CENTER FOR VOLCANIC AND TECTONIC STUDIES¹ DEPARTMENT OF GEOSCIENCE

University of Nevada, Las Vegas

Las Vegas, Nevada 89154

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ANNUAL REPORT for the Period 10/1/90 to 9/30/91 Submitted to

the Nuclear Waste Project Office

State of Nevada

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INTRODUCTION

The annual report of the Center for Volcanic and Tectonic Studies (CVTS) contains a series of papers, maps, reprints and theses that review the progress made by the CVTS between October 1, 1990 and September 30, 1991. During this period CVTS staff focused on several topics that had direct relevance to volcanic hazards related to the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. These topics included:

(1) The role of the mantle in controlling the location and composition of Pliocene-Holocene volcanism.

(2) The nature of boundaries between compositionally different mantle domains. These domain boundaries may control the location of surface faults and volcanism.

(3) The detailed geology of the Pliocene volcanic cones in Crater Flat.

(4) The detailed geology of bedrock to the east of Crater Flat on Yucca Mountain.

(5) The structural controls and emplacement mechansims of Pliocene/Quaternary basaltic volcanic centers and dikes.

(6) The study of young felsic volcanism in the southern Basin and Range.

(7) Estimating the probability of disruption of the proposed repository by volcanic eruption (this topic is being studied by Dr. C. Ho-UNLV).

<u>Activities</u>

CVTS presented papers at several professional meetings including:

(a) The Geological Society of America Cordilleran Section Meeting in San Francisco- March 25-27, 1991.

(b) The Napoli '91 International Conference on Active Volcanoes and Risk Mitigation, in Naples, Italy - August, 1991.

(c) The Geological Society of America National Meeting in San Diego, October, 1991.

In addition CVTS staff participated in several technical exchanges and field trips with NRC, ANCW and NWTRB panels, and presented numerous invited talks, seminars and field trips to the public about volcanism and the proposed nuclear waste repository. The CVTS staff feel that part of their responsibility is to provide the public with unbiased and alternative views of the issues related to the proposed Yucca Mountain high-level nuclear waste repository. Invited talk and lectures to public meetings and civic groups as well as large enrollment classes at UNLV provide the community with a source of information regarding the geology and geologic hazards related to the project.

CVTS Staff

During the period October 1, 1990 to September 30, 1991, CVTS staff included Eugene I. Smith (PI), Dan Feuerbach and Terry Naumann (Research Associates), and Tracey Tuma (Student Assistant). Jim Faulds (University of Iowa) received partial support to complete his field studies in the Malpais Mesa area of Arizona and in Crater Flat. In addition, two graduate students (Tracey Cascadden and Hayden Bridwell) were partially funded to complete Master's Thesis projects.

Organization of the Annual Report

This report includes the following contributions:

(1) "Evolution of a mantle domain boundary during regional extension: constraints from isotopic geochemistry of volcanic rocks in the Lake Mead area, Nevada and Arizona" by D.L. Feuerbach, E.I. Smith (CVTS-UNLV) and J.D. Walker (University of Kansas).

(2) A summary of a paper entitled "Isotope geochemistry of the mafic lavas of the Reveille Range, Nevada: A window into the mantle of the central Great Basin." by T.R. Naumann, E.I. Smith (CVTS-UNLV) and J.D. Walker (University of Kansas).

(3) The geologic map of Crater Flat, Nevada. The authors of the map are J. Faulds (University of Iowa), D. Feuerbach (CVTS-UNLV), A. Ramelli (UNR) and John Bell (UNR). This map and explanation will be published by the Nevada Bureau of Mines and Geology.

(4) A summary of a paper regarding the structural control and emplacement mechanism of mafic dikes by J. Faulds (University of Iowa).

(5) Copies of abstracts submitted by CVTS staff during the year of funding.

These include:

(a) "Structural control of Pliocene volcanism in the vicinity of the Nevada Test Site, Nevada: an example from Buckboard Mesa" by Naumann, Feuerbach and Smith. Presented at the Geological Society of America Cordilleran Section meeting in San Francisco.

(b) "The transition from subalkalic to alkalic volcanism in the Lake Mead area of Nevada and Arizona: geochemical and isotopic constraints" by Feuerbach, Smith, Walker and Tangeman (Kansas). Presented at the Geological Society of America Cordilleran Section meeting in San Francisco.

(c) "The eastern boundary of the extensional allochthon in the eastern Basin and Range: volcanic and structural geology of the northern White Hills, Arizona" by Cascadden and Smith. Presented at the Geological Society of America Cordilleran Section meeting in San Francisco.

(d) "New insights on structural controls and emplacement mechanisms of Pliocene/Quaternary basaltic dikes, southern Nevada and northwestern Arizona" by Faulds, Feuerbach and Smith. Presented at the Geological Society of America National Meeting in San Diego.

(e) "Intermediate and mafic volcanic rocks of the northern White Hills, Arizona: implications for the production of intermediate composition volcanic rocks during regional extension" by Cascadden and Smith. Presented at the Geological Society of America National Meeting in San Diego.

(f) "Hornblende geobarometry from mid-Miocene plutons: implications regarding uplift and block rotation during Basin and Range extension" by Metcalf (UNLV) and Smith. Presented at the Geological Society of America National Meeting in San Diego.

(g) Volcanic risk assessment studies for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, USA" by Smith, Feuerbach, Naumann and Ho (UNLV). Presented at the Napoli '91 International Conference on Active Volcanoes and Risk Mitigation in Naples, Italy.

(6) Two papers describing new K-Ar dates from the Reveille Range and Fortification Hill field published in Isochron/West.

Naumann, T.R., <u>Smith. E.I.</u>, Shafiqullah, M., and Damon, P.E., New K-Ar ages for mafic to intermediate volcanic rocks in the Reveille Range, Nevada: Isochron West.

Feuerbach, D.L., <u>Smith. E.I.</u>, Shafiquallah, M., and Damon, P.E., New K-Ar dates for mafic late-Miocene to Pliocene volcanic rocks in the Lake Mead area, Arizona and Nevada: Isochron West.

1

(7) A thesis entitled "The Sloan Sag: A Mid-Miocene volcanotectonic depression, north-

central McCullough Mountains, southern Nevada" by Hayden Bridwell. This thesis deals with a section of young (<12 Ma) felsic volcanic rocks in the McCullough Range, 16 kilometers south of Las Vegas.

(8) A thesis entitled "Style of volcanism and extensional tectonics in the eastern Basin and Range Province: northern Mohave County, Arizona" by Tracey Cascadden. The thesis deals with the formation of mafic volcanic rocks in an extensional environment.

If these theses are not included in your copy of the annual report and you wish more information, contact the CVTS (702) 739-3971.

EVOLUTION OF A MANTLE DOMAIN BOUNDARY DURING REGIONAL EXTENSION: CONSTRAINTS FROM ISOTOPIC GEOCHEMISTRY OF VOLCANIC ROCKS IN THE

LAKE MEAD AREA, NEVADA AND ARIZONA

by

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5

INTRODUCTION

In the southwestern U.S.A., three mantle isotopic provinces were defined by the use of Sr and Nd isotopic systems (Fitton et al., 1986; Menzies et al., 1983; Farmer et al., 1989) (Figure 1). These are: (1) Basin and Range characterized by ϵ Nd between +5 and +8 and initial ^{\$7}Sr/^{\$6}Sr =0.703 (Perry et al., 1987; Menzies et al., 1983; Farmer et al., 1989); (2) Transition zone between the Colorado Plateau and Basin and Range with ^{\$7}Sr/^{\$6}Sr between 0.7038 and 0.707 and ϵ Nd between -4 and +5 (Cooper and Hart, 1990; Fitton et al., 1986); and (3) Sierra Nevada or Western Great Basin province distinguished by ^{\$7}Sr/^{\$6}Sr > 0.706 and ϵ Nd between 0 and -11 (Menzies et al., 1983; Fitton et al., 1986; Fitton et al., 1991. Basalts with similar ^{\$7}Sr/^{\$6}Sr and ϵ Nd in southern Nevada (Farmer et al., 1989) also lie within this province.

The boundary between the Western Great Basin and Basin and Range provinces (Menzies et al., 1983; Fitton et al., 1991) and the contact between the OIB and EM2 mantle domains of Menzies (1989) pass through the Lake Mead area of southern Nevada (Figure 1). The Lake Mead area also contains an important crustal boundary. The Lake Mead fault zone (LMFZ) (Anderson, 1973; Bohannon, 1984; Duebendorfer and Wallin, 1991), a northeast trending set of left-lateral strike-slip faults separates the "amagmatic zone" from the Northern Colorado River extensional corridor (NCREC). The amagmatic zone is a region of minor igneous activity and little to moderate Tertiary extension that separates the Great Basin from the Sonoran Desert sections of the Basin-and-Range province in the western U.S.A. This region between 36° and 37° north, corresponds to a regional topographic slope and a gravity gradient with an amplitude of about 100 mgals (Eaton, 1982; Eaton et al., 1978). The zone also represents a boundary between contrasting migration directions of magmatism and extension (Bartley et al., 1988; Bartley, 1989; Glazner and Supplee, 1982; Reynolds et al., 1987). In contrast, the NCREC (Howard and John, 1987) experienced over 100% extension and abundant magmatism during Tertiary time. The LMFZ also separates thick sections of Paleozoic and Mesozoic sedimentary sections (to the north) from the NCREC, an area nearly devoid of these sections (Longwell et al., 1965; Anderson, 1971).

This paper focuses on the boundary between the amagmatic zone and the NCREC. We use Miocene and Pliocene mafic volcanic rocks ($SiO_2 < 55\%$) that span this mantle-crustal boundary as "a probe" into the mantle to determine (1) the nature of isotopic differences across the boundary, (2) the timing of formation of the boundary, and (3) any link between crustal and mantle processes. Our goal is to develop a three-dimensional model for the evolution of a mantle isotopic domain boundary.

In continental settings, the boundary between lithospheric mantle and asthenosphere is marked by differences in isotopic and trace-element signatures. Lithospheric mantle is enriched in incompatible elements and has high Rb/Sr and low Sm/Nd compared to asthenospheric mantle. As a result, lithospheric mantle has higher 87 Sr/ 86 Sr and lower ϵ Nd values than asthenospheric mantle. The difference in isotopic values between lithospheric and asthenospheric mantle is probably due to the long-term isolation of the lithospheric mantle from mixing caused by mantle convection.

Mafic volcanism is useful in the mapping of mantle domains (Menzies, 1989). The



Figure 1. Map showing the major mantle domain boundaries proposed for the southern Basin and Range.

lithospheric mantle is isotopically enriched and heterogeneous (Zindler and Hart, 1986; Hart, 1985; Weaver, 1991a; Leat et al., 1990; Cooper and Hart, 1990; Walker and Coleman, 1991). Chemical and isotopic heterogenety may be due to the incorporation of oceanic crust and terrigenous or pelagic sediments (Weaver, 1986,1991a) or be a result of mantle metasomatism (Hart, 1988). Mantle components such as EM1, EM2 and HIMU probably reside in the lithospheric mantle because their isotopic signature require isolation from the convecting asthenosphere for 1.0 to 2.0 Ga (Zindler and Hart, 1986). Recently, however, Weaver (1991b) suggested that these components may reside in detached slabs of oceanic crust that have accumulated deep within the mantle (mesosphere) and have not appreciably mixed with asthenosphere.

INSTUMENTAL TECHNIQUES

Whole rock major element concentrations were determined by Inductively Coupled Plasma techniques (ICP) at Chemex Labs, Inc. (Sparks, NV). Rare-earth elements and Cr, V, Sc, Co, Ta, Hf, Th were analyzed by Instrumental Neutron Activation Analysis (INAA) at the Phoenix Memorial Laboratory, University of Michigan. The multi-element standards G-2, GSP-1, BHVO-1, and RGM-1 were used as internal standards. Ba, Rb, Ni and Sr were determined by atomic absorption and Nb and Sr were determined by X-ray Fluorecence at Chemex Labs, Inc. Rb and Sr were determined by isotope dilution for samples which were analyzed for Nd, Sr and Pb isotope concentrations. Ni, Nb, Rb, Sr, Zr, Y, Ba for the samples from Fortification Hill were analyzed by XRF at the U.S. Geological Survey in Menlo Park. This study includes 45 new isotopic analyses from 11 volcanic sections which represent all major volcanic centers and a fairly complete sample of mafic volcanic rocks in the Lake Mead area. Geochemical data is summarized in Table 1.

VOLCANOLOGY

Distribution and Description of Volcanic Sections

Volcanism is rare to the north of the LMFZ in the "amagmatic" zone and is limited to low-volume Pliocene basalt centers at Black Point and in the Las Vegas Range (Figure 2a). In the eastern part of the Lake Mead area in the Gold Butte and Grand Wash trough there are numerous late-Cenozoic alkali basalt centers (Cole, 1989). Adjacent to the the LMFZ is the middle- to late-Miocene Hamblin-Cleopatra volcano (Thompson, 1985; Barker and Thompson, 1989); Boulder Wash volcanic section (Naumann, 1987); Callville Mesa volcano (Feuerbach et al., 1991); and flows of late-Miocene basalt interbedded with Tertiary sediments in Government Wash north of Lake Mead (Figure 2b). The area to the south of the LMFZ contains numerous Miocene and Pliocene volcanic centers (Figure 2b). The most notable of the Miocene centers are in the River Mountains (Smith, 1982); McCullough Range (Smith et al., 1988); Eldorado Mountains (Anderson, 1971); Hoover Dam (Mills, 1985); at Malpais Flattop and in the White Hills (Cascadden, 1991). Pliocene centers comprise the Fortification Hill volcanic



Figure 2a. Index map of the southern Great Basin and adjacent Basin and Range and Colorado Plateau showing location of mafic volcanoes. Box indicates area shown in Figure 2b. LVR = Las Vegas Range, BP = Black Point, GB = Gold Butte, GW = Grand Wash, RM = River Mountains, EM = Eldorado Mountains, LMFZ = Lake Mead Fault Zone.

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Figure 2b. Index map of the Lake Mead area showing localities described in text and major structures. HC = Hamblin-Cleopatra volcano, WH = White Hills, LC = Lava Cascade, PW = Petroglyph Wash, CM = Callville Mesa, FH = Fortification Hill, GovW = Government Wash.

Isotopic and Geochemical Data from the Volcanic Rocks in the Lake Mead Area

	VAR	VAR	OAR	OAR	SAR	SAR	SAR	тн
Sample	25-2	42-76	57-107	57-113	42-82	38-13	38-143	10-120
SiO2	44.9	45	45.35	44.15	47.52	45.79	47.97	46.32
AI2O3	16.5	16.79	16.71	15.22	16.61	14.5	16.05	15.3
FeO	11.1	10.88	13.81	13.38	10.56	12.8	11.87	13.39
MgO	· 5.7	6.21	5.54	8.0 6	5.35	8.78	5.32	8.92
CiO	7.7	8.78	11.13	10.69	9.7 9	8.38	10.16	7.93
Na2O	4.7	4.9 4	3.15	2.88	3.57	2.8 6	3.26	2.97
TiO2	1	3.7	1.2	1.1	2.11	0.84	1.4	0.9
K2O	2.4	2.54	2.07	1.76	1.76	1.41	1.46	1.16
P2O5	0.7	0.88	0.53	0.52	0.57	0.28	0.49	0.34
MnO	0.2	0.18	0.19	0.18	0.16	0.16	0.17	0.19
LOI	2.93	0.6	0.06	0.52	1.42	1.48	0.49	4.11
Total	97.83	100.5	9 9.74	98.4 6	99.42	97.28	98.64	101.53
	Trace and Ra	re Earth Eles	ments (PPM)	(XRF, ID, A	A or INAA)	noted		
Cr(INAA)	139	113	`8 0 ´	268	50	361	70	326
Co(INAA)	29.1	29.6	34.69	43.12	31.8	52.58	32.79	53.7
Sc(INAA)	18	18.6	28.63		25	26.5	26.32	24.68
V (INAA)		216	245	229	2 81	213	236	177
Hf(INAA)	6.5	7.22	4.51	3.26	4	3.38	4.18	2.83
Th(INAA)	8.5	12.4	3.6 6	3.15	5.28	2.87	3.23	1.16
Ta(INAA)	4	6.01	2.07	1.66	1.87	1.69	1.31	
La(INAA)	59.9	75.1	37.21	32.11	37.7	24.58	32.69	11.79
Ce(INAA)	116.3	151	69.7	59.18	72.3	52.42	57.45	24.73
Eu(INAA)	2.4	2.3	1.61	1.46	1.61	1.59	1.53	1.05
Yb(INAA)	2.8	2.43	2.59	2.79	2.49	2.2	2.52	2.3
Lu(INAA)	0.3	0.22	0.35	0.26	0.37		0.37	0.17
U (INAA)					1.83			
Sm(INAA)	8.8	8.61	5.95	5.27	6.16	4.83	5.53	3.07
ID(INAA)		1.33						
Sr(ID)	999.69	873.59	463.93	451.23	597.57	434.24	491.11	306.35
	20.24	43.4	11.09	9.68	22.13	14.31	14.86	14.45
	40.29	49.48	27.26	24.77	32.26		25.45	19 0
Da(AA)	/44	1520	536	480	800	475	690	
NI(AA)	10	08 85	42	126	30	166	24	
7+(XDE)	250	300	30	30	34	28	28	10
	200		100	140	155	138	138	90
Isotopic analysis by Mass Spectrometry								
143Nd/144Nd	0.5126	0.5128	0.5127	0.5128	0.5126	0.5126	0.5126	0.5125
Epsilon Nd	3.18	3.63	1.42	1.42	-0.68	-0.84	-0.9	-2.3
(87Sr/86Sr)i	0.7043	0.7035	0.7048	0.7051	0.7055	0.7057	0.7057	0.7075
206Рь/204Рь	18.737	18.741	18_591	18.67	18.263	18,194	18 123	18 022
207Рь/204Рь	15.564	15.523	15.555	15.57	15.548	15.523	15 541	15 521
208Pb/204Pb	38.639	38.476	38.535	38.612	38.397	38,309	38,156	38.0

	TH	LV Range	G.Butte	G. Wash	G.Wash	G.Wash	G.Wash	G.Wash
Sample	10-121	LV-104	3-6	4-13	5-14	6-39	7-33	8-62
SiO2	44.58	42.49	46.3	47.58	48.81	48.44	47.85	47.31
A12O3	14.35	10.76	14.64	14.4	14.95	14.57	14.53	15.99
FcO	13.82	12.79	12.59	14.53	11.73	12.75	13.83	11.37
MgO	8.7 6	13.45	9.16	8.55	7.14	8.42	7.8 6	4.73
CiÓ	6.55	9.78	7.9 8	8.74	8.64	9.88	7.41	10.43
Na2O	4.17	2.39	3.16	3	3.22	3.1	4.32	3.49
TiO2	0.7	1	1.19	1.25	1.54	0.91	1.85	2.29
K2O	1.1	1.69	1.59	1.55	1.57	1.92	2.42	1.72
P2O5	0.3	0.67	0.27	0.26	0.43	0.29	0.59	0.18
MnO	0.19	0.16	0.18	0.19	0.16	0.17	0.17	0.16
loi	3.14	1.79	1.06	0.19	1.09	0.01	0.01	1.63
Total	97.66	96.97	98.12	100.24	99.28	100.46	100.75	99.3
Cr(INAA)	271	816	253	326	256	459	189	223
Co(INAA)	56.33	57.55	46.68	50.49	39.52	47.2	47	34.3
Sc(INAA)	24.53	22.21	23.73	. 27	23.91	26.7	15.4	0.4
V (INAA)	194	234	216	242	215	208	182	255
Hf(INAA)	1.7	5.22	3.63	3.14	3.24	3.59	6.42	3.84
Th(INAA)		5.2	2.72		2.78	3.21	3.62	2.25
Ta(INAA)	0.95	0.71					3.16	1.35
La(INAA)	12.61	46.02	23.86	9.04	19.21	20.9	34.6	18.9
Ce(INAA)	24.27	91.97	46.11	21.87	44.2 6	44.8	71	39.1
Eu(INAA)	0.93	2.34	1.45	0.95	1.33	1.4	1.96	- 1.31
Yb(INAA)	1.75	1.74	2.47	1.96	2.28	0.16	1.55	2.11
Lu(INAA)	0.28	0.13	0.35	0.3	0.24	0.22	0.18	0.37
U (INAA)				·				
Sm(INAA)	3.07	10.23						
Tb(INAA)								
Sr(ID)	246.12	795.58	421.14	321.83	378.36	419.48	723.94	4 47.64
Rb(ID)	8.98	48.27	14.88	7.47	8.0 6	12.45	22.94	10.04
Nd(ID)		55.76	22.47	14.35	17.89	20.52	29.65	16.21
Ba(AA)	176							
NI(AA)	206							
ND(XKF)	13							
ZI(XRF)	TI							
143Nd/144Nd	0.5125	0.5123	0.5126	0.5126	0.5127	0.5126	0.513	0.5128
Epsilon Nd	-3.55	-7.2	-0.9	-0.27	1.87	-0.04	6.75	3.49
(87Sr/86Sr)i	0.7079	0.7068	0.705	0.7046	0.7046	0.704	0.7033	0.7042
206Рь/204Рь	17.947	18.963	18.13	17.821	18.13	18.119	18.075	17.999
207Рь/204Рь	15.499	15.642	15.527	15.55	15.51	15.518	15.473	15.5
208РЪ/204РЪ	38.291	38.845	38.068	38.05	37.83	38.034	37.704	37.758

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	C.Mesa	C.Mesa	R.Mtns	R.Mtns	R.Mtns	R.Mtns	W.Ridge
Sample	24-49	24-68	78-218	78-222	78-223	83-348	LL-88-41
SiO2	55.24	55.18	47.1	59	67.2	72.9	54.1
A12O3	15.9 8	15.84	14.5	16.6	14.2	12.6	16.9
FeO	8.97	8.49	10.9	6.9	3.5	2.7	8.9
MgO	4.1	4.33	6.3	2.6	0.9	0.2	4.5
CaO	6.9	6.64	11.2	5.5	2.3	0.5	7.4
Na2O	3.55	3.52	2.8	3.9	3.6	2.2	4.2
TiO2	2.33	2.45	1.2	2.3	4.9	7.5	2.1
K2O	1.13	1.07	1.8	0.9	0.4	0.2	1.5
P2O5	0.25	0.3	1	0.6	0.1		0.7
MnO	0.14	0.1	0.1	0.1	0.1		0.1
LOI	0.4	2.17	2.3	1	3	0.1	0.5
Total	96.98	100.18	99.2	99.4	100.2	98.9	100.9
Cr(INAA)	145	134					
Co(INAA)	28.79	27.7					20
Sc(INAA)	19.62	18.2	29.6	e 11.2	3.8	1.5	
V (INAA)	171	153					198
Hf(INAA)	3.86	4.29	8.1	7.3	4.8	4.9	5.1
Th(INAA)	4.89	5.4 6	13.2	14.9	17.6	31.2	12.4
Ta(INAA)	0.97	0.96	1.5	1	1.2	15.3	2.1
La(INAA)	33.95	34.2	107.6	81.7	52.4	55.6	123
Cc(INAA)	67.61	72.1	242.4	167.9	90.7	124.5	213
Eu(INAA)	1.38	1.4	3.9	2	1.2	1	2.6
Yb(INAA)	2.18	2.6	2.1	2.3	1.3	2.2	2.3
Lu(INAA)	0.34	0.34	0.4	0.4	0.2	0.3	0.3
U (INAA)			6.4	4.6	9.1	3.9	
Sm(INAA)	5.32	5.22	15.5	8.7	4.2	3.7	10.9
Tb(INAA)			3	1.5	0.3	0.4	
Sr(ID)	970.19	423.51		959.65	467.9 9	79.76	1155.78
Rb(ID)	40.1	50.94		83.62	129.26	198.08	42.05
Nd(ID)	29.96	25.97	98.57	54.9	28.2	22.84	76.018
Ba(AA)	840	800					
NI(AA)	36	60					
ND(AKF)	23	17					
Zf(XRF)	185	145		•.			
143Nd/144Na	0 5122	0 5121	0 5122	<u> </u>	0 512	0 512	0 5101
Ensilon Nd	_R 4Q	-10 69	_R 35	_11 28	.11 37	-12 20	_0 ec
-Ponon 110		-20162		-11.60	-11.37	- 1 <i>4</i> -47	-7.07
(87 Sr/86Sr)i	0.7089	0.7079		0.7089	0.7092	0.71	0.7082
206Рь/204Рь	17.332	17.173	18.299	17.922	17.885	18.156	17.887
207Рь/204Рь	15.496	15.453	15.605	15.537	15.553	15.578	15.537
208Рь/204Рь	38.01	37.814	38.699	38.791	38.982	38.906	38.725

	Gov.Wash	H.Clco	H.Cico	M.Flattop
Sample	EMD-209	KT82-15	KT82-183	60-4
SiO2	51.9	56.43	55.89	47.3
A12O3	15.2	16.36	16.34	14.9
FeO	9.4	6.76	7.17	12.4
MgO	3.8	3.43	3.48	6.8
CaO	8.2	6.56	5.4	8.9
Na2O	3.7	3.98	4.1	2.9
TiO2	3.2	2.47	2.72	1.1
K2O	1.8	1.31	1.39	1.4
P2O5	1.8	0.49	0.49	0.2
MnO	0.2	0.1	0.11	0.2
loi	1.2	1.38	2.85	0.77
Total	100.4	99.27	99.94	96.87
Cr(INAA)		63	47	241
Co(INAA)		20.65	22.76	41.1
Sc(INAA)		14.06	14.11	30
V (INAA)		147	145	221
Hf(INAA)		6.76	8.15	3.6
Th(INAA)		10.46	13.53	
Ta(INAA)		2.75	2.84	
La(INAA)		65.23		14.8
Ce(INAA)		114.03	126.79	35.7
EU(INAA)		1.89	1. 9 9	1.1
ID(INAA)		1.73	2.04	2.6
LU(INAA)			0.26	0.3
O(INAA)				
SII(INAA)		7.75	8.29	3.9
10(UNAA) S-(ID)	1000 45	100.05	5 00 4 4	1.4
	1299.00	432.85	588.44	297.25
Nd(ID)	/J.9/ 74.19	45.83	47.52	16.69
Ra(AA)	/4.10	45.08	45.27	16.72
$N_i(\Delta \Delta)$		•		280
Nh(XRF)				64 12
Zr(XRF)				105
14284/144814	0.5121	06124	0.5104	0.6100
Facilon Nd	0.05	U.3124	0.5124	0.5122
	-7.70	-4.84	-5.21	-8.33
(87Sr/86Sr)i	0.7073	0.7044	0.7056	0.7075
206Рь/204Рь	18.16	17.971	18.096	17.742
207Рь/204Рь	15.56	15.515	15.538	15.531
208Рь/204Рь	38.939	38.344	38.549	38.83

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field that extends discontinuously from near Willow Beach, Arizona to Lake Mead. In the Lake Mead area, for the most part, volcanism preceeded block tilting related to regional extension (9 to 12 Ma; Duenbendorfer and Wallin, 1991). Calc-alkaline intermediate lavas were erupted between 18.5 and about 11 Ma. Low-volume basaltic andesite (10.3 to 8.5 Ma) and tholeiitic and alkalic basalt (4.7 to 6 Ma) mainly postdate extension (Smith et al., 1990).

Volcanic Rocks of the NCREC

Fortification Hill Field

Fortification Hill (FH) basalt crops out in a 75 km long by 30 km wide north-northeast elongate area that extends from Lava Cascade, Arizona to Black Point, Nevada (Figure 2b). Volcanic centers occur near north-northwest trending high-angle normal faults in the northern part of the NCREC. We divide the Fortification Hill basalts into three groups based on Na_2O+K_2O , light rare-earth element (REE) enrichment (Figure 3 and 4) and modal mineralogy. The groups are: (1) Sub-alkalic basalt (SAB)(5.88-4.73 Ma; Feuerbach et al., 1991)- sub-alkalic hypersthene-normative lavas with Ce/Yb_n (4-6). SAB lavas form a cinder cone-flow sequence on the north side of Fortification Hill. (2) Older alkali-basalt (OAB)(5.88 to 4.73 Ma; Feuerbach et al., 1991)- mildly alkalic hypersthene or nepheline-normative olivine-basalt with high Ce/Yb. (4-8). OAB lavas erupted from north-northwest aligned coalesced cinder cones on Fortification Hill and from cinder cones at Lava Cascade and in Petroglyph Wash (Figure 2b). SAB and OAB lavas contain porphyritic iddingsitized olivine phenocrysts in a trachytic to pilotaxitic groundmass of olivine, andesine, labradorite, diopsidic-augite and iron oxide. Coarse-grained plugs of OAB and SAB in volcanic centers consist of olivine phenocrysts in a coarse-grained interstitial groundmass of andesine, labradorite, diopsidic-augite and olivine. (3) Young alkalic-basalt (YAB) (4.64-4.3 Ma; Feuerbach et al., 1991; Anderson et al., 1972)- highly alkalic nepheline-mormative olivine basalt with elevated Ce/Yb, (8-16). YAB lava occurs in three locations: (1) a diatreme at Petroglyph Wash, (2) en-echelon dikes and a vent, along U.S. highway 93, 10 km south of Hoover Dam, and (3) south of Saddle Island between the North Shore road and Lake Mead (Smith, 1984). The matrix of YAB ranges from glassy to interstitial or pilotaxitic and contains microlites of plagioclase, altered olivine, altered diopsidic-augite and magnetite. Olivine is the primary phenocryst phase. Rare xenoliths of plagioclase-hornblende diorite occur in YAB. Ubiquitous to these young lavas are ultramafic inclusions and megacrysts of augite and kaersutite (Nielson, manuscript in preparation; Campbell and Schenk, 1950). Besides the presence of diorite inclusions in YAB, there is no petrographic evidence of crustal contamination in Fortification Hill lavas.

River Mountains

In the River Mountains (Smith, 1982; Smith et al., 1990) (Figure 2a and 2b) an andesite-dacite stratovolcano is surrounded by a field of dacite domes. Volcanism



Figure 3. Plot of Ce/Yb normalized to chondrite vs. SiO₂ for volcanic rocks in the Lake Mead area. This plot divides mafic lavas into CM=Callville Mesa (open diamonds), OAB= old alkali basalts (open squares), SAB= subalkalic basalts (open circles), th=tholeiitic basalts (+), YAB= alkali basalts (open triangles).

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Figure 4. Chondrite normalized rare-earth element plot of volcanic rocks in the Lake Mead area. Explanation of symbols is in the caption of Figure 3.

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occurred in four pulses, the first three are characterized by the eruption of calc-alkaline andesite and dacite flows and the last by rhyolite and alkali basalt. Based on available K-Ar whole rock dates (Anderson et al., 1972) volcanism began in the River Mountains at about 13.5 Ma and terminated at 12 Ma.

Boulder Wash

The Boulder Wash in the northern Black Mountains (Figure 2b) contain a 700-mthick section of calc-alkaline dacite flows and flow breccias interbedded with flows of pyroxene-olivine andesite containing abundant xenocrysts of quartz and orthoclase (Smith et al., 1990; Naumann and Smith, 1987; Naumann, 1987). Petrographic and textural evidence of magma commingling is well developed in the volcanic section and associated plutonic rocks. Smith et al. (1990) and Naumann (1987) concluded that various mixing ratios of alkali olivine basalt and rhyolite end members are responsible for the textural variations. A dacite flow in the eastern part of the volcanic field was dated at 14.2 Ma (Thompson, 1985).

Malpais Flattop

Malpais Flattop near Willow Beach, Arizona (Figure 2b) contains a 100 m thick stack of tholeiitic basalt flows that erupted from at least two centers now expressed as wide (40 m) dikes and plugs on the west side of the Malpais Flattop mesa. A K-Ar whole rock date of 15.4 Ma was obtained from one of the dikes, however an 40 Ar/ 39 Ar date of 10.24 Ma was acquired from the same rock. These dates contrast with a 6 Ma age determined by Anderson et al. (1972). Even though the date of the Malpais Flattop is not well constrained, we conclude that eruptions at Malpais mesa occurred prior to 10 Ma; 4 m.y. earlier than the production of Fortification Hill basalts.

Eldorado Mountains

A sequence of mafic to felsic volcanic rocks erupted between 18.5 and about 12 Ma in the Eldorado Mountains (Anderson, 1971; Darvall et al., 1991) (Figure 2a). The sequence is divided into a lower section of basaltic-andesite (predominant) and rhyolite lavas (Patsy Mine volcanics; Anderson, 1971); and an upper section of basaltic andesite, dacite and rhyolite (Mt. Davis volcanics; Anderson, 1971). Mafic lavas lack petrographic and field textures characteristic of crustal contamination or magma commingling. A similiar section of mafic lavas in the White Hills, Arizona (Figure 2b) formed by partial melting of mantle peridotite without significant crustal interaction (Cascadden and Smith, 1991; Cascadden, 1991). In the Eldorado Range, lavas and associated plutonic rocks span the period of most rapid extension. Patsy Mine and the lower parts of the Mt. Davis section are tilted nearly 90 degrees. Younger units are rotated less in the same structural blocks (Anderson, 1971; Darvall et al., 1991).

Volcanic Rocks in the Amagmatic Zone

Black Point

At Black Point on the west shore of the Overton Arm of Lake Mead (Figure 2b), thin flows of tholeiitic basalt (6.02 Ma; Feuerbach et al., 1991) associated with north-striking en-echelon dikes overlie gypsiferous sediments of the Tertiary Horse Spring Formation. Total outcrop area is about 12 km^2 . Basalts at Black Point are hypersthene-normative tholeiites (TH) and have low Ce/Yb_n (2-4). They contain iddingsitized olivine, labradorite and diopsidic-augite phenocrysts within either a trachyitic or ophitic groundmass. Tholeiitic lavas also contain groundmass hypersthene and pigeonite.

Callville Mesa

Basaltic andesite erupted from compound cinder cones on Callville Mesa and in West End Wash between 10.46 and 8.49 Ma (Feuerbach et al., 1991) (Figure 2b). Basaltic-andesite contains phenocrysts of euhedral to subhedral iddingsitized olivine; subhedral andesine and labradorite; and subhedral, poikilitic diopsidic-augite. Subhedral hypersthene and pigeonite are also present. Quartz and alkali-feldspar (sanidine) occur as xenocrysts that are rimmed by glass and acicular clinopyroxene (diopsidic-augite).

The vent on Callville Mesa sits on the footwall of an east-west striking down-to-the-south normal fault (Figure 2b). Flows on Callville Mesa are offset from 5 to 20 m by south-dipping west-southwest striking high-angle normal faults. Since the presence of a Paleozoic and/or Mesozoic sedimentary section is characteristic of the amagmatic zone but not of the NCREC, the presence or absence of these rocks is our main field criterion for assigning a volcano to a specific province. The volcanic center at Callville Mesa sits on the boundary between the two provinces within the Las Vegas Valley-Lake Mead fault zone. The Bitter Spring Valley fault passes just to the north and the Hamblin Bay fault projects just to the south. It is unclear whether Mesozoic and Paleozoic sedimentary rocks lie beneath the volcanic centers on Callville Mesa since volcanoes sit on a thick section of Tertiary sediments. However just to the northeast of Callville Mesa, flows of basaltic andesite rest on Tertiary sedimentary section. This relationship prompts the assignment of the Callville Mesa volcano to the amagmatic zone.

Las Vegas Range

The Las Vegas Range locality is composed of thin flows of alkaline basalt in a fault bounded basin just to the west of U.S. highway 93 (Figure 2a). Flows (2 km²) are mostly covered by Quaternary fanglomerate and alluvium and as a result no source area was discovered. Las Vegas Range basalt has not been dated, but since the flows are neither tilted or faulted, they are assumed to be Pliocene in age.

Hamblin-Cleopatra Volcano

The Hamblin-Cleopatra volcano (14.2-11.5 Ma) (Anderson, 1973; Thompson, 1985) which lies along the north shore of Lake Mead (Figure 2b), is a 60 km³ stratovolcano comprised of shoshonite, latite, trachydacite and trachyte lava (Barker and Thompson, 1989). In addition, tephra, epiclastic sediments, intrusions and and a well developed radial dike system form the volcano. The volcano was dissected into three segments by left-lateral strike-slip faulting associated with the LMFZ (Anderson, 1973; Thompson, 1985; Barker and Thompson, 1989).

Basalt of Government Wash

Olivine-phyric alkali basalt crops out in Government Wash just north of Lake Mead. An 80-m-thick section of flows and agglomerates are interbedded with the Lovell Wash member of the Tertiary Horse Spring Formation (Duebendorfer, personal communication, 1991). Basalt of Government Wash is dated at 12 Ma (Duebendorfer et al., 1991).

Volcanic Rocks at Gold Butte and in the Grand Wash Trough

The Grand Wash trough and the Gold Butte area (Figure 2a) contain flows of olivine-phyric alkali basalt (Cole, 1989). Basalt in the Grand Wash trough is dated at 3.99 to 6.9 Ma and is younger than basalt flows to the west in the Gold Butte area (9.1 to 9.4 Ma) (Cole, 1989). Cole (1989) suggested that the alkali basalt formed by partial melting of asthenospheric spinel peridotite. Melts were not appreciably fractionated during ascent or contaminated by crustal materials.

SOURCE OF MAFIC LAVAS AND CRUSTAL CONTAMINATION

Introduction

In this section we argue that the source of the mafic volcanic rocks in the Lake Mead area was either the lithospheric mantle or asthenosphere. Our assumption is that isotopic variation is due to differences in the mantle source. The possibility exists, however, that some or all of the variation could be due to crustal contamination. We demonstrate that crustal contamination was only significant in intermediate lavas of the River Mountains and mafic lavas at Callville Mesa and was not an important component in the source of mafic lavas in other areas.

Isotopic and trace element data divide the mafic lavas into two groups (Figure 5). 1. Low ${}^{87}Sr/{}^{86}Sr$. high ϵ Nd. This group is characterized by ${}^{87}Sr/{}^{86}Sr = 0.703-0.705$ and ϵ Nd = -1 to +4 and includes the alkali basalts of the Fortification Hill field and Grand Wash trough. Trace-element distributions are similar to the OIB average of Fitton et al. (1991) (Figure 6). Basalts with this isotopic and trace element signature probably originated by partial melting of the asthenospheric mantle.



Figure 5. ϵ Nd vs. ⁸⁷Sr/⁸⁶Sr plot for volcanic rocks in the Lake Mead area. Isotopic data divides the volcanic rocks into two groups. One with high ⁸⁷Sr/⁸⁶Sr and low ϵ Nd and the other characterized by lower ⁸⁷Sr/⁸⁶Sr and higher ϵ Nd. Prior to extension (pre-9 Ma) mafic volcanic rocks both to the north and south of the Lake Mead fault zone had isotopic compositions characteristic of a lithospheric mantle source (group 2 with higher ⁸⁷Sr/⁸⁶Sr and lower ϵ Nd). After extension, the isotopic composition of volcanic rocks to the south of the LMFZ shifts to lower ⁸⁷Sr/⁸⁶Sr and higher ϵ Nd, while the signature of mafic volcanic rocks to the north of the LMFZ remains unchanged. These changing patterns of isotopic compositions demonstrate that a mantle domain boundary formed in late-Miocene time during an episode of upper crustal extension. Crustal contamination affected rocks of the River Mountains, but resulted in only a minor shift in isotopic ratios (refer to Figure 7). Mantle components are provided for reference.

Figure 6. Spiderplots of incompatible elements vs. abundance normalized to OIB average of Fitton et al. (1991).

a. Mafic volcanic rocks in the NCREC erupted after about 9 Ma (open triangles) compared with average Transition Zone lavas (solid circles) of Fitton et al. (1991).



b. Mafic volcanic rocks in the Lake Mead area erupted prior to 9 Ma (open triangles) compared with average Western Great Basin lavas (solid circles) of Fitton et al. (1991).

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2. <u>High ⁸⁷Sr/⁸⁶Sr. low ϵ Nd.</u> This group has ⁸⁷Sr/⁸⁶Sr = 0.705-0.710 and ϵ Nd = -4 to -12 and includes mafic lavas in the River Mountains, Eldorado range, Boulder Wash area, Hamblin-Cleopatra volcano, Malpais Flattop, Government Wash exposure and in the Las Vegas Range. This group is similar in isotopic and trace element composition to mafic lavas of the Western Great Basin mantle province (Fitton et al., 1991; equivalent to the Southern Nevada basalts of Farmer et al., 1989) (Figure 6) and probably formed by partial melting of the lithospheric mantle.

Mantle Components and Crustal Contamination

Andesite and dacite in the River Mountains show abundant field and petrographic evidence of assimilation and magma commingling (Smith et al., 1990). Alkali basalt lacks evidence of contamination and was considered by Smith et al. (1990) to have been generated by partial melting of mantle peridotite. Intermediate lavas in the River Mountains may represent hybrid compositions formed by the commingling of mafic and felsic end-members. This is confirmed by a positive correlation between 87 Sr/ 86 Sr and SiO₂ (Figure 7). A mixing line between basalt and rhyolite end members of the mixing sequence provides a quantitative estimate of the magnitude of isotopic shift due to magma commingling (Figure 5). This shift is no more than 4 units in ϵ Nd and 0.002 in 87 Sr/ 86 Sr.

OAB, SAB and YAB in the Fortification Hill field have ϵ Nd = -1 to 3, $\frac{87}{56}$ Sr = 0.703-0.705, ${}^{206}Pb/{}^{204}Pb$ = 17.8-18.7 and ${}^{208}Pb/{}^{204}Pb$ = 38-38.5 and lie within the field of OIB-lavas (Figures 8 and 9) (Zindler and Hart, 1986). We infer that these magmas represent the melting of a source composed of a mixture of enriched mantle with a bulk earth signature with variable amounts of depleted asthenosphere (PREMA) and HIMU-mantle. YAB, SAB and OAB plot between bulk earth composition and higher values of ϵ Nd and ²⁰⁶Pb/²⁰⁴Pb (Figure 10). If PREMA were the other end-member, trends toward lower $^{206}Pb/^{204}Pb$ and higher ϵ Nd would be expected. This is the case for alkali basalts in the Grand Wash trough, Arizona plotted for comparison on Figure 10 (Cole, 1989). We suggest that the trend toward higher rather than lower Pb is due to the addition of HIMU-mantle (ϵ Nd = 3.5, 207 Pb/ 204 Pb = 15.85). The residence of HIMU, however, is enigmatic. It may reside in the lithospheric mantle or upper asthenosphere (Zindler and Hart, 1985; Hart, 1988) or as detached oceanic slabs deep within the mantle (Weaver, 1991b). High Sr and Ba and low Nb on spiderplots normalized to the OIB average island composition of Fitton et al. (1991) suggest that OAB and SAB also contain a lithospheric component and are more similar to Transition Zone than Basin and Range suites (Figure 6). EM1, a potential candidate for the lithospheric component is ruled out, since addition of this component will result in negative values of ϵ Nd.

The isotopic characteristics of the Fortification Hill field are similar to those of the Springerville volcanic field in the Transition Zone of southeastern Arizona (Cooper and Hart, 1990). These authors attribute isotopic variation throughout the suite of Springerville lavas to mixing of PREMA, EM1 and HIMU. The other group contains high 87 Sr/ 86 Sr, low ϵ Nd and displays enriched an enriched trace element pattern compared to OIB. These mafic lavas originated by partial melting of mantle lithosphere.



Figure 7. Plot of ⁸⁷Sr/⁸⁶Sr vs. SiO₂ for volcanic rocks of the River Mountains. The positive correlation suggests that contamination with a crustal component played a part in their evolution.

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Figure 8. Plot of ϵ Nd vs. ²⁰⁶Pb/²⁰⁴Pb for volcanic rocks of the Lake Mead area. Rocks of the Lake Mead trend (Fortification Hill basalt) plot on a line that projects toward HIMU-mantle, whereas the field of Grand Wash basalts points toward PREMA. Crustal contamination of Callville Mesa lavas with a low ²⁰⁶Pb/²⁰⁴Pb, and lower ϵ Nd crustal is also displayed.

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Tholeiitic magmas at Black Point, Nevada plot on a line between enriched mantle and EM1 lithospheric mantle (Hart, 1985) on ϵ Nd-²⁰⁶Pb/²⁰⁴Pb and

 208 Pb/ 204 Pb- 204 Pb/ 204 Pb plots and probably represent a mixture of these components (Figure 8 and 9). Also, trends toward increasing Rb/Sr, Th/Nb and La/Nb (Figure 10) and elevated (0.708) suggest that these lavas may have been contaminated as they passed through the crust, however this contamination was not sufficient to appreciably change either the 87 Sr/ 86 Sr or ϵ Nd values.

Callville Mesa lavas have 87 Sr/ 86 Sr = 0.708-0.709 and ϵ Nd = -8 to -10 and are similar in isotopic compositions to mafic lavas of the Western Great Basin mantle province (Fitton et al., 1991; equivalent to the Southern Nevada basalts of Farmer et al., 1989) (Figure 6), however, Callville Mesa lavas differ by having lower Pb ratios $(^{207}Pb/^{204}Pb = 15.45-15.5; ^{208}Pb/^{204}Pb = 37.7-38; ^{206}Pb/^{204}Pb = 17.2-17.4)$ than basalts of the Western Great Basin province (207Pb/204Pb = 15.6; 208Pb/204Pb = 38.7; 206Pb/204Pb = 18.3) (Figure 6) and by displaying ample evidence of crustal contamination. The low ϵ Nd and high ⁸⁷Sr/⁸⁶Sr of Callville Mesa lavas suggests the addition of a lithospheric component like EM1. When incompatible trace element abundances (Figure 6) (Fitton et al., 1991) are compared to average distributions of magmatic provinces in the western U.S.A., Callville Mesa lavas are enriched in Ba, K, and Sr and depleted in Nb and Ti. This signature is typical of lithospheric mantle and especially of mafic lavas of the Western Great Basin and Transition zone provinces (Fitton et al., 1991). Whether Callville Mesa-magma represents a direct partial melt of lithospheric mantle or a mixture of enriched mantle and lithosphere is a matter of conjecture. The most primative Callville Mesa lava has chemical similarities to Fortification Hill basalt which has a strong enriched mantle contribution. This flow may represent Callville Mesa magma uncontaminated by lithosphere. Other Callville Mesa lavas may be mixtures of enriched mantle and a lithospheric component. Petrography, trace element chemistry and low Pb isotopic compositions suggest that Callville Mesa lavas were subsequently contaminated by crust. The crustal component has $({}^{87}Sr/{}^{86}Sr) > 0.710$, low Pb isotope ratios, and ϵ Nd < -10 (Figure 5, 9 and 10). We suggest that the crustal contaminant is similar in chemistry to Proterozoic rocks of the Mojave crustal province which extends into the Lake Mead area (Wooden and Miller, 1990). Although, rocks of the Mojave province display a wide range of Pb isotope values, low ratios (²⁰⁷Pb/²⁰⁴Pb < 15.5; ²⁰⁸Pb/²⁰⁴Pb < 38; $^{206}Pb/^{204}Pb < 17.4$) are common (Figure 8 and 9). Because of the common occurrence of Quartz and sanidine xenocrysts in Callville Mesa lavas, however, the contaminant is assumed to be a felsic rock. AFC models suggest that no more than 20% of the crustal component is required to model the generation of the basaltic andesites from their basaltic parent. This amount of assimilation would result in a maximum shift of 5 units of ϵ Nd and 0.002 in ⁸⁷Sr/⁸⁶Sr.

Summary and Discussion

Summary

There are two isotopically and chemically distinct groups of mafic volcanic rocks



Figure 9. Plot of ²⁰⁸Pb/²⁰⁴Pb vs. ²⁰⁶Pb/²⁰⁴Pb for volcanic rocks of the Lake Mead area. Fortification Hill lavas project toward HIMU-mantle whereas Grand Wash basalts trend toward PREMA. Crustal contamination of Callville lavas with a Mojave-type crust is also shown.

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Figure 10. Plots of incompatible element ratios vs. SiO_2 for mafic lavas of Callville Mesa and Fortification Hill volcanic field. (a) Rb/Sr vs. SiO_2 , (b) La/Nb vs. SiO_2 and (c) Th/Nb vs. SiO_2 . Explanation of symbols is in the caption to Figure 3. Fortification Hill lavas show no evidence of crustal contamination, but Callville Mesa and to a lesser extent the tholeiitic lavas trend toward crustal values and may have been contaminated.



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in the Lake Mead area. One characterized by low 87 Sr/ 86 Sr, high ϵ Nd and OIB trace element patterns. Lavas of this group mainly occur in the NCREC. They are similar to OIB and are the result of mixing of asthenospheric and lithospheric components. OAB and SAB are mixtures of enriched mantle of bulk earth composition with depleted mantle (PREMA) and HIMU-mantle. YAB have a greater contribution of depleted mantle than either OAB or SAB, and also contain a component of HIMU-mantle. The other group contains higher 87 Sr/ 86 Sr and lower ϵ Nd values and formed by melting of lithospheric mantle.

Crustal Contamination

Crustal contamination is a significant component only in the River Mountains and at Callville Mesa. It would require the addition of about 75% of a crustal component with ϵ Nd of -18 to change the ϵ Nd of basaltic magma from +4 to -12. This amount of contamination would greatly affect the major and trace-element composition of the mafic rocks and would significantly raise their SiO₂ content to values above 65%. Contamination is less of a factor for alkaline rocks since they are low in volume and less likely to reside in upper crustal chambers where open system processes occur. Also, high Sr and light rare-earth element concentrations of alkaline magmas tend to mask crustal contamination. Futhermore, alkaline magmas commonly contain mantle xenoliths and apparently rose quickly through the crust without contamination.

Glazner (1991) documents a time progressive trend of Sr and Nd isotopes for the Pleistocene Pisgah and Amboy volcanoes in the Mojave Desert. He attributes this trend to hybridization of an asthenospherically derived partial melt by commingling with partial melts of Late Jurassic gabbro and Proterozoic diabase. Pisgah and Amboy lavas evolved toward higher 87 Sr/ 86 Sr and lower ϵ Nd with time (Glazner, 1991). The opposite is true for FH lavas. A possible crustal contaminant for FH lavas is Precambrian (1.7 Ga) amphibolite in the footwall of the Saddle Island detachment. The amphibolite is chemically similar to FH basalts and probably is a sample of the middle to lower crust in the Lake Mead area (Duebendorfer et al., 1991). The amphibolite has 87 Sr/ 86 Sr=0.703 and may represent melting of PREMA or MORB. Mixing of this crustal component with asthenospherically derived enriched mantle will result in the observed linear trend in the 87 Sr/ 86 Sr- ϵ Nd system. We do not favor this interpretation, since the amphibolite is a rare rock type in Proterozoic exposures and therefore may not be a representative sample of the middle-lower crust in the Lake Mead area.

Depth of Melting

Our models assume that the depth of melting remains relatively constant with time. This assumption can be tested by applying what is known regarding the geochemistry of the volcanic rocks and petrologic studies of depth of magma generation (Takahashi and Kushiro, 1983). Tholeiitic basalts are generated by partial melting of mantle peridotite with the mineral assemblage clinopyroxene, olivine, orthopyroxene at pressures of 8 to 15 Kb corresponding to depths of 24 to 45 km. Alkali basalts are produced from a similar source at pressures between 15 and 20 Kb corresponding to a depth of about 45 to 60 km. Crustal extension is accompanied by the rise of the geotherm to higher levels of the lithosphere. Therefore the expected relationship between extension and volcanism is the production of tholeiitic (subalkalic) basalts during extension when isotherms are elevated and alkali basalts late when isotherms relax. In the Lake Mead area, however, the most primative basalts are generally alkalic regardless of age and relationship to extension. Exceptions are tholeiitic basalts at Black Point and Malpais Flattop. Depth of melting appears to remain relatively constant with time. Therefore, we assume that variations in chemical and isotopic compositions are due to the rise of the lithospheric mantle-asthenosphere boundary rather than changes in the depth of melting.

DISCUSSION

In the this section, we argue that the boundary between two crustal provinces, the NCREC and the amagmatic zone, corresponds to a boundary between asthenospheric mantle beneath the NCREC and lithospheric mantle beneath the amagmatic zone. We also suggest that the mantle boundary formed contemporaneously with the crustal boundary; both formed during Tertiary extension (9 to 16 Ma). Our data also show that lithospheric delamination occurred progressively to the west beneath the NCREC and reflects westward migration of crustal extension in the Lake Mead area as suggested by Axen and Wernicke (1988); Smith et al. (1990); Fitzgerald et al. (1991). We also suggest that the LMFZ represents the surface expression of the mantle boundary.

Nature of the Boundary

The boundary between the amagmatic zone and the Colorado River Extensional corridor corresponds to a contact between two mantle domains (Figures 11 and 12). The domain to the north is characterized by lithospheric mantle (EM1) (ϵ Nd = -3 to -9; ${}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.706-0.707$). To the south mafic lavas have a OIB-mantle signature and appear to have only a minor lithospheric mantle component in their source (ϵ Nd = 0 to +4; ${}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.703-0.705$). The contact appears to be sharp. Callville Mesa with a lithospheric mantle source is separated from Fortification Hill (OIB-lavas) by only 10 km. The contact trends to the northeast and passes between basalts exposed at Gold Butte (OIB-lavas) and the Hamblin-Cleopatra volcano (lithospheric mantle).

Mafic lavas in the terrane directly to the north of the boundary appear to be transitional in Pb isotopic signature between the NCREC and the Western Great Basin province (Figure 12). Grand Wash, Gold Butte, Black Point, Hamblin-Cleopatra and Callville Mesa have $^{206}Pb/^{204}Pb$ from 17.2 to 18. This compares to values of $^{206}Pb/^{204}Pb$ to the north between 18.2 and 18.9 and values to the south between 18.2 to 18.7. The origin of this northeast trending lower $^{206}Pb/^{204}Pb$ zone is unknown. It may represent a slice of low-Pb lithospheric mantle preserved along the domain boundary.

Age of the boundary



Figure 11. Map of the Lake Mead area showing distribution of Sr and Nd isotopic compositions pre- and post-8.5 Ma. Pre-8.5 Ma values are similar to the north and south of the Lake Mead fault zone and suggest the presence of a lithospheric mantle component in their source. After 8.5 Ma, values of Sr and ϵ Nd shift to lower and higher values repectively suggesting that magma formed by partial melting of asthenosphere.



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Figure 12. Map of the Lake Mead area showing the distribution of Pb isotopic compositions pre- and post-8.5 Ma. Pre-8.5 Ma values are uniform across the area. However the 206 Pb = 18 contour separates lower values to the south from higher Pb values to the north and is subparallel to the Lake Mead fault zone. After 8.5 Ma Pb compositions change. Higher values are found to the south of the LMFZ and higher values to the north.



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Pre-extension (pre-10 Ma) ϵ Nd and 87 Sr/ 86 Sr is uniform across the boundary at about -9 and 0.707-0.708 repectively. Higher values of ϵ Nd and lower 87 Sr/ 86 Sr occur only at the Hamblin Cleopatra volcano (-4 to -6; 0.704-0.705) and in the Mount Davis lavas in the Eldorado Range (-5 to -7; 0.7067). After extension 87 Sr/ 86 Sr and ϵ Nd values shift dramatically to higher and lower values, respectively, to the south of the boundary, but remain similar to pre-extension values north of the boundary. These relationships demonstrate that the mantle boundary formed in late-Miocene time during a period of upper crustal extension.

Prior to extension, $^{206}Pb/^{204}Pb$ values are slightly but significantly higher to the north of the boundary (18-18.16) than to the south (17.7-17.9)(Figure 12). The $^{206}Pb/^{204}Pb = 18$ contour corresponds to the post-9 Ma boundary suggesting that there was a compositional difference in the lithospheric mantle at the boundary between the NCREC and amagmatic zone prior to the extensional event (Figure 12). This compositional variation may be controlled by mechanical properities of the mantle and facilitated extension south of the boundary rather than to the north. Post-extension $^{206}Pb/^{204}Pb$ values flip across the boundary; higher values are present to the south rather than to the north. Higher post-extension Pb values argue for a enriched mantle or plume component in the source of basalts erupted in the NCREC. Speculatively, this plume component may be HIMU-mantle.

Three-dimensional Model for Mantle Evolution.

Spatial and Temporal Variation in Isotopic Composition

Basalt at Gold Butte in the eastern part of the Lake Mead area erupted at 9.4 Ma and has an asthenospheric mantle component in its source. To the west of Gold Butte, contemporanous eruptions at Callville Mesa (9.7-10.5 Ma) and Malpais Flattop (about 10 Ma) produced mafic lavas with a lithospheric mantle signature. This pattern suggests that at about 9.5 Ma lithospheric mantle was absent or thin in the east but present in the west. By 6 Ma, mafic lavas in the west display an asthenospheric source. These patterns infer that lithospheric mantle was thinned to the west during extension (Figure 13).

Daley and DePaolo (1991) report isotopic compositions of basalts and basalticandesites from the Eldorado Range. Samples plot in two groups. Those collected from the younger Mount Davis section (15-12 Ma) have ϵ Nd = -6 to -7 and 87 Sr/ 86 Sr = 0.707 and from the older Patsy Mine section (15-18.5 Ma) have ϵ Nd = -10 and 87 Sr/ 86 Sr = 0.708-709. Daley and DePaolo (1991) suggested that these lavas formed by melting of lithospheric mantle without recogizable crustal contamination. These changes may reflect increased asthenospheric contribution to the source of the Mt. Davis section due to the thinning of the lithospheric mantle during extension.

The Three-Dimensional Model for Mantle Evolution

During extension in the NCREC, lithospheric mantle was thinned and replaced by asthenosphere progressively to the west. The replacement front moved to the west at a



Figure 13. Model showing the evolution of mantle in the Lake Mead area during Tertiary extension.

(1) East-West cross section prior to the major phase of extension.

- (2) Extension in the east is accompanied by the thinning of the lithospheric mantle.
- Thinning occurs progressively to the west in concert with upper crustal extension.
- (3) Section after the main phase of extension.

rate comparable to the westward sweep of upper crustal extension (Figure 13). To the west of the asthenosphere replacement front, lithospheric mantle apparently thins before being overrun by this front (i.e., Eldorado Mountains). During thinning and replacement of the lithospheric mantle in the NCREC, the lithospheric mantle in the amagmatic zone remained intact. Contrasting behavior to the north and south of this boundary requires that the lithospheric mantle beneath the NCREC be ripped from mantle to the north. This tear produced the mantle domain boundary over a period of nearly 6 Ma during the westward migration of extension across the Lake Mead area. The reason for the localization of the tear is somewhat speculative. However, the difference in pre-extension $^{206}Pb/^{204}Pb$ values across the boundary suggest that the domain boundary formed subparallel to an older mantle compositional contact or gradient.

Links Between Mantle and Crustal Processes

There are two competing models for upper crustal extension. The simple shear model (Wernicke, 1981) predicts that the crust will fail along a single lithospheric penetrating detachment fault. According to this model, rocks in the allochton will deform at about the same time. The alternate model proposed by Buck (1988), Axen and Wernicke (1988), and Hamilton (1988) suggests that the allochton deforms progressively, so that the age of extension migrates toward the active high-angle segment of the detachment ("rolling hinge model"). In the Lake Mead area, Wernicke and Axen (1988), Fitzgerald et al. (1991), and Smith et al. (1990) have suggested that upper crustal extension migrated from east to west between 16 Ma and about 9 Ma. Our geochemical data indicate that lithospheric mantle was thinned progressively to the west. At Gold Butte area in the eastern part of the Lake Mead, lithospheric mantle was thinned prior to 9.4 Ma. At Callville Mesa and Malpais Flattop, thinning occurred between about 9 and 6 Ma. Therefore, there is a spatial and temporal relationship between thinning of the lithospheric mantle and crustal extension. These data support the "rolling hinge" extensional model as applied to the Lake Mead area.

Crustal Structures and Mantle Boundaries

The Lake Mead Fault zone (LMFZ), a major late-Miocene left-lateral strike-slip fault system, closely parallels the boundary described above. The LMFZ accomodated nearly 60 km of slip between about 18 and 11 Ma. The LMFZ closely corresponds to the mantle boundary over most of its length (Figure 1 and 2b). This correspondence argues for a genetic relationship between the two features (Figure 14). The LMFZ may reflect the rejuvenation of an older lithospheric structure (evidenced by the change in preextension Pb values across the boundary) or it may represent the surface expression of contrasting mantle behavior across the boundary during extension. Whatever the connection, it appears that the LMFZ reflects mantle processes. It is unlikely that the fault represents a transfer structure in the upper plate of shallow detachment or that the correspondence of the crustal and mantle features is a coincidence.



Figure 14. North-south cross section showing the change in the thickness of the lithospheric mantle at the boundary between the "amagmatic zone" and the NCREC.

CONCLUSIONS

1. There are two isotopically and chemically distinct groups of mafic volcanic rocks in the Lake Mead area. One characterized by low ${}^{87}\text{Sr}/{}^{86}\text{Sr}$, high ϵ Nd and OIB trace element patterns. They are similar to OIB and are the result of mixing of asthenospheric and lithospheric components. OAB and SAB are mixtures of enriched mantle of bulk earth composition with depleted mantle (PREMA) and HIMU-mantle. YAB have a greater contribution of depleted mantle than either OAB or SAB, and also contain a component of HIMU-mantle. The other group is characterized by higher ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ and lower ϵ Nd values. These lavas formed by melting of lithospheric mantle.

2. The boundary between the amagmatic zone and the Colorado River Extensional corridor corresponds to a contact between two mantle domains. The domain to the north is characterized by lithospheric mantle (EM1) (ϵ Nd = -3 to -9; 87 Sr/ 86 Sr = 0.706-0.707). To the south mafic lavas have a OIB-mantle signature and appear to have only a minor lithospheric mantle component in their source (ϵ Nd = 0 to +4; 87 Sr/ 86 Sr = 0.703-0.705).

3. There is a spatial and temporal relationship between upper crustal extension and the thinning of the lithospheric mantle. During extension in the NCREC, Lithospheric mantle was thinned and replaced by asthenosphere progressively to the west. The replacement front moved to the west at a rate comparable to the westward sweep of upper crustal extension. To the west of the asthenosphere replacement front, lithospheric mantle apparently thins before being overrun by this front. During thinning and replacement of the lithospheric mantle in the NCREC, the lithospheric mantle in the amagmatic zone remained intact. Contrasting behavior to the north and south of this boundary requires that the lithospheric mantle beneath the NCREC be ripped from mantle to the north. This tear produced the mantle domain boundary over a period of nearly 6 Ma during the westward migration of extension across the Lake Mead area. 4. The $\frac{206}{Pb}/\frac{204}{Pb} = 18$ contour corresponds to the post-9 Ma boundary suggesting that there was a compositional difference in the lithospheric mantle at the boundary between the NCREC and amagmatic zone prior to the extensional event. This compositional variation may be controlled by mechanical properities of the mantle and facilitated extension south of the boundary rather than to the north.

5. The Lake Mead fault zone, a major crustal shear zone, parallels the mantle domain boundary and its location is probably directly or indirectly controlled by mantle processes.

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ISOTOPIC GEOCHEMISTRY AND EVOLUTION OF MAFIC LAVAS IN THE REVEILLE RANGE, NEVADA: A WINDOW INTO THE MANTLE OF THE CENTRAL GREAT BASIN

(Summary of a paper without Figures or Tables, A complete version of the paper will be

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INTRODUCTION

The study of rift-related basaltic magmatism is an important tool in investigations of the structure and composition of the subcontinental mantle and the tectonic modification of the continental lithosphere. Geochemical and isotopic studies of late Cenozoic basalts in the Basin and Range province have revealed the provinciality of their mantle source domains as well as their derivation from both asthenospheric mantle and lithospheric mantle reservoirs (Semkin, 1984; Hart, 1985; Fitton et al., 1988, 1991; Ormerod et al., 1988; Lum et al., 1989; Farmer et al., 1989, Walker and Coleman, 1991). The asthenospheric mantle includes depleted MORB-mantle from the upper asthenosphere and the less depleted, OIB-source mantle from the deeper asthenosphere. The OIB source mantle may in part be plume-derived. The lithospheric mantle represents a highly heterogeneous reservoir enriched in incompatible elements. Melts derived from the lithospheric mantle have distinctive trace element ratios and higher ⁸⁷Sr/⁸⁶Sr and lower ¹⁴³Nd/¹⁴⁴Nd than asthenospheric mantle.

Through the study of rift-related basalts it is also possible to constrain the processes involved with thinning of the continental lithosphere. Extension by pure or simple shear may eventually lead to the physical displacement of the lithospheric mantle from beneath the rift resulting in basaltic magmas derived exclusively from the asthenospheric mantle. If thermal conversion and/or erosion of the lithospheric mantle is the dominant process by which thinning occurs then the basaltic magmas could initially be derived from a lithospheric mantle reservoir or a mixture of both lithospheric mantle and asthenospheric mantle (Bosworth, 1987; Perry et al., 1987, 1988; Fitton et al., 1988; Farmer et al., 1989; Leat et al., 1989, 1991; Altherr et al., 1990; Walker and Coleman, 1991). With continued extension and/or heating, the lithospheric mantle will eventually be replaced by the asthenospheric mantle and the isotopic compositions of both alkali and tholeiitic basalts will first show signatures of the lithospheric mantle and then change to asthenospheric mantle with time.

Basaltic volcanism has predominated throughout the Great Basin following the termination of subduction-related calc-alkalic intermediate to silicic volcanism approximately 17 Ma (Christiansen and Lipman, 1972; Best and Brimhall, 1974). In the southern Great Basin, the onset of lithospheric extension and transition to fundamentally basaltic volcanism began approximately at 10 Ma and has continued into the Holocene (Luedke and Smith, 1974, Stewart and Carlson, 1978). In the Great Basin, lithospheric extension has effected an area up to 800 km wide (Stewart, 1978) but late Cenozoic basaltic activity is not evenly distributed across the province. Rift-related basaltic volcanism has migrated through time to the margins of the Great Basin and most Late Miocene to Holocene volcanic fields are concentrated in semi-continuous zones along the boundary of the Colorado Plateau (Transition Zone) to the east and the Sierra Provence to the west (Christiansen and Lipman, 1972; Best and Brimhall, 1974; Luedke and Smith, 1974). Basaltic activity in the central part of the Great Basin is restricted to the Reveille Range and Lunar Crater volcanic fields (RR-LCVF). The RR-LCVF

combine to form a 20 km wide, 100 km long N to N30°E trending belt of alkali basalts that extends from 37° 45' to 38° 45' in the central Great Basin. The RR-LCVF contain approximately 100 eruptive centers and lavas occur as shallow intrusions, maars, domes, flows, and cinder cones. Basaltic eruptions began approximately 6 m.y. ago in the Reveille Range and 4 m.y. ago in the Lunar Crater field (Bergman et al., 1981; Foland et al., 1987; Kargel, 1987; Naumann et al., 1991). The location of the RR-LCVF in the central Great Basin represents an exception to the late Cenozoic migration pattern of basaltic volcanism. Because of the isolated location of the RR-LCVF relative to other basaltic fields, this belt represents an important "window" into the mantle (Kargel, 1987) of the vast central Great Basin where little other data on mantle compositions and structure is available.

Previous studies of the RR-LCVF have focused primarily on the geology, geochemistry and petrogenesis of the alkali basalts and mantle inclusions in the Lunar Crater volcanic field (Scott, 1969; Trask, 1969; Scott and Trask, 1971; Bergman et al., 1981; Bergman, 1982; Lum, 1986; Kargel, 1987; Foland et al., 1987). A small number of samples from the Reveille Range have been included in geochemical studies that concentrated primarily on the basalts of the Lunar Crater field (Bergman, 1982; Lum, 1986; Kargel, 1987; Foland et al., 1987; Fitton et al., 1991) and a limited number of Reveille basalts have been incorporated in provincial isotopic studies (Semkin, 1984; Lum et al., 1989; Farmer et al., 1989). Previous geochemical and isotopic studies by Foland et al., (1988); Lum et al., (1989) and Fitton et al., (1991) concluded that the earliest basaltic lavas of the RR-LCVF may have resulted from a combination of lithospheric mantle and asthenospheric mantle components. However, isotopic studies by Farmer et al., (1989), Kempton et al., (1991) and Foland et al., (1991) concluded that basalts of the RR-LCVF were derived solely from asthenospheric mantle. The identification of a lithospheric mantle component in the central Great Basin remains a pertinent question and has an important bearing on models that involve the structure and composition of the subcrustal mantle as well as geodynamic models involving the generation of rift-related magmas. No previous work has presented geologic mapping or documentation of the volcanic stratigraphy of the RR-LCVF as part of geochemical or isotopic investigations.

In this paper, we describe the Reveille Range volcanic field, a suite of predominantly basaltic lavas ranging from mildly alkalic (transitional to tholeiites) to alkalic and having trace and isotopic compositions similar to many ocean island basalts (OIB). The purpose of this study is twofold. First, through the use of major and trace element geochemistry and Nd, Sr, and Pb isotopic data we investigate whether lithospheric mantle resides beneath this portion of the Great Basin by identifying its involvement in the generation of the basaltic magmas. Second, this paper addresses the anomalous location of the RR-LCVF itself. We explore the possibility that the origin of the belt is the result of voluminous partial melting by decompression of hot asthenosphere as it convectively upwells with divergent lateral flow beneath the central Great Basin.

GEOLOGY OF THE REVEILLE RANGE VOLCANIC FIELD

Introduction

The Reveille Range is an excellent locality for determining the temporal evolution of chemical and isotopic compositions as well as the control of different mantle components on the petrogenesis of rift-related continental basalts. The western margin of the Reveille Range is the only location along the RR-LCVF where significant amounts of tectonic uplift and erosion have exposed thick volcanic sequences. Geologic mapping of this area has resulted in the discovery of multiple eruptive episodes and the establishment of a well defined volcanic stratigraphy that spans over 3 Ma of time. Detailed sampling of this stratigraphy documents the temporal evolution of chemical and isotopic trends beginning with the onset of RR-LCVF basaltic volcanism at 6 Ma (Naumann et al., 1991). In addition, the presence of ultramafic xenoliths, megacrysts and nodules in the alkalic lavas provide evidence that they ascended rapidly from their mantle source precluding significant contamination by continental crust.

Basement rocks of the Reveille Range consist primarily of intermediate to silicic ash-flow sheets of Oligocene to Miocene age that unconformably overlie Paleozoic sedimentary rocks in the northern half of the range (Ekren et al., 1973). The range is bounded by en-echelon north to northeast striking high-angle normal faults. On the western range margin, 5.7 Ma basalt flows are offset up to 300 m by three segments of the fault system but a basalt flow of similar age to the south covers a range front fault (Diggles et al., 1986). On the eastern range margin the fault system cuts Holocene valley fill deposits (Ekren et al., 1973; Dohrenwend, 1987) indicating that the range has been tilted to the west in Holocene time (Kleinhampl and Ziony, 1985).

Basaltic lavas cover approximately 180 km² and occur as shallow intrusions, domes, flows and over 60 effusive vents and dissected cinder cones. The vents are composed of massively bedded red to brown scoria, cinder, spatter, agglutinated scoria and ash. Dikes are exposed in the dissected cones and in bedrock. Dikes in bedrock pinch and swell and cut obliquely across pervasive bedrock joints. Where dikes leave bedrock and intrude scoria cones they commonly swell from a initial width of between 1.0 m - 2.0 m below the vent to become plug-like intrusions up to 20 m wide within the central vent areas. This pattern is likely the result of initial volatile-rich fissure eruptions that fountained along the length of the dike that progressively became focused at one or more nodes along the strike of the intrusion as the magma supply rate decreased. Most vents are distributed on the east and west flanks of the range and show a preferred north-northeast alignment that crudely parallels the location of extensional structures. However, even though there is a close spatial association between vents and extensional structures, no dikes or vents are located within or above mappable structures indicating that at least in the upper crust, magmas did not use joints or faults as primary conduits to the surface.

Stratigraphy. Age and Volume of Volcanism

Geologic mapping of the volcanic field was completed at a scale of 1:24,000. Map

units were distinguished on a flow-by-flow basis, based primarily on lithologic (type, size and abundance of phenocrysts and megacrysts) and morphologic criteria. Some map units represent composite assemblages of overlapping flows that originated from multiple vents while other units are spatially isolated and are composed of multiple flows from a single vent. Naumann et al., (1991) divided the lavas into three separate groups based on lithology, field relationships and K-Ar geochronology. All data and sample locations for the K-Ar ages used in this paper are found in Naumann et al., (1991). Volume estimates for each episode were calculated by determining the areal extent of each map unit with a planimeter and then combining this value with an average outcrop thickness based on field measurements and topographic data. Volumes estimates represent a minimum due to the extensive dissection of most eastern and northwestern map units and the coverage of southwestern map units that lie below modern grade level.

Episode 1 consists of basalt that crops out over approximately 150 km² on both the east and west flanks and crest of the range. Lavas range in age from 5.9 to 5.0 Ma and erupted from fifty two vents. An estimated volume of Episode 1 basalts is 8 km³. Episode 1 basalts are distinguished from Episode 2 in outcrop by a greater abundance of plagioclase megacrysts and lack of augite megacrysts. Episode 1 basalts are coarse grained with intergranular and rare trachytic texture. Lavas are porphyritic with total phenocryst content up to 20 percent. Basalts of Episode 1 contain megacrysts of andesine and labradorite (up to 40%). Plagioclase megacrysts commonly occur in glomeroporphyritic clots that range in size from 5 to 15 cm. Some feldspar megacrysts are partially resorbed and commonly contain abundant poikiolites of olivine. Olivine and plagioclase are the major phenocryst phase in all samples. Diopsidic augite phenocrysts are subhedral with strong dispersion. Groundmass phases within Episode 1 basalts include olivine (mostly altered to iddingsite), diopsidic augite, feldspar and opaque Fe-Ti oxides.

Episode 2 consists of basalts that crop out over approximately 15 km². Basalts range in age from 4.6 to 3.0 Ma and erupted from fourteen vents on the northeast flank and range crest. An estimated volume of Episode 2 lavas is 1 km³. Basalt of Episode 2 contains abundant megacrysts of diopsidic-augite (up to 40%), amphibole (up to 35%) and plagioclase (<5%) and coarse grained xenoliths of gabbro and dunite (up to 20 cm in length). Episode 2 basalts is coarse grained with intergranular to subophitic and rare trachytic texture and all samples are porphyritic with total phenocryst content up to 20 percent. Olivine, clinopyroxene and plagioclase are the major phenocryst phases. Oxyhornblende was identified in two samples. Groundmass phases are olivine, pyroxene, opaque Fe-Ti oxides with a trace of biotite and apatite. Episode 2 basalts contain mantle xenoliths while most Episode 1 lavas do not.

Trachytic domes erupted just prior to the onset of Episode 2 volcanism at 4.4 and 4.2 Ma in the northwestern Reveille Range. Trachyte and tristanite magmas containing ferrosillite and hedenburgite, anorthoclase, sanidine and andesine produced two constructional domes <0.01 km and 0.3 km³ in volume. Initial eruptions at both domes were explosive and generated a pyroclastic apron between 2 and 10 m thick that extends up to 5 km from the larger dome. The flanks of the larger dome are composed of stubby 1 flows which originated at or near the summit. The dome is compositionally zoned from

1 flows which originated at or near the summit. The dome is compositionally zoned from $60 \% \text{SiO}^2$ at the base to $58 \% \text{SiO}_2$ at the top (Naumann et al., 1990). Trachyte lavas are vesicular and porphyritic with approximately 10 percent total phenocrysts. Subhedral to anhedral grains of clinopyroxene (salite to ferrosilite) are the only phenocryst phase. Sanidine is present as microlites and microphenocrysts that are sub-parallel and are set in a matrix of colorless to pale green glass.

RESULTS (SUMMARY)

Major Elements

Reveille basalts are alkalic and are similar to alkalic basalts from extensional environments worldwide. Episode 1 (which is more voluminous) is more highly evolved than Episode 2. Smaller volume Episode 2 lavas contain xenoliths and represent more primitive magma as indicated by higher Mg #, lower SiO₂, and higher normative Ne content.

Trace Elements

Trace-element data indicates that Episode 1 lavas are produced by partial melting of lithospheric mantle and Episode 2 by melting of asthenospheric mantle. Evidence includes:

(1) lower Zr/Ba in Episode 1 compared to higher values in Episode 2 lavas. Elevated Zr/Ba is characteristic of magma generated in the asthenosphere. Lower values are indicative of a lithospheric mantle source (Ormerod, 1988).

(2) Enriched light rare-earth element (REE) abundances in Episode 1 lavas suggest a source in the lithospheric mantle.

(3) Linear trends between Episode 1 and 2 lavas on La vs. Nb and La vs. Ba plots suggest that the Reveille Range lavas in detail formed from sources that are a mixture (to varying degrees) of asthenospheric and lithospheric mantle reservoirs.

Isotopes

Older Episode 1 lavas are higher ${}^{87}Sr/{}^{86}Sr$ and lower in ϵ Nd than younger Episode 1 and Episode 2 basalts. This time progressive shift in isotopic composition represents a fundamental change in the locus of melting from asthenosphere to lithospheric mantle with time (see discussion of trace elements). Pb values are consistent throughout the range of basalt compositions indicating that crustal contamination probably played a minor role in their evolution.

DISCUSSION

Source of Reveille Magmas

We document that lithospheric mantle was involved in the generation of the Reveille

lavas and that there was a temporal shift in the mantle source from lithospheric mantle to asthenospheric mantle.

The chemical and isotopic variations in the basalts from the Reveille Range require that more than one isotopically distinct mantle component was involved in their petrogenesis. Previous geochemical and isotopic studies by Foland et al., (1988); Lum et al., (1989) and Fitton et al., (1991) concluded that the earliest basaltic lavas of the RR-LCVF may have resulted from a combination of lithospheric mantle and asthenospheric mantle components. However, isotopic studies by Farmer et al., (1989), Kempton et al., (1991) and Foland et al., (1991) concluded that basalts of the RR-LCVF were derived solely from asthenospheric mantle. A fundamental observation from our study is that Nd and Sr isotopic compositions of the alkali basalts vary systematically with time but Pb isotopic compositions remain constant. The geochemical and isotopic signature of basalts from the Reveille Range are compatible with an origin involving mixing of lithospheric mantle and asthenospheric mantle components. The small range in incompatible element ratios regardless of the relative lithospheric mantle or asthenospheric mantle contribution indicates that both lithospheric mantle and asthenospheric mantle from the region have similar ratios. This is compatible with the nearly straight-line mixing in the isotopic values. The isotopic and trace element concentrations fall within the range of known oceanic island basalt concentrations. Early Episode 1 basalts were derived from a mantle reservoir with low ϵ Nd, high ^{\$7}Sr/⁸⁶Sr, Interpreted by Menzies, Perry, Farmer and Fitton to represent lithospheric mantle. Ormerod et al., (1988) discriminated lithospheric mantle from asthenospheric mantle based on trace element concentrations with lithospheric mantle being depleted in HFSE relative to asthenospheric mantle. Late Episode 1 and Episode 2 were derived from a mantle reservoir with high ϵ Nd and low ^{\$7}Sr/⁶⁶Sr. Menzies et al., 1983, Perry et al., 1987, Farmer et al., 1989, Lum et al., 1989, Fitton et al., 1991 interpreted similar compositions from the Basin and Range and Rio Grande Rift to have been derived from upwelling asthenospheric mantle.

What are the implications of this two component system for the structure of the mantle? We prefer the two-layer mantle of Perry et al., (1987) where lithospheric and asthenospheric mantle constitute different layers rather than a single source that is isotopically heterogeneous (plum pudding). Why? because the shift in isotopic and traceelement concentrations is temporal not geographical. Early Episode 1 lavas derived from lithospheric mantle occur from varying geographic positions prior to 5 Ma. The temporal shift in the geochemical and isotopic concentrations are consistent with a model involving upwelling asthenosphere/ mantle plume where initial melts are produced in the lithospheric mantle and with time as the isotherms relax successive melt fractions are produced from the underlying asthenospheric mantle. After 5 Ma, all melts are produced from asthenospheric mantle.

Crustal Contamination?

Foland et al. (1991) have suggested that Episode 1 lavas and their isotopic signatures are the result of contamination of mantle derived magmas by continental lithosphere rather than partial melting of lithospheric mantle (enriched source) as suggested in this paper. Magmas passing through continental crust will almost certainly be contaminated by crust. To the extent that this contamination is recognizable will depend upon the quantity of continental crust consumed which will in turn depend on residence time in the crust. Isotopes of lead and oxygen are sensitive indicators of crustal contamination. Other indicators of contamination include petrographic criteria. We argue against the model of Foland et al., (1991) for the following reasons:

(1) lead values for all sample have narrow distribution (e.g., $^{206}Pb/^{204}Pb = 19.1$ to 19.4). Pb is a very sensitive indicator of crustal contamination and should show a wider variation if contamination was a significant factor.

(2) Incompatible trace element ratios do not vary significantly.

(3) There is a very narrow range of silica contents for mafic lavas (42 to 48%). The contaminant would have to be mafic (gabbro).

(4) Variations in Sr and Nd do not correlate with SiO_2

Origin of the Lunar Crater - Reveille Range Volcanic Belt

Why does basaltic volcanism occur in the Death Valley-Pancake Range belt and nowhere else in the central Great Basin during Pliocene time?

Lithospheric extension has effected an area up to 800 km wide in the Great Basin (Stewart, 1978), but late Cenozoic basaltic activity is not evenly distributed across the province. Most Late Miocene to Holocene volcanic fields are concentrated in semicontinuous zones along the boundary of the Colorado Plateau (Transition Zone) on the east and the Sierra Province on the west (Christiansen and Lipman, 1972; Best and Brimhall, 1974; Luedke and Smith, 1974). Basaltic activity in the central part of the Great Basin is restricted to the Reveille Range and Lunar Crater volcanic fields (RR-LCVF). There are several important questions about the RR-LCVF. Including:

(1) What is the significance of the RR-LCVF volcanic field?

(2) What information do these lavas provide about mantle and crustal processes.

(3) Why is there no Pliocene basaltic activity in other highly extended areas of the central Great Basin?

If the crust throughout the Great Basin has been thinned equally then the controlling mechanism may be the presence of abnormally high heat flow associated with a rising convective plume.

Several lines of evidence support the hypothesis that a thermal plume is responsible for the location of the RR-LVCF lavas rather than any structural property of the crust:

(1) Asthenospheric mantle is an important component in the generation of both Episode 1 and 2 lavas in the Reveille Range.

(2) There are no major crustal structures in the Reveille Range that might focus volcanism in this area. Also, Taylor et al., (1989) demonstrated a lack of correlation between extensional periods and volcanism indicating no direct relationship between extension and volcanism in this area.

(3) The lack of dikes in the Reveille Range indicates that there was little dilational stress at the time of the emplacement of the lavas. This observation suggests that crustal extension is not the cause of volcanism. an intrusion rate of 570 km³/m.y. vs. an extrusion rate of 5.4 to 2.4 km³/m.y. for the Coso Field, California. He also estimated a 10:1 ratio (intrusion/extrusion) for Kilauea volcano, Hawaii. Bergman (1982) calculated an eruption rate of 10-20 km³/m.y. for the RR-LCVF. If 10 times as much basalt intruded the upper mantle/lower crust and stagnated (=1000 km³), then the crust below RR-LCVF (40 Km long x 10 km wide x 50 km thick = an approximate volume of 20,000 km³) increased in volume by 5% over the last 5 m.y. This very high production rate of mafic magma is consistent with high heat flow associated with a thermal plume.

We propose that the RR-LVCF Volcanic Field resulted from voluminous partial melting related to a plume/hot spot in the asthenosphere. The upwelling may be in response to mantle convection that provided the driving force for much of the extension in the Great Basin.

The RR-LCVF is located slightly west of the north-south axis of bilateral symmetry of the Great Basin (Eaton et al., 1978). This symmetry is expressed in regional topography, gravity, heat flow, seismic activity, crustal thickness, and the chemistry of late Cenozoic volcanism (Eaton et al., 1978; Fitton et al., 1988). The symmetry and high heat flow in the Great Basin is evidence that asthenospheric mantle was upwelling to shallow depths in the region.

IMPLICATIONS FOR VOLCANIC MODELS OF THE GREAT BASIN

The RR-LCVF represents a thermal anomaly where volcanic activity has been concentrated for 6 Ma. Since the RR-LCVF represents the northern limit of a 300 km long semicontinuous belt of Pliocene to Holocene basalts defined by Crowe and Vaniman, (1980) and Vaniman et al., (1982) as the Death Valley-Pancake Range (DVPR) volcanic belt. The DVPR belt extends from the RR-LCVF in central Nevada south-southwestward through the southern Nevada volcanic field to southern Death Valley in California. The distribution of cinder cones and the geometry of basaltic vent systems within volcanic fields or individual volcanic centers along the DVPR belt show a preferred north-northeast alignment that parallels the location of late Cenozoic extensional structures (Crowe and Vaniman, 1980; Smith et al., 1989; Naumann et al., 1991). The DVPR Belt/Zone is well documented and we suggest that it is an important component of the Great Basin, since it represents the thermal anomaly that may be responsible for the geophysical and topographic characteristics of the Great Basin.

Pliocene-Holocene volcanoes in Crater Flat and at Lathrop Wells near the proposed high-level nuclear waste repository also lie within this belt.

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AN EXPLANATION TO ACCOMPANY THE GEOLOGIC MAP OF CRATER FLAT, NEVADA

(First Draft)

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MAP LEGEND

The map "Geological Map of Crater Flat, Nevada" is included in the pocket of this annual report.

- Qal Alluvium-poorly sorted gravel, sand, and silt.
- Qc Colluvium-unconsolidated angular blocks.
- QTs Late Miocene to Quaternary, flat-lying pebble to cobble conglomerate, weakly indurated, primarily of fanglomerate origin.

Geology of the Pliocene Volcanoes

- Qab Locally derived alluvium; Non-consolidated, poorly sorted angular fragments ranging from gravel to boulders. Clasts consist of basalt with subordinant pyroclastic material shed from the local basalt flows and scoria mounds and cones.
- Qts Scoria colluvium; Non-consolidated fragments of pyroclastic material shed from cinder cones and scoria mounds.
- Qb Undifferentiated Quaternary basalt flows and pyroclastic material.
- Qs Primary pyroclastic deposits; Poorly-to-moderately welded scoria, ash, bombs, and agglutiated scoria deposited by Strombolian to Hawaiian type eruptions. Deposits range from bedded to non-bedded and form the major cinder cones. Scoria mounds at Black Cone and Red Cone are comprised primarily of non-bedded poorly-to-moderately welded scoria and volcanic bombs.
- Qbn Northern basalt flows at Black Cone; Aa and block flows of alkali-basalt that erupted from scoria mounds north of Black Cone. Basalt is porphyritic with euhedral to subhedral phenocrysts of olivine in a matrix of plagioclase, diopsidic augite and olivine.
- Qbsm Scoria mound basalt flows; Aa and block flows of alkali-basalt that erupted from scoria mounds south and southeast of Black Cone. The basalt is porphyritic with euhedral to subhedral phenocrysts of olivine in a matrix of plagioclase, diopsidic augite and olivine.
- Qbl Lava lake on Black Cone; Alkali-basalt flows that probably erupted by lava fountaining at the summit of Black Cone. Basalt locally grades into

agglutinate. Sparce inclusions of Timber Mountain tuff are present.

- Qbsw Southwestern basalt flows; Aa and block flows of alkali-basalt southwest of Black Cone. The basalt is porphyritic with euhedral to subhedral phenocrysts of olivine in a matrix of plagioclase, diopsidic augite and olivine.
- Qb3 Basalt erupted from the base of Red Cone; Aa and block flows of alkalibasalt east and west of Red Cone. The basalt is porphyritic with euhedral to subhedral phenocrysts of olivine in a matrix of plagioclase, diopsidic augite and olivine.
- Qb2 Basalt flows erupted from scoria mounds southeast of Red Cone. Aa and block flows of alkali-basalt. Basalt is porphyritic with euhedral to subhedral phenocrysts of olivine in a matrix of plagioclase, diopsidic augite and olivine.
- Qb1 Basalt flows erupted from scoria mounds south and southwest of Red Cone. Aa and block flows of alkali-basalt. Basalt is porphyritic with euhedral to subhedral phenocrysts of olivine in a matrix of plagioclase, diopsidic augite and olivine.

Pliocene Units

- Tb Pliocene alkali-basalt flows erupted from a north-south fissure in southeastern Crater Flat. Olivine is the dominant phenocryst. Olivine, plagioclase and clinopyroxene phenocrysts are set in a matrix of plagioclase, olivine, and clinopyroxene. Glomeroporphyritic clots of olivine, clinopyroxene, and plagioclase are common.
- Tbs Pliocene-aged pyroclastic deposits; Poorly-to-moderately welded scoria, ash, bombs, and agglutiated scoria deposited by Strombolian to Hawaiian eruptions.

Quaternery and Pliocene Alkali-basalt dikes; Dikes intrude scoria and range in thickness from 0.5 to 3 m wide.

Tbc Alkali basalt flows of Crater Flat; K/Ar ages cluster at 3.7 Ma.

Miocene Volcanic Units

- Tmr Timber Mountain Tuff, Rainier Mesa Member undifferentiated.
- Tmrw Timber Mountain Tuff, Rainier Mesa Member: Light gray welded ash-flow tuff containing 20-25% phenocrysts of sanidine, quartz, lesser plagioclase and biotite, and rare clinopyroxene.
- Tmrn Timber Mountain Tuff, Rainier Mesa Member: White to light gray, thinly bedded to massive nonwelded tuff, air-fall, and surge deposits. Thickness increases across some faults. Contains 10% phenocrysts of sanidine, quartz, lesser plagioclase and biotite, and accessory clinopyroxene.
- Tpc Paintbrush Tuff, Tiva Canyon Member: Light purplish-gray to brown generally densely welded ash-flow tuff, with thin (< 5 m) basal nonwelded unit. Contains 5 to 15% phenocrysts of sanidine, lesser plagioclase and biotite, and rare clinopyroxene and quartz. Abundance of phenocrysts increases upward in section. Lenticular fiamme common.
- Tr Rhyolite flows: Light gray, coarse-grained, crystal-rich rhyolite containing phenocrysts of plagioclase, quartz, alkali feldspar, and biotite.
- Tpy Paintbrush Tuff, Yucca Mountain Member: Light gray to brownish-gray ash-flow tuff containing sparse (2%) phenocrysts of sanidine and plagioclase.
- Tpt Paintbrush Tuff, Topopah Spring Member: Light purplish gray to light brownish-gray welded ash-flow tuff containing 10% phenocrysts of sanidine, biotite, and minor plagioclase.

- Tptn Paintbrush Tuff, Topopah Spring Member: Pale orange to light brown nonwelded basal part of Tpt. Contains sparse phenocrysts of sanidine, plagioclase, and biotite.
- Tcp Crater Flat Tuff, Prow Pass Member: Light gray to brownish-gray ash-flow tuff containing approximately 8% phenocrysts of plagioclase, sanidine, quartz, orthopyroxene, biotite, and magnetite.
- Tcb Crater Flat Tuff, Bullfrog Member: Light gray to light brownish-gray, moderate to densely welded ash-flow tuff containing phenocrysts of quartz, plagioclase, sanidine, biotite, hornblende, and magnetite.

NEW INSIGHTS ON STRUCTURAL CONTROLS AND EMPLACEMENT MECHANISMS OF PLIOCENE/QUATERNARY BASALTIC DIKES, SOUTHERN NEVADA AND NORTHWESTERN ARIZONA

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INTRODUCTION

Yucca Mountain in southern Nevada has been proposed as the sole repository for the nation's high-level nuclear waste. Five Quaternary basaltic volcanic centers lie within 20 km of the proposed repository block. Four Quaternary centers in Crater Flat have yielded isotopic ages ranging from 1.1 to 0.7 Ma. The Lathrop Wells Cone, 20 km south of the proposed repository block, may be as young as 15 Ka (Wells et al., 1990). In addition, Pliocene (3.7 Ma) basalts were erupted from a separate 4-km-long chain of volcanic centers in Crater Flat. The youthfulness of these basaltic volcanic centers has prompted assessment of the potential volcanic hazard on the proposed repository block.

Assessment of the volcanic hazard must incorporate (1) the composition of the magmas, (2) structural controls (i.e., nature of pathways and geometry of dike systems), (3) emplacement mechanisms of dikes, and (4) probability of future eruptions. This paper focuses on the structural controls and emplacement mechanisms of basaltic dikes in the southern Nevada region. These data are then used to constrain probability estimates of future eruptions in the Yucca Mountain area.

COMPOSITION OF BASALTS

Alkali basalts characterize Quaternary and Pliocene volcanism in southern Nevada and northwestern Arizona. Geochemical and isotopic characteristics indicate derivation of most of the basalts from mantle lithosphere with little, if any, contamination or fractionation within the crust (Vaniman and Crowe, 1981; Vaniman et al., 1982). This, in turn, implies fast rates of ascent for the basaltic magmas. However, alkali basalts in the Reveille Range, central Nevada, also contain an asthenospheric component. In addition, tholeiitic basalts occur in a few areas, such as Malpais Mesa in the Fortification Hill field, northwestern Arizona.

STRUCTURAL CONTROLS

Pliocene volcanism in Crater Flat occurred along a 4-km-long north- to northnortheast-trending fissure system. Dikes within this system dip steeply (75 to 90°) and strike north-south to north-northeast. Late Tertiary/Quaternary basin-fill sedimentary rocks obscure relations between Pliocene basaltic dikes and bedrock structures.

North-south to north-northeast-trending alignments dominate the Quaternary volcanic centers near Yucca Mountain. The four Quaternary basaltic volcanic centers in Crater Flat are aligned along a north-northeast to northeast-trending, 12-km-long arcuate chain (Fig 1). The two largest centers, Black Cone and Red Cone, consist of one large cinder cone and many smaller mounds composed of scoria, cinder, ash, and bombs. Dikes commonly project into the mounds, which suggests that the mounds correspond to



Figure 1. Geologic index map of the Crater Flat-Yucca Mountain area.

volcanic vents. The dikes have near-vertical dips and range up to 3 m in width. Both the dikes and scoria mounds generally trend north-northeast (see geologic map of Crater Flat in pocket). However, at Red Cone a subordinate set of vents strikes N50°W. The Lathrop Wells cone contains both a northwest- and east-west-trending fissure system (Crowe et al., 1988).

Detailed geologic mapping of nearby bedrock geology (Faulds et al., in press; Scott and Bonk, 1984) indicates several potential near-surface north-northeast-trending channelways for the basalts. These include: (1) north-northeast-trending fault segments (see geologic map of Crater Flat in pocket); (2) layering in highly deformed Proterozoic and Paleozoic rocks (Carr and Monsen, 1988); and (3) joints. Closely-spaced north- to north-northeast-trending, generally west-dipping normal faults fragment Yucca Mountain into several gently east-tilted fault blocks. The irregular, en echelon boundary between Yucca Mountain and Crater Flat and the continuation of several bedrock faults into Quaternary faults within Crater Flat indicate that the bedrock geology beneath Crater Flat resembles that at Yucca Mountain.

North-northeast-trending normal faults may be the best candidate for near-surface north-northeast-trending channelways for the basalts. Geologic relations and drill hole data indicate that major normal faults lie in the direct vicinity of some of the volcanic centers (Fig. 2). Furthermore, we suspect that north-northeast-striking normal faults penetrate more deeply than either joints or layering in Proterozoic and Paleozoic strata and thus were more likely to influence the flow paths of the magmas. However, lack of dissection of the young volcanic centers near Yucca Mountain precludes direct observation of feeder dikes and controlling structures. To elucidate the geometry of plumbing systems beneath Quaternary volcanoes near Yucca Mountain, highly dissected Pliocene basaltic centers were studied in several fields within southern Nevada and northwestern Arizona (Fig 3.).

ANALOGUE STUDIES: FORTIFICATION HILL FIELD, NORTHWESTERN ARIZONA

The Fortification Hill field, northwestern Arizona, is best suited for investigating structural controls on basaltic volcanism because the Colorado River drainage has significantly dissected several volcanic centers. The basalts in the Fortification Hill field range from 6.0 to 4.5 Ma. Most are alkali basalts, but tholeiites dominate at Malpais Mesa. Preliminary geochronologic, geochemical, and structural data suggest that the Malpais Mesa basalts may be approximately 10 Ma. Variable levels of erosion of volcanic centers within the Fortification Hill field may ultimately permit construction of a composite cross section of a Pliocene volcano.

At Fortification Hill, the Colorado River has exhumed the periphery of several volcanic centers. Dikes have near vertical dips and are generally less than 2 m in width. A few dikes range up to 10 m in width near some of the volcanic centers at Fortification



Figure 2. Distribution of pre-6 Ma mafic volcanic rocks in the southern Basin and Range.


Figure 3. Geologic cross section from the summit of Yucca Mountain to the center of Crater Flat near Black Cone.

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Hill. Although they parallel major normal faults, dikes are rarely intruded directly along faults. Unfortunately, dikes cannot be observed directly beneath major volcanic centers at Fortification Hill.

Major volcanic centers are highly dissected, however, at both Lava Cascade and Malpais Mesa. A north-northwest-trending, 3 m wide, steeply dipping dike near the apex of Wilson Ridge fed the flows at Lava Cascade. Although parallel to nearby faults, this dike is not intruded along a fault and clearly cross cuts foliation in Proterozoic metamorphic rocks. Thus, the structural control on the dike remains obscure. However, the distribution of the lava flows suggests that only the uppermost structural level (< 100 m beneath original surface) of this dike is exposed.

The most highly dissected centers in the Fortification Hill field occur on the west flank of Malpais Mesa. The dissected parts of individual centers lie 75 to 365 m beneath the basal flows on Malpais Mesa. Dikes within and directly beneath three centers range from 10-30 m in width, 100-225 m in length, and have near vertical dips. The dikes pinch and swell, widening beneath individual centers. Two centers are linked by a 1-2 m wide dike. At one center, a dike widens upward from 2 to 26 m approximately 170 m beneath the basal basalt flows. At another center, a dike widens laterally from 2 to 10 m more than 300 m beneath the basal basalt flows.

The southernmost center is the largest and least dissected. Two plug-like bodies at this center have widths ranging from 10 to 26 m. One of the plugs clearly feeds flows at the base of Malpais Mesa. This 10 m wide plug thins to less than 1 m directly beneath the flows. Abundant scoria and volcanic bombs flank this volcanic center on the north. Although once again parallel to Miocene normal faults, the north-northwest to northwest-striking dikes at Malpais Mesa are rarely intruded along faults and some cut Miocene faults.

In summary, the dikes in the Fortification Hill field (1) have near vertical dips; (2) commonly parallel Miocene normal faults, but are rarely intruded directly along them; (3) locally cut Miocene normal faults; (4) strike north-northwest to northwest perpendicular to the inferred least principal stress during Pliocene time; (5) widen significantly 170 to 300+ m directly beneath the original topographic surface. These data strongly suggest that At exposed structural levels, dikes within the Fortification Hill field were not intruded along preexisting structures. The only apparent structural control was the orientation of least principal stress.

By analogy, we propose that dikes beneath the Quaternary basaltic volcanoes near Yucca Mountain: (1) have near vertical dips; (2) probably do not follow preexisting structures; (3) may widen significantly upward 300 m beneath the surface; (4) may widen laterally, perhaps by an order of magnitude, directly beneath some centers; and (5) may branch out into smaller feeder dikes within several meters of the surface. Some of the volcanic centers may be underlain by large plug-like bodies. Dike widths in the Yucca Mountain region are probably narrower than those in the Fortification Hill field, as evidenced by smaller volumes of basalt flows. However, the analogue studies suggest that dike widths directly beneath Quaternary volcanoes near Yucca Mountain may be larger than previously thought.

Although these data constrain the geometry of the basaltic dike systems, they do not directly resolve the structural controls on the centers. Anderson and Christenson (1989) concluded that joints commonly controlled alignments of Quaternary basaltic volcances in southwestern Utah. We cannot preclude joint control on some of the volcanic centers in the Yucca Mountain region. We suspect, however, that any control by joints is confined to discrete lithologies (e.g., Pollard and Aydin, 1988) and that such joints do not penetrate deeply. The nature of crustal-penetrating channelways that afford quick transport of magmas remains elusive.

DISCUSSION

The near vertical dips and lack of definitive structural controls may imply that the basaltic dikes propagated upward through "self-generated" fractures produced by tensile stresses near the dike tip, magmatic overpressure and buoyancy, and regional tension. The dikes were probably initiated in the mantle lithosphere perpendicular to the least principal stress. The first increments of melt presumably formed on planes normal to the least principal stress (Savage, 1969; Shaw, 1980). The melting reaction was the first in a sequence of rock failures. It was the most important, however, because it governed the eventual location of surficial volcanism. Tensile stresses near the dike tip, induced by magmatic pressure, and buoyancy (Delaney et al., 1986) allowed the dike to propagate upward to at least the level of neutral buoyancy (i.e., the level at which density of melt equals that of the surrounding rock) (Lister and Kerr, 1991). Dike propagation far beyond the level of neutral buoyancy is problematic. Lateral propagation (i.e., in a horizontal direction) could continue at the level of neutral buoyancy, but vertical propagation would be stymied.

Glazner and Ussler (1989) concluded, however, that crustal thinning and emplacement of mafic plutons during crustal extension will increase mean crustal density and consequently induce a rise in the level of neutral buoyancy. Basaltic volcanism in both the Yucca Mountain and Fortification Hill regions followed prolonged episodes of voluminous Tertiary magmatism and moderate to severe extension (e.g., Anderson, 1971; Maldonado, 1990; Schweickert and Caskey, 1990) during which the level of neutral buoyancy probably rose significantly. In addition, the Yucca Mountain region is currently under high extensional stress (Stock and Healey, 1984).

We therefore propose that magmatic overpressure and the resultant tensile stresses near the dike tip, exsolution of volatiles, a relatively shallow level of neutral buoyancy resulting from prior episodes of magmatism and extension, and concurrent regional tension allowed the basaltic dikes in the Yucca Mountain region to propagate to the surface through "self-generated" fractures oriented perpendicular to the N60°W trend of least principal stress (Fig. 4). Regional tension and magmatic overpressure were probably the most critical components to this process. Regional tension favored both the vertical and lateral propagation of cracks perpendicular to the least principal stress and magmatic overpressure allowed melt to quickly fill the cracks. If situated directly above a rising batch of magma, preexisting north-northeast-striking structures may have locally facilitated melt transport. Theoretical data suggest that basaltic magmas may rise through the entire crust in a matter of hours or days (e.g., Spence and Turcotte, 1985).

These conclusions have significant implications for hazard assessments of the proposed repository at Yucca Mountain. The potential for dike intrusion along selfgenerated fractures not associated with preexisting faults must be considered. Probability estimates of future eruptions must therefore involve delineation of an area of most recent volcanism (AMRV) (Smith et al., 1990) that is comparable in size to other Pliocene/Quaternary basaltic volcanic fields in the Basin and Range and whose long axis is perpendicular to the least principal stress. Probabilities of future eruptions can be estimated from the temporal and spatial distribution of eruptions within (a) the AMRV near Yucca Mountain, (b) analogous Pliocene volcanic fields where volcanism has ceased, or (c) larger regional volcanic belts such as the Pliocene/Quaternary Death Valley/Pancake Range belt. The available data may not permit, however, accurate determination of weighted probabilities or risk zones within an individual AMRV.

The location of at least some of the Pliocene/Quaternary basaltic volcanic fields in the Basin and Range may be related to small pull-aparts on crustal penetrating strikeslip fault zones. The Fortification Hill field occurs near the southeastern terminus of the right-lateral Las Vegas Valley shear zone (Duebendorfer and Wallin, 1991). The Yucca Mountain region may occupy a large right-step between the Las Vegas Valley shear zone and Walker Lane belt (Carr, 1984; Stewart, 1986). The continuation of the Las Vegas Valley shear zone across several extensional domains implies that the shear zone is not confined to the upper-plate of a detachment system but instead may penetrate much of the crust. Extension within small pull-aparts along this strike-slip fault zone may have served to localize melts within the mantle lithosphere and ultimately controlled the location of basaltic volcanic fields.



Figure 4. Model for the emplacement of mafic dikes during regional extension. See text for explanation.

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ABSTRACTS

LANDSLIDING AND GROUND-CRACKING IN THE EPICENTRAL REGION OF THE 1989 LONA PRIETA EARTHOUAKE

THE 1989 LORA PRIETA EARTHQUARE MOUTOUX, T.E.; VICK, G.S.; NOLAN, J.N.; WEBER, G.E.; BOL, A.J.; MILLER, S.L. Weber and Associates, 120 Westgate Dr., Watsonville, CA 95076 The epicenter of the 1989 Long Prieta earthquake lies in a

The epicenter of the 1988 Long Prietz earthquake lies in a large, rugged tract of uninhabited land included within the Forest of Misene Marks State Park in Santa Cruz County, California. We mapped surface deformation within the epicentral region of the earthquake (ground-cracks and landslides) on 1:4800 scale topographic maps. Because the earthquake related ground deformation showed an intimate association with older deformation, we also mapped of pre-visition factures including and the identificate and a deformation and a state of the state of existing features, including old landsliding and an older

existing features, including old landsliding and an older series of ground-cracks. Landslides were categorized into three failure-type groups: rotational, translational, or debris flow: and three age groups: earthquake related (1989), recent (about 50 years or less in age), and older. We recorded displacement magnitudes for cracks related to the Loma Prieta earthquake. Earthquake related landslides were sparse, and were predominantly small to medium sized translational type landslides, indicating failure of weathered surficial material. We did not see wholesale reactivation of the many large, older landslide complexes, nor did we observe the Large, older landslide complexes, nor did we observe the formation of new large landslides. These observations suggest that formation of the larger, more deep seated landslides is not being driven by Long Priets type events, at least, not under present climatic conditions. The earthquake deformation concentrates in a broad band trending margingle to a radius land deviation and trending parallel to the regional bedding and faulting, and lying just morth of the Eayante fault along the axis of the Glanwood Syncline.

Nº 12435

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FLUVIAL GEOMORPHIC INDICATORS OF NEOTECTONISM IN THE SOUTHWESTERN SACRAMENTO VALLEY, CALIFORNIA MUNK, L.P. (Dept. of Land, Air and Water Resources); UNRUH, J.R. (Dept. of Geology); MOORES, E.M. (Dept. of Geology); and SOUTHARD, R.J. (Dept. of Land, Air and Water Resources); all at: University of California, Davis 95616 The Dunnigan Hills and Plainfield Ridge are anomalous areas of subte positive relief in the otherwise nearly level southwestern Sacramento Valley. Seismic reflection data suggest that these geomorphic features are underlain by east-vergent blind thrust faults at depths of 4.7 km. We propose that Quaternary movement on these thrusts has produced surface splift and subsequent alteration of the local fluvial system. Longitudinal stream profiles, determined from moorraphic mans that preduce may produced surface splift and subsequent alteration of the local fluvial system. Longitudinal stream profiles, determined from topographic maps that predate major agricultural modifications of the drainage system, indicate that east-draining streams have convex profiles along reaches that cross the Plainfield Ridge and southern Dunnigan Hills Best-fit exponential curves developed for similar-sized streams south of the study area were used as a standard of comparison in order to analyze deviations from a graded condition. The local denarrance from a concave-up profile for reaches or one study area were used as a standard of comparison in order to analyze deviations from a graded condition. The local departures from a concave-up profile for reaches crossing the Plainfield Ridge and Dunnigan Hills are interpreted as evidence of recent tectonism. Additional evidence for recent uplift includes underfit and abandoned stream valleys, locally developed flights of fluwial terraces, and poorly integrated drainage networks developed on the uplifted terrain. Soil-stratigraphic studies are being conducted to constrain the rate and timing of deformation. These data, combined with subsurface analysis and studies of microscismicity (Eaton, 1986; Wong et al. 1988) suggest that the Dunnigan Hills and Plainfield Ridge may be the eastermost surface extension of an actively growing fold-through the analytic studiest. expression of an actively growing fold-thrust belt in the southwestern Sacramento Valley.

Nº 17699

DEVELOPMENTS IN JURASSIC STRATIGRAPHY OF THE FRANCISCAN COMPLEX, CALIFORNIA: EXPANDED AND RECALIBRATED RADIOLARIAN ZONATION COUPLED WITH POTENTIAL FOR MAGNETOSTRATIGRAPHY

MURCHEY, Benita L., U.S. Geological Survey, MS 915, Menlo Park, CA 94025; HAGSTRUM, Jonathan T., U.S. Geological Survey, MS 937, Menlo Park, CA 94025 The expansion of the number of taxa used to characterize radiolarian assemblages in the Franciscan Complex of California permits more accurate regional correlations as well as more precise age determinations. The ages of Jurassic assemblages MH-1 to MH-4 (Murchey, 1984) were recalibrated downward by comparing the ranges of more than 100 taxa in bedded chert sequences in the Marin Headlands, Mt. Umuhnum, and Geysers areas to those in well-dated sequences from Europe and North America. MH-1 is late Pliensbachian to early or middle Tourcian. MH-2 best correlates with middle and late Tourcian faunas. The boundary between MH-2 and MH-3 is not younger than early Bajocian, but is probably elder. The upper part of MH-3 is Bajocian. The base of MH-is has Baiocian batter batter and the upper part of MH-3 is Bajocian. 4 is hate Bajocian or Bathonian; the youngest known MH-4 faunas are Callovian or Oxfordian. The stratigraphic gap between MH-4 faunas and Early Cretaceous MH-5 faunas is marked by a recrystallized interval that may have been a zone of alow deposition. The discovery of a series of paleomagnetic reversals in chert with MH-1, MH-2, and

MH-3 faunas in the Mt. Umuhnum and Geysers areas holds the promise for future development of Jurassic magnetostratigraphy directly tied to radiolarian biostratigraphy. REE SYSTEMATICS OF SULFIDE-SULFATE DEPOSITS AND SEA-FLOOR SUBSTRATES AT SEDIMENT-FREE AND SEDIMENT-COVERED SPREADING CENTERS IN NORTHEAST PACIFIC OCEAN

MURINANE, Joha E., Department of Geology, Northern Illinois University, DeKalb, IL 60115; KOSKI, Randolph A., U.S. Geological Survey, MS999, 345 Middlefield Road, Menio Part, CA \$4025

Birly Aussis, Ranoopn A., U.S. GOODILLI SLIVEY, MSYY, AND MAGDELIELD Road, Meislo Part, CA 94025 The solinear-free southern segment of Jean de Fucs Ridge and she sediment-covered southern segment of the Gorda Ridge (Escanaba Trough) are contrasting sizes of hydrothermal discharge and sulfide-sulfate deposition in the northeast Pacific. On the southern Juan de Fucs Ridge, chinneys largely composed of Za and Fa sulfides + sunhytrite formed where black smoker fluids have discharged through basht sheet flowr. At Recanaba Trough, large (handreds of meters across) mounds consisting of Fe and Ca sulfides + barite are precipitated by hydrothermal fluids upwelling through the >SOO-mshick blanket of serrigenous steinmen. A suite of sampler from the two sites including basht, sediment, polymensilic sulfides, Ba and Ca sulfates, and Fe aryhydroxides was analyzed for non-earth elements (REE) by inductively coupled plasma mass spectrometry. Chondrine-normalized REE patterns of smaltered basht glass from both ridges are characteristic of a-MORB (flat to slightly depleted in LREE with (La/Sm) e =0.63 to 1.02 and small negative Eu anomalies). Sediment samples from Escanaba Trough (sand sait surbidite, hemipelagic moth have shale-like LREE-enriched gatterns with REE = 115 to 204 ppm and (La/Sm) = 2.8. The close similarity between REE gatterns with REE = 115 to 204 ppm and (La/Sm) = 2.8. The close similarity between REE gatterns with SREE = 115 to 204 ppm and (La/Sm) = 2.8. The close similarity between REE gatterns with SREE = 115 to 204 ppm and (La/Sm) = 2.8.

during subsea-floor Mg metasomatism. Massive sulfate samples have higher EREE (8 to 28 ppm) contents than massive sulfate samples (<6 ppm), but all hydrothermal samples from hoth sites ethibit LIEE enrichment patterns. Massive anhydric and barite have harge positive Eu anomalies characteristic of high-temperature hydrothermal fluids (Michard and Albarde, 1985). Anhydrates also enhibit small positive Ce anomalies. Pure sulfate samples lack Eu anomalies therefore, the positive Eu anomalies (BaRLes' SZO) in most massive militate stellent the presence of interfore, the positive Eu anomalies (BaRLes' SZO) in most massive militate stellent the presence of interfore, the positive Eu anomalies (BaRLes' SZO) in most massive militate stellent the presence of interfore, the sulfate minerals. Small negative Ce anomalies are associated with Fe-oxyhydroxide crusts from weathered surfaces of sulfide chinneys and sulfate samples containing shouthar amorphous silica. The data indicate that compositional differences of sus-floor hydrothermal deposits in comparison to the hydrothermal Buid-servater mixing processes that control sulfate deposition.

Nº 15445

STRUCTURAL CONTROL OF PLIOCENE VOLCANISM IN THE VICINITY OF THE NEVADA TEST SITE, NEVADA: AN EXAMPLE FROM BUCKBOARD MESA

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Late Pliocene to Quaternary (4 to <0.1 Ma) alkali basalt and basaltic andesite crupted in the vicinity of the Nevada Test Site (NTS) at Crater Flat, Sleeping Butte and Buckboard Mesa. Eruptions occurred along or near north to northeast striking faults that are typical of the area between Yucca Mountain to the south and Pahute Mess to the north. This structural pattern is interrupted by the Timber Mountain caldera. Buckboard Mesa is comprised of a cinder cone (Scrugham Peak) and flows of basaltic andesite that lie in the moat of the Timber Mountain caldera. The main vent zone on Buckboard Mesa is defined by the Scrugham Peak einder cone and several small vents. The vent zone is 1 km long, trends northeast, and is controlled by en echelon fault segments that strike N10E. These faults were active before, during and after the eruption of the basaltic andesite at 2.8 Ma. Evidence for this chronology includes the observations that Buckboard Mesa lavas were deposited on faulted Timber Mountain tuff and that the same fault zone cuts Buckboard Mesa lavas and Scrugham Peak. Another vent is located at the termination of a narrow ridge that extends southeast from the base of Scrugham Peak. This ridge is subparallel with the axis of a paleovalley that apparently controlled flow direction of Buckboard Mesa lavas. This ridge and went may either be tube fed and rootless or may represent eruptions from the Timber Mountain ring fracture. The eruptions at Buckboard Mesa were focused at the intersection of the northeast striking fault zone and the ring fracture zone of the Timber Mountain caldera, however, the northeast zone was the primary structure controlling magma emplacement. This is in accordance with the structural controls for other post 4-Ma volcanic centers in the NTS area in Crater Flat and at Sleeping Butte.

Nº 17690

CLAY MINERALOCY, RESIDUAL SHEAR STRENGTH AND LANDSLIDING OF THE SANTA CLARA FORMATION CLAYSTONE, SARATOCA FOOTHILLS, CALIFORNIA.

NELSON, James L., Terratech, Inc., 7891 Westwood Drive, Gilroy, CA \$5020.

Most landslides in the Saratoga foothills, California, occur along previously sheared surfaces formed in claystone units of the Pilo-Pielstocene Santa Clara Formation. The primary geologic factors that control landsliding are the presence of the clay mineral smectite and the overconsolidated nature of the claystone.

Preexisting landslide surfaces in the claystone units appear to be at, or near, the residual shear (frictional) strength of the clay minerals present. To evaluate the effects of clay mineralogy on residual shear strength, laboratory testing and X-ray diffraction were performed on claystone samples collected from landslide-prone areas in the Saratoga foothills.

1104 Nº:

VADOSE-SCHE AND GROUND-WATER TRANSPORT MODELING TO

VADOSZ-SOME AND GROUND-WATER TRANSFORT MODELING TO ESTABLISH ACCEPTABLE CLEMEUF GOALS FOR VOCS IN SOIL FARR, John K., and LANBIE, John N., Levine-Fricke, Inc. 1900 Powell Street, 12th Floor, Emeryville, CA 94608 For Superfund projects where soil contamination exists, soil cleanup goals must be established as the basis for feasibility studies and the design and implementation of remedial actions. Soil cleanup goals must be protective of underlying ground water and its designated beneficial uses. Mathematical transport models can be used to assess Mathematical transport models can be used to assess uses. the potential ground-water impacts from various levels of soil contamination, thereby siding in the selection of

the potential ground-water impacts from various lavels of soil contamination, thereby aiding in the selection of appropriate soil cleanup goals. Indirectly coupled models are generally used to represent transport in the vadose zone and the ground-water zone separately, even though the transport processes in these two zones are directly coupled. In this study, the SZ sonal SOIL compartment model (SZ SOIL) of Bonazountas and Wagner (1984 - with significant modifications by Hetrick, et al., 1989) was used to model vadose-zone transport and the Analytical Transient 1-, 2-, and 3-Dimensional model (ATI3DD) of Yeh (1981) was used to model ground-water transport. SESOIL can represent one-dimensional aqueous advection, gaseous diffusion, adsorption, and degradation in up to four soil layers with varying properties. ATI3DD can represent advective-dispersive ground-water transport away from source areas of varied dimensions, strength, and duration within homogenous, isotropic aquifers. Simulation results from the application of these models to a Superfund site in the San Francisco Bay Area were used to develop and support proposed cleanup levels for volatile erganic compounds (VOCs) in soils. (VOCs) in soils.

> Nº 3893

IMPLICATIONS OF ALONG-STRIKE VARIATIONS IN BASIN GEOMETRY ON THE KINEMATICS OF MIGCENE EXTENSION, MORTHWEST ARIZONA AND SOUTHERN NEVADA

PAULDS, J., Dept. Geology, U. So. California, Los Angeles, CA 90089; BUERENDORFER, E., Dept. Geology, U. Hevada, Las Vegas, NV 89154. Along-strike changes in graben geometry may be pertinent to kinematic models of continental extension. In the mortheramost Colorado River extensional corridor, an E-tilted half graben extends 40 km morthward from a major accommodation some. The W-dipping Wilson Ridge fault (WRF) bounds the basim on the east; the morthern basim margin is the dextral Las Veras Valley shear zone (LVVS2). The major pulse of tilting eccur-red between 16-13 Ha and 13-9 Ha in the southern and morthern parts of the basim, respectively. The accommodation zone served as a supture the basin, respectively. The accommodation some served as a rupture barriar during both events. Directly morth of the accommodation some, the basin deepens and widens morthward as displacement on the WRF and tilting both increase. Farther morth, the basin expands in two discrete steps with little increase in tilting. The steps are marked by minor sinistral offset on transfer faults and broad flexures in the strike of function expected without the steps are marked by minor of Tertiary strats indicative of anti-clockwise vertical-skis rotation. The basin is widest (20 km) at its northern margin near the LVVS2. Abundant crystalline detritus in the basin suggests that the footwall crystalline terrane of the WRF was exposed throughout Miccene extension. The WRF terminates mear the inferred juncture and apparent ter-mination of the LVVSZ and simistral Lake Mead fault system (LMFS).

The deformational style associated with expansion of the basin implies that the relative diametrical translation of the hanging wall and footwall of the MRF increases away from the accommodation some but is not proportional to the magnitude of tilting. Corval activity along the LVVSZ, LMFS, and WRF further suggests major kinematic coupling of strike-slip and normal faults at the northern end of the extensional corridor. Diametrical lateral transport of the hanging wall and footwall of the MRF may partly account for opposing senses of strike-slip motion along the LVVSZ and LMFS.

Nº 21576

SYNEXTENSIONAL BARITE-SILVER MINERALIZATION IN THE NANGING

SYNEXTENSIONAL BARITE-SILVER MINERALIZATION IN THE NANGING WALL OF THE WATERMAN MILLS DETACHMENT FAULT, CENTRAL MOJAVE DESERT, CALIFORNIA FEISS, P. Geotirey, GLAZNER, Allen F., Dept. of Geology, CBJ 3315, Univ. of North Carolina, Chapel Hill, NC 27599, BARTLEY, John M., Dept. of Geology and Geophysics, Uriv. of Urah, Sat Lake City, UT 84112 Barte-silver mineralization in the Waterman Hills, north of Barstow, CA, and large barte-silver deposits in the nearby Calico Mourtains, eccur in the hanging wall of the Waterman Hills, the deposits are exposed at the Waterman Hills, north of Barstow, CA, and large barte-silver volcanic and sedimertary toics. Mapping (1:2400) revasts that mineralization was syndepositional and derived from the station-chydrothemal system that caused pervasive K-metasomatism of the hanging wall of the WHDF and chortic atteration of the bootwal. We term the two mineralized stratigraphic horizons the tower ere horizon (LCH) and upper re horizon (UCH). The LCH and UCH each are exposed for sportburstely 1 km along strike; both consist of Bin, fine- grained, green to purple, incusting beds containing conformable jaspencidal allicz and barte with Ag-bearing vehicles. Each ere horizon records an episode of

sublacustine mineralization which was abruptly terminated by emplacement of a massive debris flow. The LOH is 5-15 m thick and is both underlain and eventain by massive volcaric debris flows. Barts and silver are absent from the stratigraphically overlying debris flows and are found in only one narrow 5 m zone in underlying nocks. The UOH is thinner than the LOH and is extensively bracciated. Fragments of jaspente, mudstone and altistone, and bedded barts are fimmed and comented by barts and by the line-grained classic matrix. The UOH is underlain by the debris flow that everies the LOH and is eventain by a monolithologic dorite megatheredia. Barts whits and towents are found in the porous debris flow underlying the UOH for a distance of 3-15 m beneath the mineralized horizon, but no mineralization is observed in the equally porous everying debris flow. The prasence of contormable interbodded tacustine sectiments, jaspentes, and bedded barts, the littler restricted to Bin lacestrine prices that barties, deconsition was

bartie, the latter restricted to thin lacustrine horizons, indicates that bartie deposition was syndepositional. Emplacement of thick debits flows and megabreccia terminated the bartieextensional leading activity that formed each are negatived a terminated are barre-depositing filemail spring activity that formed each are horizon. The deposits formed during extensional lauting because the are horizons are (1) interbedded with extremely coarse, syn-extensional debits flows, (2) filted to dips ranging from generally >70° to locatly everturned, and (3) functied by hybrids plugs that are themselves cut by the WHDF. Thus, these depo-sits and possibly those of the Galico district represent detachment-related Ag mineralization.

Nº 15446

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THE TRANSITION FROM SUBALKALIC TO ALKALIC VOLCANISM IN THE LAKE MEAD AREA OF NEVADA AND ARIZONA: GEOCHEMICAL AND ISOTOPIC CONSTRAINTS FEUERBACH, D.L. and SMITH, E.L. Department of Geoscience, University of News Las Vegas, NV 89154; WALKER, JD. and TANGEMAN, JA., Department of Geology. University of Kanza, Lawrence, KS 66045.

the to early Pliocene volcanic rocks in the Lake Mend area of Nevada and Arizona Late Mice record the transition from early, moderate-volume, suballatic basalt and besaltic andesite to later, low-volume, alkali basalt volcanism. Calc-alkalic basaltic andesites occur in the Callville Meas How-whence, alkin basis volcamin. Calculate mainly endering even in the Calculate Meas workarie field (CM) or the aorth short of Late Mead. CM invas strupted from two compound ender scores between 30.6 and 8.5 Ma. Basahie andenite (32 to 55% EO₂) shows instopic and textural ordenee of erustal contamination (inkis) ¹⁵Sr /⁴Sr = 0.708-0.709, epsilon M/s = 4.49 to - 10.69, and ²⁰Tr/¹⁰Tr = 17.173 to 17.332). We suggest that Callville magmas were generated the Ethospheric mantic as basis similar in composition to basis in Callville Wash (10.6 Ma) and younger Fortification Hill basis, but were contaminated in the erust during ascent.

Subalkalic and alkalic basalts (46 to 30% SiO2) occur in the Fortilication Hill field (FH), FH basaks erupted from at least eight volcanic centers between 6.02 and 4.3 Ma. Fortification Hill on the east side of Lake Mend is the most voluminous of these centers. We divide FH basak into use can not at Life Mesa is the most voluminous of meric senserie. We have P a start mito three groups: (1) Tholeistic two promose basak (622-57) Ma) (5AB) at Black Point and Malpak Flattop and suballalic basak at Fertilication Hill (lower section), (2) Alkali basak (5A2 to 4.74 Ma) (CAB) at Fortilication Hill (upper section), Fetroghyph Wash and Lave Causack. (3) Alkali basak (6A1 to 4.3 Ma) (YAB) slong U.S. 93 ner: Hoover Dam, Saddle Haind and in Petroghyph Wash, YAB hows commonly contain ultramatic sociales and amphibole and feldspar megacrysts. The transition from subalkalic to alkalic volcanism occurred between 3.71 and 5.42 Ma during the formation of Fortification Hill. The change from SAB to YAB is marked by an increase in Attracts of FORM and the state of the $N_{2,0} \leftarrow L_{2,0}$ (0.5 to 17%), Ce/Vb₍₂₎ (0.5 to 12,), Ta (2.5 to 9 ppm), F₂O₅ (0.3 to 0.8%), TO₅ (1.3 to 2.5%), and accusative sephelise (all values are means). CAB invas are intermediate in composition between \$AB and YAB. The change from \$AB to YAB is marked by a decrease in initial #"Se/"Se from 0.7079-0.7056 in SAB lavas to 0.7055 in QAB to 0.7035 in YAB. Epsilon Nd increases from -2.28 to -0.34 in SAB to -0.64 in CAB to 3.65 in YAB. These geochemical waintions reflect a sharee from fithersheric to astherousheric martie sources with time. This thange may sellect lithospheric prosion due to regional extension.

Nº. 11507

KINEMATIC MODEL FOR THE DEVELOPMENT OF WEST-VERGING STRUCTURES IN THE PURCELL ANTICLINORIUM, CABINET MOUNTAINS. NORTHWESTERN MONTANA

FILLIPONE, Jeffrey and YIN, An Department of Earth and Spe

Sciences, University of California Les Angeles, Les Angeles, CA 90024 The west flank of the Purcell Anticlinorium in the Cabinet Mountains, northweste Montana consists of three stajor structural elements: (1) E-verging structures including E-directed thrusts, E-verging folds, and W-dipping cleavage, (2) W-verging structures including W-verging eventurned folds, W-directed thrusts, and E-dipping eleavage, and Michaeling wereging eventuated sources were assured as an archyping surgery and (3) a series of M-reading Create-coust philons. The E-verging structures are of verging extent, and can be unced throughout the Cabinet Mountains. In sourcest, the W-verging structures are localized in the central Cabinet Mountains. The oppositely verying structures are separated to the south by a SW-dipping threat further and to the west by a Cretaceous pluton (the Dry Creek stock) and a later high-angle fault (the Rock Lake fault). E-directed thrasts lie structurally above the W-directed structures. Towards the north, W-verging structures become a series of broad folds. Cross-cutting selationships between the E- and W-verging mesoscopic structures, e.g., eleavage, are ent in the area, suggesting opeval development of the two structural elem The Dry Creek stock lies about 3.5 km west of the W-verging structures and has a coneshaped geometry on a cross-sectional view. Well developed foliation, locally styloalitic, is present on the west side of the stock. The S-C fabric indicates a top-to-the-start pense of shear on a W-dipping shear zone. This relation suggests that the E-verging structures formed either during or immediately after emplacement of the stock, and thus, all three major structural elements in the area may have formed simultaneously. On the basis of age relationships among structures in the area and the spatial relationship between the stock and the localized W-verging structures, we interpret that the development of localized W-verging structures may be the result of platon emplacement. In partic-the spreading of magma at shallow structural levels within the Belt strata may have In strucular. produced a localized, W-directed simple shear strain within the Belt rocks. As alternative model is that a W-dipping thrust ramp is present at depth and the W-verging structures were related to the emplacement of a hanging-wall anticline, a wedge-shaped indenter, to form a triangle sone. This model is, however, inconsistent with the field relationship that the W-werging structures formed beneath E-verging structures.

THE EASTERN BOUNDARY OF THE EXTENSIONAL ALLOCHTHON IN THE EASTERN BASIN AND RANGE: VOLCANIC AND STRUCTURAL GEOLOGY OF THE NORTHERN WHITE HILLS, ARIZONA.

CASCADDEN, Tracey E., and SMITH, Eagene I., Department of Geoscience, University of

Nevada, Las Vegas, NV 89154. The northern White Hills lie in the upper plate of the westward-disping Eak Spring detachment The upper plate contain 5 cast-filed structural blocks comprised of Miocene basakic andeste Saw sport part contains or sourcestor and an even uniprice under the state of an even and and contrasts. Because each block is incluted and contains only a small part of the stratigraphic section, geochemical data (La, Cr, HI, Sc, Sr and Co) was used to construct a composite section. The oldest part of the composite section consists of at least 464 meters of basaltic andesite flows and antociastic breecias. composite section consists of at least 464 useters of basahic andexite flows and antoclastic breccias. They are overlain by 0.575 meters of coarse monolithologic breccia, in which the dominant shart type is lower plate Procambrian petiter, granke, amphibolic, and mylonic. The breccis forms a discontinuous sheet that extends 12 hm west from the detachment in Sak Spring Wash to Square Peak and pinches out to the north near Lake Mead. Longwell (1576) described similar deposits in the Virgin Basin (now flooded by Lake Mead). Interbedded with source breccis is a ducite sak-flow unif (94-520 meters thick) that may correlate with a unif in the northern Black Mountains dated by Paulds (1990) at 16.5 Ma. The upper part of the section consists of 63-677 meters of basahic andexite. Adjacent to the detachment in the sasters White Hills there is a progressive decrease in addite. Adjacent to the detachment in the sasters White Hills there is a progressive decrease in the two metion from 20 to 37 mear the base to nearly horizontal at the non-Athourie starial filts eft up section from 30 to 37 mean the base to meanly horizontal at the top. Although striktal sits way from 30 to 37 in the central and wextern White Hills, they are mailorm within structural Nock

The Sak Spring detachment may represent a segment of a regional detachment zone that extends from Gold Batte to near Dolan Springe, Arizona (Opelopic detachment). This fault zone See 20 km west of the Grand Wash Chil's and reprotents both the externament boundary of the extensional allochthon and the eastern Emit of exposure of Territory igneous rocks in the mortherm Colorado trough. The lack of equivalent igneous rocks in the forwall of the detachment between Sak Spring Wash and the Colorado Plateau may place constraints on either the geometry of the detachment or the pre-extension distribution of volcanic rocks.

Nº. 2024

THE SEISMOTECTONICS OF THE SAN ANDREAS FAULT SYSTEM NORTH OF POINT ARENA ALONG THE COAST RANGES OF NORTHERN CALIFORNIA

CASTILLO, David A., Dept. of Geophysics, Stanford University, Stanford, CA 94305 and U. S. Geological Survey, Menlo Park, CA 94025; ELLSWORTH, William L., U. S. Geological Survey, Menlo Park, CA 94025

The relatively youthful segment of the San Andreas fault (SAF) system north of Point Arena occupies a -70 km wide zone of distributed deformation bounded by the San Andreas fault "proper" to the west and by the SAF-parallel Maacama and Bartlet. Springs fault zones to the east. Earthquakes (M2 1.0) occurring between 1980 and 1989 are used to develop a seismonectonic model of the youthful part of the SAF "system" as it evolves into a manne plate boundary. An upper crustal velocity model for the area, derived from seismic travel-time inversions indicates a typical Franciscan crust with compressional velocities stacking 6.0 km/sec at about 18km depth. We used this velocity model to selocate over 5000 M21.0 earthquaket.

earthquakes.

The San Andreas fault north of Point Arena is vistually assismic. In contrast, numerous microearthquakes concentrate along the Maacama and Bartlen Springs fault zones. These zones terminate abruptly at about 39°50' N, approximately 100km southeast of Cape Mendocino. Along the Maacama fault the seismicity is relatively continuous and extends to about 15 km depth, while along the Bartlett Springs fault zone the seismicity is carticly discontinuous in about 20 km deret.

extense to about 15 km depth, while along the particle springs fault able are set and by a spatially discontinuous to about 20 km depth. The sense of strain release inferred from earthquake focal mechanisms along both the Mancama and Bartlett Springs fault zones is consistent with right-lateral slip along the North American and Pacific plate boundary. Slip vectors derived from these focal mechanisms are sub-parallel to small circles about the pole of rotation for the North

American and Pacific planes. Interestingly, we find the strike-slip Maacama fault dips northeast about 60 to 75 degrees. We speculate that in the wake of the northward migrating Mendocino Triple junction, the dipping Maacama fault is now accommodating right-lateral transform motion along an older (> 2Ma) severse fault initially formed due plate margin convergence.

Nº. 2703

APATITE AND ZIRCON FISSION-TRACK AGES FROM THE SIERRA

AFAITLE AND LIRCON FISSION-TRACK AGES FROM THE SIERRA SAN PEDRO MARTIR, EASTERN PENINSULAR RANGE, BAJA CALIFORNIA, MEXICO CERVENY, Philip F., DORSEY, Rebecca J., BURNS, Beverly A., Dept. of Geology, University of Wyoming, Laramie, WY 82071 Zircon and spatite fission-track ages from the Sierra San Pedro Martir, Pair Colfornic has to conclude the Sierra San Pedro Martir, Baja California help to constrain the uplift and cooling history of this segment of the eastern Peninsular Range. Five samples were collected from granitoid rocks at elevations from 500m to 2800m above sea level. Zircon ages range from 104 ± 10 Ma. at the range crest to 75.5 ± 6.2 Ma at the base. The emplacement age of the batholith has been reported by Silver and Chappell (1988) as 120 to 105 Ma (U-Pb sircon); the uppermost sircon ission-track age thus reflects rapid cooling near the time of emplacement. Fission-tracks in zircon completely anneal at temperatures of 200-225°C, or 8-9 km depth assuming a geothermal gradient of 25°C/km. Therefore the

Abstracts with Programs, 1991 12

rocks currently at the top of Sierra San Pedro Martir were emplaced at depths of less than 8 km. Apatite ages range from 76.3 \pm 6.8 Ma (mean track length 14.2 \pm 1.3 microns) at the crest of the range to 35.6 \pm 3.7 Ma (12.9 \pm 1.5 microns) at the base, and define an uplif/cooling rate of -60 m/m.y. Mean track length distributions are unimodal for all samples, but m/m.y. Mean track length distributions are unimodal for all samples, but indicate a slightly higher degree of annealing for the 35 m.y. ages (lower elevations). The apatite ages at the base of Sierra San Pedro Martir place limits on the total amount of uplift since 35 Ma. Fission-tracks totally anneal in apatite at approximately 100°C, or about 4 km depth. Because the basal samples do not show significant annealing, they have resided at depths of less than 3 km since 35 Ma, and have likely been uplifted no more than 2 km since this time. The Sierra San Pedro Martir has had a relatively aimple cooling history consisting of emplacement and rapid cooling (120 - 105 Ma) at depths of less than 8 - 9 km, followed by slower steady rooling from 75 Ma to shout 35 Ma (a 600 mm v). Uplift, and erosion steady cooling from 75 Ma to about 35 Ma (-60 m/m.y.). Uplift and erosion of Sierra San Pedro Martir is limited to about 2 km since 35 Ma.

Nº 17703

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PALEOGEOGRAPHIC RECONSTRUCTION OF THE NORTHERN SALINIAN BLOCK USING Sr ISOTOPIC PROPERTIES CHAMPION, D. E., and KISTLER, R. W., U.S. Geological Survey, Mealo Park, CA 94025

Age and initial Se studies have been used to reconstruct the 117 to 80 Ma granicol basement of the Salinian block to form a simple pattern. The pattern places the 0.706 ⁴⁷Sr/⁴⁶Sr line at or within the northernmost plutons of the block, including Montara Mountain, with an abrupt SE increase to Sr, values over 0.707. Comparison of our work with many previously published Neogene

sedimentary/stratigraphic correlations across faults shows strong agreements. Aligning the thick sections of the Santa Cruz Mudstone at PL Reyes and in the

Santa Cruz Mountains at about 6 Ma brings elements of a distinctive granodiorite at Bodega Head and Montara Mountain together. Matching the Monterey Formation and Paleocene conglomerates at Pt. Reyes and at the Monterey peninsula requires movement on a San Gregorio splay, inboard of Montara Mountain, at about 11 Ma. Removal of this displacement brings both Montara Mountain-Ben Lomond granitoid rocks and the Pt. Reyes-Pacific Grove porphritic granodiorites into direct proximity. The total San Gregorio displacement approaches 150 km.

The 45 km of 10-15 Ma displacement on the Rinconada fault at Paso Robles, recognized by Graham and others in the central Salinian block, probably manifests itself as distributed deformation on many faults in the Santa Lucia Mountains. The Blue Rock-Miller Creek fault, for example, has abrupt isotopic variation across it, permitting some strike-slip movement. The Rinconsda fault movement caused the broad S-shaped bending of the Vergeles-Zayante fault, and was completed by the 10 Ma deposition of the Santa Margarita Formation, which overlaps the Zayante fault. Neogene stratigraphic and Late Cretaceous pluton reconstructions imply that no significant internal faulting occurred in the northern Salinian block between \$0 and 15 Ma.

Nº 6387

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FINITE STRAIN FACTORIEATION, BY TENSOR ALGEBRA, IN AN INCONGRUENT FOLD

Nº 6387 FINITE STRAIN PACTORIBATION, BY TENSOR ALGEBRA, IN AN INCONGRUENT FOLD IN THE COLFAX SEQUENCE Chen, Richard T., Department of Earth and Space Sciences, University of California, Los Angules, CA 90024-1367 The general structural trand of the fault-bounded Colfax sequence, between the Meimar fault zone (N) and the Gillis Sill fault (E) in the northern Sierra Nevada foothills follows the Mevadan trand, is predominantly BMN-SIS. Along a traverse from the estner of the sequence to its eastern limit, March strain was estimated in eight samples across a severely fractured, incongruent, asymmetrical syncline, whose fold axis trands K14T and glunges 36". Three of the sequence to its eastern limit, March strain and the ether two mear the Gillis shill fault, were taken from steeply dipping beds with Mevadan strike: the remainder were collected from the south and morth limbs and the hings area of the fold. From the west to the east, strain intensities increase monotonically from 0.40 to 0.74. The strains in the fold, furthermore, have similar intensities, 0.56 to 0.66, with little veristion in their principal values (0.3220.63, 0.1610.02, -0.3320.02) indicating that the fold was formed during a late phase of deformation involving tigid body rotation but no bulk strain. To restore the late-phase deformation, the layers in the morth limb and hinge were first unfolded by rotating them along the fold axis to esincide with the ergional trend. The total strain in this restored orientation was factorized into a compaction and a tectonic strain. Between the two events, buckling tilted the horizontal beds. Based on this model and on the variation of the total strain along the section, the rocks suffered a compaction strain of [0, 0, -0.3] followed by a tectonic strain of titted the moritontal bads. Eased on this model and on the variation of the total strain along the section, the rocks suffered a compaction strain of [0, 0, -0.3] followed by a tectonic strain of [0.13, 0.05, -0.13] in the west, increasing to [0.37, 0.07, -0.32] in the east, with the axis of shortening trending E-W and the intermediate axis paralleling to the regional MNW-SE trend.

SESSION 47. SAIC: STORAGE OF HIGH-LEVEL NUCLEAR WASTE

volcanic rocks (206Pb/204Pb = 18.11-18.24 and 201Pb/204Pb = 38.70-39.15) but diverges from it in some samples

The carbonate fraction of lead in both wein and calcrete samples resides dominantly In fine-grained, authigenic calcie. 1.5N HC also attacks and removes lead from silicate phases, but a milder 0.8N CH₃COOH dissolution procedure identifies a significantly more stranogenic lead in most of the calcit (²⁰⁶Pb/²⁰⁴Pb = 18.11-20.21 and 206Pb/²⁰⁴Pb = 38.60-39.34). Probably this radiogenic carbonate lead was transported into the win system by the downward percolation of meteoric water that had previously interacted with surficial calcuter. Windblown particulate matter derived from Palezzoic and Late Provenzoic lineatore in surfmenting mounts may be the ultimate gauge of and Late Proterozoic limestone in surrounding mountains may be the ultimate source of the calcite. Several samples, however, including two from a vein incorporating a thin zone of basaltic ash, contain *carbonate* lead that is only slightly different from their silicate lead. These isotopically more uniform samples suggest that volcanic rocks The isotopically hear or the lead to both fractions of the vein system. The isotopically hear ogeneous lead that characterizes the regional Paleozoic and Late

Proterozoic sedimentary socks and Middle Proterozoic crystalline rocks remains a candidate for at least some of the lead in the Trench 14 veins. An important finding of this study, however, is that the data do not require the more exotic origins that have been proposed for the veins. Instead, the similarity between lead isotopic properties of the veins and calcretes suggests a mutual origin related to pedogenic phenomena.

02:15 p.m. Marshall, Brian D. Nº 7474

A MODEL FOR THE FORMATION OF PEDOGENIC CARBONATE BASED ON

MARSHALL, Brian D. and MAHAN, Shannon, U.S. Geological Survey, MS 963, DFC Box 25046, Denver, CO 80225

Calcareous soils are ubiquitous in and segions such as the southwestern United States. Models describing the formation of the calcium carbonate that coments loose, porous material in these soils usually require an allogenic component for the source of the large amounts of calcium in the calcite. The isotopic composition of strontium, a common amounts of exicitin in the exicit. I ale isotopic composition of acconting, a common trace constituent in exitonates, is an ideal tracer for the origin of the calcium. Analyses of strontium in calcretes, fault-filling veins, rhizoliths, surface coatings, and colian sediment sear Yucca Mounnain, Nevada, provide important constraints on the origin of the alkaline earths incorporated in these versious surficial materials. Calcretes, fault-filling veins and rhizoliths contain carbonate-bound (=HCl

teachable) strontium with \$75,465r averaging 0.7124. This value is significantly different from the average of 0.7117 found for earbonate-bound strontium in the surface sourings and in colian acdiment. These results lead to two conclusions: (1) calcite surface coatings on bedrock derive their alkaline earths from the colian carbonate component and (2) the alkaline earths in calcrete and fault-filling-vein calcite are nor

composed and (2) the analyses of the silicate and the information of the analyses of the silicate and the second s

fractures. The $^{87}Sr^{86}Sr$ of these calcites varies from pedogenic-type values near the surface to lower values (0.7093) at and below the water table. Some of the alkaline surface to lower values (0.7053) it ind below we water made. Some of the attainte earths in these fracture coatings may be partially or totally derived from the volcanic bedrock, which has widely varying isotopic compositions. These data preclude the involvement of upwelling ground water in the genesis of surficial carbonate in the immediate vicinity of Yucca Mountain.

02:30 p.m. Stuckless, J. S.

Nº 19828

Isotopic Evidence for a <u>Per Descensum</u> Origin for Hydrogenic Veins in Faults near Yucca Mountain, Nevada STUCKLESS, J.E., PETERNAN, E.E., WHELAN, J.F., and MUHS, D.R., US Geological Survey, MS 963, Denver Fed. Ctn., Denver CO 80225

Vein-like deposits of calcite and opaline silica that infill faults and fractures in the vicinity of Yucca Mountain have been the center of considerable debate because the deposits occur near a possible site for the Nation's first high-level nuclear wasts repository. The various proposed modes of origin for the deposits, such as catastrophic upwelling of water or downward percolating fluids related to pedogenic processes, have differing implications for the performance of a geologic repository. Isotopic data for oxygen, carbon, a geologic repository. Isotopic data for exygen, carbon, strontium, and uranium in the carbonate minerals exposed at Trench 14 preclude deposition from upwelling waters from either of the regionally extansive aquifers known to exist beneath Yucca Nountain. Oxygen isotopes imply deposition of calcite at unreasonably to impossibly low temperatures; strontium is too radiogenic; and uranium activity ratios are too low. Data from calcites deposited by the adjacent Ash Meadows flow system further suggest that the isotopic compositions of ground water in Southern Nevada have not changed markedly during the last 60 to 600 k.y. and that, therefore, conclusions based on present-day water compositions are probably valid for at least the last 60 to the compositions of the Vecca Mountain calcites Data from calcites deposited by the adjacent Ash k.y. Isotopic compositions of the Yucca Mountain calcites are similar to those observed in secondary soil carbonates and, in combination with existing geologic, mineralogic, and paleontologic data, show that the carbonate and opaline silica deposits must have formed from descending water related to a pedogenic process.

Nº 16720

QUATERNARY BROSION RATES ON HELISLOPES IN THE YUCCA MOUNTAIN REGION, NEVADA

HARRINGTON, Charles D., Earth and Environmental Sciences Division, EES-1, MS D462, Box 1663, Los Alamos National Laboratory, Les Alamos, NM 87545 and WHITNEY, John W., U.S. Geological Sarvey, Federal Conter, MS 913, Denver, CO 80225

scenn w., u.s. uconogreat survey, renters ucmet, MIS 913, Denver, CD 80225 Yacca Mountain is a parties of eastward-tillud structural blocks. These blocks are composed of fine-grained, Territary volcanic rocks, primarily welded suffs that are resistant to weathering in the present saminrid elimans. In the Yacca Mountain region, Qusternary cycles of interase weathering on ridge creats and hillshopes during glacks (bluvial) episodes have resulted in a patchwork of this collavial Amounta of methic same deposits of variable ages.

Approximate long-term average erosion sates can be exiculated for hillslopes that have dated Approximate and were greened when deposits were studied on seven different slopes that have gradients ranging from 15-32 degrees. Hillshope degradation marginal to these deposits ranges from 0.2-1.1 m. Maximum incision in active channels adjacent to collavial deposits ranges from 0.3-2.8 m. Cation-ratio dating of nock varnish from surface boulders on these deposits ratio cations from TO ba to > 1 Ma. Long-term erosion states solution for hillstopes that have relict early to middle Quaternary deposits mage from 0.2 to 7.3 mm/kz and sverage 1.2 mm/kz.

Erotion mass on Vacca Moustain are relatively low compared to sates for other semiarid regions. In California and New Maxico, published long-term erotion mass range from 10-43 mm/ta on hillslopes underlain by resistant Ethologies. Erosion mass esiculated for skopes on less resistant sock types and for shorter time periods, however, are as much as two orders of magnitude larger.

Hillslopes in the Yacca Mountain area second an exceptional history of geomorphic stability from the early Queternary to the present. Several conditions contribute to these low long-term erosion states: (1) bedrock concrept as well as boulders in the hillslope deposits are erosionally-resistant welded suffs, (1) Benotice descriptions are well as boliclers in the humble acpoints are embodingly-extension vectors millistopes serve as a protoctive cap that inhibits reamoval of faser grained debris by slopewash, (4) Millistope channels include calculated debris by slopewash, if Millistope channels include calculated debris by spopersphic inversion and remove them from active caronion by remoting resulted to active channels on middle and lower hillstopes and mrely strip debris annelized areas i non el

03:00 p.m. Faulds, James E.

02:45 p.m. Harrington, Charles D.

Nº. 6918

NEW INSIGHTS ON STRUCTURAL CONTROLS AND ENVLACEMENT MECHANISMS OF PLICCEME/QUATERWARY BASALTIC DIRES, SOUTHERN NEVADA AND NORTHWESTERN

HY INSIGHTS OF STRUCTURAL CONTROLS AND ENFLACEMENT MECHANISMS OF FLOCENE/QUATERIARY EMALTIC SIELS, SOUTHERS HIVADA AND BORTHWISTERN ALIONA FAULDS, James E., Dept. of Geology, University of Iowa, Iowa City, IA S2242; FRUCHARCH, Baniel L. and EKITK, Eugene I., Dept. Geocelence, University of Hereda, Las Vegas, NV 59154 Yive Quaternary Mesaltic volcanic centers lie within 20 km of the proposed high-level suclear wasts repository at Turce Nountain. The basaits rose through the struct without containation. Previous studies suggested that relatively this (< 5 s) diless fed the basaltic centers. The Quaternary diles, scoris mounds, and sinder conce quartally trend HKL. Potential HT-striking mear-surface channelways for the basaits include sormal fault segments, layering in highly deformed Proterosoic and Falconoic rocks, and joints. Rowwer, lack of feeder dikes and controlling structures. To alucidate the geometry of plumbing systems beneath Quaternary volcances mear Yurce Mountain, highly-dissected Piloreme basaitic senters were studied in the Fortification Eill field of morthwestern Arisons. The Even Highly dissected centers are located en the wast flank of Kalpais Mesa. Merz, dikes within and directly beneath three centers are linked by a 1-2 s wide dike. Thus, dike withis increase by an order of magnitude directly beneath some centers. The ENN- to NH-striking dikes in the Fortification Eill field comonly parallel but are rarely intruded directly along premisting thructures. Some dikes out directly across Nicene bornal faults. All dikes have mear vertical digs. These observations singly that dikes may bary propagated upward through "self-generated" fractures grobably developed perpendicular to the least grineingl streas. Masard assessments of Turce Akoutain should consider the potential for dike intrusion along self-generated their som pathways perpendicular to the Boot wrisentation felses principal streas. Masard assessments of Turce Akoutain should consider the potential for dike intrusion along self-generated fa

03:15 p.m. Wesling, J. R.

Nº 25537

SURFICIAL MAPPING IN MIDWAY VALLEY: IMPLICATIONS FOR FUTURE STUDIES TO ASSESS SURFACE FAULTING POTENTIAL AT PROSPECTIVE SURFACE FACILITIES FOR THE POTENTIAL YUCCA MOUNTAIN REPOSITORY, NEVADA'

WESLING, J.R., SWAN, F.H., BULLARD, T.F., ANGELL, M.M., and PERMAN, R.C., Geometrix Consultants, Inc., One Market Plaza, Spear Street Tower, Suite 717, San Francisco, California 94105; G18SON, J.D., Org. 6315, Sandia National Gaos

Laboratories, P.O. Box SEOO, Albuquerque, New Mexico 87185. Preliminary Quaternary geologic mapping of Midway Valley sevents that some alluvial surfaces and associated deposits are of sufficient antiquity to satisfy DOE's guidelines for evaluating surface faulting potential at the aits of prospective surface waste-kandling facilities. Guidelines include mutting potential at the first of prospective surface waste-handling inclutes. Guidelines suched identifying and ovaluating faults that have had a slip rate >0.001 mm/yr during the past 100 ka. Eight alluvial surfaces (Q₀-Q₁) and associated deposits are successized in Mislway Valley based on geologic and geomorphic mapping. The oldest surface (Q₀) is preserved as a single terrace semant and may be Flio-Fleistlocene in age. Younger surfaces, anging in age from early or middle Pleistocene (Q₁) to latest Pleistocene units occur as low terraces and surfaces (Q₂) along active washes (Q₂). Colluvial units of at least three ages mantle hillslopes.

SESSION 153, MSA--IGNEOUS PETROLOGY (POSTERS III)

of the western Aleutian crust between ~43 and 15 Ma. After 15 Ma, small volumes of crystal-rich andesite and dacite were erupted on Attu Island and throughout the wester Aleutians. These strongly calculatine rocks are peochemically related to magnesian andesites of Piip Volcano which is located immediately behind the western-most Entermises of Pip Volcano & Bydrochem instructionary behave the westernistic Alcutan (dge. Pip Volcano is a hydrochemally-active sermount that has formed on small dilational structures within the regionally wans-pressive regime of the modern western Alcutans. This leaky wansform' setting is inferred to have been established at approximately 15 Ma following wans-tensional rithing and voluminous tholeinic magnatism. The switch from tholeinic magnatism related to a wans-ensional regime to strongly calculation magmatism related to a wans-pressional argime may have resulted from clogging of the Aleutian - Karnchatka junction with buoyant, subduction-related terranes. These terranes probably originated to the east and were transported by strikealio motion along the western are.

Booth 27 Higman, S. L. Nº 17231

APPLICATIONS OF CHAOS THEORY TO ZONING MORPHOLOGY IN MAGMATIC PLAGIOCLASE

HIGMAN, S.L. and PEARCE, T.H., Department of Geological Sciences,

Queen's University, Kingston, Ontario, Canada, K7L 3N6 The thicknesses and morphology of escillatory zones in magmatic plagioclase from Mt. St. Helens, Washington, and St. Kins, Lesser Amilles show sequences of ordered planar zones separated by sequences of disordered convolute sones. This pattern suggests that during crystal growth, some factor controlling crystallization in the melt changed to cause apparent periodic and chaotic zonation patterns. As a result, the zonation patterns observed suggest that plagicclase crystallization is a nonlinear dynamic process. Determining the dimensionality and functional form of the nonlinear dynamical equations represents the first

step in creating a predictive model for plagioclase crystal growth. Reconstruction of the state space of the system from the relative time-series of

some-thickness measurements reveals two types of behaviour: a spiral geometry, and a limit cycle geometry. These are indicative of a non-chaotic Hopf bifurcation. In low-dimensional chaotic systems, the same state space can be used for prediction

of the time series of zone thicknesses. Poor correlation between time-series predictions and actual some thicknesses suggests that plagioclase growth is not governed by a lowdimensional chaotic system of equations. However, this poor correlation is not inconsistent with the Hopf bifurcation hypothesis.

The correlation dimension can be used to constrain the dimensionality of the sonlinear system controlling crystal growth. Recent workers have concluded that the data requirements for this calculation are not as extreme as previously suggested. Using the method of Grassberger and Procaccia (1983), a definitive dimension cannot be obtained from the time-series of plagioclase crystals examined to date because of the limited number of zone thicknesses observed. Consequently, a different approach is required to calculate the correlation dimension in natural systems characterized by limited data.

Grassberger, P. and Procaccia, I. 1983. Measuring the strangeness of strange attractors. Physics 9D, pp. 189-208.

Booth 28 Herzig, Charles T.

6345 Nº.

CALC-ALKALINE VOLCANISM OF THE BARLY CRETACEOUS SANTIAGO PEAK VOLCANICS, NORTHERN SANTA ANA MINS., CALIFORNIA: EARLY MAGNATISM OF THE PENINSULAR RANGES BATHOLITH.

HERZIG, Charles T., Dept. of Farth Sciences, University of California, Riverside, CA, 92521. The results of detailed mapping, geochemistry, and the first microprobe mineral analyses of the Early Cretaceous Santiago Peak Volcanics (SPV) at their "type" locality in the northern Santa Ana Mins yield insights into the magnetic avolution of the Barissular Enversh hatholith (EDD the northern Santa Ana Mins yield insights into the magnatic evolution of the Peninsular Ranges batholith (FRB) during its earliest stages of emplacement. Structurally intact sequences of subarial flows, welded tuffs, volcani-clastic breecies, epiclastic rocks, and hypabyssal intru-sions are the remants of the volcanic arc built above the batholith. Flows are dominantly basaltic andesites and andesites, with lesser basalts, dacites and rhyodacites. Major element compositions of andesites, basaltic andesites and basalts are of a low-K, calc-alkaline series. Rocks of tholeiitic affinity are also present. Cpx with a composi-tional range of Wojz-agEnge-4gFsg-22 plots within the non-alkali field on discrimination diagrams, straddling the calc-alkaline - tholeiitic line of Laterrier and others (1982). The compositions of cpx from the SPV overlap with those from gabbros of the FRB. Calcic amphiboles from the SPV are pargesite and edenite with rare magnesic-horn-blende. These compositions show limited overlap with These compositions show limited overlap with blende. blende. These compositions show limited overlap with amphiboles from gabbros of the FRE. Plegioclase crystals are dominantly labradorite-bytownite (overall rangs is An_{50-B5}). Opx is completely altered to chlorite, part of a greenschist facies alteration assemblage present in all rocks. The field setting, abundance of andesitic composi-tions and calc-alkaline affinity of the rocks is consistent with an origin of the SPV as a volcanic arc constructed at or near the margin of North America.

A390 ABSTRACTS WITH PROGRAMS, 1991

Booth 29 Durant, Dolores G.

CRISTAL SIZE DISTRIBUTION STUDIES IN SPANISH PEAKS, COLORADO DURANT, Dolores G. and CLIFFORD, Paul M., Dept. Geology,

McHaster University, Hamilton, Ont. L85 4Ml The Spanish Peaks (SP) dual intrusions of southern Colorado, their surrounding radial dyke swarm and several related plugs

form a spectacular volcanic complex in the Rio Grande Rift. To shed light on the crystallization history of some Rio Grande magmas, petrographic relationships and crystal size distribution (GED) have been examined for opaques, olivine, and augite from a gabbroic dyke of Ruerfano Butte (RE) and feldspars and opaques from a "rhyolitic" dyke of the SP SM27B.

CSD plots for NB augite and NB opaques yield straight

CSD plots for NB augite and NB opaques yield straight lines with steep negative slopes. These are consistent with constant, continuous growth and nucleation during erystallization, as well as no crystal fractionation during emplacement and size independent growth. Similar plots for NB clivine, SP feldspars, and SP opaques yield asymmetric bell curves indicating fines depletion. HE clivines show resorption features on all grain sizes. The resorbed material was possibly redeposited as NB augite; this may explain the higher slope values for NB augite compared to NB opaques. SP epaques also show loss of material due to resorption.

Auglet compared to an opaques. To opaques also show to be to be the second seco a magma chamber perhaps by neutral density bourancy or by magma movement within the chamber. Decreasing CSD slopes across the SP dyke for both SP feldspars and SP opaques are probably due to thermal and chemical disequilibrium towards the centre of the dyke.

Booth 30 Cascadden, T. E.

Nº 25911

INTERMEDIATE AND MAFIC VOLCANIC ROCKS OF THE NORTHERN WHITE HILLS, ARIZONA: BAPLICATIONS FOR THE PRODUCTION OF INTERMEDIATE COMPOSITION VOLCANIC ROCKS DURING REGIONAL EXTENSION

COMPOSITION VOLCANCE ROCKS DOMING REGISTIONAL EXTENSION CASCADDEN, T.E., Dept. of Geology, University of New Mexico, Albequerque, NM 87331 SMITH, E.L., Dept. of Geosciesce, University of Newsda, Las Vegas, NV 89154 The generation of intermediate emergouilon ignous rocks during regional extension is commonly setribud to the comminging of make and fakic magnam and be basis of geochemical, petrographic and field ordence. In the Lake Mead area of the mothern Colorado extensional corridor, magna mingling produced intermediate composition calc-alkaline lavas and associated plutons in the Black Mountains, Arizons and River Mountains, Nevada, However, in some areas of the Basia and Range, thick sections of mafic to intermediate volcanic socks lack the petrographic, field and chemical evidence for examinging. As example of such as area is the sorthern White Hills (NWH), northwesters Arizona, the easternmost exposure of suid-Tertiary igneous rocks at the ade of Las Vegas.

The NWH contain three mid-Miocene mafic to intermediate volcanic senters. Lavas are subalistic to alkalic and way in composition from basah (46-37% SiO₂) to basahic trachyandesite (32 to 57% SiO₂) to trachyandesite (57-61% SiO₂). No₂O+K₂O varies from 4-8%; rocks have not been subjected to K-metasomatism. Each volcano is composed of chemically and petrographically term surfaces to transmission that we have a second second second and the second secon st. Variation within magma

mgma type are similar. All lawas sontais elivine as an equilibrium phase. Variation within magmi types is explained by fractionation of elivine or elivino-eliaopyruzene-plagioclase. These observations suggest that the intermediate volcanic suites in the White Hills were derived by partial metting of chemically different, but mineralogically similar sources. Because elivine is an equilibrium phase in the three magma types, it must have been on the liquidus in the source. We suggest that the most likely source for NWH magmas is spinel periodette. High Sr contents (ES6-1300 ppm) argue against erustal contamination. This model is similar to that proposed by Barker and Thompson (1989) for the alfalic lawas of the Hamblin-Cleopatra volcano of the methamet of the MURD has mattered with the mean mean summing model methametodel (to the northwest of the NWH) but contrasts with the magna commi ingling models proposed for the compositionally heterogeneous volcanic rocks of the River and Black Mountains. Therefore, in the Lake Mead area two independent processes (partial meking and magma comminging) were responsible for the production of intermediate composition igneous rocks during mid-Miocest

Booth 31 Hoch, Anthony R.

Nº 23712

PETROGRAPHIC EVIDENCE FOR MIXING OF ALKALINE AND SUB-ALKALINE MAGMAS IN THE RATTLESNAKE HILLS INTRUSIVE COMPLEX. CENTRAL WYOMING.

HOCH, Anthony R.; MYERS, James D.; FROST, Carol D., Dept of Geology

and Geophysics, University of Wyoming, Laramic, WY 22071. The Rattlesnake Hills of central Wyoming host Eocene intrusions and extrusive bodies of quarts-normative rhyolite and quarts latite. These are apatially divided into two groups: the eastern felsic group (EFG) and the western felsic group (WFG). Nephelinesormative phonolites, trachytes and ismprophyres comprise the central alkalic group (CAG), which is located between the EFG and WFG.

Although the EFG and WFG rocks have similar bulk-rock chemical compositions, they are petrographically different. The EFG rocks (plag+hb+exp+sit+/-qtz) are coarsely porphyritic (phenocrysts up to 7 mm) with unzoned eligoclase :

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Booth 95 Wild, Steve

Nº 24719

EDEDIATION OF PETROLEUM HYDROCARBON-CONTAMINATED GROUND

SPHEDIATION OF PETROLEUM NYDROCARBON-CONTAMINATED GROUND NATER AND SOIL USING IN-SITU AIR SPARGING AND ACTIVE SOIL VAPOR EXTRACTION AT LIST SITIS IN NEW MEXICO. WILD, Steve, New Nexico Environment Dept., 1190 St. Francis Dr., Santa Fe, EM 87503; BILLINGS, Jeffrey F., Billings & Assoc., Inc., 3816 Academy Phry N-ME, Albuquerque, EM 87103; ARDITO, Cynthia J., Albuquerque, EN 87103; ARDITO, Cynthia P., Intera, Inc., 8100 Mtn. Rd. ME, Albuquerque, NN 87110 As part of the New Mexico Environment Department's (NMED's) efforts to locate and evaluate cost-effective and efficient remediation technologies for leaking underground storage tenk (LUST) sites, NMED has been closely tracking the gubsurface Volatilization and Ventilation System (SVVS, patent pending, 1989).

Subsurface Volatilisation and Ventilation System (SVVS, patent pending, 1989). The SVVS consists of a series of well nests which are installed within the areas of soil and ground-water contamination at LUST sites. Each well nest consists of a vapor extraction well screened within the vadose some and an air-injection well screened below the water table. The SVVS utilizes three remediation processes: vadose some vapor extraction (in-situ ventilation); air sparging of the saturated zone (in-situ air stripping); and enhanced -icrobial biodegradation.

microbial blodegradation.

The SVUS has proven very effective in the remediation of LUST sites in Hew Maxico where a shallow water table exists. Significant reductions in benzene, toluene, ethyl penzene, and rylenes (BTIX) have been observed over rela-tively short time spans. SVVS treatment has been damon-strated to be an extremely efficient remediation technology when compared to conventional pump and treat systems.

Booth 96 Wyatt, D. E.

Nº 28605

SOIL GAS GEOCHEMICAL SAMPLING AS A METHOD OF GROUNDWATER FLOW DETECTION AT THE CHEMICALS, METALS AND PESTICIDES PITS (CMP PITS) AT THE SAVANNAH RIVER SITE

WYATT, D. E., BLOUNT, G. C., PRICE, V., Westinghouse Savannah River Company, P. O. Box 616, Alken, SC 29801; PIRICE, R. J., MicroSeeps Ltd., 220 William Pitt Way, Pittsburgh, PA 15238. The CMP Pits consisted of two parallel traches used for disposal of eli, organic

solvents, pesticides and metals during the years 1971 through 1979. The disposal area is centrally located within the Savannah River Site on a topographic high. In 1984, the waste was removed, the contaminated soil excavated and 20 groundwater monitoring wells were installed in a effort to monitor, remediate and close the site. Minor organic plumes are known to exist in the shallow aquifers.

Recent soil gas surveys, in support of a RCRA/CERCLA integrated investigation identified elevated concentrations of organics in areas away from the disposal site and different from the presumed groundwater flow directions. Groundwater flow directions at the site are to the north for the shallow aquifer and towards the disposal area from the north, south and east for the deeper equiler. Geological data from monitoring wells suggests that a carbonate zone underlying the disposal area may affect localized groundwater flow.

Soil gas survey data identified contaminated groundwater plumes emanating from the site but not predicted by monitoring wells. Data indicates that soil gas surveys may be utilized to retine groundwater flow directions in areas where complex shallow aquifers are contaminated with votable organics.

The information in this abstract was developed during the source of work under contract DE-AC09-89SR18035 with the U.S. Department of Energy.

SESSION 98, 1:30 p.m. TUESDAY, OCTOBER 22, 1991 T 25: CENOZOIC EXTENSION IN THE CORDILLERA: GEOMETRY. TIMING, MECHANISMS, AND **REGIONAL CONTROLS (PART II)**

SDCC: Room 16AB

01:30 p.m. Metcalf, Rodney V. Nº 26750

HORNBLENDE GEOBAROMETRY FROM MID-MIOCENE PLUTONS: IMPLICATIONS REGARDING UPLIFT AND BLOCK ROTATION BURING BASIN AND RANGE EXTENSION

METCALF, Rodney V., and SMITH, Eager e L. Department of Ge ace. University

RETCALF, Rodary V., and SMITH, Eagens L., Department of Geneciesce, University of Nevada, Las Vegas, Nevada 89154 Al-in-hornhiesde grobsrometry was sured to determine the depth of crystallization for two Miccess age platons, Wilcon Ridge (WRP) and ML. Parkins (MIPP), from the morthern Colorado River estensional corridor. The WRP exhibits a hypohymol cap to the north and extends 20 hm to the south where it intrudes Prezambrian gracies. North tranding hubs and dikes indicate the WRP has experienced estimate estimation. The MPP intrudes Prezambrian gracies with a hardward of the function of the south hord to hardward the hirak-indicate the hypabynal cap to the west and extends 3.2 km east where it is out by the low-angle Mockingbird Mise hult (Faulds, 1913). North trending diess suggest nome essi-west extension of the MPP. Paleomagnetic data suggest no slit for WRP and 50 " west tilt for MPP (Faulds, 1939). Both mposition from monzodiorite to ets monzonite. Evidence of magn n range in er comminging and large angular blocks of adder hornblende diorite occur in both platons. Hersblende soning profiles reveal complex growth histories. For this reason individual and rather than averages were used in geobarometry extendations. Small anhedral interstillal g etry exiculations. Small anhedral interstitial grains yield unrealistically low Al contents and pressures and represent grains isolated fro some senter places required by the probarometer. Some risks of harge eshedral grains also exhibited low Al contents and ware avoided. Analyses used in enclusions were taken from areas manufact new AL contrars and wave avoided. Analyses most an catchations were taken from areas of relatively uniform compaction within about 50 micross of grain edges. Using multiple grains in each, three samples of (qti) monosolicrits and one blief diorite from the seathers and of WEP yield similar results with Al-total (hased on 23 exygens) of 1.15 to 1.3. This yields pressures ranging from L49 to 3 kbars and depths of 4.9 to 6.7 kms. A varaging these results (n=10) yields PuL6 of 4.2 kbars and a depth of 5.3 of 4.95 kms. A single sample of WRP monosolis from 1.6 has control of the branch sources and the first of 1.07 km 6.7 kms. A single sample of WRP monosolis from 1.6 has south of the hypohysisal cap yields Al-totale I.02; P-0.55; and a depth of 2.5 kms. Assuming rotation about a horizontal east-west axis these results are consistent with 15 ° of 3 ° of sorthward till. Rotation of WRP must have occurred as temperatures cooled from the solidat to Bertwart HL Reinford of WAT miss also activate a supprising containing containing the born in a solution of the MPT yield Al-total of L01 to L3; pressures of 0.81 to L3 khers; and depths of 2.5 to 4.4 kms. Averaging these results (a=4) picks Poll +0-2 khars and a depth of 2.5 \pm 0.7 to 4.4 kms. This result is consistent with a westward fill of 35 \pm 0.4 \pm 0 provided that the Precumbran-Late Tortiary unconformity, 3 km west of the spex of MPP, was the surface at the time of intrusion. We infer that some or all of the rotation of the MPP occurred below the Carrie temperatury



Nº 16613

RELATIONSHIP BETWEEN MIOCENE PLUTONISM, UPLIFT, AND EXTENSION, LAKE MEAD AREA, NORTHWESTERNMOST ARIZONA AND ADJACENT NEVADA

ANDERSON, R.E., and BARNHARD, T.P., U.S. Geological Survey, Box 25046, MS 956, DFC, Denver, CO, 80225 The Lake Mead area can be added to the growing list of areas in the Conditiona that expose evidence for a close association between Cenozoic plutonism and extension. The Wilson Ridge pluton in the northern Black Mountains is a north-broadening, Hangular, composite, epizonal mass, about 20 km on each edge, that was amplied into Patternate mark and Relapping and can edge. eroscenng, sanguar, composite, epiconar mass, about 20 km en each eoge, stat was emplaced into Proterozoic crystalline rock and Paleozoic and Cenozoic cover rocks during late Miscene time. Petrogenetic studies by Larson and Smith (1990, JGR, v. 95, p.17693) indicate that it formed by commingling et a large volume of mafic magma with a smaller volume of felsic magma. The pluton is titled about 5 discrete and experiments in burgeness and and in the next and its discrete degrees north, exposing its hypabyssal zone and roof in the north and its deeper parts in the sou

The extent of preintrusion Cenozoic deformation is best evaluated in the north, where the pluton intrudes Miocene sedimentary and volcanic rocks. Those rocks show a mild to moderate degree of preintrusion titing that increases southward. The pluton there consists of thousands of dikes that record 8-15 km of synemplacement riting in an approximately east-west direction. This riting by synemplacement hung is an approximately east-west direction. This mung by dike-on-dike emplacement was accompanied by a southward-increasing degree of synemplacement extension-related tilling. In the northeramost part of the pluton, dikes are mostly vertical and preintrusive strata dip gently. By contrast, directly south of Lake Mead, preintrusive volcanic strata are subvertical, main-phase dikes dip at moderate angles, and late dikes are subvertical, indicating protracted pre-and syn-intrusion extension-related tilting events that ended with plutonism. The country nocks and pluton were tilted away from and downlauted toward the axis of the aligned to be the substrated tilting events that ended the coverd the axis of the pluton in these events, suggesting extensional collapse of the growing, rising pluton and of the rising Black Mountains structural block. Contrary to current models of extensional deformation in the area, we find no evidence that the northern Black Mountains served as a source terrane for west-transported extensional allochthons.

ANNUAL MEETING, SAN DIEGO, CALIFORNIA A245



VOLCANIC RISK ASSESSMENT STUDIES FOR THE PROPOSED HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA, USA

by

SMITH, Eugene I., FEUERBACH, Daniel L., and NAUMANN, Terry R. Center For Volcanic and Tectonic Studies, Department of Geoscience, University of Nevada, Las Vegas, NV 89154 (USA)

and

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Volcanic hazard studies by the Center for Volcanic and Tectonic Studies related to the proposed high-level radioactive waste repository at Yucca Mountain, Nevada have concentrated on producing a synthesis of Late Miocene to Quaternary basaltic volcanism in the southern Great Basin. To obtain a regional perspective of basaltic volcanism, detailed mapping and sampling of analog systems as well as volcanic centers within 50 km of the proposed repository have been completed. Important advances from these studies include the documentation of detailed chronostratigraphy within volcanic fields and development of geochemical models for the genesis of alkalic mafic magmas within continental rift environments. These data in combination with studies of the structural controls on the emplacement of mafic magmas have led to the determination of an area of most recent volcanism (AMRV) near Yucca Mountain. Data from volcanic centers within the AMRV are being used to estimate recurrence rates and conditional probability of future volcanism for risk assessment. The AMRV includes ten eruptive centers and encompasses all post-4 Ma volcanic complexes within 50 km of the proposed repository. High-risk rectangles were constructed at each cluster of Quaternary centers within the AMRV. The size, shape and orientation of these high-risk zones is based on structural and volcanic studies in the AMRV as well as in analog volcanic fields. The proposed waste repository lies within one of the risk rectangles associated with the Lathrop Wells volcano.

The possible recurrence of volcanic activity in the AMRV was evaluated by estimating the instantaneous recurrence rate using a nonhomogeneous Poisson process with Weibull intensity and by using a homogenous Poisson process to predict future eruptions. Based on data from Quaternary data, the estimated instantaneous recurrence rate for volcanism is about 5.5×10^{-6} /year. We conclude that the estimated probability of at least one eruption occurring in the AMRV in the next 10,000 years is about 5 percent.

<u>Key Words</u>: Volcanic Risk, Basaltic volcanism, Nuclear Waste Repository <u>Scientific session</u>: Volcanic Hazard and Risk Mitigation <u>Preferred Type of Presentation</u>: Poster

NEW K-Ar AGES FOR PLIOCENE MAFIC TO INTERMEDIATE VOLCANIC ROCKS IN THE REVEILLE RANGE, NEVADA

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In this paper we report 16 new K-Ar ages for Pliocene mafic to intermediate volcanic rocks in the Reveille Range, Nevada and one K-Ar date of a Miocene-aged tristanite from the vicinity of the Reveille Range.

The Pliocene volcanic rocks of the Reveille Range represent the southern half of a 20 km wide by 100 km long north to N30°E trending belt that combined with the Lunar Crater Volcanic Field extends from 37°45' to 38°45' in the south-central Great Basin (fig. 1a). According to the classification of Irvine and Baragar (1971) volcanic rocks range in composition from picrite to trachyte and occur as shallow intrusions, domes, flows and dissected cinder cones. Based on field relations, petrology and K-Ar ages volcanic rocks of the Reveille Range are divided into three episodes (Naumann and Smith, 1988) (fig. 1b and 2). These are:

- *Episode 1* (5.9 to 5.0 Ma): Basalts of Episode 1 are porphyritic olivine basalts that contain plagioclase megacrysts (up to 40 modal %). They range in composition from alkali basalt to hawaiite (44 to 48% SiO₂). Fifty-two vents occur on both the east and west flanks and near the crest of the range (fig. 1b).
- *Episode 2* (4.6 to 3.0 Ma): Basalts of Episode 2 are porphyritic olivine basalts containing megacrysts of augite (up to 40 %), amphibole (up to 35 %) and plagioclase (<5%) and coarse grained xenoliths of gabbro and dunite (up to 20 cm in length). They range in composition from picrite to trachybasalt (41 to 56% SiO₂). Fourteen Episode 2 vents occur on the northeast piedmont and flank of the range (fig. 1b).
- Evolved volcanism (4.4 & 4.2 Ma): Eruptions of trachyte (60% SiO₂) and tristanite (58% SiO₂) containing ferrosillite, hedenburgite, anorthoclase, sanidine, and andesine produced two domes (volumes are < 0.01 km³ and 0.26 km³, respectively) on the northeast flank of the range (Naumann and others, 1990) (fig. 1b). The northernmost dome is associated with an apron of pyroclastic flow and surge deposits and volcaniclastic debris (fig. 1b).

The new K-Ar dates establish that two episodes of basaltic volcanism occurred in the Reveille Range between 5.9 and 3.00 Ma. Episodes of basaltic volcanism were separated by the eruption of trachytic lavas and pyroclastic units at 4.4 and 4.2 Ma (fig, 2).

Previously published K-Ar ages for the Reveille Range include a date of 5.7 \pm 0.2 Ma on an Episode 1 basalt flow on the northwestern flank of the range (Marvin and others, 1973). Dates of 5.8 \pm 0.3 and 5.6 \pm 0.3 Ma were obtained for Episode 1 basalt flows in the western part of the range, and 3.9 \pm 0.2 and 3.8 \pm 0.3 Ma for Episode 2 basalt flows on the east flank of the range (Dohrenwend and others, 1985). The K-Ar dates reported in this paper indicate that the most recent activity in the Reveille Range occurred at 3.0 Ma rather than 3.8 Ma.

MIGRATION OF VOLCANISM

Foland and others (1987) reported that volcanism migrated to the north in the Reveille-Lunar Crater field. According to their model, volcanism initiated at about 9 Ma and migrated north to the Lunar Crater field at a rate of about 1 cm/year. Detailed dating of volcanic centers in the northeast Reveille range indicates that migration patterns are locally more complicated. For example, in the northeastern Reveille Range, Episode 1 activity migrated mainly to the south while Episode 2 volcanism migrated both north and south. The youngest Episode 2 volcano (3.0 Ma) formed in the south (fig. 3).

MISCELLANEOUS NYE COUNTY VOLCANIC ROCKS

A previously unmapped trachyte dome and flow complex located 20 km southeast of the Reveille Range in the White Blotch Springs quadrangle yielded a K/Ar date of 14.1 Ma. The dome is 1 km in diameter and 150 m high and was mapped on the Geologic Map of Southern Nye County as undifferentiated Pliocene welded Tuff (Cornwall, 1972).

ANALYTICAL TECHNIQUES

All dates were obtained from groundmass plagioclase separates. Feldspar phenocrysts and megacrysts were removed from samples prior to analysis. Analytical procedures discussed by Damon and others (1983) were used in this study (constants: $\lambda_{\beta} = 4.963 \times 10^{-10}$ yr⁻¹, $\lambda_{\epsilon} = 0.581 \times 10^{-10}$ yr⁻¹, $\lambda = 6.544 \times 10^{-10}$ yr⁻¹, 40 K/K = 1.167 × 10⁻⁴ atom/atom).

ACKNOWLEDGEMENTS

This study was funded by the Nevada Nuclear Waste Project Office. We also thank Nathan F. Stout for drafting the illustrations in this paper.

SAMPLE DESCRIPTIONS

Episode 1

 R8-1-17-LN K-Ar Porphyritic olivine basalt flow; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°4'15°, 116°7'24°; Reveille Range, Nye County, NV). Analytical data: K = 0.846, 0.849, 0.823%; *Ar⁴⁰ = 7.335, 7.462, 7.651, 7.461 × 10⁻¹² mol/gm; *Ar⁴⁰/∑Ar⁴⁰ = 54.5, 55.2, 56.4, 55.3%. Collected by: T. R. Naumann; dated by: M. Shafiqullah. Comment: This sample was collected from the youngest Episode 1 flow.

(plagioclase) 5.13 ± 0.15 Ma

[ISOCHRON/WEST, no. 57, July 1991]



FIGURE 1. - Location of Pliocene and younger volcanic rocks of the Reveille Range - Lunar Crater volcanic field. - Generalized geologic map of the Pliocene volcanic rocks in the northeastern Reveille Range. Circled numbers are sample locations for K-Ar dates.

[ISOCHRON/WEST, no. 57, July 1991]



FIGURE 2. Cartoon cross-section showing the stratigraphic relationships among the dated volcanic units in the Reveille Range. Symbols are the same as in figure 1b. Tmg = Tuff of Goblin Knobs (Monotony Tuff) a densely welded, coarsely devitrified quartz fattic to rhyolitic welded tuff. Dates for Tmg were reported in Ekren and others (1973).

- R8-1-24-LN K-Ar Porphyritic olivine basalt dike; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°3'18", 116°8'52"; Reveille Range, Nye County, NV). Analytical data: K = 0.871, 0.871, 0.891, 0.887%; *Ar⁴⁰ = 8.233, 8.390, 8.374, 8.254 × 10⁻¹² mol/gm; *Ar⁴⁰/∑Ar⁴⁰ = 78.4, 78.5, 76.4, 64.5%. Collected by: T. R. Naumann; dated by: M. Shafiqullah. (plagioclase) 5.44 ± 0.14 Ma
- 3. R8-1-28-LN K-Ar
 Porphyritic olivine basalt flow; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°5'40°, 116°8'5°; Reveille Range, Nye County, NV). Analytical data: K = 1.693, 1.683, 1.652, 1.679, 1.683, 1.679%; *Ar⁴⁰ = 16.57, 16.78, 16.80 × 10⁻¹³ mol/gm; *Ar⁴⁰/ΣAr⁴⁰ = 66.4, 68.1, 68.2%. Collected by: T. R. Naumann; dated by: M. Shafiqullah. Comment: This sample and R8-1-29-LN were collected from the same cinder cone-flow complex.

(plagioclase) 5.74 ± 0.10 Ma

4. R8-1-29-LN K-Ar Porphyritic olivine basalt plug; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°5'39", 116°8'40"; Reveille Range, Nye County, NV). Analytical data: K = 1.116, 1.079, 1.067, 1.118, 1.095%; *Ar⁴⁰ = 10.92, 10.73, 10.55, 10.48 × 10⁻¹³ mol/gm; *Ar⁴⁰/ΣAr⁴⁰ = 50.7, 49.7, 49.0, 48.6%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 5.61 ± 0.15 Ma

5. R9-1-48-LN K-Ar Porphyritic olivine basalt flow; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°9'48", 116°6'02"; Reveille Range, Nye County, NV). Analytical data: K = 1.194, 1.176, 1.229, 1.185, 1.170%; *Ar⁴⁰ = 12.08, 12.04, 12.03, 11.80 × 10⁻¹³ mol/gm; *Ar⁴⁰/ΣAr⁴⁰ = 75.7, 75.5, 75.7, 75.2%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 5.80 ± 0.13 Ma



FIGURE 3. Plot of K-Ar age against latitude for dated volcanic centers in the northeast Reveille Range. Diamonds = Episode 1 basalts; Triangles = Episode 2 basalts and trachyte levas.

[ISOCHRON/WEST, no. 57, July 1991]

14

6. R9-1-56-LN

Porphyritic olivine basalt plug; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°10'33", 116°5'30"; Reveille Range, Nye County, NV). Analytical data: K = 1.257, 1.260, 1.225, 1.209%; *Ar⁴⁰ = 12.92, 12.67, 12.66, 12.82 × 10⁻¹² mol/gm; *Ar⁴⁰/EAr⁴⁰ = 67.2, 65.7, 65.8, 66.8%. Collected by: T. R. Naumann; dated by: M. Shafiqullah. Comment: This sample was collected from the stratigraphically lowest Episode 1 flow.

(plagioclase) 5.94 ± 0.14 Ma

7. R9-1-57-LN K-Ar
Porphyritic olivine basalt; contains large plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°7'15", 116°5'45"; Reveille Range, Nye County, NV). Analytical data: K = 1.365, 1.367, 1.384, 1.393, 1.360%; *Ar⁴⁰ = 13.73, 13.73, 13.77 × 10⁻¹³ mol/gm; *Ar⁴⁰/\sum EAr⁴⁰ = 68.0, 66.9, 66.9%. Collected by: T. R. Naumann; dated by: M. Shafiqullah. Comment: R9-1-57-LN is overlain by pyroclastic deposits from the adjacent trachyte dome.

(plagioclase) 5.76 ± 0.14 Ma

Episode 2

8. R8-1-2-LN K-Ar Porphyritic olivine basalt flow; contains plagioclase and augite megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°3'30°, 116°8'20°; Reveille Range, Nye County, NV). Analytical data: K = 1.469, 1.468, 1.444, 1.469, 1.497%; *Ar⁴⁰ = 10.12, 10.24, 10.50, 10.33, 10.25, 10.29, 10.29, 10.20 \times 10⁻¹² mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 71.2, 72.9, 74.0, 68.9, 68.6, 69.0, 68.5, 72.6%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 4.03 ± 0.12 Ma

K-Ar

9. R8-1-13-LN

Porphyritic olivine basalt plug; contains large plagioclase and augite megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°4'23", 116°7'18"; Reveille Range, Nye County, NV). Analytical data: K = 0.805, 0.825, 0.839%; *Ar⁴⁰ = 6.730, 6.676, 6.607, 6.482 × 10⁻¹³ mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 68.3, 67.8, 67.3, 67.5%. Collected by: T. R. Naumann; dated by: M. Shafiqullah. Comment: This sample was collected from the oldest Episode 2 basalt.

(plagioclase) 4.64 ± 0.14 Ma

10. R8-1-18-LN K-Ar Porphyritic olivine basalt flow; contains large plagioclase and augite megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°4'20", 116°7'24"; Reveille Range, Nye County, NV). Analytical data: K = 0.999, 0.994, 0.987, 0.969, 0.972%; *Ar⁴⁰ = 6.757, 6.801, 6.867 × 10⁻¹² mol/gm; *Ar⁴⁰/∑Ar⁴⁰ = 73.7, 74.9, 75.4%. Collected by; T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 3.99 ± 0.10 Ma

11. R8-1-19-LN K-Ar Porphyritic olivine basalt flow; contains large plagioclase and augite megacrysts in a holocrystalline matrix

[ISOCHRON/WEST, no. 57, July 1991]

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of coarse plagioclase, augite and Fe-oxide $(38^{\circ}2'15^{\circ}, 116^{\circ}7'10^{\circ};$ Reveille Range, Nye County, NV). Analytical data: K = 0.911, 0.875, 0.840, 0.905, 0.874, 0.872, 0.854%; *Ar⁴⁰ = 6.387, 6.627, 6.240, 6.327 × 10⁻¹² mol/gm; *Ar⁴⁰/\SAr⁴⁰ = 68.1, 66.2, 66.1, 66.9%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 4.15 ± 0.13 Ma

- 12. R8-1-27-LN K-Ar Porphyritic olivine basalt plug; contains large plagioclase and augite megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°3'10", 116°9'23"; Reveille Range, Nye County, NV). Analytical data: K = 1.886, 1.809, 1.863, 1.833%; Ar⁴⁰ = 9.939, 9.643, 9.594, 9.355 × 10⁻¹² mol/gm; *Ar⁴⁰/ΣAr⁴⁰ = 51.9, 50.5, 50.0, 48.6%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.
 - (plagioclase) 3.00 ± 0.08 Ma
- 13. R9-1-46-LN K-Ar Porphyritic olivine basalt flow; contains large augite and plagioclase megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide. (38°10'30", 116°6'30"; Reveille Range, Nye County, NV). Analytical data: K = 1.621, 1.580, 1.584, 1.582, 1.630%; *Ar⁴⁰ = 10.47, 10.66, 10.36, 10.30 × 10⁻¹² mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 38.3, 39.0, 38.1, 38.0%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 3.76 ± 0.11 Ma

14. R9-1-58-LN K-Ar Porphyritic olivine basalt flow; contains large plagio-clase and augite megacrysts in a holocrystalline matrix of coarse plagioclase, augite and Fe-oxide (38°7'17", 116°5'45"; Reveille Range, Nye County, NV). Analytical data: K = 1.386, 1.343, 1.361, 1.371, 1.366%; *Ar⁴⁰ = 9.24, 9.51, 9.44, 9.22 × 10⁻¹² mol/gm; *Ar⁴⁰/EAr⁴⁰ = 57.2, 58.6, 58.3, 57.6%. Collected by: T. R. Naumann; dated by: M. Shafiqulah. Comment: This sample was collected from a flow that directly overlies pyroclastic deposits from the adjacent trachyte dome.

(plagioclase) 3.95 ± 0.12 Ma

Evolved Volcanic Rocks

15. R8-1-16-LN K-Ar Tristanite dome containing plagioclase and sanidine (38°3'18°, 116°8'52″; Reveille Range, Nye County, NV). Analytical data: K = 3.617, 3.517, 3.687, 3.757, 3.556, 3.567%; *Ar⁴⁹ = 27.79, 27.41, 27.55, 27.37 × 10⁻¹² mol/gm; *Ar⁴⁹/ Σ Ar⁴⁹ = 86.4, 86.0, 86.5, 86.0%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagloclase) 4.39 \pm 0.18 Ma

16. R8-1-43-LN K-Ar Trachyte flow containing sanidine and plagioclase phenocrysts in a matrix of green glass ($38^\circ7'45^\circ$, $116^\circ5'20^\circ$; Reveille Range, Nye County, NV). Analytical data: K = 4.838, 4.841, 4.931%; *Ar⁴° = 36.04, 35.79, 35.69, 35.96×10^{-12} mol/gm; *Ar⁴°/ Σ Ar⁴° = 65.2, 65.7, 65.4, 58.4%. Collected by: T. R. Naumann; dated by: M. Shafiqullah.

(plagioclase) 4.24 \pm 0.06 Ma

K-Ar

16

Miscellaneous Nya County Volcanic Rocks

17. N9-SD-LN K-Ar Tristanite dome containing sanidine and plagioclase (37°41'30", 115°56'30"; Nellis Bombing and Gunnery Range, Nye County, NV). Analytical data: K = 1.724, 1.720, 1.738, 1.727, 1.719, 1.715, 1.701%; *Ar⁴⁰ = 41.96, 41.89, 42.47, 42.14 × 10⁻¹² mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 83.4, 82.9, 83.7, 83.2%. Collected by: T. R. Naumann; dated by: M. Shafigullah.

(plagioclase) 14.1 ± 0.14 Ma

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NEW K-Ar DATES FOR LATE MIOCENE TO EARLY PLIOCENE MAFIC VOLCANIC ROCKS IN THE LAKE MEAD AREA, NEVADA AND ARIZONA

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We report the results of 13 new K-Ar radiometric ages for basaltic andesites from the Callville Mesa volcanic field on the north shore of Lake Mead, Nevada, and basalts from the Fortification Hill volcanic field, Arizona and Nevada (fig. 1). These volcanic fields are located in the northernmost part of the Colorado River extensional corridor, an area of extensive Miocene igneous activity and upper crustal extension (e.g., Longwell and others, 1965; Anderson, 1971; Anderson and others, 1972; Bohannon, 1984; Smith and others, 1990).

CALLVILLE MESA VOLCANIC FIELD

The Callville Mesa (CM) volcanic field is exposed primarily on Black and Callville Mesas north of Lake Mead. Basaltic andesite erupted from compound cinder cones on Callville

Mesa and in West End Wash between 10.46 to 8.49 Ma. These dates are slightly younger than the whole rock K-Ar dates of 11.3 \pm 0.3 Ma and 11.1 \pm 0.5 reported by Anderson and others (1972) for basaltic andesite of Callville Mesa.

Basaltic andesite of Callville Mesa locally overlies and is interbedded with the Red Sandstone unit (Bohannon, 1984), sandstone and conglomerate that was deposited in a structurally controlled basin in the upper plate of the Saddle Island detachment (Duebendorfer and others, 1990: Duebendorfer and Wallin, 1991). The basin and extensional allochthon are bounded to the north by the Las Vegas Valley Shear Zone (Duebendorfer and Wallin, 1991) (fig. 1). Callville Mesa basaltic andesite was erupted during the late stages of development of the Red Sandstone basin and represents the only volcanism during active upper



FIGURE 1. Generalized geologic map of the Lake Mead area, showing locations of samples for K-Ar dating. SI = Saddle Island: PW = Petroglyph Wash; FH = Fortification Hill; AB = alkalic basalt along U.S. 93; LC = Lava Cascade; MF = Malpais Fiattop; LMFZ = the Lake Mead Fault Zone; LVVSZ = Las Vegas Valley Shear Zone.

18



FigURE 2. Cartoon cross sections showing stratigraphic relationships and major structures. The River Mountains are primarily intermediate volcanic flows and intrusive rock (Smith, 1982). Dates for the River Mountains from Anderson and others (1972) and Weber and Smith (1987). Tmc = Muddy Creek Formation (Late Tertiary classic sediments). Trs = the Red Sandstone Unit (Tertiary classic sediments); Ths = Tertiary Horse Spring Formation. Dates for the Horse Spring Formation from Bohannon (1984); Twr = Tertiary Wilson Ridge Intrusive rocks. Date from Larson and Smith (1990); $Mz = Mesozoic sediments; P \in =$ undifferentiated Precambrian rock.

crustal extension and stratal tilting in the Lake Mead area. Since basaltic andesite dated at 10.46 Ma is tilted and younger units (10.21 to 8.7 Ma) are not, the major phase of tilting related to motion on the Saddle Island detachment occurred after 10.46 Ma (fig. 2). In other parts of the Lake Mead area, stratal tilting may have occurred as early as 13 Ma (Bohannon, 1984).

FORTIFICATION HILL BASALT

The Fortification Hill basalt field comprises at least eight volcanoes that occur in a 75 km long north-northeast trending zone that extends from Malpais Flattop, Arizona to Black Point, Nevada. Tholeiite, calc-alkalic and alkalic

basalt periodically erupted from 6.02 (this study) to 4.3 Ma (Anderson and others, 1972). The Fortification Hill basalts form the uppermost part of the Muddy Creek Formation (Longwell and others, 1965; Bohannon, 1984).

Subalkalic and alkalic basalts occur in the Fortification Hill field (FH). We divide FH basalt into three groups (table 1; refer to fig. 1 for locations): (1) Tholeiltic two-pyroxene basalt (6.02-5.71 Ma) (SAB) at Black Point and Malpais Flattop and subalkalic basalt at Fortification Hill (lower part of the section). (2) Alkali basalt (5.42 to 4.74 Ma) (OAB) at Fortification Hill (upper section), Petroglyph Wash and Lava Cascade. (3) Alkali basalt (4.61, this study; to 4.3 Ma, Anderson and others, 1972) (YAB) along U.S. 93 near Hoover Dam, Saddle Island and in Petroglyph Wash.

[ISOCHRON/WEST, no. 57, July 1991]

TABLE 1. The subalkalic and alkalic suites of mafic lavas in the Lake Mead area. Abbreviations are defined in the text.

Alkelic	Sub-elkelic	Age (Ma)
	Callville Mesa (CM)	10.46-8.49
	Black Point (SAB)	6.02
	Malpais Flattop (SAB)	5.8
Fortification Hill (OAB)	Fortification Hill (SAB)	5.89-5.42
Petroglyph Wash (OAB)		5.43
Lava Cascade (OAB)		5.16-4.74
Young Alkalic Basalt (YAB)		4.61-4.3

The transition from subalkalic to alkalic volcanism occurred during eruptions at Fortification Hill and occurred just prior to 5.42 Ma.

ANALYTICAL TECHNIQUES

All dates were obtained from groundmass plagioclase separates. Analytical procedures discussed by Damon and others (1983) were used in this study (constants: $\lambda_{\beta} = 4.963 \times 10^{-10}$ yr⁻¹, $\lambda_{\epsilon} = 0.581 \times 10^{-10}$ yr⁻¹, $\lambda = 6.544 \times 10^{-10}$ yr⁻¹, ⁴⁰K/K = 1.167 $\times 10^{-4}$ atom/atom).

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This study was funded by the Nevada Nuclear Waste Project Office. We would like to thank Nathan F. Stout for drafting the illustrations in this paper.

SAMPLE DESCRIPTIONS

Callville Mesa (CM)

- 1. F8-24-100-LN K-Ar Olivine-pyrosene basalt flow $(36^{\circ}10'19''N, 114^{\circ}42'30''W; just W of Callville Wash, Clark Coun$ ty, NV). Analytical data: K = 0.969, 0.951, 0.942,0.963%; *Ar⁴⁰ = 17.61, 17.33, 17.44, 17.15 ×10⁻¹² mol/gm; *Ar⁴⁰/EAr⁴⁰ = 62.2, 61.5, 61.3,60.3%. Collected by: D. L. Feuerbach; dated by:M. Shafiqullah. Comment: This flow is interbeddedwith tilted Red Sandstone and represents the oldestactivity associated with volcanism at Callville Mesa.(plagioclase) 10.46 ± 0.23 Ma
- 2. F8-24-88-LN K-Ar Basaltic andesite plug (36°10'33"N, 114°44'16"W; within volcanic center on Callville Mesa, Clark County, NV). Analytical data: K = 1.952, 1.978, 1.981, 1.952%; *Ar⁴° = 31.73, 31.50, 30.83, 30.37 × 10⁻¹³ mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 41.5, 41.0, 40.4, 39.6%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: This plug contains plagioclase megacrysts and xenocrysts of quartz.

(plagioclase) 9.11 ± 0.30 Ma

3. F8-24-90-LN K-Ar Basaltic andesite plug (36°10'29"N, 114°43'52"W; within volcanic center on the W side of West End Wash, Clark County, NV). Analytical data: K = 1.794, 1.805, 1.819, 1.805%; *Ar⁴⁰ = 26.52, 26.64, 27.10, 26.83 × 10⁻¹² mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 77.3, 77.4, 78.4, 78.0%. Collected by: D. L. Feuerbach; dated by: M. Shafigullah.

(plagiociase) 8.53 ± 0.22 Ma

K-Ar

- 4. F8-24-85-LN
- Basaltic andesite flow $(36^{\circ}09'51^{\circ}N, 114^{\circ}43'57''W;$ upper flow on Callville Mesa, S of volcanic center, Clark County, NV). Analytical data: K = 2.070, 2.075, 2.081, 2.067, 2.071%; *Ar⁴⁰ = 30.214, 30.474, 30.684, 30.870 × 10⁻¹² mol/gm; *Ar⁴⁰/\Sample Ar⁴⁰ = 79.0, 79.9, 80.4, 80.3. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: This sample contains xenocrysts of quartz and alkali-feldspar and is the youngest rock dated in the Callville Mesa volcanic field. (plagloclase) 8.49 ± 0.20 Ma
- 5. 88-24-146-LN K-Ar Basaltic andesite flow (36°10'37" N, 114°44'39"; flow on flank complex cinder cone on Callville Mesa, S of volcanic center, Clark Cunty, NV). Analytical data: $K = 2.230, 2.227, 2.234, 2.242\%; ^Ar^{40} = 39.65,$ 39.34, 40.48, 39.04 x 10⁻¹² mol/gm; ^Ar^{40}/\Sar^{40} = 88.4, 88.2, 92.4, 87.8%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah.

(plagioclase) 10.21 ± 0.23 Ma

Fortification Hill (SAB)

6. 87-10-129-LN K-Ar Olivine-pyroxene basalt flow (36°24'43"N, 114°23'02"W; flow directly E of feeder dike at Black Point, Clark County, NV). Analytical data: K = 0.655, 0.634, 0.639, 0.643%; *Ar⁴⁰ = 6.93, 6.70, 6.84, 6.67 × 10⁻¹³ mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 10.5, 10.1, 10.3, 10.1%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: Rocks from this exposure contain hypersthene and pigeonite as well as augite and olivine phenocrysts.

(plagioclase) 6.02 ± 0.39 Ma

7. F7-38-13-LN K-Ar Olivine basalt flow (36°03'45"N, 114°40'56"W; lowest flow at Fortification Hill, Mohave County, AZ). Analytical data: K = 0.935, 0.922, 0.943, 0.927, 0.931%; *Ar⁴⁰ = 9.446, 9.512, 9.616, 9.562 × 10^{-12} mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 52.3, 52.6, 53.3, 52.9%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: Located at the north end of Fortification Hill.

(plagioclase) 5.89 ± 0.18 Ma

8. 87-38-142-LN K-Ar Olivine-plagioclase-pyroxene basalt flow (36°03'18"N, 114°40'54"W; flow erupted from cinder cones on Fortification Hill, Mohave County, AZ). Analytical data: K = 0.932, 0.925, 0.953%; *Ar⁴° = 9.45, 9.31, 9.22, 9.32 × 10⁻¹³ mol/gm; *Ar⁴⁰/∑Ar⁴⁰ = 49.5, 48.5, 48.2, 48.7%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: This flow lies stratigraphically above F7-38-13-LN.

(plagioclase) 5.73 ± 0.13 Ma

Fortification Hill (OAB)

87-38-143-LN
 K-Ar Olivine-plagioclase-pyroxene basalt plug (36°03'02" N 114°40'37" W; one of many plugs that intrude cinder cones on Fortification Hill, Mohave County, AZ) *Analytical data:* K = 1.275, 1.268, 1.280, 1.256%
 *Ar⁴⁰ = 11.85, 11.98, 12.02, 11.96 × 10⁻¹³ mol/gm; *Ar⁴⁰/ΣAr⁴⁰ = 44.4, 44.5, 44.7, 44.3%. *Collected by:* D. L. Feuerbach; *dated by:* M. Shafiqullah.

Comment: A sample of a basalt plug that represents the youngest volcanism at Fortification Hill.

(plagioclase) 5.42 \pm 0.13 Ma

10. 87-57-131-LN K-Ar Olivine basalt plug $(35^{\circ}52'38''N, 114^{\circ}35'15''W;$ plug intruding vent center at Lava Cascase, Mohave County, AZ). Analytical data: K = 0.810, 0.793, 0.836%; *Ar⁴⁰ = 5.69, 5.63, 5.75, 5.69 × 10⁻¹³ mol/gm; *Ar⁴⁰/EAr⁴⁰ = 46.3, 46.0, 46.8, 46.1%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: Collected from a plug within the vent of the Lava Cascade at the summit of the Black Mountains.

(plagioclase) 4.74 ± 0.12 Ma

11. 87-57-132-LN K-Ar Olivine basalt flow $(35^{\circ}52'26''N, 114^{\circ}36'06''W;$ distal end of flow at Lava Cascade, Mohave County, AZ). Analytical data: K = 0.857, 0.874, 0.892, 0.878%; *Ar⁴⁰ = 8.00, 7.82, 7.74, 7.78 × 10⁻¹³ mol/gm; *Ar⁴⁰/EAr⁴⁰ = 37.2, 35.9, 35.7, 35.8%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: This sample was collected just east of U.S. 93.

(plagioclase) 5.16 ± 0.14 Ma

12. F8-42-82-LN K-Ar Olivine basalt flow (36°04'37°N, 114°35'44°W; flow at from cinder cone at Petroglyph Wash, Mohave County, AZ). Analytical data: K = 1.298, 1.268, 1.240, 1.267%; *Ar⁴⁰ = 11.68, 12.01, 12.03, 12.14 × 10⁻¹³ mol/gm; *Ar⁴⁰/ Σ Ar⁴⁰ = 52.3, 53.4, 53.5, 53.8%. Collected by: D. L. Feuerbach; dated by: M. Shafiqullah. Comment: The cinder cone is located just south of Gilbert Wash near the junction with James Bay Wash.

(plagioclase) 5.43 ± 0.16 Ma

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THE SLOAN SAG: A MID-MIOCENE VOLCANOTECTONIC DEPRESSION, NORTH-CENTRAL McCULLOUGH MOUNTAINS, SOUTHERN NEVADA

by

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in

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Tracey Cascadden, Dan Feurebach and Terry Naumann also contributed substantially to this work. The countless conversions we shared added greatly to my understanding of volcanology and the dynamic geology of the Basin-and-Range province.

With great emotion, I thank my son Ian for helping me keep my perspective over the past two years.

;

ABSTRACT

In the Hidden Valley area of the north-central McCullough Mountains, southern Nevada, mid-Miocene andesite and dacite domes, flows and pyroclastic units (the Sloan volcanics) partially fill a sag in the underlying Hidden Valley volcanics. The 13.5 km diameter sag formed during and/or after the eruption of the Sloan volcanics. Sagging was accommodated by a combination of movement on the McCullough Wash fault system, and subsidence into evacuated chambers.

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Major, trace and rare-earth element geochemistry suggests that the rocks of the Sloan volcanics belong to four groups, each of which were produced by partial melting of chemically distinct sources. With the exception of the Center Mountain dome complex, magmas rose rapidly without significant crystal fractionation or crustal contamination.

The Mount Hanna andesite member of the Sloan volcanics erupted as a hot, dry aphyric lava by a mechanism of fire-fountaining from a depth of up to 25 km, precluding a Plinian-style ash-flow event. Eruptions of felsic-to-intermediate lavas by a lava-fountaining event have been described in other areas, but the Mount Hanna andesite represents the first documentation of such an eruption in the southern Basin-and-Range.

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CONTENTS

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INTR	DUCTION	
at 1 2 7/1	Location and Geography	•
	Docation and Geography	•
	rurpose of Study	, ,
	Geologic Setting	
	Structural Geology	
	Intermediate Volcanism	
CALD	ERAS: A GENERAL DISCUSSION	1(
ANAL	TICAL METHODS	14
GEOC	IRONOLOGY	15
THE S	OAN VOLCANICS	20
]	ntroduction	20
1	re-Sloan Volcanic Stratigraphy	20
	tratigraphy of the Sloan Volconic	20
	haracteristics of the Sloop Volcanics	23
1	etrography	26
-		33
GEOCI	EMISTRY	70
ľ	fetasomatism	30
M	faior Elements	38
7	race Flements	38
. 7	emporal and Spatial Variations in Chaming 1 The	44
-	importar and Spatiar Variations in Chemical Trends	53
MAGM	PETROGENESIS	51
V	ariations Between Groups of the Sloan Volcanics	57 58
	Introduction	54 5 A
	Magma Commingling)4 (A
	Fractionation and Partial Melting)4 · /
V	triations Within Groups of the Sloan Volconia	00
-	Introduction	9
	Andesites	9
		9
	The Test of the Dian Article of the	0
	The Turi of the Sloan Volcanics	1
3(Transfer I melting	1
	Introduction	1
	rartial Melt Models	4
	Discussion	6
-		

THE SLOAN SAG	82
Evidence for a Sag in Hidden Valley	82
Introduction	82
The Hidden Valley Sag	82
Conclusion	83
Classic Caldera, or Volcanotectonic Depression?	84
Introduction	8 4
Discussion	84
Significance of the Mount Hanna Andesite	85
Introduction	85
Origin of the Mount Hanna Andesite	86
Depth of Magma Generation Versus Depth of Eruption	91
Formation of the Sloan Sag	91
Introduction	91
The McCullough Wash Fault System	92
Sagging and Tectonic Control	93
Summary of Events	94
CONCLUSIONS	97
FUTURE WORK	9 8
REFERENCES CITED	100
APPENDIX A: SAMPLE LOCATION AND PETROGRAPHY	107
APPENDIX B: CHEMISTRY TABLES	127
APPENDIX C: CIPW NORMS	138
APPENDIX D: ROCK MODES	142

FIGURES

1:	Location Map	2
2:	Location of Major Faults in the Lake Mead-Las Vegas Area	6
3:	Collapse Caldera Sequence	12
4:	Ar-Ar Date Data	18
5:	Stratigraphic Column of the North-Central McCullough Mountains	21
6:	Stratigraphic Column of the Sloan Volcanics	24
7:	Photo of the Mount Hanna Andesite Vent Center	27
8:	Sample Location Map	29
9:	Photo of Hydroclastic Tuff at Station 73	30
10:	Photo of Mount Ian Andesite Hydroclastic Breccia at Station 120	31
11:	Photo of Platy, Foliated Mount Ian Andesite	32
12:	Photo of Hypabyssal Stock in the Northern Mount Sutor Dacite Field	34

13: Harker Variation Diagrams	39
14: AFM Diagram	43
15: Harker Variation Diagrams Showing the Four Chemically Distinct	
Groups of the Sloan Volcanics	45
16: Trace Element Diagrams	46
17: Chondrite-Normalized REE Diagrams	- 54
18: Chondrite and MORB-Normalized Spider Diagrams	56
19: Chondrite and MORB-Normalized Spider Diagrams of the Sloan	
Andesites and the Hidden Valley Volcanics	60
20: Chondrite and MORB-Normalized Spider Diagrams of Tertiary	
Volcanic Rocks in the Lake Mead-Las Vegas Area	62
21: Chondrite-Normalized REE Diagram for Melt Model #1: Sloan	
Andesite From Gabbro	75
22: Chondrite-Normalized REE Diagram for Melt Model #2: Sloan Dacite	
From Gabbro	78
23: Chondrite-Normalized REE Diagram for Melt Model #3: Sloan	
Andesite and Dacite From Peridotite (2X Chondrite)	79
24: Chondrite-Normalized REE Diagram for Melt Model #4: Sloan	
Andesite and Dacite From Peridotite (Metasomatized Mantle	
Chondrite Values)	80
25: Microphoto of the Mount Hanna Andesite	87
26: Photo of the Streaky, Discontinuous Texture of the Mount Hanna	
Andesite	89
27: Formation Sequence of the Sloan Sag	95

TABLES

.

1:	New K-Ar Dates 10	б
2:	New Ar-Ar Date	7
3:	Mean Error for Trace Elements	2
4a:	Mixing Model #1	7
4b:	Mixing Model #2 67	7
5a:	Melt Model #1	3
5b:	Melt Model #2	3
5c:	Melt Model #3	7
5d:	Melt Model #4	7

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INTRODUCTION

Location and Geography

Hidden Valley is in the north-central McCullough Mountains, Clark County, southern Nevada (Fig. 1). The thesis area covers 240 km² and is included on the Hidden Valley, Sloan, Sloan NE and Sloan SE 7.5 minute quadrangle maps. Dirt roads provide access to the western and central parts of the thesis area, however the eastern part must be approached by foot. Elevations in the thesis area range from 790 to 1292 m.

Previous Work

Because of its lack of economic mineral resources, little detailed geological mapping has been done in the McCullough Mountains. Hewett (1956) mapped the McCullough Mountains as part of the Ivanpah Quadrangle, but did not subdivide the Tertiary section. Longwell et al. (1965) did reconnaissance mapping for mineral resources in Clark County, but also did not differentiate the Tertiary volcanic rocks in the McCullough Mountains. Anderson et al. (1985) and DeWitt et al. (1989) mapped the South McCullough Wilderness Study Area in the southern McCullough Mountains for a study requested by the U.S. Bureau of Land Management, the U.S. Geological Survey, and the U.S. Bureau of Mines. Mapping for the wilderness study area, however, did not extend to the north into Hidden Valley.

Two masters theses were completed in the north-central McCullough

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Figure 1: Location map of the thesis area and selected Tertiary igneous centers in the Las Vegas-Lake Mead vicinity. MPC = McCullough Pass caldera; DP = Devil Peak; TM = Table Mountain; WRP = Wilson Ridge pluton; HCV = Hamblin Cleopatra volcano; HD = Hoover Dam sag-graben caldera; LGR = Lucy Gray Range.

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Mountains. Kohl (1978) studied the nature and source of carnotite in caliche deposits in Hidden Valley. Schmidt (1987) mapped and described a small (< 3 km diameter) caldera about 3 km southeast of Hidden Valley.

Purpose of Study

The Hidden Valley area contains andesite and dacite domes and flows, dacite and rhyolite pyroclastic units, and a late-stage hypabyssal dacite stock that partially fill a sag developed in the underlying basalt. This volcanic section is herein named the Sloan volcanics. In some areas, the contact between the Sloan volcanics and the underlying basalt is conformable, while in others it is not. Questions concerning the Sloan volcanics addressed in this thesis are: 1) Do the Sloan volcanics fill a volcanotectonic depression or caldera, or simply represent a dome field situated on the flank of an older stratocone? 2) How did the sag, now filled with the Sloan volcanics, form? 3) What is the petrogenesis of the andesites and dacites of the Sloan volcanics? 4) What is the internal stratigraphy of the Sloan volcanic section? 5) What is the absolute age of the Sloan volcanic section?

The purpose of this thesis is to present concise answers to the above questions.

I will demonstrate, using stratigraphic, lithologic and geochemical evidence, that the Sloan volcanics formed during volcanotectonic sagging caused by their eruption. I also suggest that the Mount Hanna andesite member of the Sloan volcanics erupted by a mechanism of lava fountaining, and may be the hot, dry analog of an ash-flow tuff.

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Geologic Setting

The McCullough Mountains are in the southern Basin-and-Range province on the western border of the Colorado River extensional corridor. The northsouth trending range extends from the New York Mountains in California to the city of Henderson in the Las Vegas Valley (Fig. 1).

The southern part of the McCullough Mountains consists of Precambrian igneous and metamorphic rocks (Longwell et al., 1965; DeWitt et al., 1989). The northern part consists of Precambrian basement overlain by a Tertiary volcanic section. Excellent exposure of the northern section is provided in a steep eastern escarpment.

In addition to the Sloan volcanic center, other volcanoes within 30 km of the thesis area include: 1) the McCullough Pass caldera approximately 3 km south of Hidden Valley (Schmidt, 1987); 2) Devil Peak, an intrusive rhyolite plug in the southern Spring Range (Walker et al., 1981); 3) Table Mountain, a dacitic (unpublished chemical data base, E.I Smith, University of Nevada, Las Vegas) eruptive center about 10 km north of Devil Peak; 4) The River Mountains stratovolcano complex (Fig. 1).

Structural Geology and Tectonics

The McCullough Mountains are a relatively stable block compared to ranges to the north and east. During Tertiary extension, the range was extended only about 20% (Weber and Smith, 1987). The west-dipping McCullough Wash normal fault is the only major internal structure in the McCullough Mountains. This fault has a throw of at least 600 m, placing Precambrian basement against the Hidden Valley volcanic section in the central part of the range. Displacement decreases to the north to less than 50 m (Schmidt, 1987; Anderson et al., 1985). The Spring Range, to the west of the McCullough Mountains, displays minor Tertiary extension (Carr, 1983; Wernicke et al., 1988). The Eldorado Mountains, to the east of the McCullough Mountains, are highly faulted with regional dips varying from 30° east to vertical, and were extended over 100% (Anderson, 1971).

A model proposed by Weber and Smith (1987) suggests that the River and McCullough Mountains lie in the upper plate of the west-dipping Saddle Island detachment system. According to their model, the left-lateral Hamblin Bay and Bitter Spring Valley faults are transfer structures between the Saddle Island and Eldorado Valley normal faults (Fig. 2). The detachment system is at a shallow depth beneath the Eldorado Mountains resulting in a high degree of extension. The McCullough Mountains and Spring Range represent blocks overlying the detachment at a greater depth, and were transported in the upper plate without significant internal deformation (Fig. 2).

A more recent model by Smith et al. (1991) suggests that the Eldorado Valley fault may be a steep westward-dipping normal fault. Isostatic rebound caused footwall rotation resulting in flattening of the fault. The Eldorado Mountains experienced high degrees of extension in the footwall block, while the McCullough Mountains and the Spring Range remained relatively undisturbed in the hanging wall. Smith et al. (1991) also suggest that these types of deeply

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- ROCK UNITS FM: Frenchman Mountain RM: River Mountains MM: McCullough Mountains EM: Eldorado Mountains SR: Spring Range HD: Hoover Dam Volcanics NP: Nelson Pluton BCP: Boulder City Pluton WRP: Wilson Ridge Pluton
- Figure 2: Location of major faults in the Lake Mead-Las Vegas area (modified from Weber & Smith, 1987).
penetrating high angle faults may provide conduits for magma migration. A model proposed by Duebendorfer and Wallin (1991) suggests that Frenchman Mountain and the River Mountains lie in a block that is bounded to the north by the Las Vegas Valley shear zone and to the southeast by the Saddle Island detachment system. The location of the Lake Mead fault system is not well constrained west of Hamblin Mountain. Bohannon (1979) suggested that this fault system may project through Las Vegas Wash, placing the River Mountains and Frenchman Mountain in separate structural blocks (Fig. 2). Sediments of the post 13.5 Ma Horse Spring Formation, however, crop out in the Rainbow Gardens area of Frenchman Mountain and are interfingered with volcanic rocks of the River Mountains. These sediments are not disrupted across Las Vegas Wash, suggesting that no post 13.5 Ma movement on the Lake Mead fault system occurred between the River Mountain and Frenchman Mountain blocks. If the Weber and Smith (1987) model is correct, the Saddle Island detachment is part of the Lake Mead-Eldorado Valley detachment system, thus placing the McCullough Mountains in the same structural block as Frenchman Mountain and the River Mountains (Fig. 2). No major strike-slip fault system has been documented between the McCullough and River Mountains (Anderson, 1977; Weber and Smith, 1987).

According to Duebendorfer and Wallin (1991), at 12 Ma, coeval movement on the Las Vegas Valley shear zone and the Saddle Island detachment moved the River Mountains-Frenchman Mountain block westward, opening the Red

Sandstone basin to the south of the Las Vegas Valley shear zone. Because the McCullough Mountains are in the same structural block, they were also transported westward; and because no major structure exists between the McCullough Mountains and the Spring Range, the Spring Range also must have been transported westward in the same structural block.

Intermediate Volcanism

Volcanic rocks erupted during Tertiary extension in the Las Vegas area are intermediate calc-alkaline suites with only minor amounts of basalt and rhyolite (Anderson, 1971; Smith, 1982; Mills, 1985; Feuerbach, 1986; Smith et al., 1990). The intermediate volcanic section in the McCullough Mountains is an example of such an occurrence. Proposed models for the production of intermediate suites during regional extension include: 1) assimilation of felsic crustal material and mafic mantle melts during magma ascent (Damon, 1971); 2) magma mixing of felsic and mafic end members (Glazner, 1989); 3) open system models utilizing the assimilation and/or mixing of felsic material with a fractionated mafic phase (Nielson and Dungan, 1985; McMillan and Dungan, 1986; Novak and Bacon, 1986; Smith et al., 1990).

The production of intermediate igneous rocks during Tertiary extension in the Las Vegas-Lake Mead area as a result of magma commingling of felsic and mafic end members has been documented by Naumann and Smith (1987), Naumann (1987), Larsen (1989), Smith et al. (1990) and Larsen and Smith (1991). The Sloan volcanic section lacks textural evidence of magma commingling. I will

suggest in this thesis, therefore, that intermediate volcanic rocks may also have been produced from partial melts of mid-to lower-crustal material without undergoing commingling and/or contamination from other sources.

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erosion of the oversteepened walls causes enlargement of the caldera boundary and the formation of slump breccias within the crater. A resurgent dome forms when more magma enters the evacuated chamber causing upwarping of the caldera's floor. Volcanic domes may be emplaced along extensional faults on the resurgent dome or in the moat of the caldera. A typical caldera cycle ends with hydrothermal activity (Fig. 3). Not all calderas undergo complete collapse. Many calderas that erupt small-to-moderate volumes of ash-flow tuff (10-50 km³) experience incomplete subsidence along horseshoe-shaped faults (Lipman, 1984). An example is the Three Creeks Caldera in the Marysvale volcanic field, Utah (Steven, 1981). Other calderas associated with low-to-modest volumes of ash-flow tuff appear to be unfaulted sags (Lipman, 1984; Walker, 1984), such as the Taupo volcanic center, New Zealand (Grindley, 1965; Cole, 1979). Factors that may contribute to downsagging or incomplete subsidence include: 1) a magma chamber at great depth (> 10-15 km); 2) structurally coherent roof rocks; 3) resurgence of magma into the chamber during eruption preventing emptying of the chamber; 4) a small volume of magma relative to caldera area (Steven and Lipman, 1976; Steven et al., 1984; Walker, 1984).

Ninety percent of the documented Tertiary-aged calderas in the Basin-and-Range province are greater than 15 km in diameter. Worldwide, only about ten percent of all Quaternary-aged calderas exceed this size (Walker, 1984). According to Walker (1984), this size difference may be attributed to crustal type. Basement in the Basin-and-Range province is largely Precambrian crystalline rock,





Figure 3: Collapse Caldera Sequence: Stage 1: Pyroclastic eruptions occur from vents above ring faults over a shallowly-emplaced magma chamber. Stage 2: Caldera collapse occurs during and/or after the pyroclastic eruptions. Stage 3: Erosion causes embayment and enlargement of the caldera margin. Slump breccias from the oversteepened walls form within the caldera. Resurgence of magma into the chamber may cause upward doming of the caldera floor.

whereas most Quaternary calderas are emplaced in young crust. Rigid crystalline basement rock may enhance complete separation and subsidence of the caldera floor resulting in larger collapse structures. Another factor contributing to the larger size of Basin-and-Range calderas may be enlargement due to extension.

Small ash-flow calderas in the Basin-and-Range province include the 3.5 km diameter Van Horn Mountains Caldera in the Trans-Pecos volcanic province in the Van Horn Mountains, Texas (Henry and Price, 1986), and the less than 3 km diameter McCullough Pass Caldera in the central McCullough Mountains, southern Nevada (Schmidt, 1987). The 13.5 km diameter Sloan sag discussed in this thesis is an example of a small volcanotectonic depression in the Basin-and-Range province.

ANALYTICAL METHODS

Fifty seven rock samples were analyzed for major element oxides. Forty six samples were analyzed for trace elements. Fresh, unweathered samples collected in the field were ground to -200 mesh using a Dyna Mill air suspended impact attrition mill and an agate mortar and pestal. Major element oxides were analyzed by X-ray fluorescence techniques on a Rigaku 3030 X-ray spectrometer at the University of Nevada, Las Vegas (UNLV). Trace elements were analyzed by instrumental neutron activation analysis at the Phoenix Memorial Laboratory at the University of Michigan. Kohl (1978) and Schmidt (1987) provided additional analyses of the Hidden Valley Volcanics and the Tuff of Bridge Spring.

One sample each of the Center Mountain dacite and the Tuff of Bridge Spring were dated using the K-Ar method on biotite separates. Mineral separations were done at UNLV. Approximately 10 pounds of fresh, unweathered sample was crushed in the attrition mill. The sample was then separated into six fractions of differing specific gravities on a number 13 Wilfley Table. Final biotite separation was done using heavy liquids (sodium metatungstate) and a Frantz magnetic separator. K-Ar dates were done by Krueger Enterprises in Cambridge, Massachusetts.

An ⁴⁰Ar/⁶⁹Ar sanidine date was obtained from the same sample of the Tuff of Bridge Spring. Sanidine separation was done at UNLV using the above methods. Sample irradiation was done at the Ford nuclear reactor, University of Michigan. ⁴⁰Ar/⁶⁹Ar dating was performed at the University of Maine, Orono.

GEOCHRONOLOGY

K-Ar dates from biotite separates were obtained from the Center Mountain dacite member of the Sloan volcanics and the Tuff of Bridge Spring from the north-central McCullough Mountains. An ⁴⁰Ar/⁸⁹Ar date from a sanidine separate was obtained from the same Tuff of Bridge Spring sample. These are the first age dates obtained from rocks of the north-central McCullough Mountains.

The K-Ar date for the Center Mountain dacite is 16.4 + /-0.5 Ma, the K-Ar date for the Tuff of Bridge Spring is 16.6 + /-0.4 Ma (Table 1). The 40 Ar/ 69 Ar date on the Tuff of Bridge Spring, however, is 15.23 + /-0.14 Ma (Table 2; Figs. 4a & 4b).

The differences between the Tuff of Bridge Spring dates may be the result of excess argon retained by the biotite. Minerals may include argon in their crystal lattice by means other than the radiogenic decay of ⁴⁰K. Argon may be absorbed from the atmosphere or diffused into minerals from the outgassing of Kbearing minerals in the crust and/or mantle (Faure, 1986). The K-Ar dating method assumes that all of the Ar in the sample is radiogenic, produced by the radioactive decay of K in that sample. If excess Ar is present, the K-Ar method may result in an anomalously old age (Faure, 1986).

The ⁴⁰Ar/⁸⁹Ar dating method is based upon the production of ³⁹Ar by irradiation of K-bearing minerals in a nuclear reactor. It has an advantage over the K-Ar method in that only radiogenic Ar is measured. The irradiated sample

Table 1: New K-Ar Dates For The North-Central McCullough Mountains									
Sample	K%	Ar* (ppm)	Ar*/Total	K (ppm)	Date & Error				
Center Mtn. Dacite	7.92	0.007578	0.1885	7.92	16.4 +/- 0.5 Ma				
Tuff of Bridge Spring	6.323	0.007294	0.461	7.543	16.6 +/- 0.4 Ma				

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* Denotes radiogenic

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Table 2: New Ar-Ar date for the Tuff of Bridge Spring, central McCullough Mountains												
					% Total	%Radiogenic		Age and				
Temp C	40Ar/39Ar	37Ar/39Ar	36Ar/39Ar	Moles 39Ar	39Ar	(Ar40	K/Ca	error (Ma)				
750	6.461	0.0348	0.0189	127.8	1.9	13.1	14.09	12.96 +/- 0.82				
830	3.156	0.0314	0.0073	181.7	2.6	31.1	15.60	15.01 +/- 0.53				
900	1.753	0.0312	0.0026	252.2	3.7	55.9	15.72	14.99 +/- 0.47				
960	1.291	0.0306	0.0010	356.7	5.2 [.]	76.0	16.01	15.01 +/- 0.29				
1020	1.176	0.0299	0.0006	531.7	7.7	82.9	16.41	14.91 +/- 0.20				
1080	1.180	0.0295	0.0006	811.9	11.8	83.6	16.63	15.09 +/- 0.20				
1120	1.166	0.0297	0.0006	987.6	14.3	84.5	16.52	15.06 +/- 0.14				
1160	1.148	0.0291	0.0004	1012.2	14.7	87.4	16.86	15.34 +/- 0.14				
1200	1.136	0.0292	0.0004	1014.9	14.7	87.9	16.80	15.26 +/- 0.14				
1240	1.143	0.0288	0.0004	888.4	12.9	87.8	17.00	15.34 +/- 0.20				
Fuse	1.252	0.0292	0.0008	729.4	10.6	80.2	16.79	15.34 +/- 0.18				

Plateau age = 15.32 + -0.16 Ma Isotope correlation age = 15.23 + -0.14 Ma

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Y = B + MX Y - 40 Ar/ 36 Ar = 289.5103 +/- 4.017002 B - 39 Ar/ 40 Ar = 1.003595 +/- 4.162581E-03 M - Slope = -290.5509 +/- 3.220593: Slope used in calculation of data X - 36 Ar/ 40 Ar = 3.454109E-03 +/- 4.792633E-05 Intercept age = 15.23245 +/- 0.1388164 Ma

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Figure 4: Ar-Ar age date data from the Tuff of Bridge Spring, central McCullough Mountains.

is heated incrementally and the ⁴⁰Ar/⁸⁹Ar ratio for each increment is determined. If the sample has not lost or gained Ar or K since the time of its initial cooling, the ratios at each temperature will be constant. This ratio will result in a "plateau" value that is used to calculate the age of the sample (Faure, 1986).

In 40 Ar/ 69 Ar dating, the isochron correlation method may also be used. A sample may also contain atmospheric 36 Ar. On a graph of 39 Ar/ 40 Ar versus 36 Ar/ 40 Ar, values of these ratios determined for each increment of heating are plotted to produce an isochron. The slope of the isochron equals the value of 40 Ar (radiogenic)/ 69 Ar, which is used to calculate the age of the sample.

I accept the isotope correlation age of 15.23 + /- 0.14 Ma for the following reasons. The plateau values from the incremental heating of the Tuff of Bridge Spring sample have a small offset (Fig 4b). There is an initial plateau age of about 15.0 Ma, then it increases to about 15.3 Ma. The offset in the plateau suggests that the sample may be slightly altered. The plateau date of 15.32 + /- 0.16 Ma (Fig. 4b) for the sample was calculated using only the data from the higher plateau. The isotope correlation age (Fig 4a), on the other hand, takes into account all values of incremental heating, resulting in an average of the plateau ages (Faure, 1986). In this case, the isotope correlation technique has produced a higher quality date for the sample and will be accepted in this thesis.

Both of the K-Ar dates are suspect, therefore the actual age of the Sloan volcanics was not determined. I can only conclude that the relative age of the Sloan Volcanics is less than 15.23 Ma.

THE SLOAN VOLCANICS

Introduction

The Sloan volcanics consist of andesite and dacite domes and flows, dacite and rhyolite pyroclastic units, and a late-stage hypabyssal dacite stock. I suggest that they were erupted during and/or after the formation of a volcanotectonic sag in Hidden Valley.

The Sloan volcanics are the youngest volcanic rocks in the McCullough Mountains (< 15.23 +/- 0.14 Ma). They overlie the Hidden Valley volcanics, McCullough Pass volcanics, Pumice Mine volcanics, Tuff of Bridge Spring, and Eldorado Valley volcanics respectively. The entire section is underlain by Precambrian basement (Fig. 5).

Rocks were named using the chemical classification scheme of Irvine and Baragar (1971).

Pre-Sloan Volcanic Stratigraphy

Refer to Figure 5 for the stratigraphic column of the rocks described in this section.

Precambrian crystalline rocks crop out south of the thesis area and are composed of biotite monzogranite and biotite granitoid gneiss cut by pegmatite and aplite dikes (Anderson et al., 1985).

The Eldorado Valley volcanics are age equivalent to the Patsy Mine volcanics mapped by Anderson (1971) in the Eldorado Mountains. This unit is



Figure 5: Stratigraphic column of the central McCullough Mountains.

almost 300 m thick on the eastern escarpment of the central McCullough Mountains. It thins rapidly to the west and does not crop out on the western margin of the range (Smith et al., 1988). Westward thinning of this and other volcanic units in the north-central McCullough Mountains may be due to a prominent buttress of Precambrian basement that prevented volcanic units from flowing to the west (Schmidt, 1987; Smith et al. 1988). Schmidt (1987) documented two members of the Eldorado Valley volcanics in the central McCullough Mountains. The lower member consists of thinly interbedded flows of hornblende andesite, olivine andesite and dacite. The upper member is composed mainly of volcaniclastic units.

The Tuff of Bridge Spring is a rhyolite to dacite ash-flow tuff of regional extent. The tuff crops out in the Eldorado Mountains (Anderson, 1971), the Highland Range (Bingler and Bonham, 1972), the McCullough Mountains (Schmidt, 1987), and the White Hills (Cascadden, 1991) and southern Black Mountains (referred to in Cascadden, 1991), Arizona (Fig. 1). In the McCullough Mountains, the Tuff of Bridge Spring consists of a single cooling unit up to 145 m thick (Schmidt, 1987). It crops out in the central part of the range and pinches out to the southeast of Hidden Valley. Scattered outcrops also occur to the west of Hidden Valley (Plate 1), and were mapped as the Erie Tuff by Kohl (1987). A sample of the Tuff of Bridge Spring from the central McCullough Mountains was dated at 15.23 +/- 0.14 Ma (40 Ar/ 69 Ar, sanidine).

The Pumice Mine volcanics consists of andesite and basalt flows and

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breccia units up to 60 m thick (Smith et al., 1982; Schmidt, 1987). This thin unit is a marker bed separating the Tuff of Bridge Spring from the McCullough Pass volcanics.

<u>The McCullough Pass volcanics</u> are composed of rhyolite domes, dikes, flows and pyroclastic units, andesite flows and dikes, and volcaniclastic rocks that were deposited during and after the collapse of the McCullough Pass caldera (Schmidt, 1987). The outflow facies of the McCullough Pass tuff extends northward from its source into the Hidden Valley area.

The Hidden Valley volcanics are age equivalent to the upper Patsy Mine or lower Mount Davis volcanics in the Eldorado Mountains (Anderson, 1971). This unit is up to 245 m thick on the eastern escarpment of the north-central McCullough Mountains and thins to the west. The Hidden Valley volcanics consist of basalt and basaltic-andesite flows, cinder cones and scoria. Rocks contain clinopyroxene and olivine phenocrysts, and subordinate quartz xenocrysts. The Sloan volcanic section overlies the Hidden Valley volcanics in central and eastern Hidden Valley.

Stratigraphy of the Sloan Volcanics

The oldest rocks of the Sloan volcanics include the Mount Hanna andesite and the rocks of the Center Mountain dome complex. The Center Mountain dome complex is composed of the Cinder Prospect member, Tuff of the Sloan volcanics, Center Mountain dacite, and the Mount Ian andesite (Fig. 6). Since the Mount Hanna andesite member is not in contact with the Center Mountain dome



Figure 6: Stratigraphic column of the Sloan volcanics, north-central McCullough Mountains.

complex, the relative age of these sections cannot be determined (Plate 1).

Refer to Figure 6 for the stratigraphic column of the rocks described in this section. Refer to Appendices A and B for rock chemistry.

<u>The Mount Hanna andesite</u> is aphyric with SiO₂ contents ranging from 59.37 to 60.74 weight%. Flows are up to 5 m thick and are commonly platy and foliated on their surfaces.

<u>The Cinder Prospect member</u> consists of thinly interbedded dacite flows and rhyolite to dacite ash-flow tuffs with SiO₂ contents ranging from 61.31 to 69.88 weight%.

<u>The Tuff of the Sloan volcanics</u> consists of three cooling units, each approximately 2 m thick. From oldest to youngest the units are: 1) welded rhyolite ash-flow tuff (SiQ₂ = 69.76 weight%); 2) poorly-welded dacite ash-flow tuff (SiQ₂ = 64.87 weight%); 3) welded dacite ash-flow tuff (SiQ₂ = 64.26 weight%).

<u>The Center Mountain dacite</u> is composed of flows of biotite dacite with SiO₂ contents ranging from 67.67 to 68.06 weight%.

<u>The Mount Ian andesite</u> intrudes and overlies the Cinder Prospect, Tuff of the Sloan Volcanics, and Center Mountain dacite members. Its SiO₂ content varies from 57.84 to 60.22 weight%.

The youngest member of the Sloan volcanics is the <u>Mount Sutor dacite</u>. It is a biotite dacite with $SiO_2^{\frac{1}{2}}$ contents ranging from 61.67 to 64.96 weight%.

Characteristics of the Sloan Volcanic Centers

The Mount Hanna andesite differs from other members of the Sloan volcanics in that it was erupted from a single vent. This unit is up to 307 m thick and has a maximum volume of 9 km³. Other members erupted from numerous vents and domes. The Mount Hanna eruptive center is about 100 m across. The vent has been eroded and is occupied by a volcanic neck formed of resistant andesite, silicified by hydrothermal activity. Black and red oxidized autobrecciated andesite surrounds the vent (Fig. 7; Cross section C-C', Plate 1). Two small volcanic domes occur about 1 km southwest of the vent and are interpreted as parasitic vents on the flank of the Mount Hanna eruptive center. I suggest that the Mount Hanna andesite erupted at temperatures of approximately 1,000°C with a water content of less than 2% by a lava-fountaining mechanism. This eruption resulted in a lava flow analogous to a hot, dry ash-flow tuff. I will present evidence to support these observations later in this thesis.

The formation of the Center Mountain dome complex reflects the first two steps of four documented by Smith (1973) for the eruptive sequence at the Mono Craters, California. The complete sequence is: 1) creation of a tuff ring composed of ash, lapilli and ejecta, caused from hot rising magma contacting groundwater; 2) eruption of magma into the crater forming a dome; 3) cratering of the dome from explosions and/or collapse; 4) eruption of magma into the previously cratered dome. The interbedded ash-flow tuffs and dacite flows of the Cinder Prospect member and the Tuff of the Sloan volcanics were produced in

Figure 7: Photo of the Mount Hanna Andesite Vent Center

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the early stages of pyroclastic and phreatomagmatic activity and reflect the formation of a tuff ring. The upper cooling unit of the Tuff of the Sloan volcanics contains blocky glass shards suggesting a hydroclastic eruption mechanism (Fisher & Schmincke, 1984). In a canyon in the southern part of the dome, (Sta.73, Fig. 8), the tuff contains armored mud balls and discontinuous stringers of dacite (Fig. 9) suggesting hydroclastic activity and lava fountaining. The Center Mountain dacite intruded the tuff ring, erupting thick, viscous dacite over the earlier units. The approximate volume of the dome complex is 0.44 km³.

The Mount Ian andesite erupted from numerous domes and vents, many of which overlie tuff rings composed of black ash and cinder. One volcanic center (Sta. 120, Fig. 8) contains a volcanic neck of hydroclastic breccia of andesite clasts and bombs embedded in an ashy groundmass (Fig. 10). The deposit formed when hot, rising magma came in contact with groundwater. Clasts and bombs of quenched andesite were ejected from the volcano. Some fell back into the vent and became embedded in a fine-grained hydroclastic groundmass. Domes are characterized by platy andesite forming "onion skin" patterns. Foliation defined by platy slabs of andesite dip inward toward the conduit and become horizontal over the vent (Fig. 11). Single domes are less than 0.5 km in diameter, and up to 75 m high.

Both the southern and northern Mount Sutor dome fields are composed of flows of massive biotite dacite. Only two vents are exposed in the southern Mount Sutor field, but more may be buried by flows. A vent at station 91 (Fig. 8)

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Figure 9: Photo of Hydroclastic Tuff at Station 73

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Figure 11: Photo of Platy, Foliated Mount Ian Andesite

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consists of a tuff ring overlain by 3 to 4 m of explosion breccia overlain by 3 m of hydroclastic breccia, capped by dacite. This sequence suggests that an earlier dome was explosively disrupted by intruding magma creating a dacite breccia. Phreatomagmatic activity continued and resulted in the deposition of hydroclastic breccia. Viscous dacite covered these units. The northern Mount Sutor field contains a hypabyssal dacite stock that intruded its own volcanic cover (Fig. 12). The hypabyssal and volcanic rocks are chemically similar. I suggest that vents related to this shallow magma body were responsible for eruption of the dacites in the northern Mount Sutor field. Any volcanic domes and vents have since been stripped from the intrusion by erosion.

Petrography

Refer to Appendix C for detailed petrographic descriptions, and Appendix D for rock modes.

<u>Tuff of Bridge Spring</u>: The Tuff of Bridge Spring is a poorly-welded to welded rhyolite to dacite ash-flow tuff containing phenocrysts (10-33%) of sanidine, plagioclase, biotite, clinopyroxene and subordinate quartz, sphene, zircon and Fe-Ti oxides. The tuff includes pumice (1-12%), and basaltic and subordinate gabbroic and granodioritic xenoliths (1-10%). In welded units the pumice is flattened to fiamme. The groundmass consists of devitrified glass and glass shards. For further descriptions of the Tuff of Bridge Spring in the McCullough Mountains, see Kohl (1978) and Schmidt (1987).

Hidden Valley volcanics: Basalts are vesicular, subalkalic to transitional

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and contain phenocrysts (1-37%) of plagioclase, clinopyroxene and iddingsitized olivine. Some of the phenocrysts commonly occur in glomerocrysts. Two samples (Mc47 & Mc48) have phenocrysts (4-5%) of oxidized biotite or phlogopite. Some of the samples include up to 1% glass-rimmed quartz xenocrysts. The groundmass consists of microlites of plagioclase, clinopyroxene, iddingsitized olivine, and trace amounts of glass. For further descriptions, see Kohl (1978) and Schmidt (1987).

<u>Mount Hanna andesite</u>: The Mount Hanna andesite is fine-grained, hypocrystalline and commonly trachytic. Phenocrysts are rare (< 1%) and consist of highly embayed and pitted plagioclase and biotite. Andesite is characterized by microlites of subparallel plagioclase with subordinate Fe-Ti oxides, glass and highly birefringent cryptocrystalline grains (pyroxene & olivine?).

Cinder Prospect member: Ash-flows tuffs of the Cinder Prospect member contain phenocrysts (25-26%) of plagioclase, sanidine, biotite, Fe-Ti oxides and clinopyroxene with trace amounts of zircon. Subordinate basaltic, gabbroic and granodioritic xenoliths also occur. Plagioclase phenocrysts are commonly pitted and embayed. The groundmass consists of devitrified glass and glass shards, and trace amounts of granular hematite. Ash-flow tuffs are commonly vitrophyric. Biotite dacite contains glomerocrysts (4-6%) of plagioclase, biotite and Fe-Ti oxides, and phenocrysts (5-6%) of the same assemblage of minerals found in the glomerocrysts. The groundmass consists of microlites of plagioclase with subordinate oxidized biotite, zircon and glass.

<u>Tuff of the Sloan Volcanics</u>: Tuffs contain phenocrysts (17-36%) of

plagioclase, sanidine, biotite, clinopyroxene, Fe-Ti oxides, sphene and trace amounts of zircon. The basal rhyolite cooling unit (Mc59a) has trace amounts of monazite, epidote and allanite. The upper dacite cooling unit (Mc59c) has trace amounts of quartz. The tuffs also include devitrified pumice clasts (2-12%), and basaltic and gabbroic xenoliths (4-21%). The groundmass consists of devitrified glass shards. Shards from sample Mc59c are blocky.

<u>Center Mountain dacite</u>: The Center Mountain biotite dacite is holocrystalline and contains phenocrysts (6-9%) of plagioclase with subordinate oxidized biotite and Fe-Ti oxides. The groundmass consists of microlites of plagioclase with subordinate oxidized biotite, Fe-Ti oxides and clinopyroxene(?), and secondary calcite (1-5%) that coats fractures and partially replaces the groundmass. Rocks are commonly glomerocrystic and trachytic.

<u>Mount Ian andesite</u>: The fine-grained, hypocrystalline Mount Ian andesite contains phenocrysts (5-35%) of plagioclase, oxidized biotite and Fe-Ti oxides with subordinate orthopyroxene and iddingsitized olivine. Some phenocrysts occur in glomerocrysts. The groundmass consists of microlites of the phenocryst-phase minerals, dominated by plagioclase. Trace amounts of hematite and glass are also present.

<u>Mount Sutor dacite</u>: The Mount Sutor biotite dacite contains glomerocrysts (2-18%) of plagioclase, biotite and Fe-Ti oxides. Some glomerocrysts also contain orthopyroxene and/or clinopyroxene. Dacites include phenocrysts (2-6%) of the same assemblage of minerals found in the :

glomerocrysts. One sample (Mc27) has less than 1% oxidized hornblende. Plagioclase is pitted, embayed, and displays oscillatory zoning. Biotite is commonly oxidized. The groundmass consists of microlites of plagioclase, biotite and Fe-Ti oxides, with subordinate orthopyroxene, clinopyroxene, zircon and glass. Two samples (Mc118 & Mc119) collected from the hypabyssal stock in the northern Mount Sutor field are coarse-grained but have an identical mineralogy to their volcanic counterparts.

GEOCHEMISTRY

<u>Metasomatism</u>

Tertiary igneous rocks in the Lake Mead-Las Vegas area are commonly metasomatized (Feuerbach, 1986; Smith et al., 1989; Larsen, 1989). During metasomatism rocks are strongly enriched in potassium and depleted in sodium, or vice versa. For example, some of the quartz monzonite samples from the Tertiary Wilson Ridge pluton (Fig. 1) have K_2O contents as high as 10.5 weight% and Na₂O as low as 0.75 weight% (Feuerbach, 1986).

Rocks of the Sloan volcanics appear not to have been appreciably affected by metasomatism. Similar K_2O and Na_2O contents (4 to 6 and 3 to 5 weight% respectively) suggest that potassium and/or sodium enrichment has not occurred. Harker variation diagrams show that K_2O and Na_2O increase with increasing SiO₂, but the data are scattered (Figs. 13A & 13E). The scatter may be due to minor remobilization of alkali elements.

Major Elements

Rocks of the Sloan volcanics are calc-alkaline (Fig. 14) and range from 58 to 70 weight% SiO₂ (Appendix A). MgO, Fe₂O₃, CaO, Al₂O₃, TiO₂ and P₂O₅ decrease with increasing SiO₂ (Figs. 13B, 13C, 13D, 13F & 13G). K₂O and Na₂O increase with increasing SiO₂ (Figs. 13A & 13E).

Harker variation diagrams divide the rocks of the Sloan volcanics into four chemically distinct groups. These are the: 1) Mount Hanna andesite and Mount



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Figure 13: Harker variation diagrams

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Figure 13: Continued



Figure 13: Continued

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Figure 13: Continued

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Figure 14: AFM diagram showing the calc-alkaline characteristics of the rocks of the Sloan volcanics. Diagram is after Irvine and Barager (1971).
Ian andesite (greater than 1.4% MgO, 0.55% TiO₂ and 16.7% Al₂O₃); 2) Mount Sutor dacite (0.6% to 1.4% MgO, 0.25% to 0.55% TiO₂, and 15.6% to 16.4% Al₂O₃); 3) Cinder Prospect member and Center Mountain dacite (less than 1.0% MgO, 0.20% TiO₂ and 16.0% Al₂O₃); 4) Tuff of the Sloan volcanics (similar range of SiO₂ as the dacites, but higher in MgO (0.8% to 1.8%) and TiO₂ (0.45% to 0.65%), and lower in Al₂O₃ (14.4% to 15.2%)) (Fig. 15).

Trace Elements

Compatibility of the trace elements in mineral phases is directly dependent upon rock type. For example, the large ion lithophile elements (LILE) Ba and Rb are incompatible in andesite, but compatible with biotite in dacite. The transition metals Co and Cr are compatible with olivine in andesite, but relatively incompatible in dacite. The LILE Th and the rare-earth element (REE) Ce are compatible only in accessory minerals such as monazite. Felsic rocks such as rhyolite and dacite contain a higher modal concentration of accessory minerals such as zircon, sphene, apatite and monazite than andesites and basalts.

In rocks of the Sloan volcanics, the concentrations of: 1) total REE (La, Ce, Nd, Sm, Eu, Tb, Yb and Lu) increase with increasing SiO₂ (Fig. 16A). 2) Th and the incompatible high field strength elements (HFSE) Hf and Ta increase with increasing SiO₂ (Figs. 16B & 16C); 3) the LILE Sr decreases with increasing SiO₂ (Figs. 16D & 16F); 4) the transition metal Co decreases with increasing SiO₂ (Figs. 16G & 16H); 5) Eu decreases with increasing SiO₂ (Figs. 16D, 16E & 16G).



Figure 15: Harker variation diagrams showing the four chemically distinct groups of the Sloan volcanics. See Figure 13 for symbol explanation.



Figure 16: Trace element diagrams. Concentrations of SiO₂ and CaO are in weight percentage. Concentrations of trace elements are in ppm. Symbol in upper corner represents mean analytical error in ppm.

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Figure 16: Continued



Figure 16: Continued





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Chemical plots of trace elements distinguish the same four groups that are suggested by the Harker variation diagrams. For most elements, the differences between each group is greater than mean analytical error indicating that the differences between groups is statistically significant (Table 3). The andesites are more depleted in Hf, Ta and Th, and more enriched in Co than the other groups. The Mount Sutor dacite is enriched in Eu. The Tuff of the Sloan volcanics is depleted in Eu, and enriched Ta and Th. The Center Mountain dacite and the Cinder Prospect member are depleted in V.

If the rocks of the Sloan volcanics had a comagmatic relationship and were produced by a fractional crystallization or partial melting process, samples would plot on a continuous positive linear slope on an incompatible element diagram. Instead, incompatible element diagrams show four separate groupings of data (Fig. 16). A sampling bias could cause the gaps between groups. During sampling, however, I was careful to collect all the exposed compositional variations of volcanic and hypabyssal rocks. I suggest, therefore, that the four groups represent chemically distinct magma types and do not reflect incomplete sampling.

Spider diagrams may be used to distinguish the general chemical characteristics of rock suites, determine evolutionary paths and identify sources. Spider diagrams are constructed by normalizing trace element values to known concentrations and plotting them on a logarithmic scale. These diagrams minimize data scatter and emphasize general chemical trends and "signatures".

Caps					
Table 3: N	Table 3: Mean@nalytical@rror of frace				
elements	ised in che	mical plots			
	Error:	Error:			
Element	+/- ppm	+/- %Concentration			
Sc	0.04	0.68			
v	3.82	9.87			
Cr	2.15	5.93			
Co	0.16	3.94			
Rb	8.33	7.62			
Sr	114 ·	14.7			
Eu	0.07	3.23			
Hf 😳	0.21	2.32			
Ta	0.11	9.53			
Th	0.24	1.22			

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Normalized values used in this thesis are chondrite (Thompson et al., 1984) and MORB (Pearce, 1983).

Chondrite normalized REE diagrams (Thompson, 1984) show that the four rock groups have similar chemical signatures (Figs. 17A-17D). The Tuff of the Sloan volcanics differs only in that it is depleted in Eu (Fig. 17C). Rocks of the Sloan volcanics are enriched in light REE (LREE) and depleted in heavy REE (HREE). The LREE La varies from about 250 to 400 chondrite. The HREE Lu varies from about 10 to 25 chondrite.

Spider diagrams show a common depletion in P, Ti and Ta, and enrichment in Rb, K, La, Nd and Zr for the four rock groups of the Sloan volcanics (Figs. 18A-18H). The Tuff of the Sloan volcanics differs only in that it is depleted in Ba (Figs. 18C & 18G). Major and trace element diagrams are sensitive to small differences in source rocks and petrogenetic paths, while spider plots are not. The fact that the rocks of the Sloan volcanics are separated into four groups on major and trace element plots, but are not segregated on spider diagrams, suggests that the chemical differences between the groups are significant, but small.

Temporal and Spatial Variations in Chemical Trends

Spider diagrams indicate that the andesites of the Sloan volcanics have a chemically similar source as the older Hidden Valley volcanics, except that the Hidden Valley basalt is more depleted in the incompatible elements Ta, Th and La (Fig. 19). Its overall pattern is similar to the Sloan volcanics, suggesting that



Figure 17: Chondrite-normalized REE diagrams



Figure 17: Continued



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Figure 18: Chondrite and MORB-normalized diagrams for rocks of the Sloan volcanics.



Figure 18: Continued







Figure 18: Continued



Figure 18: Continued





Figure 19: Chondrite and MORB-normalized spider diagrams showing chemical similarities between the Sloan andesites and the Hidden Valley volcanics.

both had a common source.

To determine the regional extent of rocks that share the McCullough Mountain's chemical signature, Tertiary volcanic rocks from the McCullough, Eldorado and River Mountains, Devil Peak, Table Mountain, the White Hills and the Hamblin Cleopatra volcano (Fig. 1) were plotted on spider diagrams. Volcanic rocks with the chemical signature of the McCullough Mountains occur in the McCullough, Eldorado and River Mountains, and the White Hills. There are two other chemically distinct patterns. Felsic volcanic rocks occurring at Table Mountain and Devil Peak in the Spring Range are enriched in Th, Rb and Ta, and depleted in Ba, P and Ti. Basalts of the Hamblin Cleopatra volcano are depleted in Ce, Nd, Sm and La (Figs. 20A-20D).

This type of geochemical analysis suggests that the scale of significant chemical variation of source rocks in the lower crust and mantle in the Las Vegas-Lake Mead area is probably in the tens to hundreds of square kilometers. This analysis also suggests that each source area did not appreciably change chemically over the approximately five Ma represented by rocks exposed in the central McCullough Mountains.



Figure 20: Chondrite and MORB-normalized spider diagrams showing spatial similarities of Tertiary volcanic rocks in the Lake Mead-Las Vegas area. The three chemically distinct groups include rocks from: 1) the McCullough, Eldorado and River Mountains, and the White Hills; 2) the Spring Range (Table Mountain and Devil Peak); 3) the Hamblin Cleopatra volcano.



Figure 20: Continued

MAGMA PETROGENESIS

Variations Between Groups of the Sloan Volcanics

Introduction

In this section, three different models for the origin of the Sloan volcanics are introduced and discussed. The models involve magma commingling, crystal fractionation and partial melting. Using petrographic and geochemical evidence, I will show that partial melting of separate sources is responsible for the production of the Sloan volcanics.

Magma Commingling

The production of mid-Miocene intermediate igneous rocks in the Las Vegas-Lake Mead area by mechanisms of magma commingling was documented by Naumann and Smith (1987), Naumann (1987), Larsen (1989) and Larsen and Smith (1991) for the diorite to quartz monzonite of the Wilson Ridge pluton, and by Naumann and Smith (1987) and Naumann (1987) for the andesites and dacites in the northern Black Mountains (Fig.1).

Textural evidence for magma commingling includes: 1) disequilibrium mineral assemblages such as quartz in andesite or olivine in dacite; 2) resorbed, embayed phenocrysts rimmed with glass; 3) plagioclase xenocrysts displaying glass-charged zones (fretted texture); 4) mafic blobs/enclaves in intermediate rocks that show a decrease in phenocryst size toward their margins (Koyaguchi, 1986). Chemical and textural evidence must be combined to document magma commingling. On chemical plots, rocks formed by magma commingling will plot on a linear variation line between the two end members (Koyaguchi, 1986).

Rocks of the Sloan volcanics do not show petrographic evidence of magma commingling. The Mount Ian andesite, however, contains less than 1% biotite. Biotite may be an equilibrium phase in andesites with SiO₂ greater than 55% (Williams, Turner & Gilbert, 1982), or it may represent a disequilibrium phase that was introduced during magma commingling. Because of the possibility that magma commingling may have contributed to the petrogenesis of the Mount Ian andesite, it was chosen to test magma commingling models for the Sloan volcanics.

Mafic and felsic rocks from the central McCullough Mountains were evaluated as possible end member-magmas for the production of the Mount Ian andesite. A possible mafic end member is the basalt of the Hidden Valley volcanics. Possible felsic end members are the rhyolites of the McCullough Pass volcanics (Schmidt, 1987) and the dacites of the Cinder Prospect member of the Sloan volcanics. A dacite from the Cinder Prospect member of the Sloan volcanics was chosen because it plots on the same linear variation line as the Hidden Valley volcanics and the Mount Ian andesite. The McCullough Pass rhyolites were ruled out because they do not plot on this variation trend.

The computer program XLFRAC (Stormer and Nichols, 1978) (modified by Rob Helvie, 1991) was used to evaluate the possibility that the Mount Ian

andesite is a hybrid magma produced by the commingling of the Hidden Valley basalt and dacite of the Cinder Prospect member. Using a mixing model with no : fractionation, it is necessary to add 95.35% by volume Cinder Prospect dacite to basalt of the Hidden Valley volcanics (Table 4a). This model is unrealistic for two reasons. First, the sum of the squares of the residuals (R^2) is 20.04. R^2 is the square of the sum of the differences between the observed and calculated weight percentages of each oxide and must be close to 1.00 if the model is to be acceptable at the 99% level of significance. Second, the addition of 95.35% dacite magma to a basalt magma would result in abundant petrographic and field evidence of magma commingling. No mixing textures are evident in The Mount Ian andesite.

Another model was analyzed utilizing the fractionation of olivine, clinopyroxene and plagioclase from Hidden Valley basalt, along with the addition of dacite of the Cinder Prospect member. For this model, it is necessary to add 68.90% dacite to Hidden Valley basalt (Table 4b). The lack of mixing textures suggests that this model is unrealistic.

I suggest, therefore, that magma commingling may be ruled out as a major process in the petrogenesis of the Sloan volcanics.

Fractionation and Partial Melting

If a suite of rocks is produced by fractionation of a common parent, magmas derived by small amounts of fractional crystallization will be enriched in elements compatible with the fractionating phases. Rocks formed by greater

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Table 4a					
Mixing Model #1: Mixing Of Hidden Valley Basalt (Mc116)					
with Cinder	Prospect M	lember Dacite (N	10121)		
To Produce N	Iount Ian A	Andesite (Mc77).	·		
	Hidden	Cinder	Mount		
	Valley	Prospect	Ian	Model	
Composition	basalt	member dacite	andesite	rock	
SiO2	51.72	69.86	59.28	60.36	
A12O3	17.05	15.65	17.22	17.53	
Fe2O3	10.44	3.00	7.08	7.21	
CaO	9.35	1.63	4.15	4.23	
MgO	5.15	0.48	1.84	1.87	
Na2O	3.15	3.65	3.62	3.69	
K2O 1.73 5.63 4.41 4.49					
TiO2	1.40	0.11	0.61	0.62	

Total% of dacite added to basalt = 95.35Above values are in weight percentages Sum of the squares of the residuals = 20.04

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Table 4b				
Mixing Model #2: Fractionation Of				
Olivine, Clinopyroxene And Plagioclase				
From Hidden Valley	From Hidden Valley Basalt With			
Addition Of Cinder	Prospect Member			
Dacite To Produce N	Yount Ian Andesite.			
See Model #1 For R	ock Compositions.			
	Amount added			
	or subtracted			
	from Hidden			
Phase	Valley basalt			
Olivine	-2.07			
Clinopyroxene	-17.50			
Albite	-5.80			
Anorthite	-2.00			
Cinder Prospect				
member dacite	+68.90			

Values are in weight percentage.

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degrees of fractional crystallization will be depleted in these elements. For example, if plagioclase is fractionated, early-forming rocks will be enriched in Ca, Eu and Sr, while later-forming rocks will be depleted in these elements.

A chemical plot of elements compatible with the fractionating phase will display a linear trend with a positive slope. The trend should also display a continuous range of composition with no gaps between rock types. If no fractionation has occurred, rocks will plot in clusters or in vertical or horizontal trends on a compatible element diagram.

Spider plots will also indicate fractionation. If plagioclase has fractionated, a low value or "dip" in the data will occur for elements compatible with this phase. On chondrite-normalized REE diagrams, plagioclase fractionation will result in a Eu anomaly.

Plagioclase and clinopyroxene are common phenocryst phases in rocks of the Sloan volcanics. Fractionation of these phases was evaluated to analyze the relationship between the four rock groups of the Sloan volcanics. On Sr versus Eu, CaO versus Eu (plagioclase compatible), and Sc versus V (clinopyroxene compatible) plots, there are no fractionation trends relating the four rock groups to a common parent (Figs. 16D, 16E & 16I). I conclude, therefore, that the four rock groups of the Sloan volcanics were not produced by fractionation of a common melt. This analysis also suggests that the four groups are not related to each other by a fractionation process.

During partial melting, incompatible elements enter the melt early because

69

their mineral/liquid distribution coefficients are low. Rocks produced by small amounts of partial melting will be enriched in incompatible elements. Rocks produced by a larger amount of partial melting will be depleted in incompatible elements. On a plot of incompatible elements (Hf versus Th for example), rocks produced by partial melting of a common source will fall on a linear trend with a positive slope, displaying a continuous range of composition. Partial melting of different sources is suggested if data are clustered on incompatible element plots.

The four rock groups of the Sloan volcanics were analyzed to determine whether or not they represent independent partial melts. On incompatible element plots (Hf versus Th and Hf versus Ta), the rocks cluster into the same four chemically distinct groups defined by the major elements (Figs. 16B & 16C). I conclude, therefore, that each rock group evolved by partial melting of a chemically distinct source. The nature of these sources will be discussed in the "Sources for Partial Melting" section.

Variations Within Groups of the Sloan Volcanics

Introduction

In this section, fractionation processes and trends will be evaluated for the andesites, dacites and tuff of the Sloan volcanics. Refer to Figure 16 for trace element diagrams, and Figure 17 for chondrite-normalized REE diagrams.

<u>Andesites</u>

Elements that are compatible with plagioclase (Eu, Sr and Ca) were

plotted to determine if fractionation of this phase occurred in the andesites of the Sloan volcanics. The lack of a positive linear trend on these diagrams for the Mount Hanna andesite suggests that no plagioclase fractionation occurred (Figs. 16D & 16E). A positive linear trend on the Eu versus Sr plot, however, suggests minor plagioclase fractionation in the Mount Ian andesite (Fig. 16D). The lack of a Eu anomaly on the chondrite-normalized REE diagram confirms that plagioclase fractionation was minor (Fig. 17A). No positive linear trends are evident on plots of Cr versus Co and Sc versus V, suggesting no olivine and clinopyroxene fractionation respectively (Figs. 16H & 16I).

Dacites

Dacites and tuffs of the Cinder Prospect member contain phenocrysts of plagioclase and biotite. No plagioclase fractionation trend is apparent on plots of Sr versus Eu and CaO versus Eu (Figs. 16D & 16E). The lack of a Eu anomaly on the chondrite- normalized REE diagram also suggests that plagioclase did not fractionate (Fig. 17B). No biotite fractionation is apparent on a Sr versus Rb (biotite compatible) diagram (Fig. 16F).

An ash-flow tuff in the Cinder Prospect member (sample Mc78) consistently plots outside the Cinder Prospect field on compatible element diagrams. It is approximately 5 weight% lower in SiO₂, 1 weight% higher in CaO and Al₂O₃, and 3.5, 40 and 600 ppm higher in Co, V and Sr respectively than other rocks in its group. On plots of incompatible elements (Th, Ta and Hf), this tuff plots within the field of the Cinder Prospect member (Figs. 16B & 16C).

Fractionation of the tuff before eruption may be responsible for the differences in compatible element abundances.

In the Center Mountain dacite, biotite fractionation is not evident in a plot of Rb versus Sr (Fig. 16F). Chemical plots of CaO versus SiO_2 (Fig. 13D), and the lack of a Eu anomaly on the chondrite-normalized REE diagram (Fig. 17B) indicate that plagioclase did not fractionate.

In the Mount Sutor dacite, chemical plots of CaO versus Eu and Sr versus Eu (Figs. 16D & 16E), and the lack of a Eu anomaly (Fig. 17D) suggest that plagioclase was not fractionated. Plots of Sc versus V and Sr versus Rb indicate no clinopyroxene and biotite fractionation respectively (Figs. 16I & 16F).

The Tuff of the Sloan Volcanics

Chemical plots suggest fractionation of plagioclase, sanidine and clinopyroxene. Plagioclase and sanidine fractionation is suggested by the positive linear trend on a plot of the compatible elements Sr and Eu (Fig. 16D), and by a Eu anomaly on the chondrite-normalized REE diagram (Fig. 17C). Clinopyroxene fractionation is suggested by the positive correlation of the compatible elements Sc and V (Fig. 16I).

Sources for Partial Melting

Introduction

In the previous sections, it was demonstrated that magma commingling and fractionation are not responsible for the production of the four rock groups of the

Sloan volcanics. It was concluded that partial melting of chemically distinct sources was the dominant process. In this section I will propose model source rocks for the Sloan volcanics.

Geochemical modeling was used to explore possible explanations concerning magma petrogenesis. A model is non-unique and must be combined with field and petrographic analyses to be of any merit.

The Pascal computer program MELT was used to evaluate source rock compositions and the amount of partial melting required to produce the andesites and dacites of the Sloan volcanics. MELT uses trace element distribution coefficients (Arth, 1976) and calculates a model rock using the batch melting equation of Shaw (1970). In these models, a critical assumption is the mineralogy and geochemistry of the source rock.

Two source rocks were used in the models. The first is a Precambrian amphibolite exposed in the lower plate of the Saddle Island detachment, Lake Mead (Smith, 1982a, 1984, 1986; Sewall, 1988; Duebendorfer et al., 1990). The amphibolite contains plagioclase (25-40%), actinolite and chlorite. It was assumed that the protolith of the amphibolite was gabbro containing plagioclase and clinopyroxene +/- olivine. Chemistry of the amphibolite (Tables 5a & 5b) is from an unpublished data base (E.I. Smith, University of Nevada, Las Vegas). The Saddle Island amphibolite is a reasonable source rock for the following reasons: 1) it will yield intermediate composition magma upon partial melting; 2) it crops out in the Lake Mead-Las Vegas area; 3) its occurrence in the lower

Table 5a				
Melt Mod	el #1: Productio	n Of Sloan An	desite (Mc110)
From 25% Partial Melting Of Saddle Island Amphibolite.				
All Rock	Compositions [®] Ar	e In ppm.	-	
	Saddle Island	Sloan	Model	Bulk
	amphibolite	andesite	melt	distribution
Element	composition	composition	composition	coefficient
Ba	655.00	1800.00	2078.01	0.087
Sr	1396.00	2280.00	1926.18	0.633
Ce	60.07	173.00	169.37	0.140
Nd	31.20	65.50	78.82	0.238
Sm	6.90	10.00	13.17	0.365
Eu	1.81	2.57	3.07	0.454
Yb	1.80	2.53	3.07	0.448
Lu	0.19	0.32	0.34	0.405
Sc	21.45	6.47	13.83	1.735
Cr	113.00	136.00	24.50	5.817
v	291.00	70.60	315.28	0.897
Co	26.30	10.30	29.24	0.866

Mineral modal percentages of source rock: plagioclase = 30; clinopyroxene = 69; olivine = 1

Table 5b	Table 5b				
Melt Model #2: Production Of Sloan Dacite (Mc119)					
From 15%	From 15% Partial Melting Of Saddle Island Amphibolite.				
All Rock C	ompositions Ar	e In ppm.	-		
	Saddle Island	Sloan	Model	Bulk	
	amphibolite	dacite	melt	distribution	
Element	composition	composition	composition	coefficient	
Ba	655.00	1780.00	2712.66	0.108	
Sr	1396.00	1310.00	1661.51	0.812	
Ce	60.07	216.00	224.73	0.138	
Nd	31.20	101.00	93.05	0.218	
Sm	6.90	14.80	16.13	0.327	
Eu	1.81	3.32	3.44	0.442	
Yb	1.80	3.84	3.68	0.399	
Lu	0.19	0.64	0.42	0.360	
Sc	21.45	7.42	14.96	1.510	
Cr	113.00	40.20	25.48	5.040	
v	291.00	19.20	357.93	0.780	
Co	26.30	3.19	34.51	0.720	

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plate of a detachment implies that it probably represents mid-to lower-crustal rocks. The second source is spinel peridotite. Spinel peridotite occurs as xenoliths in alkali basalts in the nearby Fortification Hill field of northwestern Arizona (Wilshire et al., 1988; Nielson and Nakata, in press). Ultramafic xenoliths are also found in the alkali basalt that crops out near the Sloan limestone quarry just to the northwest of Hidden Valley (Plate 1, Appendices A and D). Felsic upper-crustal rocks were not considered as possible source rocks since the amount of partial melting required to produce andesites and dacites is unrealistically high.

Partial Melt Models

Four models were tested. They are:

1) A 25% partial melt of Saddle Island gabbro consisting of 30% plagioclase, 69% clinopyroxene and 1% olivine produces an acceptable model for the production of the Sloan andesites. There is close agreement of the REE concentrations between the model rock and andesite. Concentration of elements compatible with clinopyroxene and olivine (Sc, Cr, V and Co), however, do not match well between the model rock and andesite. Agreement between the model rock and andesite for concentrations of Sr and Ba is very good (Table 5a, Fig. 21).

2) A 15% partial melt of Saddle Island gabbro consisting of 40% plagioclase and 60% clinopyroxene provides a realistic model for the production of the Sloan dacites. With the exception of Lu, there is excellent agreement of all of the REE between the model rock and dacite. There is poor to average



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Figure 21: Chondrite-normalized REE diagram showing the chemical similarities between the Sloan andesites (Mc 110) and a 25% partial melt of gabbro.

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correspondence between compatible elements (V, Sr and Ba) in the model rock and the dacite (Table 5b, Fig. 22).

3) A 0.5% partial melt of spinel peridotite containing 56.4% olivine, 30.1% orthopyroxene, 10% clinopyroxene and 3.5% spinel, with 2 times chondrite REE concentration did not produce favorable results. The concentrations of Ce, Nd, Sm and Eu in the model rock are lower than the andesite. The concentrations of Yb and Lu in the model rock are higher than the andesite.

(Table 5c, Fig. 23).

4) A 0.5% partial melt of spinel peridotite with the same mineralogy as above, but with concentrations of 10 times chondrite for Ce, Nd and Sm, 3 times chondrite for Eu, and 2 times chondrite for Yb and Lu also does not produce favorable results (Table 5d, Fig. 24). The REE concentration in this model represents a metasomatized mantle that has been enriched in LREE.

Discussion

These models suggest that the Sloan andesites and dacites can be produced from partial melts of a rock similar to the Saddle Island gabbro. It must be kept in mind that using the Saddle Island gabbro as a source rock does not provide a unique solution. The Saddle Island gabbro may have followed a different evolutionary path than the source rocks for the Sloan volcanics. The large amount of variance between the compatible elements may be a reflection of their different petrogenetic histories. Even though these models are non-unique, they constrain the mineralogy and geochemistry of the source rocks for the Sloan

Table 5c				
Melt Mo	del #3: Producti	on Of Sloan Andc	site (Mc110) Fro	om 0.5%
Partial M	elting Of Perido	tite. Rock Compo	sitions Are In p	pm.
	Peridotite	Sloan andesite	Melt	
	composition:	composition:	composition:	Bulk
	normalized	normalized	normalized	distribution
Element	to chondrite	to chondrite	to chondrite	coefficient
Ce	2	196.59	68.47	0.026
Nd	2	109.17	40.06	0.045
Sm	2	55.25	27.71	0.068
Eu	2	37.25	26.22	0.072
Yb	2	12.65	18.52	0.103
Lu	2	9.41	19.39	0.099

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Mineral modal percentages of source rock: olivine = 56.4; orthopyroxene = 30.1;

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Table 5d					
Melt Mo	Melt Model #4: Production Of Sloan Andesite From 0.5%				
Partial M	lelting Of Perido	tite. Rock Compo	sitions Are In pr	om.	
	Peridotite	Sloan andesite	Melt		
	composition:	composition:	composition:	Bulk	
	normalized	normalized	normalized	distribution	
Element	to chondrite	to chondrite	to chondrite	coefficient	
Ce	10	196.59	324.34	0.026	
Nd	10	109.17	200.29	0.045	
Sm	10	55.25	138.55	0.068	
Eu	3	37.25	39.33	0.072	
Yb	2	12.65	18.52	0.103	
Lu	2	9.41	19.39	0.099	

Mineral modal percentages of source rock: olivine = 56.4; orthopyroxene = 30.1;



Figure 22: Chondrite-normalized REE diagram showing the chemical similarities between the Sloan dacites (Mc 119) and a 15% partial melt of gabbro.



Figure 23: Chondrite normalized REE diagram showing the chemical differences between the Sloan andesites (Mc 110) and dacites (Mc 119), and a 0.5% partial melt of spinel peridotite. Values for the spinel peridotite are two times chondrite concentration.




volcanics.

Crustal Contamination

Geochemistry suggests that rocks of the Sloan volcanics were produced in the mid-to lower-crust by the partial melting of a gabbro. In this section, crustal contamination of rocks of the Sloan volcanics will be evaluated using petrographic and geochemical evidence.

Petrographic evidence for crustal contamination is limited to the Tuff of the Sloan volcanics. The tuffs contain abundant xenoliths, many of them gabbroic.

Sr contents greater than 1,000 ppm rule out large degrees of crustal contamination. Sr contents are normally greater than 1,000 ppm in rocks derived from the lower-crust and mantle. Rocks derived in the upper-crust are enriched in Rb and depleted in Sr (< 1,000 ppm Sr). Crustal contamination, therefore, commonly results in Sr contents less than 1,000 ppm. The high Sr contents in the Mount Hanna and Mount Ian andesites, and the Mount Sutor dacite (> 1,000 ppm) suggests a lack of significant crustal contamination (Appendix B). Volumetrically, these rocks are the dominant lithologies of the Sloan volcanics. In contrast, the dacites and tuffs from the Center Mountain dome complex have Sr contents less than 1,000 ppm (Appendix B). This suggests that residence time in the crust and/or crustal contamination may have played a part in the evolution of these rocks.

THE SLOAN SAG

Evidence for a Sag in Hidden Valley

Introduction

In this section, by using field data, I will demonstrate that there is a structural sag in Hidden Valley.

The Hidden Valley Sag

Even though neither cited evidence, both Hewett (1956) and Longwell (1965) recognized the existence of a semi-circular depression in Hidden Valley. My field mapping has revealed structural evidence for a sag in Hidden Valley. In the northern part of Hidden Valley, the Tuff of Bridge Spring and the Hidden Valley volcanics dip 10°-15° south. Rocks of the Hidden Valley volcanics in the southern part of Hidden Valley dip 20°-30° north. Tuffs and basalts west of Hidden Valley dip about 10° east. East of Hidden Valley, pre-Sloan volcanic rocks dip 10°-30° west (Plate 1).

Additional evidence for a structural depression includes log data from a water well in western Hidden Valley (Plate 1). The drill hole penetrated 700 feet into alluvium, never striking bedrock.

Association to a structural sag may not be the only explanation for the east and west dips about Hidden Valley. The eastward regional dip of the McCullough Mountains (Anderson et al., 1985; Schmidt, 1987) may be responsible for the orientation of pre-Sloan volcanic rocks to the west of Hidden Valley. In the McCullough Mountains, westward dipping normal faults resulted in eastward stratal tilting of up to 40° (Anderson et al., 1985). An alternate explanation for the westward dips in the northern McCullough Mountains is suggested by the model of Weber and Smith (1987). By using a plot of relatively immobile and incompatible elements (Hf, Ta and Th), Weber and Smith chemically correlated Tertiary plutonic rocks of the Boulder City and Nelson plutons with volcanic rocks of the Eldorado and northern McCullough Mountains (Fig. 2). If their model is correct, the Eldorado and northern McCullough Mountains formed a volcano above the Boulder City and Nelson plutons. Westward dips of volcanic rocks in the northern McCullough Mountains, therefore, may represent the western flank of this stratocone.

Conclusion

The south and north dips of pre-Sloan volcanic rocks to the north and south of Hidden Valley respectively cannot be easily explained by regional trends, and I suggest that they are directly related to the formation of the Sloan sag. Although there are alternative explanations for the east and west dips of pre-Sloan volcanic rocks to the west and east of Hidden Valley respectively, I conclude that the overall inward dips of Pre-Sloan volcanic rocks about Hidden Valley indicates the presence of a structural depression. This conclusion is supported by well-log data.

84

Classic Caldera, or Volcanotectonic Depression?

Introduction

A physiographic sag filled with and surrounded by volcanic domes and flows is suggestive of a caldera. In this section, evidence for a classic collapse caldera origin for the Sloan sag will be evaluated. Using field evidence, I will show that a classic collapse caldera does not exist in Hidden Valley.

Discussion

Two of the main criteria for the existence of a collapse caldera are: 1) embayed, scalloped and faulted caldera margins with associated slump breccias; 2) an ash-flow tuff related to the caldera (Steven and Lipman, 1976; Steven et al., 1984; Walker, 1984). My initial field mapping concentrated on a search for features suggestive of a classic collapse caldera in Hidden Valley.

The Mount Hanna andesite member of the Sloan volcanics is in direct contact with older basalts of the Hidden Valley volcanics only in the eastern part of the thesis area. In other areas, contacts are covered by alluvium. Careful mapping along this contact demonstrated that it is depositional and is not a fault. In some areas the contact is low-angle and conformable, while in other places it cuts across topography and appears unconformable. (Plate 1). This relationship can be explained by the deposition of the Sloan volcanics on the irregular surface of the Hidden Valley basalt. No slump breccias are found in this, or any other area of Hidden Valley.

Ash-flow tuff occurs in the Center Mountain dome complex and in the western portion of the northern Mount Sutor field. There are also outcrops of ash-flow tuff west of Hidden Valley (Plate 1). Tuff within Hidden Valley is associated with isolated pyroclastic events related to dome formation. Chemical studies demonstrate that the tuff to the west of Hidden Valley is the Tuff of Bridge Spring, a regional ash-flow sheet whose source is unknown. None of the tuff exposures in and around Hidden Valley are associated with a pyroclastic event related to caldera formation.

The lack of slump breccias and an associated ash-flow tuff, argues strongly against a classic collapse caldera origin for the Sloan sag.

Significance of the Mount Hanna Andesite

Introduction

In this section, I will begin to discuss the origin of the Sloan sag by evaluating the significance of the thick pool of Mount Hanna andesite within the depression. High silica lava flows are typically thick and of small areal extent. Walker (1973) reported that rhyolitic lava flows have a median length of 1.1 km, with none longer than 10 km. Felsic to intermediate pyroclastic flows, however, may be very thin and travel greater than 70 km from their source (Henry et al., 1988). Ekren et al. (1984) described extensive "lavalike" rhyolite flows without pyroclastic textures in and adjacent to the Owyhee Mountains and the Owyhee Plateau of southwestern Idaho. Experimental data from one of the Owyhee flows

86

(the Little Jacks Tuff) suggests that it formed from a dry melt (2% H₂O or less) under pressures as great as 8 kilobars and temperatures of greater than 1,000 °C. Magmas originated from a depth of about 25 km. Similar deposits include the Oligocene Bracks Rhyolite (SiQ₂ = 68% to 72%) of the Trans-Pecos volcanic field, Texas, which covers an area of 1,000 km² (Henry et al., 1988), and the Middle Proterozoic Yardea Dacite (SiQ₂ = 67%) of south Australia, which covers an area of over 12,000 km² (Creaser and White, 1991). The Trans-Pecos and Yardea rocks lack pyroclastic textures. Low water content allows devolitilization and fragmentation of magma near the surface. High temperatures produce nonviscous lavas capable of flowing great distances (Henry et al., 1988). If these lavas erupted at lower temperatures and higher water contents, it is reasonable to assume that ash-flow tuffs would have been produced.

Origin of the Mount Hanna Andesite

I propose that the Mount Hanna andesite member of the Sloan volcanics is analogous to a hot, dry ash-flow tuff, similar to the Owyhee, Trans-Pecos and Yardea lavas. Geochemical modeling suggests that the Mount Hanna andesite was produced from partial melting of a gabbroic source at lower-crustal levels (Table 5a, Fig, 21). Sr contents of 1700-2280 ppm for the Mount Hanna andesite suggests a lower-crustal or mantle source for this unit. If these magmas equilibrated at temperatures of 1,000°C (similar to the Owyhee lavas), they originated at a depth of about 25 km, assuming a geothermal gradient of 40°C/km. The aphyric texture of the Mount Hanna andesite (Fig. 25) and the



Figure 25: 40x photomicrograph of the Mount Hanna andesite. The rock consists of subparallel microlites of plagioclase with subordinate Fe-Ti oxides, glass and probable clinopyroxene and/or olivine (high birefringent grains).

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lack of fractionation trends on chemical plots (Figs. 16D, 16E, 16H & 16I) suggests that the Mount Hanna andesite rose to the surface quickly, without pausing to substantially cool or fractionate. The high Sr contents also suggest that magma was not significantly contaminated by crustal material, indicating a quick ascent from its source area.

The Mount Hanna andesite erupted from a single vent, creating a large pool (exposed maximum volume of 9 km^3) of andesite lava (Plate 1; cross section C-C'; Fig. 7). The fact that such a large pool of andesite was erupted from a single vent suggests that the magma had a lower viscosity than typical andesite and was capable of flowing greater distances than would be expected of an intermediate composition lava. Its low viscosity may be attributed to high temperature and low gas content.

Sparks and Wilson (1976) proposed that a hot, dry magma will produce an eruptive column that is too dense to mix with the atmosphere. Such a column would consist only of the gas thrust phase, and would be too dense to produce a gaseous convective thrust component. Because of this, Ekren et al. (1984) envisioned lava fountain-type eruptions for the Owyhee rhyolites, as opposed to large Plinian clouds. The Mount Hanna andesite may also have erupted by lavafountaining. Much of this unit is characterized by a mottled, streaky texture consisting of black and red, or black and gray discontinuous patches (Fig.26). This texture may have formed by hot magma rain that produced droplets of magma. Upon hitting the surface, the droplets coalesced, moving away from the



Figure 26: Photograph showing the streaky, discontinuous texture common in the Mount Hanna andesite. Sample was collected at station 115 (Fig. 8). Scale bar is 1 cm long.

vent as lava flows.

Duffield (1990) has described similar textures in the Oligocene Taylor Creek Rhyolite of the Mogollon-Datil volcanic field in southwestern New Mexico. He suggests that the streaky "agglunitnated" texture in the rhyolites is a result of lava-fountaining. If the magma droplets are hot enough, upon hitting the surface they will coalesce to form homogeneously-textured rocks. Duffield proposes that if the eruptive fountain is high, magma droplets will cool before hitting the surface and not be hot enough to completely coalesce and homogenize. Fluctuating fountain height, therefore, will alternately produce homogeneous and streaky-textured rocks.

Even though the discontinuous streaks in the Mount Hanna andesite are suggestive of a primary volcanic origin, they may also represent highly sheared and attenuated flow foliation. To evaluate the origin of the streaks, I compared their size to the size-frequency distributions of particles produced during lavafountaining and pyroclastic eruptions. Heiken (1972) determined the mean droplet diameter for a variety of different magma types and eruptive styles. To evaluate if the streaky texture of the Mount Hanna andesite may reflect magma droplets, mean streak diameter was determined. The cross-sectional area of ten streaks from the Mount Hanna andesite (sample Mc115) was measured. Values were adjusted to represent the cross sectional diameter of a sphere. Diameters range from 0.8-6.8 mm, with a mean of 4.08 mm. The mean diameter of the discontinuous streaks in the Mount Hanna andesite is similar to those of magma

droplets produced in the following lava-fountaining events: 1) the basaltic strombolian eruption of Pacaya, Guatemala (6.35 mm); 2) the basaltic phreatomagmatic eruption of Capelinhos, Azores Islands (3.18 mm); 3) the rhyolitic phreatomagmatic eruption of Sugarloaf, San Francisco Mountains, Arizona (3.18 mm) (Heiken, 1972). The correlation of the mean diameter of the discontinuous streaks in the Mount Hanna andesite with recognized lavafountaining deposits supports a primary origin for the streaks.

Depth of Magma Generation Versus Depth of Eruption

Magma must migrate to shallow crustal levels before devolatilization of gases can occur, resulting in fragmentation and eruption. For magmas with SiO₂ contents comparable to the Sloan andesites and dacites, the level at which gas exsolution and magma fragmentation can occur is approximately 5.4 km (Fisher and Schmincke, 1984). Magmas with H₂O contents of 2% or less may devolatilize and fragment even closer to the surface. The above information suggests that the Mount Hanna andesite resided at these shallower depths long enough only to exsolve gas and fragment before erupting.

Formation of the Sloan Sag

Introduction

I will now consider the formation of the sag, and will suggest that: 1) the Sloan volcanics filled pre-existing grabens and half-grabens bounded by the McCullough Wash fault system; 2) sagging in Hidden Valley occurred during

and/or after the eruption of the Sloan volcanics.

The McCullough Wash Fault System

The McCullough Wash fault is the only major internal structure in the McCullough Mountains. South of Hidden Valley in the South McCullough Wilderness Study Area, this fault places Precambrian basement against rocks of the Hidden Valley volcanics and has at least 600 m of throw. Displacement decreases to the north. North of the wilderness study area, it splays into three northeast striking faults (Anderson et al, 1985). East and west dipping splays of the McCullough Wash fault system produced numerous grabens and half-grabens in the area of the McCullough Pass caldera, just south of Hidden Valley (Schmidt, 1987). These faults display only minor offset. The McCullough Wash fault system probably continues north into Hidden Valley. Most of these faults are covered by alluvium and possibly by domes and flows of the Sloan volcanics. A north-south striking, west-dipping, normal fault on the west side of the ridge just to the north of the McCullough Pass caldera (Plate 1) offsets pre-Sloan volcanic rocks, and may represent the northward projection of the McCullough Wash fault system. I propose that Hidden Valley is cut by a series of grabens and halfgrabens bounded by faults of the McCullough Wash fault system. Field mapping has also revealed an en-echelon splay of the McCullough Wash fault in Hidden Valley. The sharp, steep linear escarpment of the Mount Hanna andesite and Mount Sutor dacite in the eastern portion of Hidden Valley is suggestive of a fault scarp (Plate 1). This type of en-echelon relationship of normal faults is

common and has been documented in many areas including the East African rift zone (Morley, 1988 & 1989) and the Dead Horse graben of west Texas (Maler, 1990). The strike of this fault changes from north-south to northwest-southeast in the area of the Mount Sutor stock (Plate 1, Fig. 8). Rocks of the Mount Hanna andesite and Mount Sutor dacite are offset by this fault suggesting that it was active after eruption of these units. The McCullough Wash fault system does not appear to extend farther to the north of Hidden Valley, and its displacement decreases to the south. Based on mapping done by Schmidt (1987) along the south rim of Hidden Valley, faults may be spaced every 300 m. Accumulated displacement on buried and exposed faults in Hidden Valley is estimated to be at least 2.25 km.

Sagging and Tectonic Control

Faults of the McCullough Wash system strike north-south. If subsidence was controlled entirely by these faults, north-south oriented grabens would have formed in Hidden Valley. This is the case in the northern segment of the McCullough Pass caldera south of Hidden Valley (Schmidt, 1987). Subsidence was accommodated by faults of the McCullough Wash system, resulting in a north-south trending graben. In the case of the Sloan sag, however, contacts cut across these north-south striking structures. I propose, therefore, that sagging in Hidden Valley resulted from rejuvenation on the McCullough Wash fault system in the east and northeast, and sagging into emptied magma chambers in the west.

Summary of Events

A scenario for the formation of the Sloan sag is described below (refer to Figure 27).

 Before the eruption of the Sloan volcanics, Hidden Valley consisted of a series of grabens and half grabens, bounded by the north-south striking McCullough Wash fault system.

2) The Mount Hanna andesite and rocks of the Center Mountain dome complex were the first members of the Sloan volcanics to erupt. The Mount Hanna andesite was generated at depths as great as 25 km by partial melting of gabbro, rising to the surface and erupting quickly in a lava-fountaining event. Eruption of this unit caused sagging by reactivating faults of the McCullough Wash system in eastern Hidden Valley. Fault movement produced a surface sag over the emptied chamber. Unlike other units of the Sloan volcanics which were emitted from numerous vents and domes, the Mount Hanna andesite erupted from a single vent resulting in a pool of andesite with a maximum exposed volume of 9 km³.

3) Volcanic dome formation is represented by the rocks of the Center Mountain dome complex. Ash-flow tuffs of the Cinder Prospect member and the Tuff of the Sloan volcanics represent the early stages of pyroclastic and phreatomagmatic activity, reflecting tuff ring formation. The tuff ring was intruded by the Center Mountain dacite. The Mount Ian andesite intruded rocks of the Center Mountain dome complex, resulting in the formation of platy,



Stage 1: Pre-Sloan volcanics topography: paleo-Hidden Valley consists of half-grabens bounded by faults of the McCullough Wash system.

Stage 2: Eruption of the Mount Hanna andesite causes rejuvenation of the McCullough Wash fault system and sagging in eastern Hidden Valley.





Stage 3: Eruption of units in northern and western Hidden Valley causes sagging into shallow chambers, and the rejuvenation of a splay of the McCullough Wash system.

Figure 27: Formation sequence of the Sloan sag.

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foliated andesite domes, many of which overlie tuff rings. The Mount Sutor dacite erupted from numerous vents and domes resulting in two large pools of viscous biotite dacite.

Subsidence into shallow chambers occurred during and/or after the eruption of these units. Subsidence into shallow chambers caused renewed movement on a splay of the McCullough Wash fault system, offsetting rocks of the Mount Hanna andesite and the Mount Sutor dacite in the northeast part of Hidden Valley, resulting in more sagging.

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CONCLUSIONS

Important conclusions of this thesis are:

1) A volcanotectonic depression in Hidden Valley resulted from the eruption of the Sloan volcanics.

2) Sagging was accommodated by a combination of displacement on splays of the McCullough Wash fault system in eastern and northeastern Hidden Valley, and sagging into evacuated magma chambers in the western part of the valley.

3) The rocks of the Sloan volcanics belong to four magma groups, each of which were produced by partial melting of chemically distinct sources.

4) Partial melting of a crustal source similar to the Saddle Island amphibolite produced the andesites and dacites of the Hidden Valley volcanics.

5) Except for rocks of the Center Mountain dome complex, magmas rose through the crust rapidly without experiencing significant crystal fractionation or crustal contamination.

6) The Mount Hanna and esite member of the Sloan volcanics erupted a large pool (approximately 9 km³) of lava from a single vent. This unit may have been emplaced as a hot (1,000 °C), dry (2% H₂O or less) analog of an ash-flow tuff in a lava-fountaining event. If this magma had erupted at lower temperatures and higher water contents, a plinian-style eruption probably would have occurred, resulting in an ash-flow tuff.

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FUTURE WORK

As in any research project, unanswered questions and problems arise that cannot be answered due to time and/or financial constraints. The following is a list of projects that may provide important information about the McCullough Mountains and the southern Basin-and-Range.

1) The 40 Ar/ 69 Ar date of the Tuff of Bridge Spring is the only reliable date yet obtained from the north-central McCullough Mountains. 40 Ar/ 69 Ar dates on rocks stratigraphically above and below this unit will help constrain the absolute age and timing of eruption of the volcanic units.

2) The exotic trace mineral assemblage in the lower-most rhyolite tuff of the Tuff of the Sloan volcanics (sample Mc59a) is intriguing. Even though this tuff contains monazite, allanite, epidote, zircon and sphene, its incompatible trace element concentration is not higher than the other tuffs from this unit. A detailed study of mineral chemistry is required to understand the geochemistry of this unit.

3) Detailed geologic mapping has never been done north of Hidden Valley.
Work in the northern McCullough Mountains will test the Weber and Smith
(1987) hypothesis that a stratocone exists in this area.

4) Geochemistry suggests that volcanic rocks from the White Hills, and the River, Eldorado and McCullough Mountains have similar sources. A geochemical study of igneous rocks from a larger part of the southern Basin-and-Range may help us understand the scale of heterogeneity of crustal and mantle sources.

5) The hot, dry, fountaining-eruption mechanism of the Mount Hanna

andesite is unique. Such an eruptive mechanism may be the key to understanding the large areal extent of some felsic-to-intermediate lavas. Unless they erupt as ash-flow tuffs, intermediate-to-felsic lavas usually form short, thick deposits. The discontinuous, streaky texture displayed in the Mount Hanna andesite and the Taylor Creek rhyolites may be indicative of a lava-fountaining mechanism. Detailed mapping of the Mount Hanna andesite field along with petrographic and geochemical studies are needed to help us further understand what may be a significant eruptive mechanism.

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APPENDIX A: SAMPLE LOCATION AND PETROGRAPHY

Colors are from the Geological Society of America rock-color chart.

TUFF OF BRIDGE SPRING

Sample number: Mc53

Location: NW 1/4, Sec 31, T23S, R61E, Sloan, Nev. 7 1/2' quad: tuff that underlies Thyb in the NE part of the thesis area.

Rock name: Welded dacitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 3 mm (24.2%), subhedral, oscillatory plagioclase up to 2.5 mm (3.4%), sub-euhedral, hematized biotite up to 2 mm (3.4%), an-subhedral clinopyroxene up to 1 mm (0.8%), anhedral, oscillatory quartz up to 1 mm (0.6%), sub-euhedral sphene up to 0.5 mm (0.4%), Fe-Ti oxides up to 0.5 mm (0.2%) and trace zircon. Pumice fiamme (9.6%) are devitrified, rarely spherulitic and up to several cm long. Basaltic and granodioritic rock fragments (1.2%) are up to 1 cm. The pale red-colored groundmass (56.2%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments.

Sample number: Mc60

Location: NW 1/4, Sec 32, T24S, R60E, Jean, Nev. 7 1/2' quad: collected near the intersection of Las Vegas Blvd. and the dirt entrance road to Jean Lake.

Rock Name: Moderately welded dacitic ash-flow tuff

Description: Pyroclastic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 2 mm (7.5%), subhedral, oscillatory plagioclase up to 1 mm (1.5%), anhedral quartz up to 0.5 mm (0.8%), subhedral, oxidized biotite up to 1.5 mm (0.6%), an-subhedral clinopyroxene up to 0.5 mm (0.2%), sub-euhedral sphene < 0.5 mm (0.4%), trace Fe-Ti oxides up to 0.5 mm and trace zircon. Flattened, devitrified pumice (2.2%) is up to 1 cm in length. Basaltic, gabbroic and granodioritic rock fragments (0.8%) are up to 1 cm. The pale grayish pinkcolored groundmass (86%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments.

Sample number: Mc62

Location: SE 1/4, Sec 31, T24S, R60E, Jean, Nev. 7 1/2' quad: collected approximately 1 mile S-SE from where the railroad tracks cross under Las Vegas Blvd.

Rock name: Welded dacitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 2 mm (4.2%), subhedral, oscillatory plagioclase up to 2 mm (2.8%), anhedral, oscillatory quartz up to 1 mm (1.2%), sub-euhedral, oxidized biotite up to 2 mm (1.0%), Fe-Ti oxides up to 0.5 mm (0.4%), subhedral clinopyroxene up to 2 mm (0.4%), sub-euhedral sphene < 0.5 mm (0.6%) and trace zircon. Pumice fiamme (1.4%) are devitrified and up to 2 cm. Basaltic and granitic rock fragments (1.2%) are up to several cm. The pale red-colored groundmass (86.8%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments.

Sample: Mc64b

Location: SW 1/4, Sec 2, T24S, R60E, Sloan, Nev. 7 1/2' quad: collected from the southernmost Tbs exposure west of I-15.

Rock name: Non-welded rhyolitic ash-flow tuff

Description: Pyroclastic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 3 mm (6.0%), subhedral, oxidized biotite up to 1 mm (1.8%), anhedral, oscillatory quartz up to 1 mm (1.0%), subhedral, oscillatory plagioclase up to 1 mm (0.8%), an-subhedral clinopyroxene up to 0.5 mm (0.2%), sub-euhedral sphene up to 0.5 mm (0.2%), Fe-Ti oxides up to 0.5 mm (trace) and trace zircon. Spongy devitrified pumice (2.2%) is up to 2 cm. Basaltic rock fragments (1.8%) are up to several cm. The grayish pink-colored groundmass (86%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments.

Sample number: Mc66

Location: SE 1/4, Sec 35, T23S, R60E, Sloan, Nev. 7 1/2' quad: collected from the small Tbs exposure surrounded by Thvb: approximately 1,000' west of the railroad tracks.

Rock name: Partially-welded dacitic ash-flow tuff

Description: Pyroclastic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 3 mm (5.4%), subhedral, oxidized biotite up to 1 mm (1.6%), anhedral, oscillatory quartz up to 1 mm (1.0%), subhedral, oscillatory plagioclase up to 1.5 mm (1.2%), an-subhedral clinopyroxene up to 1 mm (0.8%), sub-euhedral sphene up to 0.5 mm (0.4%), Fe-Ti oxides up to 0.5 mm (0.2%) and trace zircon. Flattened devitrified pumice (3.4%) is up to 3 cm long. Basaltic, granodioritic and gabbroic rock fragments (3.0%) are up to several cm. The pale pinkcolored groundmass (83.0%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments. .

Sample number: Mc67

Location: NW 1/4, Sec 35, T23S, R60E, Sloan, Nev. 7 1/2' quad: collected approximately 1 mile west of the cinder outcrop in the NW portion of the Tscp.

Rock name: Welded rhyolitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 3 mm (10.4%), subhedral, oscillatory plagioclase up to 1 mm (2.0%), anhedral, oscillatory quartz up to 1 mm (0.8%), Fe-Ti oxides up to 0.5 mm, an-subhedral clinopyroxene up to 0.5 mm and trace sphene & zircon (< 0.5 mm). Pumice fiamme are not present in the thin section, and occur only rarely in hand specimens. Basaltic, granodioritic and gabbroic rock fragments (7.2%) are up to 1 cm. The light brownish gray-colored groundmass (79.0%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments. Approximately 1% of the rock has been replaced by calcite.

Sample number: Mc68

Location: SW 1/4, Sec 36, T23S, R60E, Sloan, Nev. 7 1/2' quad: collected from the Tbs exposure between the railroad tracks and I-15.

Rock name: Welded rhyolitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of an-subhedral, oscillatory sanidine up to 2 mm, (4.8%), aneuhedral, oscillatory plagioclase up to 2 mm (1.4%), sub-euhedral, oxidized biotite up to 1 mm (1.4%), an-subhedral clinopyroxene up to 0.5 mm (0.8%), anhedral, oscillatory quartz up to 1 mm (0.4%), Fe-Ti oxides up to 0.5 mm (0.4%), sub-euhedral sphene up to 0.5 mm (trace) and trace zircon. Devitrified and commonly spherulitic pumice fiamme (11.4%) are up to several cm. Basaltic and gabbroic rock fragments (9.6%) are up to 1 cm. The light brownish gray-colored groundmass (69.8%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments.

Sample number: Mc69

Location: SW 1/4, Sec 24, T23S, R60E, Sloan, Nev. 7 1/2' quad: collected from the northernmost Tbs exposure in the mapped area west of I-15.

Rock name: Welded rhyolitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 2 mm (7.0%), subhedral, oscillatory plagioclase up to 1 mm (5.0%), anhedral, oscillatory

quartz up to 1 mm (1.2%), Fe-Ti oxides up to 0.5 mm (0.6%), sub-euhedral sphene < 0.5 mm (0.6%), subhedral, oxidized, subhedral biotite up to 2 mm (0.4%), an-subhedral clinopyroxene up to 3 mm (0.4%) and trace zircon. Devitrified pumice fiamme (0.2%) are up to several cm. Basaltic

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and gabbroic rock fragments (1.0%) are up to 1 cm. The grayish redcolored groundmass (83.6%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments. Fractures are coated with calcite.

Sample number: Mc71

Location: NW 1/4, Sec 24, T23S, R60E, Sloan, Nev. 7 1/2' quad: collected approximately 1,000' N-NW of benchmark 2936 on the railroad tracks Rock name: Welded rhyolitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 2 mm (10.6%), subhedral, oscillatory plagioclase up to 1 mm (3.0%), subhedral, oxidized biotite up to 1.5 mm (1.6%), anhedral, oscillatory quartz up to 1 mm (1.4%), an-subhedral clinopyroxene up to 1 mm (1.6%), sub-euhedral sphene < 0.5 mm (0.4%), trace Fe-Ti oxides up to 0.5 mm and trace zircon. Devitrified pumice fiamme (12.0%) are up to several cm. Basaltic and gabbroic rock fragments (2.0%) are up to 1 cm. The grayish red-colored groundmass (67.4%) consists of devitrified glass and glass shards. Shards wrap around phenocrysts and lithic fragments. Fractures are coated with calcite.

HIDDEN VALLEY VOLCANICS

Sample number: Mc1

Location: SE 1/4, Sec 26, Hidden Valley, Nev. 7 1/2' quad:collected approximately 800' south of the cattle guard on the western entrance road to Hidden Valley.

Rock name: Vesicular, pyroxene olivine basalt

Description: Vesicular, aphanitic and hypocrystalline with phenocrysts of ansubhedral, iddingsitized olivine up to 1.5 mm (0.6%) and an-subhedral clinopyroxene up to 0.5 mm (0.3) in a black-colored, vesicular (11.0%) groundmass consisting of microlites of sub-euhedral plagioclase (44.3%), subhedral, iddingsitized olivine (14.0%), an-subhedral clinopyroxene (12.0%), Fe-Ti oxides (0.3%) and moderately devitrified glass (17.3%). Vesicles are coated with calcite.

Sample number: Mc3a

- Location: NE 1/4, Sec 35, T24S, R60E, Hidden Valley, Nev. 7 1/2' quad: collected from the NW corner of the N-S trending Thvb ridge south of the western entrance road to Hidden Valley.
- Rock name: Vesicular, pyroxene basalt
- Description: Vesicular, aphanitic and hypocrystalline with phenocrysts of embayed, resorbed, an-euhedral clinopyroxene up to 1.5 mm (1.0%), commonly in glomerocrysts. The grayish red-colored, vesicular (8.2%) groundmass

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consists of microlites of sub-euhedral, oscillatory plagioclase (55.0%), ansubhedral clinopyroxene (19.0%), granular hematite (13.4%: replacing clinopyroxene), Fe-Ti oxides (2.6%) and glass (0.8%). Vesicles are coated with calcite.

Sample number: Mc35

Location: NW 1/4, Sec 23, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: collected from the isolated Thyb outcrop in the southern portion of the Tsh dome field: on the southern side of the entrance to the major drainage separating Tss from Tsh.

Rock name: Vesicular, pyroxene olivine basalt

Description: Porphyritic, vesicular and hypocrystalline with phenocrysts of subhedral, iddingsitized olivine up to 2 mm (9.8%), subhedral, pitted, embayed and oscillatory plagioclase up to 1 mm (2.2%) and subhedral clinopyroxene up to 0.5 mm (0.8%). Quartz xenocrysts are up to 4 mm and rimmed with glass and cryptocrystalline clinopyroxene(?) (0.6%). The medium dark gray-colored, vesicular (2.6%) groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (58.4%), subhedral clinopyroxene (9.2%), subhedral, iddingsitized olivine (9.8%), subhedral clinopyroxene (9.2%), Fe-Ti oxides (6.2%) and glass (0.4%). Vesicles are coated with calcite.

Sample number: Mc37

Location: SE 1/4, Sec 22, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: collected 2100' south of sample Mc35.

Rock name: Vesicular, pyroxene olivine basalt

Description: Porphyritic, vesicular and hypocrystalline with phenocrysts of subeuhedral, iddingsitized olivine up to 2 mm (7.6%), sub-euhedral, pitted and embayed clinopyroxene up to 1 mm (1.4%) and subhedral, pitted, embayed and oscillatory plagioclase up to 2 mm (1.0%). Quartz xenocrysts are up to 5 mm and rimmed with glass (6.0%). The medium dark gray-colored, vesicular (1.2%) groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (57.0%), subhedral, iddingsitized olivine (8.2%), subeuhedral clinopyroxene (11.6%), Fe-Ti oxides (6.2%) and glass (0.8%).

Sample number: Mc40b

Location: E 1/4, Sec 27, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: collected from the small isolated Thyb outcrop on the W border of the Tsh dome complex.

Rock name: Vesicular, pyroxene olivine basalt

Description: Porphyritic, vesicular and hypocrystalline with commonly pitted and embayed phenocrysts of an-subhedral, iddingsitized olivine up to 1 mm (6.3%) and sub-euhedral, oscillatory plagioclase up to 1 mm (3.3%).

Quartz xenocrysts are up to 5 mm and rimmed with glass and fine-grained

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clinopyroxene (2.6%). The vesicular (9.3%), brownish black-colored groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (58.3%), an-subhedral clinopyroxene (7.3%), an-subhedral, iddingsitized olivine (7.3%), Fe-Ti oxides (2.0%) and glass.

Sample number: Mc42

Location: SW 1/4, Sec 26, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: collected from the small isolated Thvb outcrop on the NE side of major drainage on the SW Tsh dome complex border.

Rock name: Vesicular, olivine pyroxene basalt

Description: Vesicular, porphyritic and holocrystalline with commonly pitted and embayed phenocrysts of an-euhedral, mildly iddingsitized olivine up to 2 mm (5.6%), an-subhedral, up to 1 mm, commonly glomerocrystic clinopyroxene (4.0%) and sub-euhedral, oscillatory plagioclase up to 1 mm (1.0%). Quartz xenocrysts are up to 5 mm and rimmed with glass (< 1%). The vesicular (3.6%), black-colored groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (62%), an-subhedral clinopyroxene (11.6%), an-euhedral, iddingsitized olivine (5.3%) and Fe-Ti oxides (6.6%).

Sample number: Mc43

Location: NW 1/4, Sec 34, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: collected from the east side of the N-S trending Thyb ridge in the southcentral part of the mapped area.

Rock name: Vesicular, olivine pyroxene basalt

Description: Vesicular, porphyritic and hypocrystalline with commonly pitted and embayed phenocrysts of an-subhedral, up to 1 mm, commonly glomerocrystic clinopyroxene (10.0%), an-subhedral, iddingsitized, up to 1 mm, commonly glomerocrystic olivine (6%) and sub-euhedral, oscillatory plagioclase up to 1 mm (1.0%). The vesicular (3.4%) grayish black-colored groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (58.9%), an-subhedral clinopyroxene (8.8%), an-subhedral, iddingsitized olivine (5.4%), Fe-Ti oxides (3.6%) and glass (3.0%). Vesicles are commonly coated with calcite.

Sample number: Mc47

Location: E 1/4, Sec 30, T23S, R61E, Sloan, Nev. 7 1/2' quad: collected from the isolated Thvb outlier just west of the Pzcu outcrop in the NW portion of the mapped area.

Rock name: Vesicular, olivine pyroxene basalt

Description: Porphyritic, vesicular and holocrystalline with commonly pitted and embayed phenocrysts of an-subhedral, up to 1 mm, commonly glomerocrystic clinopyroxene (10.8%), subhedral, oxidized phlogopite up to 2 mm (3.6%), anhedral, up to 1 mm, commonly glomerocrystic plagioclase up to 1 mm, (0.4%) and an-subhedral, iddingsitized olivine up to 1 mm (0.4%). The vesicular (8.2%), dark gray-colored groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (50.2%), Fe-Ti oxides (10.4%), an-subhedral clinopyroxene (7.4%), granular hematite (probably replaced phlogopite, 6.4%) and subhedral, iddingsitized olivine (2.2%). Vesicles are commonly coated or filled with calcite and/or quartz.

Sample number: Mc48

Location: SE 1/4, Sec 30, T23S, R61E, Sloan, Nev. 7 1/2' quad: collected from the northern part of the Thyb exposure in the NW part of the mapped area.

Rock name: Vesicular, olivine pyroxene basalt

Description: Porphyritic, vesicular and holocrystalline with commonly pitted and embayed phenocrysts of subhedral, oxidized phlogopite up to 2 mm (4.8%), subhedral, up to 1.5 mm, commonly glomerocrystic with olivine, clinopyroxene (4.6%) and subhedral, up to 1 mm, commonly glomerocrystic with clinopyroxene, olivine (1.2%). The vesicular (10.4%), brownish blackcolored groundmass consists of microlites of subhedral, oscillatory plagioclase (58.6%), subhedral clinopyroxene (7.2%), Fe-Ti oxides (7.2%) and an-euhedral, iddingsitized olivine (6.0%). Vesicles are commonly coated with calcite.

Sample number: Mc87.

Location: SE 1/4, Sec 28, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: collected on the west side of the N-S trending Thvb ridge in the S-central part of the mapped area.

Rock name: Pyroxene olivine basalt

Description: Aphanitic, trachytic and hypocrystalline with pitted, embayed, oscillatory, fritted sub-euhedral plagioclase phenocrysts up to 1 mm (0.8%). The brownish black-colored groundmass consists of sub-parallel microlites of sub-euhedral, oscillatory plagioclase (72.4%), an-subhedral, iddingsitized olivine (17.4%), an-subhedral clinopyroxene (8.0%), Fe-Ti oxides (0.4%) and glass (1.0%).

Sample number: Mc108

Location: Collected from the basaltic dike in the Thvb on the eastern escarpment of the McCullough's, approximately 3,000' S-SE of peak 3912.

Rock name: Vesicular, olivine pyroxene basaltic dike

Description: Vesicular, porphyritic and holocrystalline consisting of phenocrysts of subhedral, oscillatory plagioclase up to 3 mm (13.2%), subhedral, embayed clinopyroxene up to 1 mm (1.6%), an-subhedral, iddingsitized olivine up to 1 mm (1.4%) and Fe-Ti oxides up to 0.5 mm (0.5%). The vesicular (18.2%), medium dark gray-colored groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (16.8%), subhedral clinopyroxene 1

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(3.8%), an-subhedral, iddingsitized olivine (1.4%), granular hematite (0.2%) and Fe-Ti oxides (0.3%).

Sample number: W-hvb

Location: NW 1/4, Sec 36, T23S, R60E, Sloan, Nev. 7 1/2' quad: collected from the northernmost Thyb exposure associated with Tbs on the west side of I-15.

Rock name: Weakly vesicular, olivine pyroxene basalt

Description: Weakly vesicular, porphyritic and hypocrystalline consisting of commonly pitted and embayed phenocrysts of an-subhedral, oscillatory plagioclase up to 5 mm (18.4%), an-subhedral, iddingsitized olivine up to 5 mm (11.4%), an-subhedral clinopyroxene up to 5 mm (9.6%) and Fe-Ti oxides up to 0.5 mm (0.5%). Approximately 10% of the clinopyroxene, olivine and plagioclase phenocrysts occur in glomerocrysts with each other. The weakly vesicular (1.6%), black-colored groundmass consists of microlites of sub-euhedral, oscillatory plagioclase (30.2%), an-subhedral clinopyroxene (5.6%), an-subhedral, iddingsitized olivine (1.4%), Fe-Ti oxides (0.5%) and devitrified glass (20.8%). Vesicles are coated with calcite.

MT. HANNA ANDESITE

Sample number: Mc31b

Location: SE 1/4, Sec 14, T24S, R61E, Sloan SE, Nev. 7 1/2' quad: collected at the southernmost Tss/Tsh contact.

Rock name: Andesite

Description: Fine-grained, trachytic and hypocrystalline consisting of sub-parallel, sub-euhedral plagioclase laths (< 0.5 mm) with subordinate interstitial devitrified glass, Fe-Ti oxides and cryptocrystalline, high birefringent minerals. Trace, subhedral, pitted, embayed, zoned and oscillatory plagioclase phenocrsyts (up to 1 mm) occur. The groundmass is very dusky red with moderate red-colored streaks.

Sample number: Mc110

Location: T24S, R62E, Sloan SE, Nev. 7 1/2' quad: collected on peak 3912 near the Tsh/Thvb contact on the eastern escarpment of the McCullough's. Rock name: Andesite

Description: Fine-grained, trachytic and hypocrystalline consisting of sub-parallel, sub-euhedral plagioclase laths (<0.5 mm) with subordinate interstitial devitrified glass and Fe-Ti oxides. Trace, subhedral, pitted, embayed, zoned and oscillatory plagioclase phenocrysts up to 1 mm occur. The slide also contains a subhedral, oxidized, 3 mm biotite phenocryst. The weakly vesicular (< 1.0%) groundmass is black. 損

Sample number: Mc112

Location: 800' east, 2400' north of the SE corner of Sec 12, T24S, R61E, Sloan SE, Nev. 7 1/2' quad: collected near entrance to the major drainage in the northern part of the Tsh dome complex.

Rock name: Andesite

Description: Fine-grained, trachytic and hypocrystalline consisting of sub-parallel, sub-euhedral plagioclase laths (< 0.5 mm) with subordinate interstitial devitrified glass and Fe-Ti oxides. Trace, subhedral, pitted, embayed, zoned and oscillatory plagioclase phenocrysts up to 1 mm occur. The weakly vesicular (< 1%), groundmass is dark gray with medium light graycolored streaks.

Sample number: Mc115

Location: NW 1/4, Sec 36, T24S, R61E, Sloan SE, Nev. 7 1/2' quad: collected on the ridge just to the SE of the major Tsh vent area.

Rock name: Andesite

Description: Fine-grained, massive and hypocrystalline consisting of sub-euhedral plagioclase laths (< 0.5 mm) with subordinate interstitial partially devitrified glass, granular hematite and Fe-Ti oxides. The slide contains two pitted, embayed, sub-euhedral plagioclase xenocrysts (1.5 mm). The groundmass is black with grayish red-colored streaks.

CINDER PROSPECT MEMBER

Sample number: Mc25

Location: SW 1/4, Sec 5, T24S, R61E, Sloan, Nev. 7 1/2' quad: dacite underlying Tsi on south-facing hillside one mile east of the Mt. Ian vent.

Rock name: Dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 2% of the rock and consist of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 2 mm and subordinate subeuhedral, oxidized biotite up to 2 mm. Individual phenocrysts form approximately 2% of the rock and consist of the same minerals found in the glomerocrysts. The medium gray-colored groundmass consists of microlites of plagioclase with trace biotite, Fe-Ti oxides, zircon and glass. Approximately 40% of the groundmass has been replaced by calcite.

Sample number: Mc78

Location: SE 1/4, Sec 6, T24S, R61E, Sloan, Nev. 7 1/2' quad: vitrophyre on the ridge approximately 1,750' SE of the Mt. Ian Tsi vent center

Rock name: Dacite vitrophyre

Description: Porphyritic and hypohyaline with commonly fragmented, pitted and embayed phenocrysts of sub-euhedral, oscillatory and seriate up to 2 mm plagioclase (12.0%), sub-euhedral, oxidized and seriate up to 2 mm biotite
(3.8%), sub-euhedral, oscillatory and seriate up to 2 mm sanidine (3.4%), Fe-Ti oxides seriate up to 0.5 mm (0.4) and trace zircon. Basaltic, gabbroic and granodioritic rock fragments (5.6%) are up to 1 cm. The mottled dark reddish brown and black-colored groundmass (74.6) consists of devitrified glass and glass shards.

Sample number: Mc79

Location: NE 1/4, Sec 6, T24S, R61E, Sloan, Nev. 7 1/2' quad: glassy, resistant vitrophyre that crops out in the NE part of Tscp.

Rock name: Rhyolite vitrophyre

Description: Porphyritic and hypohyaline with commonly fragmented, pitted and embayed phenocrysts of subhedral, oscillatory and seriate up to 1 mm plagioclase (17.4%), subhedral, oscillatory and seriate up to 1 mm sanidine (3.8%), sub-euhedral, oxidized and seriate up to 2 mm biotite (3.6%), Fe-Ti oxides seriate up to 0.5 mm (1.2%), trace sub-euhedral clinopyroxene up to 0.5 mm and trace zircon. Trace basaltic rock fragments are up to 1 mm. The mottled dark reddish brown and black-colored groundmass (74.0%) consists of devitrified glass and glass shards with trace granular hematite.

Sample number: Mc121

Location: SW 1/4, Sec 31, T23S, R61E, Sloan, Nev. 7 1/2' quad: dacite that lies stratigraphically immediately below Tts.

Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 4% of the rock and consist of commonly pitted and embayed phenocrysts of zoned, oscillatory, subhedral plagioclase up to 2 mm with subordinate subhedral hematized biotite up to 2 mm. Individual phenocrysts form approximately 6% of the rock and consist of the same minerals found in the glomerocrysts and trace Fe-Ti oxides up to 0.5 mm. The light brownnish gray-colored groundmass consists of microlites of plagioclase with trace hematized biotite, Fe-Ti oxides and glass. Approximately 1% of the groundmass has been replaced by calcite.

Sample number: Mc125

Location: S 1/4, Sec 31, T23S, R61E, Sloan, Nev. 7 1/2' quad: dacite from the Cinder Prospect Member, below the Sloan Tuff.

Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 6% of the rock and consist of commonly pitted and embayed phenocrysts of zoned, oscillatory, subhedral plagioclase up to 3 mm with subordinate Fe-Ti oxides up to 0.5 mm and subhedral biotite up to 3 mm that ranges from unaltered to totally replaced by red and black Fe oxides. Individual phenocrysts form approximately 5% of the rock and consist of the same minerals found in the glomerocrysts. The medium light gray-colored groundmass consists of

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microlites of plagioclase with subordinate oxidized biotite, trace zircon and glass. Approximately 5% of the groundmass has been replaced by calcite.

TUFF OF THE SLOAN VOLCANICS

Sample number: Mc59a

Location: SW 1/4, Sec 31, T24S, R61E, Sloan, Nev. quad: collected from the bottom cooling unit in the drainage at station 59 in the Tsc dome complex. Rock name: Welded rhyolitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral sanidine up to 3 mm (21.2%), subhedral, zoned and oscillatory plagioclase up to 2 mm (4.8%), sub-euhedral, oxidized biotite up to 1.5 mm (0.4%), Fe-Ti oxides up to 0.5 mm (< 1%), subeuhedral sphene (< 0.5 mm, 0.2%) and trace amounts of clinopyroxene, monazite, epidote, allanite, and zircon (each < 0.5 mm). Pumice fiamme (9%) are up to several cm long, devitrified and rarely spherulitic. Basaltic and gabbroic rock fragments (3.8%) are up to 1 cm. The grayish redcolored groundmass (60.6%) consists of devitrified glass shards that wrap around phenocrysts and lithic fragments.

Sample number: Mc59b

Location: SW 1/4, Sec 31, T24S, R61E, Sloan, Nev. quad: collected from the middle cooling unit in the drainage at station 59 in the Tsc dome complex. Rock name: Non-welded dacitic ash-flow tuff

Description: Pyroclastic and hypocrystalline consisting of fragmented phenocrysts of an-subhedral, oscillatory sanidine up to 2.5 mm (4.8%), subhedral, oscillatory plagioclase up to 1.5 mm (2.0%), subhedral, oxidized biotite up to 1 mm (0.8%), an-subhedral clinopyroxene up to 0.5 mm (0.2%), subeuhedral sphene up to 0.5 mm (0.2%), Fe-Ti oxides up to 0.5 mm (< 1%) and trace zircon. Spongy, devitrified, rarely spherulitic pumice (2.2%) is up to 1 cm. Basaltic and gabbroic rock fragments (13.2%) are up to 1 cm. The very light gray- colored groundmass (76.4%) consists of devitrified, axiolitic glass shards that wrap around phenocrysts and lithic fragments.

Sample number: Mc59c

Location: SW 1/4, Sec 31, T24S, R61E, Sloan, Nev. quad: collected from the top cooling unit in the drainage at station 59 in the Tsc dome complex. Rock name: Welded dacitic ash-flow tuff

Description: Pyroclastic, eutaxitic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 4 mm (8.6%), subhedral, oscillatory plagioclase up to 1 mm (2.4%), Fe-Ti oxides up to 0.5 mm (1.4%), anhedral quartz < 0.5 mm (0.4%), an-subhedral clinopyroxene up to 0.5 (1.4%), subhedral, oxidized biotite up to 2 mm (0.4%) and trace zircon. Pumice fiamme (11.6%) are up to several cm ų.

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long. Basaltic and gabbroic rock fragments (21.2%) are up to 2 cm. The pale red-colored groundmass (52.6%) consists of blocky shaped, slightly devitrified glass shards.

Sample number: Mc73

Location: NW 1/4, Sec 6, T24S, R61E, Sloan, Nev. 7 1/2' quad: collected in drainage just west of the Sta. 59 tuffs.

Rock name: Non-welded rhyolitic ash-flow tuff

Description: Pyroclastic and hypocrystalline consisting of fragmented phenocrysts of subhedral, oscillatory sanidine up to 3 mm (10.0%), anhedral quartz up to 1 mm (1.8%), an-subhedral, oscillatory plagioclase up to 3 mm (3.4%), subhedral, oxidized biotite up to 1 mm (0.6%), Fe-Ti oxides up to 0.5 mm (0.2%), trace, an-subhedral, hematized clinopyroxene up to 0.5 mm and trace amounts of sphene and zircon (sub-euhedral, < 0.5 mm). Spongy, devitrified pumice (1.6%) is up to 1 cm. Basaltic, gabbroic and granodioritic rock fragments (4.6%) are up to 1 cm. The grayish pinkcolored groundmass (77.8%) consists of devitrified, weakly axiolitic glass shards, interstitial glass and < 1% yellow Fe oxides.

CENTER MTN. DACITE

Sample number: Mc59d

Location: N 1/2, Sec 6, T23S, R61E, Sloan, Nev. 7 1/2' quad: dacite that lies stratigraphically immediately above Tts.

Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 3% of the rock and consist of commonly pitted and embayed phenocrysts of subhedral plagioclase up to 2 mm with subordinate Fe-Ti oxides and sub-euhedral, oxidized biotite up to 2 mm. Phenocrysts form approximately 3% of the rock and consist of the same minerals found in the glomerocrysts. The medium light gray-colored groundmass consists of microlites of plagioclase with subordinate hematized biotite, Fe-Ti oxides and glass. Approximately 5% of the groundmass has been replaced by calcite.

Sample number: Mc130

Location: SW 1/4, Sec 31, T23S, R60E, Sloan, Nev. 7 1/2' quad: dacite overlying Tscp in the NW section of the Center Mtn. dome complex.

Rock name: Biotite dacite

Description: Holocrystalline, and porphyritic with phenocrysts of sub-euhedral, zoned and oscillatory plagioclase up to 2 mm (4.4%), sub-euhedral, oxidized biotite up to 5 mm (1.2%) and sub-euhedral Fe-Ti oxides < 0.5 mm (0.4%). The medium gray-colored groundmass consists of microlites of plagioclase with subordinate oxidized biotite, Fe-Ti oxides and pyroxene(?), and secondary calcite (5%).

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Sample number: Mc131

Location: SW 1/4, Sec 6, T24S, R61E, Sloan, Nev. 7 1/2' quad: dacite overlying Tscp in the southern part of the Center Mtn. dome complex.

Rock name: Biotite dacite

Description: Holocrystalline, porphyritic and trachytic with sub-parallel phenocrysts of sub-euhedral, zoned and oscillatory plagioclase up to 2 mm (7.2%), sub-euhedral, oxidized biotite up to 3 mm (1.6%) and sub-euhedral Fe-Ti oxides < 0.5 mm (0.4%). The medium light gray-colored groundmass consists of microlites of plagioclase with subordinate oxidized biotite, Fe-Ti oxides and pyroxene(?), and secondary calcite (1.2%).

MT. IAN ANDESITE

Sample number: Mc93

Location: SW 1/4, Sec 5, T24S, R61E, Sloan, Nev. 7 1/2' quad: andesite that overlies dacite on the hill 1 mile east of Mt. Ian: stratigraphically above Mc25 biotite dacite.

Rock name: Andesite

Description: Fine-grained and hypocrystalline consisting of commonly pitted and embayed phenocrysts of sub-euhedral, zoned and oscillatory plagioclase up to 1 mm (5.2%), subhedral iddingsitized olivine up to 0.5 mm (0.4%), subeuhedral, commonly oxidized subhedral biotite up to 1 mm (0.4%), Fe-Ti oxides up to 1 mm and trace subhedral orthopyroxene up to 0.5 mm. The orthopyroxene commonly occurs in glomerocrysts with plagioclase and Fe-Ti oxides. The medium dark gray- colored, weakly vesicular groundmass consists of microlites of plagioclase with trace biotite, olivine, Fe-Ti oxides and glass. Vesicles are coated with calcite.

Sample number: Mc94

Location: N 1/4, Sec 5, T24S, R61E, Sloan, Nev. 7 1/2' quad: from the hilltop 1 mile east of the Tuff of the Sloan Volcanics at station 59.

Rock name: Andesite

Description: Vesicular, fine-grained and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 0.5 mm (2.4%), Fe-Ti oxides up to 0.25 mm (4%), subhedral, iddingsitized olivine up to 0.5 mm (0.4%) and trace subhedral oxidized biotite up to 0.5 mm. The vesicular (9.6%), grayish red-colored groundmass consists of microlites of plagioclase (72.8%), iddingsitized olivine (3.0%) and glass (0.6%). 7.0% of the groundmass has been replaced by hematite. Vesicles are coated with calcite.

Sample number: Mc95a

Location: NE 1/4, Sec 5, T24S, R61E, Sloan, Nev. 7 1/2' quad: massive andesite from hill 3346 just west of the major drainage separating Tsi from Tss.

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Rock name: Andesite

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Description: Fine-grained and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 1 mm (5.6%), an-subhedral chloritized(?) and oxidized biotite up to 1 mm (10.4%) and subhedral orthopyroxene up to 0.5 mm (trace) that commonly occurs in glomerocrysts with plagioclase and Fe-Ti oxides. The blackcolored groundmass consists of microlites of plagioclase (74.0%), clinopyroxene (0.2%), iddingsitized olivine (0.6%), Fe-Ti oxides (4.6%), zircon (trace) and devitrified glass (4.6%).

Sample number: Mc95b

Location: NE 1/4, Sec 5, T24S, R61E, Sloan, Nev. 7 1/2' quad: platy andesite from hill 3346 just west of the major drainage separating Tsi from Tss: lies stratigraphically below the more massive Mc95a andesite.

Rock name: Andesite

Description: Fine-grained and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 1 mm (4.0%), sub-euhedral oxidized biotite up to 2 mm (0.4%), Fe-Ti oxides up to 0.5 mm (0.2%) and subhedral orthopyroxene up to 0.5 mm (trace) that commonly occurs in glomerocrysts with plagioclase and Fe-Ti oxides. The dusky brown-colored, weakly vesicular (0.4%) groundmass consists of microlites of plagioclase (68.4%), iddingsitized olivine (3.0%), Fe-Ti oxides (4.0%), biotite (trace) and devitrified glass (19.8%). The slide contains a granodiorite xenolith 1.5 mm by 1 mm. Vesicles are coated with calcite.

Sample number: Mc97

Location: NW 1/4, Sec 4, T23S, R61E, Sloan, Nev. 7 1/2' quad: collected from the Tsi ridge-top in the NW part of the northern Tss dacite dome complex. Rock name: Andesite

Description: Fine-grained, weakly vesicular and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 1 mm (4.4%), an-subhedral, iddingsitized olivine up to 0.5 mm (2.0%), subhedral, oxidized biotite up to 0.5 mm (trace), Fe-Ti oxides up to 0.5 mm (2.0%) and subhedral orthopyroxene up to 0.5 mm (0.2%) that commonly occurs in glomerocrysts with Fe-Ti oxides. The black-colored, weakly vesicular (1.8%) groundmass consists of microlites of plagioclase (57.0), iddingsitized olivine (2.2%), clinopyroxene (0.2%), Fe-Ti oxides (0.6%) and devitrified glass (29.4%).

Sample number: Mc98

Location: SE 1/4, Sec 6, T24S, R61E, Sloan, Nev. 7 1/2' quad: collected from the Tsi dome in the SE part of the Tsc dome complex.

Rock name: Andesite

Description: Fine-grained, weakly vesicular and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 0.5 mm (4.6%), an-subhedral, iddingsitized olivine up to 0.5 mm (0.5%), Fe-Ti oxides up to 0.5 mm (2.0%) and sub-euhedral, oxidized biotite up to 0.5 mm (trace). The medium dark gray-colored, weakly vesicular (0.8%) groundmass consists of microlites of plagioclase (79.0%), iddingsitized olivine (4.1%), Fe-Ti oxides (3.4%) and devitrified glass (1.8%). Sericite (3.8%) is replacing plagioclase. The vesicles are coated with calcite.

Sample number: Mc120a

Location: S 1/4, Sec 6, T24S, R61E, Sloan, Nev. 7 1/2' quad: andesite collected from the Mt. Ian vent.

Rock name: Andesite

Description: Fine-grained and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral, seriate plagioclase up to 1 mm (31.8%), sub-euhedral orthopyroxene up to 0.5 mm (1.2%), Fe-Ti oxides up to 0.5 mm (1.5%) and subhedral, oxidized biotite up to 0.5 mm (0.2%). The grayish black-colored groundmass consists of microlites of plagioclase (50%), orthopyroxene (trace), biotite (0.6%), Fe-Ti oxides (2.1%) and devitrified glass (9.8%). Veins of fine to medium-grained quartz forms 2% of the rock.

Sample number: Mc129

Location: NE 1/4, Sec 4, T24S, R61E, Sloan, Nev. 7 1/2' quad: andesite that underlies Tss on the east side of drainage in the NW part of the northern Tss dome complex.

Rock name: Andesite

Description: Fine-grained, weakly vesicular and hypocrystalline consisting of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral, seriate plagioclase up to 2 mm (30.8%), sub-euhedral, iddingsitized olivine up to 0.5 mm (0.2%), Fe-Ti oxides up to 0.5 mm (0.2%) and sub-euhedral orthopyroxene up to 0.5 mm (trace). The weakly vesicular (1.0%), dark gray-colored groundmass consists of microlites of plagioclase (49%), iddingsitized olivine (0.6%) and Fe-Ti oxides (0.8%). Vesicles are coated with calcite.

MT. SUTOR DACITE

Sample number: Mc9

Location: E 1/2, Sec 26, T24S, R60E, Hidden Valley, Nev. 7 1/2' quad: at the Tss/Thvb contact near the western entrance road to Hidden Valley. Rock name: Biotite dacite Description: Glomeroporphyritic: glomerocrysts form approximately 10% of the

rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 3 mm with subordinate sub-euhedral biotite up to 3 mm and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 2% of the rock and consist of the same minerals found in the glomerocrysts, but many are not pitted and embayed. The medium gray-colored groundmass consists of microlites of plagioclase with trace biotite and Fe-Ti oxides, devitrified glass, and < 1% vesicles. Vesicles and fractures are coated with secondary calcite.

Sample number: Mc16

Location: SW 1/4, Sec 14, T24S, R60E, Hidden Valley, Nev. 7 1/2' quad: near the Tss/Pzcu contact on the western margin of the southern dacite dome complex.

Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 7% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 3 mm with subordinate an-subhedral orthopyroxene up to 1 mm and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 5% of the rock and consist of the same minerals found in the glomerocrysts, plus an-subhedral pitted and embayed, oxidized biotite (1.4%). Many of the individual phenocrysts do not show the disequilibrium textures displayed in the glomerocrysts. The mottled medium gray and medium dark gray-colored groundmass consists of microlites of plagioclase with trace biotite, orthopyroxene and glass.

Sample number: Mc19

Location: NE 1/4, Sec 13, T24S, R60E, Hidden Valley, Nev. 7 1/2' quad: from the NW portion of the southern dacite dome complex.

Rock name: Vesicular biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 2% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 2 mm with subordinate subhedral orthopyroxene up to 1 mm, subhedral biotite < 0.5 mm and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form 9.8% of the rock and consist of the same minerals found in the glomerocrysts, plus sub-euhedral, pitted and embayed, oxidized biotite (2.2%) up to 1 mm. The vesicular (11.8%) black-colored groundmass consists of microlites of plagioclase with trace biotite, Fe-Ti oxides, iddingsitized olivine, and glass. Vesicles and fractures are coated with secondary calcite.

Sample number: Mc21

Location: N 1/2, Sec 20, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: isolated outlier near the eastern margin of the southern dacite dome complex.

Rock name: Vesicular biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 15% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 3 mm with subordinate subhedral biotite up to 3 mm and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 3.5% of the rock and consist of the same minerals found in the glomerocrysts. The vesicular (3.8%) dark gray-colored groundmass consists of microlites of plagioclase with trace biotite, clinopyroxene, olivine and glass.

Sample number: Mc 27

Location: SW 1/4, Sec 10, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: on NW side of the entrance to the major drainage near the hypabyssal phase Tss. Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts for approximately 18% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 4 mm, with subordinate Fe-Ti oxides up to 0.5 mm, sub-euhedral biotite up to 4 mm, and subhedral clinopyroxene up to 2 mm that is commonly rimmed with black Fe oxides. Individual phenocrysts form approximately 4.5% of the rock and consist of the same minerals found in the glomerocrysts, plus < 1% anhedral hornblende up to 0.5 mm that is rimmed with black Fe oxides. The dark gray- colored weakly vesicular (1.2%) groundmass consists of microlites of plagioclase with trace biotite and glass. Vesicles are coated with secondary calcite.

Sample number: Mc28

Location: N 1/4, Sec 10, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: isolated outlier in the mouth of the major drainage near hypabyssal phase Tss. Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts for approximately 10% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 2 mm, and subordinate subhedral clinopyroxene up to 1 mm and oxidized biotite up to 3 mm. Individual phenocrysts form approximately 2% of the rock and consist of the same minerals found in the glomerocrysts. The medium gray-colored groundmass consists of microlites of plagioclase with trace Fe-Ti oxides and glass. Calcite has replaced approximately 5% of the groundmass.

Sample number: Mc31a Location: SE 1/4, Sec 14, T24S, R61E, Sloan SE, Nev. 7 1/2' quad: at the southernmost Tss/Tsh contact. Rock name: Biotite dacite Description: Glomeroporphyritic: glomerocrysts form approximately 7% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 2 mm, and subordinate subhedral, oxidized biotite up to 3 mm, an-subhedral clinopyroxene up to 1 mm, Fe-Ti oxides up to 0.5 mm and trace anhedral orthopyroxene up to 0.5 mm. Individual phenocrysts form approximately 5% of the rock and consist of the same minerals found in the glomerocrysts. The dark gray-colored groundmass consists of microlites of plagioclase with trace biotite and Fe-Ti oxides and glass. Fractures are rarely coated with calcite.

Sample number: Mc91a

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Location: NW 1/4, Sec 19, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: dacite vent center in the east-central part of the southern dacite dome complex. Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 5% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, subhedral plagioclase up to 3 mm and subordinate subeuhedral hematized biotite up to 4 mm, and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 1.6% of the rock and consist of the same minerals found in the glomerocrysts. The dark greenish graycolored groundmass consists of microlites of plagioclase with trace zircon and glass.

Sample number: Mc92

Location: NW 1/4, Sec 19, T24S, R61E, Hidden Valley, Nev. 7 1/2' quad: on hilltop 3957 just NW of the vent area at station 91.

Rock name: Vesicular biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 5.5% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase and subordinate sub-euhedral, oxidized biotite up to 2 mm, subhedral orthopyroxene up to 1 mm, and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 5.5% of the rock and consist of the same minerals found in the glomerocrysts. Biotite is rare in glomerocrysts and more abundant as individual phenocrysts. The slide contains < 1% granodiorite (?) xenoliths up to 1 cm. The vesicular (3%) medium dark gray-colored groundmass consists of microlites of plagioclase with trace biotite, orthopyroxene, Fe-Ti oxides and glass. Vesicles are coated with secondary calcite.

Sample number: Mc96

Location: W 1/2, Sec 4, T24S, R61E, Sloan, Nev. 7 1/2' quad: collected on the west-facing slope of hill 3490 in the northern Tss dome complex. Rock name: Biotite dacite Description: Glomeroporphyritic: glomerocrysts form approximately 7.5% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 3 mm and subordinate sub-euhedral, oxidized biotite up to 3 mm, rare an-subhedral clinopyroxene up to 0.5 mm, and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 5.5% of the rock and consist of the same minerals found in the glomerocrysts. There is, however, a higher percentage of individual clinopyroxene phenocrysts (an-subhedral, up to 2 mm). The slide contains a 2 mm by 0.5 mm xenocryst of fine-to medium-grained clinopyroxene and orthopyroxene with interstitial glass. The weakly vesicular (1%) dark gray-colored groundmass consists of microlites of plagioclase with trace biotite and glass.

Sample number: Mc100

Location: SW 1/4, Sec 17, T24S, R61E, Hidden Valley, Nev. 7 1/2 quad: from hilltop 3650 in the NE part of the southern dacite dome complex. Rock name: Biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 11% of the rock and are composed of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 2 mm and subordinate an-subhedral, oxidized biotite up to 2 mm, an-subhedral clinopyroxene up to 5 mm and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 4% of the rock and consist of the same minerals found in the glomerocrysts. The weakly vesicular (< 1%) brownish gray-colored groundmass consists of microlites of plagioclase with trace Fe-Ti oxides and glass. Vesicles are coated with secondary calcite.

Sample number: Mc118

Location: E 1/2, Sec 3, T24S, R61E, Sloan NE, Nev. 7 1/2' quad: hypabyssal dacite near the NW Tss hypabyssal/volcanic contact.

Rock name: Hypabyssal biotite dacite

Description: Holocrystalline, glomeroporphyritic: glomerocrysts form approximately 13% of the rock and consist of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 3 mm, subordinate subhedral, oxidized biotite up to 3 mm, and < 1% subhedral clinopyroxene up to 1.5 mm that is rimmed with fine-grained black Fe oxides. Individual phenocrysts form approximately 6% of the rock and consist of the same minerals found in the glomerocrysts. The medium gray-colored, fine-grained groundmass consists of plagioclase (80%, subhedral, < 0.5 mm), biotite (3.8%, subhedral, < 0.5 mm), and trace Fe-Ti oxides (< 0.5 mm). 1

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Sample number: Mc119

Location: NW 1/4, Sec 11, T24S, R61E, Sloan NE, Nev. 7 1/2' quad: Hypabyssal dacite near the SE Tss hypabyssal/volcanic contact.

Rock name: Hypabyssal biotite dacite

Description: Holocrystalline, glomeroporphyritic: glomerocrysts form approximately 12% of the rock and consist of commonly pitted and embayed phenocrysts of zoned, oscillatory, sub-euhedral plagioclase up to 3 mm, subordinate, oxidized biotite up to 2 mm, and < 1% subhedral clinopyroxene that is rimmed by fine-grained black Fe oxides. Individual phenocrysts form approximately 3% of the rock and consist of the same minerals found in the glomerocrysts. The medium gray- colored, finegrained: groundmass consists of plagioclase (80.4%, subhedral, < 0.5 mm), biotite (0.6%, subhedral, < 0.5 mm), and trace Fe-Ti oxides (< 0.5 mm). < 1% of the groundmass has been replaced by calcite.

Sample number: Mc128

Location: SE 1/4, Sec 24, T24S, R60E, Hidden Valley, Nev. 7 1/2' quad: from the central part of the southern dacite dome complex.Rock name: Vesicular biotite dacite

Description: Glomeroporphyritic: glomerocrysts form approximately 3% of the rock and consist of commonly pitted and embayed phenocrysts of zoned, oscillatory sub-euhedral plagioclase up to 5 mm and subordinate subeuhedral, oxidized biotite up to 4 mm, and Fe-Ti oxides up to 0.5 mm. Individual phenocrysts form approximately 3% of the rock and consist of the same minerals found in the glomerocrysts. The brownish gray-colored vesicular (3.6%) groundmass consists of plagioclase microlites and trace glass.

ALKALI BASALT

Sample number: Mc124

Location: SE 1/4, Sec 13, T23S, R60E, Sloan, Nev. 7 1/2' quad: alkali basalt exposure at the Sloan Limestone quarry.

Rock name: Weakly vesicular alkali basalt

Description: Trachytic, holocrystalline and aphanitic with ultramafic nodules and Precambrian crust xenoliths up to several cm (< 1%). The weakly vesicular (0.2%), black-colored groundmass consists of sub-parallel microlites of sub-euhedral, oscillatory plagioclase (56%), subhedral clinopyroxene (21.2%), an-subhedral, iddingsitized olivine (20.4%) and Fe-Ti oxides (2.2%). APPENDIX B: CHEMISTRY TABLES

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	Tuff of Bri	dge Sprin	3					
Sample No.	<u>ET-1</u>	<u>YT</u>	92	<u> </u>	<u> </u>	<u>V</u>	M63	M105
SiO2	72.59	70.03	69.01	68.51	67.73	66.65	66.81	66.10
AL203	14.29	13.43	14.69	14.52	15.44	14.41	15.06	16.10
Fc2O3	1.78	1.88	2.17	1.97	2.83	2.04	2.52	2.50
CaO	1.38	1.15	1.43	1.90	1.65	2.31	1.6	1.70
MgO	0.35	0.46	0.48	0.30	0.44	0.32	0.71	1.30
Na2O	4.19	3.47	4.20	3.94	4.46	4.22	4.33	4.70
K20	5.29	4.82	5.12	5.71	4.93	4.97	5.92	6.30
TiO2	0.34	0.35	0.41	0.40	0.53	0.39	0.43	0.40
MnO	0.07	0.08	0.06	0.05	0.06	0.07	0.09	0.10
P2O5	0.06	0.06	0.14	0.09	0.16	0.12	0.02	0.20
LOI	0.98	4.77	0.93	1.72	1.22	2.03	2.57	0.40
TOTAL	101.32	100.50	98.64	9 9.11	99.45	97.53	100.06	99.80
Trace elements		يري التي المحمد والمحمد و						
in ppm			••					
La							121.0	104.0
Ce =							191.0	155.0
Nd								70.0
Sm							11.0	10.0
Eu							1.7	1.9
Ъ							0.8	0.9
УЪ							3.1	1.2
Lu							0.5	0.3
U	8.5	12.0	8.2	7.3	5.2	5.9		
Th							32.2	25.0
ଦ	21.4	17.9			21.8	18.3		
HL							11.1	10.0
Ba							910	1332
Rb	248.0	480.0	217.0	217.0	159.0	179.0	157.0	143.0
Sr	214	402	233	197	563	365	264	1015
Sc [
Ta í							2.3	· 1.84
64								
Zr	330.0	344.0	118.0	389.0	422.0	350.0		414.0
Y [66.2	51.0	58.0	41.0	42.0		J
NB I								
∞								
Ti l								
v l								1
Mg#	0.14	0.17	0.16	0.12	0.12	0.12	0.19	0.31

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	Tuff of Bri	dge Spring	g: continue	2d				
Sample No.	Mc53	Mc60	Mc61	Mc62	Mc64a	Mc64b	Mc65	Mc66
SiO2	64.65	63.90	66.47	67.27	65.09	66.69	69.54	66.69
AL203	15.66	14.77	14.92	13.95	13.72	13.72	14.40	14.48
Fe2O3	3.95	3.55	3.47	2.72	3.11	3.11	3.31	3.16
CaO	2.43	3.24	1.72	2.36	5.66	0.65	0.63	4.12
MgO	0.97	1.05	0.86	0.58	1.42	1.00	1.02	0.84
Na2O	4.33	4.09	4.33	3.97	3.35	3.86	3.94	3.74
K20	6.03	5.67	6.17	5.99	4.69	6.40	4.64	5.77
TiO2	0.53	0.45	0.47	0.35	0.42	0.42	0.45	0.43
MnO	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
P2O5	0.18	0.16	0.16	0.10	0.40	0.13	0.27	0.33
LOI	1.27	1.97	1.14	2.04	1.48	0.65	4.11	3.00
TOTAL	100.06	99.00	99.87	99.4 8	99.4 9	96.78	102.46	102.71
Trace elements								
in ppm								
La	118.0	93.2	91.5	92.1		96.3		
Ce	204.0	170.0	167.0	184.0		181.0		
Nd	73.4	64.0	75.2	55.3		67.3		
Sm	9.7	8.3	11.3	11.1		11.5		
Eu	1.8	1.7	1.3	1.0		1.1		
Тъ	0.9	0.9	1.4	1.1		1.1		
Үь ј	2.9	3.1	3.9	3.5		3.8		
Lu	0.4	0.4	0.5	0.6		0.6		
U	6.3	5.4	6.4	10.9		8.9		
Th	28.6	27.3	35.8	44.3		44.6		
ଦ	32.0	45.3	35.2	9.9		15.5		
Hf	10.3	10.1	9.8	10.6		11.1		[
Ba	818	927	390	170		296		
Rb	121.0	127.0	160.0	172.0		170.0		ļ
Sr	502	781				389		J
Sc	4.7	4.2	3.9	3.2		3.6		
Ta	1.7	1.9	2.4	2.7		2.7		
Cd				•.				[
	578.0	483.0	826.0	553.0		577.0		1
Y								
Nb		64.0						1
Co	4.2	3.7	3.4	2.0		2.8		l l
Π	2980	2790	2260	2430		2100		I
<u> </u>	39.7	35.3	44.6	23.3		29.5		
Mg#	0.17	0.2	0.18	0.15	0.28	0.19	0.21	0.22

130

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Tuff of Bridge Spring: continued						Hidden Valley volcanics				
Sample No.	Mc67	Mc68	Mc69	Mc71	65	66	68	125		
SiO2	68.12	65.46	68.40	69.27	46.94	50.18	52.05	51.61		
AL203	14.60	14.32	14.46	14.88	16.87	15.11	16.04	16.69		
Fe2O3	2.91	3.19	3.07	2.93	9.64	8.94	7.86	9.18		
CaO	1.69	3.43	1.61	0.65	11.01	9.97	8.80	8.90		
MgO	0.61	0.66	0.53	0.40	7.23	7.19	5.92	5.82		
Na2O	4.38	4.10	4.33	4.44	2.69	2.61	2.69	2.75		
K2O	5.94	5.82	5.85	6.15	1.38	1.72	3.01	1.79		
TiO2	0.39	0.42	0.40	0.41	1.54	1.35	1.31	1.73		
MnO	0.15	0.14	0.15	0.15	0.13	0.14	0.13	0.14		
P2O5	0.11	0.13	0.09	0.09	0.81	0.61	0.78	0.50		
loi	1.38	2.56	1.33	0.56	1.11	2.35	3.01	0.70		
TOTAL	100.29	100.23	100.22	99.93	99.35	100.17	101.60	99.81		
Trace elements										
in ppm										
La	94.5	91.7	93.4	101.0						
Ce	173.0	177.0	184.0	188.0						
Nd	79.8	63.7	57.0	80.9						
Sm	12.8	11.8	12.1	13.7						
Eu	1.1	1.2	1.2	1.2						
Ъ	1.2	1.2	1.3	1.3						
YЪ	3.6	3.4	3.6	· 3.8						
Lu	0.6	0.5	0.5	0.6						
ບ	8.7	7.2	8.5	8.4						
Th.	39.3	39.4	41.9	42.0						
ଦ	11.7	20.9	10.4	11.2						
Hf	10.0	10.1	11.0	11.3						
Ba		303		1				1		
Rb	155.0	165.0	179.0	173.0	22.3	22.0	65.2	29.7		
Sr	219	200	168	196	940	828	1170	622		
Sc	3.2	3.9	3.4	3.3						
Ta 🛛	2.4	2.4	2.6	2.8						
Ca l										
Zr 🛛	455.0	544.0	603.0	663.0	218.0	223.0	317.0	235.0		
Y I				1	17.7	18.1	25.1	23.4		
Nb				ļ						
Co	2.0	3.9	2.5	1.9						
n i	2270	1890	2780	2220						
V	23.6	31.0	30.0	34.3						
Mg#	0.15	0.15	0.13	0.1	0.39	0.41	0.39	0.35		

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Hidden Valley			1					
	volcanics:		[
	continued	1	Mount H	anna ande	site			
Sample No.	Mc109	Mc116	Mc83b	Mc84	Mc110	Mc111	Mc112	Mc113
SiO2	57.96	51.00	58.93	59.26	60.15	60.74	60.15	59.75
AL2O3	16.18	16.81	16.90	16.83	17.31	17.07	17.05	17.00
Fe2O3	8.07	10.29	6.56	6.82	6.51	6.79	6.73	6.90
CaO	5.72	9.22	3.93	4.00	3.88	3.98	4.08	4.06
MgO	3.38	5.08	1.91	1.54	1.87	1.72	1.62	1.84
Na2O	3.35	3.11	3.91	3.80	3.46	3.53	3.62	3.75
K2O	3.47	1.71	4.29	4.25	4.45	4.52	4.40	4.23
TiO2	1.15	1.38	0.59	0.62	0.60	0.61	0.62	0.59
MnO	0.16	0.17	0.16	0.16	0.16	0.16	0.16	0.16
P2O5	0.87	0.91	0.47	0.86	0.93	1.02	0.94	0.57
LOI	0.62	0.28	0.74	0.73	0.66	0.59	0.32	0.62
TOTAL	100.93	99.9 6	98.39	98.87	<u>99.98</u>	100.73	<u>99.69</u>	99.47
Trace elements	1							
in ppm	Į							
La	72.3	40.0	88.2	92.2	89.1	89.1	89.7	90.0
C c	143.0	76.2	153.0	172.0	173.0	170.0	172.0	163.0
Nd	48.6	35.3	69.1	74.7	65.5	74.8	57.6	82.5
Sm	9.1	6.6	10.4	11.2	10.0	10.6	10.0	10.9
Eu	2.4	1.8	2.4	2.7	2.6	2.5	2.7	2.5
ТЪ	1.2	0.9	0.9	1.2	1.1	1.1	1.0	1.2
УЪ	1.8	2.6	2.2	2.8	2.5	2.7	2.4	2.6
Lu	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.4
U		1.1	1.7	3.5	2.0	3.2	2.9	2.6
Th j	11.1	4.8	12.8	14.2	15.0	13.6	14.7	13.4
Cr D	101.0	184.0	85.1	38.4	136.0	132.0	94.0	72.6
Hſ	7.7	5.0	7.1	8.1	8.0	7.7	7.9	7.4
Ba	1100	724	1650	1970	1800	1990	1840	1990
Rb j	95.8	24.9	65.5	105.0	112.0	95.2	85.3	71.6
Sr	1250	1410	1430	1790	2280	1920	2110	1830
Sc	13.6	24.9	5.7	6.4	6.5	6.2	6.7	6.2
Ta	1.3	0.6	0.8	0.8	0.9	0.8	0.8	0.9
C4								1
Zr	843.0	658.0	679.0	675.0	725.0	560.0	722.0	402.0
Y								
Nb								Í
Co]	21.7	28.2	9.3	10.3	10.3	10.0	10.9	9.8
Ti	7100	7630	3540	3300	3950	3780	4480	4420
<u>v</u>	150	203	81.2	75.1	70.6	81.3	88.8	79.7
Mg#	0.26	0.30	0.20	0.16	0.20	0.18	0.17	0.19

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J		Hidden V	alicy voic	anics: con	tinucd		
Sample No.	<u>M24</u>	<u>M27</u>	<u>M35</u>	<u>M57</u>	M58	<u>Mc87</u>	Mc108
SiO2	58.72	58.70	55.8 6	59.42	59.65	55.19	57.61
AL2O3	17.85	15.80	16.30	17.59	17.49	16.02	16.14
Fc2O3	7.14	5.11	8.47	5.41	5.55	8.9 8	7.74
CaO	5.25	4.49	7.49	4.00	4.03	7.06	5.54
MgO	2.00	2.53	4.33	1.80	1.80	5.12	3.29
Na2O	4.35	3.63	4.29	3.69	3.64	3.62	3.47
K2O	3.95	5.29	1.89	5.22	5.22	2.36	3.63
TiO2	0.71	0.82	0.95	0.55	0.55	1.08	1.18
MnO	0.06	0.09	0.08	0.35	0.12	0.17	0.16
P2O5	0.77	0.35	0.20	0.12	0.34	0.64	1.05
LOI	0.82	1.29	1.35	0.35	0.76	0.06	1.35
TOTAL	101.62	98.10	101.21	98.50	99.15	100.30	101.16
Trace elements							
in ppm							
La	97.8	102.0	26.2	99.4	98.0	48.6	69.7
Ce	182.3	168.6	42.0	167.8	166.9	85.2	139.0
Nd	68.8	74.8	23.9	76.6		32.8	42.0
Sm	14.2	13.1	4.3	12.8	12.6	6.4	8.5
Eu	3.5	2.7	1.6	2.8	2.8	1.6	2.3
Ъ	1.5	1.5	1.6	1.5	1.5	0.9	0.8
УЪ	2.9	2.8	1.4	2.9	2.9	2.4	1.9
Lu	0.6	0.4	0.4	0.5	0.5	0.3	0.4
U							1.1
Th I	12.5	20.2	6.4	13.7	13.5	8.3	10.8
Cr		•				220.0	61.2
Hf	7.0	9.4	4.3	7.6	7.6	5.5	7.3
Ba	2440	1620	655	2203	1897	802	1200
Rb	97.9	118.5	43.6	9 8.2	100.0	33.8	60.6
Sr	1741	745	455	1468	1157	556	1280
Sc						19.7	12.8
Ta	0.7	1.4	0.5	0.9	0.9	0.9	1.2
Cd							
Zr		390.0		367.8	234.1		199.0
Y							
Nb							
60						27.6	19.5
Ti I						6130	7410
v						135	149
Mg#	0.19	0.30	0.30	0.22	0.22	0.33	0.27

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	Mount Han	na					
	andesite:						
	continued		Cinder Pro	spect men	nber		
Sample No.	Mc114	Mc115	Mc59e	Mc78	<u>Mc79</u>	Mc117a	Mc121
SiO2	60.93	59.37	66.37	61.31	67.25	67.67	69.88
AL2O3	17.10	16.73	15.25	16.63	15.30	15.53	15.65
Fc2O3	6.53	6.61	3.36	5.71	3.30	3.45	3.00
CaO	3.84	4.10	2.08	3.39	1.10	2.07	1.63
MgO	1.61	1.81	0.99	1.38	0.55	0.55	0.48
Na2O	3.68	3.87	3.96	4.03	3.85	4.39	3.65
K2O	4.36	4.31	5.27	4.63	5.58	5.69	5.63
TiO2	0.57	0.57	0.16	0.45	0.13	0.11	0.11
MnO	0.16	0.15	0.16	0.16	0.16	0.17	0.16
P2O5	1.02	0.93	0.13	0.42	0.08	0.29	0.25
LOI	0.48	0.45	2.47	0.14	2.47	1.12	0.83
TOTAL	100.28	98.90	100.19	98.25	99.7 6	101.04	101.27
Trace elements							
in ppm							
La	94.8	91.4	116.0	8 8.4	123.0	121.0	129.0
Ce	171.0	171.0	210.0	182.0	216.0	227.0	222.0
Nd	72.2	69.8	83.5	60.1	77.9	88.2	101.0
Sm	11.5	10.9	11.7	10.3	11.9	12.8	13.5
Eu	2.6	2.6	2.5	2.9	2.6	2.5	2.5
То	1.0	0.9	1.3	1.0	1.2	1.0	1.2
УЪ	2.8	2.5	3.1	2.4	3.2	3.1	3.6
Lu	0.4	0.4	0.5	0.3	0.4	0.5	0.5
บ	3.8	2.4	4.9	3.1	5.1	5.8	5.0
Th	14.3	14.0	21.7	15.5	21.5	22.4	21.9
Cr	105.0	108.0	38.4	79.6	32.1	43.8	
Hſ	7.9	7.6	8.7	9.1	8.6	8.5	8.6
Ba	1930	2020	1450	1700	1840	1850	1780
Rb	85.7	94.9	127.0	108.0	125.0	120.0	121.0
Sr	1610	1700	801	1580	764	925	638
Sc	6.0	6.4	4.8	5.4	4.8	5.0	4.6
Ta	0.8	0.8	1.0	0.7	1.1	1.0	1.1
Cd					2.0		
Zr	438.0	430.0	534.0	652.0	837.0	532.0	619.0
Y I							
Nb							[
60	9.1	10.0	1.2	6.6	0.8	1.0	0.7
Ti I	3610	3430	1020	3770	1230	4151	4537
v I	70.2	79.9	15.2	58.7			
Mg#	0.17	0.19	0.20	0.17	0.13	0.12	·0.12

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	Cinder Pro	spect	T T				Center		
Į	member:	-	[Mountain		
	continued		Tuff of the	Sloan vol	canics		dacite		
Sample No.	Mc125	Mc126	Mc59a	Mc59b	Mc59c	Mc73	Mc59d	Mc120b	
SiO2	68.74	69.70	69.76	64.87	64.26	68.58	68.06	67.67	
AL203	15.35	15.45	15.08	15.09	15.12	14.56	15.94	15.67	
Fe2O3	3.05	3.11	3.34	3.95	4.42	3.10	3.58	4.11	
CaO	1.67	1.21	0.59	1.37	1.64	0.69	2.15	1.56	
MgO	0.40	0.44	0.77	1.73	1.71	1.07	0.51	0.63	
Na2O	3.85	3.69	4.32	3.73	3.92	4.62	3.75	3.70	
K2O	5.56	5.48	5.91	5.90	4.56	5.84	5.47	5.37	
TiO2	0.10	0.10	0.45	0.63	0.64	0.48	0.15	0.20	
MnO	0.17	0.16	0.15	0.15	0.15	0.15	0.16	0.17	
P2O5	0.24	0.25	0.10	0.19	0.20	0.23	0.28	0.35	
loi	0.99	2.93	0.61	1.30	2.99	0.82	1.04	0.85	
TOTAL	100.12	102.52	101.08	98.91	99.62	100.14	101.09	100.28	
Trace elements									
in ppm									
La			95.4	103.0	98.4	109.0	118.0	114.0	
Ce			183.0	192.0	185.0	216.0	217.0	206.0	
Nd			78.7	89.2	90.0	70.9	85.8	101.0	
Sm			11.9	13.2	12.5	13.7	12.2	12.0	
Eu			1.3	1.5	1.8	1.4	2.4	2.5	
Ть			1.2	1.6	1.4	1.3	1.1	0.9	
УЪ			3.2	3.3	3.4	3.6	3.3	3.4	
Lu		1	0.5	0.5	0.4	0.6	0.5	0.5	
U			7.1	6.0	6.0	6.7	4.7	4.2	
Th			37.5	32.3	33.0	38.9	21.4	19.2	
Cr D		1	58.7	47.8	66.4	21.6	31.0	27.7	
Hf			10.4	11.7	11.6	11.6	8.8	8.9	
Ba			271	380	497	366	1700	1810	
Rb			165.0	139.0	151.0	162.0	115.0	108.0	
Sr				364	670	155	784	800	
Sc		ł	3.7	5.6	6.2	4.2	5.3	5.0	
Ta			2.4	2.4	2.0	2.9	1.1	1.1	
C4						1			
Zr 🛛		·	560.0	701.0	693.0	833.0	577.0	540.0	
Y I						1			
Nb		ľ				- 1			
Co			2.7	5.9	8.0	3.2	1.2	1.9	
Ti			3039	2820	2899	2950	4662	2300	
v			26.7	37.8	52.8	31.5	15.8	16.1	
Mg#	0.10	0.11	0.17	0.27	0.25	0.23	0.11	0.12	

·	Canton		T					
	Mountain							
1	dacite: con	ntinued	Mount Ia	n andesite	, ,			
Sample No.	Mc130	Mc131	Mc72	Mc77	Mc93	Mc94	Mc95a	Mc95b
SiO2	68.43	68.06	57.85	59.28	60.22	58.12	58.24	58.94
AL203	15.52	15.48	16.72	17.22	17.32	16.71	17.18	16.89
Fe2O3	3.07	3.09	7.14	7.08	7.87	7.34	6.97	7.76
CaO	1.64	1.57	4.24	4.15	4.31	4.22	4.36	4.09
MgO	0.38	0.44	1.81	1.84	1.94	1.95	2.13	1.56
Na2O	3.51	3.86	3.74	3.62	3.64	3.65	3.77	3.51
K2O	5.65	5.73	4.16	4.41	4.18	4.19	4.10	4.41
TiO2	0.11	0.10	0.60	0.61	0.66	0.63	0.64	0.64
MnO	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
P2O5	0.21	0.16	0.97	1.02	1.00	0.98	0.54	0.85
LOI	1.03	1.10	0.66	1.04	0.25	0.33	1.18	0.72
TOTAL	<u>99.71</u>	<u>99.75</u>	<u>98.05</u>	100.43	101.55	98.28	<u>99.27</u>	<u>99.53</u>
Trace elements								
in ppm	Ĩ							
La	ļ		86.7	85.6	86.3	8 8.4	89.2	
Cc			155.0	152.0	156.0	155.0	164.0	l i
Nd			81.7	73.7	82.6	89.4	69.0	
Sm			11.4	11.4	11.2	11.1	11.1	[
Eu			2.6	2.5	2.8	2.7	2.8	J
Ть			1.2	1.0	1.1	1.0	0.9	
УЪ			2.5	1.9	2.3	2.2	2.3	J
Lu			0.4	0.4	0.3	0.4	0.3	
<u> </u>			2.7	3.8	3.4	4.7	2.3 ·	J
ть		.	13.0	11.6	12.8	11.8	12.8	
Cr]	60.7	82.5	80.0	40.1	87.2	. I
Hf			7.0	6.7	7.3	7.3	7.6	·
Ba		[1970	1930	1990	2090	2070	[
KP	131.5		91.7	71.3	71.4	95.3	97.6	
Sr	536		1640	1580	1980	1810	2070	[
Sc .		1	5.8	5.7	6.2	5.9	6.1	
Ta f			0.7	0.9	0.7	0.6	0.9	
]						ļ
	347.4		637.0	387.0	689.0	543.0	808.0	l l
Y I	12.2							1
			. .	40 -				
			10.4	10.5	11.4	10.4	10.9	ł
			4130	4110	3970	4370	3790	
v l			<u> </u>	96.4	<u> 88.2</u>			
Mg#		0.11	0.18	0.18	0.17	0.19	0.21	0.15

]	Mount lan	n andesite	c:				
	continued			Mount Su	utor dacite		
Sample No.	Mc97	Mc98	Mc120a	Mc21	Mc83a	Mc85	Mc96
SiO2	58.03	58.07	58.73	61.91	62.41	63.03	62.91
AL2O3	17.21	17.18	17.20	16.09	16.51	16.25	16.19
Fc2O3	7.19	7.14	7.77	5.71	5.48	5.85	5.14
CaO	4.30	4.43	4.17	3.13	2.45	3.20	2.44
MgO	1.92	2.16	1.72	1.34	1.16	1.15	1.20
Na2O	3.87	3.86	3.82	3.49	3.68	3.46	3.53
K2O	4.22	4.44	4.14	5.75	5.84	4.69	5.68
TiO2	0.64	0.69	0.62	0.39	0.43	0.58	0.43
MnO	0.16	0.16	0.16	0.17	0.16	0.16	0.16
P2O5	0.52	0.54	1.19	0.24	0.24	0.59	0.22
LOI	0.34	1.05	0.15	1.93	0.70	0.44	1.02
TOTAL	98.40	9 9.72	99.6 7	99.13	99.0 6	99.4 0	98.73
Trace elements							
in ppm	J						
La	85.6		81.4	118.0	115.0	111.0	119.0
Ce	159.0		149.0	220.0	219.0	199.0	210.0
Nd	59.0		62.6	112.0	87.8	112.0	120.0
Sm	11.2		10.4	14.7	13.3	14.5	14.6
Eu	2.8		2.5	3.3	3.4	3.3	3.2
Ть	1.1		1.0	1.5	1.6	1.6	2.1
ҮБ .	2.2		2.0	4.4	3.9	3.9	3.9
Lo	0.4		0.4	0.6	0.5	0.6	0.7
U	2.9		2.9	4.8	2.6	3.6	3.7
Th	12.6		12.0	20.3	20.3	17.0	19.4
C	160.0		76.1	9.0	61.6	18.3	57.6
Hf	7.3		7.0	10.7	10.8	10.4	10.3
Ba	1900		1900	2180	1780	1950	1830
Rb	75.3		85.9	118.0	135.0	109.0	109.0
Sr	1990		1880	1480	1380	1530	1600
Sc	6.0		5.9	6.7	6.7	7.8	6.7
Ta	0.8		0.7	1,3	1.0	1.2	1.0
24							
Zr	645.0		670.0	681.0	697.0	833.0	580.0
Y I							1
ND							
Co	11.2		10.6	2.8	3.3	3.6	2.8
Ti 🛛	3890		4330	3220	2630	3820	3220
<u>v</u>	88.3		79.2	24.2	24.4	34.6	23.8
Mg#	0.19	0.21	0.16	0.17	0.15	0.14	0.17

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[Alkali
	Mount Su	tor dacite	: continue	d	basalt
Sample No.	Mc100	Mc118	Mc119	Mc128	Mc124
SiO2	61.67	62.29	64.96	66.55	51.04
AL2O3	16.19	16.43	16.44	15.84	14.92
Fc2O3	5.14	5.71	5.51	3.85	8.70
CaO	2.44	2.99	2.98	1.98	8.80
MgO	1.24	1.04	1.14	0.69	7.71
Na2O	3.84	3.56	3.64	3.53	3.32
K2O	5.51	5.17	5.27	5.33	2.56
TiO2	0.49	0.48	0.43	0.25	0.96
MnO	0.17	0.17	0.17	0.16	0.16
P2O5	0.25	0.50	0.31	0.35	1.13
LOI	0.50	0.74	0.64	1.83	1.19
TOTAL	97.44	99.0 8	101.49	100.36	100.49
Trace elements		••			
in ppm					
LA	112.0	114.0	116.0		
Ce	215.0	231.0	216.0		
Nd	78.3	95.0	101.0		
Sm	13.2	14.5	14.8		
Eu	3.6	3.4	3.3		
ТЪ	1.6	1.7	1.6		
Yb	4.3	3.9	3.8	1	
Lu	0.5	0.6	0.6		
U	4.2	3.7	4.9		1
Th	. 19.1	19.6	19.1		
Cr	80.8	29.8	40.2		j
Hf	10.6	10.7	10.3		
Ba	1760	1800	1780		
Rb	120.0	135.0	109.0	1	
Sr	1460	1560	1310		
Sc	7.5	8.0	7.4		
Ta	1.0	1.1	1.1		1
			•		
Zr	844.0	602.0	732.0		1
Y					1
Nb				1	
<u>Co</u>	3.0	3.4	3.2	1	1
Ti	3300	3790	3590	ļ	
V	32.0		19.2		
Mg#	0.17	0.14	0.15 .	0.13	0.43

APPENDIX C: CIPW NORMS

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<u> </u>	Tuff of B	ridge Spi	ing												
Sample No.	ET-1	YT	92	R	Т	V	M63	M105	Mc53	Mc60	Mc61	Mc62	Mc64a	Mc64b	Mc65
Q	25	28	21	20	18	18	15	9	10	11	13	17	17	19	20
or	31	28	30	34	29	29	35	37	36	34	36	35	28	38	28
ab	35	29	36	33	38	36	37	40	37	35	37	34	28	33	36
an	5	5	6	5	7	6	4	4	5	5	3	3	9	2	2
c	0	1	0	0	0	0	0	0	0	0	0	0	0	1	2
di	2	0	0	3	0	4	3	2	5	8	4	6	12	0	0
hy	1 1	2	3	0	3	0	2	4	3	1	3	0	0	4	.5
wo	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
mt	1	1	1	1	2	1	1	1	2	2	2	1	2	2	2
lil	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ap	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
hem ···	0	· 0	0	0	0	0	0	0	÷ 0	0	0	0	0	0	0
	Tuff of B	ridge Sp	ring: con	tinued		Hidden	Valley v	olcanics							
Sample No.	Mc66	Mc67	Mc68	Mc69	Mc71	65	66	68	125	M24	M27	M35	M57	M58	Mc87
Q	15	16	13	17	17	0	0	0	2	1	7	5	8	16	2
or	34	35	34	35	36	8	10	18	11	23	32	11	31	36	14
ab	32	37	35	· 37	38	22	22	23	23	37	32	36	31	38	31
an	6	3	3	3	3	30	24	23	28	18	12	20	16	4	20
c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
di	9	4	8	4	0	16	17	13	10	1	5	10	0	2	8
hy	0	2	0	2	3	0	14	14	16	5	4	6	5	1	17
wo	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
mt	2	2	2	2	2	4	4	4	5	0	0	0	0	0	4
hil 🛛	2	1	1	1	1	3	3	2	3	0	0	0) 0) 0	2
ap	1	0	0	0	0	2	1	2	1	2	1	0) 1	0	1
ol	0	0	0	0	0	13	2	0	0	0	0	0) () 0	0
hem	0	0	0	0	0	0	0	0	0	7	5	8	6	i 3	0

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	H.V. volc	anics: co	ont.	Mount H	anna an	desite					
Sample No.	Mc108	Mc109	Mc11	Mc83b	Mc84	Mc110	Mc111	Mc112	Mc113	Mc114	Mc115
Q	8	13	0	7	6	12	12	10	9	12	9
or I	21	21	10	25	25	26	27	26	25	26	25
ab	29	29	26	33	33	29	30	31	32	31	33
an	18	18	27	16	16	13	13	14	16	12	14
C	0	0	0	(0	0	2	2	· 1	0	2	0
di	2	2	11	0	1	0	0	0	0	0	0
hy	13	8	17	11	11	11	11	13	11	10	11
wo	0	0	0	0	0	0	0	0	0	0	0
mt	4	4	4	3	3	3	3	2	3	3	3
il į	2	2	3	1	1	1	1	0	1	1	1
ар	2	3	2	1	1	2	2	2	1	2	2
ol	0	0	0	0	0	0	. 0	0	0	0	0
hem	0	0	0	0	0	0	<u> </u>	0	0	0	0
	Cinder P	rospect i	nember	•				Tuff of t	he Sloan	volcanio	\$
Sample No.	Mc59e	Mc78	Mc79	Mc117a	Mc121	Mc125	Mc126	Mc59a	Mc59b	Mc59c	Mc73
Q	16	10	19	15	22	20	23	17	14	17	12
or	31	27	33	34	33	33	32	35	35	27	35
ab	34	34	33	37	31	33	31	37	32	33	41
an	8	14	5	6	6	7	4	2	6	7	1
C	0	0	1	0	1	1	2	1	1	1	0
đi	1	0	0	2	0	0	0	0	0	0	2
hy	5	8	4	4	4	4	4	8	7	8	5
wo	0	0	0	0	0	0	0	0	0	0	0
mt	2	3	2	2	2	2	2	0	2	2	2
il	0	1	0	0	0	0	0	1	1	1	1
ар	0	1	0	1	1	1	1	0	0	0	0
ol	0	0	0	0	0	0	0	0	0	0	0
hem	1 0	0	0	0	0	0	0	1 0	n	0	0

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141

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Center Mountain dacite						Mount lan andesite									
Sample No.	Mc59d	Mc120b	Mc130	Mc131	Mc72	Mc77	Mc93	Mc94	Mc95a	Mc95b	Mc97	Mc98	Mc120a		
Q	19	21	22	19	8	3	3	4	7	8	- 5	5	- 9		
or	32	32	33	34	25	26	25	25	24	26	25	26	24		
ab	33	31	30	33	32	33	31	32	32	30	34	33	32		
an	9	5	7	7	15	15	16	17	18	13	17	16	13		
c	0	2	1	0	1	0	0	⁵ O	0	1	0	0	2		
di	0	0	0		0	2	2	1	0	0	1	2	0		
hy	5	5	4	4	12	11	12	13	12	12	11	11	13		
wo	0	0	0		0	0	0	0	0	0	0	0	C		
mt	2	2	2	່ 2	3	3	3	3	3	3	3	3	3		
61	0	0	0	0	1	1	1	1	1	1	1	1	1		
ap	1	1	0	0	2	1	1	1	1	2	1	1	3		
01	0	0	0	0	0	0	0	0	0	0	0	0	(
hem	0	0	0	0	l o	0	0	· 0	0	0	0	0	(
	Mount S	utor dacit	e		و بر دون کرد پر ک				Alkali	basalt			د المحمد بدانکا برور با		
Sample No.	Mc21	Mc83a	Mc85	Mc96	Mc100	Mc118	Mc119	Mc128	1	Mc124	1				
Q	10	10	16	12	9	13	14	20		0					
or	34	35	28	34	33	31	31	32		15					
ab	30	31	29	30	32	30	31	33		28					
an	11	11	12	11	12	12	13	7		18					
c	0	0	1	0	0	1	0	1		0					
di	2	0	0	0	1	0	0	0	1	15					
hy	6	8	8	7	7	8	8	4	1	2	2				
wo	0	0	0	0	0	0	0	0	1	0					
Int	3	3	3	3	3	3	3	2	.]	4					
hi	1 1	. 1	1	1	1	1	1	0		2	2				
ap	1 1	. 1	1	1	1	1	1	1		1	3				
61) a	0	0	0	Ō	Ō	0		14	i I				
hem	l o	0 0) Ö	0 O	0	0	Ō	0		(5				

APPENDIX D: ROCK MODES

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	Tuff of J	Bridge S	pring							Hidden	Valley w	olcanics		
Sample number	Mc53	Mc60	Mc62	Mc64b	Mc66	Mc67	Mc68	Mc69	Mc71	Mc1	Mc3a	Mc35	Mc37	Mc40b
Plagioclase	3.4	1.5	2.8	0.8	1.2	2.0	1.4	5.0	3.0			2.2	1.0	3.3
Olivine										0.6		9.8	7.6	6.3
Biotite	3.4	0.6	1.0	1.8	1.6		1.4	0.4	1.6					
Orthopyroxene														
Clinopyroxene	0.8	0.2	0.4	0.2	0.8	0.2	0.8	0.4	1.6	0.3	1.0	0.8	1.4	
Fe-Ti oxides	0.2	Trace	Trace	Trace	Trace	Trace	0.4	0.6	Trace					
Groundmass	56.2	86.0	87.2	86.0	83.0	79.4	69.8	83.6	67.4	88.1	90.8	84.0	82.8	78.5
Sanidine	24.2	7.5	4.2	6.0	5.4	10.4	4.8	7.0	10.6					
Phlogopite]				
Zircon	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	ł				
Sphene	0.4	0.4	0.6	0.2	0.4	Trace	Trace	0.6	0.4	1				
Hornblende														
Monazite										}				
Epidote														
Allanite														
Quartz	0.6	0.8	1.2	1.0	1.0	0.8	0.4	1.2	1.4			0.6	6.0	. 2.6
Calcite	1					Trace								
Pumice	9.6	2.2	1.4	2.2	3.4	Trace	11.4	0.2	12.0					
Rock xenoliths	1.2	0.8	1.2	1.8	3.0	7.2	9.6	1.0	2.0	ł				
Vesicles										11.0	8.2	2.6	1.2	9.3

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144

	Hidden	Valley w	olcanics:	continue	×d			Mount Hanna andesite Cinder Prosp					Prospect r	nember
Sample number	Mc42	Mc43	Mc47	Mc48	Mc87	Mc108	W-Hvb	Mc31b	Mc110	Mc112	Mc115	Mc25	Mc78	Mc79
Plagioclase	1.0	1.0	0.4		1.8	13.2	18.4	Trace	Trace	Trace	Trace	3.6	10.4	17.4
Olivine		6.0	0.4	1.2		1.4	11.4							
Biotite												0.4	4.0	3.6
Orthopyroxene				:			I					1		
Clinopyroxene	4.0	10.0	10.8	4.6		1.6	9.6					1		Trace
Fe-Ti oxides	1						0.5					0.8		1.2
Groundmass	91.4	79.6	76.6	79.0	98.2	65.6	58.5	100.0	100.0	100.0	100.0	69.4	85.2	74.0
Sanidine														3.8
Phlogopite			3.6	4.8										
Zircon												Trace		Trace
Sphene														
Hornblende								ł				Į		
Monazite								[
Epidote														
Allanite														l
Quartz														
Calcite												25.8		
Pumice	Į							Į.				l		
Rock xenoliths	1						•]				1		Trace
Vesicles	3.6	3.4	8.2	10.4		18.2	1.6					1	0.4	

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145

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	Cinder													
	Prospec	t r cont	Tuff of the Sloan volcanics			Center Mtn. dacite			Mount Sutor decite					
Sample number	Mc121	Mc125	Mc59a	Mc59b	Mc59c	Mc73	Mc59d	Mc130	Mc131	Mc9	Mc116	Mc19	Mc21	Mc27
Plagioclase	8.2	6.6	4.8	2.0	2.4	3.4	4.0	4.4	7.2	7.4	8.8	7.2	13.6	13.0
Olivine														
Biotite	1.8	3.6	0.4	0.8	0.4	0.6	1.4	1.2	1.6	3.2	1.4	2.2	3.4	5.4
Orthopyroxene	1				•		}			1	1.6	1.2		
Clinopyroxene			Trace	0.4	1.4	Trace							Trace	2.0
Fe-Ti oxides		0.4			1.4	0.2		÷ 0.4		0.8	0.4	1.2	1.0	1.6
Groundmass	83.6	84.0	60.6	76.6	52.6	77.8	94.6	89.0	88.6	88.0	87.8	76.4	78.2	76.4
Sanidine			21.2	4.8	8.6	10.0	ł							
Phlogopite	1									1				
Zircon	1	Trace	Trace	Trace		Trace				Trace				
Sphene			0.2	Trace		Trace				1				
Hornblende										ļ				0.4
Monazite			Trace				1			1				
Epidote	1		Trace				1			1				
Allanite			Trace							1				
Quartz			1		0.4	1.8								
Calcite	6.4	5.4						5.0	1.2	1				
Pumice	}		9.0	2.2	11.6	1.6								
Rock xenoliths			3.8	13.2	21.2	4.6]				
Vesicles			<u> </u>						1.4	0.6		11.8	3.8	1.2

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146

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	Mount	Sutor da	cite: cont	inued					
Sample number	Mc28	Mc31a	Mc91a	Mc92	Mc96	Mc100	Mc118	Mc119	Mc128
Plagioclase	14.8	8.6	4.2	6.8	8.8	11.0	11.4	7.4	3.0
Olivine	1	•							
Biotite	3.2	2.6	2.0	1.8	3.6	3.2	5.4	9.4	2.6
Orthopyroxene	1			1.7					
Clinopyroxene	Trace	0.4			0.4	0.6	Trace		
Fe-Ti oxides	1.4		0.4	0.8	0.6			0.8	Trace
Groundmass	80.6	87.6	93.4	88.9	82.6	81.4	83.2	81.0	90.8
Sanidine	1								
Phlogopite	1								
Zircon			Trace						
Sphene	1								
Hornblende	}								
Monazite									
Epidote	}								1
Allanite									
Quartz	1								
Calcite	1	0.8						1.4	
Pumice	1								
Rock xenoliths	1								
Vesicles	<u> </u>	_			4.0	3.8			3.6

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STYLE OF VOLCANISM AND EXTENSIONAL TECTONICS IN THE EASTERN BASIN AND RANGE PROVINCE: NORTHERN MOHAVE COUNTY, ARIZONA

by

Tracey Elaine Cascadden

A thesis submitted in partial fulfillment of the requirements for the degree of

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in

Geology

Geoscience Department University of Nevada, Las Vegas August, 1991

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Chairman, Eugene I. Smith, Ph.D. Examining Committee Member, Ernest M. Duebendorfer, Ph.D. Examining Committee Member, David L. Weide, Ph.D.

Graduate Faculty Representative, Diane Pyper-Smith, Ph.D.

Graduate Dean, Ronald W. Smith, Ph.D.

University of Nevada, Las Vegas June, 1991

ABSTRACT

The west-dipping Cyclopic-Salt Spring Wash-Lakeside Mine fault system marks both the easternmost boundary of the extensional allochthon in the Basin and Range Province and the eastern limit of exposure of mid-Tertiary igneous rocks at the latitude of Lake Mead. The upper plate of this fault system is exposed only in the northern White Hills (NWH), Mohave County, Arizona. The upper plate contains east-tilted mid-Tertiary volcanic and sedimentary rocks, cut by down-to-the-west normal faults. Faulting began near Salt Spring Wash during the deposition/eruption of the upper part of the mid-Tertiary section. Elsewhere in the NWH, faulting postdated eruption and deposition. Brittle deformation on the Salt Spring fault contrasts with ductile deformation on the Lakeside Mine fault and may be explained by increasing displacement and a corresponding increase in uplift northward from the Black Mountains accommodation zone.

Three groups of mafic volcanic rocks, distinguished on the basis of chemistry and petrography, were erupted from three coeval mid-Tertiary volcanic centers. The three types of mafic magma may represent similar degrees of partial melting of different K-rich sources. Each magma type evolved by fractionation in conjunction with periodic recharge by new batch melts. Mafic volcanic lavas erupted from broad shields or fissure-fed lava fields. Landslide, ash-flow tuff and fanglomerate deposits suggest the presence of a Proterozoic basement high southeast of the study area.

Correlation between the mid-Miocene mafic to intermediate (46-70% SiO₂)

volcanic rocks of the northern White Hills and volcanic rocks of the Eldorado and Black Mountains (Patsy Mine Volcanics and Tuff of Bridge Spring) is possible on the basis of stratigraphic position, geochemistry (Hf, Ta, Sc, Co, Cr, V and REE), and petrography. A new biotite K-Ar age date on the Tuff of Bridge Spring in the northern White Hills suggests that the regionally extensive Tuff of Bridge Spring may be composed of two major pyroclastic flows. The first erupted at 16.4 Ma and is exposed in the NWH, the southern Black Mountains and the McCullough Range. The second erupted at 15.18 Ma and is exposed in the Eldorado Range.
CONTENTS

INTRODUCTION	1 5
WHITE HILLS VOLCANIC STRATIGRAPHY ANDTHE EASTERN LIMIT OF THE EXTENSIONAL ALLOCHTHON	7
INTRODUCTION	. 7 7
Correlation of sections	. 9
Composite section	. 35 43
ROCKS OF THE FOOT WALL	48
STRUCTURE	54
Salt Spring Fault	54 55
Interpretations	60
PETROGENESIS OF MAFIC VOLCANICS	62
ORIGIN OF HIGH K2O CONTENTS: METASOMATIC OR MAGMATIC	62
HOW ARE THE THREE MAGMA TYPES RELATED	02
PETROGENETICALLY?	69 69
Fractional Crystallization	71
Assimilation-Fractional Crystallization (AFC)	76 77
Conclusions	78
CHEMICAL VARIATION WITHIN EACH MAGMA TYPE	79 70
Basaltic Andesite of Temple Bar	79 83
Basaltic Andesite of Squaw Peak	85
SUMMARI	8/
REGIONAL CORRELATION	88
LATE TERTIARY SEDIMENTS	oo 102
STRUCTURE	105
Regional correlation of Salt Spring fault	105 110
Ductile vs. brittle deformation	111
Geometry and displacement of Salt Spring fault	115
CONCLUSIONS	118

V

FUTURE WORK	120
APPENDIX A: STRATIGRAPHIC SECTIONS	
APPENDIX B: PETROGRAPHIC DESCRIPTIONS: ASH-FLOW TUFFS	134
APPENDIX C: PETROGRAPHIC DESCRIPTION: MAFIC VOLCANIC	
ROCKS	139
APPENDIX D: PETROGRAPHIC DESCRIPTIONS: PRECAMBRIAN	
BASEMENT	147
APPENDIX E: INSTRUMENTAL TECHNIQUES	154

List of Figures

1. Location Map	. 2
2. Regional sketch map	. 3
3. Sample location Map	. 0 ያ
5 Correlated stratigraphic sections of the northern White Hills	. 0 10
6. Composite stratigraphic section of the Northern White Hills	11
7. Harker variation diagrams for ash-flow tuffs: SiO ₂ vs. major	
oxides	14
8. Chondrite-normalized rare earth elements for ash-flow tuffs	17
9. Harker variation diagrams for ash-flow tuffs: SiO_2 and $Mg\#$ vs. Hf, Ta	
and Sc	19
10. Harker variation diagrams for asn-flow turns: SiO_2 and $Mg\#$ vs. Cr, v	20
11 Harker variation diagrams for mafic volcanic rocks: SiO, vs. total REE*	20
(La + Ce + Nd + Sm + Eu + Yb + Lu), Sc. Hf. La. Th and total alkalis	29
12. Hf/Th vs. La/Yb, TiO, and CaO, and Sc.	31
otal REE* and La/Yb plotted against light REEs Sm, Nd, & Eu	32
14. Chondrite-normalized REE plot for mafic volcanics	34
15. Models for the eruptive/depositional history of the northern White	
Hills	45
17 Simplified cross-sections	20
18. Alternative cross section from Temple Bar to Salt Spring Wash	61
19. Harker variation diagrams for mafic volcanic rocks: SiO ₂ vs. major	•••
element oxides	63
20. Classification diagram for mafic volcanic rocks (LeBas, 1986)	65
21. Alkali enrichment diagram. K ₂ O plotted against Na ₂ O	66
22. Binary chemical plots: K_2O vs. Ce, Hf, La, and Th	70
23. Harker variation diagrams: SiO ₂ vs. Ce, Hi, La and Ih	73
24. I CSIS IOI ORVINE and CHROPYROXERE MACHONATION: V VS. CO and Cr; CO	71
vo. CI allu UC	74

26. Tests for plagioclase fractionation: CaO and Na ₂ O vs. Eu	81
Ridge	82
Temple Bar	84
Squaw Peak	86
30. Regional exposures of the Tuff of Bridge Spring	89
Bridge Spring and Peach Springs Tuff: Co, Cr and V	95
Bridge Spring and Peach Springs Tuff: Hf, Sc and Ta	96
Bridge Spring and Peach Springs Tuff: Ba and Rb	97
34. Harker variation diagrams comparing NWH tuff with the Tuff of Bridge Spring and Peach Springs Tuff: Major oxides	98
35. Correlation of northern White Hills volcanic section with Eldorado)2
36. Regional exposures of Red Sandstone 10	13 14
37. Regional exposures of Muddy Creek Formation)6
38. Along-strike differences in deformational style due to northward	-
steepening of fault surface	2
fault surface about an east-west axis	3
Accommodation Zone (BMAZ) 11	6

List of Tables

.....

ţ

1: Major element data for ash-flow tuffs	12
2: Trace and REE data for ash-flow tuffs	13
3: Summary of mineralogy for ash-flow tuffs	16
4: Summary of mineralogy for mafic volcanic rocks	22
5: Major element data for mafic volcanic rocks	24
6: Trace and REE data for mafic volcanic rocks	26
7: Maximum, minimum and average major element concentrations for	
mafic volcanic rocks	28
8: New biotite K-Ar age date from ash-flow tuff in the White Hills	37
9: Summary of mineralogy for clasts from coarse breccia	38
10: Summary of mineralogy for Precambrain basement rocks	50
11: Normative mineralogy for mafic volcanic rocks	67
12: Major element fractional crystallization and AFC models	72
13: Distribution coefficients for basalt	80
14: Major element data for the Tuff of Bridge Spring and Peach Springs	

Tuff	90
15: Trace and REE data for the Tuff of Bridge Spring and Peach Springs	
Tuff	92
16: Episodic ash-flow tuff eruptions from selected calderas in western	
North America	100
17: Characteristics of Lake Mead region low-angle normal faults	109

,

List of Plates

1: Geologic map of the northern White Hills,	
Mohave County, Arizona, 1:62,500	in pocket
2: Geologic map of Salt Spring Wash, 1:24,000	in pocket

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ix

INTRODUCTION

The White Hills are situated south of Lake Mead (Figure 1) in the northern end of the Colorado River extensional corridor, north of an accommodation zone (Faulds, 1989) which separates east-tilted fault blocks to the north from west-tilted fault blocks to the south (Figure 2). The region was subjected to large scale extension during mid-Miocene time (Anderson, 1971; Spencer, 1985; Weber and Smith, 1987; Duebendorfer et al., 1990a;). Extension was accommodated by low-angle normal faults and kinematically related strikeslip faults during early phases of extension (pre-11 Ma), and by high-angle normal faults during later phases of extension (post-11 Ma) (Anderson, 1971; Spencer, 1985; Eaton, 1982 and Wernicke, 1984). Sewall and Smith (1986) documented large magnitude displacement along the Saddle Island detachment (Figure 2) in the western Lake Mead area. Duebendorfer et al. (1990) suggested that the · Saddle Island detachment may project eastward to Arch Mountain. Myers (1985) mapped a low-angle fault, the Cyclopic detachment, in the southern White Hills. The Lakeside Mine fault (Fryxell and Duebendorfer, 1990), north of Lake Mead, may be the northward projection of the Cyclopic detachment (Spencer and Reynolds, 1989). In this thesis I describe the Salt Spring fault on the east side of the northern White Hills. The Salt Spring fault may link the Cyclopic and Lakeside Mine faults. The Salt Spring fault lies 20 km west of the Grand Wash Cliffs and represents both the easternmost boundary of the extensional allochthon and the eastern limit of exposure of mid-Tertiary igneous rocks in the northern



Figure 1. Location Map. Lake Mead National Recreation Area is hatchured.



Figure 2. Regional sketch map. High-angle normal faults marked by ball on hanging wall. Low-angle normal faults marked by double tick marks on hanging wall. AM=Arch Mountain, CBM, NBM, SBM=central, northern and southern Black Mountains, FM=Frenchman Mountain, GB=Gold Butte, HP=Hualapai Plateau, HSR=Highland Spring Range, MM= McCullough Mountains, RG=Rainbow Gardens, RM=River Mountains, CD=Cyclopic detachment, LMF=Lakeside Mine fault, LMFS=Lake Mead fault system, SID=Saddle Island detachment, SSF=Salt Spring fault.

Colorado trough.

Intermediate volcanism in the Lake Mead area began at 20 Ma and continued to about 12 Ma (Smith et al., 1990). Younger, smaller volume basaltic volcanism occurred between 10.6 and 8.5 Ma at Callville Mesa, Nevada (Smith et al., 1990) and in the southern White Hills, Arizona (Calderone et al., 1991) and between 4-6 Ma in the Fortification Hill volcanic field (Anderson et al., 1972; Feuerbach and Smith, 1987). In the western Lake Mead region, volcanic stratigraphy is well established in the Eldorado and McCullough ranges (Anderson, 1971; Weber and Smith, 1987; Smith et al., 1988; Bridwell, in preparation); the River Mountains (Smith, 1982); the Hoover Dam area (Mills, 1985); northern Black Mountains (Feuerbach, 1986; Naumann, 1987); and southern Black Mountains (Faulds, 1989); but was not previously studied in detail in the eastern Lake Mead region. This thesis extends the well established stratigraphy of the northern Colorado River trough and western Lake Mead area east to the White Hills on the eastern margin of the Basin and Range.

Previous work in the northern White Hills focused primarily on the economic gold deposits to the south and east of the study area (Myers, 1985, Myers et al., 1986, Theodore et al., 1987, Santa Fe Pacific Railroad Co., 1981, and Blacet, 1968, 1969, 1972, and 1975). Longwell (1936) discussed the geology in Temple Basin and Virgin Canyon, now flooded by Lake Mead. Studies by Bohannon (1984), Blair et al. (1977, 1979), Blair and Armstrong (1989) and Bradbury et al. (1979) were concerned with deposition of the post-tectonic, Late

Miocene Muddy Creek Formation and Hualapai Limestone. The current study is the first to focus on regional correlation of mid-Miocene rock units, geochemistry and tectonics of the northern White Hills.

The purpose of this paper is to (1) determine the nature of the eastern boundary of the extensional allochthon in the eastern Basin-and-Range Province; (2) develop a model for the petrogenesis of northern White Hills volcanic rocks; and (3) correlate these volcanic rocks with others in the Lake Mead area.

TECHNIQUES

The 230 square mile study area was mapped at a scale of 1:62,500 (Plate 1). Stratigraphic sections were measured at Squaw Peak, Smith Hill, and Chuckwalla Ridge. At the Peninsula, Salt Spring Wash and Pink/Black Ridge, section thicknesses were estimated from the geologic map. One hundred-fifty samples were collected (Figure 3) for geochemical and petrographic analysis. Major elements were analyzed by the Rigaku 3030 X-ray Fluorescence (XRF) spectrometer at the University of Nevada, Las Vegas. Trace elements were analyzed by Instumental Neutron Activation Analysis (INAA) at the Phoenix Memorial Laboratory at the University of Michigan. One biotite K-Ar age date was determined by the Geochron Laboratories Division of Krueger Enterprises, Inc. A description of analytical techniques and sample preparation methods can be found in Appendix E.





Figure 3. Sample location Map

Senator Mountain

WHITE HILLS VOLCANIC STRATIGRAPHY AND THE EASTERN LIMIT OF THE EXTENSIONAL ALLOCHTHON

INTRODUCTION

The northern White Hills (NWH) lie in the hanging wall of the westdipping Salt Spring fault. The Salt Spring fault may represent a segment of a regional detachment zone that extends from Gold Butte to near Dolan Springs, Arizona (Cyclopic detachment). This fault zone lies 20 km west of the Grand Wash Cliffs and represents both the easternmost boundary of the extensional allochthon and the eastern limit of exposure of mid-Tertiary igneous rocks in the northern Colorado trough. The hanging wall of the Salt Spring fault contains six east-tilted structural blocks comprised of Miocene basalt and basaltic andesite flows and agglomerates, dacite ash-flow tuffs, megabreccia and fanglomerate. Because each block is isolated and contains only a small part of the stratigraphic section, geochemical data (Co, Cr, Eu, Hf, La, Nd, Sc, and Th) were used to construct a composite section.

VOLCANIC ROCKS OF THE NORTHERN WHITE HILLS

The six eastward-tilted structural blocks that were identified within the NWH contain distinctly different sections of Tertiary volcanic and sedimentary rocks (Figure 4). These are named the Squaw Peak, Salt Spring Wash, Pink/Black Ridge, Smith Hill, Peninsula and Chuckwalla Ridge blocks. Because the blocks are separated by late Tertiary and Quaternary sedimentary deposits, the correlation of stratigraphic sections could not be made on the basis of field



Figure 4. Simplified Geologic Sketch Map of the northern White Hills.

data alone. Correlation between the blocks is necessary to determine how the blocks are related structurally and to regionally correlate the volcanic rocks of the NWH with other volcanic sections in the Lake Mead area. Sections were correlated by the use of a combination of geochemical data, petrographic data and field relations (Figure 5). The resulting composite section is shown in Figure 6. Sections are described in detail in Appendix A. Geochemical data are summarized in Tables 1, 2, 4, 5 and 6. A new biotite K-Ar age date is reported in Table 8. Petrography is summarized in Tables 3, 7, and 9 and described in detail in Appendices B through D.

Correlation of sections

Although the stratigraphic sections in each structural block differ in lithology, there are similarities in the groupings of rock packages. Near the base of the sections at Squaw Peak, Smith Hill, Salt Spring Wash and the Peninsula is a dacite (60-71% SiO₂) ash-flow tuff. The tuff in all four sections is similar in chemistry (Tables 1 and 2, Figure 7) and mineralogy (Table 3). Although absolute concentrations of rare-earth elements (REE) vary, all samples exhibit similar chondrite-normalized REE patterns. On Figure 8, all but two samples exhibit a steady decrease in abundance with increase in atomic weight, with a moderate negative anomaly at Sm. One exception is a reworked ash from Chuckwalla Ridge (sample 102). The unusual signature for this sample may be attributed to alteration.

Variation in incompatible trace element (Hf, Sc and Ta) concentrations



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Figure 5. Correlated stratigraphic sections of the northern White Hills.



Figure 6. Composite stratigraphic section of the Northern White Hills.

Qa = alluvium, Qf = alluvial fan, Qls = landslide, Qoa = older alluvium, Qp = Colorado River pebble deposits, Qt = talus, Tbrl/Tbru = coarse breccia and debris flows, Tbre = sandstone and reworked ash, Tmcl/Tmcu = Muddy Creek Formation, Tpb = basalt of Pink/Black Ridge, Trs = Red Sandstone, Ts = fanglomerate, Tsm = basalt of Senator Mountain, Tspl/Tspm/Tspu = basaltic andesite of Squaw Peak, Tt = ash-flow tuff, Ttbl/Ttbm/Ttbu = basaltic andesite of Temple Bar.

			Salt Spri	ng Wash			S	mith Hill		S	quaw Pes	k	Penir	sula	Chuckwalls
Sample No.	54	69	73	70	⁻ 83	81	101	84	98	1	110	106	144	142	102
SiO2	68.82	69.12	63.89	67.1	68.1	68.23	62.02	65.09	65.32	63.91	63.93	62.6	69.36	68.57	60.21
A12O3	14.79	12.56	13.48	14.39	13.74	15.21	13.86	15.81	14.85	15.99	15.7	16.04	13.73	12.81	13.95
FeO*	3.97	2.98	2.91	4.23	3.73	3.73	4.84	4.03	4.48	4.44	4.18	4.68	3.64	4.76	3.07
CaO	1.25	3.23	0.75	1.1	2.2	0.32	0.43	0	: 1.16	1.79	2.25	2.7	3.49	3.51	2.05
MgO	0.93	0.45	0.52	0.08	0.73	0.56	1.75	0.59	0.89	1.12	1.29	1.67	1.28	1.36	1.9
Na20	1.75	0.27	1.38	0.8	0.8	0.59	2.54	1.97	1.97	3.66	4.06	3.95	1.94	2.79	1.89
K20	8.35	7.63	8.03	8.92	6.79	9.3	5.83	10.34	8.43	6.52	5.65	5.42	3.76	3.42	3.68
TiO2	0.51	0.38	0.38	0.49	0.45	0.49	0.56	0.51	0.59	0.63	0.58	0.69	0.41	0.47	0.18
MnO	0.14	0.12	0.14	0.15	0.15	0.14	0.15	0.13	0.14	0.14	0.14	0.15	0.14	0.14	0.14
P205	0.25	0.47	0.2	0.19	0.2	0.27	0.2	0.08	0.44	0.24	0.24	0.27	0.39	0.51	0.21
loi	3.18	4.93	2.62	3.46	3.65	2.54	3.82	2.54	2.07	2.17	2.54	1.28	3.1	2.18	8.53
Total	103.94	102.14	94.3	100.91	100.54	101.38	96	101.09	100.34	100.61	100.56	99.45	101.24	100.52	95.8

Total iron as FeO

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	\$	alt Spring V	Vest)		المتظاولية، بريد.		\$	mith Hill		\$	quew Peak		Penin	ula Ch	ockwelle
	54	69	73	70	83	81	101	84	98	1	110	106	142	144	102
La	93.1	58	90.3	99.5	84	99.6	80.1	93.1	87.3	104	93.5	99.1	49.7	52	38.9
Co	170	93.6	168	172	144 -	187	161	161	153	190	174	188	83.7	86.1	71.9
Nđ	53.3	41.5	65.2	63.9	56.8	64.6	67	57.8	54.5	63.9	66.4	74.1	41	45.7	35.2
Sm	8.41	5.79	10.3	9.03	7.77	8.89	7.77	7.76	7.63	9.9	8.84	9.77	5	4.77	5.09
Eu	1.63	1.26	1.1	1.39	1.14	1.51	1.77	1.66	1.79	2.12	1.96	2.22	1.19	1.05	0.515
УЪ	2.65	1.8	3.43	3.13	2.8	3.1	2.16	2.51	2.37	2.58	2.4	2.4	1.62	1.9	2.29
Lu	0.28	0.23	0.47	0.39	0.37	0.35	0.291	0.26	0.3	0.304	0.32	0.32	0.23	0.29	0.36
U	4.87		7.16	5.79	4.64	4.74	1.42	4.44		5.42	4.4		3.84		3.56
Th	27.1	15.3	36.7	28.4	25.6	30.1	20	23.3	17.9	23.4	22.2	20.4	10.5	11.7	21.2
Cr	20.9	13.8		19	14.1	22.3	37.9	30.6	33.3	20.6	34.1	40	16.9		16.8
Hf	10.2		10.1	9.36	9.28	10.3	9.13	8.74	9.78	10.8	10.4	11.3	5.25	6.34	4.02
Ba	924	2300		444	601	647	1390	1260	1350	1370	1130	1410	1100	1790	480
Rb	169	110	175	171	129	174	127	205	193	116	115			123	108
Sr							3970				897	1210		2330	6760
Sc	4.46	3.47	2.37	5.11	3.61	3.8	5.42	3.87	5.03	5.74	5.87	6.29	5.74	3.98	3.06
Ta	1.56	1.12	1.96	1.9	1.9	2.23	1.34	1.53	1.23	1.52	1.42	1.65	0.99	1.02	1.16
Zr	559														
Co	4.29	1.74	2.16	5.23	3.02	2.7	12.1	2.59	4.99	5.54	6.57	7.11	6.32	3.75	5.66
v	32.2	39.1	19.5	33.5	34.5	36.2	53.5	40.5	49.1	70.2	55.2	63	43.3	32.5	18.3
Dy	3.82	2.93	5.71	4.4	3.61	4.46	3.74	3.25	3.53	4.03	3.82		2.33		2.88

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Table 2: Trace and rare earth element data for ash-flow tuffs

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Figure 7. Harker variation diagrams for ash-flow tuffs: SiO₂ vs. major oxides. Diamonds=Chuckwalla Ridge, squares=Peninsula, X=Smith Hill, crosses =Squaw Peak, triangles=Salt Spring Wash. Units are weight percent.



Figure 7, continued.

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	Samola	% 1 ithic	& Pumice	% Sen-	& Place	g.	% Bio-	%	% Clipo-	%	%	%
	No.	Fragments	Fregments	idine	ioclase	Quertz	tito	Sphene	pyroxees	Olivino	Zircon	Opeques
			Y		h							
	137				21		2	0.2	8	0.3		2
Penin-	144	0.1	2	7	6		3	tr	1			.4
sula	136	15	6	1	12		3	tr	0.7		0.3	1.5
	142	4	7	4	× 9	0.4	4	1	0.7			1
	54	6	10	6	4		2	0.5	0.2		0.1	.7
Salt	69	15	1	4	3	0.4	1	tr			tr	.3
Spring	73	4	3	9	1	0.5	0.2					.2
Wash	70	10	6	0.4	1		1	0.3	0.3		0.1	.2
	83	2		6	3	1	1					1
	81	7	11	1	1		0.7	0.1	tr		0.2	.8
	101	11	2	9	4	0.2	0.6		0.1		tr	.4
Smith	84	2	2	20	11		3					.6
Hill	150	4	10	3	9		3	tr	0.6		0.8	1
	98	12	5	9	10	0.1	4	tr				2
	96	13		12	7		4	tr			tr	8.
Squaw	1	6	24	9	9	0.2	3	tr	0.9		tr	.6
Peak	111	10	12	10	15		1		2		tr	.2
	100	5 6	4	11	8		2		0.6			.2
Chuck	-											
walla Ridgo	102	2 2		4	1		1		0.3			

Table 3: Summary of mineralogy for ash-flow tuffs

* Percent based on counts of 1000 points per slide using a Swift point counter. Unreported percentage is ash matrix



Figure 8. Chondrite-normalized rare earth elements for ash-flow tuffs. The highest and lowest values from each locality are plotted. Symbols are defined on Figure 7. Chondrite values from Hanson (1980).

(Figure 9) may be due largely to variations in the abundance of accessory minerals such as sphene, zircon and apatite. Variation in compatible trace element (Co, Cr and V) concentrations (Figure 10) may be due to variation in the proportion of mafic volcanic and Precambrian lithic fragments. Alternatively, compatible trace element variation may be due to compositional zoning in the ash-flow tuff. Petrographic analysis (Table 3) demonstrates that although mineral component percentages vary, the variation between exposures is no greater than that within exposures.

Interbedded with the ash-flow tuff in the Salt Spring Wash and Squaw Peak sections is a coarse breccia in which the dominant clast types are Precambrian gneiss, granite, amphibolite and mylonite with minor mud-supported conglomerate and sandstone. The breccia is also present at Pink/Black Ridge. The deposits are similar in all four sections and are comprised mostly of crackle breccia (no matrix) and jigsaw breccia (minor matrix) according to the scheme of Yarnold and Lombard (1989). In the Peninsula section, coarse breccia is lacking, but mud-supported conglomerate is present.

The tuff and breccia are an important stratigraphic marker that aided in correlation of the stratigraphic sections. The tuff is tentatively correlated with the Tuff of Bridge Spring, a regionally extensive ash-flow sheet. Near the base of the section at Chuckwalla Ridge, 214 meters of sandstone and pebble conglomerate are interbedded with layers of reworked, biotite-rich ash that are tentatively correlated with the dacite ash-flow tuff.



Figure 9. Harker variation diagrams for ash-flow tuffs. Weight percent SiO₂ and Mg# plotted against incompatible trace elements Hf, Ta and Sc (ppm). Symbols are defined on Figure 7.



Figure 10. Harker variation diagrams for ash-flow tuffs. Weight percent SiO₂ and Mg# plotted against compatible trace elements Cr, V and Co (ppm). Symbols are defined on Figure 7.

Mafic volcanic rocks in the NWH occur as flows and autoclastic and volcaniclastic breccias in varying proportions. Samples from Pink/Black Ridge are petrographically distinct from samples from the other sections (Table 4). The only phenocryst phase in the Pink/Black Ridge samples is olivine. Samples from the other five sections contain plagioclase as the dominant phenocryst phase with subequal amounts of clinopyroxene and olivine.

March 10 - 10 - March 10 - 10 - 10

Mafic volcanic rocks form two distinct groups in terms of chemistry (Tables 5, 6 and 7). Harker variation diagrams with SiO₂ and magnesium number (Mg# = Mg/Mg+Fe) versus La, Hf, Th, Sc, total REE (La + Ce + Nd + Sm + Eu + Yb + Lu) and total alkalis (Na₂O + K₂O) (Figure 11) demonstrate the clear division between the basalt of Pink/Black Ridge and the basaltic andesite of Chuckwalla Ridge, Smith Hill, Salt Spring Wash and the Peninsula. The basaltic andesite in the Chuckwalla Ridge, Smith Hill, Salt Spring Wash and the Peninsula sections are correlated on the basis of their chemical similarity and are hereafter named the basaltic andesite of Temple Bar (Ttb).

The chemical data for the basaltic andesite of Squaw Peak (Tsp) occupy an intermediate position between the basalt of Pink/Black Ridge (Tpb) and Ttb. Plots of Hf/Th versus TiQ₂, La/Yb, Sc, and CaO (Figure 12) and of total REE and La/Yb versus Eu, Sm and Nd (Figure 13) demonstrate this clustering of rock types as well. The distribution of data points for Tsp could be explained by an intermingling of Tpb and Ttb flows in the Squaw Peak area. However, unlike Tpb basalts, Squaw Peak basalts contain clinopyroxene as a phenocryst phase.

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141 2 5 14 48 mx, a f-c, subtrachyti 141 2 5 9 25 1 64 3 mx, a f-c, subtrachyti 141 21 21 4 6 5 3 1 mx, a f-c, subtrachyti 141 11 21 4 6 1 23 3 1 mx, a f-c, felty 100 4 1 1 1 14 1 49 23 8 cx, f codes for textures: a a 23 3 4 28 cx, f codes for textures: a 1 1 1 49 23 8 cx, f codes for textures: a a a a 28 cx, f felty codes for textures: a a a a b 20 3 cx, f felty codes for textures: a a a a b a a a a a cx, f f a a a			71			. .		ব	R :			0	8			mx, f, felty
Tthm T1 Z D D M f. felty 88 21 4 6 1 22 3 1 mx, s. f., felty 88 21 4 6 1 22 3 4 28 11 mx, s. f., felty 100 4 1 1 1 14 1 49 22 8 cx, f codes for textures: s = seriate microcrystal size range s = seriate microcrystal size range c = coarse-sized microcrystal size range 28 11 mx, f, felty mx = microcrystals dominant in groundmass s = seriate microcrystal size range c = coarse-sized microcrystals 49 23 8 cx, f mx = microcrystals dominant in groundmass f = fine-grained microcrystals f = fine-grained microcrystals f f = fine-grained microcrystals		2 :	•	•					•			5	14		48	mx, a f-c, subtrachytic
Tthm 71 27 0.6 9 46 6 5 3 1 mx, a f-c, felty 88 21 4 6 1 22 3 4 28 11 mx, a f-c, felty 100 4 1 1 1 14 1 49 22 8 cx, f codes for textures: n n 14 1 49 22 8 cx, f mx = microcrystals dominant in groundmass a = seriate microcrystal size range c = coarse-sized microcrystals c = coarse-sized microcrystals a = seriate microcrystals a = seriate microcrystals f = glass dominant in groundmass f = fine-grained microcrystals f = fine-grained microcrystals a = seriate microcrystals a = seriate microcrystals		Ē	7	n					ห			-	2		e	mx, f, felty
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			PHENO	CRYSTS				GROUN	IDMASS	;					
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	No.	ioclase	Olivine	рутохево	nctito	gopite	blendo	ioclaso	Olivino	рутохово	stito	crystals	Glass	icles	Groundmass
Tpb	7	2	3		1			49	8	.9	15		10	3	mx, c, subtrachytic
	10	0.6	5					47	20	16	7	2		3	mx, s f-c, trachytic
	120	1	2			1		61	7	23	5				mx, m, trachytic
	15	0.4	0.4					49	23	7	5	7		11	mx, m, trachytic
	124	3	1			•		40	7	14	1	8		25	mx, f, trachytic
	117	6						35	10	16	12	11	1	10	mx, c, trachytic
	118		. 5					61	8	21	4			1	mx, f, trachytic
	121		.1					43	12	17	9	7		11	mx, f, trachytic
	123		1					37	13	` 13	3	24		11	mx, f, trachytic
Tsm	55	3						32		9	2	32		21	mx, s f-c, felty
	55b	. 4						52	15	12	3	3		11	mx, c, felty
	103	1	1	3	3			49	8	1	10	17		7	mx, c, felty
	114	13	2	2	1			8	5	2		60		6	mx, f, felty
Tspt	n 3	24	4					43	10	8	1		1	1	mx, s f-c, trachytic
-	21		6					39	12	5	13	12	12	: 12	mx, m, trachytic
	108		12					44	15	i	13	16			mx, f, trachytic
	126	5	2					45	16	2	11	8	11	11	mx, m, subtrachytic
	127	2	5					50	12	10	5	13	3	; 3	mx, m, subtrachytic
	128	13	9					31	3	8	1	19	10	0 10) mx, f, felty
Tsp	112	23	0.6	b				12		i	8	28	15	5 15	5 mx, f, felty
-	113	24	1					28	: 2	2 8	4	22			mx, f, felty
	20	1	9					31	S) 3	8	34			mx, f. felty

Table 4: continued

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	Тю			Ttbm							
	139	138	90	85	51	50	148	65	131	132	134
SiO2	58.48	60.45	54.56	48.98	54.15	54.26	52.43	56.97	55.78	51.61	55.93
A12O3	16	15.94	16.42	14.26	16.12	14.37	16.377	15.28	14.71	14.97	15.39
FeO*	7.31	5.81	8.04	10.87	7.13	7.57	8.351	8.16	7.1	8.28	6.2
CaO	6.53	4.83	6.5	8.87	7.48	9.62	7.217	6.99	6.72	9.4	8.74
MgO	3.09	2.07	1.69	9.44	2.82	3.47	3.183	4.23	4.94	4.72	2.83
N=20	3.46	3.15	3.66	3.18	3.6	3.28	3.185	3.2	3.38	2.86	3.3
K2O	2.7	3.94	4.26	1.38	3.79	3.63	3.528	3.56	3.72	2.86	3.14
TiO2	1.17	1	1.22	1.6	1.2	1.07	1.284	1.16	1.09	1.29	1.05
MnO	0.16	0.15	0.14	0.166	0.139	0.161	0.159	0.153	0.159	0.159	0.157
P2O5	1.04	0.77	0.66	0.53	0.6	1.42	0.988	0.63	0.63	1.41	0.65
LOI	0.65	1.61	1.95	2.14	2.96	2.76	2.23	1.79	2.03	2.3	2.98
Total	100.63	100.49	99.1	101.42	99.99	101.61	98.93	102.12	100.26	99.86	100.37

The Alexandra Salara

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Table 5: Major element data for mafic volcanic rocks

	Ttbm		Ttbu								
	135	149	49	140	133	130	86	141	71	88	100
SiO2	59.56	58.041	53.68	58.277	54.35	55.39	60.39	49.073	54.61	52.53	53.39
A12O3	14.98	15.641	14.45	15.796	15.19	15.71	16.34	15.84	15.97	14.93	16.63
FeO*	6.83	7.655	6.52	6.549	6.81	6.16	6.24	10.332	8.49	6.45	7.26
CaO	6.79	6.229	10.03	5.439	7.61	8.27	4.37	11.825	7.66	10.27	5.63
MgO	2.72	3.559	4.38	2.139	3.85	2.73	1.76	4.631	3.91	2.9	2.7
N=20	3.44	3.134	3.02	3.613	3.24	3.44	5.37	2.702	3.35	3.3	3.43
K2O	4.13	3.421	3.37	3.329	3.49	3.78	4.23	1.237	3.37	3.37	3.83
TiO2	0.99	1.141	1.03	0.956	1.03	1.04	0.87	1.383	1.2	0.99	1.01
MnO	0.147	0.154	0.159	0.146	0.158	0.147	0.149	0.161	0.158	0.161	0.148
P2O5	0.56	1.02	0.63	0.924	1.24	0.56	0.45	0.922	0.62	0.64	1.2
LOI	1.48	0.56	2.88	1.26	2.65	2.15	1.39	3.31	1.23	4.11	3.35
Total	101.63	100.56	100.15	98.43	99.62	99.38	101.56	101.42	100.57	99.65	98.57

* Total iron as FeO

	Tpb					Tsm						
	7	10	120	15	117	118	121	123	55	103	114	
SiO2	46.74	47.33	50.99	51.53	51.96	49.69	49.66	49.76	48.6	47.82	50.21	
A12O3	15.6	14.97	15.8	16.05	15.44	14.08	15.64	15.82	15.22	15.27	15.52	
FeO*	10.06	12.32	11.23	10.54	10.13	11.56	10.44	10.86	12.21	11.48	11.53	
CrO	13.98	10.24	9.57	9.95	9.1	9.85	10.62	10.41	12.55	9.41	9.58	
MgO	3.39	7.02	5.66	5.48	6.74	6.95	5	5.5	4.87	5.28	6.52	
N=20	3.07	2.87	3.36	3.27	3.14	3.43	3.32	3.37	3.21	2.61	3.24	
к20	1.75	1.2	1.71	1.56	1.66	1.3	1.86	1.91	1.15	1.2	1.39	
TiO2	1.38	1.51	1.64	1.47	1.46	1.38	1.51	1.56	1.31	1.27	1.46	
MnO	0.166	0.166	0.166	0.162	0.161	0.164	0.166	0.165	0.164	0.127	0.166	
P2O5	0.96	0.38	0.53	0.52	0.54	0.42	0.56	0.66	0.38	0.26	0.36	
LOI	2.05	1.76	1.03	0.96	1.31	1.78	0.94	1.42	1.78	4.43	1.12	
Total	99.15	99.77	101.69	101.49	101.64	100.6	, 99.72	101.44	101.44	99.16	101.1	

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	Tspm				Tspu						
	3	21	108	126	127	128	112	113	20		
SiO2	53.86	49.44	48.84	49.33	48.67	52.95	54.78	54.52	51.77		
A12O3	15.05	15.04	15.35	15.34	15.04	14.92	16.19	16.47	15.69		
FcO*	8.17	9.68	10.76	9.61	10.44	7.79	6.69	6.96	· 9.1		
C=O	6.8	8.49	7.91	9.19	8.85	7.59	6.35	6.45	6.99		
MgO	4.76	7.31	6.42	5.45	5.56	7.1	3.04	2.44	7.36		
N=20	3.08	3.3	3.16	3.55	3.42	2.6	3.41	3.34	3.93		
K20	3.91	1.73	2.06	2.04	1.89	3.1	3.9	4.03	2.14		
TiO2	1.2	1.9	1.84	1.73	2.14	1.19	1.04	1.04	1.1		
MnO	0.165	0.166	0.159	0.164	0.165	0.166	0.15	0.148	0.163		
P2O5	0.56	0.48	0.59	0.63	0.6	0.61	1.11	1.16	0.6		
LOI	2.48	2.63	4.09	2.84	3.02	2.79	2.07	2.31	1.88		
Total	100.04	100.17	101.18	99.87	99.79	100.81	98.73	98.88	100.72		

* Total iron as FeO

Table 6: Trace and rare earth element data for mafic volcanic rocks

	Ttbl			Tthm							
	139	138	90	85	51	50	148	65	131	132	134
La	71	72.7	89	41.2	82.5	79.9	66.8	73.6	73.4	75.6	73.8
Co	125	128	169	82.7	162	158	131	150	131	144	142
Nd	68.8	52.4	84.5	54.6	77.1	69	70.5	61.4	71	83.2	73.7
Sm	8.47	8.21	12.7	7.35	12.1	11.6	9.81	10.3	10.4	11.5	10.5
Eu	2	1.89	2.81	2.12	2.76	2.8	2.37	2.62	2.36	2.59	2.46
УЪ	1.99	2.1	2.44	2.16	1.88	2.46	2.62	2.05	2.28	2.46	2.33
Lu	0.33	0.31	0.38	0.33	0.31	0.3	0.32	0.26	0.33	0.33	0.35
U	3.16	3.24	5.2	0.654	6.27	3.76	6.3	2.81	3.38	3.75	4.58
ТЬ	10.3	15.2	19.1	4.11	17.7	15.1	16	15.3	15.5	14.1	14.8
Cr	45.3	43	133	501	184	176	123	188	164	248	155
Hf	6.55	8.05	8.65	5	7.96	7.4	7.31	6.94	6.76	6.59	7.17
Ba	1260	1360	1480	555	1310	1340	1210	1200	1320	1120	1170
Rb	47.4	85.1	96.9		69.3	49.8	79.4	85.1	94.9	54.4	63.5
Sr	943	906	1280	970	1340	1620	1340	1300	1060	1240	1610
Sc	14.2	10.8	15.3	20.4	17.5	15.7	18.9	17	14.9 .	20.4	17.1
Ta	1.94	1.47	1.2	0.82	1.28	0.91	0.99	1.24	1.14	1.33	1.17
Co	17.2	12.9	20.8	40.7	15.9	19.2	25.7	22.7	19.8	24.8	17
V	138	103	170		152	138	162	147	147	169	157
Dy	3.97	2.96	5.63		4.51	4.8	5.23	5.12	4.39	4.86	4.67

	Ttbm Ttbu										
	135	149	49	140	133	130	86	141	77	88	100
La	71.8	73.2	76.3	62.2	71.4	76.7	92.6	33.2	71.3	69.7	82.7
Ce	139	142	148	119	135	147	173	61.5	122	132	143
Nd	64.8	64.9	64.2	49.5	68.9	76.3	85.1	33.2	64.4	55.8	73
Sm	8.83	9.81	11.6	6.86	9.72	10.7	11	6.23	10.2	10.2	9.93
Eu	2.15	2.21	2.8	1.77	2.35	2.38	2.64	1.84	2.2	2.36	2.21
Yb	1.9	2.79	1.99	1.55	2.33	2.61	2.62	2.61	2.12	2.09	2.36
Lu	0.28	0.41	0.38	0.25	0.35	0.38	0.45	0.42	0.36	0.26	0.35
U	3.78	4.91	4.05	1.56	3.54	6.28	4.66	1.68	4.76	3.18	2.92
Th	13.2	20.7	15.2	9.56	15.3	17	15.7	3.75	12.9	13.9	13.3
Cr	9 5.7	91.7	240	41.2	163	225	31.8	236	147	155	70.1
Hf	7.25	7.72	6.69	6.51	7.04	7.56	9.18	4.41	6.15	7.06	7.55
Ba	2040	1100	1360	1270	1230	1240	1510	593	1130	1420	1480
RЬ	84.2	79.6	62.5	70.4	73.7	89.4	100		74	68.3	52.9
Sr	1580	885	1300	1290	1170	1280	987	860	876	1390	1300
Sc	13.3	15.7	18.2	12	14.6	16.5	7.66	28.9	16.7	15.6	12.1
Ta	1.36	1.37	1.07	1.26	1.21	1.08	1.33	0.73	0.85	1.03	1.13
Co	13.4	21.2	19.2	16.5	20.7	14.1	12.3	3.51	19.8	15.6	14.5
V	158	136	127	111	141	152	91.4	196	160	131	112
Dy	3.88	4.58	4.43		4.42	4.61	4.81	4.43	4.29	4.49	4.79

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Table 6: continued

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	Tpb								Tem		
	1	10	120	15	117	118	121	123	55	103	114
La	27.8	23	39.6	35.6	35.6	24.8	47.5	49.3	15.1	12.8	20.5
Ce	53.1	43.4	77.7	67.5	67.8	48	91.4	95.1	31.4	27.4	43.6
Nd		29	28.5	33.3	35.6		50.8	46.1		19.1	
Sm	5.05	4.43	6.19	5.75	5.67	4.85	6.81	7.07	3.36	3.46	4.06
Eu	1.65	1.46	2.03	1.93	1.82	1.72	1.92	2.22	1.28	1.19	1.39
ТЪ	2.24	2.14	2.28	2.23	2.24	2.12	2.34	2.16	1.55	1.86	2.16
Lu	0.31	0.28	0.33	0.31	0.25	0.29	0.25	0.29	0.23	0.36	0.26
U	2.91					2.67				2.38	
Ть	2.84	2.53	3.9	3.63	3.88		4.07	4.37		2.86	3.15
Cr	150	201	166	191	208	301	118	138	306	310	247
Hf	3.84	3.58	5.5	4.36	4.23	4.29	5.01	4.91	2.33	2.85	3.47
Ba	536	426	650	798	572	473	893	1040	344	245	391
RЬ	39.7										
Sr			854	1370	1140		1090	1440	•	2510	
Sc	25.2	25.4	27.4	25	.24.5	27.4	25.3	25	21	24.8	22.6
Ta		0.69	1	0.71	1.24	1.1	0.87	0.99	0.85	0.59	0.653
Co	27	37.8	31.8	29.8	29.5	40.3	27.6	30.2	40.4	45.7	37.8
V	181	186	198	171	191	195	187	200	162	176	170
Dy	4.14	3.4	3.5	4.13	3.77	3.36	4.56	3.48	3.01	3.57	4.33

	Tspm				Tspu							
	3	21	108	126	127	128	112	113	20			
La	76.8	34.6	51		43.8	78.3	78.5	76.2	59.4			
Ce	153	63.3	90.9		83	152	149	153	110			
Nd	74.1	37.5	57.2 °		50.9	78.4	70.1	70.7	46.8			
Sm	11.1	6.05	7.65		7.17	11.5	10.3	10	6.67			
Eu	2.6	1.72	2.09		2.17	2.53	2.26	2.43	1.92			
ЧЬ	2.57	2.29	2.58	2.52	2.42	2.28	2.11	2.42	1.88			
Lu	0.38	0.35	0.44	0.42	0.41	0.37	0.33	0.36	0.3			
U	4.29	1.26	1.53	1.27	1	3.38	3.87	4.32	1.8			
ТЪ	17.7	4.18	6.03	5.9	5.2	15.7	18.3	18.7	7.58			
Cr	252	227	264	202	217	293	81.8	88.4	271			
Hf	8.49	4.73	5.6	6.27	6.41	8.24	7.52	7.86	5.14			
Ba	1000	430	848	517	525	0	1360	2430	950			
RЬ	83.7					70.2	82	105				
Sr	987	9.46			856	928	1290	1670	848			
Sc	16.7	20.7	20.7	19.5	20.9	17.6	11.2	11.9	15.3			
Ta	1.09	1.28	1.44	1.35	1.75	1.19	1.11	1.38	1.58			
Co	22.7	33.5	37.3	30.3	33.2	27.7	16	15.7	29.7			
v	183	204	176	171	188	162	129	138	132			
Dy	5.09	4.14	4.85	5.25	4.64	4.38	4.6	4.76	3.9			

	Chuck	walla Ri	idge (7)	S	mith Hi	ll (8)	F	Peninsula (4)			
	High	Low	Average	High	Low	Average	High	Low	Average		
SiO2	59.56	51.61	55.81	60.39	48.98	53.99	60.45	49.07	56.57		
Al2O3	15.71	14.71	15.23	16.63	14.26	15.44	16	15.8	15.89		
FcO*	8.26	6.1	7.01	10.87	6.24	7.51	10.33	6.55	8.35		
CaO	9.4	6.23	7.68	10.27	4.37	7.85	11.82	4.84	7.16		
MgO	4.94	2.72	3.62	9.44	1.69	4.26	4.63	2.07	2.98		
Na2O	3.44	2.86	3.25	3.02	5.37	3.61	3.61	2.7	3.23		
K2O	4.13	2.86	3.51	4.26	1.38	3.48	3.95	1.24	2.8		
TiO2	1.29	0.99	1.09	[~] 1.6	0.87	1.12	1.38	0.96	1.13		
MnO	0.16	0.15	0.15	0.17	0.14	0.15	0.16	0.15	0.16		
P2O5	1.41	0.56	0.722	1.42	0.45	0.77	1.05	0.773	0.916		
LOI	2.98	0.56	2.02	4.11	1.39	2.69	3.31	0.65	1.7		
	Salt S	pring W	ash (3)	Pink/B	lack Rid	ge (11)	Squ	1aw Peal	k (9)		
	High	Low	Average	High	Low	Average	High	Low	Average		
SiO2	56.97	52.43	54.67	51.96	46.74	49.71	54.78	48.67	51.57		
AI2O3	16.38	15.28	15.88	16.05	14.08	15.42	16.47	14.92	15.45		
FcO*	8.49	8.16	8.33	10.06	12.32	10.89	10.76	6.69	8.8		
CaO	7.66	6.99	7.29	13.98	9.1	10.46	9.19	6.35	7.62		

Table 7: Maximum, minimum and average major element concentrations for mafic volcanic rocks

MgO 4.23 3.18 3.77 7.02 3.39 5.72 7.36 2.44 5.49 Na20 3.35 3.18 3.24 3.43 2.87 3.23 3.93 2.6 3.31 К2О 3.56 3.37 3.49 1.91 1.2 1.62 4.03 1.73 2.66 TiO2 1.28 1.16 1.21 1.64 1.38 1.49 2.14 1.04 1.45 MnO 0.16 0.15 0.16 0.16 0.17 0.16 0.17 0.15 0.14 P2O5 0.988 0.62 0.798 0.96 0.38 0.567 1.16 0.48 0.644 LOI 2.23 1.23 1.75 2.05 0.94 1.41 2.07 4.09 2.67

(#) denotes number of samples averaged

* Total iron as FeO



Figure 11a. Harker variation diagrams for mafic volcanic rocks. Weight percent SiO₂ plotted against total REE* (La+Ce+Nd+Sm+Eu+Yb+Lu), Sc, Hf, La, Th and weight percent total alkalis. Trace elements are in ppm. Diamonds=basalt of Pink/Black Ridge, X=basaltic andesite of Temple Bar, squares=basaltic andesite of Squaw Peak, circles=basalt of Senator Mountain.



Figure 11b. Harker variation diagrams for mafic volcanic rocks. Mg# plotted against total REE* (La+Ce+Nd+Sm+Eu+Yb+Lu), Sc, Hf, La, Th and weight percent total alkalis.

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Figure 12. Hf/Th plotted against La/Yb, major oxides TiO₂ and CaO, and Sc. Symbols defined on Figure 11a.


Figure 13. Total REE* and La/Yb plotted against light REEs Sm, Nd, & Eu. Symbols defined on Figure 11a.

Therefore, the clinopyroxene-bearing basalts represent a third type of magma. Because the basaltic andesite samples from Squaw Peak cluster with Ttb basaltic andesite in all diagrams, the source for these flows may be the same as that for Ttb. However, because Tsp basalts are not distinguishable from Tsp basaltic andesites in hand sample, and because of the interlayered nature of the basalt/basaltic andesite flows, all of the mafic volcanic rocks in the Squaw Peak section are mapped as Tsp, regardless of chemical composition.

Chondrite-normalized REE data (Figure 14) allow identification of a fourth type of mafic volcanic rock. Samples 114, 55 and 103 plot with lower overall REE than all other NWH mafic volcanic rocks and have chondritenormalized REE patterns similar to subalkalic basaltic andesite of Callville Mesa and basalt of Fortification Hill (Smith et al., 1990). The three locations are widely scattered (Figure 3) but chemical similarity prompts correlation as a single rock type; here named the basalt of Senator Mountain (Tsm).

On the basis of stratigraphic position, Ttb, Tpb and Tsp appear to be contemporaneous. The lowermost portions of all sections except Pink/Black Ridge contain basaltic andesite (Ttbl and Tspl) overlain by ash-flow tuff plus or minus coarse breccia or a correlative sedimentary unit. The upper part of the stratigraphic sections at Squaw Peak, Salt Spring Wash and the Peninsula consists of either Tsp or Ttb basaltic andesite overlain by sandstone, siltstone and conglomerate that is in turn overlain by basaltic andesite. Similar deposits are interbedded with basaltic andesite in the upper part of the Smith Hill section as



Figure 14. Chondrite-normalized REE plot for mafic volcanics.

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well. Clasts are dominantly Precambrian crystalline rock (70%), but mafic volcanic clasts are also common (30%).

The basalt of Senator Mountain crops out as: (1) a dike (sample 103) that intrudes the base of the section on the west side of Chuckwalla Ridge. (2) Discontinuous outcrops of basalt flows north of Pink/Black Ridge (sample 55) that are interbedded with poorly consolidated sandy gravels that dip 5-10° northnortheast. (3) Flows on Senator Mountain, situated 1.5 km south of the study area (sample 114). These flows overlie poorly consolidated gravels that appear to be continuous with gravels that unconformably overlie Tpb and Tbr at Pink/Black Ridge. Tsm is therefore younger than the tilted mid-Tertiary section in the NWH (Figure 6).

Composite section

A composite section (Figure 6) was constructed by using the maximum thickness of each stratigraphic unit.

The dacite (60-71% SiO2) ash-flow tuff (Tt) is present near the base of the sections at Squaw Peak, Salt Spring Wash, Smith Hill, and Peninsula. It is thickest (179 m) in the Peninsula section, where it contains 2 cooling units. Although no ash-flow tuff is present at Pink/Black Ridge, the presence of Tt at depth is inferred by the relatively constant thickness of the tuff to the southwest (122 m at Squaw Peak), north (150 m at Smith Hill) and northeast (94 m at Salt Spring Wash). At Salt Spring Wash, the tuff records a growth fault sequence (Switzer, personal communication). A sample of the tuff from Smith Hill (sample

84) was dated at 16.4 \pm 0.5 Ma (Table 8). The significance of this date will be discussed in a later section on regional correlation.

The tuff is poorly to moderately welded and contains phenocrysts of sanidine (0-20%), plagioclase (1-15%), biotite (0.2-4%), clinopyroxene (0-2%) and quartz (0-1%). Sphene (0-0.5%) and zircon (0-0.8%) are present as accessory minerals. Apatite occurs as inclusions in biotite and feldspar phenocrysts in many samples. Pumice fragments contain phenocrysts of biotite as well as sanidine and plagioclase in subequal proportions. Lithic fragments are of four types; dacite with plagioclase and biotite phenocrysts, basalt with plagioclase, olivine and clinopyroxene phenocrysts, two-mica granitoids and biotite schist. Devitrification is slight in most samples, but is most pronounced in samples from Salt Spring Wash, where samples have also suffered severe calcification.

Five clasts from the coarse monolithologic breccia (Tbr) interbedded with Tt were analyzed petrographically (Table 9). The crackle and jigsaw breccias that underlie and overlie Tt were produced by landslides. Minor mud-supported conglomerate and sandstone beds, found locally at the base and/or top of the unit, are interpreted as debris flow and stream channel deposits. The breccias are thickest (513 m) at Salt Spring Wash where matrix-rich zones are present near the base of the exposure. In addition, clastic dikes are exposed in small outcrops at Pink/Black Ridge. The breccias are of considerable interest in determining the unroofing history of the Salt Spring fault and is the subject of a study by Switzer (work in progress). Tbr remains thick (343 m) up to 5 kilometers to the west of

Sample	К %	(mqq) *1A	Ar*/Total Ar*	K (ppm)	Date & error
84	7.161	0.008186	0.036004	8.542	16.4 +/- 0.5 Ma

Table 8: New biotite K-Ar date on ash-flow tuff, White Hills

• denotes radiogenic

PROGRADE AND RELICT MINERALS												
Sample		Plagio-	Micro-	Micro-		Musco-						
Number	Quartz	clase	clino	Biotito	vito	Opeque	Sphene	Zircon	Apatite			
64	25	10	35	15	2	2	<1		<1			
66	43	9	33									
74	28	30	10	5			•	<1				
105 a	30	10	20									
105Ъ	30	20	20	1		3		<1				

Table 9: Summary of mineralogy for coarse breccia clasts*

Sample RETROGRADE AND INTRODUCED MINERALS

Number	Calcite	Chlorite	Epidoto	Hematito	Sericito
64		2	3		5
66	5			10	
74			2	5	20
105a					40
1056		3			23

* percentages are estimated

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the detachment at Pink/Black Ridge, but thins rapidly to the west at Squaw Peak (63 m) and to the north on the Peninsula (0-42 m). Longwell (1936) described similar deposits in the Virgin Basin (now flooded by Lake Mead). Torl is poorly resistant to weathering and thus produces talus that covers much of the contact between Tbrl and Tspl/Ttbl. On the basis of a few outcorps where the contact is exposed, Tbrl appears to rest conformably on Ttbl and Tspl without angular discordance.

The amount of time represented by the deposition of the tuff and breccia may be brief, as both types of deposits can acquire considerable thickness in a short period of time. However, the correlative (?) braided stream deposits at the base of the Chuckwalla Ridge section probably represent a longer period of time.

The Temple Bar basaltic andesite (Ttb) (49-60% SiO2) is characterized by low CaO, MgO, FeO, Mg#, Sc, Ti, Cr and Hf/Th and high Eu, Hf, Th, La/Yb and total REE relative to the other mafic volcanics of the NWH (Figures 11-14, Tables 5 and 6). Division of the lower, middle and upper portions of the Temple Bar volcanics was made on the basis of stratigraphic position, and there is no systematic vertical variation in petrography or chemistry.

The lower part of the Ttb section (Ttbl) is thickest (515 m) in the Peninsula. The base of the section is buried, and at Chuckwalla Ridge and Smith Hill, only the uppermost 74 and 180 m of Ttbl are exposed, respectively. The middle part of the Ttb section (Ttbm) is thickest (up to 1000 m) in the Chuckwalla Ridge and Smith Hill sections, where it is crystal-rich, and thins

dramatically to the east and north in the Peninsula and Salt Spring Wash sections, where it is crystal-poor. Eruption of two chemically indistinguishable basaltic andesites (Ttbm and Ttbu) was interrupted by deposition of fanglomerate (Ts) in the Peninsula, Salt Spring Wash and Smith Hill sections. Dikes chemically similar to Ttbm and Ttbu intrude the Ttbm flows at Smith Hill and at Chuckwalla Ridge. The upper part of the Ttb section (Ttbu) is 171 m thick and lies above fanglomerate (Ts) at Salt Spring Wash and in the Peninsula. At Salt Spring Wash, fanglomerates similar to Ts are interbedded with Ttbu flows. At Chuckwalla Ridge Ts is absent and the contact between Ttbm and Ttbu is obscure.

Ttb consists of flows and breccias of basaltic andesite with similar mineralogy. Within and between sections, minor changes in mineralogy are not systematic. Basaltic andesite contains phenocrysts of plagioclase (0-34%), olivine (0-6%), clinopyroxene (0-14%) and magnetite (0-6%). Plagioclase phenocrysts are rectangular and up to 4 mm long. They are embayed, fritted and sieved. Most are subhedral and many have non-pitted overgrowths. Olivine phenocrysts are embayed, subhedral to anhedral and altered to iddingsite along margins and fractures. Most are less than 0.5 mm, but may reach 1 mm in size. Clinopyroxene phenocrysts are subhedral to anhedral, pitted and embayed, and commonly have magnetite inclusions. Many have euhedral unpitted and unaltered clinopyroxene overgrowing highly altered cores. Five samples (65, 77, 130, 138 and 140) contain two populations of clinopyroxene; a small (<0.5 mm) anhedral

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variety that is highly altered and overgrown by unaltered subhedral clinopyroxene, and a second unaltered, subhedral to euhedral variety that is up to 2 mm in size. Sample 138 contains small altered needles of phlogopite (?) (0.2%) as well. Small plagioclase laths and clinopyroxene phenocrysts coexist in glomerocrysts that reach 3 mm in size. Sample 131 contains 4% basaltic xenoliths containing olivine + plagioclase microcrystals in a glassy, hematitic groundmass. Sample 86 also contains 4% phenocrysts of subhedral hematitic hornblende (xenocrysts?) up to 2 mm in size. The groundmass of Ttb ranges from cryptocrystalline with seriate fine to coarse-grained felty euhedral laths of plagioclase (3-31%), subhedral olivine altered to iddingsite (0-6%), subhedral clinopyroxene (2-7%) and hematite (0-10%), to microcrystalline with 13-59% seriate fine to coarse-grained felty to pilotaxitic euhedral laths of plagioclase with intergranular olivine altered to iddingsite (1-9%), clinopyroxene (4-17%), hematite (1-10%) and cryptocrystalline material (0-39%).

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Squaw Peak basaltic andesite (Tsp) (48-54% SiQ₂) exhibits chemical characteristics intermediate between the Temple Bar volcanics and Pink/Black Ridge volcanics. Incompatible element variation is wide over a narrow range of SiQ₂ and Mg#, while variation in compatible elements is low. Tsp also contains higher K₂O, Mg#, TiQ₂ and Yb than either Ttb or Tpb. Tsp occupies a stratigraphic position similar to that of Ttb.

Tsp contains phenocrysts of olivine (1-12%), +/- plagioclase (0-27%), +/clinopyroxene (0-9%). Variation in phenocryst mineralogy is not systematic. Plagioclase phenocrysts are sieved, embayed and fritted. Clinopyroxene phenocrysts are embayed. Olivine phenocrysts are altered to iddingsite on margins and along fractures. The groundmass contains 12-46% fine to medium-grained felty to trachytic plagioclase laths with intergranular olivine (3-15%), clinopyroxene (0-8%), hematite (1-13%) and cryptocrystalline material (0-34%).

Pink/Black Ridge basalt (Tpb) (46-52% SiQ₂) is distinguished from other mafic volcanic rocks of the NWH by low K₂O, Eu, Hf, Th, La/Yb, and total REE and high MgO, FeO, CaO, Sc, Cr and Hf/Th. Tpb overlies thick deposits of coarse breccia at Pink/Black Ridge. Tpb contains phenocrysts of olivine (1-6%), +/- plagioclase (0-3%), +/- hematite (0-3%). Olivine is euhedral to subhedral, embayed and altered to iddingsite on margins. Glomerocrysts up to 2 mm in size of small plagioclase crystals are common, but only one sample (124) contains large (1-4 mm) phenocrysts of pitted, sieved plagioclase. The groundmass of Tpb is comprised of fine to coarse-grained trachytic laths of plagioclase (35-61%) with intergranular olivine altered to iddingsite (7-23%), clinopyroxene (7-23%), magnetite (1-15%) and cryptocrystalline material (2-24%). Sample 120 also has 1% phlogopite (?) in the groundmass. Sample 117 lacks olivine phenocrysts, contains large plagioclase phenocrysts and has a plagioclase-rich groundmass.

Near the top of many sections, separating Ttbm and Tspm from Ttbu and Tspu, is sandstone, siltstone and conglomerate (Ts) interpreted as alluvial fan and stream channel deposits. Fanglomerate clasts are dominantly Proterozoic basement (70%) at Salt Spring Wash and Squaw Peak where deposits are thickest.

Mafic volcanic clasts (30%) were probably derived locally. The ratio of basement to volcanic clasts decreases to (40:60) in the thin Ts deposits in the Peninsula and very thin interbeds of fanglomerate in the upper part of the Smith Hill section.

The dikes and thin flows of the basalt of Senator Mountain contain phenocrysts up to 2 mm in size of euhedral embayed plagioclase (1-13%) and small (<0.5 mm) subhedral phenocrysts of olivine altered to iddingsite (1-4%). The dikes at Chuckwalla Ridge (sample 103) also contain phenocrysts of clinopyroxene up to 1 mm (3%). The samples have a felty plagioclase-rich groundmass.

Mid-Tertiary Eruptive/Depositional History

The lack of chemical or petrographic variation between the basaltic andesite at Chuckwalla Ridge, Smith Hill, the Peninsula and Salt Spring Wash suggests that Ttb represents the construction of a single composite volcano. Eruption of Ttb flows was interupted twice, first by the deposition of Tt and Tbr (possibly a short break) and second by the deposition of Ts (a longer break). Tpb and Tsp occupy a similar position to Ttb with respect to Tt and Tbr. This implies that two additional volcanoes formed penecontemporaneously. Ttb, Tpb and Tsp thus represent eruptions from three chemically different but coeval volcanic centers in the NWH.

Vent facies for the volcanoes were not identified during this study, so eruptive style and volcano type cannot be determined. However, it is possible to model the geometry of the three volcanic edifices on the basis of stratigraphic

thickness of the volcanic units and distribution of the sedimentary deposits. The sedimentary units and ash-flow tuff place constraints on (1) paleotopography at the time of the eruption of mafic volcanics, (2) the height and slope angle of mafic volcanic edifices, and (3) location of sources of Proterozoic clasts in Tbr and Ts. Figure 15 illustrates a model for the interplay of the mid-Tertiary volcanic and sedimentary rocks of the NWH and is discussed below.

Stage 1- Eruption of Ttbl and Tspl

Ttbl is thickest at Smith Hill (610 m) and in the Peninsula (515 m). The total thickness of Tspl and of Ttbl at Salt Spring Wash is unknown, because the basal parts of the sections are buried. The nearly continuous sheet of Tbrl and correlative units that overlies Tspl and Ttbl suggests that Tspl and Ttbl either (1) represent flows on the flanks of low, broad shield volcanoes or (2) were erupted from fissures (Figure 15a). The conformable contact between Tbrl and Ttbl/Tspl indicates that Ttbl and Tspl were not faulted or tilted at the time of Tbrl deposition.

Stage 2- Deposition of Tbrl

Tbrl (dominantly landslide deposits) is thickest at Salt Spring Wash (438 m), moderately thick at Squaw Peak (63 m) and occurs only as debris flow deposits in the Peninsula (42 m). Braided stream deposits at Chuckwalla Ridge are correlated with Tbrl, Tt (Stage 3) and Tbru (Stage 4). Landslide megabreccias were shed off of a topographic high of Proterozoic basement



Figure 15. Models for the eruptive/depositional history of the northern White Hills.

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situated to the south and/or east of the study area. Torl landslides were deposited at Squaw Peak and Salt Spring Wash and thin debris flows were deposited as far north as the Peninsula. Deposits were reworked in braided streams in the Chuckwalla Ridge area.

Stage 3- Deposition of Tt

Ash flows commonly follow topography and pond as thick deposits in topographic lows. The thick Tt deposits in the Peninsula and at Smith Hill indicate that these areas remained low during the deposition of Tt. Thinner deposits at Squaw Peak and Salt Spring Wash reflect an increase in elevation to the south toward the Proterozoic high (Figure 15c). An unresolved problem with this model is the lack of thick ash-flow tuff at Chuckwalla Ridge, which, according to the model, should have been a topographic low. The reworked tuff in the braided stream deposits suggest that these strata are time-equivalent to Tt. It is questionable whether Tt could have been deposited then eroded away. Tt may have been deflected away from the Chuckwalla Ridge area by topographic irregularities. Growth faulting in the Salt Spring Wash block began during this stage.

Stage 4- Deposition of Tbru

Tbru is thickest at Salt Spring Wash and Pink/Black Ridge, and is thin at Squaw Peak. These deposits reflect a second period of landsliding from a Proterozoic high situated to the east-southeast of the study area (Figure 15d).

Stage 5-Eruption of Ttbm/Tspm/Tpb

Mafic volcanism followed the deposition of the breccia. Interruption of mafic volcanism by the deposition of fanglomerate in the upper part of the section supports the contention that the volcanoes that erupted Ttbm and Tspm were not substantial topographic barriers. Ttbm may have erupted from numerous fissures forming a broad, flat lava field. Some basaltic andesite lavas from the Ttb volcano may have flowed into the Squaw Peak area and mingled with Tsp basalt flows. The configuration of volcanoes during this stage is best determined by the distribution of overlying Stage 6 sediments. The growth faulting in the Salt Spring Wash block continued during this stage. The fanning of dip in Ttbm west of Salt Spring Wash records approximately 10° of tilting, probably along the Salt Spring Fault.

Stage 6- Deposition of Ts

The lack of Ts at Chuckwalla Ridge may indicate that the Ttb volcano had built up to form a broad shield with a high at Chuckwalla Ridge. The absence of Ts at Pink/Black Ridge suggests that Pink/Black Ridge was high during Ts deposition. The volcano must have been high enough to deflect the fanglomerates but the restricted distribution of Tpb flows in the center of the study area suggests that the diameter of the volcano was not large (Figure 15f). Thick deposits of Ts near the top of the Squaw Peak section suggest (1) that the Tsp volcanic edifice had low relief, therefore suggesting a shield and (2) the Proterozoic source was nearby. Decreasing abundance of Proterozoic clasts and decreasing overall thickness of Ts to the north and west indicates a source to the southeast for the Proterozoic material. The western boundary of the Proterozoic high coincides with the Salt Spring fault. Uplift along the fault provides a source of clastic material for Ts. In the Salt Spring Wash section, fanning of dip in Ts records approximately 10° of tilting during Stage 6.

Eruption of mafic volcanic lavas continued after deposition of Stage 6 sediments (Ts). In the Salt Spring Wash section, a second fanglomerate is interbedded with Ttbu, suggesting continued uplift along the Salt Spring fault. In the Salt Spring Wash section, Ttbu records approximately 5° of tilting after Stage 6.

Tilting and erosion of the volcanic sections was followed by deposition of younger poorly consolidated gravel deposits (Trs, Tmcl on Plates 1 and 2) grading upward into siltstone and limestone (Tmcu). Basaltic (Tsm) volcanism, represented by dikes and flows accompanied deposition of Trs.

ROCKS OF THE FOOT WALL

The lower plate of the Salt Spring fault is composed of Precambrian basement rock of varying lithologies. Although meta-igneous rocks are dominant at Salt Spring and Senator Tank (Figure 3), where samples were collected, most of Golden Rule Peak and southern portion of Graham Ridge is composed of pelite (garnet schist and gneiss) with minor psammite and granitoid intrusions.

Eighteen samples of lower plate Precambrian crystalline basement rock were collected in Salt Spring Wash and at Senator Tank and were analyzed

petrographically (Appendix D and Table 10). Precambrian crystalline rocks from Senator Tank and Salt Spring Wash have undergone prograde metamorphism as high as lower granulite facies, and retrograde metamorphism as high as upper greenschist facies. Retrograde minerals replace prograde minerals pseudomorphically.

Samples collected from the Precambrian basement rocks belong to 3 major rock types: amphibolite, felsic gneiss, and garnet-biotite and biotite gneiss. Amphibolites contain the prograde mineral assemblage hornblende + clinopyroxene + plagioclase +/- apatite +/- quartz +/- orthopyroxene. Retrograde metamorphism resulted in partial replacement of hornblende by actinolite and chlorite, and nearly complete replacement of clinopyroxene by chlorite and epidote and of plagioclase by sericite and zoisite. Foliation in amphibolite is defined by parallel alignment of hornblende and pyroxene and by compositional banding of hornblende and pyroxene-rich layers alternating with plagioclase-rich layers. Many of the samples, especially those collected at Salt Spring Wash are cut by late stage fractures filled with calcite +/- actinolite. Amphibolites are associated in the field with quartzofeldspathic veins. A mafic igneous protolith may be inferred for these rock.

Felsic gneiss samples contain the prograde assemblage quartz + plagioclase +/- microcline +/- biotite +/- muscovite. These are felsic gneisses and schists which contain minor amounts of sphene, opaques, zircon and apatite. Retrograde metamorphism caused extensive replacement of feldspar by sericite The second s

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AMPHI	AMPHIBOLITE												
PROGRADE AND RELICT MINERALS													
Samplo	Horn-	Clino-	Ortho-	Plagio-		*.							
Number	blende	pyroxene	pyroxene	clase	Quartz	Opaque	Sphene	Apatite					
47	35				10								
79	90				2	2							
80	40	3		10									
60*	22	5	5	3		3							
75*	55	2		1			<1						
76*	45	10					<1	2					

Table 10: Summary of mineralogy for crystalline basement

Sample		RETROGRADE AND INTRODUCED MINERALS										
Number	Actinolite	Calcite	Chlorite	Epidote	Quartz	Sericite	Zoisite					
47	10		10	10		5	20					
79		2	2		3							
80		10	7	10		20						
60*	20	1	5			36						
75*	20	3	5	10		5	10					
76*	20	3		10			10					

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* denotes sample from near detachment surface

percentages are estimated

GARNE	T-BIOTT	TE GNE	ISS					· · · · · · · · · · · · · · · · · · ·	
			PROGRA						
Sample		Plagio-	Musco-			Horn-			
Number	Quartz	clase	vito	Biotito	Garnet	blende	Opeque	Zircon	Sphene
63	20	15	13	5	20		2	<1	
145	32	10		15			3	1	<1
146	. 2		15	30		30			
Sample		RETRO	GRADE AN	ID INTRO	DUCED MI	NERALS			
Number	Actinolite	Calcito	Chlorite	Epidote	Homatito	Sericite	Zoisito		
63		2	10	2		18	3		
145		1	5			30			

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10.00

Table 10: continued

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Table 10: continued

FELSIC	: GNEISS	5							
			PROGR/	ADE AND	RELICT M	INERALS			
Samplo		Plagio-	Micro-		Musco-				
Number	Quartz	cisso	cline	Biotito	vito	Opaquo	Sph ene	Zircon	Apatito
24	20	25	5	2					<1
28	45	20	25		5				
41	40	15	18	3					
44	25	13	15	2		3	4	1	2
45	20	16		2		<1	5	<1	
46	3	10	37		2				
78	45	10	40			:			
147	30			10		3		1	
58*	60								

ATTAL CONSTRUCTION

Sample	RETROGRADE AND INTRODUCED MINERALS											
Number	Calcite	Chlorite	Epidote	Hematite	Opaquo	Sericito						
24	3	8	1		1	35						
28						5						
41	2	2	<1	2	3	15						
44		5	1			30						
45		5	5			45						
46						13						
78						5						
147	5	8		3	5	40						
58*				3	2	35						

* denotes sample from near detachment surface

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and of biotite by chlorite and epidote. Foliation in these samples is defined by parallel alignment of quartz ribbons, biotite grains and zones of grain size reduction in quartz and feldspar. Late stage fractures cut the rock and are filled with calcite and hematite. A felsic igneous protolith may be inferred for these rocks.

Garnet-biotite and biotite gneiss samples contain the prograde mineral assemblage quartz + plagioclase + biotite + muscovite +/- garnet, with minor opaques and zircon. Retrograde metamorphism caused partial replacement of garnet by chlorite, of plagioclase by sericite and zoisite, and of biotite by chlorite and epidote. Foliation is defined by parallel alignment of recrytallized quartz ribbons and biotite grains and by compositional banding of layers of biotite alternating with quartz and plagioclase-rich layers. The rock is associated in the field with quartzofeldspathic veins. Gneisses have a more potassium-rich mineral assemblage than the amphibolite and felsic gneisses with which they are associated in the field. This may indicate a sedimentary or volcaniclastic protolith.

The basement rocks exposed at Salt Spring Wash and at Senator Tank are dominated by meta-igneous rocks of bimodal composition. Possible volcaniclastic protoliths are observed as well. These areas may represent a metamorphosed bimodal volcanic section. Rocks of this type are unlike the garnet-bearing pelitic rocks that dominate much of the Precambrian basement of the Lake Mead region (Duebendorfer, personal communication). Golden Rule Peak and the southern

half of Graham Ridge are dominated by the metasedimentary garnet-biotite gneiss and pelitic schist which are much more common in the Lake Mead region. At northern exposures at the open pit mine, highly hematized two-mica pegmatite veins intrude biotite gneiss. Similar pegmatite veins are exposed throughout Golden Rule Peak, but are less hematized. The breccia in the upper plate of the Salt Spring detachment contains a disproportionate abundance of granitoid and mylonite clasts relative to the observed lower plate rock exposed near the Salt Spring fault. This may suggest that the source of these landslide deposits is farther east or south of the fault.

STRUCTURE

Salt Spring Fault

The Salt Spring Fault is exposed near the eastern edge of the study area (Plate 2). It separates the tilted mid-Tertiary volcanic and sedimentary section in the hanging wall from Precambrian basement rocks in the footwall. The fault surface is exposed almost continuously from Gregg's Hideout to Salt Spring. South of Salt Spring, most of the fault trace is buried beneath alluvium and late Tertiary Red Sandstone (Trs) and Muddy Creek Formation (Tmcl) gravels. A small exposure is present at Dug's Island, 3 miles south of Salt Spring, and the location of the fault at the open pit mine is tightly constrained by the presence of exposures of lower plate crystalline rocks in trenches less than 100 meters southeast of upper plate coarse breccia and volcanic rocks. South of the open pit mine, the fault projects beneath alluvium, and may connect with the Cyclopic

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detachment (Myers, 1985) south of Senator Mountain. In addition, the fault projects northward from Gregg's Hideout, across Lake Mead toward the Lakeside Mine fault (Fryxell et al, in press), and may link with this fault as well.

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Within 200 to 600 meters of the fault surface between Gregg's Hideout and Salt Spring, at Dug's Island and at the open pit mine, the footwall rocks are highly altered and brittlely sheared (Figure 16). The rocks in the highly altered zone consist mostly of hematitic gouge derived from granitoid and/or felsic gneiss. Within 0-50 meters of the fault, the rocks are pervasively sheared to cataclasite. Thirty to two hundred meters from the fault, footwall rocks are cut by a dense network of anastomosing brittle shear zones up to 1 cm wide, spaced between 1 and 20 cm apart. These shear zones separate the rock into lenses of largely undeformed granitoid, gneiss and amphibolite that has undergone strong retrogression to actinolite, calcite, chlorite, epidote, sericite, and zoisite. Spacing of shear zones decreases with distance from the fault, and evidence of shear dies out entirely 200 to 600 meters from the fault. The attitude of the fault surface and the plunge of lineations is variable (Figure 16). North-south trending segments of the fault contain mostly down-dip striae and east-west segments contain oblique and/or strike-slip striae. Upper plate rocks near the fault trace are highly hematized and calcified.

Structures in Hanging Wall

The six east-tilted structural blocks in the hanging wall of the Salt Spring fault are unconformably overlain by: (1) late Tertiary gravel and thin basalt flows



Figure 16. Salt Spring Fault orientation data. Average strike and dip of Anastomosing Brittle Shear Zones (ABSZ) plotted with lineations.

of the Red Sandstone unit; (2) gravel, sandstone, gypsiferous siltstone and freshwater limestone of the Muddy Creek Formation (Tmc); and (3) Quaternary sediments. At Salt Spring Wash, the three upper units of the mid-Tertiary section (Ttbm/Tspm, Ts and Ttbu/Tspu) demonstrate a marked fanning of dip from 30-35° at the base to near horizontal at the top. Growth faulting also affects Tt at Salt Spring Wash (Switzer, personal communication). Elsewhere in the northern White Hills, dips are uniform within structural blocks, varying between 10° and 45°.

Each of the six structural blocks is cut by north- to northwest-striking, westto southwest-dipping high-angle (75°) to moderate-angle (45°) normal faults that repeat parts of the stratigraphic section. A west-dipping normal fault cuts and repeats Tt, Ttbm, Ts and Ttbu in the Peninsula block (Figure 17a). There, flows dip gently (9°-15°) eastward, suggesting that the fault is high-angle. In addition, east-west striking right-lateral faults cut the upper part of the section (Ttbm-Ts-Ttbu) at Teal Coves and the Campanile (Plate 1).

Several southwest-dipping faults repeat the section at Chuckwalla Ridge. Numerous southwest-dipping faults with individual displacements less than 10 meters, and cumulative displacement of approximately 150-200 meters cut the Smith Hill block. A west-northwest trending, southwest-dipping normal fault places Tt against Ttbm at the southern end of the Smith Hill block. Nearly vertical (>85°) dikes (Ttbd) intrude Ttb at Smith Hill and Chuckwalla Ridge and strike east-west, approximately normal to structural grain. The dikes are



mineralogically and chemically similar to the intruded basaltic andesite and may represent feeder dikes for overlying flows. Steeply west-dipping (75°), northtrending basalt dikes (Tsm) intrude interbedded sediments and basaltic andesites on the west side of Chuckwalla Ridge. They are oriented approximately parallel to structural grain and may have intruded along range-bounding normal faults. A southwest-dipping normal fault is proposed as the boundary between the Chuckwalla Ridge and Smith Hill blocks. In constructing Figure 17b, faults with spacings and displacements similar to those in both blocks were inferred to lie between the blocks.

No major structural boundary is apparent between the Smith Hill and Peninsula blocks. A major high-angle normal fault strikes northeast along the northwest side of Salt Spring Wash, and places the upper part of the section in the hanging wall against the lower part of the section in the footwall (Plate 2, Figure 4). Near Salt Spring are a number of east-west striking high-angle normal faults that dip both north and south and offset the upper part of the section (Ttbm-Ts-Ttbu). The upper part of the section is broadly warped in a syncline centered at Temple Bar and an anticline centered between Gateway Cove and Temple Bar (Plate 1). The syncline axis is projected to cross section B-B' and accommodates the structural relief between the Smith Hill/ Peninsula block and the Salt Spring Wash. Alternatively, the difference in structural style between the gently warped and gently dipping Salt Spring Wash block and the more steeply tilted Smith Hill block suggests the presence of a major structure between them,

Figure 18 shows a model in which an earlier growth fault near Salt Spring Wash was abandoned, with later displacement taken up by a younger fault buried beneath Tmc and Quaternary deposits east of Temple Bar. In this case, structural relief is accommodated by greater displacement on the fault east of Temple Bar.

Several west-dipping high-angle normal faults were identified on the west side of the Squaw Peak block. Pink/Black Ridge is cut by numerous northstriking, west-dipping normal faults, producing a series of north-trending ridges which together make up the west-trending Pink/Black Ridge. Flows within each north-trending ridge dip uniformly between 20° and 30° east. The boundary between the Squaw Peak and Pink/Black Ridge blocks is covered by late Tertiary and Quaternary sediments, but is inferred to be a north-striking, down-to-the-west normal fault, similar to those exposed in both blocks (Figure 17c). Spacing between faults increases and displacement along faults decreases from east to west away from the trace of the Salt Spring Fault.

High angle normal faults offset the upper Muddy Creek Formation (Tmcu) on the west side of Chuckwalla Ridge and the Squaw Peak block. Together, the Chuckwalla Ridge and Squaw Peak Blocks form a north-south trending range bounded on the west by a high-angle fault and uplifted relative to Detrital Wash.

Interpretations

Multiple episodes of faulting are evident in the NWH. The Salt Spring fault is a low to moderate-angle structure. The six structural blocks discussed above are cut by moderate- to high-angle northwest-trending faults. Homoclinal



Figure 18. Alternative cross section from Temple Bar area to Salt Spring Wash.

sequences indicate that most faulting and tilting postdated the deposition of Ttbl/Tspl and Tbr/Tt. However, fanning of dip in the Salt Spring Wash section indicates that faulting began there as early as the time of emplacement of the ashflow tuff (Tt). Blocks are bounded by high-angle north-south trending, westdipping faults that formed the present ranges.

PETROGENESIS OF MAFIC VOLCANICS

Three chemically, petrographically and geographically distinct mid-Tertiary. mafic volcanic centers in the northern White Hills (NWH) are documented above (Figures 11-14 and 19). The centers are defined by the Temple Bar, Squaw Peak and Pink/Black Ridge volcanic sections. I refer to each of the three mafic assemblages as magma types in the following section.

ORIGIN OF HIGH K₂O CONTENTS: METASOMATIC OR MAGMATIC

The mafic volcanic rocks in the NWH are basalt, trachybasalt, basaltic trachyandesite and trachyandesite according to the classification of LeBas et al. (1986) (Figure 20 and Table 11). Many samples have high K_2O contents relative to "normal" mafic intermediate volcanic rocks (Figure 21). Tpb samples and some Tsp samples plot within the field of normal calc-alkaline volcanics. Other Tsp samples and nearly all of the Ttb samples have elevated K_2O relative to "normal".

Potassium metasomatism is responsible for high K_2O concentrations in many suites of volcanic rocks in the Lake Mead area (Smith et al., 1990). However, K metasomatism should produce an inverse relationship between K_2O



Figure 19. Harker variation diagrams for mafic volcanic rocks. SiO₂ vs. major element oxides. Units are weight percent. Symbols are defined on Figure 11.



Figure 19, continued.



Figure 20. Classification diagram for mafic volcanic rocks (LeBas, 1986). Symbols are defined on Figure 11.



Figure 21. Alkali enrichment diagram. K₂O plotted against Na₂O. Rectangle defines field for "normal" Andean mafic volcanics (Wilson, 1990). Units are weight percent. Volcanic symbols defined on Figure 11. A=Cretaceous episyenite, B=contact zones around Cretaceous episyenite, C=Proteozoic biotite monzongranite, D=Proterozoic monzogranite, E=Proterozoic twomica monzogranite, W=Tertiary Wilson Ridge Pluton.

	Ttbl		Ttbm							
Sample	139	90	85	51	50	148	65	131	132	134
Rock name	TA	BTA	SB	BTA	BTA	BTA	TA	TA	BTA	BTA
AN	40.71	33.78	43.31	35.32	33.16	29.07	38.31	32.83	44.66	39.07
Quartz	11.17	2.15		1.61	2.08	7.87	5.12	2.86	1.74	6.53
Orthoclase	15.97	25.18	8.16	22.4	21.45	20.85	21.04	21.98	16.91	18.56
Albito	29.31	30.97	26.91	30.46	27.75	26.95	27.08	28.6	24.21	27.92
Anorthite	20.13	15.79	20.56	16.63	13.77	11.05	16.82	13.98	19.54	17.91
Calcite						3.27				
Diopside	4.44	10.18	16.11	13.52	20.19		11.21	12.28	14.49	17.18
Hypersthene	10.68	5.36	1.96	5.1	4.82	14.54	11.82	11.5	11.18	2.35
Olivine		•	17.14							
Magnetite	3.88	3.94	4.49	3.91	3.73	4.04	3.86	3.76	4.05	3.7
Ilmenito	2.24	2.32	3.04	2.28	2.03	2.44	2.2	2.07	2.45	1.99
Anatito	2.42	1.53	1.23	1.39	3.29	2.29	1.46	1.46	3.27	1.51

Table 11: Normative mineralogy of mafic volcanic rocks

Rock names (LeBas, 1986): SB = Subalkalic basalt BTA = Basaltic Trachyandesite TA = Trachyandesite TD = Trachydacite

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	Ttbm 💡								Ttbu		
Sample	135	149	49	140	133	130	86	141	77	88	100
Rock name	TA	TA	BTA	TA	BTA	BTA	TD	SB	BTA	BTA	BTA
AN	31.26	41.1	39.39	35.81	37.71	35.84	14.95	54.55	39.6	36.39	39.19
Quartz	8.06	9.49	1.43	11.02	4.22	3.63	2.55		1.77	0.59	3.8
Orthoclase	24.41	20.22	19.92	19.67	20.63	22.34	25	7.31	19.92	19.92	22.65
Albite	29.11	26.52	25.55	30.57	27.42	39.11	45.44	22.86	28.35	27.92	29
Anorthite	13.24	18.51	15.92	17.05	16.6	16.26	7.99	27.44	18.59	15.97	18.69
Diopside	13.76	4.68	23.92	3.21	10.57	17.11	8.9	20.74	12.59	23.73	1.13
Hypersthene	5.04	12.49	3.7	8.38	9.3	2.07	4,4	10.93	10.78		11.86
Wollastonite										0.69	
Olivine								0.16			
Magnetite	3.61	3.83	3.67	3.56	3.67	3.68	3.44	4.18	3.91	3.61	3.64
Ilmenite	1.88	2.17	1.96	1.82	1.96	1.98	1.65	2.63	2.28	1.88	1.92
Apetite	1.3	2.36	1.46	2.14	2.87	1.3	1.04	2.14	1.44	1.48	2.79
Table	11:	conti	inued								
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	Tpb								Tsm		
Sample	7	10	120	15	117	118	121	123	55	103	114
Rock name	AB	AB	SB	SB	SB	тв	AB	TB	AB	SB	SB
AN	62.69	51.14	44.7	46.97	46.54	40.14	46.14	46.6	53.84	54.46	46.37
Orthoclass	10.34	7.09	10.11	9.22	9.81	7.68	10.99	11.29	6.8	7.09	8.21
Albite	14.05	23.33	28.43	27.67	26.57	28.61	26	25.67	20.34	22.09	27.42
Anorthite	23.62	24.42	22.98	24.51	23.13	19.19	22.28	22.4	23.73	26.41	23.7
Nepheline	6.46	0.52				0.22	1.13	1.54	3.7		
Diopsido	32.77	19.58	17.23	17.56	15	22.03	21.94	20.42	29.95	15.34	17.58
Hypersthene			5.81	9.92	15.53					14.63	4.89
Olivine	1.12	15.26	7.51	3.64	2.27	13.61	8.21	10.07	8	2.42	10.58
Magnetite	4.18	4.36	4.55	4.31	4.29	4.18	4.36	4.44	4.07	4.02	4.29
llmenite	2.62	2.87	3.11	2.79	2.77	2.62	2.87	2.96	2.49	2.41	2.77
Apatite	2.22	0.88	1.23	1.2	1.25	0.97	1.3	1.53	0.88	0.6	0.083
	Tspm						Tspu				
Sample	. 3	21	108	126	127	128	112	113	20		Rock na
Rock name	BTA	TB	TB	TB	TB	BTA	BTA	BTA	BTA		AB = A
AN	37.58	43.06	44.7	40.53	41	47.48	37.51	38.97	36.18	•	SB = Su
Quartz.	0.97					1.09	4.42	4.57			TB = Ti
Orthoclase	23.11	10.22	12.17	12.06	11.17	18.32	23.06	23.83	12.65		BTA =
Albite	26.06	27.92	26.74	29.19	28.94	22	28.88	18.04	33.25		
Anorthite	15.69	21.12	21.62	19.9	20.11	19.89	17.34		18.85		
Nephelino				0.46							
Diopside	11.68	14.34	11.18	17.49	16.1	11.05	5.59	5.26	9.63		
Hypersthene	12.82	6.35	7.31		2.54	18.37	9.39	8.53	4.5		
Olivino		8.28	8.71	8.83	7.55				12.97		
Magnetite	3.91	4.93	4.84	4.68	5.28	3.9	3.69	3.69	3.77		

3.29

1.46

4.06

1.39

2.26

1.41

1.98

2.58

1.98

2.68

2.09

1.39

3.49

1.37

2.28

1.3

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3.61

1.11

Ilmenite

Apatite

Rock names (LeBas, 1986): AB = Alkali basalt SB = Subalkalic basalt TB = Trachybasalt BTA = Basaltic Trachyandesite

and Na₂O due to replacement of Na by K during metasomatism. In the NWH samples, Na₂O contents are similar to those of "normal" calc-alkaline volcanic rocks despite the elevation in K_2O . Therefore, K metasomatism does not appear to be a major cause of the high K_2O concentration in the NWH samples. Because light rare-earth elements (LREE), Th and Hf are equally incompatible with K in basaltic to basaltic andesitic magmas, covariation of these elements with K indicates that K is acting as an incompatible element (Figure 22). Therefore variation of all incompatible elements, including K, is due to a magmatic process and not to metasomatism. The covariation of K_2O and incompatible trace elements may be explained by one of the magmatic processes described in the next section.

HOW ARE THE THREE MAGMA TYPES RELATED PETROGENETICALLY?

Possible processes that may relate the three mafic magma types in the NWH are crystal fractionation, contamination, assimilation-fractional crystallization (AFC) or varying amounts of partial melting of the same or similar sources. Each of these processes is evaluated below.

Contamination

Contamination of a mafic magma with a felsic assimilant should produce a linear trend between the mafic and felsic end members on chemical plots. The mafic end member should be the most chemically primitive rock in the mafic assemblage. Because there are no truly primitive basalts (Mg#s are all <0.65), a



Figure 22. Binary chemical plots. Weight percent K₂O plotted against ppm incompatible Ce, Hf, La, and Th. Symbols are defined on Figure 21.

mafic end member cannot be positively identified. Therefore, models were attempted using several of the most primitive samples. Successful models are reported in Table 12. Potential contaminants used in models are Proterozoic monzogranite and biotite monzogranite. Because no felsic volcanic rocks are present in the NWH, it is unlikely that mafic magma mixed with felsic magma of Tertiary age such as Wilson Ridge-type magmas described by Larsen and Smith (1990). In addition, Wilson Ridge samples have incompatible trace element concentrations too low to be suitable contaminants (Figure 22).

The lack of petrographic evidence for contamination precludes large amounts of assimilation in NWH samples. Disequilibrium textures (pitted and resorbed plagioclase) are common in NWH rocks, particularly in Ttb samples, but may be attributable to reequilibration of high pressure phases. Conclusive textural evidence for contamination, such as resorbed and skeletal inclusions, disequilibrium mineral assemblages, and rimmed xenocrysts is absent.

Fractional Crystallization

Fractional crystallization would result in a continuous linear relationship between the three magma types on Harker variation diagrams and other binary plots (i.e., Figures 19 and 23). There may be inflections or changes in slope, reflecting the fractionation of different phases, but lines for each of the three magma types should form a single trend. Compatible trace element plots (Figures 24 and 25) show: (1) substantial overlap of the three fields; (2) no continuous trend connecting the three magma types; and (3) a general similarity in the

Model #	1	2	3	4	5	6	7
Phase							
Olivine	-5.84	-4.98	-6.54	-7.52	-6.23	-6.77	-6.16
Clinopyroxene		-5.94					
Plagioclase				-2.67	-2.55		
Monzogranite					31.82	26.18	
Biotite Monzogranite							2.77
Total % subtracted	5.84	10.92	6.54	10.19	8.78	6.77	6.16
Total % added					31.82	26.18	2.77
Residuals							
SiO2	1.49	1.42	1.08	0.5	-0.22	-0.17	0.66
A12O3	-0.61	-1.06	-0.54	-0.09	-0.6	-0.54	-0.26
FcO*	-0.89	-1.23	-0.56	-0.59	-1.5	-1.48	-0.63
CeO	-1.83	-0.96	-0.03	0.35	0.44	0.56	-0.82
MgO	0.25	42	0.52	0.6	0.73	0.78	0.25
N=20	0.41	0.26	-0.39	-0.61	0.36	-0.1	0.22
K2O	0.62	0.52	0.41	0.35	0.93	1.09	0.27
TiO2	0.55	0.64	-0.49	-0.51	-0.13	-0.14	0.3
Sum of squares							
of residuals	7.64	6.49	2.6	1.85	4.66	4.4	1.84
Model #		8	9	10		12	13
Phase							
Olivine		-2.94	-3.72	-2.8	-5.76	-8.7	-11.81
Clinopyroxene						-15.67	-7.48
Plagioclase				-6.31		-7.92	-0.69
Monzogranite		11.19	13.37	25.46			
Biotite Monzogranite							
Total % subtracted		2.94	3.72	9.11	5.76	32.29	19.98
Total % added		11.9	13.37	25.46			
Residuals							
SiO2		-0.21	0.15	0.09	1.44	0.51	0.56
A12O3		-0.01	-0.25	-0.28	-0.38	0.23	0.18
FeO*		-0.25	0.45	-0.49	-0.78	-0.59	-0.83
CaO		-0.4	0.6	0.45	-0.95	0.01	0
MgO		-0.01	0.38	0.34	0.57	0.75	0.88
Na2O		0.3	-0.33	0.17	0.01	-0.75	-0.95
K2O		0.18	0.33	0.15	0.17	-0.11	0.65
TiO2		0.39	-0.43	-0.43	-0.08	-0.05	-0.49
Sum of squares							
of residuals		0.54	1.2	0.89	4.09	1.8	3.36

Table 12: Major element fractional crystallization and AFC models

Model descriptions:

1,2,7,8: Parent=Primitive Tpb (10), daughter=primitive Tsp (127)

3,4,9,10: Parent=Primitive Tsp (127), daughter=primitive Ttb (132)

5 and 6: Parent=Primitive Tpb (10), daughter=primitive Ttb (132)

11: Parent=primitive Tpb (10), daughter=evolved Tpb (117)

12: Parent=primitive Ttb (132), daughter=evolved Ttb (138)

13: Parent=primitve Tsp(127), daughter=evoloved Tsp (112)

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Figure 23. Harker variation diagrams. Weight percent SiO₂ plotted against incompatible ppm Ce, Hf, La and Th. Symbols defined on Figure 21.



Figure 24. Tests for olivine and clinpyroxene fractionation. V plotted against Co and Cr, Co plotted against Cr and Sc. Fractionation vectors plotted on right side. Units are ppm. Symbols defined on Figure 21.

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Figure 25. Harker variation diagrams. Weight percent SiO₂ and Mg# plotted against ppm compatible elements Co, Cr and V. In a and b, steep trends suggest fractionation of cpx and/or ol. In c and d, steep trends suggest cpx fractionation and shallow slopes suggest ol fractionation. In e and f, steep trends suggest ol fractionation and shallow slopes suggest cpx fractionation. Symbols defined on Figure 21.

compatible element contents for the least evolved rock of each magma type. These observations suggest that the three magma types are not related by a fractional crystallization process.

Major element modelling (Table 12) confirms that no combination of olivine, clinopyroxene and/or plagioclase fractionation can produce Ttb from Tpb without significant contributions from the crystalline basement. Models 1 and 2 for producing primitive Tsp (sample 127) from primitive Tpb (sample 10) by fractionation alone have high residuals and cannot be considered successful. Residuals for models 3 and 4 for producing primitive Ttb (sample 138) from primitive Tsp (sample 127) are neither low enough to be conclusive nor high enough to be prohibitive of a fractionation relationship between Tsp and Ttb.

Assimilation-Fractional Crystallization (AFC)

XLFRAC models 5 and 6 (Table 12) for producing primitive Ttb (sample 132) from primitive Tpb (sample 10) requires 26% or 32% contamination by Proterozoic monzogranite with fractionation of 7% olivine or 6% olivine + 2.5% plagioclase. However, assimilation of such a large volume of felsic material by a basaltic magma is unlikely and would certainly have produced distinctive petrographic evidence.

Addition of a contaminant improves models for producing primitive Tsp (sample 127) from primitive Tpb (sample 10). Addition of 11% monzogranite (model 7) or 2% biotite monzogranite (model 8) improves XLFRAC models for fractionation of olivine. Small quantities (<5%) of contaminants can be

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assimilated by basaltic magma without leaving significant textural evidence. However, TiQ₂ concentration and Mg# preclude these models. The modelled evolved magma (primitive Tsp) has higher TiQ₂ than the proposed parent (primitive Tpb), but the contaminant is low in TiQ₂. TiQ₂ content should decrease rather than increase during such an AFC process. In addition, primitive Tsp samples have Mg#s higher than primitive Tpb samples. Evolution by fractional crystallization should result in a decrease in Mg#.

AFC models for evolution of Ttb from Tsp (models 9 and 10) have lower residuals than models for fractionation alone. However, the lack of petrographic evidence for assimilation precludes the large amount of assimilant (13% and 25%) required by the models.

Source differences

Differences between the three magma types may be explained by either (1) different degrees of partial melting from the same source, or (2) independent melting of different sources to the same degree.

Partial melting of the same source should result in highest
concentrations of incompatible elements at the lowest degrees of partial melting.
The large volumes of incompatible-rich volcanics (Ttb and Tsp) in the NWH
would require large degrees of partial melting of an incompatible-rich source.
Partial melting of the same source should produce positive linear trends on
incompatible element plots. Although incompatible element plots of NWH
samples show positive trends, fields overlap or are parallel and do not form a

linear trend (Figures 22 and 23).

2. Independent melting of different sources to the same or a similar degree may explain the non-linearity of fields in Figures 22 and 23. This is consistent with the fact that compatible trace element values for the most primitive samples within each magma type are similar.

Conclusions

Neither fractionation, AFC nor partial melting of the same source can produce Ttb or Tsp from Tpb. Although the three coeval NWH magma types may be cogenetic, they are not comagmatic. They formed by independent partial melting of different (although similar) sources.

All three magma types contain olivine as an equilibrium phase. Therefore, olivine must have been in equilibrium in the source (Yoder, 1976). One possible crustal source is olivine gabbro, but very large degrees of crustal melting would be required to produce the mafic NWH magmas. An alternative source is mantle peridotite, which would require lesser degrees of partial melting. Partial melts of garnet peridotite would have steep slopes on chondrite-normalized REE plots, so spinel peridotite is a more likely source material for the NWH mafic magmas.

CHEMICAL VARIATION WITHIN EACH MAGMA TYPE

Pink/Black Ridge Basalts

The fractionation of Mg and Fe-rich phases in Tpb samples is suggested by the steep negative trends in plots of SiO2 vs. FeO and MgO (Figure 19, c and d). In Figure 24, the large variation in Co with little variation in V, the positive relationship between Co and Cr, and the flat slope in the plot of Co vs Sc indicate fractionation of olivine. On Harker variation diagrams steep slopes for Cr and Co and shallow slopes for V (Figure 24, a and c) favor olivine fractionation as well. Clinopyroxene is unlikely as a major fractionating phase in Tpb magma because Cr, Co and V have high distribution coefficients (Table 13) for clinopyroxene, and these elements appear to have low bulk distribution coefficients in Tpb samples. This is consistent with the lack of clinopyroxene phenocrysts in Tpb samples. Plagioclase cannot be a major fractionating phase as CaO and Na₂0 vary little despite variation in Eu (Figure 26). This is consistent with the lack of a negative Eu anomaly on a chondrite-normalized REE plot (Figure 27) and the lack of plagioclase phenocrysts in Tpb samples.

XLFRAC model 11 (Table 12) indicates that evolved Tpb (sample 117) can be produced from primitive Tpb (sample 10) by fractionation of 6% olivine. Large residuals for the model suggest that another process may be at work. A second process, such as contamination or multiple sources is also suggested by the large range in heavy rare-earth elements (HREE) and tighter clustering in light rare-earth elements (LREE) (Figure 27). Fractionation of olivine results in a

	Plagio-	Clino-		
	clase	ругохеве	Olivine	
Ba	0.355	0.1505	0.0055	
RЬ	0.185	0.031	0.0055	
Ce	0.1255	0.103	0.0022	
Nd	0.0915	0.236	0.0034	
Sm	0.059	0.438	0.0059	
Eu	0.34	0.51	0.0068	
ҮЬ 👘	0.038	0.605	0.0177	
Lu	0.06	0.56	0.016	
Sc	0.004	3	0.25	
Cr	0.01	8.4	2.1	
v	0.01	3	0.09	
Co	0.05	1.2	3.8	
ТЪ	0.0055	0.007	0.0055	

Table 13: Distrib	ution coeffici-	ents for basalt
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Figure 27. Chondrite-normalized rare earth element plot for basalt of Pink/Black Ridge.

greater variation in HREE than LREE because distribution coefficients for LREE in ol are higher than those for HREE. Multiple pulses of magma, each representing slightly different amounts of melting from similar sources, may be responsible for the variation in LREE in Tpb samples.

Basaltic Andesite of Temple Bar

The moderate negative trend on plots of SiQ₂ vs. FeO, MgO and TiQ₂ (Figure 19 c, d and g) indicates fractionation of Mg- Fe- Ti-bearing phases such as olivine and/or clinopyroxene. Compatible element plots (Figure 24) suggest that both phases are probably significant. For example, fractionation of clinopyroxene alone would produce a slope of +3 on the Cr vs. V plot, and fractionation of olivine alone would produce a vertical vector. The Ttb vector fall between the olivine and clinopyroxene vectors and indicates the fractionation of both minerals. Each of the plots of compatible elements produces similar results. Moderate slopes on Harker variation diagrams for compatible trace elements (Figure 25) also indicate fractionation of olivine and clinopyroxene. Little change in CaO and Na₂O (Figure 26) and the lack of a Eu anomaly on Figure 28 suggests little fractionation of plagioclase.

XLFRAC model 12 (Table 12) for evolution of evolved Ttb (sample 138) from primitive Ttb (sample 113) requires fractionation of 9% olivine, 16% clinopyroxene and 8% plagioclase. However, the modelled fractionation of plagioclase is higher than expected and total fractionation (32%) is higher than generally considered reasonable for volcanic rocks. This may indicate that



Figure 28. Chondrite-normalized rare earth element plot for basaltic andesite of Temple Bar.

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. . another process in addition to fractionation is responsible for Ttb evolution. The wide range of Th over a fairly narrow range of SiO₂ (Figure 23) suggests contamination or several different partial melts for Ttb. Because Th is incompatible in basalts, it should not vary with fractionation. As discussed above, large degrees of contamination are precluded by the lack of petrographic evidence. The wide spread in chondrite-normalized REE data (Figure 28) suggests multiple batches of partial melts. Input of fresh batch melts is consistent with the lack of systematic variation in chemistry and mineralogy vertically in the sections.

Basaltic Andesite of Squaw Peak

Fractionation trends within the Tsp field are similar to Ttb. Olivine +/clinopyroxene fractionation is indicated by the moderate negative trend on plots of SiQ₂ vs. FeO, MgO and TiQ₂ (Figure 19). Both phases are probably significant, because variation in Co, Cr, Sc and V (Figure 24) is similar to that in Ttb. However, the shallower slope on the plot of Sc vs. Co may suggest olivine fractionation is more important for Tsp than for Ttb. Moderate slopes on Figure 25 also indicate fractionation of olivine and clinopyroxene. The negative relationship between CaO and Eu (Figure 26) may suggest minor plagioclase fractionation. However, the lack of an Eu anomaly (Figure 29) indicates that fractionation of plagioclase was insignificant in comparison with fractionation of clinopyroxene and olivine.

The moderate positive relationship between SiO₂ and Hf may suggest that



Figure 29. Chondrite-normalized rare earth element plot for basaltic andesite of Squaw Peak. Two magma types are delineated by flat HREE trend (dashed lines) or gently sloping HREE trend (solid lines)

some process, either contamination or multiple recharge was active in producing the Tsp suite. Chondrite-normalized REE data (Figure 29) may indicate two subtypes of Tsp magma, one high in LREE and low in HREE and another lower in LREE and higher in HREE. I propose that the Tsp chamber may have been fed by multiple pulses of partial melts from at least two different sources. One source was chemically similar to or the same as that for Ttb magmas.

XLFRAC model 13 produced the most evolved Tsp sample (112) from the least evolved sample (127), by fractionation of 12% olivine, 7% clinopyroxene, and <1% plagioclase. However, as with many other models, residuals are high and suggest that some other process such as assimilation was active in addition to fractionation.

SUMMARY

The mafic volcanic rocks of the NWH comprise three distinct magma groups in terms of chemistry, petrography and spatial distribution. Each magma type may represent independent batch melts from similar high K_2O sources. Adding to the complexity, each magma type may represent many independent magma pulses formed by partial melting. Each of the magma batches underwent a different differentiation history. Tpb evolved by fractionation of olivine alone. Ttb and Tsp both evolved by fractionation of olivine, clinopyroxene and minor plagioclase. The evolution of each magma type may be complicated by the addition of small amounts of a crustal contaminant and continued recharge of the magma chambers by new partial melts.

REGIONAL CORRELATION

MID-TERTIARY VOLCANIC ROCKS

The mafic volcanic rocks in the northern White Hills (NWH) erupted from local sources. Therefore, regional correlation of the mid-Tertiary volcanic section depends on correlation of regionally extensive units such as ash-flow tuffs. Two ash-flow tuffs crop out in this part of the Basin and Range; the Peach Springs Tuff (18.5 Ma) and the Tuff of Bridge Spring (15.18 Ma). I propose that the ashflow tuff exposed in the NWH is correlative with the Tuff of Bridge Spring. In addition, I propose that the Tuff of Bridge Spring is composed of two major pyroclastic flows. The first is exposed in the southern Black Mountains, McCullough Range and NWH (Figure 30) and erupted at 16.4 Ma. The second erupted at 15.19 Ma and crops out in the Eldorado Range.

Correlation of the tuff in the NWH with the Tuff of Bridge Spring is based on similarities in mineralogy and chemistry. The Tuff of Bridge Spring in the Eldorado Range contains abundant phenocrysts of sanidine, lesser amounts of plagioclase and biotite, minor quartz and trace amounts of clinopyroxene and sphene (Anderson, 1971). It is therefore mineralogically similar to the tuff in the NWH. The Peach Springs Tuff is similar in mineralogy to the Tuff of Bridge Spring (sanidine + plagioclase + sphene), but contains up to 2% hornblende and only trace amounts of biotite (Young and Brennan, 1974).

The NWH tuff and the Tuff of Bridge Spring are chemically similar (Tables 14 and 15), but both differ from the Peach Springs Tuff. The Peach



Figure 30. Regional exposures of the Tuff of Bridge Spring. After Anderson (1971), Bridwell (in preparation), Davis (1984), Faulds (personal communication) and Schmidt (1987).

	Eldorado	Mountain	s Tuff of l	Bridge Spr	ing						
Sample No.	BS 10	BS 12	BH-1	BH-2	BH-3	BH-4	BH-5	BH6	BH-7	BH-8	BH9
Source of Data	1	1	2	2	2	2	2	2	2	2	2
SiO2	64.99	70.22	65.8		67.06		66.1		66.58		64.79
A12O3	16.54	14.53	14.24		14.56		14.56		14.97		16.48
FeO+Fe2O3	2.04	1.74	2.96	2.45	3.46	1.47	2.4	4.83	2.39	1.96	2.68
C=O	2.07	2.55	1.42	1.66	1.01	0.82	0.7	0.91	0.69	0.63	0.67
Mgo	1.34	2.72	2.21	2.67	1.92	3.15	3.12	3.53	2.85	2.43	. 2.00
Na2O	4.59	1.65	2.45	2.16	4.04	3.27	3.98	12.53	4.08	2.51	4.72
K20	6.27	4.55	4.69	5.72	5.44	3.62	5.51	5,74	5.68	5.45	5.28
TiO2	0.5	0.39	0.6		0.51		0.41		0.47		0.52
MnO	0.06	0.06	0.08		0.07		0.07		0.07		0.0
P2O5	0.09	0.08	0.25		0.11		0.07		0.06		0.1
LOI	2.2	9.2	5.61		1.3		2.24		1.88		0.5
Total	100.69	107.69	100.47		99.59		99.23		99.88		98.1

Table 14: Major element data for Tuff of Bridge Spring and Peach Springs Tuff

Sample No.	BH-11	BH-12	BH-13	85-63	MC 62	MC 68	MC 71	MC 65	MC 61	MC 67	MC 64B	MC 53	MC 60	MC 69	MC 64A	MC 66
Source of Data	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3
SiO2				66.81	67.27	65,46	69.27	66,583	66.47	68.12	66.69	64.65	63.9	68.4	65.09	66.69
AI2O3				15.06	13.95	14.23	14.88	14,468	14.92	14.6	13.72	15.66	14.77	14.46	13.72	14.48
FeO+Fe2O3	1.27	1.3	2.06	2.52	2.27	3.19	2.93	3.727	3.47	2.91	3.11	3.95	3.55	3.07	3.11	3.16
C=O	0.53	0.52	0.66	1.6	2.36	3.43	0.65	0.497	1.72	1.69	0.65	2.43	3.24	1.61	5.66	4.12
Mgo	0.98	0.72	1.21	0.71	0.58	0.66	0.4	0.935	0.86	0.61	1	0.97	1.05	0.53	1.42	0.84
N=20	2.54	3	2.99	4.33	3.97	4.1	4.44	4.042	4.33	4.38	3.86	4,33	4.09	4.33	3.35	3.74
K20	4.71	4.01	4,44	5.92	5.99	5.82	6.15	3.721	6.17	5.94	6.4	6.03	5.67	5.85	4.69	5.77
TiO2				0.43	0.35	0.42	0.41	0.453	0.47	0.39	0.42	0.53	0.45	0.4	0.42	0.43
MnO				0.09	0.152	0.143	0.15	0.152	0.151	0.149	0.143	0.151	0.151	0.146	0.151	0.149
P2O5				0.02	0.1	0.13	0.09	0.151	0.16	0.11	0.13	0.18	0.16	0.09	0.4	0.33
LOI		<i>,</i> •		2.57	2.04	2.56	0.56	4.11	1.14	1.38	0.65	1.27	1.97	1.33	1.48	3
Total				100.06	<u>99.03</u>	100.14	99.93	98.84	99.86	100.28	96.77	100.15	99	100.22	99.49	102.7

Table 14: continued

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	Peach Spring	es Tuff (data s	iource 4)					<u> </u>			-		
Sample No.	H83M-21	H830W-163	3 H830W-164	H84CH-71	H84AE-58	JP83K1-40	JP84EP-1	JP82TM-88	1-177	PCMS-15	TPS-RF	TPS-SNG	JPS2CH-16
Location	Ship	Old Woman	Old Woman	Chomobuovi	Arica	I~40, east	Secremonio	Pyramid	Bullion	Pacific	Mobave	Chomebuevi	Chomebuovi
	Mountains	Mountains	Mountains	Mountaina	Mountains	of Kingman	Mountains	Butto	Mountains	Moes	Mountains	Mountains	Mountains
SiO2	74.7	70.4	72.3	73.2	73.5	73.5	68.6	66.6	73.3	64	75.7	70.5	70.7
A12O3	12.6	13.1	12.9	12.8	10.8	13.4	15.3	12.3	13.3	13.8	11.8	12.7	13.1
FeO+Fe2O3	1.33	1.3	1.39	1.1	1.12	1.51	2.28	1.14	1.27	2.07	1.22	1.28	1.53
CaO	0.94	1.27	1.05	0.27	3.44	0.78	0.99	5.34	0.86	4.97	0.32	3.04	1.53
Mgo	0.24	0.28	0.31	0.42	0.23	0.35	Ö.4	0.56	0.29	0.75	0.21	0.39	0.46
N=20	3.68	4.3	4.08	3.11	2.78	3.75	3.35	3.48	3.42	1.2	2.21	3.64	2.54
K2O	5.27	3.58	4.23	5.78	4.92	5.33	7.21	5.01	5.54	6.03	6.81	5.17	7.35
TiO2	0.25	0.24	0.25	0.2	0.21	0.28	0.45	0.2	0.22	0.36	0.2	0.23	0.28
MnO	0.05	0.06	0.06	0.06	0.06	0.06	0.04	0.05	0.06	0.03	0.04	0.04	0.05
P2O5					0.05			0.07	0.07	0.1			
LOI	0.32	3.95	2.52	2.01	0.45	0.35	0.14	0.43	0.52	1.86	0.42	0.29	0.39
Total	99.38	98.48	99.09	98.95	97.56	99.31	98.76	95.18	98.85	95.17	98.93	97.28	97.93

Data Source codes:

I: Cascadden, unpublished data

2: Smith, unpublished data

3: Bridwell, in preparation

4: Nielson, written communication

	Eldorado	Mountains	Tuff of Bri	dge Spring								Dolan Spr	ings*
Sample	BS 10	BS 12	BH 1	BH 2	BH 3	BH 4	BH 5	BH 6	BH 7	BH 8	BH 9	DS 10	DS 17
La		,	77.63	85.73	94.28	92.68	95.01	108.43	134.48	162.44	114	50.3	44.8
Ce			205.39	209.92	227.51	205.86	229.84	226.5	285.78	349.04	243.98	69.9	63.1
Nd			56.3	58.36	64.65	69.58	72.93	80.52	87.58	87.47	63.5	14.1	14.8
Sm			10.14	11.86	13.54	12.43	13.42	14.57	14.57	13.29	10.73	2.47	2.44
Eu			1.74	1.89	1.81	1.55	1.71	1.76	2.66	3.64	2.7	0.389	0.281
ть			1.44	1.13	1.55	1.39	1.52	1.54	1.32	1.4	1.15	1.39	0.345
УЪ			2.55	2.8	3.08	2.92	3.18	2.99	2.67	2.31	2.13	0.15	1.56
Lu			0.4	0.42	0.48	0.51	0.49	0.49	0.46	0.39	0.38	4.94	0.21
U.			6.408	8.67	8.89	10.37	9.85	. 9.08	7.61	4.98	6.52	20.2	4.04
Th			35.69	40.89	46.01	48.46	47.67	47.46	37.55	33.48	34.59	7.19	23.1
Cr			59.07	43.93	91.15	25.38	28.53	26.81	18.32	12.82	19.66	3.77	9.81
Hf			9.29	9.51	10.37	11.19	10.59	10.12	10.86	13.51	12.29	346	3.88
Ba	134:	3 37	1 383.63	355.72	279.73	275.02	267.91	206.07	634.13	1142.2	1184.1	113	190
Rb	131	l 16	2 184.28	208.55	224.14	214.67	225.36	205.97	179.57	165.56	170.48		117
Sr	47(5 31	0 59.07	43.93	91.15	25.38	28.53	26.81	18.32	12.82	19.66	i	1590
Sc			6.97	6.21	5.68	4.74	5.02	2.01	5.48	7.05	5.31	2.46	1.83
Та			1.85	5 2.06	2.21	2.16	2.32		1.68	1.35	1.83	1.09	2.06
Zr	39-	4 28	0										1.83
Co												1.49	1.47
v												16.9	9.79

Table 15: Trace and rare earth element data for Tuff of Bridge Spring and Peach Springs Tuff

Sources of data same as Table 12

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* = source #1

	McCullou	ch Mountai	os Tuff of l	Bridge Sprin	ng								
Sample	BH 11	BH 12	BH 13	85-63	MC 62	MC 68	MC 71	MC 61	MC 67	MC 64B	MC 53	MC 60	MC 69
La	107.84	98.99	93.99	120.63	92.1	91.7	101	91.5	94.5	96.3	118	93.2	93.4
Co	247.08	231.33	226.33	190.85	184	177	188	167	173	181	204	170	184
Nd	72.93	74.23	71.51	64.34	55.3	63.7	80.9	75.2	79.8	67.3	73.4	64	57
Sm	14.92	13.64	13.77	11.48	11.1	11.8	13.7	11.3	12.8	11.5	9.67	8.33	12.1
Eu	1.71	1.63	1.72	1.72	1.01	1.22	1.17	1.33	1.14	1.11	1.78	1.7	1.22
ТЪ	1.78	. 1.58	1.53	Q.8	1.1	1.17	1.26	1.41	1.16	1.06	0.934	0.86	1.27
чь	3.44	3.12	3.27	3.12	3.5	3.36	3.77	3.92	3.62	3.76	2.87	3.14	3.56
Lu	0.56	0.5	0.52	0.45	0.6	0.54	0.63	0.48	0.56	0.58	0.42	0.41	0.49
U	9.02	10.51	11.49	4.69	10.9	7.23	8.42	6.36	8.66	8.86	6.26	5.42	8.47
Th	52.3	50.28	47.88	32.22	44.3	39.4	42	35.8	39.3	44.6	28.6	17.3	41.9
Cr	20.75	37.21	43.16	10.23	9.94	20.9	11.2	. 35.2	. 11.7	15.5	5 32	45.3	10.4
Hf	11.45	9.99	10.53	11.05	10.6	10.1	11.3	9.78	10) 11.1	10.3	10.1	11
Ba	221.44	233.24	198.51	816.04	170	303		390)	296	5 818	927	1
RЪ	248.18	219.61	254.42	156.79	172	165	173	160	155	5 170) 121	127	179
Sr	20.75	37.21	43.16	264.97		200	196	3.89	219	389	502	781	168
Sc	4.25	4.45	4.56	4.13	3.23	3.85	3.25	5 2.4	3.16	5 3.63	4.67	4.21	3.39
Ta	2.43	2.32	2.41	2.31	2.71	2.36	2.76	5 826	5 2.44	2.1	7 1.74	1.86	5 2.56
Zr				390.09	553	544	663	3.41	455	5 57	7 578	483	603
Co					1.96	3.9	1.93	44.6	5 1.96	5 2.84	4.17	3.68	2.45
v					23.3	31	34.3)	23.0	5 29.	5 39.7	35.3	30
<u>.</u>	Peach Spr	ings Tuff		_	2.3		34		23.0	<u> </u>	39.1	33.3	,
Sample I	N H83M-21	H830W-	163 H83OV	V-164 H840	CH-71_H84	AR-58 JP	83KI-40 J	P84EP-1 J	P82TM-88	I-177 T	PS-RF TP	S-SNG JP	82CH-16
Hf	8.67	8.	83	8.87	7.94	6.81	9.25	13.5					
Ba						•			82	47	116	138	251
Rb	165	2	45	225	205	135	185	175	173	195	240	175	212
•	34		80	100		110		215	<i>7</i> 0	47		<i>~</i> ^	60

1.88

2.55

1.76

1.76

2.66

2.59

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Table 15: continued

Ta

Zr

2.24

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Springs tuff is a rhyolite, (Nielson, written communication, 1991) while the tuff in the NWH and the Tuff of Bridge Spring are dacitic. In addition, compatible and incompatible element fields for the NWH tuff and the Tuff of Bridge Spring overlap (Figures 31 through 34). As chemical zonation is common in ash-flow tuffs (Smith, 1979), variation in major element and compatible trace element compositions in the NWH samples is not unexpected. However, incompatible elements such as Hf, Ta and Nb are best for ash-flow tuff correlation (Hildreth and Mahood, 1985). Therefore, the tight clustering of incompatible elements suggests a common source for the Tuff of Bridge Spring in the Eldorado Range and the tuff in the NWH. Although the Peach Springs Tuff has a similar range of Rb, Hf and Ta concentrations (Figures 31 and 32), it is higher in SiO₂ and lower in Ba (Figure 32) and in total Fe, MgO, TiO₂ and MnO (Figure 33) than most of the NWH samples.

The Peach Springs Tuff was dated at 18.5 + /-0.2 Ma (Nielson et al., 1990). The tuff in the NWH yielded a K-Ar biotite date of 16.4 + /-0.5 Ma (Table 8). Faulds (1989) reported similar biotite K-Ar ages (16.4 and 15.9 + /-0.36 Ma) for a tuff in the southern Black Mountains (Figure 29), that can be traced northward into the central Black Mountains, where it contacts small rhyolite or dacite centers in the middle Patsy Mine Formation (Faulds, personal communication, 1991). Bridwell (in preparation) dated a tuff from the McCullough Range that he correlated with the Tuff of Bridge Spring at 16.6 + /-0.4 Ma (K-Ar on biotite). These four dates contrast with a date of 15.18 + /-0.2



Figure 31. Harker variation diagrams comparing NWH tuff (symbols defined on Figure 7) with the Tuff of Bridge Spring Eldorado Range (inverted triangles), Tuff of Bridge Spring from the McCullough Range (*), and Peach Springs Tuff (#). SiQ₂ in weight percent. V, Co and Cr in ppm.



Figure 32. Harker variation diagrams comparing NWH tuff with the Tuff of Bridge Spring and Peach Springs Tuff. SiO₂ in weight percent. Hf, Sc and Ta in ppm. Symbols defined on Figure 31.



Figure 33. Harker variation diagrams comparing NWH tuff with the Tuff of Bridge Spring and Peach Springs Tuff. SiO₂ in weight percent. Ba and Rb in ppm. Symbols defined on Figure 31.



Figure 34. Harker variation diagrams comparing NWH tuff with the Tuff of Bridge Spring and Peach Springs Tuff (#). Units are weight percent. Symbols defined on Figure 31.

Ma (40 Ar/ 39 Ar) reported by Gans (1991) from the Tuff of Bridge Spring in the Eldorado Range.

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I propose that the Tuff of Bridge Spring is composed of two pyroclastic flows. The tuffs in the NWH, southern Black Mountains and McCullough Range (White Hills member) may represent an earlier eruption from the same source which erupted the Tuff of Bridge Spring in the Eldorado Range (Eldorado Member) 1 to 1.5 m.y. later. This model requires that the magma chamber undergo two cycles of recharge from the same or a similar source followed by similar evolutionary paths to develop two magmas nearly identical in composition but erupted 1 to 1.5 m.y. apart. Similar episodic or cyclic pyroclastic eruptions have been described in western North America. Intervals between ash-flow tuff eruptions from the same caldera system (Table 16) range from 0.2 to 2.4 Ma. In general, magmas erupted after a longer (>1 Ma) period of quiesence tend to be more fractionated than the earlier magma (i.e., the Valles Caldera and the earlier stages of the Platoro complex). When intervals between the eruptions are shorter (<0.5 Ma) magmas from the later eruptions tend to be less fractionated than the earlier magmas (i.e., the western San Juan complex and the later stages of the Platoro complex). When intervals are between 0.5 and 1 Ma, the erupted magmas are very similar mineralogically and chemically (i.e., the Heise, Yellowstone, and Kane Spring Wash volcanic fields).

Chemical evidence supports the premise that the McCullough Range and NWH comprise a separate member of the Tuff of Bridge Spring. The broader

Table	16:	Episodic	ash-flow	tuff eruptions from
		selected	calderas	in North America

			فالاراد المكمر المسيمة فلنسير فالاشترين ومعيور والمستعادين وتعيير والس
California	D	Interval Determine	
Caldera	Date of	Reimeen	Comments.
System	Eruption	Eruptions	Comments
Pistoro,	32 Ma		Lanna is 6:02
New Mexico	60 6 1 6	2.5 Ma	Increase in SiO2
(1)	29.5 Ma		
	~ ~ ~ ~	0.2 Ma	
	29.3 Ma		
		0.1 Ma	
	29.2 Ma		General decrease in SiO2
		0.2 Ma	
	29.0 Ma		
		0.6 Ma	
	28.4 Ma		
Western	28.8 Ma	o	
San Juan,	08 4 14	U.4 M8	
New Mexico	28.4 Ma	A (14)	0
(2,3)	07 4 14	U.0 MA	General decrease in SiU2
	27.8 Ma		
		0.2 Ma	
	27.6 Ma		
Valles,	2.84 Ma	o	Erupted from zoned chambers, latter
New Mexico	1 45 14.	2.4 ME	two episodes are more shirit man
(4)	1.43 M2	0.22.14.	the first, yet similar with respect
	1.12.14.	0.33 Ma	to non-iraculorated elements.
Vallouistona	2.0.14		
Wyomine	2.0 Mit	0716	High-cilias shualitas, and similar
15 6)	12.14	0.7 Ma	mineralogically and chemically
(3,0)	L.J MIL	07.00	Enneralogically and chemically
	0616	0.7 Miz	
Maine Mal	0.0 MIZ	<u> </u>	
	0.3 MR ·	0.0.1/-	
Idaho	5634-	U.Y M2	19~1/70 Silica, all enfiched in LKEE,
	J.U MI	1 3 1/-	cach ash-now similar chemically
(7)	4 3 34-	1. <i>3 (</i> 412	
Kane Springe	15 6 kG	·····	
Wesh Neveda	13.0 MIL	0 0 M-	Two or three centrate centers eminted
(\$)	14 7 14-	V.7 MIZ	compositionally similar ash-flow biffs
(0)	17.7 NIL	0614-	combosinonsità sumist seg-non muz
	14 1 14-	O.U MIE	
Los Humeros	0 46 Ma		High-siling shuality to desite in first
Mexico	VITU MIE	0.36 M-	enotion throdesite to endesite in test
(0)	0 I M•	0.30 MIE	Fruntion rate > replanishment rate
Uncan et el	1020		6 Wildreth et el 1094
2. Lipman et al., 1989			7 Morean et al. 1984
. Lopend Line	, 1707 nan 1090		R Novek 1084
Cofferal 1	020		G Ferriz & Mahand 1084
Ronnichean at	1020		** I VIII O MAUVA, 1784
	. e., 1767		

spread of data for most elements in the NWH compared to the McCullough Range may be attributable to sampling over a broader area, as Tuff of Bridge Spring exposures in McCullough Range are more localized. Mg# is similar for both localities, and lower than for the Eldorado Member (Figures 31-33) and the White Hills Member has higher total Fe and MnO and lower MgO than the Eldorado Member. MgO contents of Eldorado Member samples are abnormally high for dacitic rocks and result in unusually high Mg#s (Figures 31 and 32). The source of this high MgO is unknown.

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The White Hills, southern Black Mountains and McCullough Range may have occupied different structural troughs than the Eldorado Range. A topographic barrier may have separated different depositional settings and prevented the older White Hills member from reaching the Eldorado Mountains and the Eldorado member from reaching eastward into Arizona.

The Tuff of Bridge Spring has been mapped in the southern McCullough and Highland Spring Ranges (Schmidt, 1987, and Davis, 1984), and an ash-flow tuff exposed in the southern White Hills may correlate with the Tuff of Bridge Spring as well. Without age dates, it is unknown whether these tuffs represent the first or second eruption. Although the southern extent and source of the Tuff of Bridge Spring are unknown, a source to the southwest is suggested by flow direction studies on the Eldorado member by Brandon (1979) using the techniques of Elston and Smith (1970) and Rhodes and Smith (1972).

On the basis of geochronologic data and the above correlation of the tuff

in the NWH with the Tuff of Bridge Spring, the mafic volcanic rocks of the NWH can be placed within the established time-stratigraphic framework of the northern Colorado Trough (Figure 35). The basalt and basaltic andesite underlying and overlying the tuff in the NWH are time correlative with the Patsy Mine section in the Eldorado Range (18.5 to 13 Ma, Gans, 1991 and Darvall, 1991).

LATE TERTIARY SEDIMENTS

The east-tilted mid-Tertiary volcanic and sedimentary section in the NWH is unconformably overlain by gently tilted (<10° NE) sediments that I correlate with the late Tertiary Red Sandstone unit and Muddy Creek Formation. In the southern half of the study area, unconsolidated sandy gravels overlie Tpb and Tsp and are overlain by Senator Mountain basalts (Tsm). Calderone et al. (1991) report a 8.5 Ma date on a basalt similar to Tsm in composition and stratigraphic position at Table Mountain Plateau in the southern White Hills, 15 km south of the study area. Theodore et al. (1987) report a 10.9 + /- 0.6 Ma date on a "basalt flow in the Muddy Creek Formation". These dates are similar to the reported range for Callville Mesa basaltic andesite (Feuerbach et al., in press) that are interbedded with the Red Sandstone unit of Bohannon (1984). I therefore mapped all gravels that are tilted $>5^{\circ}$ and intruded by or interbedded with the basalt of Senator Mountain as Red Sandstone (Trs). The Red Sandstone is exposed in the Grand Wash Trough and in the western Lake Mead area (Figure 36) and was deposited in actively extending basins (Duebendorfer and Wallin, 1991).


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Figure 36. Regional exposures of Red Sandstone. CM=Callville Mesa.

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In the northern half of the study area, Trs is overlain by untilted gravels that comprise the lower part of the Muddy Creek Formation (Tmcl). The deposits are lithologically similar to Trs and are distinguished from it by degree of tilt and lack of intruding or interlayered basalt. These coarse clastics are overlain by pink to orange gypsiferous siltstone and freshwater limestone that contains chert nodules. The capping limestone was mapped as the Hualapai Limestone Member of the Muddy Creek Formation by Blair and Armstrong (1979), Blair et al., (1979), and Bradbury and Blair (1979). For convenience in mapping, I have grouped the interbedded gypsiferous siltstone and limestone as Tmcu on Plate 1. The Muddy Creek Formation is exposed throughout the Lake Mead area (Figure 37).

Overlying the Muddy Creek sediments are unconsolidated river cobble deposits (Qp on plate 1) stranded at former levels of the Colorado River system. These are found 250 to 350 meters above the current river level (now flooded by Lake Mead) and consist of very well-rounded Colorado Plateau-type Paleozoic quartzite and carbonate clasts. They were mapped as "Old River Deposits" by Longwell (1936) and are found above river level throughout the Lake Mead area.

STRUCTURE

Lake Mead region "detachment faults"

The Lake Mead and lower Colorado River Trough regions contain numerous low-angle faults which accommodated considerable extension. These faults may be termed "detachment" faults if they exhibit the following



Figure 37. Regional exposures of Muddy Creek Formation, modified from Bohannon, 1984.

characteristics (Reynolds, 1985):

1) Significant contrast in rock type on either side of the fault, due to large magnitude normal-sense displacement.

2) Upper plate rocks are brittlely deformed, faulted and rotated, while ductilely deformed lower plate rocks are comparatively intact.

3) Normal faults in the upper plate merge with or are cut by the detachment.

4) The lower plate in the vicinity of the fault is marked by a zone of hydrothermally altered breccia and microbreccia.

The Salt Spring fault satisfies some, but not all, of these criteria. The Tertiary rocks and structural style in the upper plate contrasts markedly with the lower plate Precambrian basement. Strong retrograde metamorphism and brecciation is exhibited in the lower plate. Therefore, the Salt Spring fault may be termed a detachment. However, the amount of displacement on the Salt Spring fault is unconstrained and the lower plate near the fault lacks evidence of ductile deformation. In addition, the behavior of the upper plate normal faults at depth is unknown.

Other major low-angle normal (detachment) faults in the Lake Mead area (Figure 2) include the Cyclopic detachment (Myers, 1985, Myers et al., 1986 and Theodore et al., 1987), the Lakeside Mine fault (Fryxell et al., in press, and Fryxell and Duebendorfer, 1990), the Saddle Island detachment (Smith, 1982, Sewall, 1988, Smith et al., 1990 and Duebendorfer et al., 1990a&b), and a low angle fault at Arch Mountain (Eschner, 1989). Comparison of features associated with these faults is summarized in Table 17.

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The Cyclopic detachment (Myers, 1985) exhibits brittle deformation and alteration similar to the Salt Spring fault. Myers noted chloritic alteration in the lower plate and ferric alteration in the upper plate of the detachment. Numerous northwest-striking, high-angle brittle normal faults antithetic to the detachment are present in the upper plate. At least 5 km of displacement occurred along the detachment.

Fryxell et al. (in press) have documented the deformation and alteration associated with the Lakeside Mine fault. They described highly brecciated chloritized Precambrian basement in the footwall. The brittle deformation overprints a mylonitic fabric that displays top-to-the-west shear and west to northwest transport. Mylonite zones dip dominantly west to northwest, but some dip eastward. Upper plate rocks north of the Gold Butte fault (Figure 2) are cut by tear faults and small-magnitude high-angle normal faults.

The Saddle Island detachment exhibits all of the characteristic elements of metamorphic core complexes, including brittle deformation of upper plate rocks and mylonite in lower plate rocks. Sewall (1988) described brecciation and propylitic alteration (epidote, clinozoisite, chlorite, and calcite) of the upper plate and black microbreccia grading into chlorite schist in the lower plate. Weber and Smith (1987) documented 20 km of displacement along the detachment.

Exposed at Arch Mountain is a low angle fault that separates Precambrian,

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		Salt Spring Fault (this study)	Cyclopic Detschment (Myers, 1985)	Lakeside Mino Fault (Fryxell et al.,in press)	Saddle Island Detachment (Sewall, 1988)	Arch Mountain Fault (Eschner, 1989)
	Mylonite	No	No	Yes	Yes	No
LOWER PLATE	Brittle Deformation	Yes	Yes	Yes	Yes	Yes
	Low-angle anastomosing shear zones	Yes	Yes	Yes	Yes	Yes
	Alteration	chloritic	chloritic	chloritic	chloritic	hematitic
UPPER PLATE	High-angle brittle faults	Yes: normal & strike-slip	Yes: normal	Yes: normal & strike-slip	Yes: normal	Yes: normal
	Alteration	hematitic	hematitic	hematitic	propyllitic	hematitic
OTHER	Attitude	S: North-South D: 10 - 30 W	S: N37 -54 W D: 16-22 SW	S: NNE D: WNW	S: N65 E D: 25 NW	S: N 10 W D: 5-35 W
	Age	?	post 16.4 Ma		between 13.5 and 9 Ma	between 13.4 and 12 Ma

Table 17: Characteristics of Lake Mead region low angle normal faults

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Paleozoic and Tertiary intrusive rocks in the upper plate from the mid-Miocene Wilson Ridge pluton in the lower plate (Eschner, 1989). Eschner described cataclastic deformation along the fault surface, hematitic alteration and low-angle anastomosing brittle shear zones in the lower plate. Duebendorfer et al. (1990) suggested that this fault may represent the eastern continuation of the Saddle Island detachment and attributed the lack of mylonitization in the lower plate to an eastward shallowing of a possible regional detachment structure.

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Regional correlation of Salt Spring fault

The Salt Spring fault may be correlated with the Cyclopic detachment on the basis of spatial and geometric relationships, kinematic similarities and comparable styles of deformation and alteration. Both faults dip west to southwest, have brittlely deformed upper plates that are cut by high- to moderateangle normal faults, and exhibit strong ferric alteration. Lower plates exhibit both chloritic and hematitic alteration.

Correlation of the Salt Spring fault with the Lakeside Mine fault to the north is more speculative. Spatial and kinematic characteristics support this correlation, as both faults dip westward and upper plate transport direction was to the west. In addition, the coarse breccia and debris flow deposits (Tbr) in the NWH bear several similarities to the megabreccia and debris flows of the Thumb Member of the Horse Spring Formation exposed at Rainbow Gardens (Figure 2). The 16.4 Ma +/- 0.4 Ma age of the NWH tuff interbedded with Tbr is within the 13.5-17.2 Ma age range (Bohannon, 1984) for the Thumb breccias. Coarse clastic

deposits of the Thumb Member were interpreted as an alluvial fan deposit with a source at Gold Butte (Anderson et al., 1972, Longwell, 1974, and Bohannon, 1984). Parolini (1986) interpreted the megabreccias as landslides and debris flows shed off the scarp of a "boundary fault". The megabreccias were deposited no more than 5 km from their source (Rowland et al., 1990). Fryxell and Duebendorfer (1990) suggested that the Lakeside Mine Fault may have been that fault. Tbr may have been deposited in a similar fashion, as products of the rapidly uplifting and eroding Salt Spring fault scarp (Switzer, personal commun., 1991). Therefore, similarity of the Thumb breccias and Tbr, and their supposed relation to the Lakeside Mine and Salt Spring faults, respectively, supports the correlation of the two faults. However, the style of deformation differs between the faults, as evidence for ductile deformation is lacking along the Salt Spring fault.

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Ductile vs. brittle deformation

Brittle deformation in the lower plate of the Salt Spring fault and Cyclopic detachment contrasts with ductile deformation in the lower plate of the Lakeside Mine fault. Two models are proposed to explain the lack of ductile deformation along the Salt Spring fault and Cyclopic detachment.

1. Exposure of deeper levels in the Gold Butte area may be accomplished by either a steepening of the fault to the north (Figure 38) or corrugation of the fault surface about an east-west-trending axis (Figure 39). If the Lakeside Mine portion of the fault dips more steeply than the Salt Spring-Cyclopic portion,



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Greater rebound to the north exposes deeper levels

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Figure 39. Along-strike differences in deformational style due to corrugation of fault surface about an east-west axis.

deeper level rocks were brought to the surface more quickly there, given the same amount of displacement. However, no evidence for significant differences in dip have been observed.

If the regional low-angle fault system that includes the Cyclopic, Salt Spring and Lakeside Mine faults was corrugated as in Figure 38, the southern portion of the fault would experience deformation at a higher structural level, where brittle deformation prevails. Greater uplift to the north where the fault is deep would be triggered by greater tectonic denudation. This model is consistent with fault attitude data for all exposed segments of the fault. However, the amplitude of the corrugation would have to be rather large. Corrugated detachment fault surfaces are known in the lower Colorado River trough, but the folds are gentle features with 4-10 km wavelengths and 100-600 m amplitudes (Spencer, 1982). Still, if the corrugation is near (and cuts) the brittle-ductile transition zone, it may be possible for different styles of deformation to be simultaneously active along strike of the same fault.

2. The amount of displacement on the Cyclopic-Salt Spring-Lakeside Mine fault system, and therefore the amount of rebound, may decrease southward toward the Black Mountains accommodation zone. Greater rebound to the north would expose deeper level rocks. Greater extension north of Lake Mead is indicated by transport of Thumb Member Megabreccia 65 km west of Gold Butte to Rainbow Gardens (Longwell, 1974 and Bohannon, 1984). Although 20 km of the westward transport of Thumb breccias probably took place along the Saddle

Island detachment, 40-45 km of displacement may have been accommodated by the Lakeside Mine fault. The maximum distance for landslide travel is 15 km, and distances on the order of a few km are more typical (Yarnold and Lombard, 1989). Preliminary work by Switzer (personal communication) suggests that the NWH breccia was probably deposited within 5 km of its source. NWH breccia is known only as far west as Squaw Peak (approximately 10 km). Although more Tbr could be buried in Detrital Wash, no exposures are known west of Detrital Wash, so the unit cannot have been extended more than 25 km.

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In the Black Mountains and Eldorado Range, Faulds (1989) documented decreasing fault dips, increasing tilt of fault blocks, and increasing fault spacing away from the axis of the Black Mountains accommodation zone. Faulds documented 6 km of displacement along the Van Deemen Mine fault in the southern Black Mountains, north of the accommodation zone, and suggested that this fault may be continuous with the Saddle Island detachment. These observations indicate a northward increase in the amount of extension (Figure 40) that may be paralleled to the west in the White Hills and south Virgin Mountains. Although this model is highly speculative, it is consistent with published data regarding the Lakeside Mine fault, Thumb megabreccia, and accommodation zone.

Geometry and displacement of Salt Spring fault

Despite the substantial thickness of mafic volcanic rocks in the upper plate of the Salt Spring fault, no corresponding intrusions are known in the lower plate



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Figure 40. Extension increasing northward from the Black Mountains Accommodation Zone (BMAZ), modified from Faulds (1991).

between the Salt Spring fault and the Grand Wash Cliffs (Figure 2). Four possible explanations for this follow.

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1) The intrusions are present beneath sediments in Grapevine Wash or Hualapai Wash. If this is the case, horizontal displacement along the fault is a minimum of 10 km (Hualapai Wash) or 15 km (Grapevine Wash). No evidence for these intrusions exists because no detailed geophysical studies have been done in the area and no wells have been drilled to bedrock.

2) The volcanic sources were west, north or south of the study area and the mafic volcanics flowed into the area from outside. Corresponding intrusives would then be situated below these sources. However, the thickness of the sections precludes a distant source. In addition, no intrusive rocks equivalent to the basaltic andesite are known to the north, west or northwest of the study area. Although burial of intrusions beneath basin fill in Detrital Wash can not be ruled out, isostatic residual gravity data (Faulds, 1989) indicates a low in Detrital Valley, which is not consistent with mafic intrusions at depth. If such intrusions are present, they have been transported to the west in the upper plate of the Salt Spring fault along with the NWH.

3) The intrusions are still hidden beneath volcanic sections in the NWH. The Salt Spring fault has not experienced enough displacement to remove the volcanics from their underlying root. This model is consistent with decreasing displacement approaching the Black Mountains accommodation zone.

CONCLUSIONS

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The northern White Hills (NWH) provide a unique opportunity to study the upper plate of the regionally extensive Cyclopic-Salt Spring Wash-Lakeside Mine Fault System. The upper plate contains 6 distinct structural blocks of tilted mid-Tertiary volcanic and sedimentary rocks, isolated by intervening late Tertiary and Quaternary sediments. A composite stratigraphic section was constructed using field relations, geochemical data and petrography. At the base of the composite section are mafic volcanic rocks overlain by coarse breccia and debris flow deposits interbedded with an ash-flow tuff. The upper part of the section contains mafic volcanic rocks and fanglomerate.

Three groups of mafic volcanic rocks were distinguished on the basis of geographic distribution, chemistry and petrography. These are the basaltic andesite of Temple Bar, basaltic andesite of Squaw Peak and basalt of Pink/Black Ridge. The mafic volcanics were erupted coevally from three different volcanic centers. Eruption of mafic lavas was interrupted by landslides, debris flows, the deposition of an ash-flow tuff and fanglomerates. These areally extensive deposits allow development of a model for the eruptive and depositional history of the NWH.

The mid-Tertiary section is cut by high- to moderate-angle down-to-thewest normal faults that repeat parts of the stratigraphic section. Similar normal faults, now buried beneath Late Tertiary and Quaternary alluvium may bound and separate the blocks. Although extension and tilting began after the cessation of volcanism in most of the NWH, a growth fault at Salt Spring Wash indicates that faulting began earlier there.

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The three types of mafic magma may reflect similar degrees of partial melting of similar K-rich sources. Tpb differentiated by fractionation of olivine. Ttb and Tsp evolved by fractionation of olivine, clinopyroxene and plagioclase. Magma evolution is complex and also involves recharge by fresh batch melts.

The tuff in the NWH (16.4 Ma) is the lower member of the Tuff of Bridge Spring (White Hills member). The underlying and overlying mafic volcanic rocks correlate with the Patsy Mine Volcanics. The upper member of the Tuff of Bridge Spring (Eldorado member) may have erupted from the same vent as the White Hills member at 15.19 Ma.

The lower plate of the Salt Spring fault is composed of Precambrian basement rock of varying lithologies. Near the trace of the Salt Spring Fault, the footwall rocks are highly altered and brittlely sheared to hematitic gouge and rock flour. A dense network of anastomosing brittle shear zones separates lower plate rock within 100 m of the fault into lenses of strongly retrograded but largely undeformed granitoid, gneiss and amphibolite. A higher proportion of granitoid and mylonite clasts in upper plate landslide breccia relative to lower plate rocks near the Salt Spring fault suggests that the source of the landslide deposits is farther east or south of the fault.

Differences in style of deformation along the Cyclopic-Salt Spring Wash-Lakeside Mine fault may be explained by increasing displacement and a

corresponding increase in uplift northward from the Black Mountains accommodation zone.

A

FUTURE WORK

The tectonic significance of the thick coarse breccia and debris flow deposits (Tbr) near the base of the NWH section may be better understood through more detailed mapping of the internal structure and stratigraphy of the deposits. Depositional processes may be better defined by detailed measurement of sections within the deposits, clast population studies and transport direction studies. The maximum transport distance, paleotopography and timing of deposition and extension may be better defined through careful examination of the internal and external stratigraphic details. Reconnaissance and detailed mapping of the crystalline basement rocks of the lower plate, in Graham Ridge and on the Hualapai Plateau, may delineate a source area for the mylonite and megacrystic granite clasts common in Tbr deposits.

More definitive links between the Salt Spring fault (SSF) and the Lakeside Mine fault and the Cyclopic detachment may be possible through additional detailed mapping. However, burial of the trace of the SSF south of Salt Spring Wash beneath the Muddy Creek Formation may preclude a physical linkage of the two normal faults. On aerial photographs, the SSF appears to project north of Lake Mead at Slide Cove (Plate 1). Although most of the terrain between Lake Mead and the southern end of the Lakeside Mine Fault is covered by Muddy Creek Formation or similar sediments, it is possible that some lower plate may be exposed in deeply eroded gullies on the north side of the lake.

Intense hydrous retrograde alteration in the lower plate of the Cyclopic-Salt Spring Wash-Lakeside Mine fault contrasts markedly with the largely unaltered crystalline basement rocks of the region (i.e., the McCullough Range to the west and the Lost Basin Range to the east). Thus, retrograde alteration is spatially related to the detachment. More detailed study of the near-fault altered rocks and their unaltered equivalents is necessary to ascertain the timing of alteration and source of fluids.

The late Tertiary Red Sandstone equivalent and Muddy Creek Formation gravels in the northern White Hills were mapped from aerial photographs and during reconnaissance mapping. More detailed study of these sediments may allow new constraints on timing of basin development in the eastern Lake Mead.

Current work indicates that the Tuff of Bridge Spring merits a more detailed and comprehensive study. Mapping of extent and internal characteristics of known deposits of both members would better define the conditions of deposition and pre-eruption topography. Age dating, paleomagnetic studies and geochemical analysis of the Tuff of Bridge Spring in Highland Spring Range and southern McCullough Range would allow correlation of those exposures with either the White Hills Member or the Eldorado Member. Systematic sampling for geochemical, petrographic and age date analysis of both members would allow development of model for cyclic recharge and differentiation of a single magma chamber.

Isotopic studies would allow more quantitative and meaningful petrogenetic

modelling of the mafic volcanics of the NWH. High precision systematic age

dating of the entire section by the 40 Ar/ 39 Ar method would provide details

regarding rates of magma production and eruption. Precise age dates would also

constrain timing of synvolcanic faulting in the upper part of the section at Salt

Spring Wash.

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Explanation of symbols for Appendix A



Mafic volcanic rocks

Ash-flow tuff

Coarse monolithologic breccia

Debris flows

Fanglomerate

Sandstone and gravel

Chuckwalla Ridge 1328 m



Smith Hill 760 m



Peninsula 1010 m



Squaw Peak 1192 m



meters

Salt Spring Wash 1556 m





APPENDIX B: PETROGRAPHIC DESCRIPTIONS ASH-FLOW TUFFS 1000 points/slide

Peninsula, vitrophyre at base of Tt

20.6% Plagioclase; pitted, sieved with subhedral overgrowths, up to 3 mm

1.8% Biotite; subhedral, hematitic alteration on margins and fractures, up to 1 mm

0.2% Sphene; subhedral to anhedral, <0.5 mm

7.8% Clinopyroxene; broken, subhedral, <0.5 mm

0.3% Olivine; subhedral, embayed, altered to iddingsite on rims, <0.5 mm

2.2% Magnetite

Groundmass: slightly devitrified, dense and glassy.

144

<u>137</u>

(a)

Peninsula, 20 m from base of Tt

0.1% Lithic fragments; dacite, up to 2 mm

2.0% Pumice fragments; unflattened, up to 4 mm

6.8% Sanidine; subhedral, zoned, up to 2 mm

6.1% Plagioclase; broken subhedral laths, up to 1 mm

0.8% Biotite; subhedral, <0.5 mm

trace Sphene; broken, euhedral, <0.5 mm

1.1% Clinopyroxene; broken, euhedral, <0.5 mm

0.4% Magnetite

Groundmass: unwelded, slightly devitrified, slightly calcified

136

<u>54</u>

Peninsula, center of Tt

15.3% Lithic fragments; dacite, basalt, sparse crystalline basement, up to 5 mm

6.2% Pumice fragments; slightly flattened, up to 3 mm

0.8% Sanidine; broken, subhedral, <0.5 mm

1.2% Plagioclase; broken, subhedral, pitted <0.5 mm

2.8% Biotite; subhedral, up to 1 mm

trace Sphene; subhedral

0.7% Clinopyroxene; broken, euhedral, <1 mm

0.3% Zircon

1.5% Magnetite

Groundmass: slightly welded, moderately devitrified, moderately calcified.

142 Peninsula, 15 m from top of Tt

3.6% Lithic fragments; basalt, dacite, up to 4 mm

6.8% Pumice fragments; unflattened, up to 2 mm

4.0% Sanidine; subhedral to anhedral, blocky, up to 1 mm

9.3% Plagioclase; broken, subhedral, partially altered to calcite

0.4% Quartz; anhedral, <0.5 mm

2.0% Biotite; subhedral, hematitic alteration on margins and fractures; <1 mm

0.1% Sphene; subhedral

0.7% Clinopyroxene; broken, euhedral to subhedral, <0.5 mm

1.1% Magnetite

Groundmass: slightly welded, moderately devitrified

1.5 km west of Salt Spring Wash

5.7% Lithic fragments; dacite, crystalline basement, up to 3 mm 10.2% Pumice fragments; flattened, up to 2 mm

6.2% Sanidine; subhedral, embayed, up to 2 mm

4.2% Plagioclase; broken, subhedral, partially altered to calcite, < 1 mm

2.0% Biotite; hematitic alteration on margins and fractures, <1 mm

0.5% Sphene; euhedral

0.2% Clinopyroxene; anhedral, embayed, <1 mm

0.1% Zircon

0.7% Magnetite

Groundmass: slightly welded, moderately devitrified, moderately calcified

west side of Salt Spring Wash, base of Tt

14.5% Lithic fragments; dacite and basalt, up to 5 mm

1.4% Pumice fragments; unflattened, up to 2 mm

3.9% Sanidine; subhedral to anherdal, embayed, <1 mm

2.7% Plagioclase; broken, euherdal to subhedral, largely altered to calcite

0.4% Quartz; embayed, <0.5 mm

0.7% Biotite: <1 mm

trace Sphene

trace Zircon

0.3% Magnetite

Groundmass: moderately welded, largely devitrified, slightly calcified

73

<u>69</u>

west side of Salt Spring Wash, center of Tt

4.7% Lithic fragments; crystalline basement, dacite, up to 3 mm

2.8% Pumice fragments; blocky, nonflattened, up to 2 mm

8.7% Sanidine; broken, subhedral, embayed, up to 3 mm

1.4% Plagioclase; subhedral laths, replaced by calcite, up to 1 mm

0.2% Biotite; hematitic alteration on margins and fractures, <0.5 mm 0.2% Magnetite

Groundmass: nonwelded, largely devitrified, moderately calcified

<u>70</u>

west side of Salt Spring Wash, top of Tt

10.4% Lithic fragments; crystalline basement, basalt, up to 3 mm

6.3% Pumice fragments; slightly flattened, up to 2 mm

0.4% Sanidine; broken, subhedral, <0.5 mm

0.9% Plagioclase; replaced by calcite, <1 mm

1.3% Biotite; hematitic alteration on margins and fractures, up to 0.5 mm

0.3% Sphene

0.3% Clinopyroxene

0.1% Zircon

0.2% Magnetite

Groundmass: slightly welded, largely devitrified, slightly calcified

<u>83</u>

Dug's Island, center of Tt

2.4% Lithic fragments; basalt, dacite, up to 2 mm

6.2% Sanidine; subhedral, rounded, fractured, up to 2 mm

3.4% Plagioclase; subhedral laths, replaced by calcite, <1 mm

1.0% Quartz; anhedral, embayed, <1 mm

1.2% Biotite; hematitic alteration on margins and fractures. <1 mm 0.8% Magnetite

Groundmass: nonwelded, moderately devitrified, severely calcified

Dug's Island, top of Tt

7.0% Lithic fragments; crystalline basement and dacite; up to 3 mm

11.3% Pumice fragments; slighlty flattened, up to 2 mm

1.2% Sanidine; broken, subhedral, blocky, up to 1 mm

1.5% Plagioclase; largely replaced by calcite, < 1 mm

0.7% Biotite; hematitic alteration on margins and fractures, <0.5 mm

0.1% Sphene

trace Clinopyroxene

0.2% Zircon

0.8% Magnetite

Groundmass: slightly welded, moderately devitrified, severely calcified

101 Smith Hill, base of unit

10.9% Lithic fragments; basalt and crystalline basement, up to 6 mm 1.5% Pumice fragments; slightly flattened, up to 4 mm

8.5% Sanidine; broken, subhedral, blocky, embayed, up to 2 mm

4.4% Plagioclase; broken, subhedral laths, altered to sericite, up to 1 mm

0.2% Quartz; anhedral, embayed, < 1 mm

0.6% Biotite; hematitic alteration on margins and fractures, <1 mm

0.1% Clinopyroxene

trace Zircon

0.4% Magnetite

Groundmass: slightly welded, largely devitrified, slightly calcified

<u>84</u>

<u>81</u>

Ð

Smith Hill, 30 m from base of Tt

1.8% Lithic fragments; basalt, up to 5 mm

2.4% Pumice fragments; moderately flattened, up to 3 mm

20.3% Sanidine; broken, subhedral, slight alteration to sericite, up to 3 mm 10.6% Plagioclase; broken, subhedral, largely altere to sericite, up to 5 mm

2.5% Biotite, hematitic alteration on margins and fractures, up to 2 mm 0.6% Magnetite

Groundmass: moderately welded, moderately devitrified

150

Smith Hill, 50 m from base of Tt

4% Lithic fragments; dacite and basalt, up to 2 mm

9.8% Pumice fragments; slightly flattened, up to 4 mm

2.6% Sanidine; broken, subhedral, <1 mm

8.6% Plagioclase; subhedral, largely altered to calcite, up to 1 mm

3.0% Biotite; hematitic alteration on margins and fractures, <1 mm

trace Sphene

0.6% Clinopyroxene

0.8% Zircon

1.4% Magnetite

Groundmass: moderately welded, slightly devitrified

<u>96</u>

Smith Hill, 5 m from top of Tt

13% Lithic fragments; basalt, up to 1 cm

0.8% Pumice fragments; slightly flattened, up to 2 mm

12.1% Sanidine; broken, subhedral, embayed, blocky, up to 3 mm

7.4% Plagioclase; altered to calcite and sericite, up to 2 mm

3.9% Biotite; hematitic alteration on margins and fractures, <1 mm

- trace Sphene
- trace Zircon

0.7% Magnetite

<u>Groundmass</u>: slightly welded, slightly devitrified, moderately calcified

<u>98</u>

Smith Hill, top of Tt

12.3% Lithic fragments; basalt, up to 1 cm

5.0% Pumice fragments; slightly flattened, up to 2 mm

8.9% Sanidine; broken, subhedral to anhedral, embayed, up to 4 mm

9.5% Plagioclase; subhedral, partially altered to sericite, up to 2 mm

0.1% Quartz; anhedral, <0.5 mm

3.6% Biotite; broken, subhedral, hematitic alteration on margins and fractures, <0.5 mm trace Sphene

2.3% Magnetite

Groundmass: slightly welded, moderately devitrified

1

Squaw Peak, near base of Tt

6.2% Lithic fragments; basalt and crystalline basement, up to 3 mm

0.8% Pumice fragments; slightly flattened, up to 2 mm

9.2% Sanidine; broken, subhedral, up to 2 mm

9.3% Plagioclase; broken, subhedral, apatite inclusions, up to 1 mm

2.6% Biotite; slight hematitic alteration on margins and fractures, up to 1 mm

trace Sphene

0.9% Clinopyroxene

trace Zircon

0.6% Magnetite

Groundmass: slightly welded, slightly devitrified

111

northwest of Squaw Peak, middle of Tt

10.2% Lithic fragments; basalt, up to 7 mm

12.4% Pumice fragments; slightly flattened, up to 4 mm

9.8% Sanidine; broken, subhedral, up to 2 mm

14.6% Plagioclase; broken, subhedral, replaced by calcite up to 3 mm

1.4% Biotite; hematitic alteration on margins and fractures, up to 1 mm

1.8% Clinopyroxene

trace Zircon

0.2% Magnetite

Groundmass: slightly welded, slightly devitrified, largely calcified

<u>106</u>

northwest of Squaw Peak, 10 m from top of Tt

6.2% Lithic fragments; basalt, up to 2 mm

4.3% Pumice fragments; slightly flattened, up to'2 mm

10.8% Sanidine; anhedral to subhedral, blocky, up to 2 mm

8.4% Plagioclase; euhedral to subhedral, up to 2 mm

1.9% Biotite; hematitic alteration on margins and fractures, <1 mm

trace Sphene

0.6% Clinopyroxene

trace Zircon

0.2% Magnetite

Groundmass: slightly welded, slightly devitrified

<u>102</u>

1.6% Lithic fragments; basalt, up to 2 mm 4.3% Sanidine; anhedral, <0.5 mm 1.1% Plagioclase; subhedral to anhedral, < 0.5 mm 0.8% Biotite; broken needles, <0.5 mm

0.3% Clinopyroxene Matrix: largely devitrified ash
APPENDIX C: PETROGRAPHIC DESCRIPTION MAFIC VOLCANIC ROCKS 500 points/slide

Tibl

PENINSULA

26% Plagioclase; sieved, fritted, zoned, non-pitted overgrowths; subhedral laths seriate to 1 mm; also in glomerocrysts with clinopyroxene up to 2 mm

11% Clinopyroxene; pitted, embayed, non-pitted overgrowths; subhedral to euhedral equant less than 0.5 mm; in glomerocrysts with plagioclase up to 2 mm

2% Olivine; in glomerocrysts with clinopyroxene and plagioclase

Groundmass: 49% Cryptocrystalline material with seriate fine to coarse grained laths of Plagioclase (7%) and subhedral Clinopyroxene (5%)

138 PENINSULA Ты

18% Plagioclase; pitted, embayed; rounded subhedral laths up to 1.5 mm; also in glomerocrysts with clinopyroxene and magnetite

5% Unaltered Clinopyroxene; embayed, pitted, subhedral

3% Altered Clinopyroxene; subhedral to anhedral

0.2% Phlogopite; highly altered needles

1% Magnetite; euhedral

2% Vesicles

139

Groundmass: 66% Cryptocrystalline material with fine-grained felty laths of Plagioclase (3%) and both altered and unaltered varieties of Clinopyroxene (2%)

90 SMITH HILL Ttbl

13% Plagioclase; pitted, embayed; subhedral up to 2 mm; in glomerocrysts with clinopyroxene up to 3 mm

14% Clinopyroxene; pitted, embayed; subhedral up to 1 mm; in glomerocrysts with plagioclase up to 3 mm

7% Vesicles; filled with calcite

Groundmass: Seriate fine to coarse-grained subtrachytic laths of Plagioclase (31%); with

intergranular Clinopyroxene (7%), Hematite (4%) and Cryptocrystalline material (23%).

85 SMITH HILL Ttbm

16% Olivine; subhedral, less than 0.5 mm, altered to iddingsite on rims and along fractures.

3% Clinopyroxene; subhedral, less than 0.5 mm

1% Magnetite

1% Vesicles

Groundmass: Fine-grained trachytic laths of Plagioclase (47%); with intergranular Olivine (6%) altered to iddingsite, Clinopyroxene (17%) and Hematite (9%).

SMITH HILL 51 Tibm

22% Plagioclase; pitted, fritted; subhedral laths seriate to 2mm

2% Olivine; embayed; subhedral, less than 1 mm, altered to iddingsite

7% Clinopyroxene; subhedral, up to 2 mm; hematite inclusions.

5% Vesicles

Groundmass: 48% Cryptocrystalline material with fine-grained felty laths of Plagioclase (8%), Olivine (6%) altered to iddingsite, Clinopyroxene (2%) and Hematite (1%).

SMITH HILL <u>50</u> Ttbm

19% Plagioclase; pitted, fritted; subhedral laths up to 1 X 3 mm; in glomerocrysts with clinopyroxene

up to 3 mm

1

1% Olivine; altered to iddingsite, up to 0.5 mm

11% Clinopyroxene; pitted; up to 1 mm; in glomerocrysts with plagioclase up to 3 mm 6% Magnetite

3% Vesicles; filled with calcite

Groundmass: Seriate fine to coarse grained felty laths of Plagioclase (33%); with intergranular Olivine (9%) altered to iddingsite, Clinopyroxene (5%), Hematite (4%) and Cryptocrystalline material (8%).

Ttbm 148 **GATEWAY COVE**

16% Plagioclase; pitted, sieved; subhedral laths up to 5mm

6% Olivine; anhedral, embayed, altered to iddingsite

6% Clinopyroxene; subhedral, embayed, pitted

Groundmass: Seriate fine to coarse-grained felty laths of Plagioclase (29%); with intergranular Olivine (5%) altered to iddingsite, Clinopyroxene (4%), Hematite (1%) and Cryptocrystalline material (33%).

GATEWAY COVE <u>65</u>

Ttbm

- 15% Plagioclase; pitted, embayed; subhedral laths up to 2X4 mm; glomerocrysts with pyroxenes up to 2 mm
- 1% Olivine; anhedral, iddingsitzed, up to 0.5 mm

3% Unaltered Clinopyroxene; embayed, subhedral to anhedral, up to 1 mm

- 1% Altered Clinopyroxene; anhedral, less than 1 mm
- 1% Magnetite

Groundmass: Coarse-grained blocky microcrystals of Plagioclase (59%); with intergranular Olivine (1%) altered to iddingsite, Clinopyroxene (17%) and Hematite (3%).

131 CHUCKWALLA RIDGE

17% Plagioclase; pitted, sieved, fritted; subhedral laths up to 3 mm

2% Olivine; anhedral, altered to iddingsite along margins and fractures; up to 1 mm

7% Clinopyroxene; embayed, anhedral; up to 1 mm

4% Xenoliths; microcrystalline olivine + plagioclase with glassy groundmass

Groundmass: 48% Cryptocrystalline material with fine-grained felty laths of Plagioclase (13%),

subhedral Olivine (5%) altered to iddingsite, and Clinopyroxene (3%).

- CHUCKWALLA RIDGE 132
- 7% Plagioclase; pitted, embayed, anhedral; up to 1 mm

1% Olivine; anhedral, altered to iddingsite

8% Clinopyroxene; pitted, embayed, with non-pitted overgrowths; subhedral to anhedral

Groundmass: 51% Cryptocrystalline material with fine-grained trachytic laths of Plagioclase (13%),

subhedral Olivine (3%) altered to iddingsite, Clinopyroxene (4%) and Hematite (12%).

CHUCKWALLA RIDGE 134

26% Plagioclase; pitted, fritted, with non-pitted overgrowths; subhedral laths up to 3 mm

3% Olivine; altered to iddingsite on margins and fractures

6% Clinopyroxene; embayed, subhedral, up to 2 mm

10% Vesicles; filled with calcite

Groundmass: Fine-grained felty laths of Plagioclase (17%); with intergranular Olivine (3%) altered to iddingsite, Clinopyroxene (4%), Hematite (10%), and Cryptocrystalline material (22%).

135 CHUCKWALLA RIDGE Ttbm

Ttbm

Ttbm

Tibm

13% Plagioclase; sieved with non-pitted overgrowths; euhedral; up to 1.5 mm

1% Olivine; subhedral to euhedral, altered to iddingsite along margins and fractures; up to 1 mm 7% Clinopyroxene; subhedral to euhedral, single crystals and in glomerocrysts

17% Vesicles; partially infilled with chalcedony

Groundmass: 54% Cryptocrystalline material with fine-grained felty laths of Plagioclase (1%),

Olivine (1%) altered to iddingsite, Clinopyroxene (3%) and Hematite (2%).

149 CHUCKWALLA RIDGE

Dike = Ttbm or Ttbu

11% Plagioclase; embayed, pitted with euhedral to subhedral overgrowths; seriate up to 2 mm; inclusions of clinopyroxene

4% Unaltered Clinopyroxene; embayed, subhedral, up to 1 mm

3% Altered Clinopyroxene; subhedral to anhedral, < 1 mm

1% Magnetite

14% Vesicles; partially infilled with calcite and epidote

<u>Groundmass</u>: 41% Cryptocrystalline material with seriate medium-grained felty laths of Plagioclase (19%), and Clinopyroxene (8%).

49 SMITH HILL Tibm

10% Plagioclase; fritted, subhedral laths up to 1.5 mm

10% Clinopyroxene; embayed up to 1 mm, euhedral up to 0.5 mm

9% Vesicles; filled with calcite

<u>Groundmass</u>: Seriate medium to coarse grained felty laths of Plagioclase (24%); with intergranular Clinopyroxene (11%) and Cryptocrystalline material (37%).

125 SMITH HILL Tibm

34% Plagioclase; pitted, euhedral laths and clusters of subhedral crystals, up to 1 mm

5% Clinopyroxene; euhedral to subhedral, in glomerocrysts with plagioclase up to 1.5 mm 2% Magnetite

1% Vesicles

170 VESICIES Converdences Docti

<u>Groundmass</u>: Partially devitrified brown Glass (51%) with medium-grained felty laths of Plagioclase (4%) and Clinopyroxene (3%).

140 PENINSULA Tibm

22% Plagioclase; slightly pitted, fritted, with non-pitted overgrowths; subhedral laths up to 1 mm; glomerocrysts with clinopyroxene and magnetite up to 3 mm

3% Unaltered Clinopyroxene; embayed, euhedral to subhedral, up to 1 mm; and in large glomerocrysts with plagioclase

3% Altered Clinopyroxene; anhedral, embayed, less than 1 mm; and in large glomerocrysts with plagioclase

<u>Groundmass</u>: 48% Crytocrystals; with seriate fine to coarse-grained subtrachytic laths of Plagioclase (15%), both types of Clinopyroxene (6%) and Hematite (3%).

Tibm

133 CHUCKWALLA RIDGE

19% Plagioclase; sieved, fitted and embayed, with non-pitted overgrowths; up to 1 mm

9% Clinopyroxene; pitted, embayed; single crystals and in glomerocrysts

14% Vesicles; filled with calcite

<u>Groundmass</u>: Fine to medium-grained felty laths of Plagioclase (14%); with interganular Clinopyroxene (10%), Hematite (1%), and Cryptocrystalline material (31%).

130 CHUCKWALLA RIDGE Tibm

16% Plagioclase; fritted, sieved, embayed; subhedral laths; up to 2 mm

- 7% Unaltered Clinopyroxene; subhedral, embayed
- 3% Altered Clinopyroxene; subhedral to anhedral

6% Vesicles; many filled with calcite

<u>Groundmass</u>: fine-grained felty laths of Plagioclase (16%); with intergranular Clinopyroxene (6%) and Cryptocrystalline material (45%).

86 SMITH HILL Tibm

4% Hornblende; euhedral to subhedral; altered to hematite on rims; up to 0.5 X 2 mm

12% Plagioclase; sieved, pitted, non-pitted overgrowths; subhedral, up to 1.5 mm

- 3% Magnetite
- <u>Groundmass</u>: Fine-grained trachytic laths of Plagioclase (33%); with intergranular Hematite (9%) and Cryptocrystalline material (39%).

143 PENINSULA Tibm

48% Vesicles

<u>Groundmass</u>: Seriate fine to coarse-grained subtrachytic laths of Plagioclase (13%); with intergranular Hematite (15%) and Cryptocrystalline material (14%).

141 PENINSULA Tibm

2% Plagioclase; subhedral in glomerocrysts with olivine.

5% Olivine; subhedral to euhedral; altered to iddingsite; single crystals and in glomerocrysts with plagioclase

3% Vesicles; filled with calcite

<u>Groundmass</u>: Fine-grained felty laths of Plagioclase (25%); with intergranular Hematite (1%) and Cryptocrystalline material (64%).

Ttbu

<u>11</u> SALT SPRING WASH

27% Plagioclase; pitted; subhedral up to 2mm

0.6% Olivine; altered to iddingsite, less than 0.5 mm

4% Unaltered Clinopyroxene; subhedral, up to 1 mm

5% Altered Clinopyroxene; anhedral, less than 1 mm

<u>Groundmass</u>: Seriate fine to coarse-grained felty laths of Plagioclase (46%), with intergranular Olivine (6%) altered to iddingsite, Clinopyroxene (5%), Hematite (3%) and Cryptocrystalline material (1%).

88 SMITH HILL Ttbu

21% Plagioclase; pitted, up to 1 X 2 mm

4% Olivine; subhedral, less than 0.5 mm; altered to iddingsite

6% Clinopyroxene; euhedral, embayed, pitted; up to 1 mm

1% Magnetite

11% Vesicles; filled with chalcedony

Groundmass: Fine-grained felty laths of Plagioclase (22%) with intergranular Olivine (3%) altered to iddingsite, Clinopyroxene (4%), and Cryptocrystalline material (28%).

100 SMITH HILL Ttbu

4% Plagioclase; pitted, zoned, subhedral laths, up to 2 mm

1% Olivine; subhedral, equant, altered to iddingsite

1% Clinopyroxene; embayed, in glomerocrysts with plagioclase and olivine

1% Magnetite

4

8% Vesicles; filled with calcite

Groundmass: Fine-grained subtrachytic laths of Plagioclase (14%) with intergranular Olivine (1%)

altered to iddingsite, Cryptocrystalline material (49%) and Glass (22%).

103 DIKE WEST OF CHUCKWALLA RIDGE

Tpb

1% Plagioclase; euhedral laths less thin 0.5 mm

1% Olivine; subhedral, slightly altered to iddingsite on margins; up to 0.5 mm

3% Clinopyroxene; embayed, pitted, up to 1 mm

3% Magnetite

7% Vesicles

Groundmass: Coarse-grained felty laths of Plagioclase (49%), with intergranular Olivine (8%)

altered to iddingsite, Clinopyroxene (1%), Hematite (10%) and Cryptocrystalline material (17%).

7 PINK/BLACK RIDGE Tpb

2% Plagioclase; small laths in glomerocrysts

3% Olivine; altered to iddingsite

1% Magnetite; large, euhedral

3% Vesicles; filled with calcite

<u>Groundmass</u>: Coarse-grained subtrachytic laths of Plagioclase (49%) with intergranular Olivine (8%) altered to iddingsite, Clinopyroxene (9%), Hematite (15%) and brown glass (10%).

<u>10</u> PINK/BLACK RIDGE Tpb

0.6% Plagioclase; small laths in glomerocrysts

5% Olivine; euhedral, up to 2 mm, altered to iddingsite on margins

3% Vesicles; filled with calcite

<u>Groundmass</u>: Seriate fine to medium-grained trachytic laths of Plagioclase (47%) with intergranular Olivine (20%) altered to iddingsite, Clinopyroxene (16%), Hematite (7%) and Cryptocrystalline material (2%).

120 PINK/BLACK RIDGE Tpb

1% Plagioclase; sieved up to 0.5 mm, in glomerocrysts with olivine up to 1.5 mm

2% Olivine; altered to iddingsite; small single crystals or in glomerocrysts with plagioclase

<u>Groundmass</u>: Medium-grained trachytic laths of Plagioclase (61%) with intergranular Olivine (7%) altered to iddingsite, Clinopyroxene (23%), Hematite (5%) and Phlogopite (1%).

15 PINK/BLACK RIDGE Tpb 0.4% Plagioclase; in glomerocrysts with olivine

0.4% Olivine; subhedral crystal up to 0.5 mm and in glomerocrysts with plagioclase; altered to iddingsite on margins

11% Vesicles; some filled with calcite

Groundmass: Medium-grained trachytic laths of Plagioclase (49%), with intergranular Olivine (23%)

Tpb

altered to iddingsite, Clinopyroxene (7%), Hematite (5%) and Cryptocrystalline material (7%).

<u>124</u> PINK/BLACK RIDGE

3% Plagioclase; sieved, anhedral = one large (4mm) phenocryst in slide

1% Olivine; euhedral, altered to iddingsite on margins

25% Vesicles; filled with calcite

<u>Groundmass</u>: Fine-grained trachytic laths of Plagioclase (40%) with intergranular Olivine (7%) altered to iddingsite, Clinopyroxene (14%), Hematite (1%) and Cryptocrystalline material (8%).

<u>117</u> PINK/BLACK RIDGE Tpb 6% Olivine; subhedral, altered to iddingsite, up to 1 mm 10% Vesicles

<u>Groundmass</u>: Coarse-grained trachytic laths of Plagioclase (35%) with intergranular Olivine (10%) altered to iddingsite, Clinopyroxene (16%), Hematite (12%), Cryptocrystalline material (11%) and Glass (1%).

118 PINK/BLACK RIDGE

Tpb

5% Olivine; subhedral to anhedral, up to 1.5 mm

1% Vesicles

<u>Groundmass</u>: Fine-grained trachytic laths of Plagioclase (61%) with intergranular Olivine (8%) altered to iddingsite, Clinopyroxene (21%) and Hematite (4%).

121 PINK/BLACK RIDGE Tpb

1% Olivine; euhdral, altered to iddingsite on margins

11% Vesicles; filled with calcite

<u>Groundmass</u>: Fine-grained trachytic laths of Plagioclase (43%) with intergranular Olivine (12%) altered to iddingsite, Clinopyroxene (17%), Hematite (9%) and Cryptocrystalline material (7%).

123 PINK/BLACK RIDGE Tpb

1% Olivine; euhedral, altered to iddingsite on margins

11% Vesicles; filled with calcite

<u>Groundmass</u>: Fine-grained trachytic laths of Plagioclase (37%) with intergranular Olivine (13%) altered to iddingsite, Clinopyroxene (10%), Hematite (3%) and Cryptocrystalline material (24%).

55 NORTH OF PINK/BLACK RIDGE Tpb

3% Plagioclase; subhedral, not pitted, up to 4 mm

21% Vesicles; filled with calcite

<u>Groundmass</u>: Seriate medium to coarse-grained felty laths of Plagioclase (32%) with intergranular Clinopyroxene (9%), Hematite (2%) and Cryptocrystalline material (32%).

55B NORTH OF PINK/BLACK RIDGE Tpb

4% Olivine; subhedral, embayed, up to 1 mm, altered to iddingsite

11% Vesicles; most filled with calcite

<u>Groundmass</u>: Coarse-grained felty laths of Plagioclase (52%) with intergranular Olivine (15%)

altered to iddingsite, Clinopyroxene (12%), Hematite (3%) and Cryptocrystalline material (3%).

Tpb(?)

114 SENATOR MOUNTAIN

13% Plagioclase; embayed and seived with nonpitted subhedral overgrowths; up to 4 mm

2% Olivine; altered to iddingsite on margins; embayed; up to 1 mm

2% Clinopyroxene; subhedral, embayed; up to 1 mm

1% Magnetite

6% Vesicles; partially filled with chalcedony

<u>Groundmass</u>: 60% Cryptocrystalline material with fine-grained felty laths of Plagioclase (8%), Olivine (5%) altered to iddingsite, and Clinopyroxene (2%).

3 SQUAW PEAK

Tspm

24% Plagioclase; fritted with nonpitted overgrowths; up to 5 mm

4% Olivine; altered to iddingsite on margins; up to 1 mm

9% Clinopyroxene; pitted, embayed; up to 3 mm

1% Magnetite

1% Vesicles

Groundmass: Seriate fine to medium-grained trachytic laths of Plagioclase (43%) with intergranular

Olivine (10%) altered to iddingsite, Clinopyroxene (8%) and Hematite (1%).

SQUAW PEAK 21

6% Olivine; euhdral, altered to iddingsite, less than 0.5 mm

1% Magnetite; euhedral

12% Vesicles; filled with calcite

Groundmass: Medium-grained trachytic laths of Plagioclase (39%) with intergranular Olivine (12%) altered to iddingsite, Clinopyroxene (5%), Hematite (13%) and Cryptocrystalline material (12%).

Tspm

SOUTH OF SQUAW PEAK 108

12% Olivine; Euhedral to subhedral, altered to iddingsite and hematite

Groundmass: Fine-grained trachytic laths of Plagioclase (44%) with intergranular Olivine (15%) altered to iddingsite, Hematite (13%) and Cryptocrystalline material (16%).

SQUAW PEAK 126

5% Plagioclase; laths less than 0.5 mm in glomerocrysts

2% Olivine; embayed, subhedral; up to 1 mm; altered to iddingsite on margins

11% Vesicles; filled with calcite

Groundmass: Medium-grained subtrachytic laths of Plagioclase (45%) with intergranular Olivine (16%) altered to iddingsite, Clinopyroxene (2%), Hematite (11%) and Cryptocrystalline material (8%).

SQUAW PEAK <u>127</u>

2% Plagioclase; laths less than 0.5 mm in glomerocrysts

5% Olivine; embayed, subhedral; up to 1 mm; altered to iddingsite on margins

3% Vesicles; filled with calcite

Groundmass: Medium-grained subtrachytic laths of Plagioclase (50%) with intergranular Olivine

(12%) altered to iddingsite, Clinopyroxene (10%), Hematite (5%) and Cryptocrystalline material (13%).

SOUAW PEAK 128

13% Plagioclase; fritted, embayed; subhedral laths up to 2 mm

9% Olivine; altered to iddingsite and hematite

7% Clinopyroxene; subhedral, up to 2 mm

10% Vesicles; some filled with chalcedony

Groundmass: Fine-grained felty laths of Plagioclase (31%) with intergranular Olivine (3%) altered to iddingsite, Clinopyroxene (8%), Hematite (1%) and Cryptocrystalline material (19%).

EAST OF SQUAW PEAK 112

23% Plagioclase; pitted, fritted, embayed, up to 2 X 4 mm; inclusions of clinopyroxene

0.6% Olivine; small crystals in glomerocrysts with clinopyroxene, altered to iddingsite.

8% Clinopyroxene; rounded single crystals up to 2 mm; or in glomerocrsyts with plagioclase and olivine up to 2 mm

15% Vesicles:

- Groundmass: Fine-grained felty laths of Plagioclase (12%), with intergranular Olivine (6%) altered to iddingsite, Hematite (8%) and Cryptocrystalline material (28%).
- EAST OF SQUAW PEAK 113

24% Plagioclase; pitted, up to 2 X 3 mm

1% Olivine; included in clinopyroxene, altered to iddingsite

6% Clinopyroxene; pitted, embayed, rounded; subhedral up to 1 mm; also in glomerocrysts up to 2

Tspm

Tspm

Tspm

Tspu

Tspu

TSDE

mm

<u>Groundmass</u>: Fine-grained felty laths of Plagioclase (28%) with intergranular Olivine (2%) altered to iddingsite, Clinopyroxene (8%), Hematite (4%) and Cryptocrystalline material (22%).

Tspu

20 EAST OF SQUAW PEAK

1% Plagioclase; euhedral, sector zoning; up to 3 mm

9% Olivine; subhedral, embayed; altered to iddingsite; up to 1mm

2% Clinopyroxene; zoned, sub-euhedral; up to 1 mm

2% Magnetite

<u>Groundmass</u>: Fine-grained trachytic laths of Plagioclase (31%) with intergranular Olivine (9%) altered to iddingsite, Clinopyroxene (3%), Hematite (8%) and Cryptocrystalline material (34%).

APPENDIX D: PETROGRAPHIC DESCRIPTIONS-PRECAMBRIAN BASEMENT Percentages are estimated

24 Rock type: Felsic gneiss Location: Golden Rule Peak, west end Probable protolith Felsic igneous Prograde or relict minerals: 25% Plagioclase, equant, largely replaced by sericite 20% Quartz, recrystallized ribbons 5% Microcline, equant, partially replaced sericite 2% Biotite, largely replaced by chlorite and epidote <1% Apatite, equant, small Retrograde minerals: 35% Sericite, replaces feldspars 8% Chlorite, replaces biotite 1% Epidote, replaces biotite Introduced or remobilized minerals: 3% Calcite, in late stage fractures

1% Opaque and hematite

Texture: Crude foliation defined by recrystallized quartz ribbons and by compositional banding of quartz and feldspar-rich layers alternating with biotite/chlorite-rich layers. Late stage fractures filled with calcite and hematite.

28 Rock type: Quartzofeldspathic vein

Location: Golden Rule Peak, south side

Probable protolith: Felsic igneous

Prograde or relict minerals:

45% Quartz, elongate approaching ribbon shape, deformation bands, localized zones of recrystallization and thin film between feldspars

25% Microcline, blocky equant grains, slightly sericitized, contains internal, optically misoriented sectors suggesting crystal plastic deformation

20% Plagioclase with pericline twins, blocky equant grains, slightly sericitized

5% Muscovite

Retrograde minerals:

5% Sericite, replaces feldspars

Texture: Weak, discontinuous foliation defined by quartz grains aligned with primary muscovite. Other: Veins cut parallel and subparallel to gneissic foliation.

41 Rock type: Felsic gneiss
Location: Senator Tank
Probable protolith: felsic igneous
Prograde or relict minerals:
40% Quartz, ribbons with deformation bands, recrystallized on margins
18% Microcline, partially sericitized
15% Plagioclase, partially sericitized
3% Biotite, partially replaced by chlorite and epidote
Retrograde minerals:
15% Sericite, replaces feldspars
2% Chlorite, replaces biotite
<1% Epidote, replaces biotite

Introduced or remobilized minerals:

5% Opaque and hematite, fills late stage fractures

2% Calcite, fills late stage fractures

Texture: Foliation defined by quartz ribbons and zones of grain size reduction in quartz and feldspar. Brittle fractures oriented parallel to and perpendicular to this foliation are filled with hematite, clays and calcite.

Other: Associated in field with chlorite-biotite schists.

44 Rock type: Schistose partially recrystallized protomylonite

Location: Senator Tank

Probable protolith: Felsic igneous, possibly intrusive

Prograde or relict minerals:

25% Quartz, recrystallized ribbons

15% Microcline, up to 5 mm equant slightly sericitized porphyroclasts, and smaller equant highly sericitized grains in matrix

13% Plagioclase, up to 3 mm equant porphyroclasts, small grains in matrix and lath-shaped inclusions in microcline porphyroclasts, altering to sericite

4% Sphene, rounded, anhedral, quartz and opaque inclusions

3% Opaque, euhedral, locally mantled by sphene

2% Biotite, altering to chlorite

1% Apatite

1% Zircon

Retrograde minerals:

30% sericite, replaces feldspars, especially small matrix grains

5% chlorite, replaces biotite

1% epidote, replaces biotite

Texture: Foliation defined by recrystallized quartz ribbons and crude alignment of original biotite. Other: Associated in field with similar schists bearing large feldspar porphyroclasts up to 1.5 cm.

45 Rock type: Biotite gneiss

Location: Senator Tank

Probable protolith: Felsic igneous

Prograde or relict minerals:

20% Quartz, recrystallized ribbons, granoblasite polygonal grains with undulose extinction

16% Plagioclase, largely replaced by sericite

5% Sphene

2% Biotite, largely replaced chlorite and epidote

<1% Opaque

<1% Zircon

Retrograde minerals:

45% Sericite, replaces plagioclase

5% Chlorite, replaces biotite

5% Epidote, replaces biotite

Texture: Crude foliation defined by recrystallized quartz ribbons.

46 Rock type: Quartzofeldspathic part of coarsely banded gneiss

Location: Senator Tank

Probable protolith: Felsic igneous

Prograde or relict minerals:

37% Microcline, some sericite replacement

33% Quartz, subgrain development and deformation bands

10% Plagioclase, largely replaced by sericite 2% Muscovite Retrograde minerals:

13% Sericite, replaces feldspars

2% Opaques

Texture: No obvious foliation, feldspar and quartz grain boundaries are corrugated and/or sutured. Other: Gneiss is coarsely banded with 5-10 cm bands of quartzofeldspathic material and 2-3 cm bands of schistose material.

47 Rock type: Amphibolitic gneiss
Location: Senator Tank
Probable protolith: Mafic igneous
Prograde or relict minerals:
35% Hornblende, subhedral, replaced on margins by epidote
10% Quartz, subequant
Retrograde minerals:
20% Zoisite, replaces plagioclase (now completely gone)
10% Actinolite, replaces hornblende
10% Chlorite, replaces actinolite
10% Epidote, replaces actinolite

5% Sericite, replaces plagioclase

Texture: Foliation defined by parallel alignment of hornblende and compositional banding of hornblende-rich layers alternating with formerly plagioclase-rich layers.

Other: Associated in the field with medium grained quartzofeldspathic gneiss, phyllite and schist

58 Rock type: Cataclasite

Location: Salt Spring, at detachment surface

Probable protolith: Quartzofeldspathic vein (?)

Prograde or relict minerals:

60% Quartz, undulose extinction, granoblastic-polygonal

Retrograde minerals:

35% Sericite, may have replaced an earlier mineral, probably a feldspar

2% Opaque

Introduced or remobilized minerals:

3% Hematite, concentrated along fractures

Texture: Granoblastic-polygonal quartz grains cut by fractures with abundant alteration to sericite and hematite

Other: Grungy yellow hand sample found right at detachment surface

60 Rock type: Amphibolite

Location: Salt Spring, near detachment

Probable protolith: Mafic igneous

Prograde or relict minerals:

22% Hornblende, brown in plane polarized light

5% Clinopyroxene, subequant, largely replaced by chlorite

5% Orthopyroxene, elongate, partially replaced by chlorite

3% Plagioclase, largely replaced by sericite

3% Opaque, euhedral

Retrograde minerals:

33% Sericite, replaces plagioclase

20% Actinolite, needle-like, replaces hornblende

5% Chlorite, replaces pyroxenes

Introduced or remobilized minerals:

3% Sericite along fractures

1% Calcite along fractures

Texture: Foliation defined by parallel alignment of hornblende and by compositional banding of hornblende and clinopyroxen-rich layers alternating with plagioclase-rich layers. Late stage fractures are filled with sericite and calcite.

Other: Associated in the field with amphibolitic gneiss and quartzofeldspathic veins.

<u>63</u> Rock type: Biotite-garnet gneiss Location: Salt Spring, at detachment Probable protolith: Pelite or garnet-bearing igneous (?) Prograde or relict minerals: 20% Quartz, ribbons, partial recrystallization and subgrain development 20% Garnet, fractured, partially replaced by chlorite, quartz inclusions 15% Plagioclase, altering to sericite 5% Biotite, altering to chlorite 3% Muscovite 2% Opaque <1% Zircon Retrograde minerals: 18% Sericite, replaces plagioclase 10% Chlorite, replaces biotite and garnet 3% Zoisite, replaces plagioclase 2% Epidote, replaces biotite Introduced or remobilized minerals: 2% Calcite, along fractures Texture: Foliation defined by compositional layering, quartz ribbon alignment and parallel orientation of micas Other: Associated in the field with quartzofeldspathic veins, parallel and subparallel to foliation <u>75</u> Rock type: Amphibolite Location: Salt Spring, near detachment Probable protolith: Mafic or ultramafic igneous Prograde or relict minerals: 55% Hornblende, euhedral, replacement by actinolite and chlorite on grain boundaries

2% Clinopyroxene, mostly replaced by epidote and chlorite

1% Plagioclase, mostly replaced by zoisite

<1% Sphene

Retrograde minerals:

20% Actinolite, replaces hornblende

10% Epidote, replaces clinopyroxene

5% Chlorite, replaces hornblende and clinopyroxene

4% Zoisite, replaces plagioclase

Introduced or remobilized minerals:

3% Calcite, in fractures

Texture: Weak foliation defined by parallel alignment of hornblende. Fractures filled with actinolite and calcite cut across foliation.

Other: Associated in the field with amphibolitic gneiss and quartzofeldspathic veins.

<u>76</u> Rock type: Amphibolitic gneiss

Location: Salt Spring, near detachment

Probable protolith: Mafic igneous

Prograde or relict minerals:

45% Hornblende, partially replaced by actinolite and epidote

10% Clinopyroxene, largely replaced by epidote

2% Apatite

<1% Sphene

Retrograde minerals:

20% Actinolite, replaces hornblende

10% Epidote, replaces hornblende and clinopyroxene

10% Zoisite, replaced all of former plagioclase

Introduced or remobilized minerals:

3% Calcite, in fractures

Texture: Foliation defined by parallel alignment of hornblende and pyroxene and by compositional banding of hornblende and pyroxene alternating with former plagioclase. Overprinted by late-

stage fractures filled with calcite.

Other: Associated in the field with amphibolite and quartzofeldspathic veins.

78 Rock type: Quartzofeldspathic vein

Location: Salt Spring

Probable protolith: Felsic igneous

Prograde or relict minerals:

45% Quartz, elongate grains with length 4 times width, sutured grain boundaries

40% Microcline, slightly elongate grains with length 2 times width, grain boundaries straight parallel to twins, sutured perpendicular to twins

10% Plagioclase, slightly elongate grains with length 2 times width, altering to sericite Retrograde minerals:

5% Sericite, replaces plagioclase

Texture: Granitoid, weak foliation defined by slightly elongated quartz and feldspars Other: Granitoid layers associated in the field with amphibolites

79 Rock type: Amphibolite

Location: Salt Spring

Probable protolith: Mafic, possibly ultramafic, igneous

Prograde or relict minerals:

95% Hornblende, large and small grains with granoblastic-polygonal textures

2% Opaque, equant, interstitial between hornblende grains

1% Quartz, equant, included in large hornblende grains

Retrograde minerals:

2% Chlorite, altered from fine-grained hornblende

Introduced or remobilized minerals:

3% Quartz, along fractures

2% Calcite, along fractures

Texture: No obvious foliation, randomly oriented grains. Overprinted by late-stage fractures filled with quartz and calcite.

Other: Associated in field with quartzofeldspathic veins

80 Rock type: Amphibolite Location: Salt Spring Probable protolith: Mafic igneous Prograde or relict minerals: 40% Hornblende, straight or curved boundaries
10% Plagioclase, rounded, replaced by sericite
3% Clinopyroxene, largely replaced by chlorite and epidote
Retrograde minerals:
20% Sericite, replaces plagioclase
10% Epidote, replaces clinopyroxene

7% Chlorite, replaces clinopyroxene

Introduced or remobilized minerals:

10% Calcite, along fractures

Texture: No obvious foliation, randomly oriented mixture of hornblende, plagioclase and clinopyroxene. Late stage fractures are filled with calcite.

Other: Associated in field with quartzofeldspathic veins

145Rock type: Biotite schistLocation: Salt Spring WashProbable protolith: Felsic igneous or Sedimentary (?)Prograde or relict minerals:35% Quartz, elongated, undulose extinction15% Biotite, partially replaced by chlorite10% Feldspar, largely replaced by sericite3% Opaque1% Zircon<1% Sphene</td>Retrograde minerals:30% Sericite, replaces feldspar

5% Chlorite, replaces biotite

Introduced or remobilized minerals:

1% Calcite, along fractures

Texture: Foliation defined by parallel alignment of biotite and elongate quartz crystals. Other: Associated in the field with amphibolitic gneiss and felsic gneiss.

146 Rock type: Amphibolitic schist

Location: Salt Spring Wash

Probable protolith: Mafic igneous or volcaniclasitic (?)

Prograde or relict minerals:

30% Hornblende, large megacrysts, irregular shapes, hematized, and locally altered to actinolite on boundaries

30% Biotite, interleaved with muscovite, hematized

15% Muscovite, interleaved with biotite

2% Quartz, anhedral

Retrograde minerals:

10% Zoisite, replaces biotite

3% Actinolite, replaces hornblende

Introduced or remobilized minerals:

10% Hematite, altering biotite, hornblende, and filling fractures

Texture: Foliation defined by parallel alignment of micas and hornblende and by compositional banding of hornblende alternating with mica-rich layers. Late stage pervasive fractures are filled with hematite.

Other: Associated in the field with quartzofeldspathic veins which both parallel foliation and cut foliation at high angles.

147 Rock type: Biotite schist
Location: Salt Spring Wash
Probable protolith: Felsic igneous
Prograde or relict minerals:
30% Quartz, elongated with length 4 times width, undulose extinction
10% Biotite, altering to chlorite and hematite
3% Opaque
1% Zircon
Retrograde minerals:
40% Sericite, replaces feldspar (now entirely gone)
8% Chlorite, replaces biotite

Introduced or remobilized minerals:

5% Calcite, in fractures

3% Hematite, in fractures

Texture: Foliation defined by parallel alignment of biotite and elongated quartz crystals. Late stage fractures are filled with calcite and hematite.

Other: Associated in the field with amphibolitic gneiss and felsic gneiss.

APPENDIX E: INSTRUMENTAL TECHNIQUES

Whole-rock major element analyses were done on the Rigaku model 3030 Xray Fluorescence spectrometer at the University of Nevada, Las Vegas. Unweathered samples were ground to 200 mesh by the Dyna Mill air suspended impact attrition mill and an agate mortar and pestle. Fused glass disks were produced by heating 0.5 g. of sample, 4.0 g. of lithium tetraborate and 0.08 g. of ammonium nitrate to 1100°C in a graphite crucible and pouring the resulting melt onto a heated aluminum press. After cooling to room temperature, the one side of each disk was polished smooth with sandpaper. Disks are stored in a desiccator to prevent hydration. The polished side was used in XRF analysis. The UNLV Rigaku 3030 was calibrated using USGS standards PCC-1, AGV-1, QLO-1, BHVO-1 and W-2. Individual analytical runs are standardized with UNLV standard M2. Precision for major element analyses is given in Table F-1. Loss-on-ignition (LOI) was determined by heating 2 to 4 g of sample to 1000°C for 2 hours. The weight loss was divided by initial weight X 100 to determine percent LOI.

Samples were analyzed for trace and rare earth element concentrations by Instrumental Neutron Activation Analysis at the Phoenix Memorial Laboratory, University of Michigan. Samples were ground to 200 mesh as above. Samples (180-220 mg) were shipped in sealed nalgene vials. Percent error reported by Phoenix labs for each element is given in Table F-2.

A K-Ar date on biotite was determined for one ash-flow tuff sample at

154

Krueger Enterprises, Inc., Geochron Laboratories Division. The sample was carefully selected to minimize basaltic lithic fragments. No Precambrian or other potential biotite-bearing lithic fragments occur in the tuff at the locality from which the sample was collected. The sample was ground to medium sand size by the Dyna Mill air suspended impact attrition mill. The sand was separated by density on a number 13 Wilfley table. The bulk of the magnetite was removed by pouring the heavy fraction through a glass tube surrounded by a large magnet. Remaining magnetite was removed in the Frantz isodynamic magnetic separator model L-1. Individual biotite grains were separated from less dense ground rock fragments by density in sodium metatungstate. Biotite grains were separated from biotite-rich rock fragments by handpicking under a microscope. The biotite sample was shipped to Krueger Geochron in a glass vial. Analytical data are in Table 8.

155

SiO2	Mean 59.81	S.D.	% Error	
		0.2	0.3	
AI2O3	16.9	0.08	0.5	
FeO*	7.51	0.14	1.9	
CaO	4.85	0.02	0.4	
MgO	1.3	0.02	1.7	
N=20	4.62	0.08	1.7	
K20	3.3	0.04	1.2	
TiO2	1.1	0.01	0.9	
MnO	0.158	0.004	2.5	
P2O5	0.91	0.01	1.1	

Table F-1: Precision for major element analyses

Data from 5 replicate analyses of USGS

standard AGV-1 on Rigaku 3030, UNLV.

* Total iron as FeO

Table F-2:	Precision for t	race and				
rare-earth element analyses						
Maximum Minimum Average						
La	0.4	1.3	0.7			
Ce	. 0.9	5.1	1.5			
Nd	3.3	22.1	7.9			
Sm	0.2	0.9	0.4			
Eu	1.7	5.6	3.3			
Yb	4	9.9	5.9			
Lu	4.1	14.4	7.8			
U	7	24.4	13.7	•		
ТЪ	1.1	12.8	3.6			
Cr	0.9	7.5	2.3			
Hf	2.5	10.3	4.4			
Ba	1.9	22.8	8.2			
Rb	8.9	21.2	12.5			
Sr	8.3	20.8	12.3			
Sc	0.3	0.6	0.4			
Ta	6.8	23.9	11.9			
Co	1	2.1	1.4			
v	2.1	8.4	2.6			
Dy	8.78	6.1	13.2			

Percent error: reported by Phoenix Memorial Laboratory, University of Michigan