

Text and references to accompany NBMG Map 101

## STRATIGRAPHIC AND STRUCTURAL FRAMEWORK OF THE CRATER FLAT AREA, NEVADA

by

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The map area incorporates a series of north-trending, gently tilted fault blocks and a small intermontane basin known as Crater Flat. The fault blocks are largely composed of Miocene rhyolitic ash-flow tuffs (Scott and Bonk, 1984; Carr, 1988), which range in age from 13.25 to 11.45 Ma. The Miocene rocks rest on folded and thrust-faulted Proterozoic and Paleozoic sedimentary and metamorphic rocks, which are exposed directly west of Crater Flat at Bare Mountain (e.g., Carr and Monsen, 1988; Monsen and others, 1992). Pliocene-Pleistocene basalts and Quaternary sedimentary rocks crop out within the Crater Flat basin. Yucca Mountain and the proposed high-level nuclear waste repository lie directly east of the map area.

This geologic map generally includes previously unpublished data obtained by the authors. However, the mapping of Pliocene basalts by Crowe and others (1983) and Paleozoic-Proterozoic rocks by Monsen and others (1992) was incorporated into the southern part of the map area. In addition, the mapping of Scott and Bonk (1984) was utilized in cross sections A-A' and B-B', which extend approximately 1.37 and 3.55 km, respectively, east of the map area. The cross sections were extended east of the map area in order to illustrate the structural and stratigraphic relations between Crater Flat and Yucca Mountain.

The Miocene stratigraphy within the map area follows that established within the Yucca Mountain/Crater Flat region by Christiansen and Lipman (1965), Lipman and McKay (1965), McKay and Sargent (1970), Orkild and O'Connor (1970), Byers and others (1976a), Christiansen and others (1977), Scott and Bonk (1984), Swadley and Carr (1987), and Frizzell and Shulters (1990). Most of the exposed tuffs are outflow sheets erupted from the Timber Mountain/Oasis Valley caldera complex, which primarily lies directly north of the map area (Byers and others, 1976b; Christiansen and others, 1977; Carr, 1988). The northeasternmost part of the map area does include, however, the southern margin of the Claim Canyon caldera, which is the source of the Tiva Canyon Member of the Paintbrush Tuff (Byers and others, 1976b). The caldera margin is marked by rhyolite flows and domes (Tr) and a significant northward thickening of the Tiva Canyon Tuff (cross section C-C'). The rhyolites abut against the steep topographic wall of the Claim Canyon caldera and were probably intruded along its ring fracture. Data from drill hole USW VH-2 near Black Cone (Carr and Parrish, 1985) and Scott and Bonk (1984) were utilized to define those parts of the Miocene section not exposed within the map area. The aggregate thickness of the Miocene section probably exceeds 3 km within the Crater Flat basin.

The Pliocene-Pleistocene basalts within the Crater Flat basin were erupted from several local volcanic centers.

The 3.7-Ma Pliocene basalts were erupted from a 4-km-long north-trending fissure in the southeastern part of Crater Flat (Vaniman and Crowe, 1981; Vaniman and others, 1982). The Quaternary basalts, which range from 0.7 to 1.1 Ma, were erupted from four centers in a 12-km-long northeast-trending arcuate belt in the central and southwestern parts of Crater Flat (Crowe and Carr, 1980; Vaniman and Crowe, 1981; Vaniman and others, 1982; Crowe and others, 1983; Feuerbach and others, 1990; Smith and others, 1990). Most of the Quaternary volcanic centers show evidence of polycyclic activity (Wells and others, 1990), involving multiple eruptive cycles over  $10^4$  to  $10^5$  years (Turpin and Renne, 1987; Renault and others, 1988; Crowe and others, 1989). Individual dikes within the Pliocene fissure system strike north- to north-northeast, whereas dikes, scoria mounds, and volcanic complexes are aligned along a N35°E to N50°E trend in the Pleistocene belt. Although the trend of the basaltic dikes parallels nearby normal faults, no faults were identified along the dike swarms. Studies of more highly dissected, basaltic volcanic centers in other regions of the Basin and Range indicate that basaltic dikes need not be emplaced along faults (Anderson, 1988; Faulds and others, 1991).

Quaternary alluvial units in Crater Flat are mapped as allostratigraphic units, defined as stratiform bodies of sedimentary rock delineated by bounding discontinuities (geomorphic surfaces and soils). These units are informally named for geomorphic features located in proximity to the sites where they are best expressed, described, and/or dated. The map delineations and numerical ages are based on data obtained by Peterson (1988) and Peterson and others (in press). A variety of aerial photography was utilized for surficial mapping (e.g., 1:24,000 color, 1:24,000 black and white, and 1:12,000 and 1:6,000 low sun-angle black and white photographs). Soil terminology is based on updates to U.S. Soil Conservation Service (1975). Stages of secondary carbonate accumulation follow Gile and others (1966).

Alluvial deposits throughout the map area are characterized by sandy or silty gravel, poor to moderate sorting, poor to moderate stratification, and pebble- to cobble-sized, angular to subangular clasts of volcanic and locally sedimentary rock. Individual alluvial units in many parts of Crater Flat are thin (< 1 m). Well-cemented alluvium of Qfs age or older probably underlies much of Crater Flat at shallow depths. Geomorphic inset relations between units are commonly very slight even between units of greatly different ages. Veneering and anastomosing relations are more common than indicated by prior mapping efforts (Swadley and others, 1984; Swadley and Parrish, 1988). The youngest dominant map units are delineated here.

Minimum age estimates of alluvial deposits are based on geomorphic character, soil development, rock varnish, and uranium-series dating. Rock varnish ages are derived from radiocarbon dating of organic matter encapsulated at the base of the varnish (Crater Flat, Little Cones, and late Black Cone units) and from cation ratio analyses (early Black Cone, Yucca, and Solitario units). Uranium-series disequilibrium dating of secondary pedogenic carbonate also provides minimum-limiting ages.

Numerous tonal and/or vegetation lineaments cut Quaternary alluvial surfaces in Crater Flat. Some of the stronger lineaments are shown on the map because they may have structural or tectonic significance. In general, surficial evidence is insufficient to verify the structural origin of the lineaments. However, numerous lineaments elsewhere in Crater Flat have been correlated with fractures spatially associated with Quaternary faults (Ramelli and others, 1989).

The major structural features in the map area are (1) several narrow, generally east-tilted fault blocks, (2) closely spaced, moderately to steeply dipping, north- to northeast-striking normal faults that bound the fault blocks, (3) the Crater Flat basin, and (4) the east-dipping Bare Mountain fault. Most of the closely spaced faults dip moderately to steeply westward (average fault attitude is N14°E, 68°NW). Tilting of exposed units generally does not exceed 15°. The east-tilted fault blocks and west-dipping normal faults give way to west-tilted fault blocks and east-dipping normal faults westward and southward across the map area (cross sections A-A' and B-B'). Several of the faults mapped within the Miocene bedrock also cut Quaternary alluvial units within Crater Flat (e.g., Windy Wash fault).

The closely spaced faults are arranged in an en echelon pattern and display significant along-strike displacement gradients. In many cases, displacement varies by orders of magnitude within individual fault segments. For example, displacement along a northeast-striking, west-dipping segment of the Windy Wash fault decreases from 300 m to 0 in less than 1.5 km. Northeast-striking fault segments commonly link longer north-striking segments. Displacement does not vary systematically with fault trend. The irregular displacement patterns produced several gentle, east-trending folds within the north-trending fault blocks (cross section C-C'). In a few cases, abrupt north- or south-facing monoclines occur directly adjacent to particularly sharp displacement gradients. Displacement on many of the faults decreases northward toward the Timber Mountain/Oasis Valley caldera complex.

Faults cutting Miocene strata generally exhibit a steeply plunging west-northwest-trending slipline, as evidenced by the orientations of R1 Riedel shears, rough facets, striae, and hardrock fragments and associated grooves. The average slipline is 60° N77°W (plunge and trend) on north- to north-northeast-striking faults and 66° N63°W on northeast-striking faults. Thus, most faults accommodated normal dip-slip motion. However, northeast- and north-northwest-striking faults commonly show small components of left and right slip, respectively.

The Crater Flat basin is a structural depression situated between Bare Mountain to the west and Yucca Mountain and associated fault blocks to the east. The en echelon array of closely spaced normal faults and attendant narrow, gently tilted fault blocks form an irregular eastern margin to the basin. Structural relief on middle Miocene

tuffs exceeds 1 km between the crest of Yucca Mountain and Crater Flat near Black Cone (cross section B-B'). In contrast to the diffuse eastern margin, the western edge of Crater Flat is well defined by the Bare Mountain fault, a major east-dipping, range-front fault. The depth of the pre-volcanic surface in Crater Flat, as inferred from seismic-refraction data, suggests a minimum of 2,600 m of post-early Miocene displacement on the Bare Mountain fault (Ackermann and others, 1988), which includes recurrent late Quaternary movements (Reheis, 1988).

Seismic-refraction (Ackermann and others, 1988) and gravity (Snyder and Carr, 1984) data further imply that the depth of the pre-volcanic surface ranges from 3.2 km beneath the center of Crater Flat to 1.3 km below southern Yucca Mountain. This implies that the Miocene volcanic section in the central part of Crater Flat approaches 3 km in thickness, significantly exceeding that in the southern part of Yucca Mountain. Carr and others (1986) therefore concluded that the Crater Flat structural depression resulted primarily from middle Miocene caldera collapse related to the 13.25-Ma Crater Flat Tuff.

Although a 13.25-Ma caldera cannot be ruled out, several features indicate that the Crater Flat basin is primarily a structural depression. For example, the irregular, en echelon eastern margin of Crater Flat and continuation of several faults from the Miocene bedrock into the Quaternary alluvium of the basin demonstrate that the system of closely spaced normal faults and narrow, gently tilted fault blocks continues beneath Crater Flat. In addition, the Miocene stratigraphy displayed in two shallow drill holes in Crater Flat (Carr, 1982; Carr and Parrish, 1985) differs little from that exposed in fault blocks north and east of Crater Flat. Moreover, as displacement along the Bare Mountain fault and major faults bounding Yucca Mountain decrease to the north and south, the Crater Flat basin terminates. We therefore propose that the Crater Flat basin essentially represents a large synform produced by displacement maxima and associated displacement gradients along the east-dipping Bare Mountain fault and the system of west-dipping normal faults flanking Yucca Mountain. It is analogous to the smaller, east-trending folds developed within individual fault blocks in response to displacement gradients on bounding normal faults. The displacement maximum on the Bare Mountain fault is probably the single most important feature controlling the location of the Crater Flat basin. On the basis of stratigraphic, petrologic, geochemical, and structural relations, Scott (1990) and Fridrich and Price (1992) also concluded that the Crater Flat basin is a structural depression rather than a caldera.

The boundary between east- and west-tilted fault blocks appears to migrate eastward from the northwestern and southwestern corners of the map area commensurate with increasing displacement on the Bare Mountain fault. West-tilted fault blocks are inferred to underlie much of the western and central parts of the Crater Flat basin. This implies that most of the Crater Flat basin is a west-tilted half graben. The boundary between the east- and west-tilted fault blocks is essentially a large open anticline, which can be described as an interference accommodation zone (e.g., Scott and Rosendahl, 1989). Anticlines within interference accommodation zones are generally not contractional in nature, but instead result from the across-strike (i.e., parallel to extension direction) intersection of two

oppositely dipping, concave-upward normal faults or fault systems and attendant, opposing tilt-block domains. In the Crater Flat area, the west-tilting of bedrock blocks probably results from rotation on a concave-upward, east-dipping normal fault system, particularly the Bare Mountain fault. The east-tilting in the eastern part of the map area and at Yucca Mountain stems from rotation on a system of concave-upward, west-dipping normal faults. These oppositely dipping fault systems intermesh and terminate in the Crater Flat region, producing the anticline.

Extension in the Crater Flat/Yucca Mountain region probably began during late Oligocene time (Schweickert and Caskey, 1990) and has continued, perhaps episodically, to the present. The regional extension direction has apparently rotated from west-southwest/east-northeast in early to middle Miocene time to northwest/southeast in late Miocene to Quaternary time (Zoback and others, 1981; Stock and Healy, 1988; Wernicke and others, 1988). Carr (1988) concluded that the major episode of extension occurred between 12.7 and 11.6 Ma (corrected using new  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of D. A. Sawyer and others, written commun., 1993). We concur that significant displacement took place during this time interval. For example, the 11.6-Ma Rainier Mesa Member of the Timber Mountain Tuff (Tmr and Tmrw) and underlying bedded tuffs (Tmrn) are appreciably thicker on the downthrown side of several normal faults, indicating that they were deposited in topographic lows generated by faulting. In addition, the 12.7-Ma Tiva Canyon Member of the Paintbrush Tuff is commonly more highly tilted than the Rainier Mesa Member of the Timber Mountain Tuff (Scott, 1990). Megabreccias of Paleozoic rock occur at two intervals in drill hole USW VH-2, the oldest of which is situated between the 12.7-Ma Tiva Canyon Member and 11.6-Ma Rainier Mesa Member (Carr and Parrish, 1985). The Bare Mountain block is the only probable source area for the megabreccias. Thus, unroofing of the Bare Mountain block and significant displacement along the Bare Mountain fault probably occurred prior to 11.6 Ma.

In other areas, however, the Rainier Mesa Member of the Timber Mountain Tuff and Tiva Canyon Member of the Paintbrush Tuff exhibit little discordance in the magnitude of tilting. Moreover, significant faulting and tilting disrupt the Timber Mountain Tuff throughout the Crater Flat area. Thus, a significant amount of extension in the Crater Flat-Yucca Mountain region postdated eruption of the Timber Mountain Tuff, as also surmised by Scott (1990). The major pulse of extension postdating Timber Mountain Tuff in the Crater Flat-Yucca Mountain region may have coincided with the 8- to 10-Ma pulse of extension (Maldonado, 1990) in the Bullfrog Hills area to the west. Displacements of 3.7-Ma basalts and Quaternary alluvium in Crater Flat provide younger constraints on extension in the area and likely reflect reactivation of older structures with lower rates of activity.

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