Text and references for Nevada Bureau of Mines and Geology Map 127

GEOLOGY OF THE FRENCHMAN MOUNTAIN QUADRANGLE

CLARK COUNTY, NEVADA

by

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GEOCHRONOLOGY

Nine new $^{40}Ar/^{39}Ar$ ages were determined on seven samples from the Horse Spring Formation and overlying informal red sandstone of Bohannon (1984) (table 1). Two ages were determined by M. Perkins (written commun., 1999) on glass shards from red sandstone and Muddy Creek Formation ash beds using geochemical correlation techniques (Perkins and others, 1998). Additionally, we compiled published $^{40}Ar/^{39}Ar$, K-Ar, and fission-track ages to constrain the timing of magmatism and sedimentation in the area.

For $^{40}Ar/^{39}Ar$ dating, mineral separates were obtained from our samples by crushing, sieving, and magnetic and density separation. Sanidine and plagioclase were leached with dilute HF to remove adhering matrix. Biotite and hornblende concentrates were handpicked to obtain primarily monomineralic grains free of alteration. Samples were irradiated at Texas A&M University and analyzed at the New Mexico Geochronological Research Laboratory (New Mexico Institute of Technology; methodology discussed in McIntosh and Chamberlin, 1994) and the Nevada Isotope Geochronology Laboratory (University of Nevada, Las Vegas; methodology in Justet and Spell, in review). In both labs, single grains of sanidine were quantitatively fused using a CO_2 laser. Other samples were heated in a low-blank, resistance furnace, generally in eight to ten 10-minute increments between about 700°C and 1450°C. Fish Canyon sanidine (27.84 Ma, relative to an age of 520.4 Ma on hornblende MMhb-1; Cebula and others, 1986; Samson and Alexander, 1987) was used to monitor neutron fluence. Calculated ages and $\pm 1\sigma$ uncertainties are listed in table 1. $^{40}Ar/^{39}Ar$ ages reported by Beard (1996) and Harlan and others (1998) use the same monitor ages. However, Sawyer and others (1994) used an age of 513.9 Ma for MMhb-1. We therefore recalculated their ages for direct comparison.

Most ages were readily interpretable as either means (sanidine) or plateaus (biotite and hornblende) (table 1, fig. 1). Eleven sanidine grains from C95-38 gave a tight mean with no indication of inherited grains. Sanidine from sample C95-3 included several probable xenocrysts, which were excluded from the final age calculation. Hornblende and biotite pairs from samples C95-64 and C95-29 differ by more than 1σ but are indistinguishable at 2σ. The spectrum for plagioclase from sample C95-50 was slightly disturbed; an inverse isochron plot gives an age of 13.12±0.24 Ma with an MSWD of 2.11. We consider this a reliable age, because it agrees well with stratigraphic relations and ages of other samples (fig. 1).

Our $^{40}Ar/^{39}Ar$ ages from all samples except C95-3 and JF99-455 (red sandstone) range narrowly between 13.12 and 13.94 Ma. Along with published data (fig. 1), these indicate that the upper part of the Horse Spring Formation was deposited rapidly, with no discernible age difference between rocks of the Bitter Ridge and Lovell Wash Members. Moreover, ages are indistinguishable from those of the "igneous rocks of Lava Butte" (e.g., the dacite intrusion that makes up Lava Butte; sample C95-29) and K-Ar ages on igneous rocks from the River Mountains volcanics (Anderson and others, 1972; Faulds and others, 1999). In contrast, our new age (13.94±0.03 Ma; C99-14) and published ages on the Thumb Member are distinctly older, ranging from about 14 to 16 Ma. The Rainbow Gardens Member is still older; the youngest age reported by Beard (1996) is 18.8 Ma, and ages range back to 26 Ma.

The red sandstone (Bohannon, 1984) is noticeably younger. Our sanidine ages agree closely with $^{40}Ar/^{39}Ar$ ages on a tuff in the red sandstone reported by Harlan and others (1998) and, within their large uncertainties, with fission-track ages on zircon reported by Bohannon (1984). Additionally, the age for sample C95-3, at 11.47 Ma (table 1), is indistinguishable from the reported age of the Ammonia Tanks Tuff, a regionally extensive high-silica rhyolite to alkali trachyte ash-flow sheet from the Timber Mountain caldera about 150 km northwest of the Frenchman Mountain Quadrangle (Sawyer and others, 1994). Sample C95-3 is mineralogically similar to the Ammonia Tanks Tuff (with phenocrysts of quartz, sanidine, plagioclase, biotite, pyroxene, and hornblende) and is likely a distal fall from that tuff.

The two ages determined using geochemical correlation include one for a tuff bed from the red sandstone unit that was also dated by $^{40}Ar/^{39}Ar$, giving identical dates (JF99-452, table 1). This tuff, which is correlative with the CPT IX ash bed of Perkins and others (1998), lies beneath a white

Table 1. $^{40}Ar/^{39}Ar$, K/Ar, fission track, and chemical correlation ages, Lake Mead area.

Reference	Sample No.	Location N. Lat.	Location W. Long.	Stratigraphic unit		Rock type	Mineral	Age Method		n*or %^{39}Ar	Age (Ma)	±1σ
Spencer and others, 1998		35°58'29"	114°24'47"	Hualapai Limestone		tuff	biotite	Step heating	plateau		5.97	0.07
this study	JF99-455	36°15'12"	114°56'37"	Muddy Creek Fm		air-fall tuff	glass	Geochemical correlation			6.0	
Feuerbach and others, 1991		36°09'51"	114°43'57"	Volcanics of Callville Mesa		basaltic andesite lava	plagioclase	K/Ar			8.49	0.20
"		36°10'37"	114°44'39"	"		basaltic andesite lava	plagioclase	K/Ar			10.21	0.23
"		36°10'19"	114°42'30"	"		basalt lava	plagioclase	K/Ar			10.46	0.23
Harlan and others, 1998		36°10'28"	114°48'45"	"		basalt lava	whole rock	Step heating	plateau		11.41	0.07
Sawyer and others, 1994		Yucca Mtn. area		Ammonia Tanks Tuff		ash-flow tuff	sanidine	Single crystal	mean		11.59	0.03
Bohannon, 1984		Frenchman Mtn. quad		"		air-fall tuff	zircon	Fission track			10.6	0.90
"		White Basin		"		"	"	"			11	0.90
this study	C95-3	36°08'34"	114°55'11"	"		"	sanidine	Single crystal	mean	20	11.47	0.05
"	JF99-452	36°14'30"	114°58'35"	red sandstone		"	sanidine	Single crystal	mean	8	11.59	0.06
"	"	"	"	"		"	glass	Geochemical	correlation		11.60	
Bohannon, 1984		White Basin				"	zircon	Fission track			11.9	0.90
Harlan and others, 1998		36°14'01"	114°48'20"			crystal vitric tuff	sanidine	Step heating	plateau		11.70	0.04
Harlan and others, 1998		"	"			crystal vitric tuff	biotite	Step heating	plateau		11.86	0.05
Bohannon, 1984		Lovell Wash		Horse Spring Fm.	Lovell Wash Mbr.	air-fall tuff	zircon	Fission track		13	0.80	
this study	C95-50	36°08'03"	114°55'43"	"	"	plagioclase	Step heating		isochron	7	13.12	0.24
"	C95-64	36°10'42"	114°54'19"	"	"	"	hornblende	"	plateau	51.9	13.12	0.12
"	C95-64	"	"	"	"	"	biotite	"	plateau	88.8	13.40	0.05
Harlan and others, 1998		36°09'10"	114°51'31"	"	"	basalt lava	whole rock	"	isochron		13.28	0.05
Harlan and others, 1998		36°10'39"	114°48'52"	"	"	basalt lava	whole rock	"	plateau		13.17	0.05
this study	C95-38	36°08'06"	114°56'18"	"	Bitter Ridge Mbr.	ash-flow tuff	sanidine	Single crystal	mean	11	13.07	0.08
this study	C95-20	36°08'49"	114°53'04"	River Mountains Volcanics equiv.		basalt lava	whole rock	Step heating	plateau	100	13.16	0.18
Anderson and others, 1972		River Mtns.		River Mountains Volcanics		silicic lava	biotite	K/Ar			13.2	0.40
"		"		"		"	"	"			13.2	0.30
Weber and Smith, 1987		"		"		lamprophyre dike	"	K/Ar			13.4	0.30
Harlan and others, 1998		36°10'46"	114°50'14"	Intrusion in Thumb Member		diorite sill	hornblende	Step heating	plateau		13.19	0.06
this study	C95-29	36°08'58"	114°56'18"	Dacite porphyry (Lava Butte)		dacite intrusive rock	biotite	Step heating	plateau	93.3	13.16	0.05
"	C95-29	"	"	"		"	hornblende	"	plateau	95.3	13.50	0.16
Anderson and others, 1972		Frenchman Mtn. quad		Igneous rocks of Lava Butte		biot.-hornbl. rhyodacite	biotite	K/Ar			13.7	0.70
Bohannon, 1984		"		Horse Spring Fm.	Thumb Mbr.	air-fall tuff	zircon	Fission track			13.2	0.90
this study	C99-14	36°15'24"	114°51'15"	"	"	air-fall tuff	biotite	Ar/Ar	plateau	94.2	13.94	0.03
Beard, 1996		Lime Ridge		"	"	tuff	biotite	Ar/Ar			14.2	0.50
"		Gold Butte		"	"	"	"	"			14.4	0.30
"		Wilson Ridge		"	"	"	sanidine	"			15.1	0.10
"		Pakoon Ridge		"	"	"	"	"			15.4	0.04
Anderson and others, 1972		SE of Muddy Mtns.		"	"	"	biotite	K/Ar			15.6	0.70
Beard, 1996		Pakoon Ridge		"	"	air-fall tuff	sanidine	Ar/Ar			15.7	0.20
Bohannon, 1984		Frenchman Mtn. quad		"	"	"	zircon	Fission track			16.2	0.80
Beard, 1996		Horse Spring		"	Rainbow Gardens Mbr.	"	anorthoclase	Ar/Ar			18.8	0.20

This study * n = number of single crystals analyzed; %^{39}Ar = percentage of ^{39}Ar that defines plateau.
Decay constants after Steiger and Jager (1977) and $^{40}Ar/^{39}Ar$ ages normalized to a monitor age of 520.4 Ma on MMhb-1 hornblende (27.84 Ma on Fish Canyon sanidine).
Step heating and single crystal ages are by $^{40}Ar/^{39}Ar$ method.

tuff that may be the Ammonia Tanks Tuff (Perkins, written commun., 1999). In addition, a geochemical correlation age was determined for a fine-grained vitric tuff in the Muddy Creek Formation just to the north of the Frenchman Mountain Quadrangle (JF99-455, table 1). This age (6.0 Ma) was critical to the determination of the age of the enclosing rocks and the overlying limestone in the Muddy Creek Formation, which was previously assigned to the older (ca. 13.5 Ma) Bitter Ridge Member of the Horse Spring Formation by Bohannon (unpublished mapping, Apex Quadrangle).

CHEMICAL ANALYSES

Whole-rock major oxide analyses were performed at Washington State University and at the Nevada Bureau of Mines and Geology Analytical Laboratory using XRF analysis of fused lithium borate disks. Data are presented in table 2.

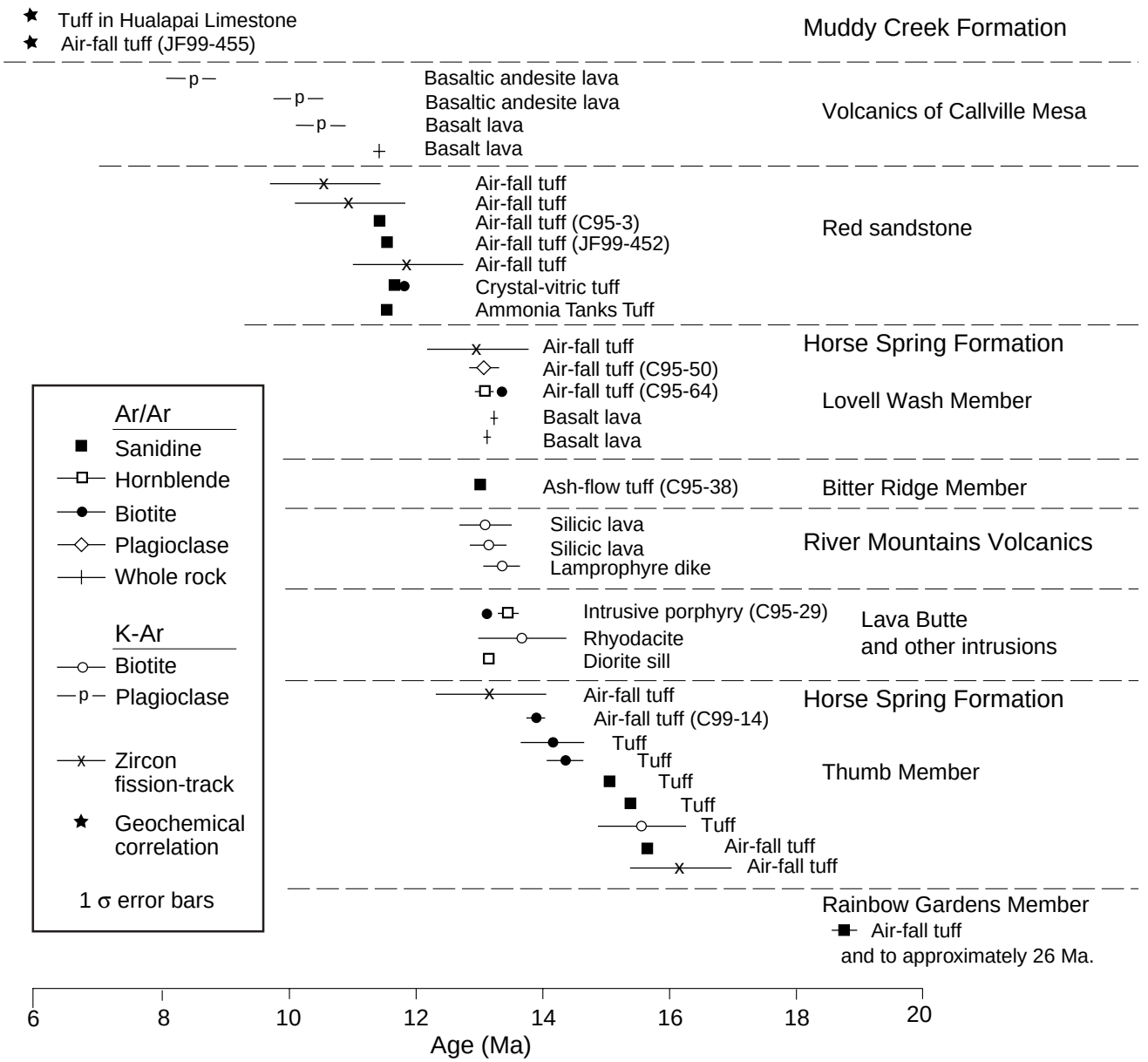


Figure 1. Isotopic and geochemical correlation ages, Frenchman Mountain Quadrangle and vicinity. Data are from this study (numbered samples), and from Anderson and others (1972), Sawyer and others (1984), Weber and Smith (1987), Feuerbach and others (1991), Bohannon (1994), Beard (1996), Harlan and others (1998), and Spencer and others (1998); see table 1. Samples from individual sources are arranged in stratigraphic order.

Table 2. Whole-rock major oxide contents of samples from the Frenchman Mountain Quadrangle. All analyses were conducted at Washington State University, except for samples C95-9 and C95-29, which were analyzed by the Nevada Bureau of Mines and Geology.

Sample	C95-3	C95-4	C95-9	C95-20	C95-29	C95-38	C95-50	C95-64
Map unit	Tr	Tr	Tb	Tb	Td	Thb	Thl	Thl
Latitude	36°08'34"	36°08'39"	36°09'01"	36°08'50"	36°08'58"	36°08'06"	36°08'03"	36°10'42"
Longitude	114°55'11"	114°55'18"	114°55'11"	114°53'04"	114°56'18"	114°56'18"	114°55'43"	114°54'19"
SiO_2	72.36	74.45	52.86	47.89	68.59	73.22	63.47	62.30
TiO_2	0.22	0.21	1.58	1.58	0.39	0.15	0.46	0.58
Al_2O_3	13.86	12.65	15.57	15.19	14.50	13.17	14.46	18.31
Fe as Fe_2O_3	1.49	2.04	8.81	10.40	2.21	0.92	2.87	4.72
MnO	0.08	0.04	0.12	0.16	0.05	0.02	0.07	0.08
MgO	1.80	0.96	6.37	9.25	0.99	0.81	4.39	2.11
CaO	1.13	1.11	7.97	9.12	2.74	0.56	4.67	4.98
Na_2O	2.25	2.11	3.72	3.02	3.53	2.20	2.56	2.90
K_2O	5.07	4.64	1.96	1.13	5.29	6.73	2.72	2.53
P_2O_5	0.04	0.01	0.49	0.37	0.16	0.03	0.20	0.22
Total	98.30	98.22	99.45	98.12	8.45	97.81	95.87	98.73

STRUCTURE

The Frenchman Mountain Quadrangle occupies a position critical to understanding the structural and tectonic framework of southern Nevada (fig. 2). It contains beautifully exposed Paleozoic, Mesozoic, and Tertiary stratigraphic sections that have strong affinities to sections far to the east near the western margin of the Colorado Plateau, portions of large middle to late Miocene basins, part of a major range-bounding normal fault that has accommodated Quaternary displacement and poses a potential seismic hazard to the city of Las Vegas, and several strike-slip fault zones. Much of the rock in the Frenchman Mountain Quadrangle may have originated 60 km or more to the east, having been transported to its present position by systems of strike-slip and normal faults (Anderson, 1973; Bohannon, 1984; Rowland and others, 1990; Duebendorfer and others, 1998). The discussion below addresses the geometry and kinematics of the most prominent structural features within the quadrangle.

The Frenchman Mountain Quadrangle contains at least five major structural elements, here referred to as the Frenchman Mountain block, Boulder basin, Sunrise Mountain block, Nellis basin, and Las Vegas Valley (fig. 3). The Frenchman Mountain block is bounded by the Frenchman fault and Las Vegas Valley on the west, Boulevard fault zone and Sunrise Mountain block on the north, and the Boulder basin on the east. The Frenchman Mountain block is dominated by north-northeast striking, moderately to gently east-tilted Paleozoic, Mesozoic, and Miocene strata (fig. 4a). Directly west of the Quadrangle on the west flank of Frenchman Mountain, the Cambrian Tapeats Sandstone rests directly on Early Proterozoic gneiss (e.g., Rowland and others, 1990; Matti and others, 1993). The boundary between the Frenchman Mountain block and Boulder basin was placed at the contact between the Rainbow Gardens and Thumb Members of the Horse Spring Formation, because this marks the approximate stratigraphic level where tilts begin to decrease up-section (i.e., tilt fanning). Tilt magnitudes within the Rainbow Gardens Member are similar to those of Paleozoic and Mesozoic strata, despite the minor angular unconformity at the base of the Tertiary. Several widely spaced north-northeast to north-northwest striking, generally west-dipping normal faults cut the Frenchman Mountain block. Some of these faults cut the Boulevard fault zone. In the northeast part of the block, several of these faults curve northeastward and become parallel with the left-lateral Boulevard fault zone (fig. 3). The eastern part of the boundary between the Frenchman and Sunrise Mountain blocks steps southward from the Boulevard fault zone to follow the eastern portion of one of these curved faults, here referred to as the Dry Wash fault. The eastern part of this fault accommodated about 2.7 km of left-lateral separation. The area between the eastern part of the Dry Wash fault and Boulevard fault zone was included in the Sunrise Mountain block because the attitude of strata within that area is significantly oblique to that within most of the Frenchman Mountain block but subparallels that within the Sunrise Mountain block.

The Boulder basin lies directly east of the Frenchman Mountain block and consists primarily of middle to late Miocene sedimentary strata. It occupies the eastern part of the quadrangle and covers much of the western Lake Mead area (fig. 2). On a broad scale, Miocene strata within the western part of the basin (i.e., within the quadrangle) are tilted gently to moderately eastward, with the magnitude of tilting progressively decreasing up-section. Thus, the basin may correspond, at least in part, to an east-tilted half graben that developed in the hanging wall of the Saddle Island detachment (Duebendorfer and Wallin, 1991). However, the northern extent of the Saddle Island detachment is poorly defined. Moreover, the northern part of the Boulder basin is complicated by an east- to northeast-trending fold belt. This

fold belt extends from the eastern part of the Frenchman Mountain Quadrangle (fig. 4c) eastward through the Government Wash (Duebendorfer, in review) and Callville Bay Quadrangles (Anderson, in review). If once a half graben or series of half grabens, the Boulder basin has since been significantly modified by north-south shortening, possibly associated with the intersection of the left-lateral Lake Mead fault system and right-lateral Las Vegas Valley shear zone (Çakir and others, 1998). Anderson (in review) has suggested that sedimentation patterns in the red sandstone and Muddy Creek units were controlled by east-trending folds rather than by northerly striking faults. The late Miocene Muddy Creek Formation is commonly mildly deformed throughout this area. The tilted and folded strata are onlapped by latest Miocene(?) to Quaternary fan deposits. To the south of the quadrangle, the Boulder basin appears to join with the River Mountains structural block (fig. 2), which is dominated by middle Miocene intermediate to felsic lavas (Anderson and others, 1972; Bell and Smith, 1980; Smith, 1982, 1984).

The Sunrise Mountain block is bounded by the Frenchman fault and Las Vegas Valley on the west and northwest, the Nellis basin and Munitions fault on the northwest and north, the Boulder basin and Dry Wash fault on the southeast, and the Frenchman Mountain block and Boulevard fault zone on the southwest (fig. 3). In contrast

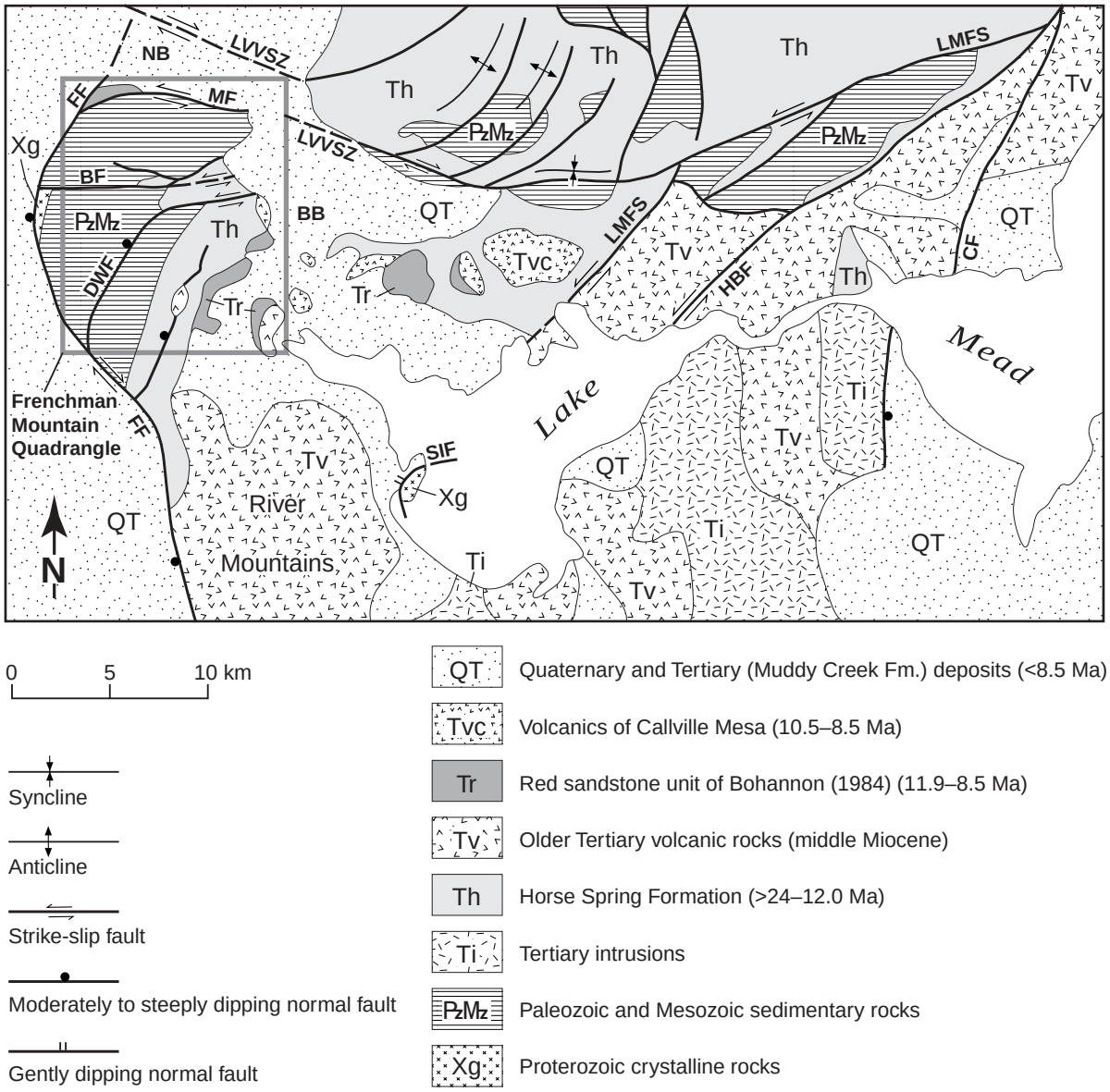


Figure 2. Generalized geology of the western Lake Mead area. Faults or fault zones labelled are: BF - Boulevard fault zone; CF - Cleopatra fault; DWF - Dry Wash fault; FF - Frenchman fault; HBF - Hamblin Bay fault of Lake Mead fault system; LMFS - Lake Mead fault system; LVVSZ - Las Vegas Valley shear zone; MF - Munitions fault; SIF - Saddle Island fault. Basins labelled are: BB - Boulder basin; NB - Nellis basin.

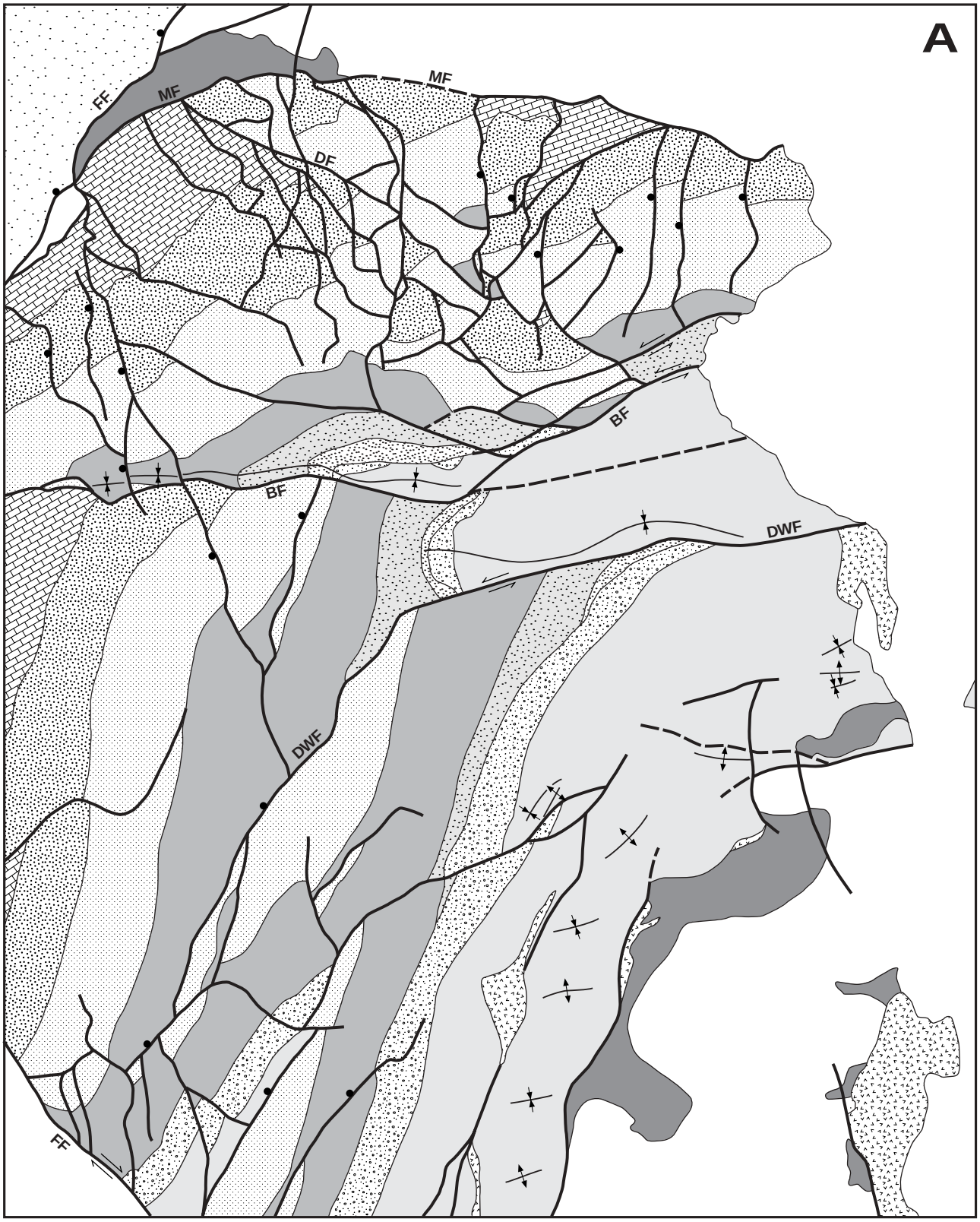


Figure 3A. Simplified geology of the Frenchman Mountain Quadrangle. Faults or fault zones labelled are: BF - Boulevard fault zone; DF - Demolition fault; DWF - Dry Wash fault; FF - Frenchman fault; MF - Munitions fault.

Figure 3B. Map showing major structural elements discussed in text.

Contact

Strike-slip fault, dashed where uncertain

Normal fault, dashed where uncertain

Syncline, anticline

Basin fill (Quaternary-Tertiary)

Muddy Creek Fm. (late Miocene)

Volcanic rocks (mid-late Miocene)

Red sandstone (mid-late Miocene)

Horse Spring Fm.,
Thumb-Lovell Wash Mbrs. (early-mid Miocene)

Horse Spring Fm.,
Rainbow Gardens Mbr. (early-mid Miocene)

Aztec Sandstone (Jurassic)

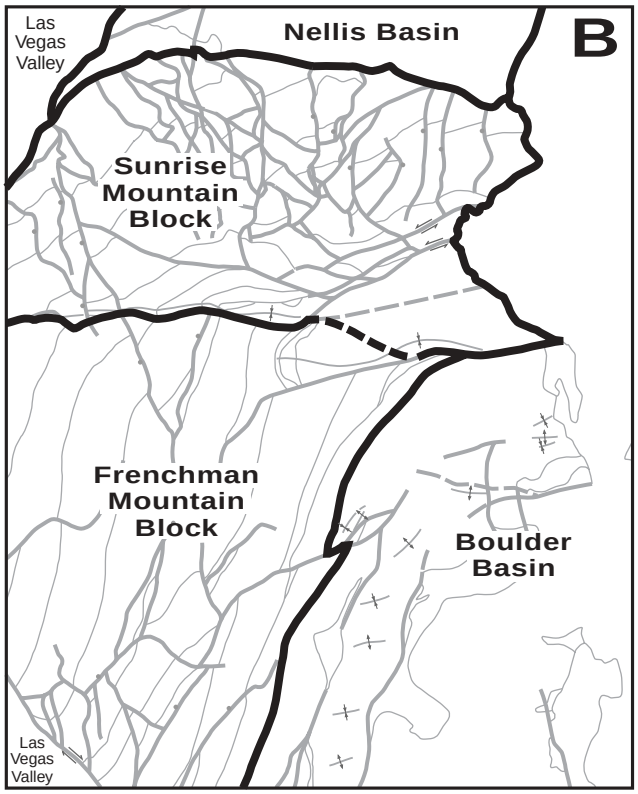
Chinle-Moenave Fms. (Triassic-Jurassic)

Moenkopi Fm. (Triassic)

Queantoweap-Kaibab-Toroweap Fms. (Permian)

Callville Limestone and Pakoon Fm.
(Pennsylvanian-Permian)

Cambrian-Mississippian rocks



to the Frenchman Mountain block, the Sunrise Mountain block is dominated by east-northeast striking, moderately southeast-dipping Paleozoic and Mesozoic strata (fig. 4b) that are cut by a complex array of closely spaced normal, oblique, and strike-slip faults. The multiple fault sets fragment the Sunrise Mountain block into a myriad of small blocks. The most prominent fault sets in the Sunrise Mountain block are: 1) north-northwest to north-northeast striking, moderately to steeply dipping normal faults that generally dip west; 2) east-northeast-striking, steeply dipping, mainly sinistral faults, some of which can be considered splays of the Boulevard fault zone; and 3) west-northwest-striking, moderately to steeply dipping dextral and sinistral faults, although the dextral faults predominate. In addition, a few minor northeast- and west-northwest-striking reverse separation faults were observed. Although normal faults of the first set commonly truncate and offset the east-northeast- and west-northwest-striking fault sets, important exceptions can be found. For example, near the northern margin of the quadrangle, several normal faults swing northwestward and appear to merge with a major west-northwest-striking sinistral-normal fault, here referred to as the Demolition fault (fig. 3a) because it bisects a demolition range on Nellis Air Force Base.

The structural complexity in the Sunrise Mountain block increases northward toward a major east-striking fault zone that dips gently to moderately (29° to 39°) northward. This fault zone bounds the Sunrise Mountain block on the north and is referred to as the Munitions fault, because it extends through the munitions storage area of the Nellis Air Force Base. The Munitions fault cuts the post-6-Ma limestone member of the Muddy Creek Formation but does not cut Quaternary fan deposits. The N80°E strike of much of the Munitions fault suggests that it may be a splay of the right-lateral Las Vegas Valley shear zone. However, the Munitions fault accommodated a large component of normal separation and curves to a northeasterly strike as it merges westward with the largely normal Frenchman fault. The northeast-striking portion of the Munitions fault accommodated sinistral-normal oblique slip. These relations imply that the Munitions fault has experienced a complex kinematic history and cannot be directly related to the Las Vegas Valley shear zone.

Relatively thick sections of middle to late Miocene sedimentary rocks and isostatic gravity data (Langenheim and others, 1998; in press) indicate that a small, 2- to 3-km-deep, late Tertiary basin lies directly north of the Munitions fault, straddling the northern margin of the Frenchman Mountain Quadrangle. This basin is referred to as the Nellis basin, because it contains the eastern part of Nellis Air Force Base. The limestone member of the Muddy Creek Formation (Tml) is essentially confined to this basin. A 6.0-Ma air-fall tuff lies beneath the limestone. This limestone is typically gently tilted and cut by widely spaced faults in the Frenchman Mountain Quadrangle. However, to the north in the Apex Quadrangle it is warped into several north-northwest- to east-trending folds (R.G. Bohannon,

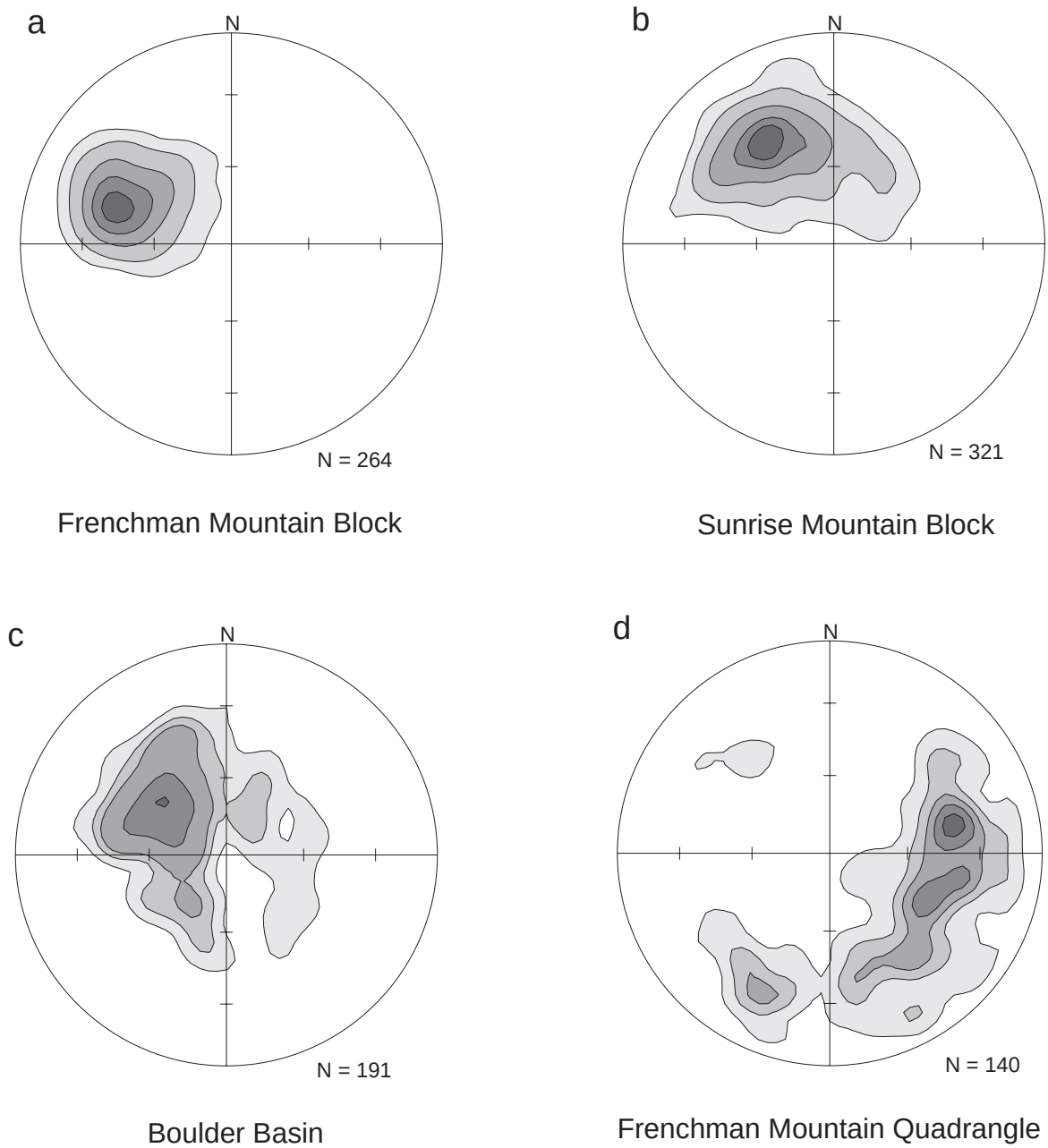


Figure 4. Equal-area density contour stereograms. Density contours were calculated utilizing Gaussian counting. N - number of measurements. (a) Poles to bedding of Cambrian strata through the early Miocene Rainbow Gardens Member in the Frenchman Mountain block; density contours at 0, 4, 16, 32, and 48% per 1% area; bedding attitude averages N17°E, 47°SE; (b) Poles to bedding of Cambrian through early Miocene strata in the Sunrise Mountain block; contours at 0, 4, 12, 20, and 24% per 1% area; bedding attitude averages N54°E, 47°SE; (c) Poles to bedding of middle to late Miocene strata (Thumb Member of the Horse Spring Formation through Muddy Creek Formation) in the Boulder basin; contours at 0, 2, 4, 12, and 20% per 1% area; bedding attitude averages N41°E, 31°SE. (d) Poles to fault planes in the entire Frenchman Mountain Quadrangle; contours at 0, 2, 4, 6, and 8% per 1% area; faults generally strike north-northeast to north-northwest and dip to the west, but a significant subset strikes west-northwest and dips to the north.

unpublished mapping). Within the Frenchman Mountain Quadrangle, nearly flat-lying beds beneath the limestone rest in angular unconformity on the moderately east-tilted red sandstone unit, which contains an 11.6 Ma air-fall tuff. This suggests that most of the tilting in this area occurred between 11.6 and 6.0 Ma.

It is noteworthy that the red sandstone unit in this area contains abundant clasts of Proterozoic gneiss and granite. Possible sources of this detritus include the Proterozoic exposures on the west flank of Frenchman Mountain, Proterozoic detritus in the Thumb Member of the Horse Spring Formation south of the Sunrise Mountain block, and Proterozoic exposures far to the east in the Gold Butte area. Considering the present position of the Nellis basin, it would be difficult to derive detritus from any of these sources. However, much of the tilting of the Nellis basin and Frenchman Mountain block clearly postdates deposition of the red sandstone unit. Thus, the paleogeography during deposition of the red sandstone unit probably differed significantly from the present physiography. It is also important to note that the strike of strata within the Nellis basin (e.g., north-northwest strike of red sandstone unit beds) is highly discordant to that in the Sunrise Mountain block (e.g., east-northeast strikes of Paleozoic through middle Miocene strata). This suggests that the Nellis basin and Sunrise Mountain block were essentially decoupled and followed somewhat different evolutionary paths.

The Las Vegas Valley shear zone is a major west-northwest-striking right-lateral fault zone that extends across much of southern Nevada (fig. 2). It has accommodated as much as 65 km of dextral displacement to the west of the Frenchman Mountain Quadrangle (Longwell, 1974; Wernicke and others, 1988; Duebendorfer and Black, 1992), and is associated with large-magnitude clockwise rotations as reflected in a major oroclinal flexure and documented by paleomagnetic data from Paleozoic and Tertiary rocks (Nelson and Jones, 1987; Sonder and others, 1994). The Las Vegas Valley shear zone essentially bounds both the Boulder and Las Vegas basins on the north. On the basis of gravity data, Campagna and Aydin (1994) and Langenheim and others (1998; in press) have suggested that parts of the Las Vegas Valley originated as pull-aparts in right steps of the Las Vegas Valley shear zone. The shear zone may have also served as a major transfer zone (cf., Faulds and Varga, 1998) that linked en echelon domains of extension (Liggett and Childs, 1977; Duebendorfer and Black, 1992). Dextral motion on the shear zone has been kinematically linked to normal displacement on the Saddle Island detachment fault (Weber and Smith, 1987; Duebendorfer and Black, 1992). However, a direct linkage between the Saddle Island detachment and Las Vegas Valley shear zone is not supported by the distribution of rock units or structural relations in the Frenchman Mountain and adjacent quadrangles. Furthermore, gravity and seismic reflection data showed no evidence for a major detachment fault in the Frenchman Mountain area (Langenheim and others, in press).

The west-northwest elongated Nellis basin may have developed in a right step or pull-apart near the eastern end of the Las Vegas Valley shear zone. Isostatic gravity data define a 7-km-long basin that trends approximately N70°W, parallel to the eastern part of the shear zone (fig. 5). Although the Munitions fault on the southern margin of the western part of the basin did not accommodate dextral motion, it may intersect the western end of a southern strand of a right-stepping dextral shear zone to the east. The main strand of the Las Vegas Valley shear zone may bound the Nellis basin on the north. Opening of the Nellis basin may have been accommodated along its northern margin by dextral motion on a northern strand of the Las Vegas Valley shear zone and along its southern margin by sinistral-normal movement on the Munitions fault (fig. 5).

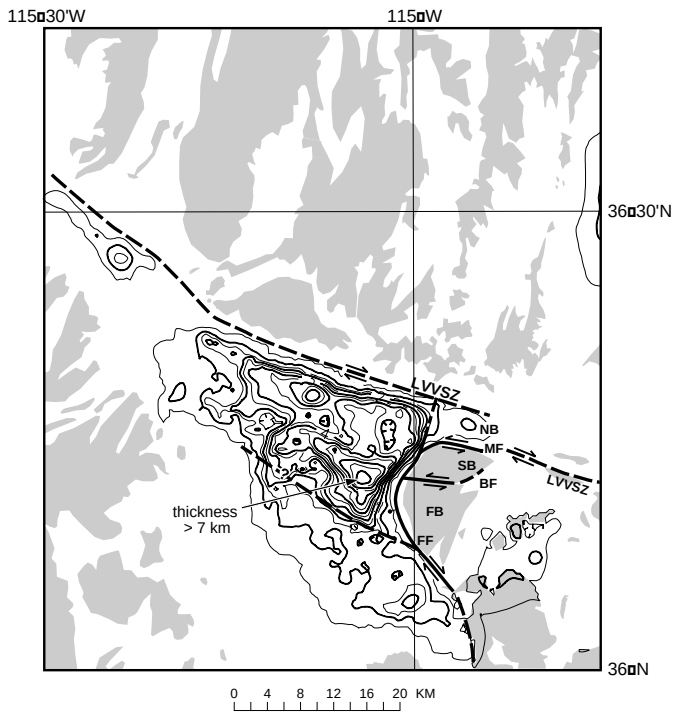


Figure 5. Thickness of Cenozoic basin fill and inferred location of major faults in the Frenchman Mountain area, based on isostatic residual gravity data (modified from Langenheim and others, 1997). Contour intervals at 0.5 and 1.0 km. Basin model utilized the seismically derived density-depth function, as discussed in Langenheim and others (1997). Faults designated as in figure 2; FB = Frenchman Mountain block, NB = Nellis basin, SB = Sunrise Mountain block.

The swing from northerly striking strata in the Frenchman Mountain block to east-northeast-striking strata in the Sunrise Mountain block is interpreted to reflect oroflexural deformation associated with right-lateral displacement and/or north-south shortening accommodated by the Las Vegas Valley shear zone. Sonder and others (1994) documented more than 75° of clockwise rotation within the Thumb Member of the Horse Spring Formation near the Boulevard fault zone. The magnitude of clockwise rotation decreases appreciably to both the north and south of the Las Vegas Valley shear zone (Sonder and others, 1994). On the basis of the average strike of strata (figs. 4a, b), clockwise rotation of the Sunrise Mountain block, relative to the Frenchman Mountain block, probably averages about 45°. In general, stratal rotations in the Sunrise Mountain block increase to the east, with maximum rotations occurring in the southeast part of the block near the Boulevard fault zone.

The Boulevard fault zone separates the Frenchman and Sunrise Mountain blocks in the western part of the quadrangle and cuts through the southern part of the Sunrise Mountain block in the east. This fault was formerly termed the Frenchman fault by Longwell (1966) but was renamed due to the proximity of much of the fault zone to Lake Mead Boulevard. The western part of this fault zone dips moderately northward (~35° to 65°) and accommodated normal-sinistral separation, whereas the eastern part of the fault zone dips steeply and accommodated both normal-sinistral and reverse-sinistral separation. Riedel shears and striae indicate that the eastern part of the fault zone accommodated mostly left-slip. Sinistral separation across the zone ranges from about 3.5 to 5.0 km. The Boulevard fault zone may represent a segment of the left-lateral Lake Mead fault zone that has been offset by the Las Vegas Valley shear zone. Alternatively and perhaps more likely, the Boulevard fault zone may have simply accommodated the northward increase in clockwise rotation toward the Las Vegas Valley shear zone, particularly the differential rotation between the Sunrise and Frenchman Mountain blocks. Sinistral-normal movement on the subparallel Munitions fault to the north may have also accommodated clockwise rotation of the Sunrise Mountain block. Thus, the Munitions and Boulevard fault zones may be kinematically related to one another, both having accommodated clockwise rotation associated with oroflexural folding along the Las Vegas Valley shear zone. A possible problem with this model is the apparent lack of clockwise rotation in the Nellis basin, which presumably lies astride the Las Vegas Valley shear zone.

The large-magnitude clockwise rotation may have significant implications for interpreting the origin of some of the fault sets and folds within the Sunrise Mountain block and Boulder basin, respectively. For example, removal of 45° to 75° of clockwise rotation restores many of the west-northwest striking left-lateral faults in the Sunrise Mountain block to east-northeast strikes, subparallel to other major left-lateral faults in the region. In addition, the clockwise rotation of the Sunrise Mountain block would likely generate some north-south shortening to the southeast of the block, and thus may have induced some of the folding in the Boulder basin as well as the greater stratal rotations in the southeast part of the block. The reverse-sinistral motion on some splays of the eastern part of the Boulevard fault zone is compatible with this model. East-northeast-striking faults in this area do not consistently display a reverse component of motion, however, as evidenced by the eastern part of the Dry Wash fault, which accommodated normal-sinistral separation directly north of many of the folds in the Boulder basin. Reverse and normal components of motion on similarly oriented faults implies that the rotating fault blocks experienced a complex kinematic history involving both local and regional forces. The eastward continuation of this fold belt through the western Lake Mead region further suggests that regional forces were at least partly responsible for the folding. Possible regional forces include broad north-south shortening accommodated by the left-lateral Lake Mead fault zone and right-lateral Las Vegas Valley shear zone (Anderson and Barnhard, 1993), north-south shortening resulting from opposing senses of motion on the left-lateral Lake Mead fault zone and right-lateral Las Vegas Valley shear zone (Çakir and others, 1998) and localized near their intersection, and wrench-style tectonics near the strike-slip faults (e.g., Wilcox and others, 1973). In the latter case, dextral motion on the west-northwest-striking Las Vegas Valley shear zone could induce northwest-southeast to north-south shortening in the local strain field. This may account for at least some of the northeast- to east-trending folds within the region. Furthermore, such folding could be episodic and coincide with major periods of movement on the Las Vegas Valley shear zone, alternating perhaps with intervals in which regional extension dominated. The east-trending synclines directly adjacent and parallel to the Boulevard and Dry Wash fault zones may exemplify the complex three-dimensional strain field, as the eastern parts of the folds may reflect north-south shortening associated with movement on the Las Vegas Valley shear zone and clockwise rotation of the Sunrise Mountain block, whereas the western parts of the folds may have resulted from normal drag along the Boulevard and Dry Wash fault zones induced by the clockwise rotation of the Sunrise Mountain block.

Intense deformation with multiple intersecting fault sets similar to that in the Sunrise Mountain block probably characterizes much of the Las Vegas Valley shear zone within the northern part of Las Vegas Valley and may greatly influence groundwater flow. Possible strands of the shear zone are covered by sediments in Las Vegas Valley but may follow strong gravity gradients (Langenheim and others, 1998; in press). Although the uplifted Sunrise Mountain area contains relatively little groundwater, it is noteworthy that most of the faults are not sealed. The central Nevada carbonate aquifer empties into the northern part of Las Vegas Valley, flows laterally along the Las Vegas Valley shear zone,

and discharges near the shear zone in several springs, many of which are marked by Quaternary carbonate mounds (G.L. Dixon, personal commun., 1998). Multiple intersecting fault sets along the shear zone probably provide abundant channelways for the groundwater. Major strike-slip transfer zones play a major role in controlling groundwater flow patterns elsewhere within the Basin and Range province (e.g., Rowley, 1998; Faulds and Varga, 1998).

The Frenchman fault bounds both the Frenchman and Sunrise Mountain blocks on the west and consists of at least two distinct strands (fig. 2). The southern strand strikes northwest, dips steeply to both the northeast and southwest, and accommodated normal dextral (our mapping) and reverse dextral motion (R.E. Anderson, personal commun., 1998). The trace of this strand cuts the southwest corner of the quadrangle. The southern strand of the Frenchman fault may bifurcate directly west of the quadrangle. One strand appears to continue to the northwest into the Las Vegas basin, as indicated by northwest-trending isostatic gravity and aeromagnetic discontinuities, and may ultimately link northwestward with the Las Vegas Valley shear zone (Langenheim and others, 1998; in press). A second branch merges northward with the central strand of the Frenchman fault. This central strand surfaces directly west of the quadrangle (Matti and others, 1993) and extends northward into the northwest corner of the quadrangle. It strikes north-northwest to north-northeast, dips 35° to 50° westward, and primarily accommodated normal slip, as evidenced by Riedel shears and other kinematic indicators. This strand is best exposed in road cuts on the eastern fringe of Las Vegas (figs. 2 and 3) and along the northwest flank of Sunrise Mountain. It is important to note that the trace of the central strand of the Frenchman fault and the major basin-bounding fault imaged by gravity data may not be the same. For example, the trace of the central strand of the fault lies about 2 km east of the steeply dipping fault that forms the east margin of the Las Vegas basin (Langenheim, written commun., 1999).

Both the Munitions and Boulevard fault zones may also be related to the Frenchman fault. The Munitions fault clearly splays from the Frenchman fault (figs. 2 and 3). The Frenchman fault has much less displacement north of its juncture with the Munitions fault, suggesting that much of its displacement is transferred to the Munitions fault. Prior to >45° clockwise rotation of the Sunrise Mountain block, the Munitions fault presumably had a more northerly strike, implying that much of the fault initially accommodated primarily normal slip similar to the central strand of the Frenchman fault. Interestingly, the Las Vegas basin deepens significantly southward (fig. 5) near the intersection of the Frenchman and Boulevard fault zones, suggesting that some slip on the Frenchman fault may also be transferred to the Boulevard fault zone. It may also be noteworthy that the Munitions fault and the southern and central strands of the Frenchman fault collectively form a surface that is convex to the west, mimicking the pattern of the Dry Wash fault to the east (fig. 2). In the case of the Frenchman and Munitions faults, the apex of the footwall corresponds to the topographically and structurally elevated summit of Frenchman Mountain.

Moreover, the apparent kinematic linkages between northerly striking normal, northwest-striking dextral, and east-northeast-striking sinistral faults suggest that all such faults were active pene-contemporaneously in a complex three-dimensional strain field that accommodated both north-south shortening and northwest-southeast extension (e.g., Anderson and Barnhard, 1993). For example, if the Frenchman fault is kinematically linked to the Munitions and Boulevard faults, which accommodated clockwise rotation of the Sunrise Mountain block induced by dextral motion on the Las Vegas Valley shear zone, it seems likely that movement on the Las Vegas Valley shear zone, Frenchman fault, and Munitions and Boulevard faults occurred more or less simultaneously.

The Frenchman fault cuts late Pleistocene stream-terrace and fan-terrace alluvium as well as intermittently active alluvium of probable Holocene age. Although scarps in alluvium of modern washes were not observed along the Frenchman fault, it does pose a potential seismic hazard to the Las Vegas Valley. More detailed studies are necessary to determine the age of most recent movement, frequency of major earthquakes, and magnitude of past events on the fault. Studies of seismic hazards in this region must consider the possibility of coeval normal, strike-slip, and possibly reverse motion on individual faults or closely related groups of faults.

Deformational History

As noted by others (e.g., Anderson and Barnhard, 1993; Duebendorfer and Simpson, 1994), a complex three-dimensional strain field has characterized the Cenozoic evolution of the Lake Mead region. Reviewing all models and timing relations within the region is beyond the scope of this report. We therefore focus on what can be gleaned from critical structural relations within the Frenchman Mountain Quadrangle.

As discussed above, the apparent continuity of several individual faults or groups of faults suggests that normal slip on north- to north-northeast-striking faults, sinistral movement on east-northeast-striking faults, and dextral motion on northwest-striking faults were all roughly contemporaneous. Clockwise rotation of the Sunrise Mountain block probably coincided with activity on these three sets of faults, as some of the east-northeast-striking faults (e.g., Boulevard fault zone) appear to have accommodated differential rotation between the Sunrise and Frenchman Mountain blocks. These relations further suggest that northwest-southeast extension accommodated by the normal faulting and strike-slip faulting overlapped in time with north-south shortening accommodated by the east-trending fold belt, clockwise rotation of the Sunrise Mountain block, and strike-slip faulting. A major question is when did such deformation occur.

The slightly greater tilt magnitudes in the Rainbow Gardens Member of the Horse Spring Formation compared to that within the younger Tertiary units (compare fig. 4a to 4c) suggest that minor east-tilting and presumably east-west extension began during deposition of the Thumb Member of the Horse Spring Formation. Age constraints on the Thumb Member as well as relations to the east in the Lake Mead region (e.g., Beard, 1996) indicate an onset of extension at about 16 Ma.

However, the most significant episode of deformation in the Frenchman Mountain area probably postdated deposition of at least the 11.9- to 11.5-Ma lower part of the red sandstone unit, which clearly experienced the bulk of tilting within both the Boulder and Nellis basins, as well as significant folding within the east-trending fold belt in the western Lake Mead region. For example, the 11.6-Ma tuff intercalated within the red sandstone unit in the Nellis basin is tilted about 60°. In contrast, the Muddy Creek Formation is generally gently tilted (<10°). General similarities in the red sandstone unit sections in the northwest and eastern parts of the quadrangle suggest that a continuous basin may have extended across the Frenchman and Sunrise Mountain blocks at least until about 11 Ma (i.e., the Nellis and Boulder basins were originally part of the same basin). The 6.0 Ma age from an essentially flat-lying tuff directly below the limestone member of the Muddy Creek Formation indicates that most of the tilting had ceased by 6.0 Ma.

The kinematic linkages between the normal and strike-slip faults suggest that northwest-southeast extension and north-south shortening also occurred between 11.6 and 6.0 Ma. Thus, most of the east-tilting of the Boulder and Nellis basins, east-trending folding within the western Lake Mead region, rotation of the Sunrise Mountain block, and movement on the Frenchman Mountain fault and Las Vegas Valley shear zone may have been contemporaneous. It is possible that northwest-southeast extension and north-south shortening may have been somewhat episodic, perhaps induced by perturbations in the regional stress field (e.g., Angelier and others, 1985). For example, north-south shortening associated with pulses of movement on the Las Vegas Valley shear zone may have alternated with episodes dominated by northwest-southeast extension. Thus, rotation of the Sunrise Mountain block may have been accompanied by periodic extension, which generated new sets of northerly striking normal faults as older sets were rotated into positions unfavorable for accommodating regional extension. This may explain the complex multiple fault sets in the Sunrise Mountain block. Alternatively, some of the northwest-southeast extension may have been driven by north-south shortening, as blocks such as Frenchman and Sunrise Mountain were extruded laterally in the wake of a southward advancing block on the north side of the Las Vegas Valley shear zone and Lake Mead fault system (e.g., Anderson and others, 1994), similar in some respects to grand-scale extrusion or indentor tectonics (e.g., Molnar and Tapponier, 1975; Tapponier and others, 1982).

ECONOMIC GEOLOGY

Gypsum

The PABCO Gypsum Mine, which has also been called the Apex Mine, is located in the northeast part of the Frenchman Mountain Quadrangle and extends to the east into the Government Wash Quadrangle. It is one of four active gypsum mines in Nevada and has been the site of continuous mining since 1959 and sporadic earlier activity. It is owned and operated by Pacific Coast Building Products, Inc., which operates a wallboard plant near the mine site. Production from the mine has ranged between 400,000 and 600,000 tons annually since 1989; however, the ore contains about 80% gypsum, and production figures for beneficiated gypsum (92% or more gypsum by weight) must be adjusted downward to account for this factor. Exploratory drilling indicates that the thickness of the gypsum exceeds 35 m in the vicinity of the mine (L. Ordway, PABCO Mine Manager, personal commun., 1997). The gypsum is generally covered by less than 2 m (6 feet) of sandy overburden and occurs in an area of 13 km^2 (5 square miles) (Papke, 1987). On this basis, mineable reserves are quite large, probably more than 400 million tons.

The ore mined by PABCO is generally friable and porous, mostly consisting of fine intergrown gypsum crystals with various amounts of admixed clay and sand. In the open pit, it is white to grayish orange, depending on the gypsum content, but some light-greenish-gray sandy material was noted high on the eastern pit wall. Locally it contains layers of fine-grained, sugary, compact gypsum and in places relatively large selenite crystals or masses of crystals are present (Papke, 1987). Selenite crystals as much as 20 cm long were noted during our examination of the deposit. Steeply dipping northwest-striking faults that probably have only minor amounts of offset are exposed in the pit. Outcrops are commonly efflorescent gypsite. The PABCO Mine has been excavated into a gently south-dipping plateau capped by the gypsum, which is slightly more resistant than the underlying characteristic redbeds of the Muddy Creek Formation (unit Tm).

Gypsum has been mined and prospected for at several other sites in the Frenchman Mountain Quadrangle in the past, and gypsum prospect pits are common. The Pennsylvanian-Permian Pakoon Formation is the oldest unit that has been prospected for gypsum. Other units that contain beds of relatively pure gypsum are the Toroweap, Kaibab, Moenkopi, and Horse Spring Formations. At the White Eagle Mine near the southern edge of the quadrangle, gypsum was mined from a series of narrow pits between 1938 and 1956 by PABCO (Papke, 1987). Here, the gypsum is white to pale greenish yellow, may be as much as 35 m thick, contains some silty interbeds, and is in the lower redbed unit of the Moenkopi Formation. Gypsum was mined by PABCO from the Thumb Member of the Horse Spring Formation about 1 km east of and 5 km northeast of the White Eagle Mine in the 1950s at the Rainbow Gardens and Rainbow Gardens North properties, respectively (Papke, 1987). The latter property was also the

site of small-scale mining by Nevada Gypsum and Mining in the late 1980s (Castor, 1989). In the Rainbow Gardens North pit, the gypsum sequence is about 150 m wide and is thought to be repeated by faulting or folding.

Limestone

Relatively pure limestone suitable for use in portland cement and possibly high-calcium lime occurs in the Frenchman Mountain Quadrangle but has not been mined. At Apex, about 12 km north of the quadrangle, large amounts of high-calcium lime are produced annually from pure micritic limestone in the upper part of the Crystal Pass Member of the Sultan Formation. Similar rock is present in the unit in the Frenchman Mountain Quadrangle, but access is poor and economic exploitation is unlikely. Lacustrine algal limestone that we map in the Muddy Creek Formation in the northeast part of the quadrangle (unit Tml) may have more potential because of its location and easily mined geometry. This limestone unit is as much as 50 m thick in places, has nearly flat-lying bedding, and is exposed over a large area (about 25 km^2) in the Frenchman Mountain Quadrangle and in the Apex Quadrangle to the north. However, the chemistry of this limestone has not been characterized and its suitability for commercial use is unknown.

Lithium clay

During the 1970s, relatively high growth in lithium consumption, driven by new uses and coupled with apprehension about future availability for the production of deuterium, prompted significant lithium exploration by the U.S. Geological Survey. Exploration mainly focused on modern playa deposits in Nevada and California, but deposits of older lithium-rich lacustrine sedimentary rocks were also studied. The upper part of the Lovell Wash Member of the Horse Spring Formation in the Frenchman Mountain Quadrangle was found to contain a 40-m-thick section with average lithium content of 1,000 ppm (Brenner-Tourtelot, 1979), and the presence of hectorite, a trioctahedral lithium-rich clay mineral, was suspected.

Samples collected from the Lovell Wash Member in both the Frenchman Mountain and Henderson Quadrangles were found to have Li contents as high as 900 ppm on the basis of atomic absorption analyses at the Nevada Bureau of Mines and Geology Analytical Laboratory. In addition, XRD analysis indicates that clay separates from one of these samples contains trioctahedral clay. On this basis, hectorite is considered to have been positively identified in the area.

Silica

According to Longwell and others (1965), the Sunrise Mountain silica deposit, which is probably in the Aztec Sandstone, lies in the Frenchman Mountain Quadrangle. No production has been recorded from this deposit and its location is poorly constrained. In addition, we found no evidence of mining in the Aztec Sandstone exposures in the quadrangle. Analyses given in Hewett and others (1936) for Aztec Sandstone from a silica prospect in the Muddy Mountains indicate that SiO_2 content, at about 94%, is too low to meet specifications for glass sand. On this basis, potential for silica production in the Frenchman Mountain Quadrangle is thought to be low.

ACKNOWLEDGMENTS

C.D. Henry performed $^{40}Ar/^{39}Ar$ dating on samples collected during our mapping, and we acknowledge him for most of the information in the Geochronology section. In addition, we thank him for preparation of figure 1 and for assistance in the compilation of table 2. The $^{40}Ar/^{39}Ar$ dating was performed at laboratories at the New Mexico Institute of Technology and University of Nevada, Las Vegas, and we thank W.C. McIntosh, Lisa Peters, and T.L. Spell for providing access to, and their assistance at, these facilities. M.E. Perkins is acknowledged for providing two ages for ash beds using geochemical correlation techniques. This map benefited from rigorous reviews by R.E. Anderson, R.G. Bohannon, and A.R. Ramelli. Discussions with L.S. Beard, Vicki Langenheim, E.M. Duebendorfer, and E.I. Smith were also helpful. Colonel S.A. Arrington, Captain R.J. Brown, and Sergeant Votaw of the U.S. Air Force are thanked for providing access to Nellis Air Force Base.

Partial funding for this research was provided by the STATEMAP Program of the U.S. Geological Survey (grant numbers 1434-94-A-1242 and 1434-HQ-97-AG-01766). In addition, the Las Vegas office of the U.S. Geological Survey is acknowledged for providing vehicular support during part of this study, for which we thank Gary Dixon. The U.S. National Park Service at the Lake Mead National Recreation Area kindly provided housing at Callville Bay during mapping of the north half of the quadrangle, for which we thank Kent Turner and Darlene Carnes. The views and conclusions contained in this document are, however, those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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