Style of volcanism and extensional tectonics in the eastern Basin and Range Province: Northern Mohave County, Arizona

Tracey Elaine Cascadden

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Style of volcanism and extensional tectonics in the eastern Basin and Range Province: Northern Mohave County, Arizona

Cascadden, Tracey Elaine, M.S.
University of Nevada, Las Vegas, 1991

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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

Master of Science
in
Geology

Geoscience Department
University of Nevada, Las Vegas
August, 1991
The thesis of Tracey Elaine Cascadden for the degree of Master of Science in Geology is approved.

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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.
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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 strike-slip 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.
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 Instrumental 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
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 west-dipping 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
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% SiO$_2$) 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
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/Ttibm/Ttbu = basaltic andesite of Temple Bar.
Table 1: Major element data for ash-flow tuffs

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Total iron as FeO
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.
Table 3: Summary of mineralogy for ash-flow tuffs

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<th>Sample</th>
<th>% Lithic Fragments</th>
<th>% Pumice Fragments</th>
<th>% Sanidine</th>
<th>% Plagioclase</th>
<th>% Quartz</th>
<th>% Biotite</th>
<th>% Sphene</th>
<th>% Clino-</th>
<th>% Olivine</th>
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* 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 SiO$_2$ 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 SiO$_2$ 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.

Mafic volcanic rocks form two distinct groups in terms of chemistry (Tables 5, 6 and 7). Harker variation diagrams with SiO$_2$ and magnesium number (Mg$^#$ = Mg/(Mg+Fe)) versus La, Hf, Th, Sc, total REE (La + Ce + Nd + Sm + Eu + Yb + Lu) and total alkalis (Na$_2$O + K$_2$O) (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 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 TiO$_2$, 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.
Table 4: Summary of mineralogy for mafic volcanic rocks*

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*percent based on counts of 500 points per slide using a Swift point counter

codes for textures:
s = seriate microcrystal size range
mx = microcrystals dominant in groundmass
cx = cryptocrystals dominant in groundmass
ex = glass dominant in groundmass
m = medium-sized microcrystals
f = fine-grained microcrystals

* percent based on counts of 500 points per slide using a Swift point counter
Table 4: continued

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### Table 5: Major element data for mafic volcanic rocks

|       | T61  | T61b | T62  | T62b | T63  | T63b | T64  | T64b | T65  | T65b | T66  | T66b | T67  | T67b | T68  | T68b | T69  | T69b | Total  |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-------|
|       | 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|
| FeO*  | 7.31 | 5.81 | 8.04 | 10.87| 7.13 | 7.57 | 8.351| 8.16 | 7.1  | 8.28 | 6.2  |
| MgO   | 3.09 | 2.07 | 1.69 | 9.44 | 2.82 | 3.42 | 3.413| 4.23 | 4.94 | 4.72 | 2.83 |
| Na2O  | 3.46 | 3.15 | 3.66 | 3.18 | 3.18 | 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| 0.157| 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 |

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

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(# 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.
Figure 12. Hf/Th plotted against La/Yb, major oxides TiO$_2$ 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 chondrite-normalized 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.
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° north-northeast. (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
was dated at 16.4 ± 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
Table 8: New biotite K-Ar date on ash-flow tuff, White Hills

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* denotes radiogenic
Table 9: Summary of mineralogy for coarse breccia clasts

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* percentages are estimated
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). Tbrl 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 outcrops 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
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%).

Squaw Peak basaltic andesite (Tsp) (48-54% SiO₂) exhibits chemical characteristics intermediate between the Temple Bar volcanics and Pink/Black Ridge volcanics. Incompatible element variation is wide over a narrow range of SiO₂ and Mg#, while variation in compatible elements is low. Tsp also contains higher K₂O, Mg#, TiO₂ 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% SiO$_2$) is distinguished from other mafic volcanic rocks of the NWH by low K$_2$O, 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 interrupted 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.
situated to the south and/or east of the study area. Tbrl 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
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* denotes sample from near detachment surface
percentages are estimated
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**GARNET-BIOTITE GNEISS**

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* denotes sample from near detachment surface
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 recrystallized 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
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.

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, west-to 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
Figure 17a. Cross section A-A' through the Peninsula. Location of cross section lines are on Figure 4. Shaded unit is Tt and equivalent Tbre.

Figure 17b. Cross section B-B'-B" through Chuckwalla Ridge, Smith Hill and Salt Spring Wash.

Figure 17c. Cross section C-C' through Squaw Peak and Pink/Black Ridge.
ninsula. Location of cross
nit is Tt and equivalent

Squaw 5 km
mineralogically and chemically similar to the intruded basaltic andesite and may represent feeder dikes for overlying flows. Steeply west-dipping (75°), north-trending 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 north-striking, 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 Ttbr/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 ash-flow tuff (Tt). Blocks are bounded by high-angle north-south trending, west-dipping 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 K$_2$O 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$_2$O contents relative to "normal" mafic intermediate volcanic rocks (Figure 21). Tpb samples and some Tsp samples plot within the field of normal cale-alkaline volcanics. Other Tsp samples and nearly all of the Ttb samples have elevated K$_2$O relative to "normal".

Potassium metasomatism is responsible for high K$_2$O 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$_2$O
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. $K_2O$ plotted against $Na_2O$. 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 = Proterozoic biotite monzongranite, D = Proterozoic monzogranite, E = Proterozoic twomica monzogranite, W = Tertiary Wilson Ridge Pluton.
### Table 11: Normative mineralogy of mafic volcanic rocks

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Rock names (LeBas, 1986): AB = Alkali basalt, SB = Subalkalic basalt, TB = Trachybasalt, BTA = Basaltic Trachyandesite
and Na$_2$O due to replacement of Na by K during metasomatism. In the NWH samples, Na$_2$O contents are similar to those of "normal" calc-alkaline volcanic rocks despite the elevation in K$_2$O. Therefore, K metasomatism does not appear to be a major cause of the high K$_2$O 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$_2$O 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 $K_2O$ 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
Table 12: Major element fractional crystallization and AFC models

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Residuals

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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=primitive Tsp (127), daughter=evolved Tsp (112)
Figure 23. Harker variation diagrams. Weight percent SiO$_2$ plotted against incompatible ppm Ce, Hf, La and Th. Symbols defined on Figure 21.
Figure 24. Tests for olivine and clinopyroxene 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.
Figure 25. Harker variation diagrams. Weight percent SiO$_2$ 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
assimilated by basaltic magma without leaving significant textural evidence. However, TiO$_2$ concentration and Mg#$ $ preclude these models. The modelled evolved magma (primitive Tsp) has higher TiO$_2$ than the proposed parent (primitive Tpb), but the contaminant is low in TiO$_2$. TiO$_2$ 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.

1. 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 Na2O 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
Table 13: Distribution coefficients for basalt

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<tr>
<td>Th</td>
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<td>0.007</td>
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Figure 26. Tests for plagioclase fractionation. Weight percent CaO and Na$_2$O plotted against ppm Eu. Symbols defined on Figure 21.
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 SiO₂ vs. FeO, MgO and TiO₂ (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.
another process in addition to fractionation is responsible for Ttb evolution. The wide range of Th over a fairly narrow range of SiO$_2$ (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 SiO$_2$ vs. FeO, MgO and TiO$_2$ (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 SiO$_2$ 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_{2}O 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 ash-flow 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).
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Data Source codes:
1: Cascadden, unpublished data
2: Smith, unpublished data
3: Bridwell, in preparation
4: Nielson, written communication
### Table 15: Trace and rare earth element data for Tuff of Bridge Spring and Peach Springs Tuff

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<td>Rb</td>
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<td>Hf</td>
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<td>8.83</td>
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<td>6.81</td>
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</tr>
<tr>
<td>Ba</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Rb</td>
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<td>89</td>
<td>100</td>
<td>44</td>
<td>110</td>
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<tr>
<td>Ta</td>
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<td>2.59</td>
<td>2.66</td>
<td>2.55</td>
<td>1.88</td>
<td>1.76</td>
<td>1.76</td>
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<tr>
<td>Zr</td>
<td>245</td>
<td>252</td>
<td>218</td>
<td>220</td>
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<td>510</td>
<td>225</td>
<td>256</td>
<td>197</td>
<td>215</td>
<td>270</td>
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</table>
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 (#). SiO₂ 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. SiO$_2$ 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 ($^{40}\text{Ar}/^{39}\text{Ar}$) reported by Gans (1991) from the Tuff of Bridge Spring in the Eldorado Range.

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 quiescence 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

<table>
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<tr>
<th>Caldera System</th>
<th>Date of Eruption</th>
<th>Interval Between Eruptions</th>
<th>Comments</th>
</tr>
</thead>
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<tr>
<td>Platoro, New Mexico (1)</td>
<td>32 Ma</td>
<td>2.5 Ma</td>
<td>Increase in SiO2</td>
</tr>
<tr>
<td></td>
<td>29.5 Ma</td>
<td>0.2 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29.3 Ma</td>
<td>0.1 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29.2 Ma</td>
<td>0.2 Ma</td>
<td>General decrease in SiO2</td>
</tr>
<tr>
<td></td>
<td>29.0 Ma</td>
<td>0.6 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28.4 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western San Juan, New Mexico (2,3)</td>
<td>28.8 Ma</td>
<td>0.4 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28.4 Ma</td>
<td>0.6 Ma</td>
<td>General decrease in SiO2</td>
</tr>
<tr>
<td></td>
<td>27.8 Ma</td>
<td>0.2 Ma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>27.6 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valles, New Mexico (4)</td>
<td>2.84 Ma</td>
<td>2.4 Ma</td>
<td>Erupted from zoned chambers, latter two episodes are more silicic than the first, yet similar with respect to non-fractionated elements.</td>
</tr>
<tr>
<td></td>
<td>1.45 Ma</td>
<td>0.33 Ma</td>
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<td></td>
<td>1.12 Ma</td>
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<tr>
<td>Yellowstone, Wyoming (5,6)</td>
<td>2.0 Ma</td>
<td>0.7 Ma</td>
<td>High-silica rhyolites, each similar mineralogically and chemically</td>
</tr>
<tr>
<td></td>
<td>1.3 Ma</td>
<td>0.7 Ma</td>
<td></td>
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<tr>
<td></td>
<td>0.6 Ma</td>
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<tr>
<td>Heise Volcanic Field, Idaho (7)</td>
<td>6.5 Ma</td>
<td>0.9 Ma</td>
<td>74–77% Silica, all enriched in LREE, each ash-flow similar chemically</td>
</tr>
<tr>
<td></td>
<td>5.6 Ma</td>
<td>1.3 Ma</td>
<td></td>
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<tr>
<td></td>
<td>4.3 Ma</td>
<td></td>
<td></td>
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<tr>
<td>Kane Springs Wash, Nevada (8)</td>
<td>15.6 Ma</td>
<td>0.9 Ma</td>
<td>Two or three separate centers erupted compositionally similar ash-flow tuffs</td>
</tr>
<tr>
<td></td>
<td>14.7 Ma</td>
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<td>14.1 Ma</td>
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<tr>
<td>Los Humeros, Mexico (9)</td>
<td>0.46 Ma</td>
<td>0.36 Ma</td>
<td>High-silica rhyolite to dacite in first eruption, rhyodacite to andesite in second. Eruption rate &gt; replenishment rate</td>
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<td></td>
<td>0.1 Ma</td>
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1. Duncan et al., 1989
2. Lipman et al., 1989
3. Hon and Lipman, 1989
4. Goff et al., 1989
5. Bonnichsen et al., 1989
6. Hildreth et al., 1984
7. Morgan et al., 1984
8. Novak, 1984
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.

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° 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).
Figure 35. Correlation of northern White Hills volcanic section with Eldorado Mountains section.
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 elastics 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 Tmcl 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.

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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</tr>
<tr>
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<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Brittle Deformation</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Low-angle anastomosing shear zones</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
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</tr>
<tr>
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<td>chloritic</td>
<td>chloritic</td>
<td>hematitic</td>
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<tr>
<td>Alteration</td>
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<td>hematitic</td>
<td>hematitic</td>
<td>propyllitic</td>
<td>hematitic</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>?</td>
<td>post 16.4 Ma</td>
<td>between 13.5 and 9 Ma</td>
<td>between 13.4 and 12 Ma</td>
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</table>
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.

**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 moderate-angle 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.

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,
Fault steepens northward along strike Upper plate is denuded

Greater rebound over more deeply denuded area results in exposure of deeper level rocks along a N-S line

Figure 38. Along-strike differences in deformational style due to northward steepening of fault surface.
Fault is corrugated about an E-W axis

Upper plate is denuded

Greater rebound to the north exposes deeper levels

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.

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
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.

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

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-the-west 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.

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.

**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

1250 m

BASALTIC ANDESITE

Pyroxene-dominant

Flows = 30%
Autoclastic breccias = 50%
Volcaniclastic breccias = 20%

Plagioclase = 5-10%; Olivine = 0-1%; Clinopyroxene = 0-5%

Plagioclase = 5-8%; Olivine = 2-5%; Clinopyroxene = 3-4%

Intruded by BASALTIC ANDESITE dikes:

Plagioclase = 11%; Clinopyroxene = 7%

1000 m

BASALTIC ANDESITE

Cordierite-dominant

Flows = 20%
Autoclastic breccias = 40%
Volcaniclastic breccias = 30%
Volcaniclastic sandstones = 10%

Plagioclase = 5-10%; Olivine = 1-5%; Clinopyroxene = 0%

750 m

SANDSTONE AND PEBBLE CONGLOMERATES

Clasts = basaltic andesite; Matrix = sand, silt and clay.

Interbedded with:

a) Thin (1-2 m) propylitic BASALTIC ANDESITE flows:

Plagioclase = 10%; Olivine = 5%; Clinopyroxene = 0%

b) and reworked, biotite-rich ash.

500 m

BASALTIC ANDESITE

Pyroxene-dominant

Thin, highly vesicular flows

Plagioclase = 15%; Olivine = 10%; Clinopyroxene = 0%

250 m

392 m

0 m

meters

Smith Hill 760 m

750 m

DACITEASH-FLOW TUFF

Nonwelded at base and top, moderately welded in center

Lithics = 2-20%; Pumice = 1-10%; Sandine = 3-20%;

Plagioclase = 0-1%; Quartz = <1%; Biotite = 1-4%;

Sphene = <1%; Clinopyroxene = <1%; Zircon = <1%

500 m

BASALTIC ANDESITE

Pyroxene-dominant

Flows = 30%
Autoclastic breccias = 40%
Volcaniclastic breccias = 30%

Plagioclase = 1-10%; Olivine = 0-1%; Clinopyroxene = 3-12%

Flows = 20%
Volcaniclastic sandstones/Debris flows = 10%
Autoclastic breccias = 40%
Volcaniclastic breccias = 30%

Plagioclase = 3-10%; Olivine = 0-3%; Clinopyroxene = 3-12%

Intruded by BASALTIC ANDESITE dikes:

Plagioclase = 12%; Olivine = 4%; Clinopyroxene = 2%

610 m

150 m

0 m

meters
Peninsula 1010 m

132

BASALTIC ANDESITE
Gray flows = 40% Autoclastic breccias = 40% Volcaniclastic breccias = 20%
Clasts = basal andesite up to 2 cm, matrix = sand & silt

BASALTIC ANDESITE
Phenocryst-poor
Pyroxene-dominant
Gray flows = 50% Red-purple autoclastic breccias = 30%
Red volcaniclastic breccias = 20%
Plagioclase = 5%; Olivine = 0%; Pyroxene = 3%

Squaw Peak 1192 m

BASALTIC ANDESITE
Dense, gray massive flows = 90% Red autoclastic breccias = 10%
Plagioclase = 1-24%; Olivine = 2-9%; Clinopyroxene = 1-6%

VOLCANICLASTIC SANDSTONE, SILTSTONE AND CONGLOMERATE
Clasts = basal andesite up to 2 cm, moderately rounded
Matrix = orange clay and silt

BASALTIC ANDESITE
Dense, gray massive flows = 70%
Red-purple or gray autoclastic breccias = 20%
Red-orange volcaniclastic breccias = 10%, confined to upper 100 m
Plagioclase = 0-24%; Olivine = 3-10%; Clinopyroxene = 0-5%

MONOCLITHIC BRECCIA with clastic dikes
BASALTIC ANDESITE
Gray flows = 50% Red-purple autoclastic breccias = 30%
Red volcaniclastic breccias = 20%
Plagioclase = 3-12%; Olivine = 0-5%; Clinopyroxene up to 5 mm = 5-10%

DACITE ASHFLOW TUFF
Nonwelded at base and top; moderately welded in center
Lithics = 6-10%; Pumice = 4-24%; Sandstone = 8-24%
Plagioclase = 8-15%; Quartz = 1-7%; Biotite = 1-3%
Sphene = 1-7%; Clinopyroxene up to 5 mm = 1-3%
Zircon = 1-3%
Conglomeratic sandstone beds near base

BASALTIC ANDESITE
Pyroxene-dominant
Red flows = 30% Autoclastic breccias = 30% Volcaniclastic breccias = 40%
Plagioclase = 5%; Olivine = 0%; Pyroxene = 3%
**Salt Spring Wash 1556 m**

- **1750 m**
  - **BASALTIC ANDESITE**
  - Pyroxene-dominant
  - Gray flows = 30%
  - Red & gray autoclastic breccias = 25%
  - Red volcanioclastic breccias = 20%
  - Volcanioclastic sandstones in central 25%
  - Plagioclase = 0-20%; Olivine = 0-1%; Clinopyroxene = 5-9%

- **145 m**
  - **SANDSTONE AND CONGLOMERATE**
  - Clasts = basaltic andesite and Precambrian basement up to 20 cm
  - Matrix = sand and silt

- **1250 m**
  - **BASALTIC ANDESITE**
  - Pyroxene-dominant, phenocryst-poor
  - Gray flows = 30%
  - Red and gray autoclastic breccias = 40%
  - Volcanioclastic breccias = 30%
  - Plagioclase = 2-15%; Olivine = 0-1%; Clinopyroxene = 2-3%

- **1000 m**
  - **COARSE MONOLITHOLOGIC BRECCIA**
  - Crackle breccia and jigsaw breccia
  - Clasts = blocks of Precambrian basement up to 60 m in size

- **750 m**
  - **DACITE ASH-FLOW TUFF**
  - Unweathered
  - Lithics = 2-15%; Fumicite = 0-11%; Sanidine = 1-9%
  - Plagioclase = 1-4%; Quartz = <1%; Biotite = 1-2%
  - Sphene = <1%; Clinopyroxene = <1%; Zircon = <1%

- **500 m**
  - **COARSE MONOLITHOLOGIC BRECCIA**
  - Crackle breccia (fragments show little to no separation and rotation)
  - Jigsaw breccia (internal fragments separated by thin bands of matrix)
  - Clastic dikes near base of exposed section
  - Matrix-supported debris flow at top

- **250 m**
  - **BASALTIC ANDESITE**
  - Pyroxene-dominant
  - Plagioclase = 5%; Olivine = 1%; Clinopyroxene = 9%

**Pink/Black Ridge 785 m**

- **750 m**
  - **BASALTIC ANDESITE**
  - Olivine-dominant
  - Flows = 70%
  - Autoclastic breccias = 20%
  - Volcanioclastic breccias = 10%
  - Plagioclase = 0-10%; Olivine = 1-6%; Clinopyroxene = 0-4%

- **442 m**
  - **COARSE MONOLITHOLOGIC BRECCIA with clastic dikes**
  - Jigsaw breccia dominates
  - Discontinuous sandy conglomerate and siltstone at top and near base of exposure

- **343 m**
  - **BASALTIC ANDESITE**
  - Olivine-dominant
  - Flows = 70%
  - Autoclastic breccias = 20%
  - Volcanioclastic breccias = 10%
  - Plagioclase = 0-10%; Olivine = 1-6%; Clinopyroxene = 0-4%
APPENDIX B: PETROGRAPHIC DESCRIPTIONS
ASH-FLOW TUFFS
1000 points/slide

137 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 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 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

54 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
62% Sanidine; subhedral, embayed, up to 2 mm
42% Plagioclase; broken, subhedral, partially altered to calcite, < 1 mm
20% Biotite; hematitic alteration on margins and fractures, <1 mm
5% Sphene; euhedral
2% Clinopyroxene; anhedral, embayed, <1 mm
1% Zircon
0.7% Magnetite

Groundmass: slightly welded, moderately devitrified, moderately calcified

69
- West side of Salt Spring Wash, base of Tt
- 14.5% Lithic fragments; dacite and basalt, up to 5 mm
- 14% Pumice fragments; unflattened, up to 2 mm
- 3.9% Sanidine; subhedral to anhedral, embayed, <1 mm
- 2.7% Plagioclase; broken, euhedral 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
- 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

70
- 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

83
- 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; slightly 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

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

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 altered 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

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

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

**Groundmass:** slightly welded, slightly devitrified, moderately calcified

98

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

106

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
reworked ash from west of Chuckwalla Ridge

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

139 PENINSULA Ttbl
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 Ttbl
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
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%).

51 SMITH HILL Ttbm
22% Plagioclase; pitted, fritted; subhedral laths seriate to 2 mm
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%).

50 SMITH HILL Ttbm
19% Plagioclase; pitted, fritted; subhedral laths up to 1 X 3 mm; in glomerocrysts with clinopyroxene
up to 3 mm
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%).

148 GATEWAY COVE Tbm
16% Plagioclase; pitted, sieved; subhedral laths up to 5 mm
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%).

65 GATEWAY COVE Tbm
15% Plagioclase; pitted, embayed; subhedral laths up to 2X4 mm; glomerocrysts with pyroxenes up
to 2 mm
1% Olivine; anhedral, iddingsitized, 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 Tbm
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%).

132 CHUCKWALLA RIDGE Tbm
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%).

134 CHUCKWALLA RIDGE Tbm
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 Tbm
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 chaledony

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 = Ttbn 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

Groundmass: 41% Cryptocrystalline material with seriate medium-grained felty laths of Plagioclase
(19%), and Clinopyroxene (8%).

49 SMITH HILL
Ttbn
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

Groundmass: Seriate medium to coarse grained felty laths of Plagioclase (24%); with intergranular
Clinopyroxene (11%) and Cryptocrystalline material (37%).

125 SMITH HILL
Ttbn
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

Groundmass: Partially devitrified brown Glass (51%) with medium-grained felty laths of Plagioclase
(4%) and Clinopyroxene (3%).

140 PENINSULA
Ttbn
22% Plagioclase; slightly pitted, fritted, with non-pitted overgrowths; subhedral laths up to 1 mm;
gomerocrysts with clinopyroxene and magnetite up to 3 mm
3% Unaltered Clinopyroxene; embayed, euhedral to subhedral, up to 1 mm; and in large
gomerocrysts with plagioclase
3% Altered Clinopyroxene; anhedral, embayed, less than 1 mm; and in large glomerocrysts with
plagioclase

Groundmass: 48% Cryptocrystals; with seriate fine to coarse-grained subtrachytic laths of Plagioclase
(15%), both types of Clinopyroxene (6%) and Hematite (3%).

133 CHUCKWALLA RIDGE
Ttbn
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

Groundmass: Fine to medium-grained felty laths of Plagioclase (14%); with intergranular
Clinopyroxene (10%), Hematite (1%), and Cryptocrystalline material (31%).

130 CHUCKWALLA RIDGE
Ttbn
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

**Groundmass:** fine-grained felty laths of Plagioclase (16%); with intergranular Clinopyroxene (6%) and Cryptocrystalline material (45%).

86 SMITH HILL Ttbm
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

**Groundmass:** Fine-grained trachytic laths of Plagioclase (33%); with intergranular Hematite (9%) and Cryptocrystalline material (39%).

143 PENINSULA Ttbm
48% Vesicles

**Groundmass:** Seriate fine to coarse-grained subtrachytic laths of Plagioclase (13%); with intergranular Hematite (15%) and Cryptocrystalline material (14%).

141 PENINSULA Ttbm
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

**Groundmass:** Fine-grained felty laths of Plagioclase (25%); with intergranular Hematite (1%) and Cryptocrystalline material (64%).

77 SALT SPRING WASH Ttbu
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

**Groundmass:** 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
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 than 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

Groundmass: Coarse-grained subtrachytic laths of Plagioclase (49%) with intergranular Olivine (8%)
altered to iddingsite, Clinopyroxene (9%), Hematite (15%) and brown glass (10%).

10 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

Groundmass: 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

Groundmass: 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%)
altered to iddingsite, Clinopyroxene (7%), Hematite (5%) and Cryptocrystalline material (7%).

124 PINK/BLACK RIDGE Tpb
3% Plagioclase; sieved, anhedral= one large (4mm) phenocryst in slide
1% Olivine; euhedral, altered to iddingsite on margins
25% Vesicles; filled with calcite

Groundmass: Fine-grained trachytic laths of Plagioclase (40%) with intergranular Olivine (7%)
altered to iddingsite, Clinopyroxene (14%), Hematite (1%) and Cryptocrystalline material (8%).

117 PINK/BLACK RIDGE Tpb
6% Olivine; subhedral, altered to iddingsite, up to 1 mm
10% Vesicles

**Groundmass:** 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

**Groundmass:** 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; euhedral, altered to iddingsite on margins

11% Vesicles; filled with calcite

**Groundmass:** 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

**Groundmass:** 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

**Groundmass:** 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

**Groundmass:** Coarse-grained felty laths of Plagioclase (52%) with intergranular Olivine (15%) altered to iddingsite, Clinopyroxene (12%), Hematite (3%) and Cryptocrystalline material (3%).

### 114 SENATOR MOUNTAIN Tpb(?)

13% Plagioclase; embayed and sieved 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

**Groundmass:** 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%).

21 SQUAW PEAK  Tspm
6% Olivine; euhedral, 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%).

108 SOUTH OF SQUAW PEAK  Tspm
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%).

126 SQUAW PEAK  Tspm
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%).

127 SQUAW PEAK  Tspm
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%).

128 SQUAW PEAK  Tspm
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%).

112 EAST OF SQUAW PEAK  Tspu
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 glomerocrysts 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%).

113 EAST OF SQUAW PEAK  Tspu
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
Groundmass: Fine-grained felty laths of Plagioclase (28%) with intergranular Olivine (2%) altered to iddingsite, Clinopyroxene (8%), Hematite (4%) and Cryptocrystalline material (22%).

EAST OF SQUAW PEAK

1% Plagioclase; euhedral, sector zoning; up to 3 mm
9% Olivine; subhedral, embayed; altered to iddingsite; up to 1 mm
2% Clinopyroxene; zoned, sub-euhedral; up to 1 mm
2% Magnetite

Groundmass: 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, granoblastic 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.

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

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

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.

63 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

75 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.

76 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

145 Rock type: Biotite schist
Location: Salt Spring Wash
Probable protolith: Felsic igneous or Sedimentary (?)

Prograde or relict minerals:
35% Quartz, elongated, undulose extinction
15% Biotite, partially replaced by chlorite
10% Feldspar, largely replaced by sericite
3% Opaque
1% Zircon
< 1% Sphene

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 volcanoclastic (?)

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.
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 X-ray 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
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.
Table F-1: Precision for major element analyses

<table>
<thead>
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<th></th>
<th>Mean</th>
<th>S.D.</th>
<th>% Error</th>
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<tr>
<td>SiO₂</td>
<td>59.81</td>
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<td>Al₂O₃</td>
<td>16.9</td>
<td>0.08</td>
<td>0.5</td>
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<tr>
<td>FeO*</td>
<td>7.51</td>
<td>0.14</td>
<td>1.9</td>
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<tr>
<td>CaO</td>
<td>4.85</td>
<td>0.02</td>
<td>0.4</td>
</tr>
<tr>
<td>MgO</td>
<td>1.3</td>
<td>0.02</td>
<td>1.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.62</td>
<td>0.08</td>
<td>1.7</td>
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<tr>
<td>K₂O</td>
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<td>TiO₂</td>
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<td>0.01</td>
<td>0.9</td>
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<td>MnO</td>
<td>0.158</td>
<td>0.004</td>
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<td>P₂O₅</td>
<td>0.91</td>
<td>0.01</td>
<td>1.1</td>
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Data from 5 replicate analyses of USGS standard AGV-1 on Rigaku 3030, UNLV.
* Total iron as FeO

Table F-2: Precision for trace and rare-earth element analyses

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<tr>
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<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
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<tr>
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<td>1.3</td>
<td>0.7</td>
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<tr>
<td>Ce</td>
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<td>5.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Nd</td>
<td>3.3</td>
<td>22.1</td>
<td>7.9</td>
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<td>Sm</td>
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<tr>
<td>Eu</td>
<td>1.7</td>
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<tr>
<td>Cr</td>
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<tr>
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<td>21.2</td>
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<tr>
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<td>20.8</td>
<td>12.3</td>
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<tr>
<td>Sc</td>
<td>0.3</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Ta</td>
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<td>23.9</td>
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<td>2.6</td>
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<tr>
<td>Dy</td>
<td>8.78</td>
<td>6.1</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Percent error: reported by Phoenix Memorial Laboratory, University of Michigan
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

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University Microfilms International
Geologic Map of the Northern White Hills
Mohave County, Arizona
Tracey Cascadden, 1991
the Northern White Hills
County, Arizona
Cascadden, 1991
LITHOLOGY

SEDIMENTARY ROCKS

QUATERNARY DEPOSITS

Qa  Channel Deposits. Nonindurated, poorly sorted, sand and gravel in channels of ephemeral streams.

Qoa Older Channel Deposits. Nonindurated to poorly indurated sands and gravels forming terraces above active channel deposits.

Qf  Alluvial Fan Deposits. Moderately indurated sand, gravel and boulders. Caliche layers common. Clasts of volcanic rocks predominate except on east side of map area where Precambrian clasts occur.

Qt  Talus Deposits. Angular, volcanic rock debris on moderate to steep slopes.

Qls Modern Landslide Deposits.

Qp  Old River Deposits. Poorly indurated quartz sand and well-rounded pebbles and cobbles. Clasts are predominantly Paleozoic limestone and quartzite.

LATE TERTIARY DEPOSITS

Tmcu/Tmcl Muddy Creek Formation. Lacustrine and subaerial basin-fill deposits, dip <5°. Tmcu: Gypsiferous pink to orange siltstone interbedded with and overlain by micritic limestone with calcite nodules (Hualapai Limestone Member). Tmcl: Poorly to moderately indurated sand and coarse gravel.

Trs  Red Sandstone Unit. Poorly to moderately indurated sand and coarse gravel, interbedded with and intruded by basalt of Tsm. Beds dip >5°.

MID-TERTIARY DEPOSITS
UNCONFORMITY

VOLCANIC ROCKS

LATE TERTIARY

Tsm  Basalt of Senator Mountain. Alkali and subalkalic basalt flows and dikes interbedded with and intruding Trs. Phenocrysts of olivine and plagioclase.

MID-TERTIARY

Tpsu/Tpsm/Tspo  Basaltic Andesite of Squaw Peak. Trachybasalt and basaltic-trachyandesite flows and breccias containing phenocrysts of olivine, clinopyroxene and plagioclase.

Ttbu/Ttbm/Ttbi  Basaltic Andesite of Temple Bar. Basaltic trachyandesite, trachyandesite and trachydacite flows and breccias containing phenocrysts of olivine, clinopyroxene and plagioclase.

T1  Ash-flow tuff. Poorly to moderately welded. Contains phenocrysts of sanidine, plagioclase, biotite and clinopyroxene, and trace amounts of quartz, sphene and zircon.

CRYSTALLINE ROCKS

P-C  Precambrian Basement: Felsic gneiss, garnet-biotite gneiss, biotite gneiss, granitoid and amphibolite.
LITHOLOGY

SEDIMENTARY ROCKS

QUATERNARY DEPOSITS

Qa Channel Deposits. Nonindurated, poorly sorted, sand and gravel in channels of ephemeral streams.

Qoa Older Channel Deposits. Nonindurated to poorly indurated sands and gravels forming terraces above active channel deposits.

Qf Alluvial Fan Deposits. Moderately indurated sand, gravel and boulders. Caliche layers common. Clasts of volcanic rocks predominate except on east side of map area where Precambrian clasts occur.

Qt Talus Deposits. Angular, volcanic rock debris on moderate to steep slopes.

Qls Modern Landslide Deposits.

Qp Old River Deposits. Poorly indurated quartz sand and well-rounded pebbles and cobbles. Clasts are predominantly Paleozoic limestone and quartzite.

LATE TERTIARY DEPOSITS

Tmcu/Tmcl Muddy Creek Formation. Lacustrine and subaerial basin-fill deposits, dip <5°. Tmcu: Gypsiferous pink to orange siltstone interbedded with and overlain by micritic limestone with chert nodules (Hualapai Limestone Member). Tmcl: Poorly to moderately indurated sand and coarse gravel.

Ts Red Sandstone Unit. Poorly to moderately indurated sand and coarse gravel, interbedded with and intruded by basalt of Tsm. Beds dip >5°.

MID-TERTIARY DEPOSITS

T Fanglomerate.


Tbre Sandstone and reworked ash, time equivalent to Tbr and Tt.
VOLCANIC ROCKS

LATE TERTIARY

Tsm Basalt of Senator Mountain. Alkali and subalkalic basalt flows and dikes interbedded with and intruding Trs. Phenocrysts of olivine and plagioclase.

MID-TERTIARY

Tpb/TPb/Tpb Basalt of Pink/Black Ridge. Alkali and subalkalic basalt flows and breccias containing olivine phenocrysts.

Tsp/Tsp/Tsp Basaltic Andesite of Squaw Peak. Trachybasalt and basaltic trachyandesite flows and breccias containing phenocrysts of olivine, clinopyroxene and plagioclase.

Ttb/Ttb/Ttb Basaltic Andesite of Temple Bar. Basaltic trachyandesite, trachyandesite and trachydacite flows and breccias containing phenocrysts of olivine, clinopyroxene and plagioclase.

T1 Ash-flow tuff. Poorly to moderately welded. Contains phenocrysts of sanidine, plagioclase, biotite and clinopyroxene, and trace amounts of quartz, sphene and zircon.

CRYSTALLINE ROCKS

P-C Precambrian Basement: Felsic gneiss, garnet-biotite gneiss, biotite gneiss, granitoid and amphibolite.

Contact

High- to moderate-angle normal fault. Dashed where approximately located, dotted where concealed. Ball on hanging wall. Arrow indicates fault plane attitude.

Low-angle normal fault. Dashed where approximately located, dotted where concealed. Double tick marks on hanging wall.

Strike-slip fault. Dashed where approximately located, dotted where concealed. Arrows indicate relative horizontal movement.

Strike and dip of volcanic flows and sedimentary beds.

Strike and dip of foliation.
PLEASE NOTE:

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University Microfilms International
Geologic Map of Salt Spring Wash
Mohave County, Arizona
Tracey Cascadden, 1991
LITHOLOGY

SEDIMENTARY ROCKS

QUATERNARY DEPOSITS

Oa  Channel Deposits. Nonindurated, poorly sorted, sand and gravel in
channels of ephemeral streams.

Ood  Older Channel Deposits. Nonindurated to poorly indurated sands and
gravels forming terraces above active channel deposits.

Of  Alluvial Fan Deposits. Moderately indurated sand, gravel and boulders.
Cell-like layers common. Clasts of volcanic rocks predominate except on
east side of map area where Precambran clasts occur.

Ot  Talus Deposits. Angular, volcanic rock debris on moderate to steep
slopes.

Ois  Modern Landslide Deposits.

Op  Old River Deposits. Poorly indurated quartz sand and well-rounded
pebbles and cobbles. Clasts are predominantly Paleozoic limestone
and quartzite.

LATE TERTIARY DEPOSITS

Tmcu/Tmc  Muddy Creek Formation. Lacustrine and subaerial basin-fill deposits,
dip <5°. Tmcu: Gyspiferous pink to orange siltstone Interbedded with
and overlain by micritic limestone with chert nodules (Hualapai
Limestone Member). Tmc: Poorly to moderately indurated sand and
coarse gravel.

Tr  Red Sandstone Unit. Poorly to moderately indurated sand and coarse
gravel, interbedded with and intruded by basalt of Tsm. Beds dip >5°.

MID-TERTIARY DEPOSITS

Ta  Fanglomerate.

Tbru/Tbr  Landslide deposits. Crackle and jigsaw breccias, clastic dikes and
debris flow deposits. Tbru: Precambrian basement clasts. Tbr:
Precambrian and Ash-flow tuff (T) clasts.

VOLCANIC ROCKS

LATE TERTIARY

Tbm  Basalt of Senator Mountain. Alkali and subalkalic basalt flows and
dikes interbedded with and intruding Trs. Phenocrysts of olivine and
plagioclase.

MID-TERTIARY

Tpb  Basalt of Pink/Black Ridge. Alkali and subalkalic basalt flows and
breccias containing olivine phenocrysts.
VOLCANIC ROCKS

LATE TERTIARY

Tam Basalt of Senator Mountain. Alkali and subalkaline basalt flows and dikes interbedded with and intruding Trs. Phenocrysts of olivine and plagioclase.

MID-TERTIARY

Tpb Basalt of Pink/Black Ridge. Alkali and subalkaline basalt flows and breccias containing olivine phenocrysts.

Ttba/Tbca/Tbbl Basaltic Andesite of Temple Bar. Basaltic trachyandesite, trachyandesite and trachydacite flows and breccias containing phenocrysts of olivine, clinopyroxene and plagioclase.

Tt Ash-flow tuff. Poorly to moderately welded. Contains phenocrysts of sanidine, plagioclase, biotite and clinopyroxene, and trace amounts of quartz, sphene and zircon.

FAULT ROCKS

Tc Cataclasite. Sheared Precambrian basement rocks.

CRYSTALLINE ROCKS

PCf Felsic gneiss.

PCg Garnet-biotite and biotite gneiss.

PCh Amphibolite:

Contact

High- to moderate-angle normal fault. Dashed where approximately located, dotted where concealed. Ball on hanging wall.

Low-angle normal fault. Dashed where approximately located, dotted where concealed. Double tick marks on hanging wall.
Plate I

Geologic Map of the Northern White Hills
Mohave County, Arizona
Tracey Cascadden, 1991

SEDIMENTARY ROCKS

GEOLOGIC MAP

1. Volcanic breccia, basalt flows, and pyroclastic deposits.
2. Short Creek Formation.
3. Precambrian basement.
4. Basement granite.
5. Precambrian basement.
6. Precambrian basement.
7. Precambrian basement.
8. Precambrian basement.
11. Precambrian basement.
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