Text and references for Nevada Bureau of Mines and Geology Map 146

GEOLOGY OF THE FRASER FLAT QUADRANGLE and the WEST HALF OF THE MOSES ROCK QUADRANGLE

WASHOE COUNTY, NEVADA

by

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INTRODUCTION

The mapped area, which contains about 220 km^2, is located about 30 km northeast of Reno (fig. 1). It includes a significant part of Warm Springs Valley (locally called Palomino Valley) and the adjacent mountain ranges. The mountainous area east of Warm Springs Valley is called the Pah Rah Range, and the name is also applied to the range along the southwest part of the valley. Parts of Hungry Ridge, Warm Springs Mountain, and Dogskin Mountain bound the western part of the map area (fig. 2). The southeast tip of the Virginia Mountains makes up the northern edge of the Fraser Flat Quadrangle. Most of the map area is private land, particularly in Warm Springs Valley and the Pah Rah Range; however, about 30% of the map area along the western and northern edge is federal land under the aegis of the U.S. Bureau of Land Management. A small part of the Pyramid Lake Indian Reservation is included in the northeast corner of the map area. Although the area is considered rural, it has seen considerable development over the last 20 years as new houses have been built on parcels of 40 acres or more. Many area residents work in the Reno-Sparks urban area. The area is crossed by State Route 445 (the Pyramid Lake Highway) as well as many graded gravel roads that provide access to homes.

Previous geologic mapping in the area includes a 1:250,000-scale geologic map of Washoe County (Bonham and Papke, 1969) and a somewhat more modern map of similar scale (Green and others, 1991). A generalized geologic map of the Warm Springs Valley area was prepared as part of a gravity study (Gimlett, 1967), and parts of the area have been mapped in association with a dissertation or thesis (Wallace, 1975; Fontaine, 1997). Figure 1 shows published geologic mapping at 1:24,000-scale in the surrounding area.

The geologic map of the Fraser Flat Quadrangle and western half of the Moses Rock Quadrangle was prepared using field mapping techniques, aerial photographs (mainly color aerial photographs at a scale of approximately 1:19,000 from Spencer B. Gross, Inc. of Reno) and topographic maps. Compilation of line and point data was done on scale-stable, 1:24,000 topographic and orthophoto (U.S. Geological Survey) maps. Preliminary versions of the geologic maps for these quadrangles were released as open-file reports (Castor and others, 1999; Garside and others, 1999).

Mineral contents reported for igneous rocks were estimated visually from thin sections and rock slabs (which were stained for potassium feldspar). Igneous rock names are based on the IUGS classification (e.g., Le Maitre, 1989). All K-Ar ages reported have been calculated using the new decay constants and isotopic abundances given by the International Union of Geological Sciences Subcommission on Geochronology (Steiger and Jager, 1977); if the age is recalculated using the originally reported data, this is noted by the word "recalculated." Unit thicknesses were estimated from the geologic map and topographic base map. Strikes and dips for most areas were averaged or rounded to the nearest 5º unless accuracy was better than that. Map-scale photolinear features were mapped in part by examination of low sun-angle photographs.

^{40}Ar/^{39}Ar Dating

^{40}Ar/^{39}Ar analyses were done on sanidine, hornblende, plagioclase or biotite phenocrysts, on whole-rock samples,

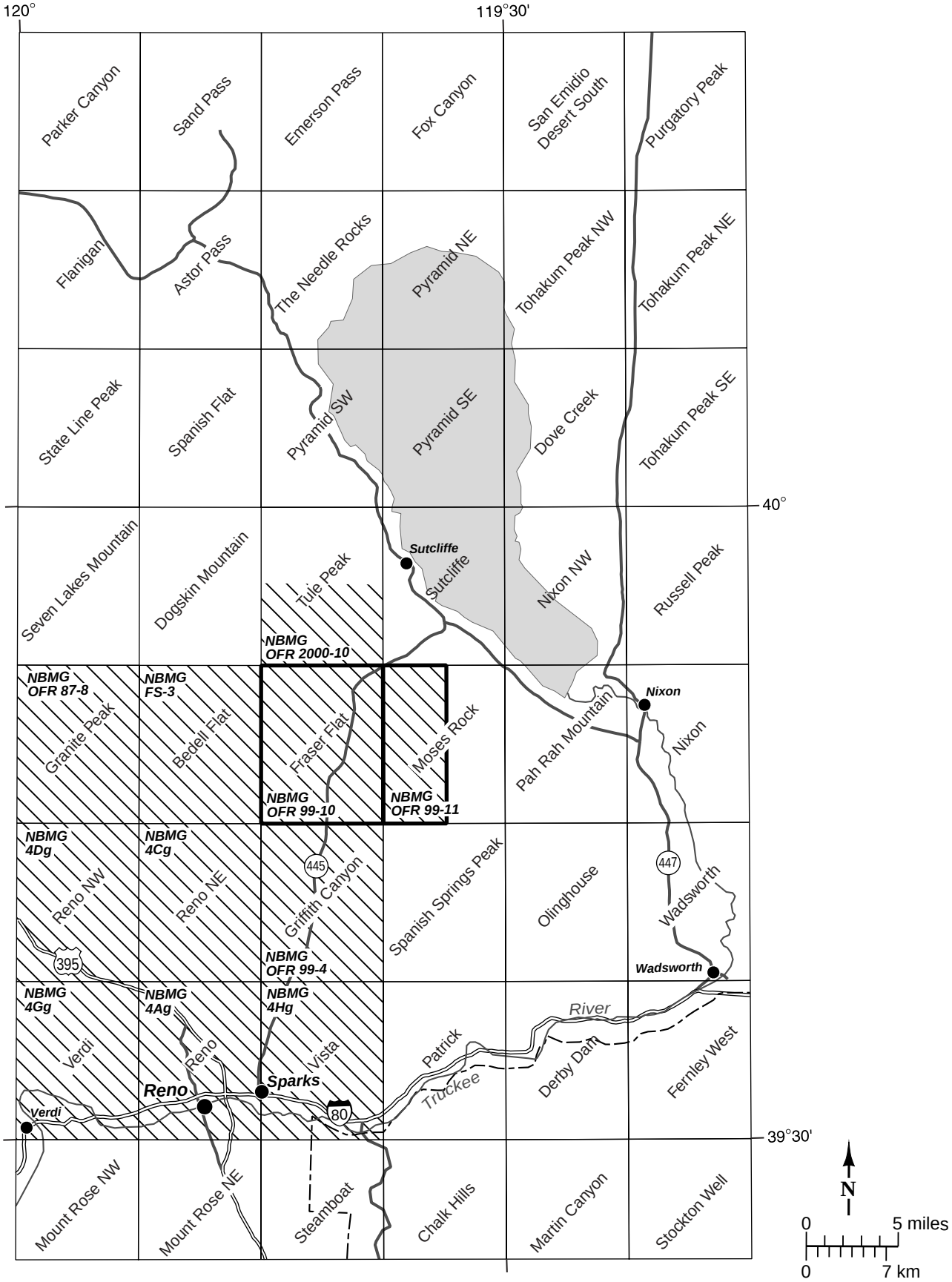

Figure 1. Regional map showing location of the Fraser Flat and Moses Rock Quadrangles and nearby published 1:24,000-scale geologic maps. Two-letter abbreviations for quadrangle names are used in tables 1 and 2.

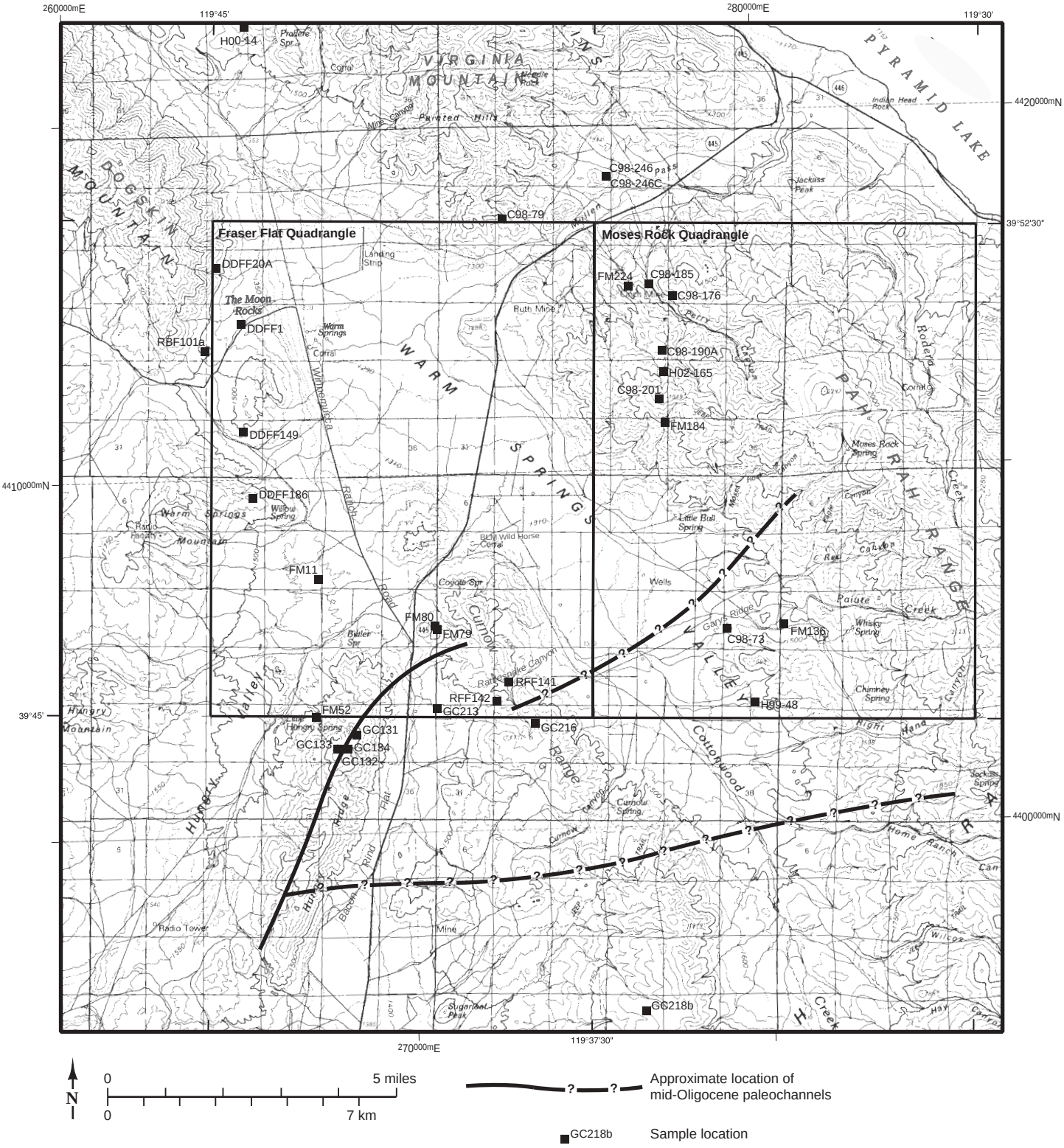

Figure 2. Map showing the location of the Fraser Flat and Moses Rock Quadrangles, sample sites, proposed Oligocene paleochannels, and cultural features mentioned in the text. Topographic base map modified from the USGS topographic map of the Reno 30x60-minute Quadrangle.

or on sericite after biotite (table 1). Phenocrysts were concentrated to >99% purity using magnetic and density separation, leaching with dilute HF (feldspars only), and hand picking. Samples were irradiated at Texas A&M University and analyzed at the Nevada Isotope Geochronology Laboratory (methodology discussed in Justet and Spell, 2001) or the New Mexico Geochronology Research Laboratory (methodology in McIntosh and Chamberlin, 1994) by C.D. Henry (NBMG). Fish Canyon sanidine was used as a neutron fluence monitor. New Mexico uses an age of 27.84 Ma, relative to an age of 520.4 Ma on hornblende MMhb-1 (Cebula and others, 1986; Samson and Alexander, 1987), whereas Nevada uses 27.90 Ma based on average K-Ar ages reported by Steven and others (1967) and Cebula and others (1986). For this report, all analyses were normalized to 27.84 Ma. Individual plagioclase and sanidine grains were completely melted using a CO_2 laser operating at 5 watts. Hornblende and whole-rock samples were heated incrementally in a low-blank, resistance furnace.

Chemical Correlation Dating

A tephra sample from a Quaternary alluvial fan (table 1) was dated by M.E. Perkins, Dept. of Geology and Geophysics, University of Utah, using chemical correlation techniques described in Perkins and others (1998). The age is based on preliminary correlation with Summer Lake tephra NN (Davis, 1985).

Rock Analysis

Chemical analyses of rock samples (table 2) were performed by Dianne Johnson at the Geoanalytical Laboratory, Washington State University and at NBMG. The XRF procedures used to analyze 14 samples (table 2) at Washington State are described in Johnson and others (1999). The analytical techniques for the four samples (table 2) analyzed by the Nevada Bureau of Mines and Geology Analytical Laboratory are described in the following paragraph (P. Lechler, written commun., 1998).

For samples analyzed at NBMG, major oxides were determined using 200 mg of sample pulp (nominally 98% minus 200 mesh). After dissolution with 6 mL of hydrofluoric acid and 1 mL of aqua regia in a sealed Teflon reaction vessel (175°C for 1 hour) 100 mL of boric acid solution (44 g/L) were added and the mixture was diluted to 200 mL. The major oxides were determined by atomic absorption spectroscopy by comparison with U.S. Geological Survey standard reference materials BCR-1 (basalt), AGV-1 (andesite), and RGM-1 rhyolite (modified from Hutchison, 1974). Quantification of P_2O_5 was based on the colorimetric method of Shapiro (1975) and loss-on-ignition was measured gravimetrically as described by Lechler and Desilets (1987). Trace elements were determined by x-ray fluorescence on pressed pellets (3 g sample and 1.125 g Chemplex binder; 30,000 psi for 2 minutes). A Philips PW1404 sequential, wavelength-dispersive x-ray fluorescence spectrometer was employed after calibration with 12 U.S. Geological Survey standard rocks. Mass absorption differences were corrected from peak height changes induced in the rhodium tube Compton peak.

MESOZOIC ROCKS

Metavolcanic and Metasedimentary Rocks

The oldest rocks in the map area are metavolcanic and metasedimentary units that are found as small pendants in the Cretaceous granitic plutons. These rocks are apparently the equivalent of rocks in more extensive roof pendants of the Reno/Carson City area (Garside, 1998). In those areas, intermediate composition metavolcanic rocks are commonly correlated with the Peavine sequence and feldspathic sandstone and limestone with the Gardnerville Formation. These metamorphic rocks crop out east of Willow Spring in the Fraser Flat Quadrangle and north of Right Hand Canyon at the southern edge of the Moses Rock Quadrangle. They have been metamorphosed to hornfels or schist, which is somewhat more intense metamorphism than that seen in larger pendants of the Reno/Carson City area, except near their margins.

Cretaceous Plutonic Rocks

With the exception of small pendants of metamorphic rocks, the pre-Tertiary rocks of the map area consist of plutonic rocks that range from granite to diorite in composition, and comprise the eastern edge of the Sierra Nevada batholith. Isotopic dating of the granitoid rocks in the region indicates that they are all Cretaceous, ranging in age from about 93 to <85 Ma (Garside and Nials, 1999; Garside and others, 1992). In western Nevada, Jurassic plutons of the Sierra Nevada batholith seem to be restricted to the area east and south of Carson City (see John and others, 1993). Our interpretations of the age relationships of the plutonic units are illustrated in the correlation column on the map. For a number of the units it is difficult to determine relative ages, because the intrusive masses either do not exhibit recognizable field contact features or compositionally different units are not seen in contact because of overlying Tertiary and Quaternary units (which make up about 85% of the map area). Age criteria are further described in some unit descriptions.

The granitoid rocks in the map area are fine- to coarse-grained, commonly equigranular rocks. Based on chemical analyses of samples from four map units (table 2) and other analyses from the Griffith Canyon Quadrangle to the south (Garside and Nials, 1999), the rocks are petrochemically similar to other Cretaceous granitic rocks of the Reno 1x2-degree Quadrangle (John, 1992; John and others, 1993). John and others (1993) reported that in contrast to the Jurassic rocks of the southwestern Reno 1x2-degree Quadrangle, the Cretaceous granitoids are richer in silica, have notably higher potassium and zirconium contents, and generally have lower aluminum content.

Table 1. $^{40}Ar/^{39}Ar$ **and chemical correlation ages, Fraser Flat and Moses Rock Quadrangles and vicinity. FF, Fraser Flat Quadrangle; GC, Griffith Canyon Quadrangle; MR, Moses Rock Quadrangle: SS, Spanish Springs Peak Quadrangle: TP, Tule Peak Quadrangle.**

Sample No.	Rock Type	Quad	Map Unit	N. Latitude	W. Longitude	Mineral	Age Method	n* or $\%^{39}Ar$	Age (Ma)	±1σ
Quaternary Alluvium										
Warm Springs Valley										
F02-044	Tephra bed in alluvium	FF	Qfdi				chem. correl.		0.23	0.05
Mid-Late Miocene to Present Mafic-Bimodal Volcanism										
Spanish Springs and Warm Springs Valleys										
H99-47	Basaltic andesite lava, Warm Springs Valley	SS		39° 41.92'	119° 33.66'	whole rock	isochron	all	9.12	0.66
GC218b	Basaltic andesite lava, Spanish Springs Pk	SS		39° 40.57'	119° 36.42'	whole rock	plateau	50.7	11.12	0.06
Pyramid Sequence										
C98-246	Dacitic tuff of Mullen Pass	TP	Tmu	39° 53.2'	119° 37.25'	hornblende	plateau	98.3	13.77	0.15
H00-14	Basaltic andesite, Tule Peak Quad	TP	Tba	39° 55.51'	119° 44.38'	whole rock	isochron	8.0	13.62	0.12
Miocene Intermediate Volcanism										
Northern Spanish Springs Valley										
FM52	Hornblende andesite flow(?)	FF	Tal	39° 45.01'	119° 42.90'	plagioclase	plateau	71.6	20.85	0.21
FM80	Hornblende andesite dike	FF	Tha	39° 46.39'	119° 40.62'	hornblende	plateau	90.0	20.69	0.25
GC213	Hornblende andesite dike	FF	Tha	39° 45.14'	119° 40.53'	hornblende	plateau	90.4	20.82	0.19
Pyramid District and Warm Springs Valley										
H99-48	Ash bed, Warm Springs Valley	MR	Ts	39° 45.26'	119° 34.29'	hornblende	plateau	82.1	8.75	0.15
C98-190A	Hornblende andesite dike	MR	Ta	39° 50.55'	119° 36.18'	hornblende	plateau	89.6	22.33	0.26
C98-201	Hornblende andesite dike	MR		39° 49.83'	119° 36.18'	hornblende	plateau	89.5	22.54	0.21
FM224	Pyramid district alteration	MR		39° 51.54'	119° 36.76'	sericite	isochron		22.60	0.11
Oligocene Ash-Flow Tuff Volcanism										
Pyramid District and Vicinity										
Perry Canyon caldera										
C98-185	tuff of Perry Canyon	MR	Tpu	39° 51.6'	119° 36.43'	hornblende	plateau	88.0	23.23	0.26
C98-79	low-silica rhyolite intrusion	TP	Tri	39° 52.55'	119° 39.28'	sanidine	plateau	82.5	23.51	0.08
" "	" "	" "	" "	" "	" "	biotite	integrated age	100	23.54	0.26
H02-165	tuff of Painted Hills	MR	Tcs(Tph)*	39° 50.21'	119° 36.08'	sanidine	single crystal		24.68	0.07
Northern Spanish Springs Valley										
C98-73	tuff of Painted Hills	MR	Tph	39° 46.35'	119° 34.85'	sanidine	single crystal	15	24.73	0.06
GC133	tuff of Chimney Spring	GC	Tcs	39° 44.5'	119° 42.5'	sanidine	single crystal	16	24.90	0.07
GC132	Nine Hill Tuff	GC	Tnh	39° 44.5'	119° 42.4'	sanidine	single crystal	14	25.07	0.07
GC134	tuff of Coyote Spring	GC	Tcys(Tdm)*	39° 44.5'	119° 42.3'	plagioclase	plateau	82.2	29.13	0.17
GC131	tuff of Whisky Spring	GC	Tws	39° 44.7'	119° 42.1'	sanidine	single crystal	15	29.72	0.10
FF142	unnamed tuff	FF	Tpn	39° 45.25'	119° 39.38'	sanidine	single crystal	17	31.08	0.07
FF141	tuff of Rattlesnake Canyon	FF	Tpn	39° 45.53'	119° 39.13'	sanidine	single crystal	11	30.88	0.09
GC216	tuff of Axehandle Canyon	GC	Tpn	39° 44.91'	119° 38.59'	sanidine	single crystal	15	30.96	0.08

* = number of grains analyzed; $\%^{39}Ar$ = percent ^{39}Ar in plateau; monitor age = 27.84 Ma, Fish Canyon sanidine

$I_b = 4.963 \times 10^{-10}\ yr^{-1}$; $I_{e+e'} = 0.581 \times 10^{-10}\ yr^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$

Analyses by C.D. Henry at New Mexico Geochronological Research Laboratory and Nevada Isotope Geochronology Laboratory.

Unit names in parantheses are names of units as described in the descriptions of map units for this publication

*this pub (source), Tph (Tcs), Tdm (Tcys)

Table 2. Chemical analyses of igneous rocks from the Fraser Flat and Moses Rock Quadrangles and vicinity. FeO*, total Fe calculated as FeO; if originally reported as Fe_2O_3, recalculated as FeO. Ten major oxide values normalized to 100% after recalculation of total Fe to FeO. Total is sum of 10 major oxides before normalization; LOI (loss on ignition), if reported, is included in Total** (and must be subtracted from Total** to be comparable to analyses without LOI values). WSU, Washington State University GeoAnalytical Laboratory; NBMG, Nevada Bureau of Mines and Geology Analytical Laboratory. FF, Fraser Flat Quadrangle; GC, Griffith Canyon Quadrangle; MR, Moses Rock Quadrangle: SS, Spanish Springs Peak Quadrangle: TP, Tule Peak Quadrangle.**

Sample	**C98-73**	**C98-79**	**C98-176**	**C98-185**	**C98-201**	**C98-246C**	**FM11**	**FM79**	**FM136**	**FM184**	**DDFF1**	**DDFF20A**	**DDFF149**	**DDFF186**	**RBF101a**	**RFF141**	**RFF142**	**GC213**
Map symbol	Tph	Tri	Tob	Tpu	Ta	Tmu	Ts	Tnh	Tpn	Tfd	Kgr	Kqmd	Kqm	Kf	Tws	Tpn	Tpn	Tha
Rock name	rhyo ignb	rhyolite	basalt	dacite tuff	andesite	dacite tuff	rhyolite tuff	ash-flow tuff	dacite ash-flow	microdiorite	granite	granodiorite	qtz monzonite	qtz monzonite	rhyolite tuff	rhyolite tuff	rhyolite tuff	andesite
Quad	MR	TP	MR	MR	MR	TP	FF	FF	MR	MR	FF	FF	FF	FF	BF	FF	FF	GC
N. Lat	39°46.35'	39°52.55'	39°51.38'	39°51.6'	39°49.83'	39°53.2'	39°47.1'	39°46.38'	39°46.43'	39°49.45'	39°50.95'	39°51.77'	39°49.3'	39°48.3'	39°50.53'	39°45.53'	39°45.25'	39°45.14'
W. Long	119°34.85'	119°39.28'	119°35.95'	119°36.43'	119°36.18'	119°37.25'	119°42.90'	119°40.55'	119°33.73'	119°36.1'	119°44.43'	119°44.9'	119°44.37'	119°44.17'	119°45.13'	119°39.13'	119°39.38'	119°40.53'
Lab	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	WSU	NBMG	NBMG	NBMG	NBMG
SiO_2	71.70	70.21	51.20	65.44	57.96	67.73	71.54	75.37	66.21	65.84	74.55	61.90	70.88	73.05	75.01	74.73	72.91	60.08
TiO_2	0.303	0.434	1.060	0.554	0.817	0.593	0.190	0.182	0.554	0.492	0.132	0.805	0.312	0.200	0.11	0.16	0.41	0.69
Al_2O_3	14.78	15.15	16.36	16.82	18.35	16.27	17.03	14.18	16.91	17.33	14.53	17.12	15.43	15.10	14.45	14.18	14.04	18.06
FeO*	2.01	2.76	8.50	3.84	6.75	2.63	1.41	1.09	3.56	3.38	0.95	5.39	2.14	1.11	0.73	1.62	2.06	5.29
MnO	0.037	0.035	0.158	0.089	0.182	0.078	0.098	0.086	0.024	0.055	0.036	0.092	0.043	0.023	0.05	0.10	0.03	0.06
MgO	0.40	1.06	9.69	1.68	3.71	0.76	0.63	0.19	0.59	1.30	0.15	2.72	0.77	0.30	0.06	0.02	0.28	3.04
CaO	1.36	2.43	8.32	4.08	6.22	2.39	2.99	0.67	1.37	4.25	1.32	5.35	2.62	1.22	1.03	1.03	1.43	6.35
Na_2O	3.43	3.73	3.18	4.05	3.61	4.43	3.18	3.38	2.79	4.46	4.12	3.52	3.90	4.11	3.97	4.27	3.24	4.23
K_2O	5.90	4.04	1.16	3.25	2.19	4.95	2.86	4.84	7.81	2.73	4.18	2.96	3.82	4.82	4.56	3.85	5.48	1.91
P_2O_5	0.094	0.149	0.373	0.199	0.211	0.164	0.073	0.013	0.175	0.182	0.036	0.144	0.088	0.067	0.04	0.04	0.12	0.29
LOI															0.35	4.57	3.36	2.27
Total**	98.47	99.09	98.95	98.64	97.94	98.17	95.60	97.02	98.56	99.38	99.51	99.39	99.22	99.59	99.18	99.11	99.14	99.28
Sc	6	11	23	11	19	12	2	7	8	14	4	12	6	4	<2	<2	15	21
V	26	59	204	85	143	54	1	3	47	68	8	137	42	11	3	12	7	116
Cr	0	8	308	11	15	2	2	0	4	9	4	16	6	0	36	14	14	68
Ni	4	4	172	7	3	3	6	6	2	2	6	11	5	2	9	5	7	13
Cu	1	5	72	15	26	3	6	0	3	15	2	39	16	4	<2	<2	<2	20
Zn	59	51	93	63	172	70	43	63	51	62	13	72	36	22	29	56	45	85
Ga	18	18	15	16	19	16	15	17	21	20	14	18	17	18	14	13	13	16
Rb	145	107	13	83	59	93	41	156	175	69	90	125	107	177	91	206	203	33
Sr	218	322	737	554	533	294	547	97	284	631	245	422	359	265	140	119	82	750
Y	20	13	16	14	20	30	13	19	16	13	14	13	10	7	13	18	20	15
Zr	222	154	88	143	131	339	157	190	208	137	79	144	98	104	50	167	163	152
Nb	17.9	10.9	6.4	10.4	8.1	18.1	8.8	14.4	12.2	5.9	6.1	5.8	8.1	6.9	9	10	13	10
Ba	1249	1242	512	1087	874	1468	984	687	1422	1276	1872	800	773	1062	915	706	1820	1160
La	46	34	21	29	19	18	23	50	34	13	24	23	23	21				
Ce	87	50	25	47	37	70	49	85	56	42	32	20	28	39				
Pb	21	21	7	17	38	20	14	36	20	16	16	8	13	38	17	26	18	9
Th	17	12	0	11	5	6	4	17	14	3	10	8	22	13	10	31	32	5

Several of the granitoid units are cut by dikes and irregular masses of aplite and aplite-pegmatite of granite composition. Some of these contain rare red garnet (e.g., in the Rattlesnake Canyon area); similar garnet is found in unit Kgr and in unmapped aplite/pegmatite dikes within it in the "Moon Rocks" area. Diorite dikes cut all pre-Tertiary units and the aplitic dikes. There is no indication that these dikes cut Tertiary rocks, but their age is uncertain; they probably belong to the same period of magmatism as the Cretaceous plutons and aplite dikes.

TERTIARY ROCKS

In the Fraser Flat and western Moses Rock Quadrangles, the Mesozoic basement is overlain by a regional Oligocene (31–24.7 Ma) silicic ash-flow tuff sequence. In the Mullen Pass area, an early Miocene caldera sequence includes intracaldera tuff and andesitic to rhyolitic intrusive rocks. This ash-flow sequence is locally overlain by a thick group of intermediate lahars or mafic lavas with minor ash flows and sedimentary rocks. The term Hartford Hill Rhyolite (now abandoned; Bingler, 1978) was used in the past for the sequence of ash-flow tuffs that lie above Mesozoic rocks and below Miocene intermediate or mafic flows. Miocene and Pliocene(?) sedimentary rocks were deposited on the older volcanic rocks in sedimentary basin areas.

Western Nevada middle to late Tertiary tectonics, magmatism, and hydrothermal mineralization are closely related to events at the western margin of the North American Plate. In the mid-Tertiary volcanism extended over much of the Great Basin (Christiansen and Yeats, 1992). This has been referred to by a number of authors as the "great ignimbrite flareup" (e.g., Best and Christiansen, 1991). After about 20 Ma in western Nevada, magmatism represents a complex interplay between a predominantly andesitic calc-alkaline magmatic arc that was a predecessor to the modern Cascade arc and bimodal basalt-rhyolite extension-related magmatism (Christiansen and Yeats, 1992). Eruption of both subduction-related andesites and extension-related basalts (plus less abundant rhyolites) continued into the Pliocene. Basaltic rocks as young as about 1 Ma are represented in western Nevada. Calc-alkaline magmatism was probably relatively continuous in this area between 20 Ma and 1 Ma. The north edge of the subducting slab (i.e., the southern terminus of the magmatic arc) which essentially cut off arc volcanism as it moved north along the transform boundary of the Pacific and North American plates stalled at about the latitude of Reno after 4 Ma (Atwater and Stock, 1998).

Tertiary Silicic Ash-Flow Tuffs from Remote Sources

The sequence of Oligocene rhyolitic ash-flow tuffs lies with angular unconformity on Mesozoic basement rocks. The erosion surface above these Jurassic(?) and Cretaceous metamorphic and plutonic rocks represents a considerable hiatus, 45 to 60 million years, during which time Mesozoic volcanic cover, developed along a magmatic arc of that age, was eroded away, leaving the underlying plutons and somewhat older pendants. The eroded material was transported west, across the area of the later-developed Sierra Nevada, to where it is found today in the Great Valley sequence of central and northern California (Miller and others, 1992). It is clear that the pre-tuff erosional surface had some relief (e.g., Bingler, 1978), and there apparently was a well-developed system of westward-flowing streams in western Nevada, which headed in a central Nevada highland (Wernicke and others, 1996; Wolfe and others, 1997; Dilek and Moores, 1999). These streams apparently flowed in broad paleocanyons and paleovalleys developed on the basement. Locally, stream deposits are preserved in the central parts of these valleys below the rhyolitic ash-flow tuffs (Davis and others, 2000). Deposition of the tuffs has preserved these paleovalleys. The source calderas of the outflow ash-flow tuffs of the map area are believed to have been to the east, in western or central Nevada (e.g., Deino, 1994; Garside and others, 2002). The tuffs filled the channels and may have covered the surrounding higher ground as well. They were thicker in the channels and thus became more strongly welded there, possibly producing slightly lower surfaces directly above the channels and allowing subsequently developed stream channels to follow the original, pre-tuff drainages rather closely.

Indications of these paleovalleys in the area northeast of Reno include: 1) remnants of Oligocene-Miocene ash-flow tuffs on eroded Cretaceous granitic terrain surrounded by areas where later Miocene andesitic flows lie directly on the basement, 2) rare cobble to boulder conglomerate (with pre-Tertiary clasts) below the oldest tuff or between tuff units, 3) considerably thickened tuff units or the oldest tuff units as remnants in paleovalleys, 4) channel-like steep or irregular tuff-basement contacts, and 5) older tuffs partly to completely cut out by inter-tuff erosion, with overlying tuffs lying on eroded (valley-wall?) remnants. Map-scale variations in thickness of ash-flow tuff units or the absence of certain units on the pre-Tertiary basement is observed on both sides of Warm Springs Valley in the southern part of the map area. Although later faulting has obscured some of these relationships, we suggest that many observed stratigraphic irregularities in the ash-flow tuff section can be explained by original deposition at least partly in paleochannels. Disconformities are locally found within the tuff section where some ash-flow tuffs pinch out below younger units, and tuffs that fill channels in older tuffs are also observed (Bingler, 1978; Deino, 1985; Hutton, 1978; Garside and Nials, 1999). However, angular unconformities between the tuffs have not been noted. Thus, there is no evidence of significant extensional faulting in this area before or during the time that the ash-flow tuffs were deposited. Based on the tuff outcrop pattern and rare pre-tuff fluvial deposits (shown on the map where they were observed), we speculate that one mid-Oligocene paleochannel continues northeast from Hungry Ridge across the Curnow Range; a continuation, possibly offset by strike-slip faulting, may be found across Warm Springs Valley, in the Moses Rock Canyon area (see fig. 2).

The oldest ash-flow tuffs in the map area are included in the pre-Nine Hills tuff sequence (Tpn). This unit contains several informal ash-flow units that have recently been identified in the region that range between 31.00 and 28.65 Ma (C.D. Henry and J.E. Faulds, personal commun., 2003). In many areas, the unit contains a number of ash-flow tuff cooling units, most of which are reddish-brown ledge-forming units that contain phenocrysts of sanidine, plagioclase, and biotite, but only rare phenocrystic quartz. In the west part of the map area, the pre-Nine Hill tuffs are overlain by a slope-forming plagioclase- and biotite-rich tuff informally called the tuff of Dogskin Mountain (Tdm), which was originally named the tuff of Coyote Spring. In the eastern part of the map area, this tuff was not distinguished during mapping, but is included in the pre-Nine Hill tuff sequence. Tuffs that are lithologically similar to the tuff of Dogskin Mountain are intercalated with ledge-forming tuffs in the eastern part of the map area, particularly in and south of Moses Rock Canyon, and we map them there as a single unit, pre-Nine Hill tuffs, undivided (Tpn). $^{40}Ar/^{39}Ar$ age determinations (table 1) on sanidine from samples near the base of the pre-Nine Hills tuff sequence are approximately 31.0 Ma and on samples from units near the top they are about 29.7 Ma. $^{40}Ar/^{39}Ar$ age determinations on plagioclase from the tuff of Dogskin Mountain (nee Coyote Spring) exposed on Hungry Ridge to the south in the Griffith Canyon Quadrangle (fig. 1) and on plagioclase and sanidine from a tuff near the top of the pre-Nine Hills sequence in the southern Tule Peak Quadrangle just north of the map area (Faulds and others, 2000) indicate that the sequence is as young as about 29 Ma. Where mapped separately, the tuff of Dogskin Mountain is as thick as 100 m; the pre-Nine Hill tuffs are probably several hundred meters thick in Moses Rock Canyon. The thickest sections probably were deposited in paleocanyons on the pre-Tertiary bedrock.

A distinctive quartz-bearing ash-flow tuff is found locally above the pre-Nine Hill tuff sequence. The quartz phenocrysts of this tuff are highly vermiculated ("wormy"). The unit, which we refer to as the tuff of Campbell Creek, is recognized at this stratigraphic position, below the Nine Hill Tuff, at a number of localities in western and west-central Nevada and adjacent California. We apply the name "tuff of Campbell Creek" to the outflow and intra-caldera facies of the rhyolite of Campbell Creek of McKee and Conrad (1987).The tuff of Campbell Creek is presumed to have its source caldera in the Desatoya Mountains of central Nevada and is correlated with the wormy-quartz tuff in this part of western Nevada (unpub. data, C.D. Henry, 2002).

The Nine Hill Tuff (Tnh) is a distinctive and widespread welded tuff unit in western Nevada that was named for exposures on Nine Hill north of Carson City (Bingler, 1978). This is a ledge-forming, sparsely porphyritic, strongly welded, commonly vapor-phase-altered ash-flow tuff that is predominantly high-silica rhyolite. Locally, the unit consists of a lower, nearly aphyric part and an upper more phenocryst-rich unit (Best and others, 1989, p. 105–107). The thickness of the Nine Hill Tuff is variable (0–130 m), presumably because it was deposited in channels or on an otherwise irregular erosion surface or because it was partly eroded before deposition of overlying ash-flow tuffs. The age of the unit is about 25 Ma (see table 1), based on $^{40}Ar/^{39}Ar$ dating at a number of localities in western Nevada (Deino, 1989; Garside and others, 2000, table 1). The source of the Nine Hill Tuff is unknown, but it is correlated with the D unit of the Bates Mountain Tuff (Best and others, 1989) an extensive unit in central Nevada, and a caldera source was probably located in west-central Nevada.

The tuff of Chimney Spring (Tcs) commonly lies above the Nine Hill. It is also a distinctive ash-flow tuff unit, containing smoky, bipyramidal quartz, glassy (locally adularescent) sanidine, and sparse plagioclase and biotite. The tuff of Chimney Spring is named for exposures in the vicinity of Chimney Spring, in the eastern Moses Rock Quadrangle. It is recognized at Seven Lakes Mountain 25 km to the northwest (Deino, 1985), near Carson City as the "crystal tuff" (Trexler, 1977), as the New Pass Tuff of central Nevada (Best and others, 1989), and as the upper unit of the tuff of Poco Canyon at its caldera source in the Stillwater Range 120 km to the east (John, 1993). The tuff of Chimney Spring is dated by $^{40}Ar/^{39}Ar$ methods at about 24.9 Ma at several nearby localities (Garside and others, 2000, table 1). A somewhat similar ash-flow tuff, herein referred to as the tuff of Painted Hills for exposures in the Painted Hills of the Tule Peak Quadrangle (see Faulds and others, 2000), is found locally above the Chimney Spring. It contains somewhat more biotite and plagioclase, and is a separate cooling unit dated at 24.73 Ma (table 1) from a sample collected at "Gary's Ridge" in the southeast part of the map area. The tuff of Painted Hills also occurs above the tuff of Chimney Spring, but was not mapped separately from it, just south of the large exposure of lower tuff of Perry Canyon, as shown by a 24.68-Ma age on sample H02-165 (table 1). The source of this tuff, which is about 0.2 Ma younger than Chimney Spring, is unknown. It is also present in the Olinghouse Quadrangle to the southeast (Garside and Bonham, 1992), and in the Tule Peak Quadrangle to the north. In the Tule Peak Quadrangle, it has been dated at 24.74 Ma (Faulds and others, 2000).

Rocks of the Perry Canyon Caldera

We propose that an area of dacite to low-silica rhyolite (~65% SiO_2) ash-flow tuff that we have informally named the tuff of Perry Canyon is in the Perry Canyon caldera, an east-west elongate volcano-tectonic structure south of Mullen Pass in the northeast part of the map area (fig. 3). The tuff, which consists of shallowly northward-dipping intracaldera ash flows largely confined to the proposed caldera, reaches a thickness of at least 600 m and has yielded an $^{40}Ar/^{39}Ar$ age of 23.23 ± 0.26 Ma on hornblende (table 1). The tuff is made up of an upper unit (Tpu) and a lower unit (Tpl), separated locally by megabreccia consisting predominantly of large clasts of andesite (Tmb). Wall rocks for the Perry Canyon caldera consist of older ash-flow tuffs. An alternate explanation for this restricted mass of relatively young ash-

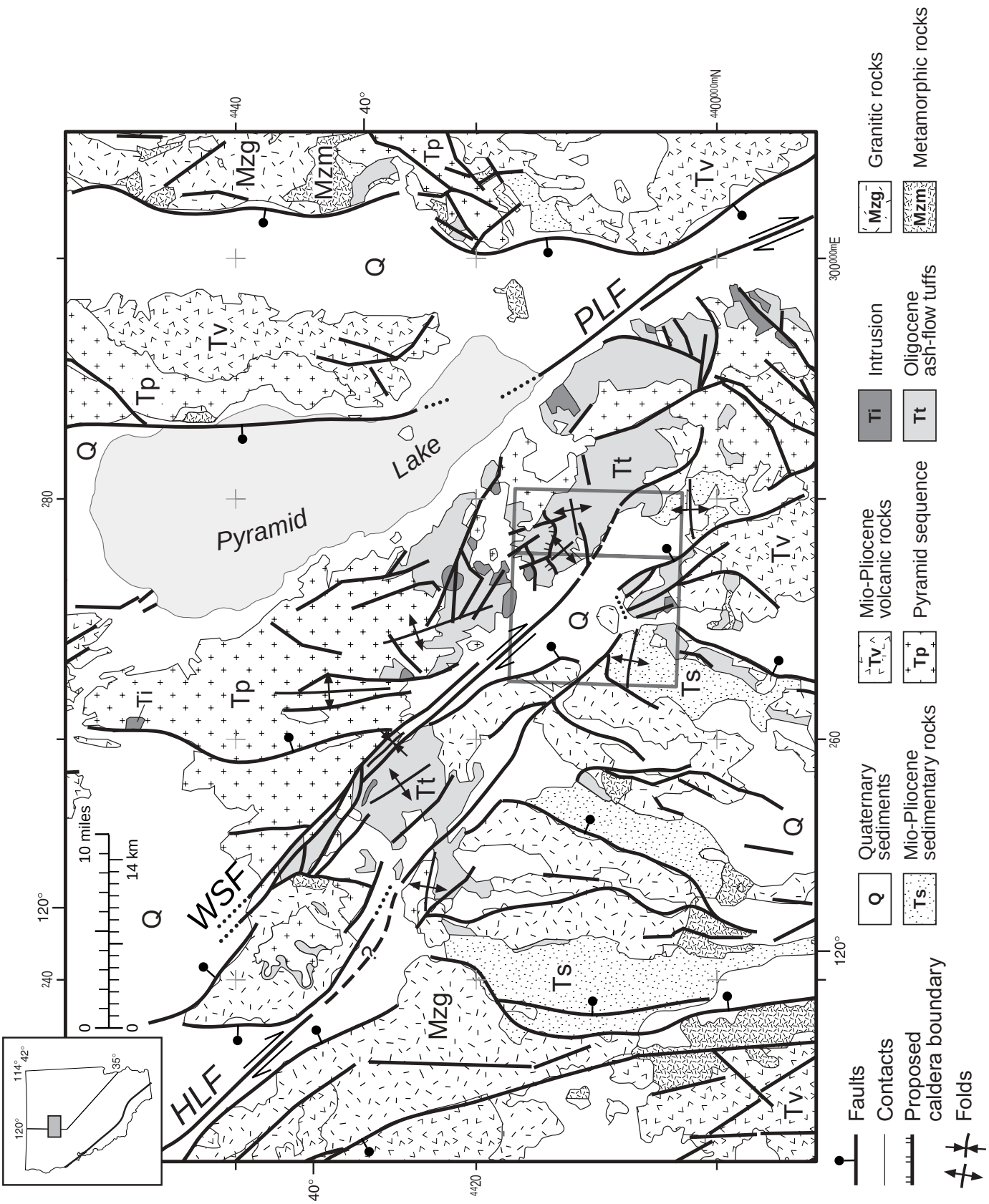

Figure 3. Generalized geologic map of the Reno-Pyramid Lake region of western Nevada showing the boundary of the Fraser Flat Quadrangle and the west half of the Moses Rock Quadrangle with major structural features. HLF, Honey Lake-Bedell Flat fault zone; PLF, Pyramid Lake fault zone; WSF, Warm Springs Valley fault zone. Modified from C. Henry (personal commun., 2003)

flow tuff is that it occupies a paleovalley similar to those that contain the older tuffs (see above); however, the thickness of the tuff of Perry Canyon, its uniqueness, and the occurrence of megabreccia strongly suggest the presence of a caldera. If so, the Perry Canyon caldera is the only such feature known in the northern Walker Lane structural zone.

In the vicinity of Mullen Pass, the tuff of Perry Canyon is associated with rhyolite to dacite porphyry (Tri) and overlain by flow rock of similar composition (Trf). The porphyry yielded an $^{40}Ar/^{39}Ar$ age of 23.51±0.08 Ma (table 1). The age of the porphyry is indistinguishable from that of the tuff of Perry Canyon, and we suggest it formed caldera margin intrusive rocks related to the magma chamber for the tuff. However, on the basis of new mapping to the north of the Fraser Flat and Moses Rock Quadrangles (e.g., Faulds and others, 2000), similar porphyry is now thought to occur as much as 3 km north of Mullen Pass, and is thus not closely restricted to the area of the proposed Perry Canyon caldera. Although these intrusive rocks are common along the northern margin of the proposed caldera, they are notably lacking to the south.

Early Miocene Andesite and Diorite

Hornblende andesite (Ta) dikes (ca. 58% SiO_2; table 2), mostly with northwesterly strikes, cut the tuff of Perry Canyon and older rocks. They have yielded $^{40}Ar/^{39}Ar$ dates of 22.33 ± 0.26 and 22.54 ± 0.21 Ma (table 1). A small sill-like mass of similar rock is also present near the center of the Perry Canyon caldera. Fine-grained diorite intrudes the lower tuff of Perry Canyon and older ash-flow tuffs south of the caldera, and we interpret this diorite as closely related to the andesitic dikes.

In addition to the andesitic intrusions in the Pyramid district, hornblende andesite dikes and irregular intrusive masses (Tha) cut the tuff of Whisky Spring in the southern part of the Fraser Flat Quadrangle. Here, hornblende from a dike along a northwest-striking right-lateral strike slip fault yielded a $^{40}Ar/^{39}Ar$ age of 20.69 Ma; another hornblende andesite dike from the northern Griffith Canyon Quadrangle just to the south yielded an $^{40}Ar/^{39}Ar$ age of 20.82 Ma (samples FM80 and GC213, respectively, table 1).

Hornblende andesite lahars and minor associated andesite flow(?) and intrusive rocks of similar composition (Tal, Tali) intrude and lie with angular unconformity on Oligocene ash-flow tuffs exposed at the north end of Hungry Ridge. Hornblende from a flow(?) below thick lahars yielded an $^{40}Ar/^{39}Ar$ age of 20.85 Ma (sample FM52, table 1). This age is very close to the age of the dikes (Tha) described above, which suggests that these dikes probably represent the deeper parts of a once more extensive ancestral Cascade arc stratovolcano that lay above the Oligocene ash-flow tuffs in the southern Fraser Flat Quadrangle. The andesitic lahars underlie 18.73 Ma basalt to the south in the Griffith Canyon Quadrangle (Garside and Nials, 1999; Garside and others, 2000).

Pyramid Sequence

Bonham and Papke (1969) first applied the informal name Pyramid sequence to an areally extensive suite of intermediate to mafic volcanic rocks and interbedded sedimentary rocks that are exposed in the mountain ranges around Pyramid Lake. In general, the Pyramid sequence of Bonham and Papke (1969) in the Pah Rah Range included rocks that lie above the Oligocene ash-flow tuffs (formerly the Hartford Hill Rhyolite) or above the Alta Formation (in the Truckee River canyon) and below either younger andesitic and dacitic rocks (Kate Peak Formation and similar rocks as young as 8.2 Ma; Garside and others, 2000) or late Miocene basaltic flows (e.g., Lousetown Formation). The Chloropagus Formation, named in the Hot Springs Mountains, over 50 km to the east of the map area (Axelrod, 1956), has been considered at least a partial correlative of the Pyramid sequence (Bonham and Papke, 1969; Rose, 1969; Axelrod, 1992). However, because of some differences in lithology between the units, as well as the lack of detailed geologic mapping in the intervening area, we prefer to continue the use of the informal stratigraphic terminology. Axelrod (1992) has applied formation names (Pyramid Formation and Mullen Formation) to parts of the unit that we informally refer to as the Pyramid sequence. McJannet (1957) was the first to use the term Pyramid Formation.

In the map area, the Pyramid sequence consists of a basal unit of tuffaceous sedimentary rocks and basaltic lahars (Tps). This unit includes some structurally complex masses of breccia with olivine basalt clasts (Tpb), which represent local volcanic centers or phreatic explosions. It is overlain by olivine basalt flows (Tob) with interbedded lahars (Tl), which are themselves overlain by two related dacitic ash-flow tuff cooling units of the tuff of Mullen Pass (Tml and Tmu). The upper unit of the Pyramid sequence in the map area consists of a small exposure of basaltic andesite flows (Tba) that lie above the tuff of Mullen Pass.

The Pyramid sequence of the map area is as old as 13.84 ±0.15 Ma, based on an $^{40}Ar/^{39}Ar$ age determination (Swisher, 1992, p. 201) on the tuff of Mullen Pass (map unit Tml) just north of the quadrangle. This age was determined on plagioclase from a sample (KA1244) first dated by Evernden and James (1964) using K-Ar methods (C. Swisher, written commun., 2001). An essentially equivalent $^{40}Ar/^{39}Ar$ age of 13.77 ±0.15 (table 1) was obtained on the upper unit of this same tuff during the course of our work. A diatomite unit that contains the Pyramid flora of Axelrod (1992) north of Mullen Pass is reported to be unconformably overlain by the tuff of Mullen Pass near the flora locality, and to be conformably overlain nearby by a basalt flow (Bonham and Papke, 1969, p. 30). This basalt, which has been dated by K-Ar methods at 15.8±2.4 Ma (converted to new constants from Bonham and Papke, 1969, table 25), is unconformably overlain by the tuff of Mullen Pass (Bonham and Papke, 1969, p. 30). The flora-bearing diatomite unit is stratigraphically equivalent to our map unit Tps. Because of the large uncertainty in the K-Ar age, we can not be certain that the Pyramid sequence is older than ~14 Ma. For

example, basaltic lava from near the base of the Pyramid sequence in upper Jones Canyon of the Olinghouse Quadrangle about 20 km to the south yielded an $^{40}Ar/^{39}Ar$ age of 13.02 Ma (sample OG285, Garside and others, 2000, table 1), and basalt from the lowest flow of the Pyramid sequence exposed to the north in the Tule Peak Quadrangle is dated at 13.62 Ma (C.D. Henry, written commun., 2001; table 1). Thus at least the lower part of the Pyramid sequence is of late Barstovian land-mammal age (according to the time scale developed by Woodburne and Swisher, 1995).

Sedimentary Rocks

Fluvial and lacustrine sedimentary rocks (Ts) lie with angular unconformity on Oligocene ash-flow tuffs in the Hungry Ridge area and on Cretaceous granitic rocks near Willow Spring about 3 km to the north. In the southeastern part of the map area, similar rocks lie on Cretaceous basement. The rocks consist of tuffaceous, arkosic, and volcaniclastic sandstone and siltstone, with less conglomerate. Coarse rock-avalanche deposits interpreted to be in the unit are mapped separately north of Hungry Ridge. Sediment sources for Ts include the Oligocene ash-flow tuffs, Cretaceous granitic rocks, and basaltic flow rocks. Silicic volcanic ash probably makes up a significant component of the fine lacustrine beds of the tuffaceous siltstones of northern Hungry Valley and a few thin intermediate-composition lapilli tuffs are found interbedded with fluvial units in northern Hungry Valley and southeastern Warm Springs Valley.

The Tertiary sedimentary rocks contain fossil mammal limb bones that are not genera or age diagnostic (localities FM 17 and 22, ~2 km south of Willow Spring, Fraser Flat Quadrangle). A flora from the rocks exposed in the northern part of Hungry Ridge is estimated to be late Miocene (probably 8-7 Ma; Howard Schorn, written commun., 2001). Hornblende from a lapilli tuff from the base of the sedimentary unit in the southeastern part of the map area yielded an $^{40}Ar/^{39}Ar$ age of 8.75 Ma (table 1; C.D. Henry, written commun., 2001); basalt flows interbedded in the lower(?) part of the sedimentary package south of the map area in southern Warm Springs Valley are 9.12 Ma (table 1; C.D. Henry, written commun., 2001). These ages are comparable to those of similar western Nevada sedimentary units; it is possible that several Tertiary sedimentary packages now separated by fault-bounded mountain ranges (i.e., sedimentary rocks of the Verdi-Boca basin, those in Long Valley on the California-Nevada boundary, as well as those exposed in Warm Springs and Hungry Valleys) were deposited in a single basin between 12 and <3 Ma (e.g., Henry and Perkins, 2001).

Late Tertiary or Quaternary Deposits

Alluvium

In the southeastern part of the map area, a coarse, poorly consolidated gravel (QTg) was deposited on Oligocene ash-flow tuffs in probable channels. The gravel appears to be slightly tilted, but apparently is not cut by faults that cut the tuffs. The gravel is probably either late Tertiary or early Quaternary.

An uplifted alluvial fan deposit (QTa) occurs along the Warm Springs Valley fault system in the northwest part of the map area. This deposit forms a linear ridge that is parallel to the fault. It extends into the Dogskin Mountain Quadrangle to the north, where a tephra from fine-grained sedimentary beds in the lower part of the ridge yielded an $^{40}Ar/^{39}Ar$ age of 3.57 ±0.17 Ma (C.D. Henry, personal commun., 2001). Because there is a significant unconformity in the ridge above the tephra and a change in depositional character and provenance across this unconformity, the QTa in the upper part of this ridge may be considerably younger than this age.

Landslide Deposits

A number of deposits in the map area are interpreted as the products of slope movement or mass wasting (map unit QTls). We include in this category debris flows, rock avalanches, and possibly rotational slumps. Many of the rock avalanche and debris flows are monolithologic while probable rotational slump deposits are heterolithologic. Commonly, the deposits are poorly exposed; surfaces are littered with lag of larger fragments. Where the deposits are better exposed they are seen to vary from a chaotic mixture of block- to sand-sized material to large blocks in a mass of disrupted rock. These deposits are probably of varying age, but most cap ridges or stand above Quaternary alluvial units, and thus have been considerably dissected. We suspect that they predate all Quaternary surficial units in the map area.

Quaternary Deposits

Quaternary deposits in the map area are in piedmont and basin settings, with several units related to the late Pleistocene Lake Lahontan. Piedmonts are composed of alluvial deposits making up fans emanating from the Pah Rah Range, Dogskin Mountain, and Curnow Range southwest of Warm Springs Valley. Basin sediments were deposited on the floor of Warms Springs Valley, and include lacustrine, alluvial, and eolian facies. Several deposits associated with Lake Lahontan were also mapped, including lacustrine deposits and nearshore-modified and shoreline deposits. Piedmont deposits are divided into three time chronologic units based on superposition of deposits, surficial character, and degree of soil formation. Shorelines from Lake Lahontan are also useful in discriminating pre- and post-lake piedmont deposits. Piedmont deposits are dominated by granitic rocks along the Dogskin Mountains, the eastern Warm Springs Mountains, and the small hills within western Warm Springs Valley, and are generally dominated by Tertiary volcanic rocks elsewhere.

The oldest Quaternary deposits (Qao, Qfi, and Qfdi) are alluvial fan and terrace deposits of sands, gravels, and cobbles, with sporadic boulders in proximal parts of fans. These deposits are found as 1- to 4-m-thick eroded fan remnants, some in ballena landforms, and as buried deposits.

Surfaces developed on these older Quaternary deposits are smoothed, have moderately to well developed pavements, and have well-developed drainage patterns formed on them. Soils developed on older Quaternary deposits consist of a reddened, sticky, clayey argillic horizon that is as much as 0.5 m thick, overlying a calcic horizon (with up to stage III carbonate development) and/or a silica hardpan. These deposits are early to middle Pleistocene in age, based on the degree of soil formation. A tephra bed within Qfdi in the northwest part of the Fraser Flat Quadrangle has been correlated with a tuff dated at 0.23 ±0.05 Ma (M.E. Perkins, personal commun., 2003).

The intermediate age deposits (Qfy_2 and Qfd_2) are alluvial fan and terrace deposits that make up a little less than half of the piedmont. These deposits are 0.2 to >2 m thick, and consist of sands, gravels, and cobbles, with sporadic boulders in proximal parts of fans, and silty sands in the middle and distal parts of the fans. Surfaces developed on intermediate age deposits are usually smoothed with poorly to moderately developed pavements, and intermittent relict gravel, cobble, and boulder bars that have had the fines winnowed from them. Soil development in intermediate age deposits usually includes a cambic horizon or an argillic horizon 0.2 to 0.5 m thick, and occasionally a calcic horizon with up to stage II carbonate development.

The youngest Quaternary alluvial deposits (Qfy_1 and Qfd_1) make up over half of the piedmonts, and consist of alluvial fan gravels, channel deposits, and some distal parts of fan deposits that have flowed out onto the floor of Warms Springs Valley. Deposits consist of sands, gravels, and cobbles, with occasional boulders in the proximal parts of fans, and gravelly silty sands in the middle and distal parts of the fans. Surfaces on the youngest Quaternary deposits commonly have fluvial microtopography, including bar-and-swale morphology, and broadly undulating and pocketed surface morphology. The youngest alluvial deposits either lack soils or have minimal A/C profile development, with the A horizon consisting of eolian silt with local vesicles and platy structure. Some of the oldest of these deposits have 20-cm-thick, slightly reddened or darkened cambic horizons as well.

Several types of basin sediments were deposited on the flat floor of Warm Springs Valley, including alluvial deposits from the distal parts of fans and in broad floodways adjacent to exiting streams, eolian deposits including small (~1 m high) dunes, lacustrine deposits from Lake Lahontan, and various shoreline and bar deposits associated with Lake Lahontan. Basin floor deposits include sandy lobes from drainages that spill out onto the basin floor, and eolian silts and clays that form light-brown, vesicular, A soil horizons and muds where saturated for periods of time. Lacustrine tan to brown and gray sandy-clayey silts to clayey-silty sands underlie most of central Warm Springs Valley, and are either exposed, with a common whitish salt-encrusted surface, or are covered by thin alluvial, eolian, or near-shore bar deposits. Small amounts of diatomaceous earth are present in the northwesternmost part of the map area, along the creek from Winnemucca Valley, and as stringers within the basin deposits.

STRUCTURAL GEOLOGY

Regional Framework

Warm Springs Valley and the Pah Rah Range are located within the northern part of the Walker Lane belt, a northwest-striking zone of right-lateral strike-slip faulting and diverse topography that separates the Sierra Nevada to the west from the generally north-northeast striking basin-range topography to the east (Stewart, 1988). The Walker Lane belt has been subdivided into several regional blocks (Stewart, 1988), based on differences in structural style. The area of this map is included in the northern, Pyramid Lake block of the Walker Lane belt (fig. 3).

The Walker Lane belt has been proposed to accommodate at least a part of the right-lateral component of plate motion between the Pacific and North American plates that is not taken up by the San Andreas fault system (Atwater, 1970; Stewart and Crowell, 1992; Bennett and others, 1999; Thatcher and others, 1999). It is predominantly a Cenozoic feature, although some faults in certain segments may be reactivated Mesozoic faults (Stewart, 1988).

The Pyramid Lake block is the northernmost segment of the Walker Lane belt, and the Carson block adjoins it to the south. Most of the Pah Rah Range and ranges to the west are included in the Pyramid Lake structural block (of the Walker Lane belt), whereas the Virginia and Carson Ranges are in the Carson block (Stewart, 1988). In general, these two blocks are distinguished by differences in style and direction of faulting; northwest-striking faults with probable right-lateral offset characterize the Pyramid Lake block, whereas zones of northeast-striking, presumed left-lateral faults (and an absence of the northwest-striking right-lateral faults), characterize the Carson block (Stewart, 1988). The boundary between the Carson and Pyramid Lake blocks is placed at the northern extent of northeast-striking faults, which are parallel to the left-lateral Olinghouse fault (Stewart, 1988, fig. 25-3). In general, this boundary passes northeast-southwest through Reno and is located 1 to10 km north of the Truckee River (the line of separation between the Pah Rah and Virginia Ranges). Major faults of the Pah Rah Range are predominantly northwest striking, with a component of right-lateral offset. West of Warm Springs Valley the major faults are north- and north-northeast-striking, range-bounding normal faults (fig. 3) that accommodate west tilting of half grabens. These faults are presumed to have dominantly dip-slip displacement. The basinal areas are underlain by Neogene sedimentary units. Offset on the right-lateral faults in the Pyramid Lake block of the Walker Lane belt has been estimated at 32 km by Bonham and Papke (1969) on the basis of the apparent offset of the northern extent of the Oligocene to early Miocene ash-flow tuffs.

The Pyramid Lake block of the Walker Lane consists of a 25-km-wide zone of left-stepping, right-lateral, strike-slip faults. Several of the longer and more continuous of these (Pyramid Lake fault, Warm Springs Valley fault, and

Honey Lake-Bedell Flat fault) have Quaternary displacement (Bell and Slemmons, 1979; Anderson and Hawkins, 1984; Bell, 1984; Cashman and others, 1992). Northwest-striking faults in the bedrock areas of this part of the Walker Lane belt may represent older, predominantly inactive right-lateral faults. The northerly striking, range-bounding normal faults southwest of the Walker Lane belt, which bound several west-tilted half grabens (e.g., Spanish Springs Valley to the south) that are filled with Neogene deposits, may be kinematically linked to northwest-striking right-lateral faults within the Walker Lane.

Age of Faulting

There is little evidence for Tertiary faulting before the deposition of Oligocene ash-flow tuffs in broad channels on an apparent west-sloping surface of relatively low relief (Davis and others, 2000). The correlation of relatively thin Tertiary ash-flow tuffs, such as the Nine Hill Tuff, over an extensive area of western and central Nevada (e.g., Deino, 1994) also suggests negligible late Oligocene fault-controlled topography.

The age of onset of strike-slip faulting in the northern Walker Lane is poorly known. The main part of the Pyramid mining district in the Perry Canyon caldera is cut by northwest-striking and generally steeply dipping veins that have roughly the same orientation as the 22.3- to 22.5-Ma andesite dikes. Sericitic alteration along the veins, which are mineralized faults with slickenlines that indicate both dip-slip and strike-slip movement, has been dated by $^{40}Ar/^{39}Ar$ methods at 22.6 Ma (table 1). These structures are roughly parallel to northwest-striking faults of the Walker Lane. Wallace (1975) reported that the mineralized faults of the Pyramid district have characteristics suggestive of original strike-slip movement. These include their near vertical dip; northwest strike parallel to right-lateral faults of the Walker Lane in the region, and presence of cymoidal bends and cymoidal loops (curving bends, and opposing pairs of such bends that produce lenses or wedges of unfaulted rock bounded by curving faults). The mineralized faults parallel numerous unmineralized faults to the south of the district that have strike-slip separation. Thus, if the mineralized faults of the Pyramid district are faults of the Walker Lane belt, the oldest motion on this part of the belt is older than 22.6 Ma (but only slightly, as the faults cut the 23.2-Ma caldera-fill tuff of Perry Canyon). Alternatively, these faults may be normal faults that developed during a period of northeast-southwest extension, or post-collapse caldera-related faults.

In the south part of the map area, in the range northeast of Bacon Rind Flat, additional evidence indicates early Miocene motion on northeast-striking right-lateral faults. The tuffs and underlying Cretaceous granitic rocks in this area to the south of State Route 445 are cut by four or five northwest-striking faults that are interpreted to have right lateral strike-slip offset (Fontaine, 1997; Garside and Nials, 1999; Garside and others, 1999). One of these faults has about 2.3 km of right-lateral separation on a 20.8-Ma dike-like hornblende andesite intrusive body and a similar amount of separation on a steep contact between two Cretaceous granitic units in the Griffith Canyon Quadrangle to the south. These relationships suggest that movement on this fault was entirely after 20.8 Ma. However, a parallel fault has a similar hornblende andesite dike (dated at 20.7 Ma; table 1) along it. This later fault probably has only a few hundred meters of right-lateral offset, but this motion appears to predate the 20.7-Ma dike (and postdate the 23.9-Ma tuff of Chimney Spring it cuts). Neither of these faults seems to cut Quaternary units, and thus are considered inactive. A third northwest-striking fault to the east, mainly in Sec. 17, T22N, R21E, contains striae that rake northwesterly at a low (~30º) angle, indicating lateral movement. These striae were observed near the southwest corner of Sec. 8, 1.5 km southeast of the BLM Wild Horse corrals.

Normal faulting in western Nevada and consequent development of sedimentary basins probably began about 12 to 13 Ma (Stewart, 1992; Dilles and Gans, 1995; Henry and Perkins, 2001). In the map area, present evidence suggests that the basinal sedimentary rocks are no older that about 10 Ma (see previous section on Tertiary sedimentary rocks). This faulting continued, at least intermittently, to the present in conjunction with right-lateral strike-slip faulting of the Walker Lane. Thus, any strike-slip faulting prior to or during 22.6-Ma mineralization in the Perry Canyon caldera began in this area 5 million years or more before extensional normal faulting. Angular unconformities have not been observed between the Oligocene tuffs (common disconformities are probably related to deposition in channels), and sedimentary units below and between the tuffs are uncommon, and thin where present. The present basin-and-range topography is probably a result of more closely spaced normal faulting since 10 Ma (Zoback and others, 1981; Henry and Perkins, 2001). The development of the elevation separation between the Sierra Nevada and the Basin and Range along the Sierra Nevada frontal fault that bounds the Carson Range south of Reno (fig. 3) is no older that this and probably began at about 3 Ma (Unruh, 1991; Henry and Perkins, 2001).

Honey Lake–Bedell Flat Fault System

The Honey Lake-Bedell Flat Fault system, a major strand of the northwest-striking right-lateral Walker Lane system, extends at least 80 km from Honey Lake in California to the southwest part of the map area (fig. 3). To the northwest of the map area, it can be traced across Bedell Flat, to the south of Fort Sage Mountain, and along the west side of Honey Lake (Grose, 1992) where the fault is reported to have a right-lateral Holocene slip rate of approximately 2 mm/yr (Willis and Borchardt, 1993).

In the map area, the Honey Lake-Bedell Flat fault system is represented by a fault that cuts Mesozoic and Quaternary units along the northeast side of Warm Springs Mountain. It cannot be traced southeast of the Winnemucca Ranch Road. It either dies out, steps or bends to the left, or its displacement is transferred to the east-dipping normal

fault that bounds the west side of Spanish Springs Valley to the south of Bacon Rind Flat in the Griffith Canyon Quadrangle (figs. 1, 2, and 3). The Cottonwood Creek fault, which bounds the west side of southern Warm Springs Valley, may represent a left-stepped extension of the Honey Lake-Bedell Flat fault system. However, on the basis of gravity data (Gimlett, 1967) the Cottonwood Creek fault has considerable dip-slip offset.

South of the southern mapped end of the Honey Lake-Bedell Flat fault system, State Route 445 (fig. 2) passes between a large outcrop area of Cretaceous quartz monzodiorite to the north and generally northerly dipping Oligocene ash-flow tuffs in the range to the south. This range is known as the Curnow Range, although it is a western arm of the Pah Rah Range. A concealed, northeast-striking, down-to-the-south fault, located slightly west of the highway, must separate these two blocks (fig. 3). The dip of this fault is not known; it may be a northwest-dipping reverse fault or a southeast-dipping normal fault. In addition, continuation of this postulated fault is uncertain. It may be an extension of the down-to-the east, basin-bounding fault of Bacon Rind Flat (and Spanish Springs Valley) to the south, or it may represent the boundary of a pop-up feature (McClay and Bonora, 2001) in a restraining bend (left step) along a possible southeastward continuation of the Honey Lake-Bedell Flat fault. Contraction did occur in the area, as evidenced by folding in Tertiary sediments and possibly in Quaternary sediments in Hungry Valley (see below). However, the chronological relationship between the fault system and the folding is not clear.

Hungry Valley Folds

In northern Hungry Valley, south and west of the apparent termination of the Honey Lake-Bedell Flat fault system, Tertiary sedimentary rocks are warped into at least eight broad, open folds. These folds plunge gently (10º–20º) west toward a north-striking normal fault that bounds the west side of the Hungry Valley west-tilted half graben (fig. 3). The fold traces are slightly sinuous, and limbs commonly dip less than 35º. Some of the folds appear to have a right-stepping pattern, and their plunge directions are away from the Honey Lake Valley-Bedell Flat fault. At least one of these folds (the southernmost on the map) may have had Quaternary deformation, because Quaternary deposits lie along (Qfi) or near (Qfy_2) the synclinal fold axis. The simplest explanation for the formation of these folds is that they are en-echelon folds related to the northwest-striking Honey Lake-Bedell Flat fault. Such folds form at an oblique angle to the principal direction of shear, and tend to have axes which are 10° to 35° from the strike of the strike-slip fault (Sylvester, 1988). Similar folds have been formed in laboratory experiments on clay cakes (Wilcox and others, 1973).

Warm Springs Valley Fault System

The Warm Springs Valley fault system, which includes a northwest-striking fault that crops out at the north end of Warm Springs Valley, is one of three major right-lateral fault systems in the northern Walker Lane. It is parallel to, and about 7 km to the east of, the Honey Lake-Bedell flat fault system. The Warm Springs Valley fault system has accommodated uplift of late Tertiary gravels directly north of the map area (Faulds and others, 2000). It can be followed northward along the north side of Fort Sage Mountain and into Honey Lake Valley (Bonham and Papke, 1969; Stewart, 1988). It may continue to the south along the east edge of Warm Springs Valley toward Whiskey Spring in the Pah Rah Range (figs. 2 and 3).

In the map area, the Warm Springs Valley fault system is represented by a fault defined by a well-defined northwest-striking lineament and a low scarp in the north part of Sec. 24, T23N, R20E. This fault offsets latest Holocene deposits, and has had multiple latest Pleistocene and Holocene paleoevents, as determined by trench investigation (dePolo and Ramelli, 2003). It has intermittent geomorphic expression of small scarps, vegetation lineaments, and small push-up mounds that formed during the last few events. Much of Warm Springs Valley has had latest Holocene deposition or modification at the surface. Consequently, large portions of the Warm Springs Valley fault system are buried or eroded away and are represented only by lineaments or are not distinct at the surface.

On the basis of linear features defined by magnetic work (Widmer, this publication), the fault system is well defined in the north part of Warm Springs Valley and may lie along the eastern margin of a shallow platform of granitic basement in central part of Warm Springs Valley. To the southeast it is poorly defined by northwest-striking lineaments that extend southeastward from the trenched area and cross State Route 445. We suggest that the southeastward continuation of the fault is an apparent right-lateral fault that cuts late Oligocene ash-flow tuffs south of Moses Rock Canyon and continues southeast of the map area toward Chimney Spring and Right Hand Canyon where the contact between Tertiary ash-flow tuffs and Cretaceous granitic rocks is displaced about 3 km in a right-lateral sense (Bonham and Papke, 1969, plate 1). If this is the case, the Warm Springs Valley fault system merges with the steep northeast wall of a basin in southern Warm Springs Valley (Widmer, this publication) that is filled with Quaternary and possibly late Tertiary sediments. Alternatively, the basin may be the result of a right stepping pull-apart along the Warm Springs Valley fault system, with the main strand of the fault represented by the Cottonwood Creek fault southeast of State Route 445. Knowledge of the location and geometry of the Warm Springs Valley fault system is important in terms of active tectonic processes in the region because evidence from detailed study of trenches along it indicates seven latest Pleistocene and Holocene paleoearthquakes (dePolo and Ramelli, 2003).

Perry Canyon Caldera

A proposed caldera that is filled by the tuff of Perry Canyon (fig. 3) has a shallowly to moderately north-dipping southern wall south of the Pyramid mining district. Andesite

megabreccia (Tmb) in the tuff near this wall indicates caldera-wall collapse during tuff emplacement. The western part of the caldera is likely covered by alluvium in Warm Springs Valley, and may be displaced along the Warm Springs Valley fault beneath the valley alluvium. The eastern part of the caldera is covered by rocks of the Pyramid sequence. For the most part, the northern border lies beneath alluvium in Mullen Pass because possible outflow tuff correlative with the tuff of Perry Canyon is significantly thinner to the north of Mullen Pass (Faulds and others, 2000). The proposed caldera is strongly elongated along an east-northeast-striking axis lying just south of Mullen Pass. The caldera may be a "trap-door" caldera with a steeply south-dipping northern wall along Mullen Pass marked by porphyry domes (Tri), the emplacement of which has locally warped tuff units that are older than the tuff of Perry Canyon into dips as steep as 70° around the intrusive margins.

An east-northeast-striking fault has been mapped between the caldera-filling tuff of Perry Canyon and older tuffs just to the south of Mullen Pass. It is marked by poorly exposed limonitization and alteration near the Nevada Dominion Mine, but is unexposed elsewhere. It is considered to be a post-collapse fault rather than a caldera wall because foliation defined by collapsed pumice in the adjacent tuff of Perry Canyon is perpendicular to the fault trace. However, it may represent caldera collapse subsequent to ash-flow extrusion. It was displaced by northwest-striking faults that hosted mineralization in the Pyramid district.

MINERAL DEPOSITS

The Pyramid mining district covers the northwest quarter of the Moses Rock Quadrangle and the northeast part of the Fraser Flat Quadrangle. Parts of the McClellan mining district (also referred to as the Cedar mining district in Washoe County Mining Claims Records) and the Dogskin Mountain mining district are in the south and west part of the map area, respectively. The Pyramid mining district and prospects outside it are described separately below.

Pyramid Mining District

Ore deposits in the main part of the Pyramid mining district consist of a swarm of northwest-striking precious-metal-bearing veins in the northern Pah Rah Range in an area of about 20 km^2 bounded by Mullen Pass to the north, Warm Springs Valley on the west, the crest of the Pah Rah Range on the east, and the Perry Canyon caldera wall on the south. Silver-rich veins were discovered in this area in 1863; however, intensive mining did not begin until 1876 with the location of the Monarch Mine (Earl, 1990). Production records, which are fragmentary prior to 1888, show that most production occurred between 1881 and 1912, although minor production was recorded as late as 1952 (Bonham and Papke, 1969). This total recorded production was about $95,000 in gold, silver, and copper, mainly from the Nevada Dominion (Franco-American) Mine, but because early production records are incomplete total production may have been higher. There is an unsubstantiated report of the production of $260,000 in precious metals from a single mass of ore in the Jones-Kincaid Mine (NBMG mining district files). Washoe County Claim Location Records and Deeds show this mine was originally the Jones and Kinkead Mine, which was active between 1876 and 1883. The Guanomi Mine, a gold-silver prospect developed near the southwest shore of Pyramid Lake in the 1920s and prospected for copper and molybdenum in the 1930s and 1970s, is also included in the district although it is about 10 km east of the precious-metal veins and well outside the map area (Garside and others, 2000). In addition, the district was enlarged to include uranium deposits discovered in the 1950s in "Mine Canyon" about 2 km north of the map area, and uranium prospects about 2 km south of the main part of the district (Bonham and Papke, 1969; Castor and Henry, 2000).

The veins of the Pyramid district were described by Overton (1947), and Bonham and Papke (1969). They were mapped and studied in detail by Wallace (1975), and were recently sampled and analyzed by the NBMG (Tingley and others, 1999). In addition, under the tutelage of L. Larson, the veins were studied by legions of economic geology students from the Mackay School of Mines from the 1970s to the 1990s. Since the 1950s, industry geologists have explored the Pyramid district for various mineral targets, including surface and underground exploration for uranium in the Mine Canyon area in the 1950s and 1970s, mapping and drilling for copper and molybdenum in the Perry Canyon and Guanomi Mine areas in the 1970s, and precious-metals exploration in the main part of the district in the 1980s and 1990s (Tingley and others, 1999).

Precious metals were mined from moderately to steeply dipping, northwest-striking, high-sulfidation veins ("ledges") in the main part of the Pyramid district. There are three northwest-striking vein systems that we call the Ruth, Burrus, and Bluebird vein systems from prominent mines along them (fig. 4). Alteration and small prospects along other veins of similar orientation are north and east of these vein systems. Farther to the east the altered and mineralized rocks are covered by unaltered 14-Ma and younger Pyramid sequence rocks. It is not known how far to the east the related alteration extends, but it may include the alteration, precious-metal mineralization, and weak copper and molybdenum enrichment at the Guanomi Mine.

Samples from the 1-km-long Ruth vein system (fig. 4) yielded median values of 1.3 ppm gold and 131 ppm silver (Tingley and others, 1999). Gold content is variable along the vein system; the highest gold content, about 8 ppm, was from the Surefire Mine (table 3). Base metals are highest in the northwest part of the vein system, whereas copper is higher to the southeast. In addition to abundant quartz and pyrite, vein minerals in unoxidized ore from the Ruth vein system include barite, anglesite, galena, sphalerite, acanthite, gold, and cassiterite (table 3). Wallace (1975) also reported tetrahedrite and chalcocite. Oxidized samples contain limonite, copper sulfate minerals, and copper carbonate minerals. Enargite is notably absent in samples from the Ruth vein system.

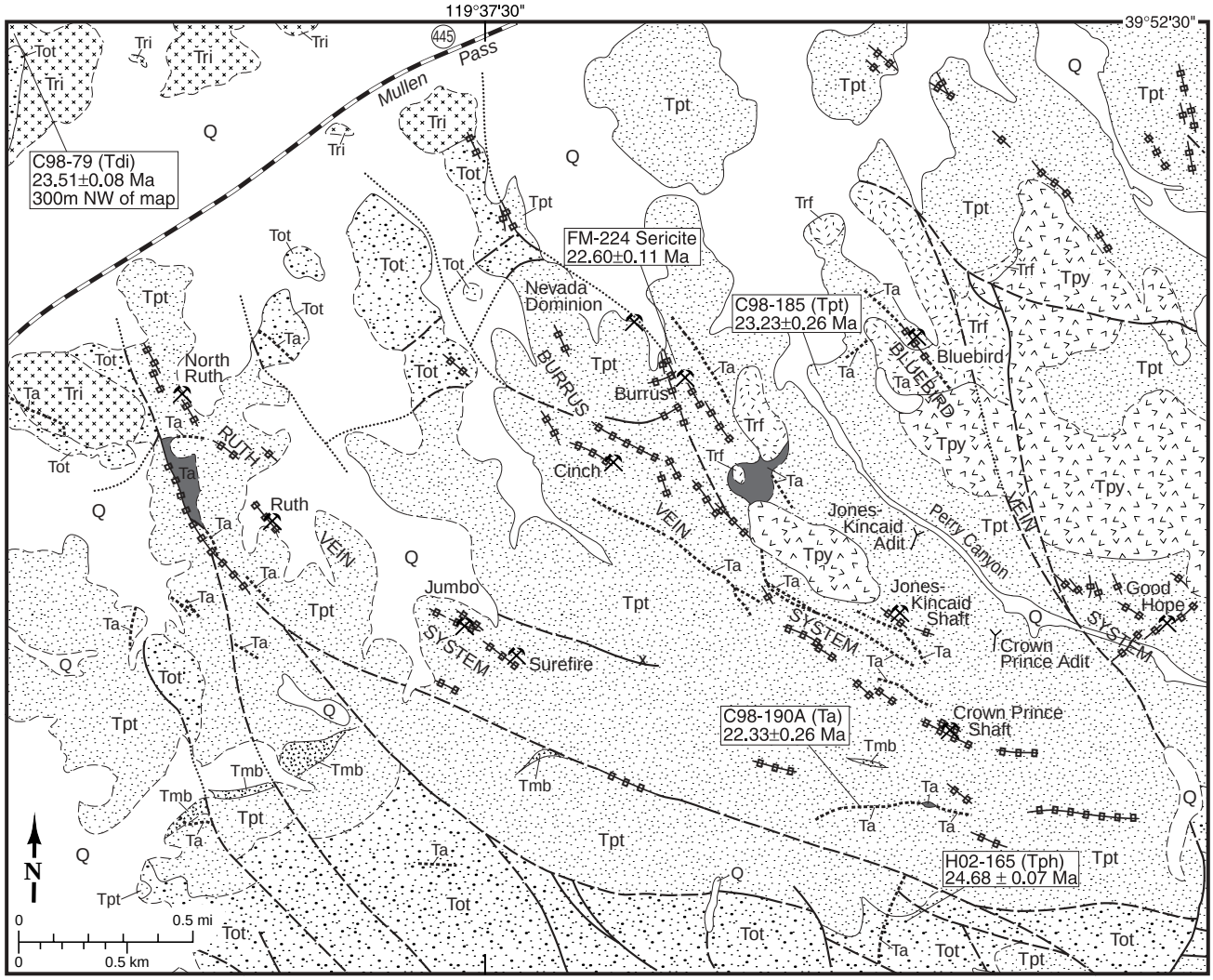

Figure 4. Simplified geologic map of the Pyramid mining district showing dated samples and mine and vein names.

Fault, dashed where unexposed, dotted where covered.

Dike.

Quartz±clay±sericite±diaspore±alunite±pyrophyllite vein.

Q — Quaternary deposits: alluvial fans and terraces with some older debris flows.

Tpy — Pyramid sequence: andesitic basalt flows, sedimentary rocks, volcanic breccia, and dacite tuff.

Ta — Hornblende andesite: numerous dikes and a small sill-like mass (not Alta Fm. as on fig. 1).

Trf — Dacitic flow rock.

Tri — Dacite or low-silica rhyolite intrusions.

Tmb — Megabreccia within Tpy.

Tpt — Tuff of Perry Canyon.

Tot — Older Tertiary tuffs: tuff of Painted Hills and older units.

The 4-km-long Burrus vein system extends from the Crown Prince Mine on the southeast, through the Jones-Kincaid, Burrus, and Nevada-Dominion Mines, to unnamed workings to the northwest (fig. 4). As exposed in the Burrus Mine area, the vein system consists mainly of northwest-striking, southwest-dipping silica ledges, although northeast-striking ledges with shallow to moderate northerly dips are also present. The silica ledges crop out in a 100-m-wide zone of bleached and altered rock. The alteration ranges from strong propylitization, through sericitization, to advanced argillic alteration. The latter is most strongly developed directly adjacent to the silica ledges, and is characterized by kaolinite, diaspore, and pyrophyllite.

Samples from the Burrus vein system have relatively lower gold and higher silver than from the Ruth vein system, with median values of 0.42 ppm gold and 190 ppm silver (Tingley and others, 1999). The highest gold content, about 4 ppm, is in oxidized ore from the northwest part of the vein system (table 3). Copper and arsenic contents in the Burrus vein system are generally correlative, which is consistent with the presence or absence of enargite. Base-metal contents are variable, but range as high as 1.0% lead and 1.3% zinc.

Primary minerals in the Burrus vein system are pyrite, enargite, luzonite, galena, sphalerite, acanthite, and complex silver- and bismuth-bearing sulfides. Some silver-rich samples do not contain identifiable silver-bearing phases, suggesting that the silver is present at low levels in enargite. Enargite is absent northwest of the Nevada-Dominion Mine, but is common in the southeast part of the vein system (table 3) where copper and arsenic contents are relatively high and base-metal contents relatively low. Enargite was also identified in Bluebird Mine ore, which has similar chemistry to enargite-bearing samples from the Burrus vein system (Table 3). In addition to enargite and pyrite, Bluebird ore was found to contain tin-, bismuth-, and silver-bearing sulfides.

On the basis of metal ratios in 19 unoxidized samples, Wallace (1975; 1979) reported district-wide metal zoning with high Ag, Cu, As, and Sb values relative to base metals in the southeastern part of Burrus vein system, and low ratios peripheral to this area. He proposed that the metal zoning

Table 3. Pyramid district mines and prospects in the Fraser Flat Quadrangle and the west half of the Moses Rock Quadrangle.

Mine or Prospect	Vein Orientation	Gangue Minerals	Ore Minerals	Max. ppm Au	Max. ppm Ag	Other Enriched Metals
Ruth vein system						
Ruth	N15-55W, steep NE to vertical	qtz, ba	py	6.2	217	Hg, Mo, Pb (As, Cd, Cu, Sb, Se, Te, Zn)
Ruth SE	N45W(?)	qtz	py	6.2	131	Cd, Hg, Pb, Zn (As, Bi, Cu, Mo, Sb, Se)
Jumbo	N60W, 80SW	qtz, ba	ga, mal, az	1.3	386	Bi, Cu, Hg, Pb, Sb (As, Cd, Mo, Se, Sn, Te, Zn)
Surefire	N50W, 40-50SW	qtz, ba	py, ga, sph, ac, tet, pol, anglesite, roquesite	8.1	605	Sb (Bi, Cu, Hg, Mo, Pb, Se, Zn)
unnamed, 250m E of Surefire	N50W, 85SW	qtz	py, ac, go, cas, tsu(?), mal, az, Ag sulf-telluride	4.3	5180	Cu, Hg, Te, Pb, Sb (As, Bi, Cd, Mo, Se, Sn, Zn)
unnamed, 700m E of Surefire	N50-80W, 45-55SW	qtz	py, mal, az	1.5	183	Cu, Sb (Bi, Cd, Hg, Mo, Pb, Se, Zn)
unnamed, 1.3km SE of Surefire	N25W, 75SW	qtz	py	0.3	22	(As, Bi, Cu, Hg, Mo, Pb, Sb, Se)
Burrus vein system						
unnamed, 700-1000m NW of Nevada Dominion	N10-30W, 75SW	qtz, ba	py, sph, ac, ang, tsu(?), mal, az, Cu-Zn carbonate	4.2	3182	Bi, Cd, Cu, Hg, Pb, Sb, Te, Tl (As, Mo, Se, Sn)
Nevada Dominion	N45W	qtz, ba	py, en, ga, sph	0.4	186	As, Bi, Cu, Hg, Pb, Sb, Zn (Cd, Mo, Se, Te)
Burrus	N30-40W, 60-80SW; N60-70E, 30-35N	qtz, ba, pyrophyllite	py, en, lz, ac, Ag-Cu-Se sulf, Bi-Pb-Ag sulf, olivenite, richelsdorfite	0.8	327	As, Bi, Cu, Hg, Sb, Se, Sn, Te (Mo, Pb, Tl, Zn)
Jones Kincaid	N40-45W; 75SW	qtz	py, en	2.5	353	As, Bi, Cu, Hg, Mo, Sb (Cd, Pb, Se, Sn, Te, Zn)
Crown Prince	N80W, 60-75SW; N25W, 70SW-35NE	qtz, ba	py, en, lz, ga	0.4	299	As, Cu, Sb, Sn (Bi, Hg, Mo, Pb, Se, Te, Tl)
Bluebird vein system						
Bluebird	N25W(?)	qtz	py, en, ten, tet, st, hs, f Pb-Bi-Ag-Cu sulf, Cu-Bi sulf, Bi-Ag sul	0.1	175	As, Cu, Hg, Sb, Sn (Bi, Cd, Mo, Pb, Se, Te, Tl, Zn)
Good Hope Mine & prospect 300 m NW	N30-40W, 45-65W; N45E	qtz, diaspore	py	0.1	1	(Mo)

Minerals: ac = acanthite, ang = anglesite, az = azurite, ba = barite, cas = cassiterite, en = enargite, ga = galena, go = gold, hs = hessite, lz = luzonite, mal = malachite, pol = polybasite, py = pyrite, qtz = quartz, sph = sphalerite, st = stannite, sulf = sulfide, ten = tennantite, tet = tetrahedrite, tsu = tsumebite.
Elemental enrichment levels: As >1000 (>100), Bi >100 (>10), Cd >100 (>10), Cu >2000 (>200), Hg >20 (>2), Mo >50 (>5), Pb >2000 (>200), Sb >100 (>10), Se >50 (>5), Sn >100 (>10), Te >100 (>10), Tl >10 (>1), Zn >2000 (>200), geochemical data from Tingley and others (1999).

and variations in ore and alteration mineral assemblages were consistent with highly acidic hydrothermal solutions with relatively high sulfur and oxygen fugacities in the southeastern part of the district (the area around the Crown Prince Mine) and that the potential for large disseminated copper deposits was highest in that area.

Although our samples include some oxidized ore, our mineral and chemical analyses have generally verified the mineral and chemical zoning proposed by Wallace (1975; 1979) with some exceptions. Samples from the southeast part of the Burrus vein system and Bluebird Mine were found to contain enargite (±luzonite) and were also found to have very high copper and arsenic. Samples from the north part of the Burrus vein and from the Ruth vein contain galena, sphalerite, acanthite, and gold, but no enargite or luzonite. In addition, the highest gold contents occur near the north end of the Burrus vein and central to northern parts of the Ruth vein, suggesting that a distal location for gold may fit into Wallace's overall district pattern. However, the lack of enargite along the whole length of the Ruth vein, as well as erratic levels of base metals there, are problematic for this model.

Our geochemical data show that the Burrus and Bluebird vein systems have higher contents of metals that are considered to be characteristically enriched in high sulfidation deposits (e.g., bismuth, tin, and tellurium). A review of the data by location within the vein systems indicates that higher bismuth and tellurium contents are generally in samples from the southeastern part of the Ruth vein system. However, this pattern does not hold for the Burrus vein system, where the highest bismuth and tellurium values were obtained from samples from the northwest part of the vein system.

Hydrothermal alteration in the Pyramid district is extensive. A 2-km^2 area of intense advanced argillic alteration (silica, sericite, kaolinite, diaspore, and pyrophyllite) occurs in Perry Canyon where the principal vein systems appear to converge. (Wallace, 1975; Nielsen, 1981a; Garside and others, 2000). Elevated gold values were noted during exploration of this area (Nielsen, 1981a; Schurer and Fuchs, 1989). Propylitic alteration (chlorite, epidote, albite, calcite) in the tuff of Perry Canyon and older rocks extends at least 4 km south and west of the main part of the district and more than 3 km to the northeast (where it is largely covered by post-alteration Pyramid sequence rocks); however, it does not extend northwest across Mullen Pass.

Veins in the main part of the Pyramid district are in the 23.2-Ma upper tuff of Perry Canyon (Tpu). Argillic and sericitic alteration near the veins and in a 2-km^2 area southeast of the veins was dated at 22 Ma (K/Ar on sericite, recalculated) by Wallace (1975) and more recently at 22.60±0.11 Ma by $^{40}Ar/^{39}Ar$ analysis (table 1). The tuff of Perry Canyon is overlain to the east by basalt, sedimentary rocks, and 13.77-Ma dacitic ash-flow tuff of the Pyramid sequence (Tpy, fig. 4; table 1); none of these appear to have been affected by hydrothermal alteration although in places they lie directly on hydrothermally altered tuff.

In our view, the high-sulfidation veins in the main part of the Pyramid district are most likely related to the intrusion of the hornblende andesite (Ta) dikes, which occupy the same northwesterly structures as the veins and are concentrated in the same area, or to a larger source intrusion beneath the dike swarm (Castor and others, 1999; Garside and others 1999). The most compelling evidence for this is overlap of our new age for alteration near the Burrus vein (at 22.60 ± 0.11 Ma) with the age of the dikes (at 22.33 ± 0.26 Ma and 22.54 ± 0.21 Ma) (table 1). The mineralization age does not overlap with that obtained for the more extensive dacite or low-silica rhyolite intrusions along Mullen Pass (at 23.51 ± 0.08 and 23.54 ± 0.26) which were proposed by Bonham and Papke (1969) as the source of mineralizing fluids. Instead the ages of these felsic intrusions are indistinguishable, within analytical precision, from that for the tuff of Perry Canyon (23.23 ± 0.26 Ma).

The large intensely altered area southeast of the vein systems in Perry Canyon is similar to the more constrained alteration that envelops the high-sulfidation veins. Wallace (1979) and others (Nielsen, 1981a; Gold Fields Mining, 1990) focused on it as evidence for porphyry-type mineralization related to a relatively large intrusion with the vein systems to the northwest as satellitic features. While this is a workable model, it should be noted that there are other possibilities. The altered area could be related to a separate intrusion, possibly along caldera ring fractures, that is unrelated to the hornblende andesite (Ta) that is spatially and temporarily associated with the veins. This intrusion may be similar to the Guanomi granitic intrusion in Tom Anderson Canyon 10 km to the east, where similar low-grade copper and molybdenum enrichment took place at 24.0 ± 0.7 Ma (Wallace, 1975), an age that is indistinguishable from that of the tuff of Perry Canyon and related intrusions. The comparison between the relatively widespread alteration at Guanomi and in Perry Canyon is, in part, based on the similarity between extensive but low-grade copper and molybdenum enrichment in both areas, as shown by drilling (Prochnau, 1973; Nielsen, 1981b), respectively. The caldera defined by the tuff of Perry Canyon is an elongate east-west feature and the Guanomi intrusion may be a related magmatic feature along the same general trend.

Uranium prospects

Four areas of uranium prospects have been described in the map area (Bonham and Papke, 1969; Garside, 1973; table 4), all south of the main part of the Pyramid mining district in the Pah Rah Range. Deposits in three of the prospected areas are described as uranium minerals along faults, fractures, and joints in "Hartford Hill Rhyolite" (Garside, 1973); the fourth property is not described, but is presumably similar. Only one, the Lost Partner group, is thought to have produced uranium ore, probably less than 100 tons. Samples from the Bing group of prospects contained more than 2% equivalent U_3O_8, the highest uranium content reported from these deposits. Bonham and Papke (1969) proposed that uranium mineralization in the Pah Rah Range was distal but related to intrusive and hydrothermal activity in the main part

of the Pyramid district; however, Castor and Henry (2000) described similar uranium mineralization in the "Mine Canyon" area north of the map area that may have been deposited by cold ground water and postdated intrusion of a mafic dike that is younger than the 22.6-Ma precious- and base-metal vein deposits and is probably related to the ~13- to 14-Ma Pyramid sequence (Henry, personal commun., 2002).

Veins in Cretaceous Granitic rocks

Six areas with metallic mineral deposits in Cretaceous granitic rocks were known or noted during our mapping in the Fraser Flat Quadrangle (table 4). These have all been developed as minor prospects, and include quartz veins and pegmatites. At the B and B claims, northeast-striking quartz veins to more than 60 cm thick occur in a 60 m x 10 m area and may extend for an additional 300 m on the basis of float. The Double Jack claims were staked on thin, variably oriented aplite and pegmatite dikes that contain minor amounts of copper. The FTN claims contain gossan and northwest-striking veins of iron oxide with elevated copper and molybdenum contents. An unnamed prospect on the east flank of the Curnow Range just north of the southern boundary of the map area is in a north-striking brecciated quartz vein with as much as 16.5 ppm silver and 770 ppm bismuth (Tingley and others, 1999). Two unnamed prospects, also in brecciated quartz veins, occur in the granitic hill that lies just northwest of the Curnow Range.

Industrial Minerals

Oil-Dri Corporation of Nevada has proposed to mine clay material from Tertiary sedimentary rocks (equivalent to map unit Ts) in Hungry Valley about 3 km southwest of the southwest corner of the map area. The proposed operation would mine an approximately 30 m thick section of fine-grained lacustrine claystone for industrial and consumer absorbents (including cat litter) and for flow enhancer material for grain products (U.S. Bureau of Land Management, 2001). The clay material is reported to consist of 65–70% calcium montmorillonite, 10–15% unaltered feldspar, and 10–15% quartz (U.S. Bureau of Land Management, 2001). Fine-grained lacustrine deposits continue north of the proposed mine, into the southwesternmost part of the Fraser Flat Quadrangle; some of these deposits may also have potential as industrial mineral commodities. A zeolitized (chabazite and heulandite) ash bed in map unit Ts is exposed in an exploration trench located in the center of N½ SE¼ NW¼ Sec. 21, T22N, R20E.

GEOTHERMAL RESOURCES

Warm Springs Valley

Three areas of geothermal activity are known from the Warm Springs Valley area. Warm springs for which the valley is named are located in the northwest part of the mapped area (in Secs. 22 and 23, T23N, R20E; see fig. 2). An approximately 11-km^2 area of thermal groundwater is found to the east and southeast of the Warm Springs, based on water well records on file in the Office of the State Engineer (Nevada Division of Water Resources). This thermal area and two others located to the southeast, one near the U.S. Bureau of Land Management Wild Horse Facility and one near the mouth of Curnow Canyon just south of the Fraser

Table 4. Uranium occurrences and veins in the Fraser Flat Quadrangle and the west half of the Moses Rock Quadrangle.

Mine or Prospect	Location (Section; Township: Range)	Structure Orientation	Gangue Minerals	Ore Minerals	Max. ppm U	Max. ppm Cu	Other Enriched Metals
Uranium prospects in volcanic rocks							
Lost Partner group	24; T23N; R21E	N85W, 85SW fault		autunite, torbernite(?), pitchblende(?)	<10	145	nd
Bing group	28; T23N; R21E	NW fault	Fe oxide	autunite(?), torbernite(?)	21300	nd	nd
Thunderbird group	35; T23N; R21E	N70E, 80SE breccia and gouge zone		py, autunite, uranophane	1915	<100	nd
Snap property	2(?); T22N; R21E				nd	nd	nd
Veins in Cretaceous granitic rocks							
B and B claims	21, 22, 27, 28; T23N, R20E	N40-60E	qtz, Fe oxide		nd	nd	nd
Double Jack claims	9, 6; T23N, R20E	N17W to N54E veins and dikes	qtz, fs, bi, tm	Cu stains	35	1665	(Ag, Mo)
FTN claims	4, T22N, R21E	N30W, steep NE	Fe oxide	Cu stains	<10	4000	Mo (Ag, Se)
unnamed prospect	28; T22N; R21E	N	Fe oxide		11	23	Ag, Bi, (Mo, Sb)
unnamed prospect	1; T22N, R21E		qtz		nd	nd	
unnamed prospect	12; T22N, R21E	N35-45E, NW	qtz		nd	nd	

Minerals: bi = biotite, fs = feldspar, py = pyrite, qtz = quartz, tm = tourmaline. Chemical data: nd = no data,
Ag >10 (>1), Bi >100 (>10), Mo >50 (>5), Sb >100 (>10), Se >50 (>5), geochemical data from Tingley and others (1999) and Garside (1973)

Flat Quadrangle; fig. 2), are all along the west boundary of Warm Springs Valley. Probably several northwest-striking faults form the valley-mountain range boundary, and the geothermal areas are almost certainly related to that fault system. None of the geothermal waters from the wells are used for their contained energy; unless higher temperature fluids were found, the main potential uses are space heating (including geothermal heat pumps) and soil warming.

Anomalous groundwater temperatures are known from several Sections in the vicinity of the Warm Springs (Secs. 22, 23, 25, 26, and 35, T23N, R20E). The temperatures appear to be hottest (68°C) near the springs, and lower (down to 25°C) at a distance (well driller's reports in the State Engineer's Office). The approximately 11-km^2 geothermal area is apparently elongate in a northwest-southeast direction, parallel to and east of a possible basin-bounding fault; the hotter temperatures at the west edge of this area suggest that the cooler temperatures to the east and south result from mixing of geothermal water, which rises along the fault, with shallower cool groundwater in the basin-fill deposits. Well depths range from 153 to 617 feet (47–188 m).

An apparently more restricted area of thermal groundwater is found in an approximately 1 km^2 area just south of State Route 445 in the vicinity of the Wild Horse Facility, in Sec. 7, T22N, R21E. Three wells there have reported water temperatures of 43, 43, and 29°C (well driller's reports in the State Engineer's Office). There are several possible subsurface projections of faults in this area that could be conduits bringing hot water from depth.

Another area of warm water wells is reported near the mouth of Curnow Canyon, about 8 km south of the Wild Horse Facility and 1.5 km south of the Fraser Flat Quadrangle. Two driller's logs report "warm" water from 738-foot (225 m) and 350-foot (107 m) deep wells, and another reports 60ºC in a 615-foot (188 m) deep well.

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AEROMAGNETIC LINEAMENT ANALYSIS WARM SPRINGS VALLEY

by Michael C. Widmer

Airborne Geophysical Data

Dighem, Inc. was contracted by the Washoe County Department of Water Resources to conduct an airborne geophysical survey of Warm Springs Valley (Dighem, 1994). The results were used to further the understanding of geologic structure, particularly fault structure. Magnetic and electromagnetic instrumentation was installed in a Lama turbine helicopter (Geoseis Helicopters, Inc.) which flew at an average airspeed of 100 km/hr (62 mph) with a magnetometer bird height of 30 m (98 feet) above ground level. The survey consisted of 414 km of traverse line (257 miles) oriented at 50º/230º to geographic north with 667-m (2000-foot) line spacing. Two tie lines were oriented at 140º/320º to geographic north. The magnetic data were collected with a Picodas 3340 optically pumped cesium vapor magnetometer. The sampling rate was 10 per second with a sensitivity of 0.01nT. Navigation and positioning consisting of a Sercel NR 106 real-time differential global positioning system with <5 m accuracy. A Scintrex MEP-710 cesium vapor magnetometer was operated at the survey base to record diurnal variations. The base station clock was synchronized with that of the airborne system to permit subsequent removal of diurnal drift. Data processing by Dighem Inc. consisted of corrections for diurnal variations and leveling. Data processing by Washoe County consisted of reduction to pole and 50 m of upward continuation (Geosoft, Inc., 1999). The reduction to the pole shifts asymmetric magnetic fields to a symmetrical field that aides in determining the edges of magnetic bodies. The asymmetry represents the signature of a magnetic body's geometry. Upward continuation reduces short-wavelength noise.

Results

Figure 5 displays the gridded total field magnetic data that was reduced to the pole and upward continued 50m. The range between the low and high magnetic values is 2,500 nT (51,825 to 54,357 nT). Also shown are lineaments that were interpreted from the total horizontal gradient of the magnetic data. The total horizontal gradient is the maximum horizontal rate of change of the strength of the magnetic field (first horizontal derivative of the magnetic field). It is a useful analytic tool to determine where magnetic slopes have their maxima. The edges of magnetic bodies or structures can be inferred where the magnetic gradients reach their maxima. Most of these lineaments trend northwest although some trend north to northeast.

The highest magnetic signature shown is associated with Tertiary basaltic rocks that crop out southwest of the southern end of Warm Springs Valley. The magnetic low centered on Warm Springs Valley south of State Route 445

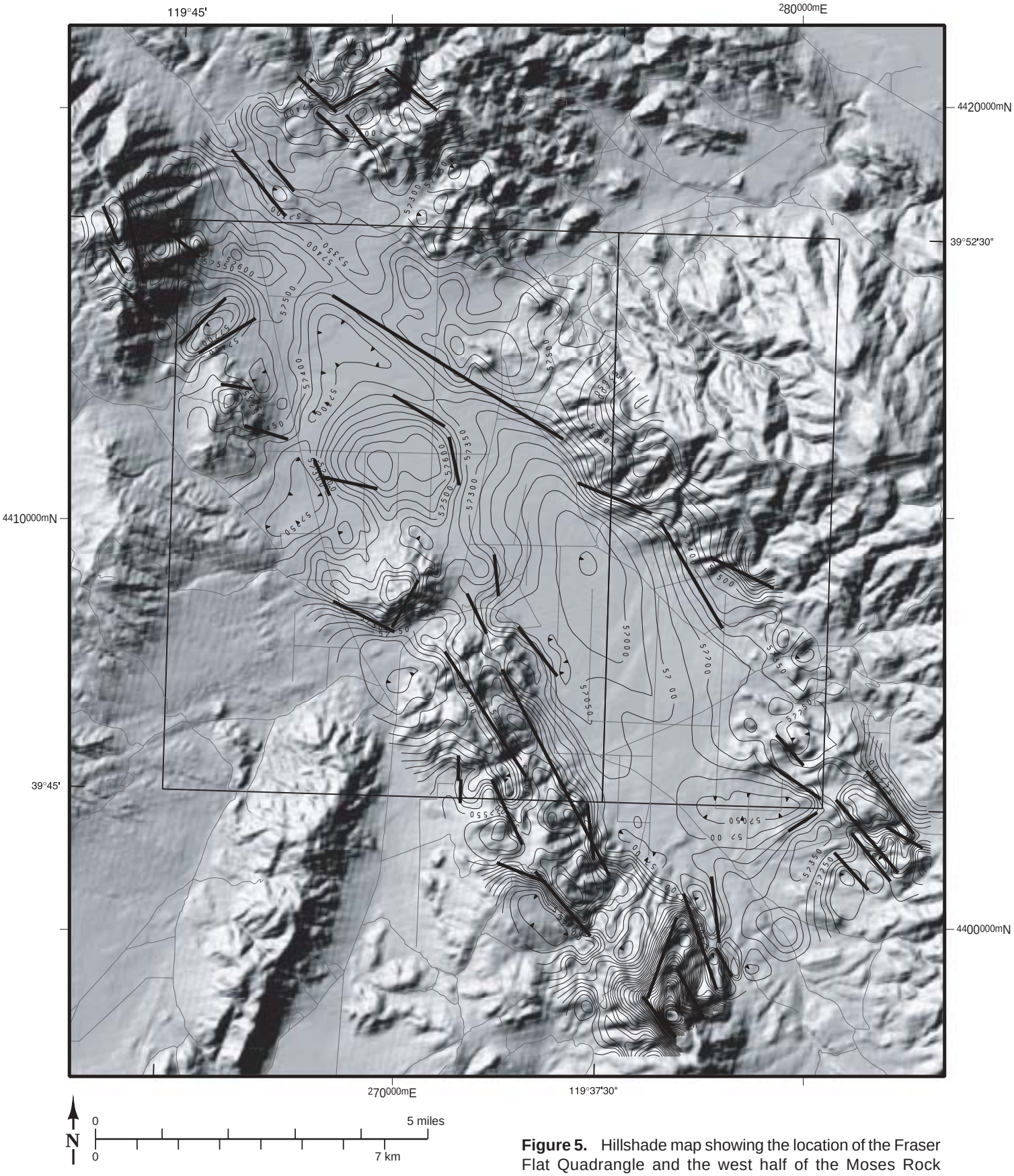

Figure 5. Hillshade map showing the location of the Fraser Flat Quadrangle and the west half of the Moses Rock Quadrangle, total magnetic field contours for the Warm Springs Valley area (50 nT contour interval), and lineaments (heavy lines) interpreted from total horizontal gradient.

(the Pyramid Lake Highway) is associated with basin fill sediments that have been estimated at 300 m thickness (Hartley, 1995). This conclusion is supported by the gravity work of Gimlett (1967) showing a gravity depression in the same general area with much higher complete Bouguer anomalies to the northwest. In southern Warm Springs Valley, magnetic highs are well correlated with the Pah Rah Range and the magnetic lows with relatively thick sedimentary basin-fill. The broad magnetic high west of State Route 445 represents a magnetic body that appears to be associated with the subsurface continuation of granitic rock that crops out immediately to the south. Thus, this granitic rock is interpreted to be relatively shallow below valley fill material. In Winnemucca Valley near the northern edge of figure 5 there is a magnetic ridge that trends northwest. This coincides with the Warm Springs Valley fault, which is projected to extend to the southeast along the east margin of Warm Springs Valley.

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