Chapter I

Tectonic Significance of the Rock Valley Fault Zone, Nevada Test Site

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Abstract

The Rock Valley fault zone comprises several east-northeast-striking left-lateral faults and numerous other fault-related structures in a zone about 4 kilometers wide within Rock Valley, Nevada Test Site, Nye County, Nevada. The fault zone marks a tectonic boundary within the Walker Lane, between upper Miocene volcanic rocks of the southwest Nevada volcanic field to the north and lower Paleozoic carbonates to the south. The east end of the zone is obscured by alluvium in Frenchman Flat, but it may be accommodated by strike-slip faulting in east-west-oriented ridges between Mercury and Indian Springs, Nevada; the west end is complicated by N. 30° E.-striking faults that cross Rock Valley west of Skull Mountain. Field evidence and seismicity indicate that the fault zone originated probably in late Oligocene time, is presently active, and could generate earthquakes of magnitude 7.0 or larger. The Rock Valley fault zone is similar in style and size to other left-lateral fault zones in the Walker Lane; it does not appear to be part of a conjugate system, nor does it seem to be an accommodation zone related to detachment faulting. The fault zone is interpreted to be an active domain boundary within the Walker Lane that concentrates extensional strain between the Spring Mountains domain and volcanogenic terrane to the north.

Introduction

The Rock Valley fault zone is one of several relatively small (20–40 km long and several kilometers wide) east-north-east-trending left-lateral fault zones in the southwestern part of the Great Basin (fig. 1). Some of the east-northeast-trending fault zones are sites of persistent clustered seismicity or rather large ($M_L \geq 6.0$) historical earthquakes (Yount and others, 1993; Rogers and others, 1987). Some of the zones are part of the Walker Lane (fig. 1) and therefore may share a genetic relation to pervasive northwest-trending right-lateral shear; others, such as the Pahranagat fault zone (fig. 1), are interpreted as “accommodation zones” that separate terranes of differing amounts of extension.

The Rock Valley fault zone is presently of great interest because of its potential as a source of damaging earthquakes within 25 km of Yucca Mountain, the site of a potential repository for radioactive waste. An evaluation of earthquake hazards indicates that the fault zone could generate earthquakes of M 7.0 or larger (Office of Civilian Radioactive Waste Management, U.S. Department of Energy, written commun., 1998). An understanding of how the Rock Valley fault zone fits into the regional tectonic framework and how it accumulates strain is therefore important. However, very little is known about its origin and history. Basic structural features of the Rock Valley fault zone were mapped by Hinrichs (1968) and Barnes and others (1982). Topical studies include attempts to interpret the zone in the context of adjacent and nearby tectonic features (Carr, 1984; Ander, 1984) and to relate it to a regional stress field (Ander, 1984; Harmsen and Rogers, 1986; Frizzell and Zoback, 1987). Structural interpretation of a seismic reflection profile across the central part of the valley and details on acquisition and processing of the data are presented by Majer and others (1996).

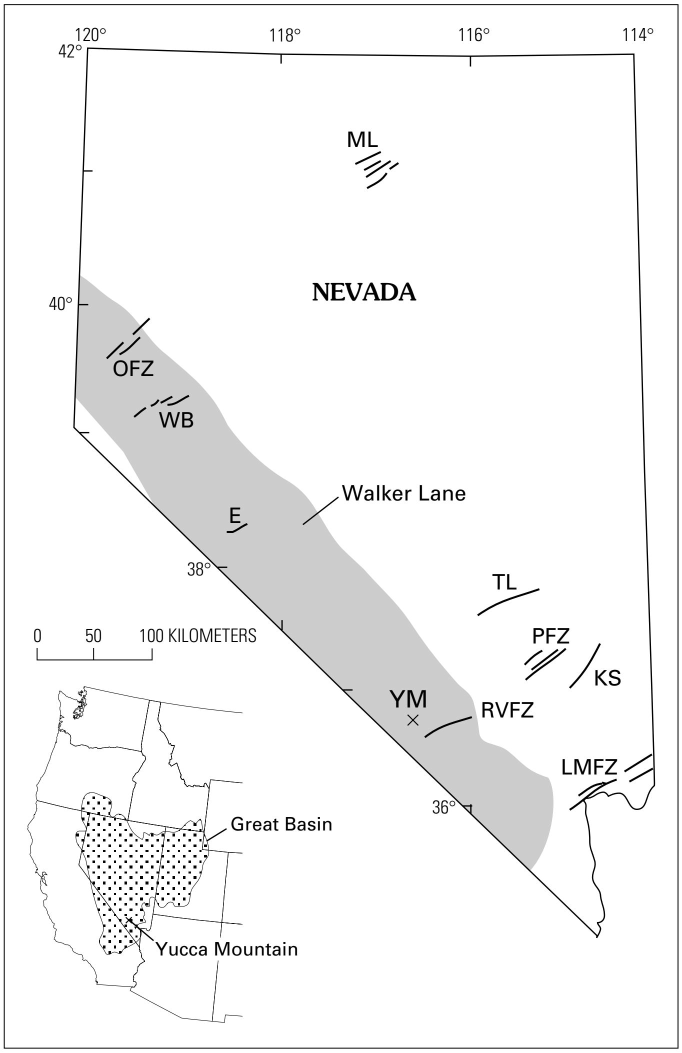

Figure 1. East-northeast-trending fault zones of southern Great Basin and the Walker Lane, Nevada. E, Excelsior Mountain fault; KS, Kane Spring fault zone; LMFZ, Lake Mead fault zone; ML, Midas lineament; OFZ, Olinghouse fault zone; PFZ, Pahranagat fault zone; RVFZ, Rock Valley fault zone; TL, Timpahute lineament; WBL, Wabuska lineament; YM, Yucca Mountain.

This report presents geologic observations of the Rock Valley fault zone that pertain to its longevity, episodic activity, and seismicity, as well as its role in a proposed model of regional deformation.

Acknowledgments

The focus and organization of this paper benefited greatly from comments and criticisms by R.E. Anderson and J.C. Yount of the U.S. Geological Survey.

General Geology of the Rock Valley Fault Zone

The Rock Valley fault zone comprises primarily three main left-lateral strike-slip faults oriented approximately N. 70° E., in Rock Valley in the Nevada Test Site (figs. 2, 3). The faults extend for distances of 18 km or more westward from the longitude of Mercury, Nev., and gradually veer southward toward the southern wall of the valley formed by the Specter Range (fig. 2). The main faults are bridged by splays or by separate strike-slip, N. 30°–40° E. - striking faults that show both normal and left-lateral offset (fig. 4). Less common north-south- to N. 15° W. - striking faults cut the strike-slip set and show right-lateral and normal offsets. Whether the Rock Valley fault zone projects southwestward past the Striped Hills and into the Amargosa Desert or northeastward beyond Frenchman Flat is not known; thus, the actual length of the fault zone is unknown. The average width of the zone is about 4 km, but this is also uncertain because nowhere are its boundaries clearly defined by zone-parallel continuous faults, and faults similar to those within the zone merge into it from the north and out of it to the south.

Rock Valley itself is approximately 5 km wide and 32 km long. It is bounded to the north by landforms that include Skull Mountain, Little Skull Mountain, Hampel Hill, and Mt. Salyer (fig. 2), all consisting of block-faulted, variously tilted Neogene volcanic strata; it is bounded to the south by a complex

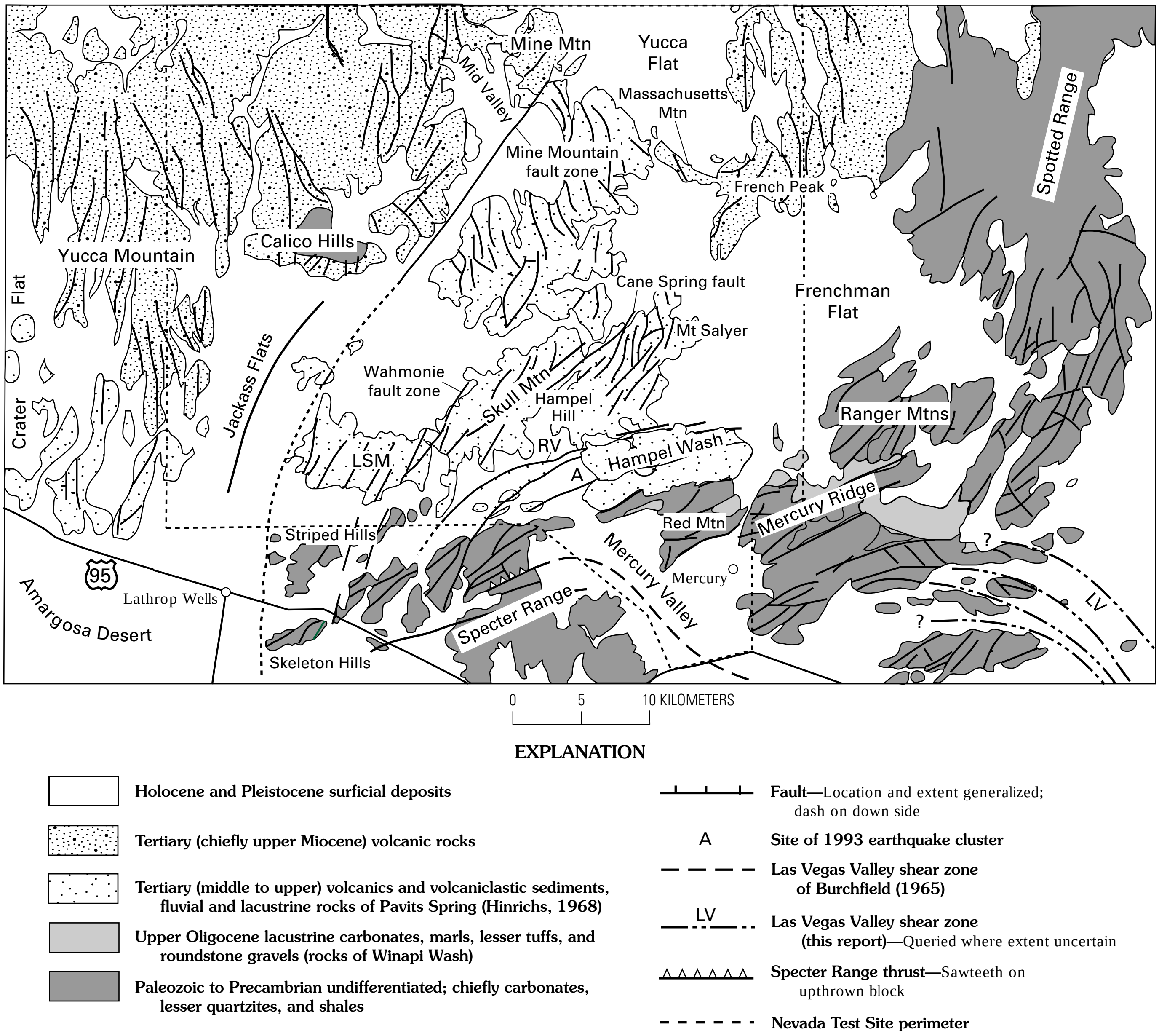

Figure 2. General geology of Rock Valley fault zone (based on Stewart and Carlson, 1978). LSM, Little Skull Mountain; RV, Rock Valley fault zone.

discontinuous escarpment formed on Paleozoic carbonate rocks of Red Mountain and the north flank of the Specter Range. The Paleozoic strata that bound the southern flank of the valley dip variably to the southeast and west. Toward the east end of the valley, along the northern flank of Red Mountain, the Paleozoic strata are sliced by N. 70° E.-trending faults that form discontinuous horst and graben.

To the west, the Striped Hills, consisting of prominent inliers of steeply dipping to overturned Paleozoic to Precambrian strata, are separated along the axis of Rock Valley by N. 30° E.-striking left-lateral faults having lateral offset as much as 1.4 km. These faults, an extension of the Wahmonie fault zone, cut across Rock Valley and strike southwestward along the flanks of the westward-extended Specter Range (fig. 2). Faults of the Wahmonie fault zone exposed in the saddle between Skull and Little Skull Mountains have an apparent component of down-to-the-west normal displacement.

The floor of Rock Valley is underlain by lower to middle Miocene lacustrine, fluvial, and volcaniclastic rocks of Pavits Spring, which rest on calcareous, coarse clastic, and volcanogenic sediments of latest Oligocene age that are unconformable on the Paleozoic rocks (Hinrichs, 1968). On the basis of lithology, Hinrichs (1968) provisionally assigned this lower, calcareous Oligocene unit to the Horse Spring Formation. However, it is much older than the middle Miocene Bitter Ridge Limestone Member of the type Horse Spring Formation (Bohannon, 1984), which the Paleogene calcareous strata of Rock Valley closely resemble. The uppermost Oligocene strata in and around Rock Valley have been informally named the rocks of Winapi Wash (J.C. Yount, oral commun., 1995), a

Figure 3. View east along northernmost major oblique left-lateral fault plane in Rock Valley.

designation used in this report. The unit is similar in age and lithology to the Titus Canyon Formation, with which it is most likely correlative.

Along the eastern part of the valley drained by Hampel Wash, the faulted valley-floor strata form generally north dipping, locally arched cuestas; shallow north-northwest dips continue upsection into the units exposed on the northern flank of the valley (Miocene Wahmonie Formation and tuffs of the Paintbrush and Timber Mountain Groups). Toward the central part of the valley, south of Skull Mountain, the Tertiary valley-floor strata are complexly deformed into shallow-axis and steep-axis folds and are cut by numerous faults. Farther west, in the vicinity of the Striped Hills, the Tertiary strata are complexly faulted and broadly folded. Generally, the strata form a north-younging homocline unconformable on steeply dipping Paleozoic strata of the Striped Hills. Tertiary structure in the valley between the Striped Hills and the northern flank of the Specter Range is presently unknown because of extensive cover by Pleistocene deposits.

Displacement along the east-northeast-striking faults of the Rock Valley fault zone is consistently left lateral, as shown by rare offset units south of Hampel Hill, by drag folds, and by various slip features along the fault planes. However, a scarcity of offset units precludes a reliable estimate of total and incremental amounts of displacement. The only clear evidence of displacement is found where the northernmost fault trace in the valley cuts an east-dipping trachyte of the Miocene Salyer Formation. Total displacement at this site is approximately 20 m, left-lateral. Estimates of total displacement along the Rock Valley fault zone are based on gross unit offsets and are likely not more than about 4 km (Barnes and others, 1982; Kane and Bracken, 1983). Given the estimated total offset in Rock Valley, the inferred age of inception (30 Ma), and a 20° slip plunge, an inferred rate of slip of 0.089 mm/yr is calculated. This long-term slip rate is almost five times the rate (0.02 mm/yr) calculated by J.C. Yount (oral commun., 1994) on the sole basis of Pleistocene offsets. If this difference in calculated slip rates is true, then the indication is that slip during the late Pleistocene has contributed little to the cumulative displacement; thus the fault zone has been relatively quiescent since late Pleistocene.

Figure 4. View (looking south) of northeast-trending fault in Hampel Wash shows complex fracturing, chiefly normal (down-to-east) displacement.

Terminations of the Rock Valley Fault Zone

Understanding the nature of the Rock Valley fault zone terminations is important for determining the relation of the fault zone to other tectonic features, including the Las Vegas Valley shear zone, the fault pattern at Yucca Mountain, the Amargosa Valley basin, and the faults along the Spotted Range. However, little direct evidence exists as to the location and form of these terminations. The east end of the Rock Valley fault zone is covered by thick alluvium of Frenchman Flat; the west end is apparently involved with the northeast-trending faults that separate the Striped Hills and is ultimately obscured by the alluvium of Rock Valley Wash and Jackass Flats.

The problem of fault-zone terminations was addressed by Carr (1984), who grouped the Rock Valley fault zone with two other northeast-trending faults of similar style, the Mine Mountain and Cane Spring faults, into the Spotted Range–Mine Mountain "structural zone" (fig. 5). This grouping ensured that the component fault zones do not begin and end in isolation. As part of this broad zone, the Rock Valley fault zone is terminated against an inferred major north-northwest-trending right-lateral fault, the Yucca-Frenchman shear zone (fig. 5), thought by Carr (1984) to extend southeast along the axis of Yucca Flat into Frenchman Flat. Because east-northeast-trending left-lateral faults that could represent extensions of the Rock Valley fault zone are unknown in the Spotted Range east of Yucca Flat, some such termination is a strong possibility. An alternative explanation is that the east end of the Rock Valley fault zone may arc to the north beneath Frenchman Flat and merge with more northerly or northeasterly faults that either follow the axis of Yucca Flat and Frenchman Flat (Ander, 1984), or bound and (or) obliquely transect the Spotted Range. A third possibility, supported in part by detailed examination of aerial photographs, is that the Rock Valley fault zone curves southward and loses displacement between the Ranger Mountains and the south end of the Spotted Range where left-lateral shear strain is accommodated by complex crushing and a succession of parallel east-northeast left-lateral faults that slice the Paleozoic rocks east of Mercury and west of Indian Springs (figs. 2, 5).

Carr (1984) projected the Spotted Range–Mine Mountain structural zone west into California to the Furnace Creek fault

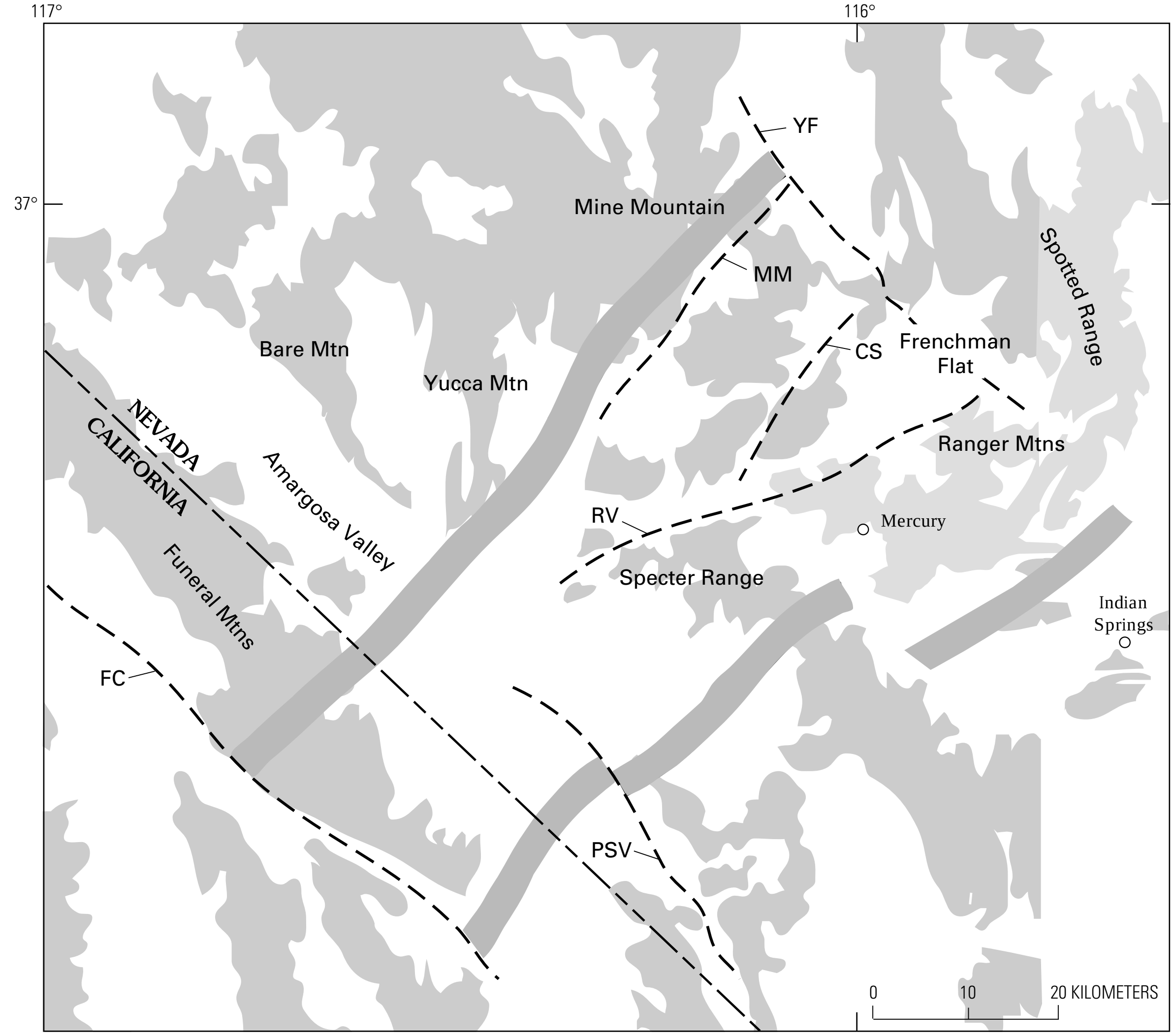

Figure 5. Spotted Range–Mine Mountain structural zone of Carr (1984) depicted by northeast-trending dark-shaded borders. Dashed line, labeled fault or shear zone: CS, Cane Spring fault zone; FC, Furnace Creek fault zone; MM, Mine Mountain fault zone; PSV, Pahrump–Stewart Valley fault zone; RV, Rock Valley fault zone; YF, Yucca-Frenchman shear zone. Light-shaded areas, bedrock exposure; unshaded areas, Quaternary deposits.

zone (fig. 5). However, no faults resembling the Rock Valley fault zone are known to transect the Funeral Mountains. The Rock Valley fault zone probably extends no farther west than a line drawn from the west side of Little Skull Mountain south to the west end of the Skeleton Hills (fig. 2). Laterally sheared Paleozoic rocks (and local Miocene volcanic rocks) exposed along this line imply the existence of a N. 5°–15° E.-striking fault or shear zone. A fault along this trend is also indicated by gravity and aeromagnetic anomaly gradients (Winograd and Thordarson, 1975) and seismic reflection data (Brocher and others, 1993).

Attempts to find a segment of the Rock Valley fault zone west of the line just described have been unsuccessful (Donovan, 1991; L.W. Anderson, U.S. Bureau of Reclamation, oral commun., 1994), but northeast-southwest-trending lineaments in the Amargosa Valley suggest that a segment of the Rock Valley fault zone exists beneath the Amargosa Valley, a segment that must ultimately terminate against the Pahrump–Stewart Valley fault (fig. 5). On the other hand, the main strands of the Rock Valley fault zone veer to the south into the Specter Range east of the Striped Hills, so the question remains whether the zone, as exposed by Pleistocene fault traces, extends all the way to the west end of Rock Valley (as it is shown to do in fig. 5). The north-northeast-striking left-lateral Wahmonie fault zone that extends southwest into Rock Valley between Little Skull Mountain and Skull Mountain (fig. 2), and other similar faults that cut Little Skull Mountain form the dominant structures at the west end of Rock Valley. Exposed structures in this area, however, do not show any clear evidence that a N. 70° E.-striking Rock Valley fault zone extends through toward Amargosa Valley. If the Rock Valley fault zone does extend that far west, it is probably segmented and offset by the more northerly striking transverse faults.

Antiquity of the Rock Valley Fault Zone

Sparse field evidence indicates that the east-northeast-trending faults, and the erosional features related to these faults, gave the southern flank of Rock Valley its present general configuration before deposition of the rocks of Winapi Wash. Assuming that the widely cited Oligocene date (based on K/Ar) for the tuff in Rock Valley assigned to the Horse Spring Formation of Hinrichs (1968; the rocks of Winapi Wash) is valid (Axen, 1991), then the faulting along the southern flank of Rock Valley was established at least by late Oligocene time (Carr, 1984; Axen, 1991).

Evidence for a Paleogene origin for the Rock Valley fault zone includes (1) onlap of marl that is arguably part of the rocks of Winapi Wash onto an old, weathered (terra rosa) east-northeast-trending fault scarp formed in the Eureka Quartzite on the northern flank of Red Mountain; (2) unconformable onlap of the rocks of Winapi Wash on monomict carbonate-clast conglomerate derived from faulted Paleozoic strata near Red Mountain; and (3) onlap of the rocks of Winapi Wash on more extensively fractured and rotated blocks of lower Paleozoic limestone of the Specter Range.

Drag folding of carbonate beds of the rocks of Winapi Wash against vertical fault planes formed in Paleozoic carbonate rocks along the northern flank of Red Mountain indicates that appreciable left-lateral and vertical movements followed deposition of the Paleogene limestone. Sinistral movement also occurred at various times during the Miocene, as indicated by lateral scoring along slices of tuff and conglomerate caught in the fault planes, by fault fissure fills of conglomerate of the rocks of Pavits Spring, and by at least 20 m of displacement across a trachyte flow assigned to the Salyer Formation (Hinrichs, 1968) that was subsequently buried by Pleistocene alluvium. These stratigraphic and structural features indicate that the Rock Valley fault zone was active from late Oligocene through middle Miocene time.

Deformation following emplacement of the 10.2-m.y.-old basalt that caps Skull Mountain (Crowe and others, 1983) established or accentuated a general northward tilt to units within Rock Valley, perhaps by arching or uplift. Deformation during the 11–9 Ma interval led to local subsidence and normal faulting in areas to the north that had also undergone northeast-striking left-lateral faulting but not piecemeal rotations (Hudson and others, 1994). Thus, late Miocene deformation that led to the modern physiographic expression of Rock Valley includes downward rotation of north-dipping slices presently expressed as cuestas, differential uplift and subsidence along and across strike, and imposition of northeast-striking faults that slice the Striped Hills.

Deformation that has occurred primarily in Pleistocene time includes subsidence of Frenchman Flat, perhaps accompanied by uplift farther west in Rock Valley leading to severe headward erosion along Hampel Wash, formation of a graben in the valley south of Skull Mountain (Swadley and Huckins, 1990), and near-surface fracturing expressed as vegetation lineaments in the youngest Pleistocene surface.

Present Fault Activity in Rock Valley

Repeated, clustered, low-magnitude ($M_L \leq 4.0$) earthquakes within Rock Valley and adjacent terrane indicate that the Rock Valley fault zone is presently active. In May 1993, a cluster of 16 low-magnitude earthquakes (M_L 2.0–3.7), located in a slice of the fault zone between the middle fault strand and the southern strand (site A, fig. 2), was recorded. The cluster formed a N. 65° E. trend about 2 km long and 100 m wide aligned with a fault exposed to the east in Hampel Wash. The fault-plane solution for the largest event indicated left-lateral slip on a fault having an attitude of N. 38° E., 71°SE., rake –21° (Smith, Shields, and Brune, this volume).

Small earthquakes also occurred in Rock Valley adjacent to and just within the northern flank of the Specter Range during March 1994 and September 1995. The 1995 earthquake had nearly pure left-lateral displacement at a depth of 3.8 km along a fault plane N. 50° E., 70°NW. (Smith, Shields, and Brune, this volume). This fault is essentially aligned with the trace of the southern Rock Valley fault strand as it crosses into the Specter Range.

Historically, earthquakes are more frequent toward the west end of the valley, in the vicinity of Little Skull Mountain, the Striped Hills, and the Specter Range. Strike-slip and oblique slip occur from near-surface to about 15 km depth; fault-plane solutions for the pre-1993 earthquakes are in accord with the sense of slip of the mapped faults, but no individual seismogenic faults have been identified (Rogers and others, 1987).

The relatively high seismic activity at the west end of Rock Valley is unexplained. Seismic records kept since 1973 indicate that the seismicity in this area is typical of the southern Great Basin and that northeast-trending strike-slip is active within a uniform regional stress field (Harmsen and Bufe, 1992). This suggests that local stress fields are not significant in controlling present fault slip; fault strength may therefore be an important limiting factor for local seismic activity. A possible explanation is that the intersection of the Rock Valley fault zone with the more northeasterly trending Wahmonie fault zone creates a volume of crust unable to store large strain because of the character and geometries of the fault interactions. The frequency of fault slip at apparently low stress thresholds, to depths of 10 km, may indicate that the faults that strike on the Rock Valley trend (≈ N. 70° E.) have a relatively low frictional strength. This is not to say, however, that the entire fault zone is weak and does not store significant strain. Numerous critical asperities may fail at low effective stress thresholds as strain builds for the entire zone, thus priming the Rock Valley fault zone for larger earthquakes.

In this respect it is puzzling that the M_L5.6 Little Skull Mountain earthquake of June 29, 1992 (Smith, Shields, and Brune, this volume), was generated by normal displacement on a N. 55°–60° E.-striking fault rather than by left-lateral slip, especially as oblique slip was recorded from a number of aftershocks that were located farther south and on strike with the more easterly Rock Valley trend. This earthquake, the largest ever recorded at the Nevada Test Site, is generally thought to have been remotely triggered by dynamic stress applied by the Landers M_L 7.0 earthquake which occurred 24 hours earlier near Landers, Calif. Stress field inversion applied to the Little Skull Mountain earthquake focal plane indicated that the mainshock occurred under near-maximum shear stress, assuming behavior according to the Mohr-Coulomb criterion (Harmsen, 1994). In other words, this was not an especially weak fault; it may have slipped because of a critical azimuthal relation to compressive wave propagation from the Landers earthquake, or the southeast-dipping fault plane may have been at the right attitude at the 11–12 km focal depth to optimize transient pore pressure. Meremonte and others (1995) speculated that the post-Landers earthquake triggering was facilitated by a network of interconnected faults extending northward from the Landers epicenter.

No uniform stress field was found that provided a resolved shear stress on most of the aftershock fault planes strong enough to overcome a typical coefficient of friction $\mu \geq 0.5$, which characterized the mainshock fault plane; an apparent $\mu \approx 0.3$ is required to simulate slip on many of the aftershock faults (Harmsen, 1994). Harmsen (1994) suggested that those strike-slip aftershocks indicating a relatively low μ value of about 0.3 were conditioned by local and temporally elevated pore pressures consequent to the Little Skull Mountain earthquake. Local reservoirs of pore fluid that lower effective stress for east-northeast-striking fault geometries may contribute to the relatively frequent left-lateral fault slip at apparently low stress thresholds to depths of 10 km along the Rock Valley fault zone.

In Search of a Tectonic Model

As a tectonic domain boundary having a long history of activity, and one capable of generating large earthquakes, the Rock Valley fault zone would seem to be a key component in the process of extension that formed and continues to form the southern part of the Walker Lane. The relation of the Rock Valley fault zone to regional structures, however, is poorly known, and important questions arise. Is the Rock Valley fault zone kinematically associated with the Las Vegas Valley shear zone? Is it an accommodation zone? Is it possibly a kind of local bridging structure peculiar to extension in the Walker Lane? In particular, there is a need to satisfactorily explain why the fault zone has undergone a number of episodes of left-lateral slip, both transpressional and transtensional, since late Oligocene time, yet none of this deformation is apparently reflected in structures east or west of the fault zone.

A tectonic model is required to rationalize the structural elements and deformation history of the Rock Valley fault zone. Such a model should provide insight into three problems of interest: (1) the relation of the Rock Valley fault zone to proximal faults and structures, (2) the process by which stress is transmitted to the fault zone over time, and (3) mechanisms by which the Rock Valley fault zone accumulates strain and releases it as earthquakes (possibly large magnitude earthquakes).

Only one regional tectonic model has been proposed that explicitly incorporates the Rock Valley fault zone, and that is the Spotted Range–Mine Mountain structural zone model of Carr (1984; see fig. 5). Carr (1984) inferred that the structural zone follows a pre-Miocene zone of crustal weakness that might constitute a tectonic link with the east-northeast-trending, seismogenic Pahranagat fault zone located 75 km to the northeast of the Rock Valley fault zone (fig. 1); however, no structural evidence for such a link has been found. Carr (1984) further inferred that a north-northwest-trending right-lateral fault (the Yucca-Frenchman shear zone, fig. 5) extends from Yucca Flat southeast into Frenchman Flat, truncating the east end of the Spotted Range–Mine Mountain structural zone. Existence of this right-lateral fault was based on apparent right-lateral drag folding of Miocene units exposed in Massachusetts Mountain (fig. 2). Paleomagnetic studies by Hudson (1992) show that, although the faults that cut French Peak are arcuate, the rocks cut by the faults were not rotated; therefore, existence of the Yucca-Frenchman shear is questionable at best.

The Spotted Range–Mine Mountain structural zone appears to have acted independently of adjacent tectonic blocks, including the basin and range terrane to the east (Stewart, 1988). On this basis, Stewart (1988) defined the Spotted Range–Mine Mountain structural zone as one of nine structural blocks or "sections" that constitute the Walker Lane "belt." Despite this compelling zonal geometry, whether all the strike-slip faults in the Spotted Range–Mine Mountain structural zone are genetically related is not clear. From late Pleistocene time to the present, the Rock Valley fault zone has been the dominantly active, and perhaps the only active, component of the Spotted Range–Mine Mountain structural zone. Therefore, the question arises as to (1) whether the Rock Valley fault zone represents a diminished locus of tectonism that originally generated the Spotted Range–Mine Mountain structural zone as a distributed fault system, or (2) whether the Rock Valley fault zone represents a long-lived domain boundary and the other faults that make up the structural zone are sometimes-active ancillary structures. In case (1) the Rock Valley fault zone could be considered an accommodation zone that has involved the entire Spotted Range–Mine Mountain structural zone. In case (2) the Rock Valley fault zone may represent a more typical "Walker Lane" structure, that is, a possible domain boundary (Stewart, 1988).

Hudson (1992) explained the Massachusetts Mountain–French Peak oroclinal folding as the expression of a nearly east oriented accommodation zone that is projected as far west as Mid Valley (fig. 2). A similar interpretation could apply to the Rock Valley fault zone, but a number of problems present themselves:

1. Hudson's (1992) explanation requires north-northeast-oriented right-lateral shear, which is difficult to reconcile with the Rock Valley fault zone.

2. Extension directed parallel to and bounded by the Rock Valley fault zone is evident only in the Specter Range, but the Paleozoic terrane farther east and south records no significant west-directed extension. South-flanking Paleozoic rocks from the central Specter Range eastward through the Ranger Mountains (fig. 2) are best characterized as a highly faulted and locally strongly brecciated southeast-dipping sequence. Although bedding attitudes are variable in detail, southeast dips tend to predominate in rocks directly adjacent to the poorly defined southern boundary of the Rock Valley fault zone. Activity along the Rock Valley fault zone since middle Miocene time has not involved differential extension to either side of the zone, but rather a series of subparallel strike-slip faults, or strike-slip faults that diverge westward and veer south out of Rock Valley and into the Specter Range.

3. Terrane north of Rock Valley shows no pattern of fault-parallel extension such as that adduced for the Las Vegas Valley shear zone (Guth, 1981; Duebendorfer and Black, 1992; W.B. Hamilton, written commun., 1994) or the Pahranagat fault zone (Jayko, 1990). Instead, faulting is dominated by northeast-striking, oblique left-lateral faults (the Cane Spring, Mine Mountain, and Wahmonie fault zones; fig. 2), and major tectonic landforms that indicate discrete, domainal tectonism, including Little Skull Mountain, Skull Mountain, Calico Hills, and Mid Valley (fig. 2), each with its own style and history of deformation.

4. The Rock Valley fault zone includes folds and graben that indicate complex modes of compression and extension effected at a high angle to the fault zone, not subparallel to it.

Differential extension is thought to be facilitated by detachment faulting (Faulds and others, 1990). How might the Rock Valley fault zone be structurally linked to detachment faulting? Guth (1981) extended the Sheep Range detachment west along the north side of the Las Vegas Valley shear zone to the Specter Range. This projection implies that the Rock Valley fault zone is part of a post-15 Ma detachment system expressing almost 100 percent extension. However, the structural features described do not favor this interpretation. Earthquake mechanisms, most notably the Little Skull Mountain earthquake, indicate that normal and strike-slip faulting occurs over the full thickness of the brittle crust in the vicinity of Rock Valley. These results suggest that if detachment faulting is present, it must occur at or below the brittle-ductile transition in the middle crust. Detachment at this depth has not been proposed for the Rock Valley region (Guth, 1990), nor has evidence for it been recognized. Furthermore, a detachment surface must at some place slice updip through the crust as one or more normal faults; no such faults have been identified for the Rock Valley region.

If the Rock Valley fault zone is a domain boundary, what is its strain history with relation to the adjacent domains and adjacent boundaries? To address this question, it is necessary to examine how the Rock Valley fault zone and the Spotted Range–Mine Mountain structural zone fit into the tectonic framework of the Walker Lane and its associated faults, including the Las Vegas Valley shear zone.

The Cenozoic pattern of faulting in the central to northern part of the Walker Lane is thought to have been initiated about 26–25 Ma as a dextral, northwest-trending strike-slip fault zone partly superimposed on and partly bounding older extended terrain of the Basin and Range farther east (Ekren and Byers, 1984; Hardyman and Oldow, 1991; Dilles and Gans, 1995). Walker Lane deformation is characterized by the evolution of east-northeast-trending oblique left-slip faults locally expressed as graben-bounding faults within a westward-widening zone of transtension (Hardyman and Oldow, 1991; Dilles and Gans, 1995). However, the orientation of extension within this belt of generalized shear through time is uncertain, and partitioning of shear evidently was not a matter of conjugate or transcurrent fault generation. Deformation may have involved clockwise rotation of stress axes through time as well as alternating modes of fault slip related to changes in principal stress ratios (Wright, 1976; Stewart, 1988; Frizzell and Zoback, 1987; Bellier and Zoback, 1995).

The history of superposed deformation documented in the northern and central Walker Lane (Stewart, 1988) seems also to be true for the Rock Valley area. Here, earliest extension appears to have been west-directed, as evidenced by the extended Specter Range, which, by reason of unconformable relations with the rocks of Winapi Wash, is pre-late Oligocene. It is not clear whether this extension predates or postdates imposition of the steep to overturned dips of the Striped Hills section or the east-northeast-striking ramping and folding of the Red Mountain–Mercury Ridge terrane; all that can be said, based on presently available data, is that this latter east-west-striking deformation also predates late Oligocene.

The Las Vegas Valley shear zone (fig. 2) represents the eastern boundary of the Walker Lane south of Rock Valley (Stewart, 1988), but the tectonic relation of the Rock Valley fault zone with the Las Vegas Valley shear zone is uncertain. The angle subtended by the two zones is about 120°, precluding a simple conjugate relation. The generally accepted displacement of about 50 km along the central part of the Las Vegas Valley shear zone (Burchfiel, 1965; Longwell, 1974) is thought to have occurred between 15 and 10 Ma (Bohannon, 1984), requiring a slip rate of about 1 cm/yr. This high slip rate and great displacement are difficult to accord with the small lateral offset of the Rock Valley fault zone during the middle Miocene (≤ 4 km), especially as some of the displacement is ascribed to a northwest-directed detachment, the Sheep Range detachment (Guth, 1981), the relation of which to the Spotted Range–Mine Mountain structural zone is uncertain.

Burchfiel (1965) considered the northwestern projection of the Las Vegas Valley shear zone to continue into the Specter Range thrust (fig. 2). Burchfiel's (1965) hypothesis requires an episode of substantial south-southeast-directed compression in early Tertiary to effect 1,830 m (6,000 ft) of stratigraphic offset along the 50° to 60° northwest-dipping Specter Range thrust, as well as approximately 35 km of right-lateral offset along the Las Vegas Valley shear zone as projected into Mercury Valley. This interpretation seems incompatible with north-northwest-directed extension coeval to the west and with left-lateral offset that dominated the Rock Valley area since Oligocene time. However, significant north-south-oriented compression must predate the Rock Valley fault zone, whereas the Las Vegas Valley shear zone postdates or is coeval with Miocene extension to the east and is generally thought to be a late Cenozoic (post-Oligocene) right-lateral feature (Burchfiel and others, 1983; Hudson and others, 1994). The accommodation model (Duebendorfer and Wallin, 1991) requires 10–20 km of slip to be absorbed by oroclinal bending in the Specter Range, but evidence for such compression during the 14–13 Ma interval has not been recognized in or near Rock Valley (J.C. Yount, written commun., 1995). Therefore, arcing the Las Vegas Valley shear zone to the west through Mercury Valley into alignment with the left-lateral Rock Valley fault zone is not a reasonable tectonic interpretation. Also, the hypothesis of a reverse fault (the Specter Range thrust) arcing clockwise to a northwest-trending strike-slip fault is difficult to accept in terrane where no other reverse faults are known to have such geometric relations.

Paleomagnetic data indicate that the ranges flanking the north side of the Las Vegas Valley shear zone were rotated clockwise before 13 Ma, during a period of short-lived but intense deformation (Hudson and others, 1994). Paleomagnetic studies also indicate that clockwise bending around vertical axes in ranges along the north side of the Las Vegas Valley shear zone (for example, the Las Vegas Range) is not a consequence of simple fault drag (Anderson and others, 1994; Sonder and others, 1994), but represents a broad zone of combined crushing and local rotations of blocks a few kilometers in lateral dimension (Nelson and Jones, 1987; Sonder and others, 1994). North-south compression that accounts for as much as 55 km of crustal shortening in late middle Miocene is well documented by deformation in the northern Black Mountains along the Lake Mead fault zone (Anderson and others, 1994), which is compatible with both right-lateral slip and domain-boundary compression along the Las Vegas Valley shear zone (Anderson and others, 1994). Compressive deformation with west-directed escape is also compatible with late Miocene activity within the Spotted Range–Mine Mountain structural zone, local folding within the Rock Valley fault zone, and structural crowding along the south end of the Spotted Range where the Las Vegas Valley shear zone is inferred to form an oroclinal bend to the west (figs. 2, 6).

Proposed Tectonic Model

The tectonic events previously described suggest the following model for the evolution of the Rock Valley fault zone: (1) the Rock Valley fault zone originated about 29 Ma as a left-lateral half-graben that transects an older extended terrane (represented by the Specter Range) within the "ancestral Walker Lane" (fig. 6*B*); (2) the Las Vegas Valley shear zone may have originated as part of the ancestral Walker Lane also, but right-lateral transpressive activity seems to have culminated in a late Miocene event that involved crushing and bending of extended terrane north and east of the shear zone (fig. 6*B*); and (3) extension in the Sheep and Desert Ranges evidently continued during deposition of strata tentatively correlated with the Thumb Member of the Horse Spring Formation (Guth, 1981), in which case right-lateral transpression that possibly had begun as early as 29 Ma must have peaked prior to about 14–13 Ma. If the deformed Tertiary strata are equivalent to the rocks of Winapi Wash, peak transpression may be considerably older, possibly before 16–15 Ma.

Deformation along the Lake Mead fault zone (LM, fig. 6*A*) and at the south end of the Las Vegas Valley shear zone (LV, fig. 6*A*) suggests that transtension developed along the Las Vegas Valley shear zone around 12 to 8 Ma (Ron and others, 1986; Campagna and Aydin, 1994; Anderson and others, 1994). A large section of crust was displaced along the Lake Mead fault zone south of the Las Vegas Valley shear zone into the vicinity of Las Vegas Valley (LVV, fig. 6*A*; Anderson and others, 1994). In response to this displacement, or possibly in conjunction with it, the Spring Mountains domain (fig. 6*A*) moved northwest, opening away (clockwise) from Las Vegas Valley (fig. 6*C*). This domainal translation is inferred to have produced transpression along the Rock Valley fault zone and to have activated or created the more northeast-striking strike-slip faults of the Spotted Range–Mine Mountain structural zone north of the Rock Valley fault zone. Strike-slip activity of the Mine Mountain fault zone, for example, probably occurred around 11 Ma. In a sense, the Spotted Range–Mine Mountain structural zone could be interpreted as a complex east-directed escape block which could be active under conditions of extreme clockwise rotation of the Spring Mountains domain. In this case, the west end of the Rock Valley fault zone could be seen as curving south to merge with the Pahrump–Stewart Valley fault, and the Spotted Range–Mine Mountain structural zone could be seen as simply a shear-damaged southeast corner of the Goldfield domain (fig. 6*A*).

The phase of deformation involving clockwise rotation of the Spring Mountains domain (SMD, fig. 6*A*) probably continued until about 10 to 7 Ma. Around 9 to 7 Ma a general clockwise rotation of principal stress axes occurred in the Walker Lane, and the principal horizontal compressive stress axis rotated from north-south to about N. 30° E. (Minor, 1995). As a result, the Las Vegas Valley shear zone underwent renewed compression, but with little if any offset; the shear zone remains

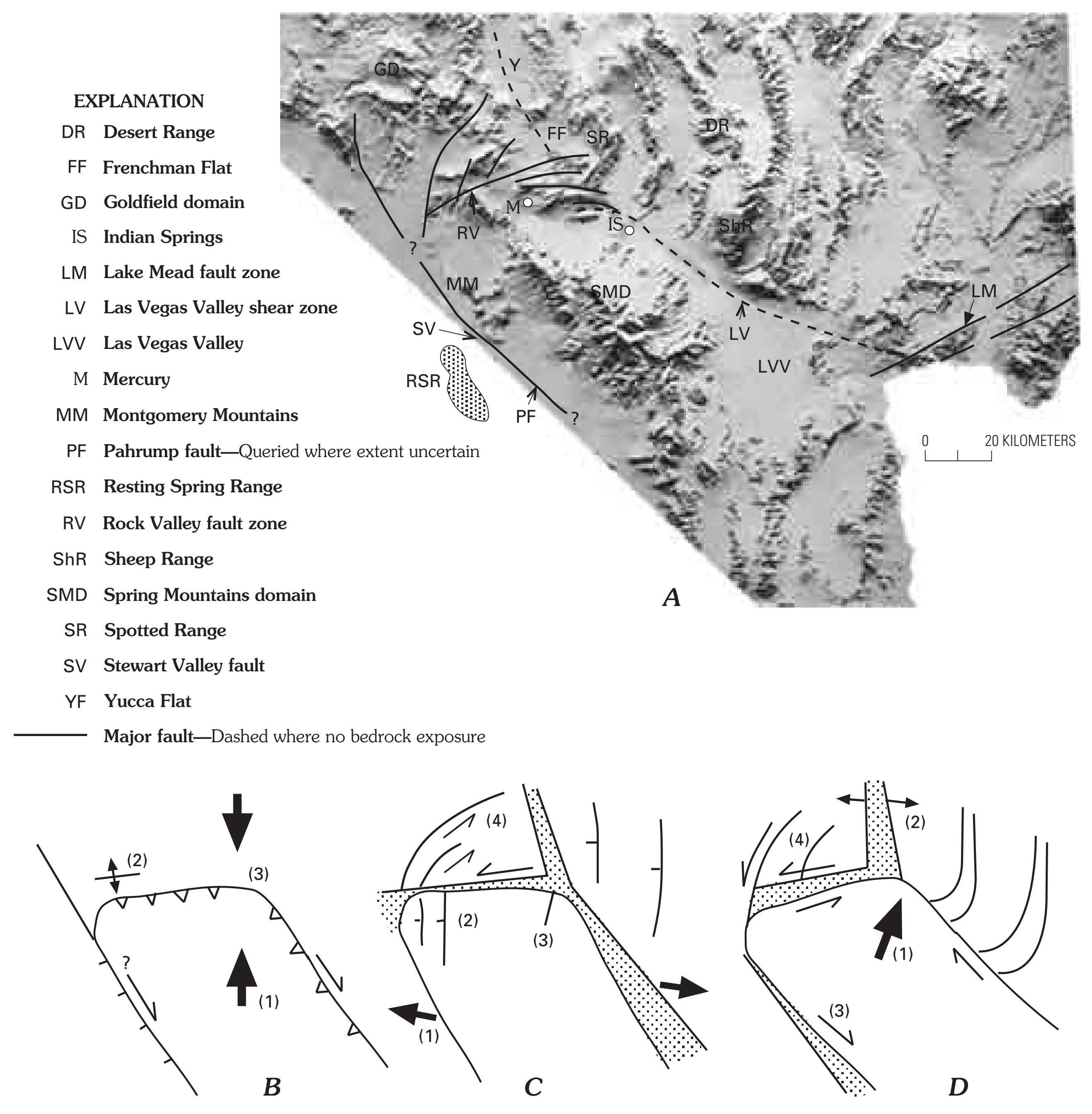

Figure 6. Inferred relations among major tectonic features associated with Rock Valley fault zone and the Spring Mountains tectonic domain. Stipple pattern in diagrams indicates area of subsidence and transtension. *A*, shaded relief map. *B, C, D*, diagrams showing inferred relations among major tectonic features. *B*, North-south compression (1), Paleogene or older; Striped Hills backfold (2); crowding and shearing at northeast corner of SMD (3). *C*, General extension (1); formation of Specter Range (2); sediments in RV (3); later slip along RV and formation of Spotted Range–Mine Mountain structural zone (4). *D*, North-northeast compression (1); east-west extension (2); counterclockwise rotation (3); strike-slip in RV and LV and to north and east (4).

locked at present, whereas the Rock Valley fault zone (RV, fig. 6*A*) has experienced minor left-lateral movement, and the ancillary faults of the Spotted Range–Mine Mountain structural zone have experienced little if any movement.

At present, movement of the Rock Valley fault zone may be dominated by west-northwest-east-southeast aligned extension confined to the Walker Lane, in which the Goldfield domain is pulling away to the northwest, producing transtension along the Rock Valley fault zone and subsidence along the Yucca Flat–Frenchman Flat axis (fig. 6*D*). A conspicuous result is increasing subsidence beneath Frenchman Flat.

The preceding deformation scenario is predicated on a model wherein large, semi-coherent fault-bounded slabs of brittle crust (domains) move in response to deep crustal viscous flow. The domains are free to rotate, collide, and slip past and pull away from each other. Essentially this model was utilized by Sonder and others (1994), who modeled the Las Vegas Valley shear zone deformation as occurring within a quasi-continuum of small, rigid blocks representing the shattered margin of a 10-20-km-thick brittle upper crust decoupled from a ductile lower crust that undergoes transcurrent shear. (For example, see Anderson and others, 1994.)

The rates and areal extent of upper crustal rafting must depend on the amount of viscous traction (coupling) applied to the brittle crust. Obviously this traction is not constant but is a function of time-dependent heat flux softening, pore pressure, and overall extension patterns established by plate motions.

Perhaps domainal activity occurred on a lower crust that became wetter and weaker (increasingly ductile) as the Tertiary magmatic front moved south through the Great Basin, reaching the Rock Valley area (≈37° N.) in middle Miocene. If heat and pore fluid have been supplied to the lower crust by an asthenospheric upper mantle located north of lat 37° N. (Saltus and Thompson, 1995), then the latitude of Las Vegas may be a general zone of collision and domain crowding. Since about 7 Ma and the waning of magmatism in the Rock Valley area, the lower crust has congealed such that the brittle and ductile layers are more completely coupled, having increasing traction and shear strength. This means that extension at present is not likely manifested by detachment but by local rips or tears that extend deeply into a strengthening crust and are manifested by basaltic volcanism and the formation of basins such as Frenchman Flat and Yucca Flat.

Conclusions

The Rock Valley fault zone is one of the early formed (approximately 29 Ma) east-northeast-trending left-lateral fault zones of the Walker Lane. It originally controlled the development of an elongate basin, possibly a half-graben, in which upper Oligocene conglomerate, lacustrine limestone, and ashfall tuff were deposited. Faulting associated with deposition continued in Neogene time, but deformation also included generally north-south oriented compression or transpression. Pleistocene deformation seems to be dominantly or exclusively transtensional. At present, the fault zone is seismically active, apparently subjected to transtension.

The Rock Valley fault zone is not an accommodation zone for differential extension; it is apparently totally unrelated to the Pahranagat fault zone farther east. The Rock Valley fault zone is a domain boundary that separates the Spring Mountains domain to the south from a complex, extended volcanogenic domain (Goldfield structural block) to the north. In this broader context, the fault zone is seen as a boundary activated by the displacement of large blocks of brittle upper crust (domains) rafted on a ductile lower crust.

Despite evidence of strike-slip and oblique-slip fault activity that dates back to Oligocene time, cumulative displacement of the Rock Valley fault zone is small (≈≤4 km). Its history of activity and its structural interaction with other proximal northeast-trending faults or fault zones of the Spotted Range–Mine Mountain structural zone remain unclear. Although the fault zone is grouped with other northeast-striking left-lateral faults of the Spotted Range–Mine Mountain structural zone, these other faults do not share the long history and the major domain-bounding geometry of the Rock Valley fault zone. Other features within the Spotted Range–Mine Mountain structural zone represent a relatively brief phase of tectonism in the history of the Rock Valley fault zone.

The model discussed herein supposes that the east end of the Rock Valley fault zone merges with the north end of the Las Vegas Valley shear zone in the vicinity of the south end of the Spotted Range. This proposed model also implies a remote tectonic relation to deformation of the Lake Mead fault zone. However, south- or southwest-directed stress does not directly control the Rock Valley fault zone, in contrast to the Lake Mead fault zone, because the Rock Valley fault zone does not flank the Basin and Range domain through which such stress has been transmitted to the Lake Mead fault zone.

Compressional stress may have been applied to the Rock Valley fault zone within the last 7 m.y. along a N. 30° E. vector from clockwise movement applied by the Spring Mountains domain. This could have been a consequence of the westward tectonic escape along the Lake Mead fault zone. More likely, under the present stress regime, the Rock Valley fault zone is undergoing west-northwest-directed transtension as the Goldfield block is pulling away to the northwest, opening the Yucca Flat–Frenchman Flat axis, and applying oblique transtension to the Rock Valley fault zone. Because the Basin and Range domain and the Spring Mountains domain are in mutual compression, the Las Vegas Valley shear zone is presently locked and experiences little seismicity.

The proposed model implies that the Rock Valley fault zone is a crustal break that penetrates through at least the seismogenic crust and is therefore capable of generating earthquakes at focal depths of approximately 15 km. The fault zone could accumulate strain along its entire length, depending on motion of the Spring Mountains or the Goldfield domains, but the Spring Mountains domain is unlikely to be active and is probably anchored in congealed lower crust, whereas the Goldfield domain may be pulling away on a perhaps still ductile lower crust.

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