Wash, nonwelded pyroclastic flows locally include pumice breccia with pumice blocks as much as 30 cm. The pyroclastic flows contain variable amounts of lithic clasts typically 1–5 cm in diameter that includes devitrified, flow-foliated felsic lava, pumiceous tuff, and obsidian. To the southeast of benchmark Fred (fig. 6), the pyroclastic deposits that underlie the Fred lava flow contain clasts of crystallized lava flow that are 3–7 m in diameter. Lithic-poor deposits have between 1 and 5 percent lithic clasts, whereas lithic-rich deposits have 5 to 10 percent clasts with localized zones in which the lithic content is 10 to 50 percent (Moyer and Geslin, 1995).

For Paintbrush Canyon, Dickerson and Drake (1998) used several terms for the mapped pyroclastic rocks. "Massive tuff" represented thick, pumiceous, lithic-bearing pyroclastic flows. "Bedded tuff" described thin pyroclastic flows, pyroclastic-fall deposits, and reworked deposits. "Fused tuffs"

Photograph taken by Wayne Belcher, U.S. Geological Survey, 2014

View looking due north. Scale is variable due to the effect of perspective; field of view across the center of the image approximately 1 kilometer. Spot elevations, in feet, are shown with an "x" at three points on the image.

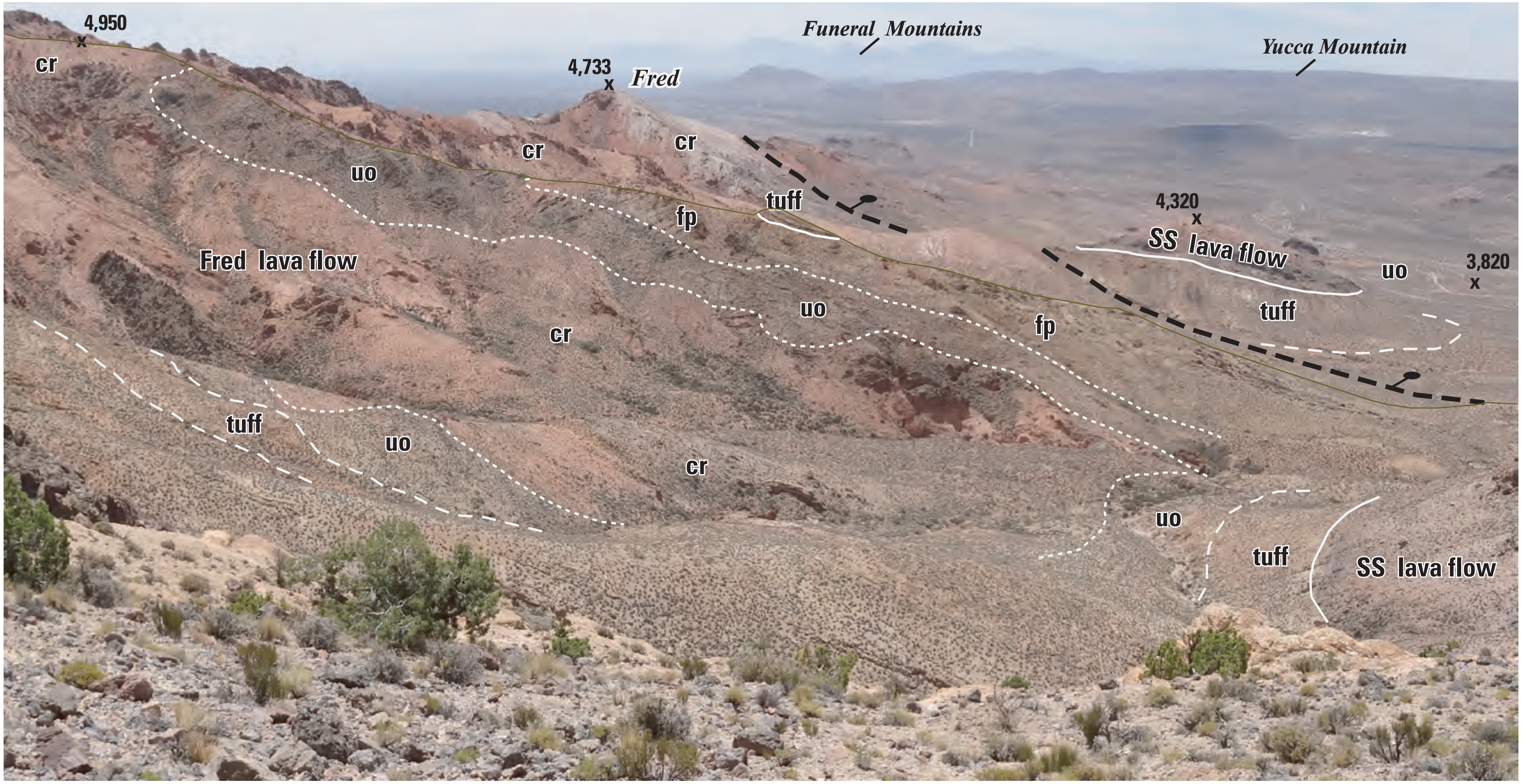
Geology modified from Orkild and O'Connor (1970)

EXPLANATION

Geologic contact—Dashed where approximately located. Dotted where concealed from view. Contacts appear irregular in part due to the effect of topography on outcrop pattern

Stratigraphic section 2 (SS2)—Shown on figure 8

Figure 12. Rhyolite lava flows and associated zeolitically altered tuffaceous deposits within the Calico Hills Formation exposed to the east of Fortymile Canyon; view to the north to Point 4979. Most rock units in this view are informal units of the Calico Hills Formation, individual informally named rhyolite lava flows are labeled. Lithofacies within the SS flow are labeled along one vertical transect as follows: lo, lower obsidian; cr, crystallized rhyolite; uo, upper obsidian; fp, fragmental pumiceous rhyolite. Light-colored intervals above, below, and adjacent to the flow, labeled "tuff," include zeolitically altered pyroclastic flow and fall deposits of the Calico Hills Formation. Paintbrush Group rocks that overlie the Calico Hills Formation include: Tpp, Pah Canyon Tuff; and Tpd, rhyolite of Delirium Canyon; SS, stratigraphic section.



Photograph taken by Wayne Belcher, U.S. Geological Survey, 2014

View looking south-southwest. Point 5225 is out of view, to the left of the upper left corner of the photo. Scale is variable due to the effect of perspective; field of view across the center of the image approximately 2.5 kilometers. Spot elevations, in feet, are shown with an "x" at four points on the image.

Geology modified from Orkild and O'Connor (1970)

Figure 13. Rhyolite lava flows and interbedded tuffaceous deposits within the Calico Hills Formation exposed to the east of Fortymile Canyon near benchmark Fred; view to the south-southwest. All rock units in this view are informal units of the Calico Hills Formation, except for rocks in the distance at Yucca Mountain and the Funeral Mountains. Individual informally named rhyolite lava flows are labeled. Lithofacies within the Fred flow are separated with dotted lines and labeled as follows: cr, crystallized rhyolite; uo, upper obsidian; fp, fragmental pumiceous rhyolite. A small remnant of tuffaceous rocks that overlies the Fred lava flow is present above the Fred flow on the ridge just above the center of the photo. Contacts appear irregular in part due to the effect of topography on outcrop pattern. Light-colored intervals above and below lava flows, labeled "tuff," include zeolitically altered pyroclastic flow and fall deposits. Label "uo" closest to right-hand edge of the image denotes outcrops of the upper vitrophyre of the Fred lava flow. SS, stratigraphic section.

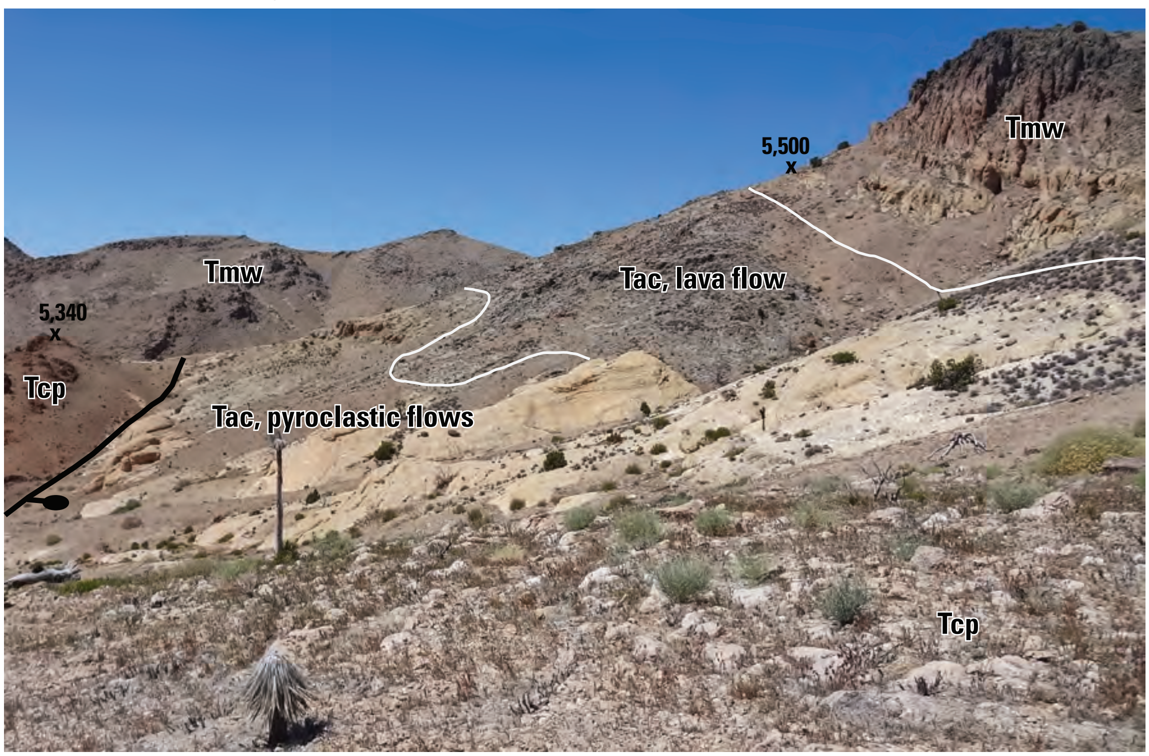
A. Calico Hills Formation, east side of Prow Pass

Photograph by D.S. Sweetkind, U.S. Geological Survey, 1998

View looking west. Scale is variable due to the effect of perspective; field of view across the center of the image approximately 1 km. Spot elevations, in feet, are shown with an "x" at two points on the image. Tpt, Topopah Spring Tuff; Tac, Calico Hills Formation; Tcp, Prow Pass Tuff.

Geology modified from Day and others (1998)

B. Calico Hills Formation, west side of Prow Pass



Photograph by D.S. Sweetkind, U.S. Geological Survey, 1998

View looking west. Scale is variable due to the effect of perspective; field of view across the center of the image approximately 1 kilometer. Spot elevations, in feet, are shown with an "x" at two points on the image. Tac, Calico Hills Formation; Tcp, Prow Pass Tuff; Tmw, rhyolite of Windy Wash of Timber Mountain Group.

Geology modified from Potter and others (2002)

Figure 14. Rhyolite lava flows and tuffaceous pyroclastic deposits within the Calico Hills Formation at Prow Pass. *A*, east side of Prow Pass, view looking to the west; *B*, west side of Prow Pass, view looking to the east.

Photograph taken by Wayne Belcher, U.S. Geological Survey, 2014

View looking due north-northeast. Scale is variable due to the effect of perspective; field of view across the center of the image approximately 1.5 kilometers. Spot elevations, in feet, are shown with an "x" at four points on the image.

Geology modified from Orkild and O'Connor (1970)

EXPLANATION

Fault—Ball-and-bar on downthrown side

Geologic contact—Dashed where approximately located. Contacts appear irregular in part due to the effect of topography on outcrop pattern

Figure 15. The edge of the informal SS rhyolite lava flow exposed to the east of Point 4979 east of Fortymile Canyon; view to the north-northeast. Most rock units in this view are informal units of the Calico Hills Formation, individual informally named rhyolite lava flows are labeled. Lithofacies within the SS lava flow are labeled as follows: lo, lower obsidian; cr, crystallized rhyolite; uo, upper obsidian; fp, fragmental pumiceous rhyolite; obs, undifferentiated obsidian. Light-colored intervals above, below, and adjacent to the flow, labeled "tuff," include zeolitically altered pyroclastic flow and fall deposits. Tpt, Topopah Spring Tuff of the Paintbrush Group unconformably overlies the Calico Hills Formation. SS, stratigraphic section.

where tuffaceous rocks were upwardly partially to densely welded (or fused) beneath by lava flows. Most of these descriptions were generalized for map units and contained the overall ranges in sizes and abundances of clasts and phenocrysts. However, the descriptions were not representative of specific beds, so stratigraphic trends and specific correlations were not presented.

Although some boreholes in the southern parts of Yucca Mountain contain pyroclastic deposits with vitric glass shards and pumice clasts, most of the original glassy fragments have been zeolitically altered (Broxton and others, 1989; Moyer and Geslin, 1995) in the northern parts of Yucca Mountain and exposures in Yucca Wash, Paintbrush Canyon and the Fortymile Canyon areas. Locally in the upper Paintbrush and Fortymile Canyon areas, zeolitic alteration obscures contacts between the autoclastic lava flow breccia and blocky, massive tuff (Dickerson and Drake, 1998). Buesch and Spengler (1999) describe some of the compositional and textural controls on zeolitization such as the need for glassy material, high original porosity and permeability, and large surface area of grains. Highly porous and permeable, nonwelded and partially welded tuffs were identified as being highly susceptible to zeolitization (Buesch and Spengler, 1999); highly porous obsidian and pumice would be expected to be similarly susceptible. Rocks with low initial porosity and permeability such as densely welded tuff were identified as having low susceptibility to zeolitic alteration (Buesch and Spengler, 1999); obsidian and crystallized rhyolite lava would be expected be similarly unaffected, except adjacent to fractures. Buesch and Spengler (1999) also describe the vitric-zeolitic boundary between vitric rocks and pervasively zeolitized rocks at Yucca Mountain, and how this regional contact relates to the lithostratigraphic and structural history of the Yucca Mountain area.

Weathering zones or paleosol horizons generally are not observed within the sequence of pyroclastic flows, nor are they present at the contact between the pyroclastic deposits and an overlying rhyolite lava flow. Moyer and Geslin (1995) describe some reworked and paleosol horizons, especially in the lowermost bedded tuffs, and in the possibly reworked bedded deposits in borehole USW G-3 surficial exposure near Busted Butte. Absence of paleosols indicates that there are no large time breaks between eruptions of successive pyroclastic flows or between the pyroclastic deposits and the eruption of rhyolite lava, or that paleosols were subsequently removed by erosion prior to deposition of overlying volcanic units. Locally, in surface exposures such as near Busted Butte (fig. 1) and north of Jake (fig. 6), and in boreholes such as USW SD-9 (fig. 2), the uppermost pyroclastic deposits in the Calico Hills Formation have an incipient paleosol upon which the Topopah Spring Tuff was deposited, indicating an unspecified length of time between these two formations (David C. Buesch, USGS, written commun., 2014). In Paintbrush Canyon, Dickerson and Drake (1998) noted some intraformational angular discordance, indicating at least local deformation and tilting during the time of the deposition of the Calico Hills Formation, but in general strong angular relations are not seen within the formation.

Fracture Characteristics of Lava Flows and Tuffaceous Deposits

Data on fracture characteristics in the tuffaceous deposits of the Calico Hills Formation come from a single locality exposed near Prow Pass (fig. 2). Fractures at surface exposures of zeolitically altered tuffaceous rocks occur as two steeply dipping fracture sets, a prominent northwest-striking set and a slightly less well developed northeast striking set (table 2). Fractures rarely showed shear displacement; nearly all fractures were interpreted to be extension features. Because the tuffaceous pyroclastic deposits are nonwelded, all fractures are interpreted to be of tectonic origin and not primary joints related to cooling of the deposits. At Prow Pass, northwest-striking fractures occur in widely spaced northwest-trending zones. Each zone consists of northwest-striking fractures that are 5–10 m long and closely spaced (0.5 to 1 m). These northwest-trending zones are spaced 50 to more than 100 m apart; in between the zones, northwest-striking joints are sparse, with a fracture spacing of 2 to greater than 4 m.

The nature of fracturing within the rhyolite lava flows of the Calico Hills Formation varies with position in the flow and lava flow lithostratigraphy (table 3). The upper and lower obsidians typically have the best-developed cooling joint sets. Joints in the lower obsidian are typically the best developed with three vertical sets oriented approximately 120 degrees (°) to each other and as much as 3 to 4 m in length. Joint development in the crystallized interiors of rhyolite flows of the Calico Hills Formation differs from that described in thicker, massive rhyolite flows elsewhere, where regular patterns of vertical columnar cooling joints are observed (Bonnischsen and Kauffman, 1987; Henry and others, 1990). Crystallized interiors of Calico Hills Formation lava flows may have crude rectangular networks of cooling joints where the flows are massive. Where flow banding is well developed, the primary discontinuities are partings along the flow foliation. Tectonic fractures may link the partings, but in general there is no strong pattern of vertical fracturing; instead, the flow foliation creates a sheet-like fracture pattern.

Discussion

Surface and subsurface geologic data can be combined to interpret the overall thickness of the Calico Hills Formation and the proportion of lava flow lithology in parts of the study area. Geologic mapping and field-based correlation of individual lava flows allow for the interpretation of the thickness and extent of specific flows and the location of their source areas.

Total Thickness and Proportion of Rhyolite Lava Flows in the Formation

The total thickness of the Calico Hills Formation was estimated by combining and contouring: (1) borehole data (table 4), (2) modeled thickness extracted from the Yucca Mountain site-scale hydrogeologic framework model (Bechtel SAIC Company, 2002), and (3) modeled thickness extracted from the 3D hydrogeologic framework model of the Death Valley regional groundwater flow system (Faunt and others, 2010) (fig. 16). The Calico Hills Formation attains its maximum thickness near Fortymile Canyon where it is at least 500 m thick. In this area, formation thickness is derived from the regional framework model (Faunt and others, 2010), because the base of the formation is not penetrated by borehole UE-29 a#2 nor is the base of the formation exposed in outcrop (fig. 16). Thickness of the formation decreases to the southeast where the unit has been removed by erosion above the domical uplift of the Calico Hills (Simonds, 1989; Potter and others, 2002) (fig. 16). Thickness of the formation decreases to the southwest across Yucca Mountain, except for a localized southward-trending region of thicker accumulation immediately to the east of Yucca Mountain (Moyer and Geslin, 1995; Buesch and Spengler; 1999).

The proportion of rhyolite lava flow lithology as a percentage of total thickness of the Calico Hills Formation was calculated for selected boreholes in the study area (table 4) and for vertical profiles of surface outcrops. Only five boreholes in the northeastern part of Yucca Mountain, in Yucca Wash and in Fortymile Canyon, penetrated lava flows; boreholes farther to the south intercept only nonwelded pyroclastic flows and fallout tephra deposits (Broxton and others, 1987; Moyer and Geslin, 1995) (table 4; fig. 16). Outcrops in lower Fortymile Canyon have the greatest proportion of lava flows; outcrops to the east of benchmark Fred are of lava-flow lithology (fig. 16). In general, the proportion of lava flows within the formation decreases to the south and west away from the Fortymile Canyon area. The rhyolite lava flows at Prow Pass are more than 10 km to the west of the thick lava flows in Fortymile Canyon and are unlikely to have been erupted from the same source area as the lava flows near Fortymile Canyon. Using borehole data from Yucca Mountain, Moyer and Geslin (1995)

Table 2. Fracture characteristics of tuffaceous pyroclastic deposits within Calico Hills Formation at Prow Pass.

[All fractures interpreted as tectonic joints. Orientation of fracture sets reported as strike direction in degrees east or west of north and dip in degrees. Fracture length is the range of mean lengths of the fracture sets; m, meter; N, north; W, west; S, south; E, east]

Number of fractures	Strike	Dip	Trace length	Average spacing
134	Peak strike orientation, N35W to N15W; range in strike direction, N45W to N–S	85–88 degrees to northwest or southwest	Typically 3–5 m, up to 10 m	Fractures occur in zones spaced 50–100 m apart; spacing within zones 0.5–1 m; spacing between zones 2–4 m
68	Peak strike orientation, N55E to N70E; range in strike direction, N50E to N85E	75–85 degrees to the northwest	1–2 m	2 m

Table 3. Fracture characteristics of lava flows within Calico Hills Formation.

[m, meter; °, degree]

Lithofacies	Fracture characteristics
Pumiceous rhyolite	Poorly fractured. Dominantly short fractures of tectonic origin.
Upper vitrophyre	Cooling joints may be moderately to well-developed.
Crystallized flow interior	Where flow foliation is absent, cooling joints form a crude rectangular network with spacing of 2–3 m. Where flow foliation is well-developed, foliation-parallel partings are the primary type of discontinuity.
Lower vitrophyre	Crudely developed columnar jointing as three vertical sets of cooling joints oriented at 120° to each other. Joints up to 3–4 m in height.
Basal flow breccia	Fractures have short trace lengths and nonsystematic orientations.

constructed an isopach map of the Calico Hills Formation and used it to (1) describe the subsurface distribution of rhyolite lava flows in Yucca Wash, and (2) suggest the lava flows at the north end of Yucca Mountain were topographically controlled and confined to a paleovalley.

Based on the thickness map and the distribution of rhyolite lava flow, the volume of erupted material in the study area is estimated as 37 cubic kilometers (km^3), of which 17 km^3 is rhyolite lava flow and 20 km^3 tuffaceous pyroclastic deposits. The volumetric estimate incorporates considerable uncertainty because (1) the Calico Hills Formation is covered by younger units over much of the study area, (2) borehole data are largely limited to the Yucca Mountain area, and (3) most boreholes did not penetrate the base of the Calico Hills Formation, so thickness estimates rely on projection of contoured values across covered areas and on the results from geologic framework models. Sawyer and others (1994) estimated the erupted volume of the Calico Hills Formation at approximately 250 km^3, and this included the area south of the Rainier Mesa caldera and the subsurface accumulation beneath Pahute Mesa.

Thickness and Extent of Individual Lava Flows

The three largest-volume rhyolite lava flows, the informally named SS, Fred, and R lava flows, form a stratigraphic package and have their greatest thicknesses in the Fortymile Canyon area (figs. 16 and 17). The stratigraphically lowest R lava flow has its greatest thickness of at least 240 m in the southeastern part of the study area, adjacent to faults that separate the volcanic section from underlying Paleozoic bedrock (Potter and others, 2002). The overlying Fred lava flow attains its greatest thickness nearby, to the east of Fortymile Canyon, where it is at least 150 m thick. These lava flows are buried by younger flows and do not crop out again until thin (25–35 m) distal remnants are exposed in the east-tilted structural block in upper Paintbrush Canyon. Stratigraphically highest of the three main flows is the SS lava flow, which is approximately 60 m thick to the east of Fortymile Canyon and thickens to 110 m to the south of Comb Peak (fig. 17). Orientation of the mapped edges of the SS lava flow, combined with interpreted flow direction as indicated by flow banding, suggest that it flowed from northeast to the southwest. The SS lava flow might have thinned above a preexisting topographic volcanic highland created by the R and Fred lava flows and reached its maximum thickness farther to the west, beyond this paleotopographic high.

Other flows in the study area form isolated exposures without stratigraphic context (fig. 17) and are harder to interpret in terms of thickness variations. Compared to the distal parts of flows in Paintbrush Canyon, the thickness of more than 120 m for the rhyolite lava flow in Pah Canyon is anomalously thick, as is the greater than 356 m of lava flow lithology present in borehole UE-29 a#2, with the base of the lava flow interval not penetrated.

The SS flow is the only lava flow in which both edges are exposed and for which a flow width may be measured (fig. 17). The apparent width, transverse to interpreted flow direction, of the SS flow beneath the east side of Comb Peak is approximately 3 km, and it has an exposed length of at least 5.2 km from east of Point 4979 to Paintbrush Canyon. The Fred lava flow is at least 2.5 km wide measured from the exposed base south of Fred to Point 4979 where it is buried, and a length of at least 6 km from the thick crystallized rhyolite lava at Point 5225 westward to Paintbrush Canyon. Length-to-height ratios of 10:1 or greater for these rhyolites suggest that they are lava flows with a tongue-shaped geometry, instead of circular domes, and also suggest lateral movement away from the vent instead of accumulation over a vent.

Source Area of the Rhyolite Lava Flows

On the basis of the presence of lava to the north of the Yucca Mountain area, the absence of lavas beneath most of Yucca Mountain, and the general southwestward thinning of the formation, source vents for the rhyolite lavas within the Calico Hills Formation might be in the Calico Hills, in the Fortymile Canyon area, and in upper Yucca Wash (Dickerson and Drake, 1998; Buesch and Spengler, 1999). Geologic mapping performed during the present study did not identify any physical feature that could be positively identified as a vent, however, several lines of evidence suggest that the primary vent areas for at least some of the lava flows in the study area are on the east side of Fortymile Canyon, to the east of benchmark Fred near Point 5225 (fig. 2), including:

Thickness.—On the east side of Fortymile Canyon, the Calico Hills Formation appears to reach its maximum thickness (fig. 16). Two of the most extensive rhyolite lava flows, the Fred and R lava flows, have their greatest thickness in this area (>150 m and >240 m, respectively) (fig. 17).

Proportion of rhyolite lava.—Near Point 5225 (fig. 17), the Calico Hills Formation consists primarily of crystallized rhyolite lava flows, and these areas are the topographically highest accumulations of thick, crystallized rhyolite lava in the study area. In a study of rhyolite domes of the Taylor Creek, New Mexico rhyolite, Duffield and others (1995) suggested that the topographically highest part of any rhyolite eruptive unit marks the pre-erosion vent area, because erosion is predominantly vertical, not lateral.

Flow banding.—The rhyolite lava flows near Point 5225 have a preponderance of steeply dipping flow bands, which may be expected close to a source vent (Christiansen and Lipman, 1966; Fink, 1983), but no distinct concentric pattern of flow bands was identified.

Clast size within the pyroclastic deposits.—To the southeast of benchmark Fred (fig. 6) the pyroclastic deposits that underlie the Fred lava flow thicken eastward and contain clasts of crystallized rhyolite material that are 3–7 m in diameter. These are the largest clasts observed in the nonwelded pyroclastic deposits anywhere in the study area; clasts of this size are inferred to be proximal to an eruptive vent.

Table 4. Thickness of Calico Hills Formation and lava flow thickness as a percentage of total thickness for selected boreholes and outcrop sections.

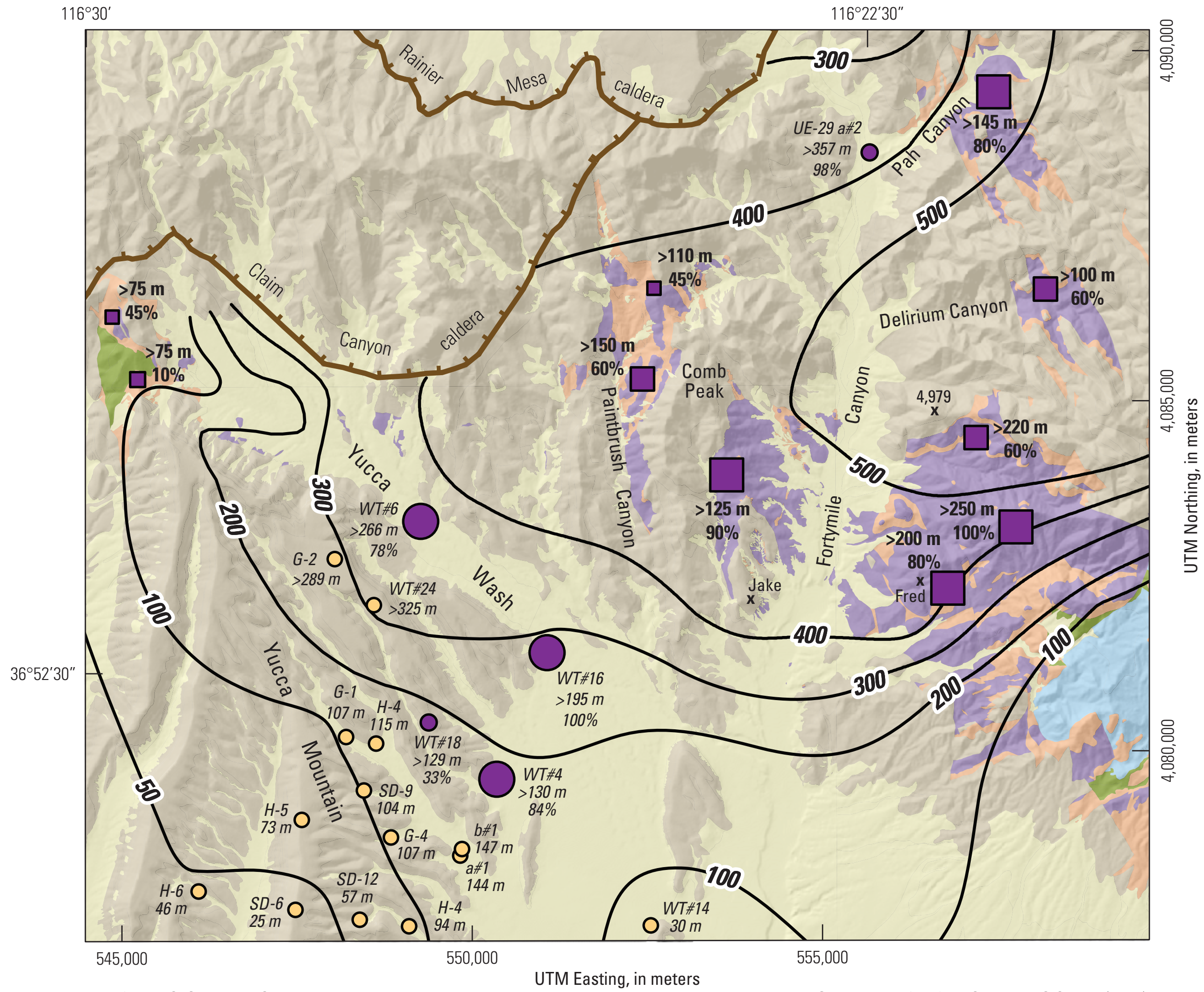
[Thickness reported in feet to maintain consistency with original data; nr, not reported; >, well bottomed in Calico Hills Formation or base of formation not exposed in outcrop, so actual formation thickness is greater than that reported; ---, value not calculated]

Location name	Location		Thickness of Calico Hills Formation (feet)	Aggregate thickness of lava-flow intervals (feet)[2]	Lava flow thickness, as percentage of total thickness[2]
	Northing[1]	Easting[1]			
Boreholes					
UE-25 a#1	4,078,527	549,845	471.8	0	0
UE-25 b#1	4,078,620	549,869	483.9	0	0
USW NRG-7A	4,079,723	548,825	15.4	0	0
UE-25 WT#4	4,079,617	550,365	>426	356	84
UE-25 WT#6	4,083,289	549,281	>873.5	683.5	78
UE-25 WT#14	4,077,534	552,558	>100	0	0
UE-25 WT#16	4,081,419	551,077	>641	641	100
UE-25 WT#18	4,080,422	549,392	>423	140	33
UE-29 a#2	4,088,548	555,673	>1,194.9	356.5	98
USW G-1	4,080,215	548,219	373.5	0	0
USW G-2	4,082,751	548,058	947.7	0	0
USW G-4	4,078,787	548,858	352	0	0
USW H-1	4,080,123	548,647	351.1	0	0
USW H-4	4,077,519	549,115	255	0	0
USW H-5	4,079,035	547,585	239.9	0	0
USW H-6	4,078,013	546,116	152	0	0
USW SD-6[3]	4,077,750	547,498	81.1	0	0
USW SD-9	4,079,453	548,470	340.8	0	0
USW SD-12	4,077,612	548,412	188	0	0
USW WT-24[3]	4,082,094	548,611	1,065.2	0	0
Outcrop locations					
Upper Paintbrush Canyon	552,346	4,085,422	500	300	60
Head of Paintbrush Canyon	552,486	4,086,605	350	150	43
Northwest of Prow Pass	544,882	4,086,452	250	120	48
Pah Canyon	557,355	4,089,508	480	400	83
Delirium Canyon	558,151	4,086,633	300	200	67
Pt. 4969	557,160	4,084,554	>720	420	60
Benchmark “Fred”	556,742	4,082,406	633	500	79
East of benchmark “Fred”	557,718	4,083,215	>1,200	1,200	100
East side of Comb Peak	553,616	4,083,996	>400	360	90

[1]Universal Transverse Mercator projection, UTM Zone 11, North American Datum of 1983 (NAD 83).

[2]Where well penetrated a partial thickness of the formation; calculated thicknesses are for the interval penetrated.

[3]Absence of rhyolite lava flows in USW SD-6 and USW WT-24 from David Buesch, U.S. Geological Survey, written commun., 2014.



Base from U.S. Geological Survey digital data 1:100,000 1978–89; Hillshade from USGS 3-arc-second National Elevation Dataset (NED)
Universal Transverse Mercator (UTM) projection, Zone 11
North American Datum 1983 (NAD 83)
Location of map area shown on figure 2

0 1 2 MILES
0 1 2 KILOMETERS

Geology modified from Orkild and O'Connor (1970); Christiansen and Lipman (1965); Simonds (1989); Dickerson and Drake (1998); Day and others (1998); Potter and others (2002)

EXPLANATION

Geologic unit

- Quaternary deposits, undivided
- Post-Calico Hills Formation volcanic rocks, undivided
- Calico Hills Formation
  - Lava flow and flow breccia
  - Tuffaceous rocks
- Pre-Calico Hills Formation volcanic rocks, undivided
- Pre-Cenozoic sedimentary rocks, undivided

Topographic or structural caldera boundary (modified from Potter and others, 2002)

Jake x **Location of named topographic feature**

—100— **Thickness of Calico Hills Formation, in meters (m)**—Contour interval 100 m; 50 m contour shown to southwest of Yucca Mountain. Contours near Yucca Mountain modified from Moyer and Geslin (1995) and Bechtel SAIC Company (2002); other contours modifed from Faunt and others (2010)

Borehole showing thickness of Calico Hills Formation and proportion of lava flows as percent (%) of total thickness—Borehole designations are abbreviated from that shown in appendix 1. Thickness of Calico Hills Formation penetrated in meters (m) is shown below borehole; thickness preceded by ">" indicates hole bottomed in unit without penetrating full thickness

0% lava flows	<50% lava flows	50–75% lava flows	>75% lava flows
H-5 73 m	WT#18 >129 m 33%	not present in any borehole	WT#6 >266 m 78%

Outcrop section showing thickness of Calico Hills Formation and proportion of lava flows as percent of total thickness—Thickness, in meters is preceded by ">" indicating that reported thickness is a minimum value because base of section is not exposed

All outcrop sections contained lava flows.	<50% lava flows	50–75% lava flows	>75% lava flows
	>75 m 45%	>100 m 60%	>200 m 80%

Figure 16. Contoured thickness of the Calico Hills Formation, showing proportion of the formation composed of lava flow lithology for boreholes and outcrop sections.

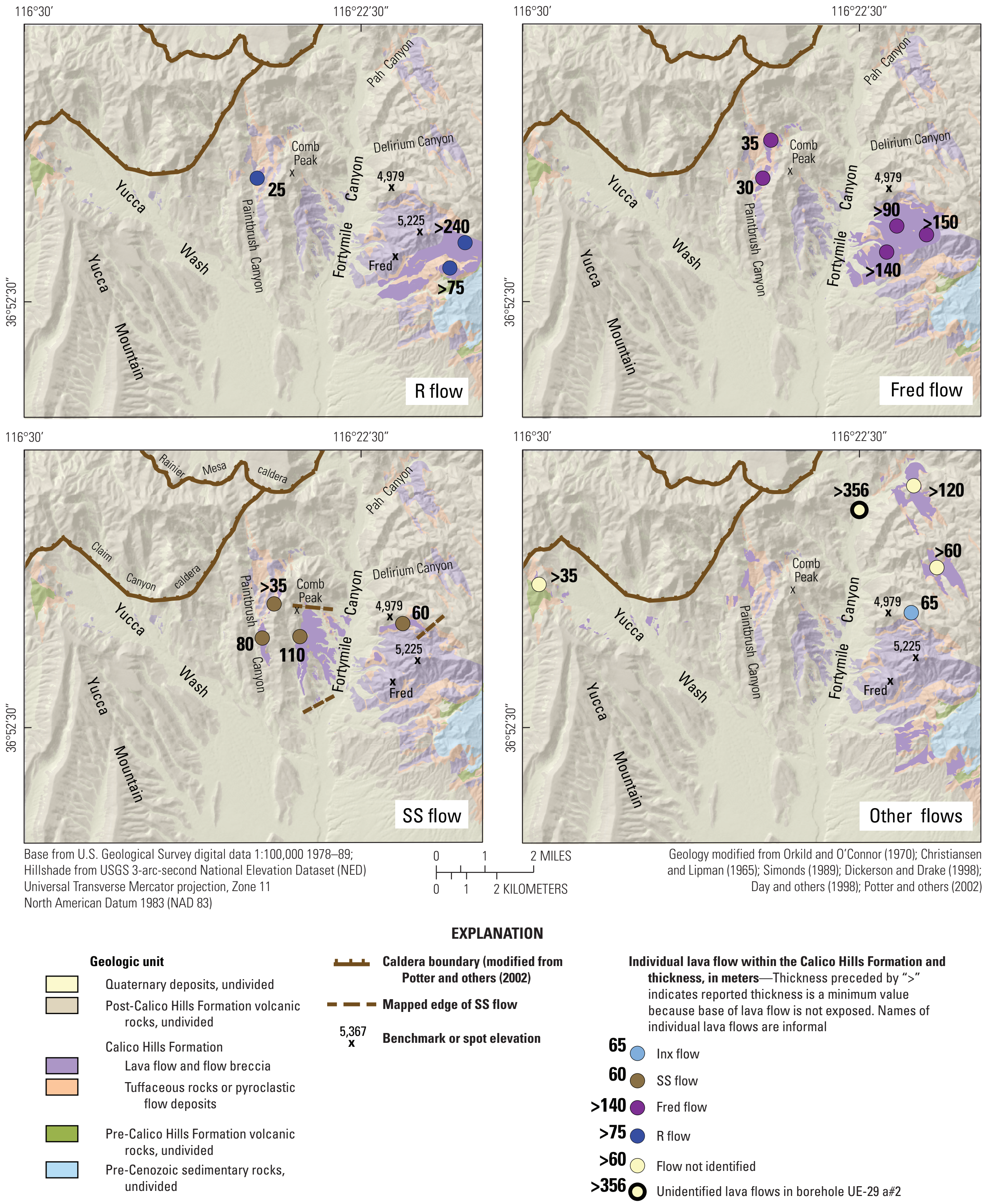


Figure 17. Thickness variations of mapped informal rhyolite lava flows (R, Fred, and SS) within the Calico Hills Formation.

Local intrusive features.—To the north of benchmark Fred (fig. 6), the upper obsidian of the Fred lava flow is invaded by local vertical injection dikes of crystallized rhyolite lava. Similar intrusive features have been described in the upper breccia of the rhyolite of Comb Peak (Christiansen and Lipman, 1966, p. 675). These dikes represent intrusion of lava into the brecciated upper part of the flow and could be the result of endogenous growth adjacent to a source vent, where the upper surface of the flow is inflated and invaded by new lava from a nearby vent.

Thickness of the Topopah Spring Formation.—Changes in the thickness of the Topopah Spring Tuff indicate topographic highlands formed by the lava flows in the Calico Hills Formation. In many places near Shoshone Mountain and the Calico Hills (fig. 2), the Topopah Spring Tuff directly overlies the Calico Hills Formation (fig. 3; Orkild and O'Connor, 1970). In outcrops where both the top and base of the Topopah Spring Tuff are preserved, the formation thins to the southwest toward Fortymile Canyon and the present outcrops of Calico Hills Formation. For example, the Topopah Spring Tuff is 125–150 m thick at Shoshone Mountain, but thins to as little as 10 m in Pah Canyon, Delirium Canyon, and near Point 4979 (Orkild and O'Connor, 1970). The thinning of the Topopah Spring Formation is interpreted to be the result of a preexisting constructional volcanic high created by the near-vent accumulation of rhyolite lava flows of the Calico Hills Formation. Similarly, there are large changes in the thickness of the Topopah Spring Tuff from exposures in upper Paintbrush Canyon area where the tuff is 1 to 2 m thick (Dickerson and Drake, 1998) southwestward to approximately 370 m thick in boreholes USW H-1, USW NRG-7a, and USW SD-9 at Yucca Mountain (Buesch and Spengler, 1999). Most of the changes in thickness are north and northeast of USW NRG7a toward Yucca Wash where it is 93 to 109 m thick, and these changes resulted from deposition of the Topopah Spring Tuff across topographic highlands formed on lava flows of the Calico Hills Formation (Buesch and Spengler, 1999).

Thick rhyolite lava flows in Delirium Canyon and Pah Canyon are only partly exposed; however, the thicknesses of the lava flows in these two areas suggest that they too may be proximal to source vents. If these exposures are linked to those lava flows east of benchmark Fred near Point 5225, this suggests a possible north-south alignment of vents along the east side of Fortymile Canyon.

The rhyolite lava flow at Prow Pass may have been erupted from a separate vent. This flow is 10 km from inferred source areas discussed above. Lava flows are intermittently exposed along Yucca Wash, but there are only tuffaceous rocks exposed for approximately 1.5 km between the westernmost lava flow in Yucca Wash and the lava flow at Prow Pass. Many of the lava flow exposures in Yucca Wash are of monolithologic breccia of flow-banded rhyolite that may represent marginal breccia at the edge or front of a lava flow. In contrast, the rhyolite lava flow at Prow Pass contains the lithofacies zonation typical lava flows elsewhere in the study area. Based on geologic mapping, the lava flow appears to be close to a vent area and not be the distal end of a lava flow.

Summary

Near the Calico Hills and Fortymile Canyon, rhyolite lava-bearing and tuffaceous rocks of the Calico Hills Formation crop out over an area of approximately 85 square kilometers (km^2) and correlative tuffaceous pyroclastic deposits underlie a similar-sized area to the southwest beneath Yucca Mountain. Based on borehole control at Yucca Mountain, outcrop observations, and the results of three-dimensional geological modeling, the formation is as much as 500 (meters) m thick near Fortymile Canyon, and it thins to the south and southwest where it is between 50 and 200 m thick beneath Yucca Mountain.

Rhyolite lava flows within the Calico Hills Formation have lithofacies patterns recognized in lavas of the Paintbrush Group at Pahute Mesa (Prothro and Drellack, 1997) and in rhyolite lava flows in other volcanic fields (Bonnichsen and Kauffman, 1987; Fink and Manley, 1987; Manley and Fink, 1987; Duffield and others, 1995). The lava flows typically have a core of crystallized, locally flow-banded rhyolitic lava, surrounded by a carapace of obsidian, and in many exposures are mantled by blocky, pumiceous rhyolite lava and flow-generated breccia. The crystallized core and the obsidian intervals are the most highly fractured parts of the lava flow.

Rhyolite lava flows were correlated and mapped on the basis of distinctive appearance in outcrop and stratigraphic sequence in addition to the presence of stratigraphic markers. The rhyolite lava flows have length-to-height of ratios of 10:1 or greater. One lava flow has a width measured transverse to interpreted flow direction of 2–3 km and a length of at least 5 to 6 km. Lava flow thickness varies from 150–250 m above interpreted source vents to 30–80 m in more distal locations.

Subjacent and superjacent pyroclastic deposits consist of a series of intercalated pyroclastic flows, bedded ash-fall, and reworked tuff that have varying amounts of pumice and volcanic rock clasts. Absence of paleosols indicates that there were no large time breaks between eruptions of successive pyroclastic flows or between the pyroclastic deposits and the eruption of rhyolite lava, or that paleosols were subsequently removed by erosion prior to deposition of overlying volcanic units.

The rhyolite lava flows and associated pyroclastic deposits were erupted within a 1 Ma time frame within the study area. Based on the contoured thickness of the formation and its areal distribution, the volume of erupted material in the study area is estimated as 37 km^3, of which 17 km^3 is rhyolite lava flow and 20 km^3 tuffaceous pyroclastic deposits.

Acknowledgments

Ronald Drake, II (U.S. Geological Survey, Denver, Colorado) provided written communication from Richard Spengler that contained lithologic descriptions for boreholes USW WT-6 and USW SD-9. He also provided preliminary and unpublished digital line work for the Dickerson and Drake (1998) mapping in Paintbrush Canyon. Claudia Faunt (U.S. Geological Survey, San Diego, California) provided digital files from the Yucca Mountain site-scale geologic framework model. Mark Tynan (U.S. Department of Energy, Office of Nuclear Energy) facilitated search for borehole records for USW SD-6 and USW WT-24 from the Yucca Mountain project legacy records management system. Funding for this study was provided by the U.S. Department of Energy Office of Environmental Management, National Nuclear Security Administration, Nevada Site Office, under Interagency Agreement DE-NA0001654/004.

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Appendix 1. Lithologic Description of Calico Hills Formation From Selected Boreholes in the Study Area

Data compiled within appendix 1 include lithologic descriptions of the Calico Hills Formation for downhole intervals from boreholes in the study area. All subsurface intervals are reported in appendix 1 as measured depth—the depth as measured along the length of the borehole. Depth to the top and bottom of each described lithologic interval is given in feet, as originally recorded at the time of drilling. Stratigraphic nomenclature within the driller's lithologic descriptions follows that of Slate and others (1999) and Potter and others (2002). Appendix 1 is available at http://pubs.usgs.gov/sir/2015/5022/downloads/sir15-5022_appendix1.pdf.

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Sweetkind and Bova—**Field-Based Description of Rhyolite Lava Flows of the Calico Hills Formation, Nevada National Security Site, Nevada**—SIR 2015–5022

Printed on recycled paper

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20155022