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Geologic evaluation of the Oasis Valley basin, Nye County, Nevada

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INTRODUCTION

This report documents the results of a geologic study of the area between the underground-nuclear-explosion testing areas on Pahute Mesa, in the northwesternmost part of the Nevada Test Site, and the springs in Oasis Valley, to the west of the Test Site. The new field data described in this report are also presented in a geologic map that is a companion product (Fridrich and others, 1999) and that covers nine 7.5-minute quadrangles centered on Thirsty Canyon SW, the quadrangle in which most of the Oasis Valley springs are located[1]. At the beginning of this study, published detailed maps were available for 3 of the 9 quadrangles of the study area: namely Thirsty Canyon (O'Connors and others, 1966); Beatty (Maldonado and Hausback, 1990); and Thirsty Canyon SE (Lipman and others, 1966). Maps of the last two of these quadrangles, however, required extensive updating owing to recent advances in understanding of the regional structure and stratigraphy. The new map data are integrated in this report with new geophysical data for the Oasis Valley area, include gravity, aeromagnetic, and paleomagnetic data (Grauch and others, 1997; written comm., 1999; Mankinen and others, 1999; Hildenbrand and others, 1999; Hudson and others, 1994; Hudson, unpub. data).

Developing an understanding of the geology of the Oasis Valley area is challenging because:

(1) most of the area between Pahute Mesa and Oasis Valley is covered by alluvium or by post-10-Ma volcanic units that postdate development of the major structures at the depth of the water table; hence, the geologic features that control groundwater flow are largely concealed, and

(2) the structure and stratigraphy of this area are complex because it lies at the boundary

1 New maps for 2 of the 9 quads have been previously published (Minor and others, 1997a;1998).

between the central caldera complex of the southwest Nevada volcanic field (Sawyer and others, 1994; and references therein) and the southern part of the Walker Lane belt (Stewart, 1988; Hardyman and Oldow, 1991) -- a domain characterized by strong, multi-stage, extension and strike-slip deformation (Figure 1) and, in the area of interest, by detachment faulting (Figures 2A and 2B).

Because of these problems, as well as the sparseness of drill-hole control, any interpretation of the study area is inevitably somewhat tentative. Nonetheless, the goal of developing a defendable preliminary interpretation of the basic structure and stratigraphy of the Oasis Valley area is achievable because:

(1) the large-scale geologic context of the area has been well established by the 35 years of geologic studies that have been conducted in and around the Nevada Test Site (e.g., see Byers and others, 1989; and see articles in Wernicke, 1990),

(2) there is a wealth of geophysical data on this area, and

(3) this is an area in which geophysical methods provide excellent constraints on the locations of concealed geologic structures, owing to strong contrasts in the physical properties of the principal groups of rock units (Grauch and others, 1997; written comm., 1999; Hildenbrand and others, 1999; Mankinen and others, 1999).

The new geophysical data have permitted identification of many of the major concealed structures in the area of interest, as covered in recent reports by Grauch and others (1997; written comm., 1999; and see Fridrich and others, 1996), and in the new work by Mankinen and others (1999; and see Figures 3, 4, and 5). The goal of this report is to integrate the new geologic map data with the geophysical data to develop a comprehensive, testable model of the structure and stratigraphy of the Oasis Valley area.

For the sake of clarity in the discussions below, it is necessary to define certain features in the vicinity of Oasis Valley. The topographic feature called Oasis Mountain (Figure 3) is bordered

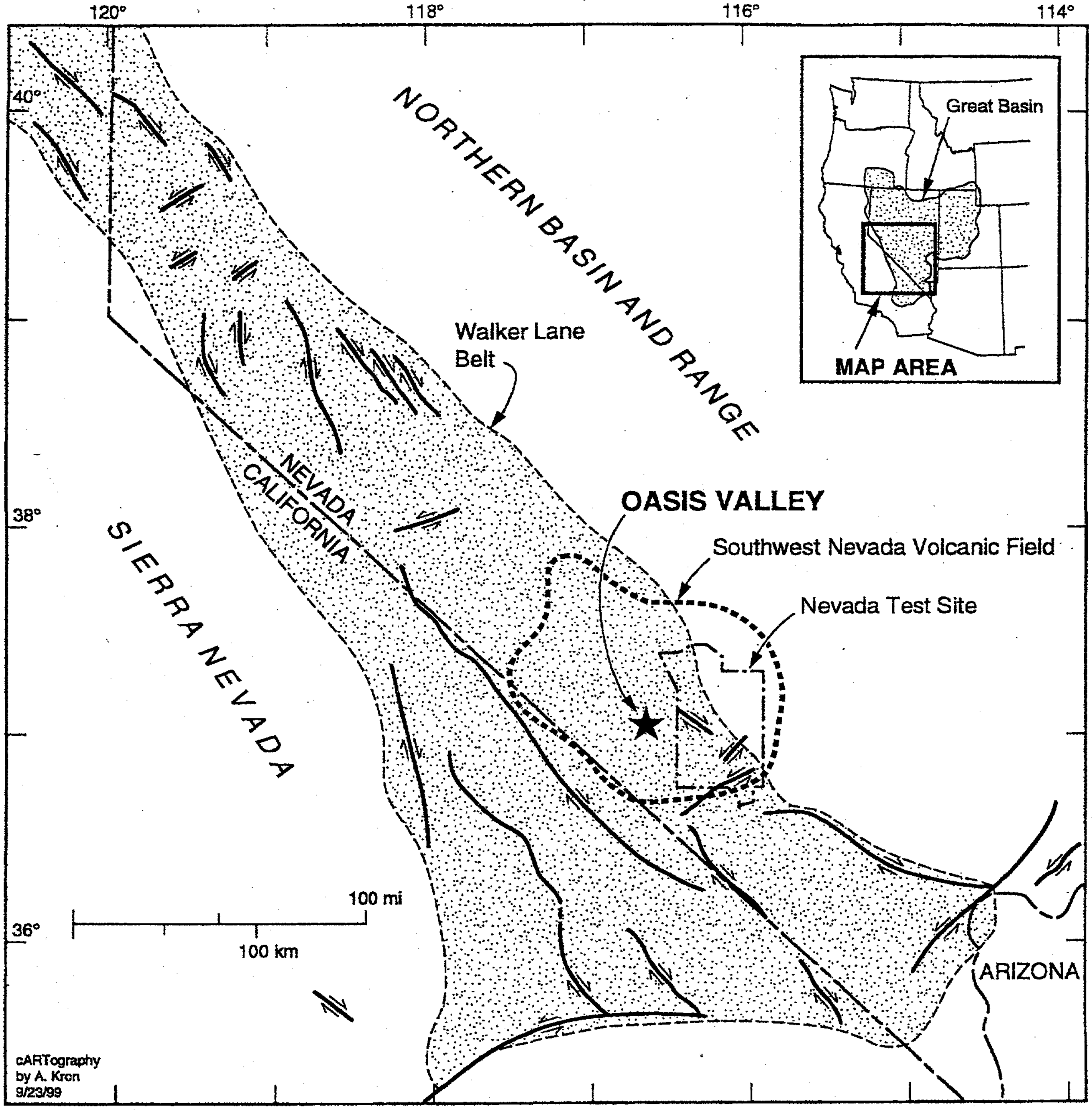


Figure 1. Location map of Oasis Valley in the southwest Nevada volcanic field of the western Great Basin, with schematic representations of the major faults of the Walker Lane belt that have large components of strike-slip offset, modified from Stewart (1988).

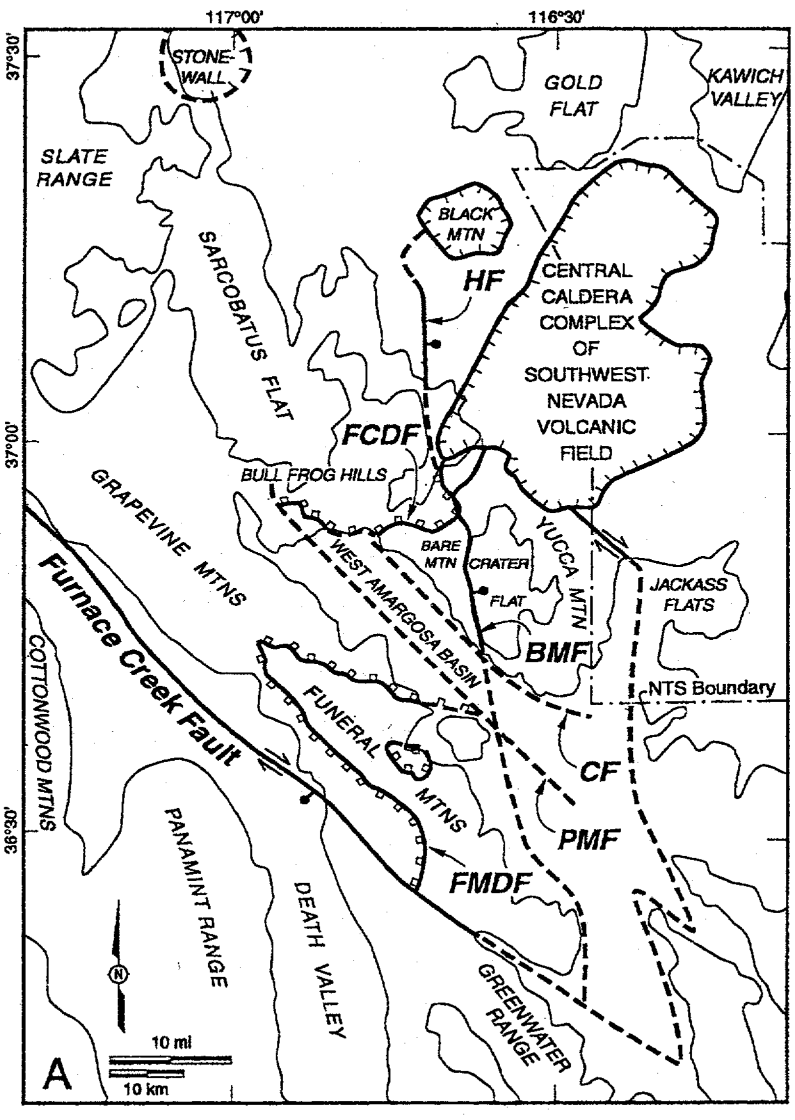


Figure 2A. Location map of the northeast Death Valley detachment fault system showing bedrock-alluvium contacts (thin lines), western boundary of the Nevada Test Site (dot-dash line), major faults (thick lines) including caldera margins (thick lines with ticks), exposures of the regional detachment fault of this system (thick lines with square teeth), trailing-edge faults (thick lines with ball and bar), and buried faults (dashed lines). From north to south, major faults shown include the Hogback fault (HF), Fluorspar Canyon-Bullfrog Hills detachment fault (FCDF), Carrara fault (CF), Porter Mine fault (PMF), and Funeral Mountains detachment fault (FMDF).

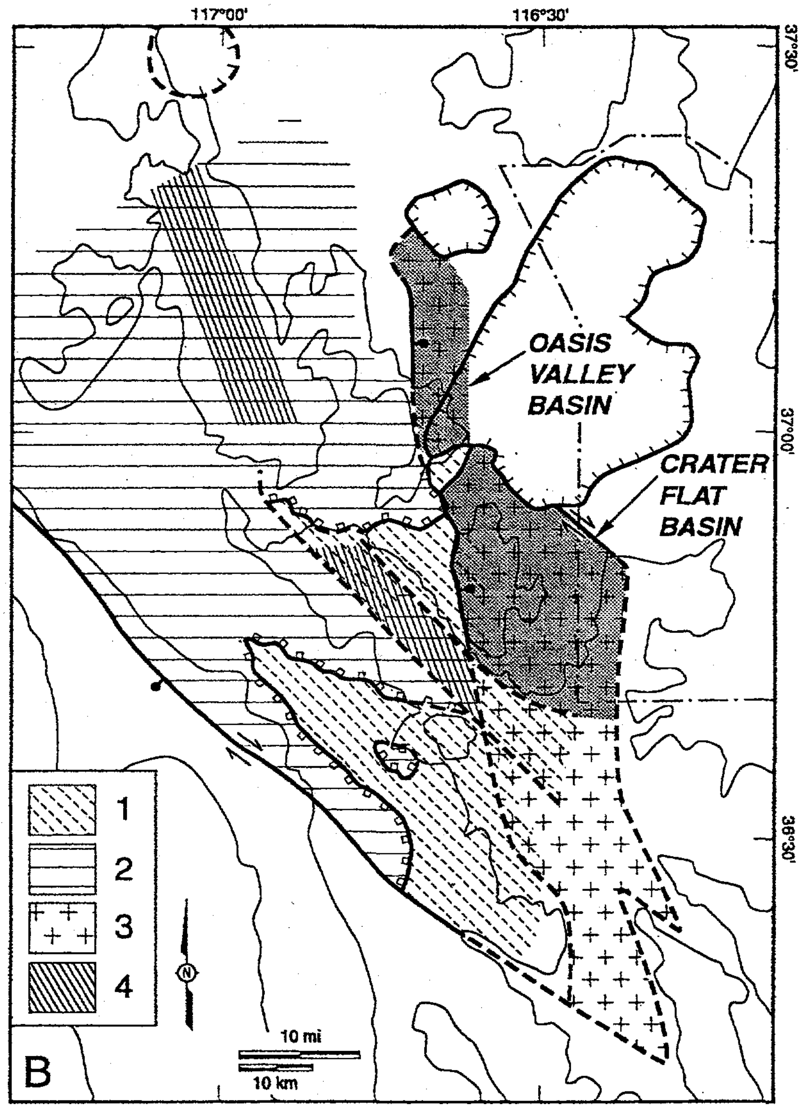


Figure 2B. Same area as figure 2A, showing the partially overlapping structural domains of the northeast Death Valley detachment fault system, which are numbered: 1, areas of tectonic denudation along the main detachment fault; 2, extended upper-plate rocks; 3, trailing-edge basins; 4, transverse basins. Two of the half-graben basins that formed on the trailing-edge of the detachment fault system are highlighted—the Oasis Valley and Crater Flat basins.

on its southeast side by a rectangular bedrock exposure we call the Hogback, and we use the term Oasis Mountain Hogback to mean both of the these features together. Oasis Valley is that part of the Amargosa River valley that lies between Oasis Mountain and Bare Mountain (Figure 3), and is so named because of the abundance of springs and vegetation. The Oasis Valley basin lies entirely to the east of Oasis Valley and is separated from it by the Oasis Mountain Hogback (Figure 3). We use the term SNVF caldera complex to mean the whole central caldera complex of the southwest Nevada volcanic field, which is comprised of: (1) a northern part, the Silent Canyon caldera, (2) a central part, the Timber Mountain caldera complex, which is a composite of the Rainier Mesa caldera and the Ammonia Tanks caldera, and (3) a small southern part, the Claim Canyon caldera (see Figures 2A, 2B, and 3). Summaries of the general stratigraphy and tectonic history of the western part of the Nevada Test Site region are presented in table form in the back of this report so that they can be used as reference material (Tables 1 and 2; both modified from Fridrich, 1998 and in press).

From the time of the early geologic studies of the southwest Nevada volcanic field (Byers and others, 1976; 1989; Christiansen and others, 1977), the area between the Transvaal Hills and Oasis Mountain (Figure 3) has been recognized as a basin because: (1) it is an area of almost total alluvial cover, (2) the strata in bordering bedrock exposures dip toward this area of cover on the west, south, and east sides, and (3) it is an area of low gravity. The nature of this basin has, however, been controversial. The major disputes have focused on whether the Oasis Valley basin is a tectonic basin or part of a caldera (a volcanic collapse basin), and if it is a caldera, which major ash-flow tuff unit(s) of the volcanic field are associated with it (Byers and others, 1976; 1989; Christiansen and others, 1977; Noble and others, 1991; Sawyer and others, 1994; Grauch and others, 1997; written comm., 1999). The new geological and geophysical data gathered in the last eight years permit a more definitive analysis of this basin and its structural setting than was previously possible.

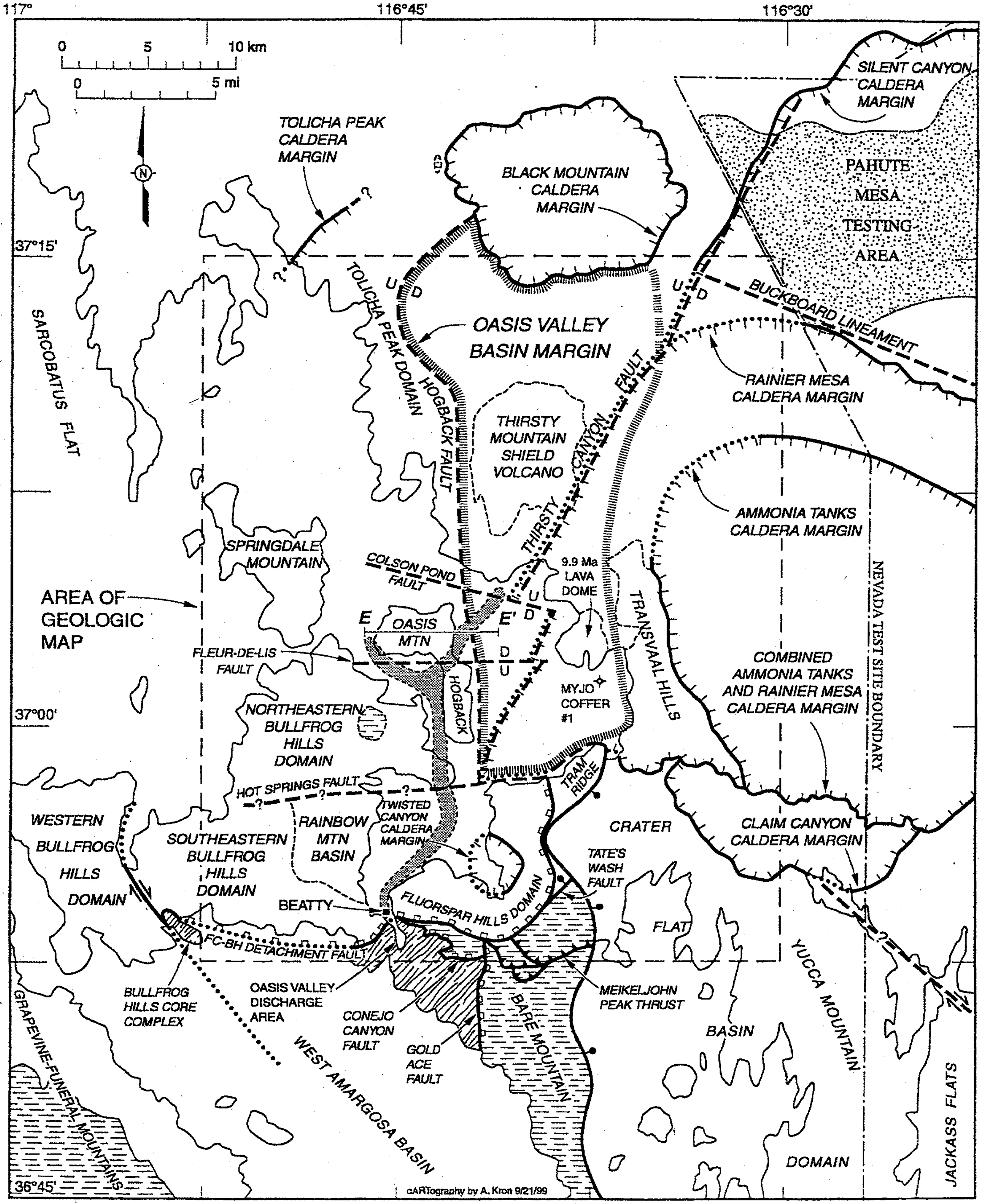
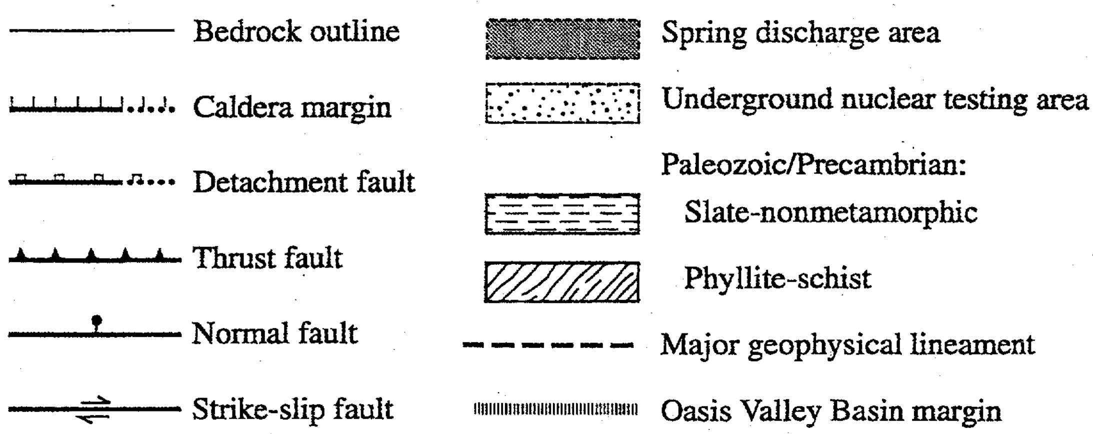


FIGURE 3. Caption, explanation of symbols, structural domain map, and index to quadrangles on next page.



INDEX TO 7.5 MINUTE QUADRANGLES

(117°, 116°45', 116°30'; 37°15', 37°, 36°45')

Tolicha Peak SW	Tolicha Peak	Black Mtn	Trail Ridge	Silent Butte
Springdale NW	Springdale NE	Thirsty Canyon NW	Thirsty Canyon	Scrugham Peak
Springdale SW	Springdale	Thirsty Canyon SW	Thirsty Canyon SE	Timber Mtn
Bullfrog Mtn	Beatty	Beatty Mtn	East of Beatty Mtn	Topopah Spring NW
Daylight Pass	Gold Center	Carrara Canyon	Crater Flat	Busted Butte

STRUCTURAL DOMAIN MAP

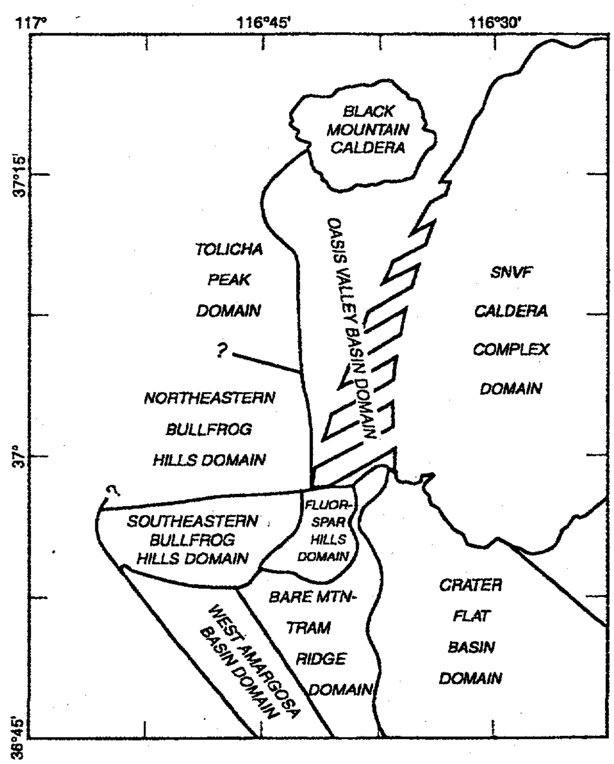


Figure 3. Index map for the Oasis Valley basin and vicinity showing the Pahute Mesa testing area, Oasis Valley discharge area, caldera outlines, and selected major faults and physiographic features (facing page). Figure covers the area of the 9-quadrangle geologic compilation map that is a companion publication for this report (Fridrich and others, 1999—USGS OFR 99-xxx-B), as well as a one-quadrangle-wide perimeter. This page provides an explanation, as well as two maps. One shows the 25 quadrangles covered in this figure and the other is a structural domain map.

DESCRIPTION OF THE OASIS VALLEY BASIN

The Oasis Valley basin is a roughly rectangular feature on the west side of the exposed part of the SNVF caldera complex (Figure 3). Owing to poor exposure in many areas, the boundaries of this basin are best defined in many cases by gravity and magnetic data (Figures 4 and 5), which allow the discrimination of six major concealed structures in the area between Pahute Mesa and the southernmost of the Oasis Valley springs (Figure 3). Four of these structures were recognized by Grauch and others (1997; written comm., 1999; and see Fridrich and others, 1996); the last two below are newly recognized by Mankinen and others (1999). These structures are:

(1) Hot Springs fault, referred to as the E-W structure by Grauch and others (1997).

(2) Hogback fault, referred to as the N-S structure by Grauch and others (1997).

(3) Buckboard lineament, referred to as the WNW structure by Grauch and others (1997).

(4) Thirsty Canyon fault, referred to as the NNE structure by Grauch and others (1997).

(5) Fleur-de-Lis fault, which we extend several kilometers further west than Mankinen and others (1999) did (see Figure 4), based on surface geologic relations, and

(6) Colson Pond fault (Mankinen and others, 1998).

The Hot Springs and Hogback faults form the southern and western boundaries of the Oasis Valley basin, respectively, whereas the northwestern and eastern boundaries of the basin are formed by the southern margin of the Black Mountain caldera and the western margin of the Transvaal Hills, respectively (Figures 3, 4, and 5). The Thirsty Canyon, Fleur-de-Lis, and Colson Pond faults are three major structures that cut through the middle of the Oasis Valley basin, and that extend beyond it. The Buckboard lineament is near the northeastern limit of the basin, but apparently is outside the basin (Figure 3). In the following discussion, the geologic and geophysical characteristics of these structures are described, along with the nature of the structural domains that border the Oasis Valley basin. This discussion starts with the southern margin of the basin, where the relations are clearest,

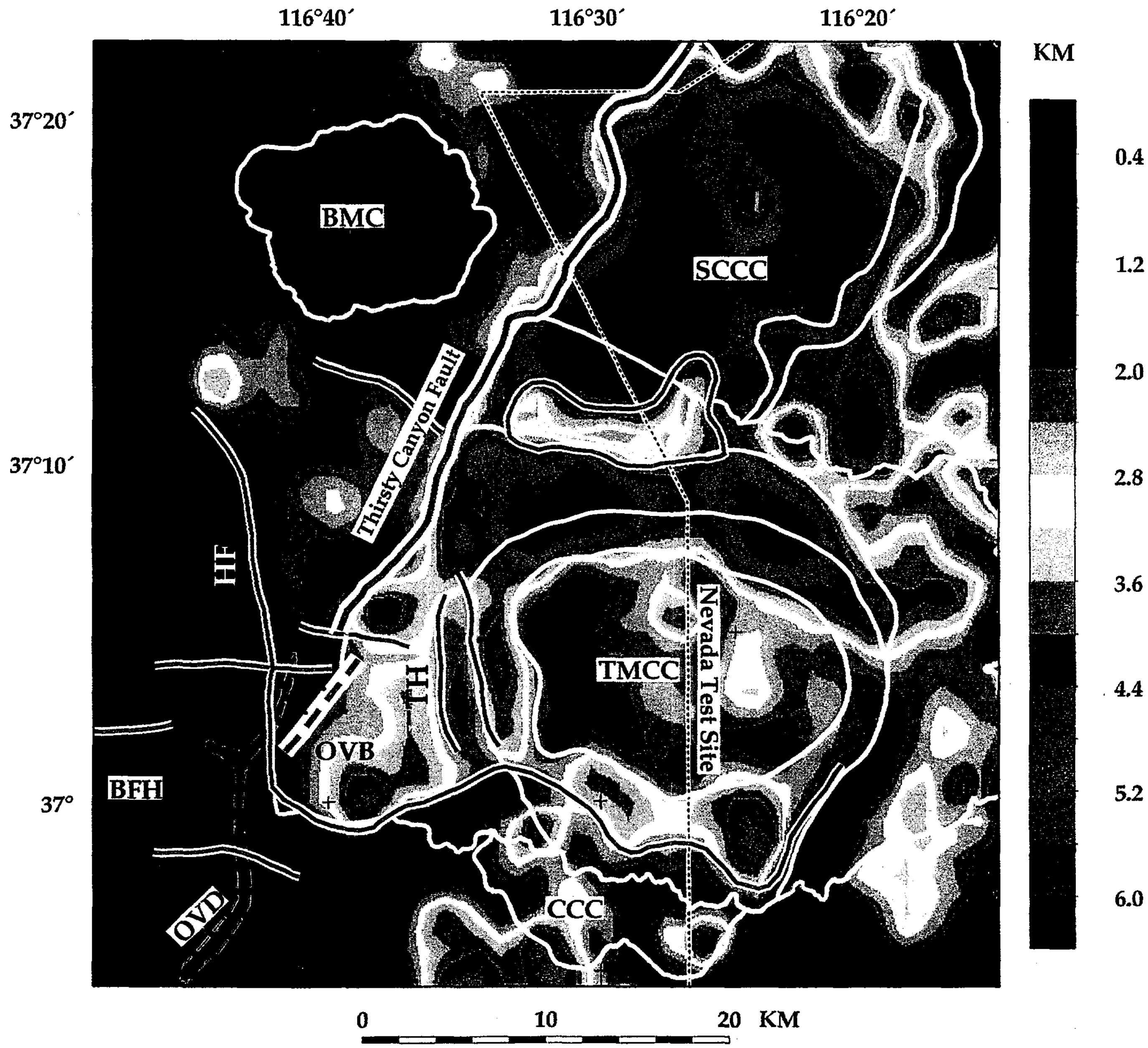


Figure 4. Thickness of Cenozoic volcanic rocks and sedimentary deposits based on gravity data and constrained by well data (from Hildenbrand and others, 1999). Heavy white/blue lines delineate inferred density boundaries. Solid white lines are caldera boundaries (see Hildenbrand and others, 1999). BFH, Bullfrog Hills; BMC, Black Mountain caldera; CCC, Claim Canyon caldera; HF, Hogback fault; OVB, Oasis Valley basin; OVD, Oasis Valley discharge area; SCCC, Silent Canyon caldera complex; TH, Transvaal Hills; TMCC, Timber Mountain caldera complex. Modified from Mankinen and others (1999).

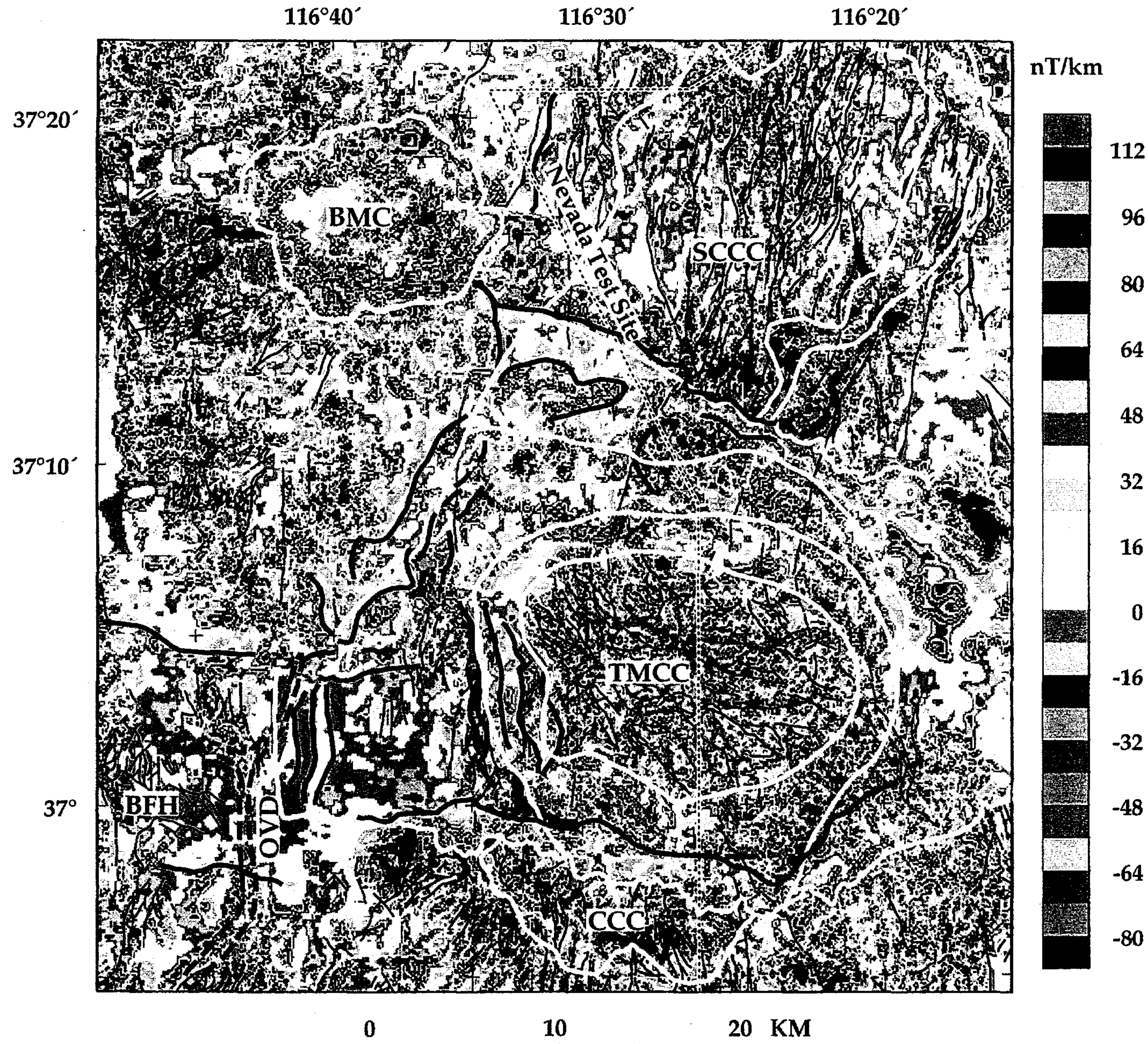


Figure 5. Residual reduced-to-pole magnetic field. The magnetic field was upward continued 100 m and then subtracted from the original data to produce the residual field. Anomalies enhance the expression of near-surface sources. Heavy black lines are inferred major magnetic boundaries in the area between Pahute Mesa and Oasis Valley. Red lines are mapped faults (Wahl and others, 1997). Reproduced from Mankinen and others (1999).

and advances generally to the north.

The large-scale geometry of the Oasis Valley basin is that of a half-graben. The basin is bounded on the west side by a large (>1 km throw) master fault, the Hogback fault, and most of the rocks in the basin appear to dip toward that fault. Moreover, the stratigraphic units that fill this basin thin eastward from the west side of the basin; the basin thus has a wedge-like geometry. The timing of formation of the Oasis Valley basin is constrained by the ages of angular unconformities, landslide breccias, and similar features that formed in relation to the structures that bound the basin. The relations show that the Hogback fault, the master fault at the western margin of this half-graben basin, initially formed shortly before emplacement of the 11.6 Ma Rainier Mesa Tuff. The major activity on this fault occurred between ~11.2 and ~10.5 Ma, however, and fault slip probably ceased by ~9.5 Ma. Relations on other sides of the basin support ~11.4-to-~10.5 Ma as the interval of peak tectonism that formed this basin.

Southern Boundary of Oasis Valley Basin

The southern margin of the Oasis Valley basin, the Hot Springs fault (Figures 3, 4, and 5), is a structure that strikes east-west to east-northeast and that is marked by a steep lower-to-the-north gravity gradient (Mankinen and others, 1999). In an earlier interpretation, Grauch and others (1997; written comm., 1999; and see Fridrich and others, 1996) correlated this gravity gradient at the south end of Oasis Valley basin with an aligned but opposite-sense (lower-to-the-south) gravity gradient to the west, and thus interpreted the Hot Springs fault as extending beyond the basin. If this second characterization is accurate, then the along-strike reversal in the direction of the related gravity gradients indicates that this lineament does not correspond to any single simple type of structure such as a normal fault, as is discussed more below. An abrupt change in magnetic character also is present along the Hot Springs fault (Figure 5). Alternating, strong, positive-and-negative, mostly northeast-trending magnetic anomalies characterize the area to the south of this structure (Figure 4). The area to the north, within the Oasis Valley basin and to the west of the Oasis Mountain Hogback, also has alternating positive-and-negative magnetic anomalies, but they are more regular and strictly north-trending, and the anomalies are defined by a much smaller range in magnetic values (Figure 5).

That part of the Hot Springs fault that bounds the southern part of the Oasis Valley basin coincides spatially with a north-dipping bedrock scarp which locally is mantled by rock-avalanche breccias. These breccias are immediately overlain by the Rainier Mesa Tuff, which is locally draped over the scarp and dips at a progressively greater angle northward as the Oasis Valley basin is approached from the south. This scarp can be followed eastward and is continuous with a scarp to the east that unequivocally is the southern margin of the Rainier Mesa caldera (Figure 3). The close association of the Rainier Mesa Tuff with rock-avalanche breccias in this area as well as the draping of this tuff over the scarp these breccias mantle indicate that the scarp along the south side of Oasis Valley basin is the southwestern topographic wall of the Rainier Mesa caldera.

Other relations along the southern boundary of the Oasis Valley basin indicate, however, that this boundary is more than just the westward continuation of this caldera margin. For example, on the eastern flank of the basin, the largely north-striking and largely down-to-the-east faults within the Transvaal Hills bend southwestward as the Hogback fault is approached from the north (see companion map; Fridrich and others, 1999). These faults evidently do not cross the Hot Springs fault as most of the faults to the south are down-to-the-northwest and predate the 11.45 Ma Ammonia Tanks Tuff, whereas the major faults in the Transvaal Hills slipped mostly between ~11.2 and ~9.5 Ma. In addition, the direction of predominant stratal tilting changes across the Hot Springs fault from west-to-southwest-dipping to the north of this boundary to southeast-dipping to the south. Hence, the Hot Springs fault accommodates a change in fault-block tilt polarity as well as a change in the major timing of extensional faulting across it.

On the west side of the basin, the Hogback Fault, which was strongly active both before and especially after emplacement of the Ammonia Tanks Tuff, as discussed below, evidently terminates against the Hot Springs fault. Based on the timing of all of the faulting that terminates against the Hot Springs fault, the structural accommodation that was occurring along this fault continued at least until 9.9 Ma; that is, for at least 1.3 m.y. after the end of the Timber Mountain caldera cycle (at ~11.2 Ma). This timing indicates that the structural accommodation across the Hot Springs fault occurred as a process of regional tectonism rather than as an aspect of caldera evolution; moreover, the differing fault sets that are accommodated at this structure are tectonic faults, rather than caldera faults. The Hot Springs fault is thus a complex composite structure; it evidently is a caldera margin fault as well as a tectonic accommodation zone.

Four distinct structural domains lie along the south side of the Hot Springs fault – the Crater Flat, Bare Mountain-Tram Ridge, Fluorspar Hills, and southeastern Bullfrog Hills domains (Figure 3). The Crater Flat basin lies to the southeast and is a broad half-graben bounded on the west by the Bare Mountain range-front fault (Fridrich, 1998 and in press). The internal structure of this basin is characterized by a tilted-domino pattern of closely spaced down-to-the-west-northwest faults bounding east-to-southeast-dipping fault blocks. The Crater Flat basin is a domain characterized by southward- and westward-increasing extension and related strike-slip strain, and thus appears to have opened like a fan (Fridrich, 1998 and in press; Fridrich and others, 1998 and in press). This basin formed immediately to the east of, and contemporaneously with the uplift of the Bare Mountain-Tram Ridge domain.

The Bare Mountain-Tram Ridge domain is the exposed footwall (lower plate) of the Fluorspar Canyon-Bullfrog Hills (FC-BH) detachment fault, which forms the northern boundary of Bare Mountain and western boundary of Tram Ridge (Figure 3). This exposure of the lower plate was strongly uplifted as it was tectonically denuded by displacement of the upper plate to the west-northwest along the detachment fault (Hamilton, 1989; Monsen and others, 1992; Hoisch and others, 1997; Fridrich, 1999). The major part of the uplift, Bare Mountain, is composed mainly of Paleozoic and late Proterozoic sedimentary rocks in which the degree of metamorphism increases to the west-northwest, in the direction of transport along the detachment fault; Bare Mountain is thus a metamorphic core complex (Crittenden and others, 1980). The west- to northwestward-dipping detachment-fault system originally reached the surface in the vicinity of the eastern boundary of the Bare Mountain uplift, and a narrow zone of minor tectonic denudation probably is concealed beneath the basin fill of westernmost Crater Flat basin to the east (Figure 6); however, there is no evidence for detachment faulting under this basin (Fridrich, 1998 and in press).

The Tram Ridge subdomain is separated from Bare Mountain by a northeast-striking high-angle normal fault, the Tate's Wash fault (Figure 3). The main, northern part of this subdomain is Tram Ridge (topographic feature) which appears to be a domical uplift -- a turtleback (Figures 2A, 2B, and 3). Unlike Bare Mountain, both the amount of stratigraphic omission and the total area of tectonic denudation in the Tram Ridge subdomain is small and ends eastward within this subdomain; it does not extend into the northwestern part of the Crater Flat basin. Only the upper part of the middle Miocene volcanic section is missing at Tram Ridge.

The Fluorspar Hills and southeastern Bullfrog Hills domains are structurally continuous with each other, but differ in the timing and style of major tectonism. Both are domains of extreme extension and strong coeval strike-slip deformation in the hangingwall of the FC-BH detachment fault (Maldonado, 1990; Ryder and Fridrich, 1997). Bedrock exposures in these two domains are of the highly extended upper plate that was transported to the west-northwest off of Bare Mountain. Field relations show that the interval of peak deformation was progressively later in time as one moves to the west-northwest across the combined area of the Fluorspar Hills and southeastern Bullfrog Hills domains, and that a break in the timing of peak tectonism is present at the boundary between the two domains.

In the Fluorspar Hills, the largest pulse of tectonism began at ~12.7Ma, peaked between

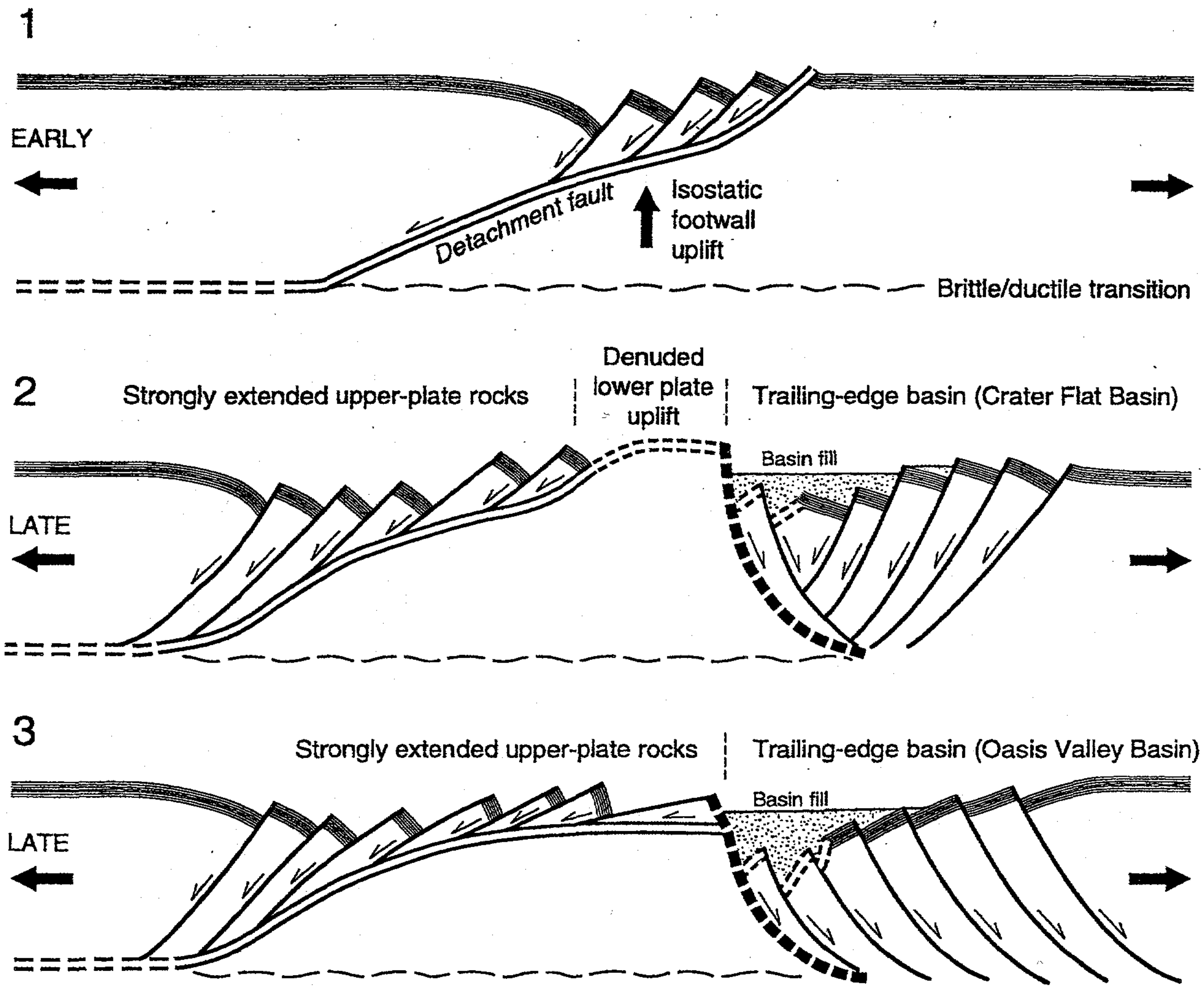


Figure 6. Schematic cross sections drawn in the direction of extension, showing the evolution of the northeast Death Valley detachment fault system in two areas: 1, Stage 1—initiation of detachment faulting—applies to both areas; 2, Stage 2—exposure of a tectonically denuded metamorphic core complex (Bare Mountain) and development of a trailing-edge basin dominated by antithetic internal faults (Crater Flat basin) at the eastern limit of the core complex, in the area where the detachment fault originally daylighted; 3, Stage 2 further north—development of a trailing-edge basin dominated by synthetic internal faults (Oasis Valley basin) at the limit of an area of extreme extension of the upper plate (northeastern Bullfrog Hills).

11.7 and 11.6 Ma, and declined strongly and progressively thereafter, largely ending by ~10.5 Ma. In the southeast Bullfrog Hills, only trivial faulting and tilting occurred between 12.7 and 11.6 Ma. Major tectonism began at ~11.2 Ma, peaked between 11 and 10.5 Ma, and largely ended by ~ 9.5 Ma. The timing of deformation in the Fluorspar Hills is virtually identical to that in the Crater Flat basin. The timing of tectonism in the southeastern Bullfrog Hills differs from both of those last-mentioned domains, but is similar to that of the Oasis Valley basin. A further similarity to the Oasis Valley basin is that a deep depression, the Rainbow Mountain basin, opened up in the eastern part of the southeastern Bullfrog Hills in the same interval in which the major exposed faults on the east and west margins of Oasis Valley basin, and by inference the basin itself, formed (Figure 3). The Rainbow Mountain basin appears to terminate northward against the western part of the Hot Springs fault in much the same fashion that the Oasis Valley basin terminates southward against the eastern part of this same structure. Each of these basin terminations is a geometry problem that is solved if the two basins are related, en echelon features that are linked by an accommodation fault (the Hot Springs fault) that transferred strain between the two.

Southeastern Boundary of the Oasis Valley Basin

The southeastern boundary of the Oasis Valley basin is located along the western margin of the Transvaal Hills (Figure 3). This boundary has a subtle but clearcut expression in both the gravity and magnetic data. The Transvaal Hills coincide with a small gravity high (relative to the Oasis Valley basin), and is an area of stronger alternating positive-and-negative magnetic anomalies than the adjacent basin. The exposed western boundary of the Transvaal Hills is a dip slope; there is no evident fault that separates these hills from the Oasis Valley basin. Structurally, the Transvaal Hills could, therefore, be considered to be part of the Oasis Valley basin – the distinction between the two is more physiographic than structural.

In its structural form, the Transvaal Hills is a hogback with a half-dome internal geometry, which is reflected in the map pattern of exposed units (see companion map; Fridrich and others, 1999). The oldest exposed rock unit, the upper part of the 11.6 Ma intracaldera Rainier Mesa Tuff, with its intercalated caldera-collapse breccias, forms the topographically highest, east-central part of the Transvaal Hills, and progressively younger units are exposed onlapping the Rainier Mesa Tuff to the west, northwest, and southwest. Stratal dips shallow upsection, and generally dip outward and westward from the east-central highland. Moreover, the units overlying the Rainier Mesa Tuff thin toward the east-central highland, indicating onlapping of these younger units around an older uplift. Based on this geometry, earlier workers considered the Transvaal Hills to be a remnant of the resurgent dome of the Rainier Mesa caldera that is truncated on its east side by the western topographic wall of the Ammonia Tanks caldera (Figure 3; Byers and others, 1976; Christiansen and others, 1977; Sawyer and others, 1994).

Whereas the above characterization is accurate; it is not the whole story. The pattern of onlapping of younger units changes upsection in the Transvaal Hills. The 11.45 Ma Ammonia Tanks Tuff onlaps and dips radially outward to the west from the east-central high of Rainier Mesa Tuff; for example, in the southern part of the Transvaal Hills, stratal dips in the Ammonia Tanks Tuff are mostly to the southwest. However, the overlying ~11.2 Ma Tuff of Cutoff Road and ~11-10.5 Ma Rainbow Mountain bedded tuffs lap up just onto the western flank of the Transvaal Hills and stratal dips in these units are simply to the west. Hence the western flank of the resurgent dome of the 11.6 Ma Rainier Mesa caldera evidently was buried by the 11.45 Ma Ammonia Tanks Tuff, and the later structure, onlapped by the next two younger units, is just that of a simple west-tilted structural block. That westward tilting continued after deposition of the Tuff of Cutoff Road, which has stratal dips locally >20E; however, toward the top of the sequence of Rainbow Mountain bedded tuffs, stratal dips are so shallow (mostly ~10E) that they may be only slightly steeper than the primary depositional angle.

The westward tilting of the Transvaal Hills after deposition of the Ammonia Tanks Tuff is probably related to extensional tilting rather than to caldera evolution. In support of that, field relations along the major faults in the Transvaal Hills indicate that the major fault set formed mostly if not entirely after the end of the Timber Mountain caldera cycle (after emplacement of the Tuff of Cutoff Road). Moreover, a similar pattern of faulting is exposed within the eastern part of the Oasis Valley basin, just to the west of the Transvaal Hills, in a lava dome that is dated at 9.9 Ma (Figure 3). The faulting exposed in this lava dome is the major surface exposure of internal structures within the Oasis Valley basin, although the major fault set in the Transvaal Hills perhaps should also be considered as structures of the Oasis Valley basin. In addition to the major fault set in the Transvaal Hills, discussed above, an older system of faults is present only in the core of intracaldera Rainier Mesa Tuff, and these faults probably are related to resurgence of the Rainier Mesa caldera.

Northeastern Boundary of the Oasis Valley Basin

The northeastern boundary of the Oasis Valley basin is totally covered by the outflow sheet of the 9.4 Ma Thirsty Canyon Tuff (see Fridrich and others, 1999). Moreover, geophysical data do not show any clear boundary to the basin in this direction. As in the Transvaal Hills, discussed above, it may be that there is no distinct boundary to this basin in this quadrant. Along its entire eastern side, the basin probably is gradational, with minor structural interruptions, into the western part of the SNVF caldera complex.

Southwestern Boundary of the Oasis Valley Basin

The western margin of the Oasis Valley basin is marked geophysically by a long and largely linear gravity gradient (Figure 4), that coincides spatially with the eastern boundary of the Oasis

Mountain Hogback and that extends for at least 10 km to the north. Surface geologic relations indicate that this feature is a buried fault, the Hogback fault (Figure 3). Modeling of the gravity data suggests that the base of the Tertiary section lies about 1-to-4 km deeper on the east side of this fault (inside the Oasis Valley basin) than it does to the west (Figure 4; Hildenbrand and others, 1999; Mankinen and others, 1999). The reason for the large range in the depth estimate is that the southwestern part of the basin is much deeper than the northwestern part. Recent drilling evidence has shown that, near the south end of the Oasis Valley Hogback, the Hogback fault is roughly vertical near the surface (Robledo and others, 1998). The steepness of the gravity gradient associated with this fault indicates that this structure is high-angle but not vertical; hence this fault evidently becomes shallower-dipping with increasing depth – it's a listric fault.

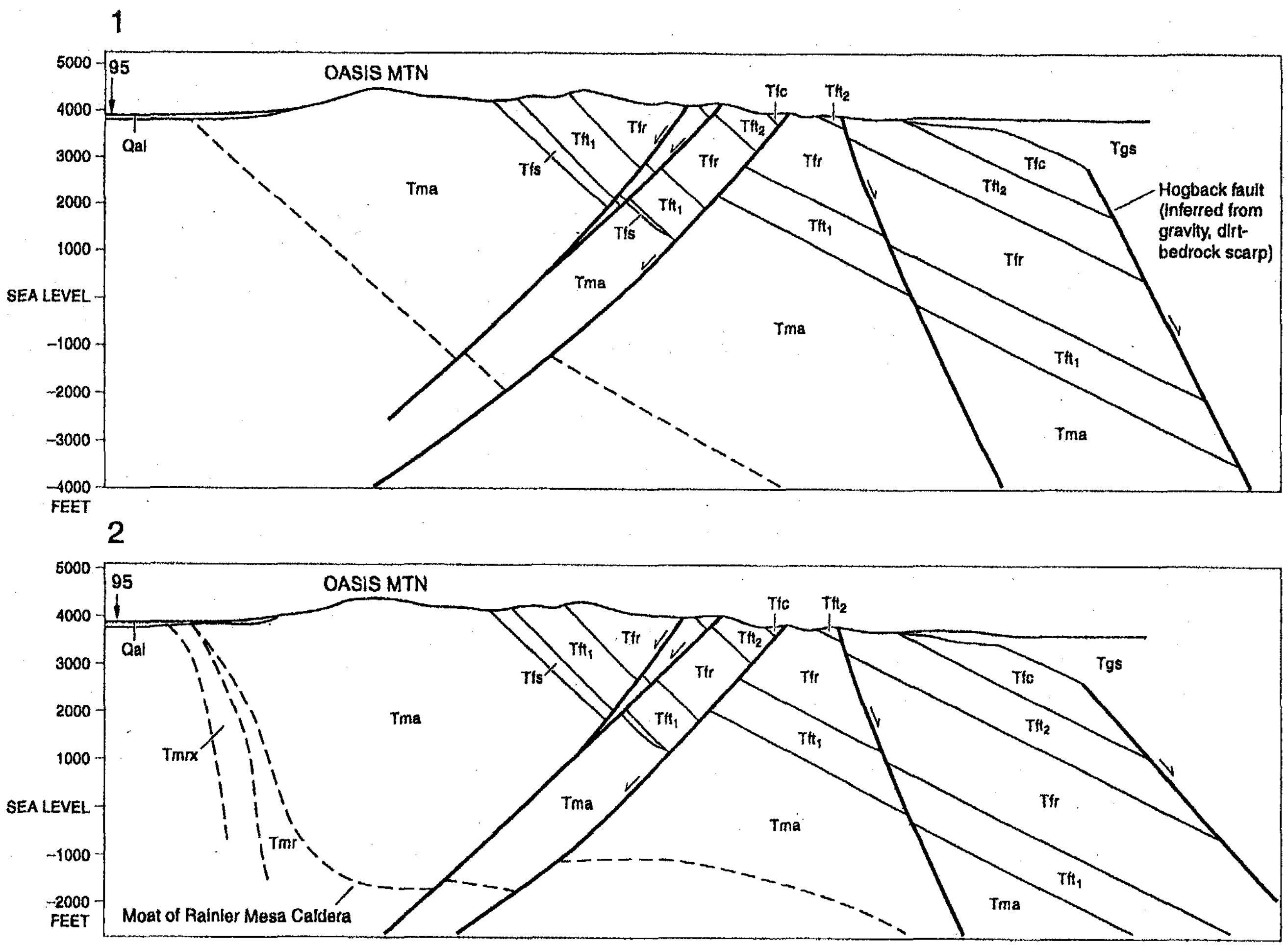
The Hogback fault is not exposed, but the eroded scarp of this fault forms the eastern edge of the Oasis Mountain Hogback. Two aligned scarps are also exposed to the north of the Hogback, one immediately west of the 4.4 Ma Thirsty Mountain shield volcano (Minor and others, 1998) and the other in a small bedrock exposure to the southwest (Figure 3). The continuity and overall linearity of the gravity gradient associated with these three scarps indicates that they are associated with a single fault. Whereas relations at Oasis Mountain Hogback document a major faulting-and-tilting event between 11.2 and ~9.5, relations to the north, along the scarps immediately west and southwest of Thirsty Mountain, indicate mainly that they formed before emplacement of the 11.6 Ma Rainier Mesa Tuff. In total, these relations indicate that the Hogback fault had a protracted history of movement.

The Oasis Mountain Hogback, along the southwestern boundary of the Oasis Valley basin, is evidently a separate structural domain (Figure 3). The northeastern Bullfrog Hills domain lies immediately to the west. Based on the limited information available, the structure and stratigraphy of the Oasis Mountain Hogback is very similar to that of the Oasis Valley basin; a similar stratigraphic section was encountered in the only deep well in the basin, the Myjo-Coffer#1 (Figure

3). The Oasis Mountain Hogback is a single structural block, which, for the area it covers, has remarkable structural simplicity for this region -- it is an east-dipping homocline with a very simple pattern of internal faults that are mostly north-striking and down-to-the-west (see companion map; Fridrich and others, 199). Exposures in the adjacent domains to the west and south host much more complex structure in rocks of the same age (see Fridrich and others, 1999). The younger (post-11.6 Ma) structure of the Transvaal Hills is similar to that of the Oasis Mountain Hogback, and the aeromagnetic pattern over the Oasis Valley basin also indicates a similar structural simplicity and, permissively, a similar structural style, suggesting that these three domains are closely related.

The volcanic sequence exposed in the Oasis Mountain Hogback consists of a very thick (1.5-to-3 km) and unusually lithic-rich section of Ammonia Tanks Tuff overlain by the slightly younger tuffs and lavas of Fleur-de-Lis Ranch and the Tuff of Cutoff Road (Figure 7). These units overlying the Ammonia Tanks Tuff are thicker (300-1500 m) on the Oasis Mountain Hogback than in any other bedrock exposure and, on a regional scale, they evidently thin to the east, pinching out on the western flank of the Transvaal Hills. The exceptional thickness of the Ammonia Tanks Tuff and of these slightly younger units in the Oasis Mountain Hogback is key to the controversy concerning the origin of the Oasis Valley basin, and so is an interpretive issue that is discussed further below.

The most conspicuous feature of the northeastern Bullfrog Hills domain, to the west of the Oasis Mountain Hogback, is a central topographic high composed of early Cambrian nonmetamorphosed clastic sedimentary rocks (Figure 3; Minor and others, 1997a). This central highland is flanked on all sides by landslide deposits that can be grouped into two types: (1) rock-avalanche breccias with clasts of rocks that are the same 11.5-11.2 Ma units exposed in the Oasis Mountain Hogback and that, in many cases, have characteristics that are found in these units (in place) only in the Oasis Mountain Hogback, and (2) giant landslide blocks and breccias composed of older rock units usually including the 11.6 Ma Rainier Mesa Tuff but no younger units. The central highland of the northeastern Bullfrog Hills is cut by a closely spaced set of northwest-striking



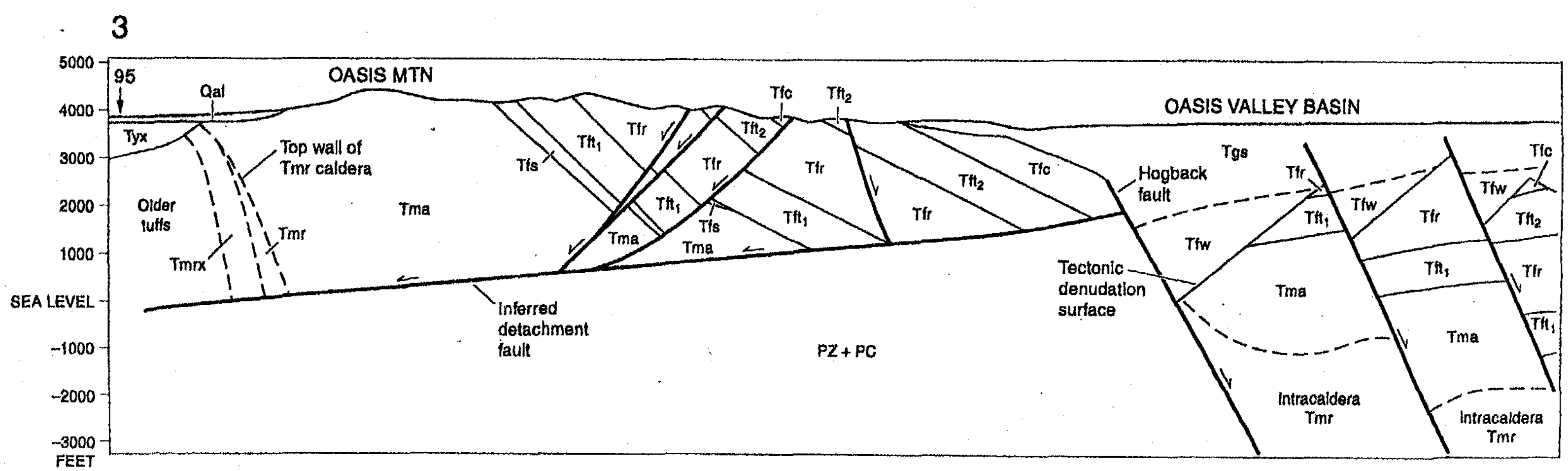


Figure 7. Conceptual development, in three stages, of an east-west cross-section across the northeastern Bullfrog Hills, Oasis Mountain, and western Oasis Valley basin (location of E–E' cross section is shown on figure 3): 1, simple extrapolation of the exposed structure and stratigraphy; 2, the above section modified to reflect the interpretation that the Ammonia Tanks Tuff on Oasis Mountain is rheomorphically stretched and folded because it buried the western moat of the Rainier Mesa caldera; 3, the above section modified to fit the gravity data by inferring a subhorizontal detachment fault under Oasis Mountain and the northeastern Bullfrog Hills.

right-oblique-slip faults. These faults are, for the most part, difficult to discern in the landslide breccias that surround the central highland, but they clearly do cut the breccias.

The timing of tectonism in northeastern Bullfrog Hills domain is constrained by four features: (1) the only evident angular unconformities in this domain that predate the landsliding are the basal Tertiary contact and a minor local unconformity between 12.7 Ma Tiva Canyon Tuff and the 11.6 Ma Rainier Mesa Tuff, (2) the landslide deposits virtually always include clasts of the Rainier Mesa Tuff, and so can be no older than this unit, (2) in the southern part of the domain, the first and younger group of breccias discussed above commonly are intercalated with several thin bedded tuffs that we tentative correlate with the rhyolite of Rainbow Mountain, and these minor tuffs were faulted, tilted, and hydrothermally altered along with the breccias, and (3) these younger breccias are locally capped by the youngest of the Rainbow Mountain Tuffs, which postdated most but not all of the tilting, faulting, and alteration in the southern part of the domain (but not in the northern part), and (4) the older group of breccias locally underlie the Ammonia Tanks Tuff. Based on these observations, the major tectonism in the northeastern Bullfrog Hills domain began at least by ~11.5 Ma, with the largest pulse of tectonism evidently having occurred between ~11 and 10 Ma. The timing of tectonism in the northern Bullfrog Hills therefore appears to be roughly the same as that of the Oasis Valley basin.

The southern boundary of the northeastern Bullfrog Hills domain, against the southeastern Bullfrog Hills domain, is the western part of the Hot Springs fault which, based on its gravity signature, is a large steep down-to-the-south or -southwest fault. This southern domain boundary is concealed under landslide deposits or alluvium and so cannot be observed directly. The northern boundary of the Oasis Valley basin with the Tolicha Peak domain, is totally obscure.

The stratigraphic and topographic relations of the northeastern Bullfrog Hills domain with the Oasis Mountain Hogback reflect a complex tectonic history on the west side of the Oasis Valley basin. In the earliest discernable stage in this history, from >11.6 to ~11.2 Ma, the areas of the

Oasis Mountain Hogback and Oasis Valley basin were evidently a single domain, a deep basin in which the units of this age ponded to great thickness, whereas those units are thin or absent in the eastern Bullfrog Hills domain, indicating it was high ground at the time. In the next discernable stage, from ~11 to ~10 Ma, that earlier basin (or caldera) was tectonically reconfigured to form the Oasis Mountain Hogback and the Oasis Valley basin. During this second stage, landslide masses were being shed off of the Oasis Mountain Hogback to the west and became intercalated with the landslide deposits that were sourced within the northeastern Bullfrog Hills domain. The topography evidently sloped down to the west at that time. At some point near the end of major tectonism in this area, at about 10 Ma or slightly later, the northeastern Bullfrog Hills evidently was uplifted relative to the Oasis Mountain Hogback, because the landslide deposits that slid westward off of the Oasis Mountain Hogback into the northeastern Bullfrog Hills are now, for the most part, topographically higher than the Oasis Mountain Hogback.

Northwestern Boundary of the Oasis Valley Basin

The northwestern boundary of the Oasis Valley basin is formed by the northern part of the Hogback fault, discussed above. This fault is north-striking and linear over most of its length but, based on gravity data, bends to the northwest and then back to the northeast, forming a reentrant in its northernmost part, and is then cut off by the younger (9.4 Ma) Black Mountain caldera at its north end (Figure 3). Grauch and others (1997; written comm., 1999) interpreted this reentrant and coincident strong positive magnetic anomaly as possible expression of the 14.3 Ma Tolicha Peak caldera. New field data show however that the Tolicha Peak caldera extends beyond this reentrant. To the northwest of the reentrant, on the southern flank of Tolicha Peak (Figure 3), the Tolicha Peak Tuff is abruptly downfaulted and, on the downthrown (southeast) side, is at least twice as thick as, and possibly greatly thicker than this tuff is to the north, as the base of the tuff is nowhere exposed to the south (Minor and others, 1993). Moreover, the uppermost part of the downthrown tuff contains blocks up to 30 m across of several older volcanic units and these blocks are internally brecciated but not disaggregated. This tuff-matrix megabreccia is evidently a caldera-collapse breccia, and the adjacent fault is evidently part of the northwestern margin of the Tolicha Peak caldera. The field relations in this area thus support Grauch and others' interpretation of a caldera related to the 14.3 Ma Tuff of Tolicha Peak in this area, but they do not support the idea that the reentrant in the gravity field is an expression of the geometry of this caldera. Furthermore, the intracaldera Tuff of Tolicha Peak has been extended in a tilted-domino fashion with ~30-40 degrees of tilting in most exposures (Minor and others, 1998). After than much extensional deformation, it appears doubtful that the geometry of the caldera would be well reflected in the gravity field anymore. Local thickening of the 11.6 Ma Rainier Mesa Tuff into the reentrant (Minor and others, 1998; Fridrich and others, 1999) suggests that the reentrant is a much younger feature than this caldera. We propose that the reentrant is simply part of the geometry of the Oasis Valley basin (Figure 3).

The other field relations documented along the northern part of the Hogback fault, to the north of the Oasis Mountain Hogback, cast little light on the origin of Oasis Valley basin. Most exposures in this area are of volcanic units that predate 12.7 Ma or that postdate 9.5 Ma, and the exposed faults in this area are mostly older than 12.7 Ma or younger than 9.4 Ma (Minor and others, 1998). Based on relations to the south, in the vicinity of Bare Mountain, the pre-12.7 Ma structures of this region are unrelated to the post-12.7-Ma structures; they are part of an earlier cycle of tectonism (Fridrich, 1998 and in press). The post-9.4-Ma structures evidently are related to the creation of the Sarcobatus Flat basin (see Figure 3) and are younger than the Oasis Valley basin, but may reflect the northwestward migration of the focus of the post-12.7 Ma tectonism that is found in much of this region (Fridrich, 1998 and in press).

Internal Structures of Oasis Valley Basin

Internal structures of the Oasis Valley basin are largely concealed and are therefore known primarily from geophysical evidence. They can be categorized into three types based on their strikes and relative age: (1) older, northwest- and northeast-striking structures, (2) intermediate-age east-striking structures, and (3) younger north-striking structures. The northwest- and northeast-striking structures are the Thirsty Canyon fault and Buckboard lineament (Figure 3).

In previous geophysical surveys, it appeared that the Thirsty Canyon fault merged into the Hogback fault near in the west-central part of the Oasis Valley basin and that the whole southern part of the basin was several kilometers deep (Grauch and others, 1997; written comm., 1999; Fridrich and others, 1996). New gravity data indicate that the Thirsty Canyon and Hogback faults are physically separate structures that come together only in the area where both of them end against the southern margin of the Oasis Valley basin (Figures 3 and 4; Mankinen and others, 1998). The southern half of the Hogback fault thus has a much smaller throw than it appeared to have in the old data and the Tertiary section in the Oasis Valley basin is several kilometers deep only in areas downdropped on (east of) both the Hogback and Thirsty Canyon faults.

North of the Buckboard lineament, the Thirsty Canyon fault is known from drilling evidence to be the western ring-fracture zone of the Silent Canyon caldera (Grauch and others, 1997; written comm., 1999). The interpretation that best fits both the new geologic and geophysical data is that, south of the Buckboard lineament, the Thirsty Canyon fault is the western ring-fracture zone of the Rainier Mesa caldera; hence, the Thirsty Canyon fault is a composite of at least two caldera boundaries. The rough linearity of this N20E-striking structure suggests that caldera collapse may have utilized a preexisting structure which, given its strike, may have formed as an extensional tectonic fault (Mankinen and others, 1998). Geoelectric surveys across the Thirsty Canyon fault show that it has a stepped character resembling that of well studied caldera ring-fracture zones and that it coincides with a zone of high electrical conductance, suggesting it was a focus of clay-forming hydrothermal activity as caldera ring fracture zones typically are (Mankinen and others, 1998).

The Buckboard lineament is an aeromagnetic feature with no apparent gravity expression (Figure 4 and 5) that lies immediately north of, and roughly parallel to, the northern boundary of the Rainier Mesa caldera (Figure 3) as defined by Sawyer and others (1994) and Grauch and others (1997; written comm., 1999). These last-mentioned workers defined the caldera boundary based on a large, arcuate, lower-to-the-south gravity gradient and the spatially coincident northern boundary of a strong negative magnetic anomaly they interpreted as the northern limit of the thick, reversely magnetized, intracaldera Rainier Mesa Tuff (Figure 4 and 5). New geophysical data collected by Mankinen and others (1998) shows that the Buckboard lineament is a shallow and apparently gently southward-dipping feature. Given this geometry, it appears probable that the northern boundary of the caldera as defined by Sawyer and others (1994) and by Grauch and others (1997) is the deep ring-fracture zone of the Rainier Mesa caldera and that the Buckboard lineament is the corresponding topographic wall of the caldera that extends outward from the ring-fracture zone a short distance to the north, as concluded by Mankinen and others (1999).

The second group of internal structures listed above consists of two major, roughly east-striking features, the Colson Pond and Fleur-de-Lis Faults. Large changes in stratigraphic thickness and character are present in the 11.7-to-~11.2 Ma Timber Mountain age volcanic units across these structures; hence, it appears that they were growth faults during deposition of this sequence. A possible alternative is that they may be strike-slip faults that offset deep basin (or intracaldera) sections against extrabasin (or extracaldera) sections. Exposed stratigraphic relations provide unequivocal evidence of the existence of these faults; however, the strike of these buried structures is unclear from exposed bedrock constraints. Gravity data indicate that they are roughly east-striking (Figures 3 and 4; Mankinen and others, 1998). These roughly east-striking structures do not fit any well-accepted model of caldera structures but they probably are related to the caldera rather than to regional tectonism based on their close temporal and physical association with the Rainier Mesa caldera, as is discussed below in the analysis section of this report.

The younger, north-striking structures listed above are indicated by subtle alternating negative and positive, north-trending magnetic anomalies that form a ribbed appearance in the aeromagnetic map of the Oasis Valley basin. Only a couple of these anomalies are evident in the residual magnetic map included here (Figure 5); the pattern is more clearcut in more detailed aeromagnetic maps. The ribbed appearance in the magnetic data extends beyond the Oasis Valley basin over bedrock exposures on the east and west margins of the basin (i.e., over the Oasis Mountain Hogback and the Transvaal Hills), where it is clear that the magnetic "ribs" correspond to small, closely spaced, north-striking normal faults. These faults bound fault blocks dip westward, in tilted-domino fashion, and were active primarily between ~11.2 and ~9.5 Ma based on stratigraphic relations. Within the basin, these younger faults are synthetic to the Hogback fault, and appear to be related to that fault as part of the half-graben geometry of the Oasis Valley basin. These faults are a product of regional extension.

The half-graben geometry of the Oasis Valley basin is based on surface and subsurface geologic relations, for example, that the stratigraphic units of the 11.5 to ~7.5 Ma interval thin eastward across this basin and pinch out in or near the eastern boundary of the basin, on the western flank of the Transvaal Hills. This geometry is not reflected in the gravity data; hence, the gravity data and the geologic constraints appear at odds. The probable explanation is that the gravity field integrates two overlapping features: (1) the westward-deepening post-11.45-Ma half-graben and (2) the westernmost part of the 11.6-Ma Rainier Mesa caldera which is known to underlie the majority of the area of the Oasis Valley basin, and which probably is eastward-deepening.

ANALYSIS OF THE OASIS VALLEY BASIN

Because most features of the Oasis Valley basin are covered by alluvium and by post-tectonic volcanic units, and because there is only one deep drill hole in the basin (the Myjo-Coffer#1; Figure 3), our best interpretation of this basin inevitably is nonunique. The interpretation we propose below is premised strongly on our understanding of the regional context as well as on our understanding of the processes that created this basin and the much-better-exposed structural features that surround it.

That part of the southern Walker Lane belt that adjoins the Oasis Valley basin on its west side is largely occupied by a regional-scale detachment fault system, whereas that part of the northern Basin and Range that flanks the east side of Oasis Valley hosts the broad SNVF caldera complex (Figures 1, 2A, 2B, and 3). Both the detachment fault system and the caldera complex were at their peak of activity during the period of tectonism that formed the major structural features of the area of interest, including the Oasis Valley basin. The zone of transition/overlap between the caldera complex and detachment fault system is poorly exposed and undoubtedly complex; however, an advantage that we have in this case is that the Crater Flat basin, located immediately to the southeast of the Oasis Valley basin (Figures 2A, 2B, and 3), has a similar setting, is well exposed, and has been studied in detail (Fridrich, 1998 and in press, Fridrich and others, 1998 and in press). Our approach in this analysis consists of three parts. First and second, we examine the roles of the caldera complex and of the detachment fault system, respectively, in the formation of the Oasis Valley basin. Third, we use the Crater Flat basin as an analogue -- examining how the Oasis Valley basin is similar to the Crater Flat basin, and how it differs.

SNVF Caldera Complex and its Role in Formation of the Oasis Valley basin

In the discussions above, it was explained that the southern boundary of the Oasis Valley basin is coincident with the southwestern margin of the 11.6 Ma Rainier Mesa caldera, and that the Thirsty Canyon fault, within the basin, is the inferred western limit of this caldera. We also discussed the fact that the exceptional thickness of Timber Mountain Group rocks associated with the area of the Oasis Valley basin extends westward of the basin, ending at the western flank of the Oasis Mountain Hogback. These two things together present an enigma because the great stratigraphic thickness of Timber Mountain rocks at the Oasis Mountain Hogback would be most easily explained as a consequence of ponding within the Timber Mountain caldera complex and yet this feature lies 2-to-6 kilometers westward of the western limit of the Rainier Mesa caldera as interpreted from the gravity data. Field evidence alone does provide a solution to this enigma, but it helps us to better understand the nature of the problem.

On Oasis Mountain, Noble and others (1991) documented a pattern of flow-foliations and related features in the 11.45 Ma Ammonia Tanks Tuff that indicate this tuff buried a steep east-dipping topographic slope, and flowed down this slope as the tuff welded. Noble inferred that this buried slope was the western topographic wall of the SNVF caldera complex for three reasons: (1) because of the great thickness (>1 km) of the Ammonia Tanks Tuff ponded in this location, against this paleoslope, (2) because, in this locale, the Ammonia Tanks Tuff was deposited on a thick section of landslide and talus breccias, deposits that resemble caldera-related breccias (see also Minor and others, 1997a) and (3) because this tuff locally contains xenoliths as much as 10 m in diameter near the west flank of Oasis Mountain. Xenoliths of this size are very rare in tuffs emplaced outside of calderas. These features indicate that a major scarp of some kind was present along the west side of Oasis Mountain during deposition of the Ammonia Tanks Tuff and suggest that that scarp was a caldera margin. Noble (unpub. manuscript, 1966, quoted in Byers and others,

1976) initially interpreted the paleoslope on the west side of Oasis Mountain as the western topographic wall of the Ammonia Tanks caldera. Noble and others (1991) reinterpreted it as western margin of the Rainier Mesa caldera because other evidence indicates that the western boundary of the Ammonia Tanks caldera is the scarp that forms the eastern boundary of the Transvaal Hills (Byers and others, 1976).

New mapping conducted in this study shows that the pattern of flow foliations in the Ammonia Tanks Tuff changes laterally across Oasis Mountain; the foliations showing eastward flow down a paleoslope end eastward in a zone of rheomorphic folding with fold axes striking roughly north-south. This folding suggests that the Ammonia Tanks Tuff of Oasis Mountain did not simply flow eastward as it welded, it evidently flowed downward from both the east and west into a north-trending trough that was located under the central part of Oasis Mountain (Figure 7). This is consistent with Noble and others' (1991) interpretation if this paleotrough is the western moat of the Rainier Mesa caldera. The northward trend of the buried trough could also be explained as a regional tectonic feature, such as a structural valley between two hogbacks, because the trend of this feature is consistent with the strike of tectonic faults in the region. However, the rapidity with which this >1.5 km deep trough formed (in the interval between the Rainier Mesa and Ammonia Tanks eruptions - 150 k.y. or less) would require fault-slip rates (>1 cm/yr) that appear inconsistent with the scale of this feature if it formed by regional extension; Noble and other's (1991) caldera interpretation is easier to reconcile with this time scale.

A further feature of interest within the Oasis Mountain Hogback involves apparent stratigraphic growth across the two roughly east-striking structures on the north and south sides of Oasis Mountain, introduced above. For example, the change in thickness of the Ammonia Tanks Tuff between Oasis Mountain (~1.5 km) and the Hogback (1 km) coincides with a large structural offset of this unit down to the north. This offset occurs across a locally exposed paleoscarp that has a relief of at least 1 km because it cuts across the entire 1 km thickness of Ammonia Tanks Tuff in the northern part of the Hogback. This scarp was then buried by the slightly younger tuffs and lavas of Fleur-de-Lis Ranch. The trend of the surface exposure of the paleoscarp is northwestward; however, the strike and dip of the scarp surface is not obtainable from the existing exposure – it could be anything from northwest-striking to purely east-striking. Gravity data in this area (Figure 4; Mankinen and others, 1998) show an east-striking gradient just to the north of the paleoscarp, at the north end of the Hogback, namely the Fleur-de-Lis fault discussed above, a concealed fault that the partly exposed paleoscarp is evidently related to.

The throw of the Fleur-de-Lis fault is estimated at 1.5 km - the sum of the thickness of Ammonia Tanks Tuff cut out by the eroded scarp related to this fault (1 km) plus the increase in thickness of this tuff across the fault (0.5 km). The throw could also be estimated based on the total downdropping of the base of the Ammonia Tanks Tuff from the Hogback to Oasis Mountain or by the thickening of the whole Ammonia-Tanks-Tuff-through-Tuff-of-Cutoff-Road section between the Hogback (1.5 km) and Oasis Mountain (3 km); all three approaches yield the same estimated throw - 1.5 km. Curiously, the gravity data indicate a down-to-the-north offset of the Tertiary/Paloezoic contact of only about 0.5 km across this fault, which is odd but consistent with other elements of the enigma involving the Oasis Mountain Hogback.

A fault that roughly parallels the Fleur-de-Lis fault, the Colson Pond fault (Figures 3 and 4), is inferred along the north flank of Oasis Mountain based on two lines of evidence. First, the gravity data show a west-northwest-trending gravity gradient in this location indicating an offset of the Paleozoic/Tertiary contact of about 0.5 km, which in this case is down to the south. Second, exposed bedrock relations show a stratigraphic change between Oasis Mountain and the first bedrock exposure to north. To the north, the whole ~3-km-thick section of 11.5-11.2 Ma units exposed on Oasis Mountain (Ammonia Tanks Tuff, Fleur-de-Lis Ranch tuffs and lavas, and Tuff of Cutoff Road; see Table 2) is for some reason missing and the Timber Mountain age (11.7-11.2 Ma) section is represented only by an exposure of Rainier Mesa Tuff which is only 50 m thick, too thin to be an intracaldera tuff. The throw of the Colson Pond fault is at least 3 km based on the structural offset across it. The presence of an extra 3 km of section on the downthrown (south) side of this fault relative to the north side could be explained either by growth faulting or by erosion on the upthrown side; however, moderate-to-low-relief areas in southern Nevada, such as Oasis Valley, have incurred only a small amount of erosion in the last 10 m.y. (Whitney and Harrington, 1993). Hence we favor the interpretation that the Colson Pond fault is a large growth fault that formed during Timber Mountain time, i.e., that it is a fault that is similar to and probably related to the Fleur-de-Lis fault.

Several features of the Fleur-de-Lis and Colson Pond faults are difficult to explain in terms of standard tectonic models. For example, the increases in stratigraphic thickness across these two faults (1.5 and 3 km) evidently developed over an interval of only about 0.2 m.y. and possibly much less based on the radiometric ages of the units involved (Sawyer and others, 1994), suggesting slip rates for these faults off at least 0.75 and 1.5 cm/year, respectively – very high rates for such short faults. Even more striking is the large total throws of these faults relative to their short lengths, which would be very unusual for regional tectonic faults (Wells and Coppersmith, 1994). Moreover, few other tectonic faults of this region that formed around 11 Ma strike roughly east-west as these faults do. We therefore favor the interpretation that the Colson Pond and Fleur-de-Lis faults formed as radial faults to the subcaldera magma body owing to circumferential extension around the caldera. Such faults have been predicted in structural analyses of deformation induced by magma overpressure in high-level magma chambers (Anderson, 1951). Local deviation of the regional tectonic fault pattern into a pattern that is largely radial about the Timber Mountain caldera complex has also been documented in the northern part of the Crater Flat basin by Minor and others (1997).

Detachment Faulting and its Role in Creating the Oasis Valley basin

The crux of the enigma discussed above is that surface geologic relations appear to indicate that the western margin of the Rainier Mesa caldera is located on the western flank of the Oasis Mountain Hogback, as interpreted by Noble and others (1991), whereas gravity data suggest it is located within the Oasis Valley basin, at the Thirsty Canyon fault. Regional structural relations, in combination with the gravity data, suggest a possible explanation based on the following points.

First, the gravity data collected at the Oasis Mountain Hogback do not reflect the very thick (1.5-to-~3 km), moderately tilted (~30E on average) sections of the Timber Mountain age rocks exposed on the surface; instead, they indicate that the Paleozoic/Tertiary contact under this domain is subhorizontal and lies at a depth of only 0.5-to-1 km (Figure 4; Mankinen and others, 1998). The Paleozoic/Tertiary contact under this domain is therefore a feature that cuts across bedding at an angle of approximately 30 degrees (Figure 7). Because this contact is roughly planar and cuts across bedding, it is reasonable to conclude that it is a fault. Assuming that bedding was flat when this fault formed, the fault originally dipped about 30 degrees to the west, and has since been tilted eastward to its current subhorizontal attitude (Figure 6).

A conceivable alternative hypothesis is that the concealed subhorizontal contact indicated by the gravity data is an angular unconformity at the base of the Tertiary section, rather than a fault. However, as discussed above, the Colson Pond and Fleur-de-Lis faults have gravity expressions that indicate much smaller offsets of the Paleozoic/Tertiary contact than are indicated by the stratigraphic offsets associated with these faults on the surface. This is easily reconciled if the concealed subhorizontal contact is a fault that is younger than the Colson Pond and Fleur-de-Lis faults. It is incompatible with the concealed contact being a basal Tertiary unconformity because this hypothetical unconformity would be older then the Colson Pond and Fleur-de-Lis faults and would, therefore, be offset by these structures at least as much as the rocks exposed on the surface are.

Second, the throw of the inferred subhorizontal fault is at least one and a half kilometers at the Hogback and at least 3 km at Oasis Mountain because those are the thicknesses of the exposed volcanic section that evidently are offset against Paleozoic rocks under these two physiographic features. We can assume that stratal tilting in this area follows a tilted-domino pattern because that is what we see in all of the domains that surround the Oasis Valley basin. Based on the eastward stratal tilts in the Oasis Mountain Hogback as well as the pattern of intersection of these tilts against the underlying fault, the upper plate of this fault was therefore transported westward from its point of origin as it tilted eastward in domino fashion. The upper plate of this fault (the rocks exposed on the Oasis Mountain Hogback) is a slice of rock that was derived from the area of the current Oasis Valley basin.

Third, when we look eastward into the Oasis Valley basin, the area where this upper-plate fault slice presumably was derived, we see a steep down-to-the-east gravity gradient, the Thirsty Canyon fault, discussed above. Across this buried fault, the gravity data show that the Tertiary section abruptly increases in thickness westward by about 2-to-4 km, an amount that is approximately equal to the eastward thickening of the Timber Mountain Group section that we see between the northeastern Bullfrog Hills domain and the Oasis Mountain Hogback. The Thirsty Canyon fault, in the basin, and the stratigraphic thickening across the paleoscarp on the western flank of the Oasis Mountain Hogback, just west of the basin, could therefore be correlative features. If so, this is a piercing point between the upper and lower plates of the currently flat fault that underlies the Oasis Mountain Hogback.

Fourth, in support of the above interpretation, we can estimate that the throw of the currently flat fault under the Oasis Mountain Hogack is at least one-and-a-half to three kilometers, as discussed above. Given the 30 degrees of eastward tilting that occurred to bring this fault to its current subhorizontal attitude, that throw will be expressed today as a horizontal offset having about twice the magnitude of the throw, which is consistent with the 3-6 km magnitude of horizontal offset that we see between the abrupt stratigraphic thickening on the west flank of the Oasis Mountain Hogback and the abrupt depression of the Paleozoic/Tertiary contact that we see across the Thirsty Canyon fault. These are the two features that are proposed to be the western boundary of the Rainier Mesa caldera. If they are in fact the same feature that has been split in two by a fault, then both interpretations of the location of the western boundary of the Rainier Mesa caldera are correct; one is the upper-plate location of the caldera margin and the other is the lower-plate location (see Figure 7 and cross section A-A' of the companion map; Fridrich and others, 1999).

Fifth, the detachment fault interpretation is supported by the fact that the area of high gravity under the Oasis Mountain Hogback is just a small part of a much larger gravity high that includes the areas of the Fluorspar Hills and southeastern Bullfrog Hills domain, where the Fluorspar Canyon-Bullfrog Hills detachment fault system is well exposed (Figure 4). We thus are not invoking a new detachment fault system; we are proposing that the well-documented detachment fault system immediate to the south extends at least under the Oasis Mountain Hogback, and probably throughout the area of the large gravity high in the western half of the nine-quadrangle study area (Figures 3 and 4).

Like many other detachment faults, we propose that the one we infer under the Oasis Mountain Hogback formed at a moderate-to-low angle, and was subsequently rotated to a very shallow angle owing to uplift of the footwall of the fault. That footwall uplift is presumed to be an isostatic response to the large amount of unloading of the footwall block that occurs during large-scale extensional transport of the upper plate of the detachment fault (Buck, 1988). Further, we propose that the rolling-hinge model (e.g., Spencer and Reynolds, 1991) provides an explanation for the west-northwestward younging of tectonism across the Fluorspar Hills/southeastern Bullfrog Hills domains and that the same process is probably responsible for the complex history of alternating uplift and subsidence of the Oasis Mountain Hogback relative to the northeastern

Bullfrog Hills domain, discussed above.

Crater Flat Basin as an Analogue for Oasis Valley Basin

In our interpretation above, the Hogback fault lies along the eastern boundary of the area of large-magnitude footwall uplift associated with the detachment fault system. Similar high-angle normal faults, that facilitated abrupt lateral transition to multi-kilometer footwall uplift, have been documented along the trailing edges of other detachment fault systems, that is, near the edge where these detachment faults originally terminated by reaching the surface. A local example is the Bare Mountain fault, which is exposed in the southern part of the Oasis Valley region and is related to the same detachment fault system that we propose extends under the Oasis Mountain Hogback (Figures 2A, 2B, and 3; Fridrich, 1999; Fridrich and others, 1997). Fridrich and others (1997) proposed that such faults that form at the trailing edge of detachment fault systems be called trailing-edge faults and that the basins that form with these faults as the master faults of the basins be called trailing-edge basins. We thus propose that the Bare Mountain and Hogback faults are en echelon trailing-edge faults and the Crater Flat and Oasis Valley basins are en echelon trailing-edge basins formed within a single detachment fault system (Figures 2A and 2B; Fridrich, 1999).

The major similarities between the Crater Flat and Oasis Valley basins are that:

(1) both are half-grabens with their master faults along their western margins,

(2) based on the aeromagnetic pattern within Oasis Valley basin (Figure 5), it apparently resembles Crater Flat basin in having an internal extensional structure dominated by a simple pattern of closely spaced normal faults with associated domino-style tilting,

(3) westward thickening of the fill of both basins indicates a westward increase in the magnitude of extension and in associated subsidence as the master fault at the western edge of these basins is approached.

The two basins differ in that:

(1) in Oasis Valley basin, the internal extensional faults appear to be dominantly synthetic to the master fault at the west margin of the basin, whereas in Crater Flat basin, they are dominantly antithetical (Figure 6),

(2) in Oasis Valley basin, the dominant north-striking internal faults are roughly parallel to the master fault of the basin and to each other, whereas in Crater Flat basin the internal faults describe a large-scale fanning pattern across the basin, indicating westward and southward increasing extension and strike-slip strain (Fridrich, 1998 and in press; Fridrich and others, 1998 and in press),

(3) the master fault of the Crater Flat basin, the Bare Mountain fault, has a maximum throw of as much as 4-to-5 km and bounds a core complex (Bare Mountain), whereas that of the Oasis Valley basin, the Hogback fault, has a throw of only about 1-to-1.5 km and the lower plate, under the detachment fault, is not exposed on the upthrown side (Figure 6),

(4) whereas the Crater Flat basin terminates northward at the south margin of the SNVF caldera complex and extends more than 25 km to the south, the Oasis Valley basin overlaps the caldera complex extensively and no part of it is more than ~8 km from the western deep-ring-fracture-zone of the caldera complex, and

(5) Oasis Valley basin was a site of moderate-volume volcanic venting (probably several 10's of km3 of magma erupted) of bimodal (rhyolite and lesser basalt) character during its structural evolution, whereas Crater Flat basin was the site only of relatively small-volume (<3 km3) strictly basaltic volcanism.

In summary, the major differences all involve the extent and nature of involvement of the caldera complex and associated magmatic system in the evolution of these two otherwise-similar trailing-edge half-grabens. The fan-like internal geometry of faulting and extension within the Crater Flat basin appears to reflect the fact that the magma chamber under the Claim Canyon caldera, at the north end of the basin, was largely solidified during the opening of this basin. This intrusion evidently acted as "a nail through the crust," a point of minimum extension and strike-slip strain that is the fulcrum point about which this fan-like basin opened (Scott, 1990; Fridrich, 1998 and in press; Minor and others, 1997b).

In contrast, the Oasis Valley basin extensively overlaps the western part of the Timber Mountain caldera complex (Figure 3) and developed coevally with the final stage of silicic magmatism in this system. Nearly all of the internal structures of the Oasis Valley basin are either roughly parallel to the western margin of the Timber Mountain caldera complex or are roughly perpendicular to it; they are either radial to the western margin of the caldera complex or they are roughly concentric to it. This type of geometry is consistent with that predicted by Anderson (1951), in which the inability of the underlying/nearby (liquid) magma system to sustain shear exerts the dominant control on fault geometry.

Another point is that the internal faults of Oasis Valley basin are predominantly synthetical to the master fault at the western margin of the basin, in contrast to the antithetical faults that dominate within Crater Flat basin. In the case of the Crater Flat basin, it appears that the crust was weaker to the west and so was extending by sliding down in domino fashion in that direction, toward the direction in which the detachment fault system was rooted. In the case of Oasis Valley basin, however, domino-style extensional faulting and counterposed tilting occurred down toward the caldera complex, suggesting the crust was weaker on the caldera side than on the detachment-fault side. Otherwise the two basins appear to be structurally analogous and our interpretation that they are analogous is reflected primarily in how we have interpreted the geometry of the Oasis Valley basin in cross sections (see Figure 6 and 7).

SUMMARY AND TENTATIVE HYDROLOGIC IMPLICATIONS

In summary, we conclude that the area between testing areas on Pahute Mesa and the springs in Oasis Valley is occupied primarily by the Oasis Valley basin. We propose that the simplest interpretation of the existing geological and geophysical data is that this basin is a half-graben that formed at the trailing edge of the FC-BH detachment fault system wherein: (1) the master fault at the western boundary of the basin, the Hogback fault, formed to facilitate an abrupt transition to large-magnitude footwall uplift to the west, (2) a zone of tectonic denudation associated with the detachment faulting is present in the southwestern part of the basin, and (3) the internal fault pattern associated with the formation of the Oasis Valley basin is one of small, closely spaced, north-striking faults that are mostly synthetic to the master fault at the west edge of the basin and that bound west-dipping fault blocks. This basin also overlaps the westernmost part of the Rainier Mesa caldera, and the western ring-fracture boundary of that caldera - the Thirsty Canyon fault - cuts from northeast to southwest across the basin. Further, two large roughly east-striking structures, the Colson Pond and Fleur-de-Lis faults, cut across the middle of the basin, and are growth faults in the welded tuff section.

These geologic/geophysical interpretations do not lead to a unique hydrogeologic model for the Oasis Valley basin, but they serve as a basis for formulating a proposed model, which can be tested by drilling, hydrochemical studies, and by other data gathering and modeling. The proposed model consists of the following points:

(1) Two major aquifers are present in Oasis Valley basin, an unconfined alluvial aquifer and a confined welded tuff aquifer. The welded tuff aquifer extends eastward and northward of the basin and is the host rock for most of the underground nuclear tests that were conducted on Pahute Mesa. The welded tuff aquifer has low effective porosity and a moderate fracture permeability, which presumably decreases downward, forming a

gradational base to the hydrologic system. The alluvial aquifer has moderate matrix permeability and a much higher effective porosity than the welded tuff aquifer. The two aquifers in the basin are separated by the nonwelded tuff confining unit, which has a fairly high matrix porosity, but little permeability. Groundwater probably leaks upward from the confined welded tuff aquifer to the unconfined alluvial aquifer along faults that cut the nonwelded tuff confining unit and the underlying welded tuffs.

(2) Both of the major aquifers of the Oasis Valley region largely terminate in the general vicinity of the southern and western boundaries of the basin (Figure 8). As flow in this system is evidently to the southwest, based on the water-table configuration (Laczniak and others, 1996), the general pinchout of these aquifers to the southwest forces groundwater flow to the surface, hence the springs (Figure 8). The alluvial aquifer actually continues southwestward of the Oasis Valley basin but largely only as the fill of the narrow Amargosa river channel. Rather than actually terminating against the southern and western boundaries of the Oasis Valley basin, the welded tuff aquifer actually declines in thickness to about 1 km across these boundaries. This aquifer does finally pinch out almost totally to the west, on the west side of the Oasis Mountain Hogback, against the hydrothermally altered and probably impermeable landslide breccias of the northeastern Bullfrog Hills. It also pinches out to the south against the FC-BH detachment fault on the north side of Bare Mountain (see Figures 3 and 8). The lower-plate pre-Tertiary rocks that the welded tuff aquifer ends against at the detachment are either clastic rocks - which are generally impermeable - or consist of imbricated, steeply north-dipping structural blocks of both carbonate and clastic rocks. The carbonate rocks probably are not an effective aquifer in this case because of the lack of continuity (this domain in which the carbonate aquifer is present but discontinuous is shown as the small unpatterned area in the center of Figure 8). To the west of the Oasis

Valley basin, the only exposed pre-Tertiary rocks are impermeable clastic rocks. Hence,the only evident pathways for groundwater to escape from Oasis Valley are to the south, in the narrow alluvium-filled channel of the Amargosa River and possibly also to the southeast, where a pathway into the tuff and/or carbonate aquifers under Crater Flat basin is conceivable, but difficult to evaluate with existing data. Under the ridge that separates Oasis Valley basin from Crater Flat basin, the water table is much higher than it is at the Amargosa River channel, suggesting that the this channel is a more important pathway for groundwater escape than the possible connection into Crater Flat basin.

(3) The welded tuff aquifer is thin in a narrow west-northwest-trending septum that separates the Silent Canyon and Rainier Mesa calderas. This septum is the triangular area between the Buckboard lineament and the northwestern margin of the Rainier Mesa caldera (Figures 3 and 4). However, this septum disappears about 8 km east-southeast of the Thirsty Canyon fault and, otherwise, there are no evident features that would form a hydrologic barrier between the Oasis Valley basin and the testing area to the northeast on Pahute Mesa. Given the characteristics of the welded tuff aquifer in the Oasis Valley basin and and the proximity of this basin to the central caldera complex of the SNVF, there probably is little contrast between this basin and the caldera complex in hydrologic properties, and thus little chance of a major hydrologic barrier between the two, as has been concluded before by Laczniak and others (1996) and by Grauch and others (written comm., 1999).

(4) Unlike the welded tuff aquifer, both the alluvial aquifer and the nonwelded tuff confining unit thin and eventually pinch out to the east, against the western flank of the Transvaal Hills (against the eastern margin of the Oasis Valley basin), as well as to the north, at different points within the basin. The alluvial aquifer appears to end northward approximately in the position of the Colson Pond fault (Figure 3). The nonwelded tuff

confining unit pinches out further northward in a location that is concealed, but that is southwestward of the testing area on Pahute Mesa.

(5) Major faults in the Oasis Valley region probably constitute important hydrologic units, forming both pathways and barriers to groundwater flow. For example, the Thirsty Canyon fault zone may form a preferred pathway for flow from Pahute Mesa to Oasis Valley (along its strike in the fault zone itself). This fault also appears to form a barrier to flow perpendicular to strike as water-table elevations are locally much higher to the west of this fault than they are to the east (Laczniak and others, 1996). Faults may also control the locations of springs in some cases. For instance the northeasternmost springs of the Oasis Valley discharge area, at Colson Pond, are located approximately at the intersection of the Thirsty Canyon and Colson Pond faults (Figure 3). Groundwater may discharge at this location because this fault intersection may create a pathway for upwelling from the confined welded tuff aquifer. Alternatively, the large stratigraphic changes that are present across both of the faults that intersect in this location may result in a southwestward change in transmissivity that results in spring discharge.

Based on the above geologic framework, there are several alternative pathways for groundwater flow in the Oasis Valley region and the pathways probably differ for springs in different parts of the discharge area, which should be reflected in hydrochemical data. Much of the groundwater flowing through the southern part of the system probably passes through the alluvial aquifer on its way from the welded tuff aquifer to the springs. In contrast, groundwater discharging at Colson Pond probably comes almost directly from the welded tuff aquifer to the surface, passing through the nonwelded tuff confining unit at the above-described fault intersection. The relatively high temperature of Bailey's (Hick's) hot spring in the southern part of the system supports the geologic/geophysical interpretation that a deeply penetrating east-striking fault (the Hot Springs fault; Figure 3) is present near this spring, creating a unique pathway.

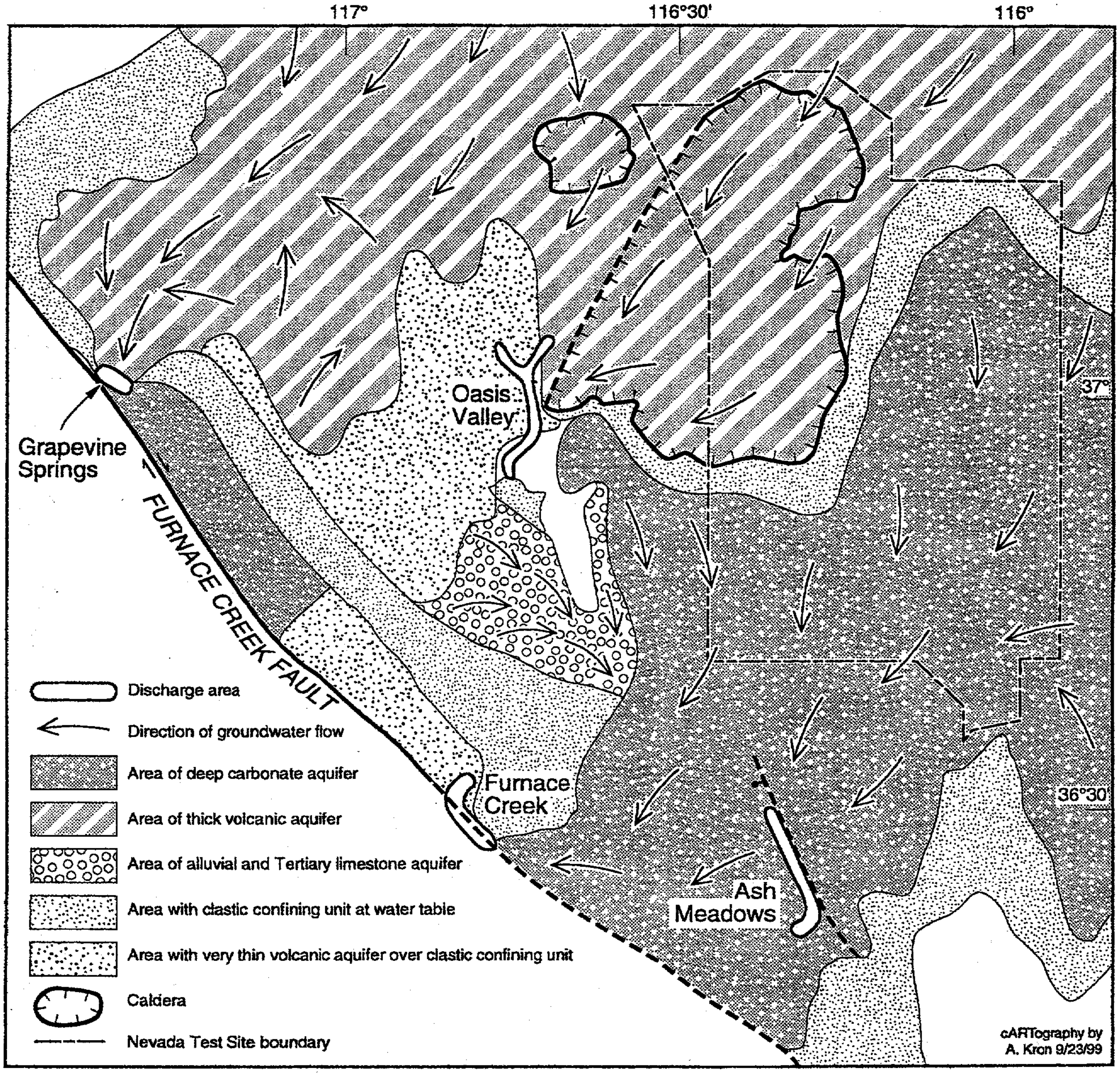


Figure 8. Generalized model of the Death Valley groundwater flow system showing the areas of major aquifers, major barriers to flow formed by confining units, and discharge areas; the Furnace Creek fault, and outlines of the Nevada Test Site and the central caldera complex of the southwest Nevada volcanic field shown for geographic context.

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TABLE 1: Generalized Stratigraphic Column of the Oasis Valley region
(underlined units are those discussed in the text).

Alluvium

|
| Black and Hidden Cone basalts ~0.2 Ma
| Thirsty Mountain shield volcano (basalt) 4.4 Ma
|
| Spearhead Tuff 7.5 Ma *[source: Stonewall caldera]*
|
| Sarcobatus Group (Obsidian Butte and Talisman rhyolites) ~8.5 Ma
|
| Thirsty Canyon Group and associated rocks
| late basalts ~9-8 Ma
| Thirsty Canyon Tuffs 9.4 Ma *[source: Black Mountain caldera]*
| (Gold Flat, Trail Ridge, and Pahute Mesa Tuffs)
|
| Rhyolite of Colson Pond and coeval basalts 10-9.5 Ma
|
| Donovan Mountain Latite 10.4 Ma
|
| Rhyolite of Rainbow Mountain ~11 to ~10.5 Ma

Breccia*

Timber Mountain Group

- Tuff of Cutoff Road/Beatty Wash Fm/basalt ~11.2 Ma?
- Fleur-de-Lis Ranch/West Cat Canyon tuffs and lavas
- Ammonia Tanks Tuff 11.45 Ma *[source: Ammonia Tanks caldera]*
- Tannenbaum Hill/Twisted Canyon tuffs and lavas (&basalt) 11.55 Ma
- Rainier Mesa Tuff 11.6 Ma *[source: Rainier Mesa caldera]*
- Rhyolite of Fluorspar Canyon and local basalt 11.7 Ma

Breccia*

Paintbrush Group *[source: Claim Canyon caldera]*

Tiva Canyon Tuff 12.7 Ma

Yucca Mountain Tuff

Rhyolite of Echo Peak

Pah Canyon Tuff

Topopah Spring Tuff 12.8 Ma

Calico Hills Formation 12.9 Ma

Crater Flat Group

Bullfrog Tuff 13.25 Ma

Rhyolite of Prospector's Pass 13.35 Ma

Tram Tuff 13.45 Ma

Older Tuffs and Lavas of southwest Nevada volcanic field

Lithic Ridge Tuff 14 Ma

"Rhyolite" of Picture Rock (rhyodacite-to-latite mostly) 14 Ma

"Old Yeller" sediments □

| Tuff of Sleeping Butte 14.1 Ma

| Tolicha Peak Tuff 14.3 Ma

| unidentified older units (~16.5-14.5 Ma)

|

"Green" Conglomerate □ ~17 Ma? conglomerate with sandstone matrix derived from reworked biotite dacite tuff

Titus Canyon Formation (36 Ma- to -?)

Laterite-matrix conglomerate

basal breccias*

Mesozoic Rocks:

Cretaceous granite, one small fault sliver - NW margin of Bare Mtn ~100 Ma

Hornblende gabbro dikes in NW Bare Mtn have Tertiary cooling ages, but have plutonic textures and could be as old as the nearby granite

The Paleozoic and latest Proterozoic sedimentary rocks of NW Bare Mtn are metamorphosed and the age of this metamorphism is Cretaceous based on data collected by Hoisch and others (1997)

Paleozoic and latest Proterozoic Sedimentary Rocks:

Mississippian and Devonian upper clastic confining unit (Eleana Formation)

Cambrian to Silurian deep carbonate aquifer (Bonanza King, Nopah, Pogonip Group, Ely Springs, Roberts Mountain, and Lone Mountain Formations, and locally some lower Devonian carbonates)

late Proterozoic to earliest Cambrian lower clastic confining unit (Zabriskie, Wood Canyon, and Stirling Formations and older units)

breccia* - landslide (rock-avalanche) and talus breccias associated with major unconformities

□ "Old Yeller" sediments and "Green" Conglomerate are informal names used here for two stratigraphic units that lack formal stratigraphic names

TABLE 2: Generalized Tectonic History of the Oasis Valley Region:

I. Late interval of feeble extension:

- Began at ~10 to ~7 Ma regionally depending on location, but mostly at ~10 Ma in the Oasis valley area, and continuing sporadically but at an overall declining rate to the present.
- Characterized by trivial widely-spaced normal faulting with negligible associated tilting in the study area. Probably related mostly to the strong coeval extension to the southwest that created Death Valley as we know it. Predominant area of activity in this interval within the area of interest is Crater Flat basin.

II. Major Tertiary interval of strong extension and strike-slip deformation:

- Began at ~12.7 Ma, and continued to ~10 to ~7 Ma, depending on location, as above.
- Within the Black Mountain caldera and the Timber Mountain caldera complex, and to the east and north of those, extension was evidently weak to moderate, and there was little or no accompanying strike-slip deformation. To the west and south of the those calderas, extension was moderate to extreme, with a strong component of northwest-directed right-lateral strike-slip deformation, and with the ratio of strike-slip to extensional deformation generally increasing to the southwest. A widespread detachment fault system formed in the area of extreme extension. This system terminated eastward by daylighting in the western parts of the Crater Flat and Oasis Valley basins. Bare Mountain is a metamorphic core complex that was tectonically denuded and uplifted in association with the activity on the Fluorspar Canyon-Bullfrog Hills detachment fault system formed in this interval.

III. Early Interval of Tertiary Extension:

- Probably began in the late Eocene or early Oligocene and continued sporadically, but at a strongly declining rate, overall, reaching a state of virtual tectonic quiescence by ~13.2 Ma.

- Evidenced by angular unconformities, growth faulting, and local fanning dips in the Oligocene and early Miocene sediments, in the few places where these are exposed, and probably responsible for forming the major internal extensional structures of Bare Mountain including, especially, the Gold Ace and Coñejo Canyon detachment faults.

IV. Mesozoic compression:

- Began as early as the late Permian and continued episodically possibly into the early Tertiary, but mostly Mesozoic.
- Characterized by thrust faulting and locally by related folding, as well as by regional metamorphism. The Paleozoic/late Proterozoic section may locally have been thrust imbricated to as much as triple original thickness based on the degree of metamorphism (depth of tectonic burial) of some exposed pre-Mesozoic rocks.