Geology of the Indian Spring Area,
Northern Washoe County, Nevada

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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Abstract

The Indian Spring study area is composed of Miocene volcanic and sedimentary rocks. Resting upon basal outcropping dacite are several units of the Canon Rhyolite. Sedimentary units lay unconformably upon the Canon Rhyolite.

The Dome Rhyolite Series member of the Canon Rhyolite consists of ash flow tuffs and banded lava flows that form an extrusive dome. The dome was emplaced along a fault zone that parallels the regional fault pattern.

The study area rhyolites are highly differentiated peralkaline rhyolites whose origin relates to the regional extensional tectonic setting in western Nevada. As such, they have a possible uranium deposit potential.
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INTRODUCTION

Objective

This thesis study was undertaken to partially fulfill the requirements for a Master of Science degree in Geology at the University of Nevada, Reno. The Indian Spring site was chosen for investigation to gain further insight into volcanic processes, especially those associated with sialic chemical composition vulcanism. Sialic composition vulcanism has recently come under industry investigation for its association with uranium mineralization.

Acknowledgements

I wish to thank the Rocky Mountain Energy Company for financial assistance given to me for this project. I am especially indebted to Joe Johnson, formerly of Rocky Mountain, for bringing this project to my attention and for helping me to obtain funding from RMEC.

Location and Accessibility

The Indian Spring area is in northern Washoe County, Nevada, approximately sixty miles northwest of Gerlach, Nevada and forty miles east of Cedarville, California (Figure 1). Access to the site is provided by Nevada Highway 34, a graded gravel road passing southwest of the site. The study area itself is traversed by an unimproved dirt road.
Figure 1. Location and Accessibility Map of the Study Area
Physiography

Indian Spring is part of a dissected high plateau composed of volcanic and minor sedimentary rock. It lies within the transitional zone between the Basin and Range and Columbia Plateau physiographic provinces.

Average elevation at the study site is approximately 6,200 feet with a relief of some 1,000 feet. The topography varies from cliffs with twenty-five to fifty foot scarps to gently sloping hills and alluvial valleys.

Climate and Vegetation

The climate about the Indian Spring region falls within a semiarid continental classification. Climatic data taken at Vya, Nevada, a road maintenance station approximately twenty-five miles west of the study site, indicates an annual precipitation rate of 10.45 inches and a mean annual temperature of $40.4^\circ F$ with a January mean of $29.4^\circ F$ and a July mean of $65.9^\circ F$ (Bonham, 1969).

Vegetation is sparse about Indian Spring and consists primarily of Basin sage (Artemisia tridentata), with rabbit bush (Chrysothamnus nauseosus), desert peach (Prunus andersonii), plateau gooseberry (Ribes velutinum), bitter brush (Purshia tridentata), and hairy-horse brush (Tetradymia glabrata) found in small amounts.
Previous Work
Little has been published about the Indian Spring region. The most comprehensive work is the county report for Washoe and Storey Counties by Bonham (1969).

Merriam (1910) described the geology and age of the Tertiary rocks in Virgin Valley, Humboldt County, Nevada. His lithologic descriptions were useful to this study in that the rock units he examined extend into the Indian Spring region.


Field Work
Geologic information for this thesis was gathered from photogeologic studies of the region, both from landsat imagery and low level air photos, followed by site inspection of the study area. All information was transferred to U.S.G.S. 7-1/2 minute topographic base
maps. Rock specimens were collected from all lithologic units in the study zone and thin sectioned, with selected samples singled out for whole rock geochemical analysis.

Field work totaled twenty-one days of work between October, 1979 and May, 1981. This period was followed by several months of thin section preparation and analysis, geochemical analysis, and report preparation. A final field check of the area was performed during June, 1984.

The regional level and gross structural fabric surrounding the Indian Spring area is a manifestation of the extensional tectonic setting of western Nevada. The extensional tectonics, which are not fully covered in this report, are due to movements along the North American plate and ancestral plate interface.

The volcanic rocks in and about Indian Spring occur along the southern edge of a broad region of volcanic rock, the Columbia Plateau, that extends from southwestern Oregon to the Snake River Plain of Idaho (Bonnichsen and others, 1978). The volcanic rocks in and about mountain in the million years old with the older rocks consisting mostly of andesite lava flows and ash tuff suites while the younger rocks are mostly basalt (Stewart, 1980). The lithology at Indian Spring is representative of the upper repetitions of the Columbia Plateau sequence.
REGIONAL GEOLOGY

The region about the Indian Spring study area is transitional between the Basin and Range and Columbia Plateau physiographic provinces. Therefore, both the horst and graben structure of the Basin and Range and the thick volcanic sequences of the Columbia Plateau are found near Indian Spring.

The regional horst and graben structure found surrounding the Indian Spring area is a manifestation of the extensional tectonic setting of western Nevada. The extensional tectonics, which are more fully covered in the regional genesis section of this report, are due to movements along the North American plate and Pacific plate interface.

The volcanic rocks in and about Indian Spring occur along the southern edge of a broad region of volcanic rock, the Columbia Plateau, that ranges from southeast Oregon to the Snake River Plain of Idaho (Armstrong and others, 1975). The volcanics range in age from seventeen to six million years old with the older rocks consisting mostly of rhyolite lava flows and ash flow tuffs while the younger rocks are mostly basalt (Steward, 1980). The lithology at Indian Spring is representative of the older rhyolites of the Columbia Plateau sequence.
Structure

More immediate to the northern Washoe County study area, the dominant structure is the dissected, high elevation, volcanic plateau of the southern Columbia Plateau. High angle dip slip faults, which trend from a northeast to northwest direction, are found along the margins of the plateau in northern Washoe County. These structures have shown major displacement during the late Pliocene and Pleistocene. However, faulting within the plateau has the last substantial displacement dated as late Miocene in age (Bonham, 1969). Therefore, it seems likely that the plateau has acted as a separate, resistant block from the rest of the region since the late Miocene. This hypothesis is further substantiated by Bonham's (1969) observation that lake beds of late Miocene age within the plateau are basically flat lying, hence, little deformation has occurred in the plateau since the Miocene.

The most prominent example of an extensional tectonic horst and graben structure about the Indian Spring area is the Hays Canyon Range, approximately twenty miles west of the study area (Figure 2). The range is a complexly faulted horst some sixty miles long extending along the California-Nevada border. Displacement of at least twenty-five hundred feet has occurred along a series of north to northwest trending high angle Miocene to Pliocene age faults (Bonham, 1969).
Figure 2. Geologic Map of a Portion of Northern Washoe County
(from Bonham, 1969)
Only minor folding is exhibited in northern Washoe County and, when found, is most often associated with fault movement. Bonham (1969) reports that Long Valley, ten miles west and north of the study area (Figure 2), is a depression formed by fault action in the north and synclinal downwarping to the south. The Massacre Lake basin, fifteen miles north of the study area (Figure 2), is part of a synclinal bend related to a tilted fault block mountain range.

**Lithology**

Rocks of the region about the Indian Spring study area are part of a series of Miocene volcanic and subordinate sedimentary rocks as mapped by Bonham in the 1969 Washoe County report (Figure 2). Four distinct rock units from this Miocene series are found in proximity to the study area; the South Willow Formation, the Canon Rhyolite, the High Rock sequence, and an unnamed set of extensive basalt flows.

**South Willow Formation (TsW):** The South Willow Formation crops out twelve miles west of the study area (Figure 2). However, the Indian Spring Area Geology chapter of this report tentatively identifies an outcrop of South Willow Formation within the study area (Appendix C, Plate I).

The South Willow Formation consists mostly of intermediate to mafic composition volcanics. While the
The original thickness of the unit is unknown due to erosion of the formation top, the South Willow Formation reaches a maximum thickness of over three thousand feet in Washoe County (Bonham, 1969). The formation is compositionally zoned with more mafic rocks generally occurring in the lower part of the formation and more sialic rocks occurring in the upper portions of the formation.

From Bonham (1969), the lower South Willow Formation basalts consist of dense black rocks with small (two to three mm) phenocrysts of olivine, augite, and plagioclase in a dark brown glassy matrix. Pyroxene and hornblende andesites are the dominant rock types. They typically contain phenocrysts of augite and brown hornblende or oxyhornblende respectively, plus phenocrysts of hypersthene and oscillatory-zoned plagioclase in a fine-grained matrix of pyroxene and plagioclase. The upper South Willow Formation dacite mineralogy is similar to that of the andesites described above except for an increased alkali content in the plagioclase feldspar plus the presence of matrix quartz.

The South Willow Formation unconformably overlays pre-Tertiary rocks and is in turn unconformably overlaid by the Canon Rhyolite and Pliocene basalts. No fossils with which to age date the formation have been reported. However, Bonham (1969) states that a radiometric age date
obtained from an upper South Willow Formation dacite dike
gave an age of 31.3 (± 1.2) x 10^6 years.

Canon Rhyolite (Tcr): The Canon Rhyolite found
within the study area (Figure 2) consists of a series of
flows, domes, and intercalated pyroclastic rocks. The
unit is widespread in Washoe County, attaining an exposed
thickness of fifteen hundred feet (Bonham, 1969).

The rhyolite varies in color from light grey to
red-grey to an occasional tan on a fresh surface. It
commonly weathers to a tan orange to dominantly red-brown
color. The Canon Rhyolite is characterized by thin, well
developed flowage bands which are distinguishable both by
color banding and mineralogical differences. The banding
tends to be contorted due to turbulent primary flowage and
secondary flowage.

The rocks of the Canon Rhyolite tend toward a
microcrystalline groundmass with clear, usually fractured
phenocrysts of alkali feldspar. X-ray diffraction work
(Bonham, 1969) showed a composition range from Or_{39}
(An+Ab)_{61} to Or_{55} (Ab+An)_{45} in the feldspar
phenocrysts. The same above mentioned work also revealed
the feldspars to be unmixed sanadine cryptoperthites.
Occasional mafic phenocrysts, biotite and amphibole, are
present.
Lithophysal cavities are abundant in the Canon Rhyolite and frequently contain vapor phase crystallization of quartz and alkali feldspar. Spherulitic structures are another common occurrence in the rhyolite and range in size from less than 0.5 mm to 5 cm. According to Bonham (1969), the spherulitic rhyolite is the most common rock type in the Canon Rhyolite sequence. The units in the Canon Rhyolite are classified as soda rhyolites petrographically while chemical analysis indicates that the sodic nature of the rhyolite is due to a deficiency in $\text{Al}_2\text{O}_3$ rather than an excess of $\text{Na}_2\text{O}$ (Bonham, 1969).

The Canon Rhyolite unconformably overlays the South Willow formation in Washoe County and is unconformably overlaid by upper Miocene volcanics and tuffaceous sediments. A sample of nonhydrated rhyolite glass collected three miles south of the Indian Spring study area has been age dated at $15.1 \pm 0.5$ m.y. (McKee and Marvin, 1974). Bonham (1969) reports that a sample of Canon Rhyolite perlitic glass from Virgin Valley was age dated at approximately 14 m.y. These age dates give a late Miocene or Barstovian age to the Canon Rhyolite.

High Rock Sequence (Tts): The High Rock Sequence, found within the study area (Figure 2), consists of a series of ash-flows, ash-falls, tuffaceous
fluviolacustrine deposits, mafic tuffs, and mafic flows. The sequence is of variable thickness in Washoe County, ranging from zero to twelve hundred feet (Bonham, 1969).

The tuffs of the High Rock sequence commonly consist of pumice lapilli, up to ninety percent of the rock, in a matrix of quartz, sodic plagioclase, sanidine, and mafics with the mafic minerals biotite and riebeckite varying from zero to ten percent (Bonham, 1969). The tuffs grade basinward from subaerial tuffs to cream colored, well sorted, well stratified fluviolacustrine tuffs.

Two general types of silicic tuffs are found in the High Rock sequence (Bonham, 1969). One variety is a soda rhyolite with sodic sanidine phenocrysts of composition $\text{Or}_{43} \ (\text{Ab+An})_{57}$ to $\text{Or}_{46} \ (\text{Ab+An})_{54}$ plus phenocrysts of quartz and soda amphibole. The second variety is a soda trachyte containing phenocrysts of anorthoclase and biotite. Intercalated among the silicic tuffs are a series of basaltic flows, lapilli tuffs, and sedimentary rocks. The basaltic rocks are also of two types, one a phenocryst poor, dense, vitreous rock and the second a highly porphyritic, olivine and pyroxene-rich basalt.

The dominant sedimentary rock within the High Rock sequence is diatomite. Included in the rest of the non-volcanic rocks are tuffaceous sandstone, shale, siltstone, claystone, plus some conglomerate. The High
Rock sequence sediments found in the study area belong to the coarser group of sediments. This occurrence is explained in the High Rock sequence section of the Indian Spring Area Geology chapter of this report.

The High Rock sequence usually sits upon the underlying Canon Rhyolite in an angular unconformity and is in turn overlaid by upper Miocene to Pliocene basalts in a disconformable fashion (Bonham, 1969). However, the upper Canon Rhyolite and basal High Rock sequence interfinger with one another on a local basis.

According to Bonham's 1969 county report, the fossil record found in the High Rock sequence gives a Barstovian age to the sequence. A potassium-argon age date taken from a High Rock sanidine gave an age of 15.6 m.y., or late Miocene Barstovian age (Evernden, Savage, Curtis, and James, 1964).

Basalt (Tba): The basalt flows, seven miles west of the study area (Figure 2), are correlative with the Warner Basalt of Oregon and California. In northern Washoe County, the basalt flows range in thickness from one hundred feet or less to over one thousand feet thick in some localities (Bonham, 1969).

According to Bonham (1969), the most common type of basalt is a dark grey, equigranular, olivine-pheocryst basalt. A diktytaxitic texture is characteristic of the
lavas but is not always present. The tops and bottoms of the flows are generally vesicular to scoriaceous with the central portion of the flows microvesicular.

The basalt flows sit upon the underlying High Rock sequence in a disconformable fashion. However, Bonham (1969) notes that there is a concordance between the base of the basalt flows and the attitude of the High Rock sequence, indicating that there was no significant faulting or deformation during the interval separating the emplacement of the two units. A K-Ar age date taken from an Adel, Oregon basalt flow correlative with the northern Washoe County basalt flows gave an age of 14.5 million years (Bonham, 1969).
Lithology

The Indian Spring study site is composed of Miocene volcanic and sedimentary rocks of the South Willow Formation, the Canon Rhyolite, and the High Rock sequence (Appendix C, Plate I). The contacts between the three units are obscured throughout most of the study area but, where visible, they indicate an unconformable relationship from one unit to the next.

South Willow Formation

Dacite: The stratigraphically lowermost unit found within the study area is a dacite according to Streckeisen's 1967 classification of igneous rocks. The unit has been provisionally correlated with the dacites of the upper South Willow Formation although Bonham's 1969 Washoe county geologic report does not show any South Willow Formation rocks within the study area (Figure 2).

In a hand sample, the Dacite occurs both as a dense unit without void space (Figure 3) and as a scoriaceous unit (Figure 4). The voids in the scoriaceous unit, occupying thirty percent of the rock, range from one half to five millimeters in size and are all elongated in a similar direction. This elongation of the voids indicates a late stage of flowage in the dacite lava where early
Figure 3. Non-scoriaceous Dacite of the South Willow Fm.

Figure 4. Scoriaceous Dacite of the South Willow Fm. Note the elongated and similarly oriented void spaces and the slight to strong amygdaloidal filling of many of the voids.
formed and originally spherical gas bubbles were stretched out by the late stage movement along the direction of flowage.

Both the scoriaceous and non-scoriaceous dacite flows are black on a fresh surface and weather to a red brown color. Phenocrysts of pyroxene, plagioclase, and minor hornblende, two millimeters or less in size, compose from seven to fifteen percent of the rock while the remaining portions of the rock are void space or a microcrystalline groundmass. Most of the pyroxene phenocrysts appear altered, possibly chloritized. The gas bubbles in the scoriaceous unit show from slight to strong amygdaloidal form with apparent clay minerals lining the cavity walls.

Microscopically, the dacite matrix is composed of plagioclase feldspar and pyroxene laths, less than three tenths millimeter in size, with a very fine grained infilling between laths. The laths have little to no preferred orientation. The plagioclase feldspar phenocrysts, as well as some of the lath feldspars, have normal to oscillatory zoning within the crystals. Apparently unzoned plagioclase feldspars within the dacite are optically negative with a high 2V angle characteristic of feldspar with the composition of andesine. The zoned feldspars vary in composition from labradorite at the core to andesine at the outside edge.
Pyroxene phenocrysts consist of both the clinopyroxene augite, optically positive with a 2V angle of approximately 60 degrees and an extinction angle of 20 degrees, and the orthopyroxene enstatite, optically positive with parallel extinction. Both pyroxenes are colorless to slightly green under the microscope and both are strongly altered. A reaction rim of tremolite-actinolite is common about the crystals, which are fractured and resorbed about the edges. The hornblende phenocrysts are likewise strongly altered, showing a bright red-orange oxidation. The amygdaloidal fillings could not be positively identified under the microscope due to their extremely fine grained size. The weak birefringence and brownish to yellow green color may indicate the presence of clay minerals.

Canon Rhyolite

Plateau Rhyolite Lava Flows: The stratigraphically second lowermost unit to outcrop in the study zone and the lowermost unit of the Canon Rhyolite consists of the Plateau Rhyolite Lava Flows found in the western study area (Appendix C, Plate I). The Plateau Rhyolite Lava Flows are characterized macroscopically by: (1) a grey to blue-grey color which weathers to tan and reddish brown, (2) lithophysal cavities which occupy up to eight percent of the rock and usually contain vapor phase
crystallization, and (3) alkali feldspar phenocrysts from three to five millimeters long comprising from five to ten percent of the rock. Spherulitic structures, from one to four millimeters in size, are more common than not in the rhyolite (Figure 5). The rhyolite varies structurally from massive to strongly flow banded (Figure 6). When flow banding is present, the spherulites tend to be entrained in layers parallel to the flow banding plus the long axis of the phenocrysts and lithophysal cavities are oriented parallel to the banding.

Microscopically, the Plateau Rhyolite Lava Flows have an almost totally devitrified groundmass. Devitrification has formed fine (less than one half millimeter) spherulitic structures plus, less commonly, fine anhedral quartz and feldspar grains and feldspar microliths. The spherulites tend to be heavily dusted with very fine (less than one tenth millimeter) opaque material and form dark bands when flow banding is noted. The feldspar microliths form a felty texture with no discernable preferred orientation to the microliths. The microliths and fine grained anhedral feldspar form the lighter colored bands where flow banding is noted.

The alkali feldspar phenocrysts were optically identified as orthoclase by their biaxial negative sign and 2V of about 70 degrees. The crystals are subhedral
Figure 5. Spherulitic Canon Rhyolite. Spherulites are 3mm in diameter. Note entraining of spherulites parallel to flow banding.

Figure 6. Strongly Flow Banded Canon Rhyolite. Individual flowage-induced layers are 0.5mm to 1.0mm thick.
with resorption of the crystal edges common and occasionally the core is resorbed. Some zonation of composition has been noted in a very few crystals. The phenocrysts are strongly fractured. As noted previously in this report, x-ray work by Bonham (1969) showed a composition range from $\text{Or}_{39} (\text{Ab+An})_{61}$ to $\text{Or}_{55} (\text{Ab+An})_{45}$ in the Canon Rhyolite phenocrysts. As calculated from CIPW normative values generated for this study (Appendix B), all of the rhyolites found in the Indian Spring study area show a composition range from $\text{Or}_{36} (\text{Ab+An})_{64}$ to $\text{Or}_{58} (\text{Ab+An})_{42}$ while the Plateau Rhyolite Lava Flows specifically range from $\text{Or}_{36} (\text{Ab+An})_{64}$ to $\text{Or}_{50} (\text{Ab+An})_{50}$.

Minor plagioclase phenocrysts are present in the rhyolites. The plagioclase is anhedral, resorbed, and shows some Carlsbad twinning and rare albite twinning. Mafic phenocrysts include augite (biaxial positive, $2V$ of 60 degrees, extinction angle of 44 degrees) which may range up to three percent of the rock but is more commonly one percent or less. Aegerine-augite is present in minor amounts as is magnetite, ilmenite, hornblende, biotite, and allanite, usually one percent or less. The biotite and hornblende appear to be part of the vapor phase mineralization as they mostly occur about the lithophysal zones. Quartz, while present in the groundmass, does not appear as a phenocryst.
Dome Rhyolite Series: Lying stratigraphically above the Plateau Rhyolite Lava Flows are the units of the Dome Rhyolite Series. The Dome Rhyolite Series consists of ash flow tuffs overlaid by lava flows that form an extrusive dome in the eastern study area (Appendix C, Plate I).

Dome Ash Flow Tuff: The Dome Ash Flow Tuff is an ash flow tuff unit that has a change in its characteristics from the bottom to the top of the unit or may possibly represent two similar ash flow tuff units. Outcrop of this unit is to the western edge of the extrusive dome and is such that no contact between the upper and lower tuff unit is observed.

The tuff ranges in color from pink to tan at its base to grey at the top (Figures 7 & 8). The observed unit shows mostly vitroclastic texture with no to only slight welding having occurred except at portions of the unit top (see next section, Dome Welded Tuff). Pumice is found throughout the unit and varies in concentration from thirty percent of the rock at the base to sixty-five percent of the rock in the upper part of the unit. The basal pumice are from two millimeters to one half centimeter in size, are moderately sorted, and are oriented subparallel to one another. The upper pumice are also two millimeters to one centimeter to size but are poorly sorted and show no common orientation. The lower
Figure 7. Upper Dome Ash Flow Tuff of the Canon Rhyolite.

Figure 8. Lower Dome Ash Flow Tuff of the Canon Rhyolite. Note subparallel orientation and flattening of the pumice.
portion of the unit contains vapor phase crystals of quartz, feldspar, and biotite in the pumice void spaces but gaseous crystallization is absent in the upper portion of the tuff. Feldspar phenocrysts, one millimeter in size and comprising two percent of the unit, are found throughout the observed unit. The phenocrysts are orthoclase crystals (biaxial "-", high 2V) which have been fractured and partially resorbed. Lithic fragments are found unit wide but are more numerous lower in the unit where they compose eight percent of the rock. The fragments are altered rhyolite pieces made up of feldspar microliths in an oxidized groundmass. The fragments represent pieces of the extrusive vent wall that were caught up in the expulsion of the tuff unit and may be pieces of the stratigraphically lower Plateau Rhyolite Lava Flows.

The situation of subparallel orientation of pumice reflects the initial stages of welding within the lower ash flow which led to the lineation of the pumice fragments. However, welding within the unit is only slight as compression of the pumice fragments within the ash flow is minor and a strong vitroclastic texture remains in the ash flow groundmass. Welding occurred in response to heat buildup within the ash flow but the unit was not of sufficient magnitude to generate the temperature and compressive pressure necessary to form a more strongly welded tuff.
In thin section, the upper portion of the tuff contains very fine grained calcite. The calcite may originate from alteration of the feldspar in the unit or from secondary introduction of calcite by groundwater. The generally unaltered appearance of the rock favors groundwater introduction of the calcite, although some devitrification of glass shards has occurred towards the base of the unit. Groundwater is also responsible for weathering pyrite crystals in the unit to limonite.

Dome Welded Tuff: The welded tuff is a thin, two to three feet thick where exposed, welded zone of the Dome Ash Flow Tuff. It is very limited in outcrop, occurring along the outer edge of the north to northwest portion of the extrusive dome in the southeast quarter of Section 12. The rhyolite is black on a fresh surface and weathers to a grey-tan color. The tuff is glassy with no sign of devitrification and is slightly to moderately welded with the volcanic glass shards being fused together. However, the overall rock possesses a somewhat pumiceous texture, hence its classification as slightly to moderately welded. Some compaction of the glass shards has occurred with welding and this imparts a weak lineation to the unit. Orthoclase phenocrysts are irregularly present and compose from zero to four percent of the rock. The phenocrysts are one millimeter in size and are generally
broken and rounded. The abrasion and fracturing of the phenocrysts occurred during the eruption of the tuff rather than during welding. Lithic fragments are rare within the unit.

The welded tuff formed in response to the emplacement of the overlying Dome Lava Flows (see next section). The temperature of these later rhyolite flows was sufficiently high at emplacement to cause the glass shards in the underlying ash flow to become plastic, deform, and weld together.

Dome Lava Flows: The lava flows within the extrusive dome are rhyolites similar in appearance to the stratigraphically lower Plateau Rhyolite Lava Flows (Figure 9). The rhyolite lava of the Dome Lava Flows are characterized macroscopically by a grey to blue-grey color which weathers to a tan or more commonly a red-brown. Lithophysal cavities compose from one to ten percent of the rock and usually contain vapor phase crystallization of quartz and alkali feldspar with minor biotite and hornblende. Alkali feldspar phenocrysts comprise only one to two percent of the flows and are not present in all of the flows. The rhyolite is dominated structurally by a moderate to strong flow banded texture with massive rhyolite rarely occurring. The flow banding is accentuated by spherulitic structures, from one to four
Figure 9. Typical dome Lava Flow Rhyolite of the Canon Rhyolite. Individual flow bands are 0.5mm to 1.0mm thick.

millimeters in size on the average, which are entrained in layers parallel to the flow banding.

Microscopic examination of the lava flows shows a devitrified groundmass that is dominantly spherulitic in texture. The spherulites, less than one millimeter in size, occupy up to eighty percent of the groundmass and are often imperfectly formed due to growth competition with surrounding spherulites. Interstices between spherulites are occupied by coarser, one millimeter sized, crystals of alkali feldspar and quartz. Tabular feldspar crystals, less than one half millimeter in size, are often
found growing along the outside edges of the spherulites with their long axis oriented radially about the spherulitic core.

Alkali feldspar phenocrysts in the flows are identified as orthoclase by their biaxial negative sign and high 2V angle. The phenocrysts are strongly fractured and can be so strongly resorbed that only the outer shell of a crystal remains with its interior having been removed. Minor exsolution textures, exhibiting a wormy, myrmekitic form, were observed in a very few phenocrysts. As with the Plateau Rhyolite Lava Flows, the Dome Lava Flows feldspars have calculated CIPW normative values showing a composition range from Or$_{36}$ (Ab+An)$_{64}$ to Or$_{58}$ (Ab+An)$_{42}$ (Appendix B).

Minor mafic phenocrysts, less than one percent by volume and two millimeters in size, occur in the flows. Hornblende is the most common mafic mineral followed by biotite and pyroxene. The hornblende and biotite, along with equally sized grains of quartz and feldspar, are usually found about the margins of lithophysal cavities and represent vapor phase crystallization products. However, the hornblende and biotite are not found exclusively in this environment but can occur throughout the groundmass. The pyroxenes, identified as aegerine-augite by the biaxial negative sign, light
green-clear to dark green pleochroism, are strongly fractured, resorbed, and altered to secondary hornblende and magnetite-hematite. Accessory minerals irregularly present within the lava flows include zeolites, magnetite, pyrite, allanite, pervoskite, jasperoidal silica, and opaline silica.

The pyroxene and orthoclase phenocrysts of the flows represent early formed crystals in the parent magma that were being resorbed before eruption and were fractured during the emplacement of the lava flows. The hornblende, biotite, and feldspar about the lithophysal cavities are clearly post-lava emplacement crystal growths.

Dome Pumice: The Dome Lava Flows are overlaid by an apparent remnant pumiceous outer shell which has mostly eroded away except for several small occurrences found scattered throughout the Dome Lava Flows (Appendix C, Plate I). The significance of the outer pumiceous shell will be discussed under the Dome Rhyolite Series Flow Dome Complex section of this report. The remnant pumice is white to offwhite in color, glassy, and possesses a silky sheen on a fresh surface. When weathered the pumice exhibits a chalky appearance as the volcanic glass is altered to clays and/or silica. It is found in foliated individual pieces up to six inches long but probably occurred as a more or less continuous sheet topping the
dome. No devitrification appears to have occurred and
phenocrysts of alkali feldspar, one millimeter in size and
three percent of the rock by volume, were observed in the
pumice.

High Rock Sequence

Minor amounts of sedimentary rocks are found
stratigraphically above the rhyolitic tuffs and flows of
the Canon Rhyolite in the study area and are
representatives of the High Rock sequence. Where
available, the bedding attitudes of the sediments have
been high, approximately twenty to forty degrees. The
high attitudes reflect the steep nature of the underlying
topography upon which the sediments were deposited as
there was little tectonic activity between the deposition
of the Canon Rhyolite and the High Rock Sequence by which
to deform the sediments.

Two genetically different sediments are present at
Indian Spring, one a coarse grained rock incorporating
locally derived detritus and the other a finer grained
silt sized rock made up mostly of material of unknown
origin. However, both sediment types are atypical of the
High Rock Sequence as the local Indian Spring sediments
are much coarser than the High Rock sediments Bonham
(1969) has described as being dominantly diatomaceous.

The reason for the atypical nature of the Indian
Spring and High Rock sediments is that the sediments about
the Indian Spring area were deposited adjacent to highland areas whereas the typical High Rock sediment of Bonham (1969) is found towards the center portion of a shallow basin. The highland adjacent location of the Indian Spring area High Rock sediments is reflected by the high angle dips of the sediments as they approach the steeper shoreline terrain as well as by the coarser nature of the sediments. Much of the coarser detritus composing the sedimentary rocks is similar in composition and appearance to the adjacent rhyolitic lava flows. Even the finer grained siltstones contain detritus similar to the adjacent rhyolite lavas. It is probable that if one were to progress away from the rhyolite lava highlands towards the basin center, a more typical High Rock diatomite or diatomaceous siltstone would be encountered.

Pumiceous Breccia: The stratigraphically lowermost sediment consists of the Pumiceous Breccia. The unit is very limited in outcrop, occurring in the northwest dome region in the southeast quarter of the northeast quarter of Section 12 (Appendix C, Plate I). The rock is tan when fresh and weathers to a grey-tan. The rock is poorly indurated, poorly sorted, with poor to moderate bedding, and is composed of tuff, pumice, rock fragments, feldspar and quartz crystals, and carbonaceous material.
Tuff comprises fifty percent of the rock and is the matrix of the breccia. Its origin is unknown. Within this matrix pumice occupies thirty percent of the rock by volume. It is white to grey in color and occurs as subangular to subrounded pieces from two millimeters to one half centimeter in size. The pumice is very similar in appearance to the pumice found in the Dome Ash Flow Tuff which is located adjacent to the breccia.

Rock fragments are subangular to subrounded and are two millimeters to one-half centimeter in size. Two varieties are found. The most common is a light green siliceous material while the second is a blue-grey rhyolite fragment similar in appearance to the surrounding Canon Rhyolite Plateau Rhyolite Lava Flows and Dome Lava Flows. The rock fragments comprise ten percent of the rock.

Feldspar and quartz crystals and carbonaceous material are minor accessories. The crystals are one millimeter in size or less and are generally fractured and broken. The carbonaceous material is mostly very fine grained and commonly occurs in discreet, carbonaceous material-rich layers.

Tuffaceous Sandstone/Siltstone: Stratigraphically above the Pumiceous Breccia are multiple tuffaceous sedimentary units of sand to silt grain size. Due to lack
of outcrop the relationships among the contacts of these units is unknown. However, two separate and probably contemporaneous units can be distinguished, a tuffaceous silty sandstone and a tuffaceous siltstone.

A pervasive sandstone unit exists about the Nellie Spring area in the northeast quarter of Sections 23 and 26 (Appendix C, Plate I). The unit is tan on a fresh surface and weathers to orange. The sandstone is moderately to well indurated, moderately to poorly sorted, and moderately to poorly bedded. The rock matrix consists of silty material plus some volcanic tuff and occupies forty percent of the unit volume. Within this matrix are found obsidian, rock fragments, feldspar and quartz crystals, pumice, and carbonaceous material. The above detritus is generally subrounded and averages less than one millimeter in size. However, some of the pumice and carbonaceous fragments may run from two to three millimeters in size.

To the north and east of the extrusive dome area a pervasive but erratically outcropping tuffaceous siltstone is found (Appendix C, Plate I). The siltstone is yellow to grey when fresh and weathers to a tan color. The unit is moderately indurated, moderately to well sorted, and is generally well bedded. The siltstone is heavily tuffaceous, greater than fifty percent by volume, and
appears to be all tuff in some locations. Some of the siltstone may also be diatomaceous but only to a small degree. Detritus in the siltstone can be identified as obsidian plus feldspar and quartz crystals. In the northeast area of its outcrop, within the unsurveyed portions of the study area, the siltstone is calcified.

Recent Opaline Veins: Stratigraphically younger than the sedimentary units of the High Rock Sequence are a series of opaline silica veins that cross cut the tuffaceous siltstone in the unsurveyed lands northeast of the Dome Lava Flows (Appendix C, Plate I). The veins vary in width from a few inches to three feet and can be traced along their strike for up to two hundred feet. The opal is white to green-grey on a fresh surface and takes on a yellowish hue as it weathers. The material is highly fractured but is massive in texture.

Alluvium: Alluvial deposits mark the youngest rock type within the borders of the study area. The alluvium ranges from clayey to silty soils through gravel to cobble sized rhyolite fragments. The material is unconsolidated for the most part but has been calcified in some locations. The caliche forms a coating over the larger gravel sized rock fragments as well as a hardpan layer.
The alluvium is poorly sorted and moderately to poorly bedded.

Perlitic Alteration: Within the Dome Lava Flows of the Dome Rhyolite Series, in the SE/4 of the NE/4 of Section 12, perlite is found in contact with devitrified rhyolite and sediments of the High Rock sequence. In studies on volcanic glasses and perlite formation, Ross and Smith (1955) concluded that perlite forms by the hydration of obsidian after the obsidian has been emplaced. They further concluded that the water for hydration originated from a post-magmatic source or episode such as rain, snow, or groundwater. Friedman and Smith (1958) supported Ross and Smith's results by showing that the deuterium content of water extracted from a perlite sample was the same as that found in the regional groundwater while the deuterium content of the water taken from an obsidian sample surrounded by the above perlite showed no such similarity to the groundwater deuterium levels.

At Indian Spring, perlite is not found in the higher elevations of the Dome Lava Flows or the Plateau Rhyolite Lava Flows which were never covered by the High Rock sequence sediments. Indeed, obsidian found in the upper elevations of these flows are completely unaltered. Perlitic alteration in the Indian Spring rhyolites is
restricted to zones that were overlaid by High Rock sediments. It seems probable that the perlite formed in the Dome Lava Flows from water introduced into the cold flows when the water-laid High Rock sediments were deposited over the flows.

Beyond adding water to the parent volcanic glass, perlitic alteration has been shown to remove existing volatiles from the glass. In elemental analyses run on an unaltered obsidian and a second hydrated portion of the same obsidian, Shepherd (1938) established that the magma derived volatiles CO₂, CO,Cl₂, S₂, and F₂ were strongly depleted in the hydrated sample and replaced with water.

Friedman and others (1966) noted that perlites form in a sequential fashion with the rate of formation dependent upon temperature; the higher the temperature the quicker the hydration process. After an approximately twenty micrometer thick layer of hydrated glass forms in an obsidian undergoing hydration, the volume change in this thickness of glass associated with the addition of the hydration water creates enough stress that a crack forms between the hydrated and non-hydrated glass. The hydration process then starts anew on the fresh glass.
The hydration rates that Friedman and others (1966) determined were occurring naturally are consistent with perlitic formation during the late cooling of a volcanic glass or after the glass has cooled to surface temperatures.

Structure

Dome Rhyolite Series Flow Dome Complex: The dominant structural feature of the Indian Spring site is the structural extrusive flow dome complex composed of the Dome Rhyolite Series rocks in the eastern portion of the study area (Appendix C, Plate I). The dome is three and one half to four miles in diameter; presently exhibits some four hundred and fifty feet of topographic relief; has a slightly elliptical shape; and has a well established radial stream drainage pattern. Utilizing terminology established by Williams (1932) concerning volcanic domes, the Indian Spring dome is dominantly an exogenous dome with some influence by endogenous processes.

Work by Christiansen and Lipman (1966), Holecek (1979), and Fink (1983), among others, on rhyolitic flows and domes has indicated that rhyolitic flows exhibit a typical structural zonation. Following their work, an initial basal tuff is overlaid by an often pumiceous breccia, followed by a fluidal lava core which may be glassy (obsidian) or crystallized (felsitic or
spherulitic), above which is a pumice carapace that may be brecciated. Most of the above elements are present in the dome rhyolites at Indian Spring (see Indian Spring Area lithology-Dome Rhyolite Series). It should be noted, however, that due to the age of the Indian Spring dome many of the primary features of the domal structure have been altered. Erosion has removed most of the pumiceous outer carapace, the basal tuff was not found, and weathering has obscured many contacts between the different zones. Also, much of the glass in the dome has long since devitrified.

Figure 10 is a schematic illustration which shows how the emplacement of the Indian Spring structural dome took place. In profile A, the initial air fall basal tuff is erupted. This is followed in profile B by the eruption of the pumiceous Dome Ash Flow Tuff unit with the upper and distal portions of this ash flow brecciated by late internal flow movement after the outer shell has solidified. Much of the gases contained within the parent magma have been vented by earlier ash fall and flow so that the eruption of the fluid lavas, profiles C and D, are non-explosive events. Two distinct fluid lava emplacements are indicated at Indian Spring by the presence of two geochemically differentiated lavas. The residual gases within the fluidal lavas are vented off
A. Eruption of the Ash Fall Tuff

B. Eruption of the Pumiceous Ash Flow and its Brecciation

C. Emplacement of the Lower Lava Flow

D. Emplacement of the Upper Lava Flow and Carapace Formation

Figure 10. Formation of the Dome Rhyolite Series Flow Dome Complex (after Holecek, 1979)
during and immediately after emplacement of the lava to form the outer pumiceous carapace, the Dome Pumice, plus layers of vesiculated lava found in the core of the lava flows.

The fluidal lava flows of the dome exhibit strong flow ridge structures as viewed on aerial photographs. Figure 11 is a schematic representation of the flow ridge structure. The formation of the ridges are a function of the emplacement of the lava plus the rheological characteristics of the lavas (Loney, 1968; Holecek, 1978). As such, they give an indication of flow direction and, hence, the location of the eruptive source vent for the flows. Flow mechanics indicate that the concave side of the crescent-shaped flow ridges face in the direction that the flow came from. Examination of Figure 11 clearly shows the flowage of the Dome Lava Flows to have been from the south to the north and east. However, no distinct vent area was observed in the southern dome area. It is probable that the extruded lavas are obscuring the source vent from view. The similarity in orientation of flow ridges between the two geochemically distinct lava flows points to a single source area for the Indian Spring dome flows.

Flow Banding: Both the Dome Lava Flows and the Plateau Rhyolite Lava Flows more often than not exhibit
Figure 11. Flow Ridge Structures within the Dome Lava Flows (from aerial photographs)
laminar flow banding within their lavas. The flow bands are small scale features, characteristically one millimeter thick and up to a few tens of feet in length, as compared to the large scale, one quarter mile or greater in length, of the flow ridges. The formation of flow bands is very common within silicic volcanic rocks but is not fully understood. The flow banding is commonly accentuated by color differences between the bands. A portion of the Indian Spring rhyolite flow banding is accentuated by alternating light bands of microvesiculated lava and dark bands of non-vesicular lava. MacDonald (1972) suggests that the bands result from laminar flow drawing out zones of gas-rich and gas-poor lava into thin sheets. Portions of the Indian Spring lava flows that do not exhibit any flow banding may have been extremely gas-poor and hence had no opportunity to form flow bands.

Not all of the Indian Spring rhyolitic flow banding can be related to vesiculated and non-vesiculated zones. Thin section examination of rock samples showing flow banding divided the bands into spherulitic and non-spherulitic zones. In his studies on artificial lava flows, Pirson (1910) noted the presence of very fine grain spherulitic layers separated by layers of clear, non-crystallized glass. He determined that the spherulites first formed in clusters in the lava and were
later spread out with flowage of the lava to form spherulitic layers. Zones of inherent weakness are found between the spherulitic zones and the non-spherulitic zones due to the reduced bonding strength between the two zone types. The zones of weakness are easily cleavable and thus promote a banded or laminated structure within the lava flow.

Figure 12 shows the trend and plunge of the Dome Lava Flows flow banding foliation throughout the dome. Comparison of the trend components of the flow banding with the orientation of the flow ridges shows a close correlation, indicating that the flow banding is a function of the laminar flow mechanics under which the lava flow was emplaced. The variable plunge component of the flow banding reflects the different topographic surface dip upon which the lava was deposited plus the effects of some non-uniform or non-laminar flowage within the lava. The non-laminar flowage may be caused by eddies or other similar features in the flowing lava during its emplacement or by late movement within the solidifying flow.

Not all of the flow banding trend components correspond with the flow ridge orientations. Anomalous zones of non-uniform foliation probably represent areas where topographic features, such as the steep side of the
Figure 12. Orientation of the Dome Lava Flows
Flow Banding Foliation
previous lava flow, have disrupted the smooth flowing lava and given it a new direction in which to flow. Chapin and Lowell (1979) discovered zones of non-uniform foliation and flow folds in ash flow tuffs. They determined that differential deposition of material in and about a paleovalley can cause the formation of flow folds. More material is deposited on the edge of the valley than down along its axis, creating steepened slopes along the paleovalley edge. The material on the oversteepened sides then slumps down into the valley axis to create local areas of deformed flowage. Both of the above described processes may be responsible for the major anomalous flowage orientation in the Dome Rhyolite Flows. Smaller scale flow folds may more properly reflect the drag friction effects between adjacent flow layers that are moving at different rates or minor compressional stresses caused by secondary flowage within the solidifying lavas.

Lenticule Formation: Both the Dome and Plateau Rhyolite flows are characterized by the presence of lenticules or lithophysal gas cavities, plus thin, elongated bands of pumice-like rock. Both features are a function of gases caught within the lava flows. Cavities may be formed in a lava by the weathering out of pumice that was incorporated into the flows either as air fallout or as detrital pieces picked up by the lava flow.
However, the large majority of the Indian Spring lava cavities are not restricted to weathered surfaces, but are found in the interior portions of the flows. Further, no transitional phases of the weathering out of pumice are found; simply empty cavities or vesiculated zones. It therefore seems likely that the lenticules were formed not by the weathering process but were formed during the extrusion of the lava. The process that would form cavities under such circumstances is the trapping of gas pockets within the lavas as they cooled. The cavities are often elongated, having been stretched out during minor late primary or more probably secondary flowage within the lava.

The bands of thin, elongated pumice-like rock found in the lavas range from a few inches to several feet in length and width with their thickness an order of magnitude smaller than the other two dimensions. They are similar to ash flow features described by Chapin and Lowell (1979) and are formed in the same manner, by the release of gases trapped along flowage planes. The differential movement of the lava within the flow creates flowage planes along which the shear stress or, essentially, the confining pressure is reduced, thus allowing the gases in the lava to effervesce out and form the pumice-like texture. On a weathered surface the effervescent zone will often erode faster than the surrounding rock and form an erosional cavity.
Spherulitic Structure: Two genetically different sets of spherulitic structures are found within the Indian Spring rhyolitic lavas. The first set are siliceous spheres formed by the filling of rounded or spherical cavities found within the lavas. The cavities represent small gas pockets trapped within the lavas that were later filled by silica, which originated from the devitrification of the glassy lavas and formed the spherulites. The more or less spherical shape of these spherulites indicates that the gas cavities formed after laminar flowage within the flow had ceased. If the cavities had formed prior to the completion of flowage, the laminar flow would have stretched out the cavities to a more elliptical shape. Spherulites of the cavity-filled variety range from two to three millimeters to one centimeter in size.

The second set of spherulites, which occur more often in the rhyolite lavas than the first type and are of much greater significance, have formed by the devitrification of the glassy rhyolitic lavas. These spherulites form the basis of the Plateau Rhyolite Lava Flows and Dome Lava Flows spherulitic lavas.

In his examination of experimentally produced devitrification textures in natural rhyolitic glass, Lofgren (1971a) distinguished two stages of
devitrification and postulated the existence of a third. Rocks of the first stage, the glassy stage, are dominated by undevitrified glass that contain only widely spaced spherulites. In the second stage, the spherulitic stage, rocks are dominated by intimately intergrown spherulites and/or micropoikilitic quartz with no obvious traces of glass remaining. The postulated third stage is the granophyric stage where recrystalization has removed all evidence of the spherulites and formed a granophyric texture. The three stages represent different conditions of cooling, temperature, pressure, or increasing water content. These physical conditions are all increasing as devitrification proceeds from the glassy stage to the granophyric stage. Examination of the Indian Spring rhyolites places them within the spherulitic stage of devitrification.

The Indian Spring devitrification spherulites are one half to one millimeter diameter spheres composed of alkali feldspar crystals that have a fibrous to bladed crystal form centered about a common focus. As previously cited, the morphology of the individual spherulites varies as a function of the temperature at which they were formed. The Indian Spring spherulitic morphology is typical of that found in intermediate temperature (400° to 650°C) spherulite growth in rhyolitic glass (Lofgren, 1971b).
Based upon Lofgren's (1971b) work, and others, the spherulites are able to remain stable during their growth through the complex interaction of a lower temperature component of the rhyolitic melt with a second high temperature, spherulite-forming material. The interaction takes place at the interface of the melt and growing crystals. The effect is such that the low temperature components create a supercooled zone about the spherulite crystals and liquid melt interface. Within this zone, small but stable projections of the crystals form. The high temperature material grows out from these projections to increase the size of the fibrous or bladed crystal while the flanks of the crystal growths are stabilized and supported by the accumulation of the low temperature component.

The same stages and processes of devitrification described above from experimental melts occur both in the devitrification of natural magma melts and in the devitrification of previously glassy lavas. The time span for devitrification is much longer for the existing cold, glassy lavas than for the cooling of a hot melt but spherulite morphology and texture remain similar. It is therefore difficult to say whether the devitrification texture of the spherulitic rhyolites at Indian Spring was directly from the hot melt or lava or whether the lava first cooled to a glass and then started to devitrify. Indeed, the processes of devitrification is the same for
both the hot melt or cold glass, only the time span involved is different.

Faulting: Two prominent lineations with an approximately N30°W orientation, as observed on low level aerial photographs, are present within the flow dome complex. Examination of the 7-1/2 minute topographic maps of the area reveals that a topographic trough, with one hundred to two hundred and fifty feet of relief, exists between the two major dome lineations (Appendix C, Plate I). The establishment of the graben-like feature within the dome appears to have been contemporary with or occurred just after the formation of the dome itself. The approximately equal elevations found on the scarps both east and west of the graben are not consistent with a pre-existing graben or major paleochannel. It is difficult to conceive of the dome lavas moving from west of the graben, down through a major trough or downdrop, and up east of the trough and still be spread uniformly. Yet the flow ridges and flow foliations in the dome indicate just such a direction to the flow pattern.

Examination of the margins of the structural dome indicates a condition opposite to that presented above, namely, that there was a pre-existing trough of some type. The indication of this pre-existing trough is seen along the north to northwestern margin of the dome in the eastern half of Section 12 and east into the unsurveyed
lands (Appendix C, Plate I). At this point there is a tongue-like extension of the Dome Lava Flows which projects out beyond the more or less circular northern side of the dome. When the extension position is compared to the graben location, the tongue of lava fits within the confines of the graben, as if the lava flowed down an existing graben or topographic trough to form the northerly dome extension.

The contemporary formation of the dome and graben reconciles the contradictory information presented previously. It is postulated that the extrusion of the flows occurred on an initially more or less flat surface. Towards the end of their extrusion or just after, collapse took place along the dome lineations to form the graben. Indeed, it is probable that the collapse took place in response to extrusion of the dome lavas emptying a magma chamber below the dome. The contemporaneous timing of events allows the dome to form at or close to its full topographic height yet allows the graben to form while the lava flow is still plastic enough to flow out along the trough and form the northern tongue of the dome. The plasticity of flow helps to explain the observation of the continuity of flow ridges and flow banding from the scarps through the graben.

No other faulting is observed in the study area. There is no trace of the dome faults beyond the dome
boundaries. However, this may be the result of younger, stratigraphically higher units covering any traces of further faulting. Examination of the regional faulting pattern (Figure 2) shows a strong northwesterly Basin and Range trend to the faulting as well as a northeast trend. The dome faults, of northwesterly trend, are related to this regional trend. It is probable that the dome formation was due to the dome fault intersecting a silicic, fractionated magma chamber and providing a conduit to the surface for the magma. The subsequent collapse of the chamber along the fault trace gave the graben its northwesterly orientation.

Jointing: Two sets of joints exist in the Indian Spring rhyolites. The first set consists of hairline fractures that occur parallel to the flow foliation surfaces. These joints are related to shear forces along the foliation surfaces caused by late movement of the lavas, especially during secondary flowage.

The second set of joints are high angle fractures, 75 degrees or greater, with no particular strike orientation. Holecek (1978) related high angle fractures he encountered at Hot Creek to minor extensional solid state movements. In addition to solid state movement, fractures and joints at Indian Spring are related to cooling as fractures form in response to volume changes in the lava upon its cooling. Joints come about as
differential cooling within the lava builds up stress until it is released by fracturing of the rock.

Lofgren (1971a) reports that an approximately ten percent volume change accompanies the devitrification of volcanic glass. The strongly devitrified character of the Indian Spring rhyolites, with its attendant volume change, must also have expressed itself through the formation of joints. It is probable that both high angle jointing and low angle jointing parallel to the flow foliation are the result of these volume changes.
General Rhyolite Characteristics

Bonham (1969) has characterized the Canon Rhyolite as a soda rhyolite due to a deficiency in $\text{Al}_2\text{O}_3$ rather than a surplus of $\text{Na}_2\text{O}$. However, Table 1, page 56, indicates that although the Dome Lava Flows and the Plateau Rhyolite Lava Flows units in Indian Spring are also somewhat $\text{Al}_2\text{O}_3$ deficient they are extremely $\text{Na}_2\text{O}$ rich compared to Daly's (1933) average rhyolite plus the other listed rhyolites. The Indian Spring rhyolites are geochemically quite similar to true $\text{Na}_2\text{O}$ rich soda rhyolites.

Differentiation of Rhyolite Flows

The Indian Spring area rhyolitic lava flows are difficult to distinguish from one another in both hand sample and thin section. The Dome Lava Flows and Plateau Rhyolite Lava Flows have almost the same colors, textures, mineralogy and so forth. The only major exception to this similarity is that the Plateau Rhyolite Lava Flows are phenocryst rich, from five to eight percent, compared to the Dome Lava Flows with one to two percent phenocrysts.
**TABLE 1**

Comparison of chemical composition of Indian Spring rhyolites with Bonham's Canon Rhyolite, a Shoshone Range soda rhyolite and with average rhyolite.

<table>
<thead>
<tr>
<th></th>
<th>Average Dome Lava Flows</th>
<th>Average Plateau Lava Flows</th>
<th>Canon Rhyolite</th>
<th>Soda Rhyolite</th>
<th>Average Rhyolite</th>
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<tr>
<td>SiO₂</td>
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<td>MnO</td>
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<td>.11</td>
<td>T</td>
<td>.08</td>
<td>.06</td>
</tr>
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<td>Total</td>
<td>98.924</td>
<td>99.06</td>
<td>98.57</td>
<td>98.97</td>
<td>98.10</td>
</tr>
</tbody>
</table>

1 Canon Rhyolite in Indian Spring, 5 sample average
2 Canon Rhyolite in Indian Spring, 4 sample average
3 Canon Rhyolite in Virgin Valley after Fuller (1931)
4 Pipe Canyon Breccia Pipe after Gilluly and Gates (1964)
5 After Daly (1933)

Geochemically, however, the flows are much more distinguishable.

Table 1, page 56, illustrates the geochemical differences between the Dome and Plateau Lava Flows. The Dome Lava Flows are two and a half percent higher in total SiO₂ and consistently lower in the mafic constituents.
FeO and Fe$_2$O$_3$, MgO, CaO, and MnO than the Plateau Rhyolite Lava Flows. As seen in Table 1, the Dome Lava Flows also average a full percent less in Na$_2$O content than do the Plateau Lava Flows.

Examination of each geochemical sample analysis (Appendix A) allows for some differentiation of individual lavas within the Dome and Plateau Lava Flows. The location of each sample is shown on the geologic map in Appendix C. Such differentiation is virtually impossible to do by hand sample or thin section only.

Two separate lava flows have been discriminated within the Dome Lava Flows. Samples IS-2 and IS-41 (Appendix A and Appendix C) have almost identical geochemical analyses while samples IS-72, IS-76, IS-79, and IS-84 are very similar in their analyses. Comparing the two groups, samples IS-2/IS-41 have SiO$_2$ values of eighty percent compared to seventy-seven percent in the second group with group IS-2/IS-41 also having ten times more P$_2$O$_5$ and ten times less TiO$_2$ than group IS-72/IS-76/IS-79/IS-84. While not as strong a difference as found in the previously mentioned elements, samples IS-2/IS-41 are also consistently less endowed in Al$_2$O$_3$, CaO, K$_2$O, and Na$_2$O than the second group.

Within the Plateau Rhyolite Lava Flows, it is not geochemically possible to definitively separate out
flows. The four Plateau Rhyolite Lava Flow samples, IS-9, IS-28, IS-46, and IS-66 (Appendix A and Appendix C) are very similar in their main constituents with SiO\textsubscript{2} values just at or below seventy-six percent, Al\textsubscript{2}O\textsubscript{3} values from eleven to eleven and one half percent, and Fe\textsubscript{2}O\textsubscript{3} values above two percent. Samples IS-9 and IS-28 have P\textsubscript{2}O\textsubscript{5} values five to six times greater than those for samples IS-46 and IS-66 while the latter two samples have TiO\textsubscript{2} values some ten times greater than found in the first two samples. However, the use of such minor components as P\textsubscript{2}O\textsubscript{5} and TiO\textsubscript{2}, whose total percentage is less than one half of one percent, is insufficient to absolutely differentiate any separate Plateau Rhyolite Lava Flows. Indeed, the similarity of elemental compositions suggests a single magma source is present in the Plateau Rhyolite Lava Flows.
GENESIS OF THE VOLCANISM

Regional

Two major episodes of volcanism characterized the Basin and Range during Cenozoic time. The first ranged from approximately 37 m.y. ago to 22 m.y. ago and the second from 17 m.y. ago until the present (Noble, 1972; Armstrong, et al., 1969; Christiansen and Lipman, 1972). Recent studies by a number of different workers have correlated these volcanic episodes with major changes in the tectonic regime of western North America (Armstrong, et al. 1969; Atwater, 1970; Christiansen and Lipman, 1972; Noble, 1972).

The early to middle Cenozoic, thirty-seven to twenty-two million years before present, volcanism has been related to an episode of continental-margin plate subduction where the Farallon plate, located between the North American and Pacific plates, was being subducted beneath the North American plate (Figure 13, A). The result of this subduction, which occurred in the island arc subducting environment of plate tectonics, was a major episode of predominantly intermediate composition volcanism. This phase of volcanic and tectonic activity lasted for approximately fifteen million years until it was terminated by the collision of the subducting trench.
Figure 13. Diagram of Plate Movement at the Western Edge of North America

(from Atwater, 1970)
and the East Pacific Rise spreading zone (Figure 13, B and C) (Atwater, 1970; Christiansen and Lipman, 1972). The Farallon plate was essentially consumed by the end of this tectonic period with the North American and Pacific plates now in contact (Figure 13, D).

The late Cenozoic, seventeen million years ago to present, phase of volcanism was and still is related to the new tectonic setting of contacting North American and Pacific plates. The plates are moving in relation to one another along the San Andreas transform fault zone, although the exact motion is still imperfectly known (Figure 6, D). It does appear, however, that this motion has been in an oblique manner and has led to the initiation of crustal extension in the Basin and Range province (Atwater, 1970; Noble, 1972). Crustal extension led to the second phase of volcanism which Lipman, Prostka, and Christiansen (1972) have described as fundamentally basaltic in composition. Volcanism occurred in the region as the "Basin and Range"-type faulting caused by the crustal extension provided conduits through which deep seated mafic magmas could reach the surface. The fundamentally basaltic composition volcanics of this period include basalt fields, differentiated alkalic basaltic suites, and a bimodal association of basalt and alkalic high-silica rhyolite (Christiansen, et.al., 1972).
Indian Spring Area

Within the previously described regional genetic framework, the Indian Spring area is representative of the bimodal basalt-rhyolite association phase of late Cenozoic volcanism. Christiansen and Lipman (1972) characterized the rhyolites of the bimodal association as being chemically distinct from the calc-alkaline rhyolites associated with the earlier intermediate volcanism. The bimodal rhyolites are noted for commonly containing more than seventy-two percent SiO$_2$, having alkali contents that are larger in relation to their calcium content, a Na/K ratio which is greater than that found in the calc-alkalics, and alkali feldspars that are more Na rich with Or/Ab ratios that are more sodic than Or50 Ab50. In addition, ferroaugite and fayalite may be present.

Results of chemical analyses performed on the alkali rhyolites in the Indian Spring area compare closely with the above described bimodal rhyolite characteristics (Appendix A). The SiO$_2$ values at Indian Spring range from 75.2% to 80.1% SiO$_2$ while alkali elements are found in concentrations approximately forty times greater than that of calcium. The ratios of Na$_2$O to K$_2$O are at 0.9 or greater, a value larger than that found in normal calc-alkalic rhyolites. No chemical analyses were run on the phenocrysts to determine the OrxAbx values but
calculated normative figures suggest Or/Ab ratios at or more sodic than Or_{50}Ab_{50} (Appendix B). Normative calculations also indicate the presence of mafic minerals compatible with those proposed by Christiansen and Lipman (1972) and Noble and Parker (1974) for the bimodal rhyolites (Appendix B).

The volcanic rocks found in the basalt-rhyolite bimodal association may have their origin in the direct differentiation and rise of mantle material. In the Basin and Range, this rise of magma occurred in conjunction with the beginning of crustal extension. Noble (1972) suggests that crustal extension not only allowed for the eruption of the volcanics by providing pathways through the crust but it also helped trigger an upwelling of mantle material, resulting in the generation of primary mafic magmas for later differentiation.

It has been noted by several workers that the basalts of the bimodal association are generally more abundant in the younger portion of a sequence (Noble, 1972; Armstrong, et al., 1969). This is a reflection of the later tapping of deeper, mafic magmas by high angle Basin and Range faults following the extrusion of shallow, differentiated bimodal rhyolites.

It should be noted that the basal Dacite unit that crops out at Indian Spring is representative of the intermediate composition volcanism associated with the
earlier plate tectonic subduction zone setting of northwestern Nevada (Lipman, et al., 1972). The subduction of more or less sialic composition crustal material led to the melting of this material and, when combined with primary basaltic magmas at depth, gave existence to intermediate composition magma and volcanism.

The younger basalt-rhyolite bimodal association at Indian Spring is related to the extensional tectonic setting of northwestern Nevada and is noted for a general lack of intermediate composition volcanism (Noble, 1974; McKee, 1971). Sialic magmas differentiated from mafic magmas generated in the extensional tectonic setting were buoyant enough to reach the surface before the extensional tectonics initiated faulting in northwestern Nevada. Following the onset of faulting, deeper and more mafic magmas were tapped for eruption. The much greater volume of primary basaltic magma over differentiated intermediate composition magma led to a dominantly basaltic nature for this faulting-related stage of volcanism. Together, the pre- and post-faulting eruptions gave a strong bimodal character to northwestern Nevada and, hence, to Indian Spring.

While no basalts are found within the Indian Spring study area boundaries, the region about the study area, especially to the north and west, is covered with basalts younger than the Canon Rhyolite found at Indian Spring.
The stratigraphic section of Bonham's (1969) Washoe County report shows the Canon Rhyolite is overlaid by the silicic and mafic rocks of the High Rock sequence which in turn is overlaid by extensive flows of late Miocene and Pliocene olivine basalts, the "Warner" basalt.

The rhyolitic magmas of the bimodal association are highly differentiated products of primary mafic magma (Noble, 1972; Armstrong, et.al., 1969). Beyond the close time and space relationship which link the basalt and rhyolite together, Noble (1974) has found that the \( \text{Sr}^{87}/\text{Sr}^{86} \) ratios for most intermediate and silicic volcanic rocks of late Cenozoic age in the Great Basin are within 0.002 of the values obtained from basalts of similar age in the same region. These values, from 0.702 to 0.707, indicate not only a similarity of source for the rocks but the absolute value of the \( \text{Sr}^{87}/\text{Sr}^{86} \) ratios are indicative of magmas that contain little to no melting of sialic crust. This information supports the differentiated primary magma genesis for the Basin and Range region bimodal association and hence the origin of the Indian Spring rhyolites.

Work by Smith (1979) on the Bandelier Tuff of New Mexico and by Hildreth (1979) on the Bishop Tuff of California established that the high (up to eighty percent) \( \text{SiO}_2 \) content of the Indian Spring rhyolites clearly puts their origin in the highly fractionated magma
framework. Smith and Hildreth further indicated that to fractionate to such a high SiO₂ content, the magmatic system being fractionated has not undergone any leakage from the magma chamber or the system has experienced leakage but then had sufficient time between leakage events to allow progressive enrichment of SiO₂ to become re-established.

The Indian Spring rhyolites vary in SiO₂ content from seventy-five percent to eighty percent. This variability may be indicative of the tapping of different levels of a single magma chamber either simultaneously or over a short time interval. Alternate possibilities are that multiple magma chambers are being tapped either simultaneously or over a short time span or that there has been the sequential eruption of magma from a single system over a long time span so as to allow the system to re-equilibrate before subsequent eruptions.

The similarity in overall whole rock geochemistry and the close time and spatial relationships between the Dome and Plateau rhyolites indicates, regionally, the similarity of source material for the Indian Spring rhyolites, e.g., a strongly differentiated magma. However, the SiO₂ contents of the Dome and Plateau Lava Flows rhyolites, seventy-eight to eighty percent SiO₂ and 76 percent SiO₂ respectively, point towards a separate or multiple magma chamber source. A separate
source is indicated since, as was previously stated in this report, high SiO₂ magmas form from magmatic systems that have not undergone leakage. The eruption of the earlier high SiO₂ Plateau Rhyolite Lava Flows would preclude the eruption of the higher SiO₂ content Dome Lava Flows from the same magma chamber. It seems doubtful, considering the short time frame between the emplacement of the Plateau and Dome Lava Flows, that the Plateau source magma had sufficient time to re-establish SiO₂ enrichment and produce an even more differentiated magma following the eruption of the Plateau Rhyolite Lava Flows.

Smith (1979), in his study on ash flow magmatism, stated that in compositionally zoned magma chambers the systems are normally tapped from the top down. At Indian Spring, the older Plateau rhyolites are not from the most fractionated magma normally found at the top of the magma chamber if a single source magma is postulated. The higher silica but younger Dome rhyolites would have been expected to have been erupted first. This anomalous situation can be reconciled if two magma chambers, possibly from a single differentiated source, are assumed to exist at Indian Spring.
The Indian Spring study area contains Miocene volcanic and subordinate sedimentary rocks from three different rock groups; the South Willow Formation, the Canon Rhyolite, and the High Rock Sequence. Dacite of the South Willow Formation is the stratigraphically lowermost unit to cropout in the study area. It is overlaid by the Plateau Rhyolite Lava Flows, a member of the Canon Rhyolite. The Plateau Rhyolite Lava Flows form a thick series of spherulitic, mostly flow banded, rhyolitic lavas. They in turn are overlaid by another unit of the Canon Rhyolite, the Dome Rhyolite Series. The Dome Rhyolite Series is composed of a basal non-welded to moderately welded ash flow tuff found underneath a series of spherulitic, flow banded rhyolite lava flows that form an extrusive structural dome. The Canon Rhyolite units are overlaid by sedimentary rocks of the High Rock Sequence. The Indian Spring area High Rock sediments are coarser than the typical diatomaceous High Rock units due to their location adjacent to a highland during High Rock sediment deposition.

The extrusive structural dome formed by the Dome Rhyolite Series rocks is the main structural feature in the Indian Spring area. The dome, while strongly eroded,
shows many of the diagnostic features of a rhyolitic dome including an initial pumiceous ash flow, a flow banded lava core, and a pumice carapace. The dome is cut by northwest trending faults running through the center of the dome. It is thought that these faults provided the conduit through which the Dome Rhyolite Series was extruded to form the structural dome at Indian Spring.

The Canon Rhyolite is a product of the regional extensional tectonic setting of western Nevada. The extensional tectonics, which occur as a result of interaction between the Pacific and North American tectonic plates, have provided conduits through which highly differentiated magmas have been able to reach the surface. The Indian Spring area members of the Canon Rhyolite, the Plateau Rhyolite Lava Flows and the Dome Rhyolite Series, are strongly differentiated units that have very high SiO₂ values and low mafic contents and are classified as peralkaline rhyolites.

Two separate magma chambers are believed to exist for the origin of the Plateau Rhyolite Lava Flows and the Dome Rhyolite Series rocks. The more highly differentiated Dome Lava Flows of the Dome Rhyolite Series formed in a magma chamber that has not experienced any leakage. It therefore does not seem likely that the stratigraphically lower Plateau Rhyolite Lava Flows could have been extruded
from a magma chamber which then quickly extruded a more highly differentiated magma that formed the Dome Rhyolite Series. A second magma source is required for the Dome Rhyolite Series of highly differentiated rocks. However, the two magma sources, by nature of their close chemical composition, spatial arrangement, and time of emplacement, may be related to a single differentiated source at greater depth.

To further explore the source of the rhyolites found in the Indian Spring study area, trace element geochemistry needs to be performed. The trace element analyses may be useful in further differentiating the individual rhyolite units found at Indian Spring as well as helping to link the units to one another through a similarity in their trace element suites. Isotope geochemistry would allow a better classification of the ultimate origin of the Indian Spring area rhyolites as magmas derived from differentiated basalts have different Sr isotope ratio values than those magmas derived from remelted sediments.

The Indian Spring area has been shown to contain rocks formed from highly differentiated silicic magmas. Such magmas are known to contain elevated levels of uranium and as such may contain potentially mineable uranium deposits. The Indian Spring area may hold such an
occurrence. Both the extrusive structural dome and the High Rock sediments are potential targets. The dome may provide a vein-type of uranium concentration and the sediments a roll-front or oxidation/reduction front-type deposit with the uranium provided through the leaching out of uranium found in the highly differentiated lavas. A start to this exploration process would be to determine if, indeed, the Indian Spring area has rock units containing anomalous levels of uranium and if so whether this uranium is held in a form that makes it available for concentration to economic levels. Further actions would depend upon the results of these initial studies.
REFERENCES


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**APPENDIX A**

**WHOLE ROCK GEOCHEMICAL ANALYSES**

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Total: 99.902 100.312 99.488 99.997 100.423 100.008 100.518

**Description of Analyzed Samples**

1. Obsidian fragments from lava within Dome Lava Flows, glassy.
2. Slightly welded tuff, 50% pumice/fragments, glassy, from Dome Ash-Flow Tuff.
4. Black moderately-welded tuff, glassy, from Dome Uplap Tuff.
5. Pyroclastic pumice-rich crystalline lava, from Dome Uplap Tuff.
Whole Rock Chemical Analyses of Rocks
From the Indian Spring Area,
Northwestern Nevada

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Description of Analyzed Samples
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2. slightly welded tuff, 30% pumice fragments, glassy, from Dome Ash Flow Tuff
3. non-welded tuff, 65% pumice fragments, glassy, thin section shows secondary calcite present, from Dome Ash Flow Tuff
4. black moderately-welded tuff, glassy, from Dome Welded Tuff
5. pyroxene phenocryst-rich crystallized lava, from Dacite
6. banded, spherulitic finely crystallized lava, from lava of Dome Lava Flows
7. banded, spherulitic finely crystallized lava, from lava of Dome Lava Flows
### Description of Analyzed Samples

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<td>%K₂O</td>
<td>3.97</td>
<td>3.73</td>
<td>4.52</td>
<td>3.87</td>
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<td>%TiO₂</td>
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<td>0.049</td>
<td>0.43</td>
<td>0.48</td>
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<td>%MnO</td>
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<td>0.024</td>
<td>0.014</td>
<td>0.13</td>
<td>0.10</td>
<td>0.10</td>
<td>0.12</td>
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<td>%P₂O₅</td>
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<td>0.008</td>
<td>0.008</td>
<td>0.034</td>
<td>0.044</td>
<td>0.006</td>
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<td>0.35</td>
<td>0.70</td>
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<td>0.42</td>
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8. banded, spherulitic, finely crystallized lava, from Dome Lava Flows  
9. banded, spherulitic, finely crystallized lava, from Dome Lava Flows  
10. banded, spherulitic, finely crystallized lava, from Dome Lava Flows  
11. finely crystallized feldspar phenocryst-rich lava, from Plateau Rhyolite Lava Flows  
12. finely crystallized feldspar phenocryst-rich lava, from Plateau Rhyolite Lava Flows  
13. strongly banded, finely crystallized feldspar phenocryst-rich lava from Plateau Rhyolite Lava Flows  
14. weakly banded, spherulitic feldspar phenocryst-rich, finely crystallized lava, from Plateau Rhyolite Lava Flows
APPENDIX B

NORMATIVE CALCULATIONS AND ROCK CLASSIFICATIONS*

* University of Nevada, Reno - Geology Dept. System:
BASIC-OLD, PETCAL
SAMPLE NUMBER 1

SiO₂ 78  Al₂O₃ 10.7  Fe₂O₃ 1.9  P₂O₅ 0.21  P₂O₅ 0.13  M₃O 0.051  
MgO 0.07  CaO 0.2  Na₂O 4.07  K₂O 4.53  
TiO₂ 0.021  TiO₂ 0.123584  H₂O 0.70312  
MgO 0.07  CaO 0.2  Na₂O 4.07  K₂O 4.53  
TiO₂ 0.021  P₂O₅ 0.13  M₃O 0.051  
MODIFIED Fe₂O₃ = 1.521  
MODIFIED P₂O₅ = 0.341024  
SUM OF OXIDES 99.634

*NORMATIVE MINERALS*
QUARTZ 37.6472  
ORTHoclASE 26.7684  
ALbite 29.8153  
ACMITE 4.07124  
DIOPSIDE 0.123584  
H₂O 0.70312  
MAGNETITE 0.164927  
ILMENITE 3.98842E-2  
APATITE 0.301022  
SUM 99.6347  
WOLLASTONITE (DIOPSIDE) 5.99912E-2  
ENSTATITE (DIOPSIDE) 1.44594E-2  
FERROSILITE (DIOPSIDE) 4.91335E-2  
ENSTATITE (HYPERSTHENE) 0.159872  
FERROSILITE (HYPERSTHENE) 0.543248

*NORMATIVE RATIOS - CIPW*

OR:AB:AN 47.3075 52.6925 0  
NORMATIVE PLagioclase CONTENT = AN 0  
NORMATIVE COLOR INDEX = 1.03152

*PETROCHEMICAL INDICES*

ALKALI INDEX 52.6744  
FELSIC INDEX 97.7273  
MAFIC INDEX 96.3769  
SOLIDIFICATION INDEX 0.674398  
DIFFERENTIATION INDEX 94.2309  
CRYSTALLIZATION INDEX 0.143234  
WEATHERING INDEX (PARKER, 1970) 76.6766  
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 51.8602  
PERALUMINOUS INDEX -11.7957
SAMPLE NUMBER 2

SI02 80.1  AL2O3 10.5  FE2O3 1.62  FEO 0
MGO .02  CAO .12  NA2O 3.99  K2O 3.24
TI02 .015  P2O5 .041  MNO .01
MODIFIED FE2O3=1.515
MODIFIED FEO=.094479
SUM OF OXIDES 99.6455

*NORMATIVE MINERALS*
QUARTZ 44.3239
CORUNDUM .309259
ORTHOCLESE 19.1456
ALBITE 33.7599
ANORTHITE .327696
HYPERTHENE .049809
MAGNETITE .293634
HEMATITE 1.31248
ILMENITE 2.8488E-2
APATITE 9.49378E-2
SUM 99.6456
ENSTATITE (HYPERSTHENE) .049809

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 35.9655 63.4189 .615586
Q:OR:AB 45.5869 19.6912 34.7219
Q:OR:AB:AN 45.4338 19.625 34.9412
NORMATIVE PLAGIOCLASE CONTENT = AN .961336
NORMATIVE COLOR INDEX = 1.68442

*PETROCHEMICAL INDICES*
ALKALI INDEX 44.8133
FELSIC INDEX 98.3673
MAFIC INDEX 98.7726
SOLIDIFICATION INDEX .229682
DIFFERENTIATION INDEX 97.2293
CRYSTALLIZATION INDEX .362604
WEATHERING INDEX (PARKER, 1970) 64.6419
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 44.2334
PERALUMINOUS INDEX 2.01128
SAMPLE NUMBER 4

SI02 75.6  AL2O3 11.7  FE2O3 1.96  FEO 0
MGO .1  CAO 1.66  NA2O 2.67  K2O 5.1
TI02 .025  P2O5 .017  MNO .038
MODIFIED FE2O3 = 1.525
MODIFIED FEO = .391413
SUM OF OXIDES 98.8264

*NORMATIVE MINERALS*
QUARTZ 37.5978
ORTHoclASE 30.1366
ALBITE 22.5912
ANORTHITE 4.8775
WOLLASTONITE 1.06735
DIOPSIDE .537212
MAGNETITE 1.31293
HEMATITE .619492
ILMENITE 4.74812E-2
APATITE 3.93644E-2
SUM 98.8269

WOLLASTONITE (DIOPSIDE) .288167
ENSTATITE (DIOPSIDE) .249045

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 52.3157 39.2172 8.46711
Q:OR:AB 41.6248 33.3644 25.0108
Q:OR:AB&AN 39.4922 31.655 28.8527
NORMATIVE PLAGIOCLASE CONTENT = AN 17.7566
NORMATIVE COLOR INDEX = 2.51711

*PETROCHEMICAL INDICES*
ALKALI INDEX 65.6371
FELSIC INDEX 82.3966
MAFIC INDEX 95.0407
SOLIDIFICATION INDEX 1.03803
DIFFERENTIATION INDEX 90.3256
CRYSTALLIZATION INDEX 5.41469
WEATHERING INDEX (PARKER, 1970) 72.4193
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 54.5645
PERALUMINOUS INDEX -10.5169
SAMPLE NUMBER 9

SI02  76.2  AL203  11.4  FE2O3  2.14  FEO  0
MGO .08  CAO .12  NA2O  4.69  K2O  5.16
TI02 .049  P2O5 .044  MNO .1
MODIFIED FE2O3 = 1.549
MODIFIED FEO = .531782
SUM OF OXIDES 99.9238

*NORMATIVE MINERALS*
QUARTZ  32.3488
ORTHOCLASE  30.4911
ALBITE  29.9084
ACMITE  4.48132
SODIUM METASILICATE  1.09098
DIOPSIDE .267959
HYPERSTHENE  1.14144
ILMENITE  9.30632E-2
APATITE .101884
SUM 99.9251

WOLLASTONITE (DIOPSIDE) .128651
ENSTATITE (DIOPSIDE) .021671
FERROSILITE (DIOPSIDE) .117637
ENSTATITE (HYPERSTHENE) .177565
FERROSILITE (HYPERSTHENE) .963879

*NORMATIVE RATIOS - CPIW*
OR:AB:AN 50.4823 49.5177 0
Q:OR:AB 34.8781 32.8751 32.2469
Q:OR:AB:AN 34.8781 32.8751 32.2469
NORMATIVE PLAGIOCLASE CONTENT = AN 0
NORMATIVE COLOR INDEX = 1.50247

*PETROCHEMICAL INDICES*
ALKALI INDEX  52.3858
FELSIC INDEX  98.7964
MAFIC INDEX  96.2976
SOLIDIFICATION INDEX .674788
DIFFERENTIATION INDEX  92.7484
CRYSTALLIZATION INDEX .171189
WEATHERING INDEX (PARKER, 1970)  87.5637
ALTERATION INDEX (ISHIKAWA ET AL, 1976)  52.1393
PERALUMINOUS INDEX -18.5835
SAMPLE NUMBER 20

SiO₂ 78.1  Al₂O₃ 10.5  Fe₂O₃ 1.81  FeO 0
MgO 0.05  CaO 0.36  Na₂O 3.24  K₂O 5.53
TiO₂ 0.016  P₂O₅ 0.007  MnO 0.032
MODIFIED Fe₂O₃ = 1.516
MODIFIED FeO = 0.264541
SUM OF OXIDES 99.6155

*NORMATIVE MINERALS*
QUARTZ 38.4583
ORTHOCLASE 32.6775
ALBITE 23.2196
ACMITE 3.69511
WOLLASTONITE 0.299373
DIOPSIDE 0.873336
MAGNETITE 0.346186
ILMENITE 0.030388
APATITE 1.62089 E-2
SUM 99.616

WOLLASTONITE (DIOPSIDE) 0.427229
ENSTATITE (DIOPSIDE) 0.124522
FERRSILITE (DIOPSIDE) 0.321585

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 58.4601 41.5399 0
Q:OR:AB 40.759 34.6324 24.6086
Q:OR:AB&AN 40.759 34.6324 24.6086
NORMATIVE PLAGIOCLASE CONTENT = AN 0
NORMATIVE COLOR INDEX = 1.24991

*PETROCHEMICAL INDICES*
ALKALI INDEX 63.0559
FELSIC INDEX 96.057
MAFIC INDEX 97.2686
SOLIDIFICATION INDEX 0.478531
DIFFERENTIATION INDEX 94.3553
CRYSTALLIZATION INDEX 0.268595
WEATHERING INDEX (PARKER, 1970) 77.8744
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 60.7843
PERALUMINOUS INDEX -14.0002
SAMPLE NUMBER 28

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<td>FeO</td>
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<td>MgO</td>
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<tr>
<td>CaO</td>
<td>0.21</td>
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<td>Na₂O</td>
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<tr>
<td>K₂O</td>
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<tr>
<td>TiO₂</td>
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<td>P₂O₅</td>
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<td>MnO</td>
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Modified Fe₂O₃ = 1.549
Modified FeO = 0.909698
Sum of oxides = 99.0417

*NORMATIVE MINERALS*

- Quartz: 30.214
- Orthoclase: 22.8683
- Albite: 38.633
- Acmite: 4.48132
- Sodium Metasilicate: 0.202535
- Diopside: 0.714704
- Hypersthene: 1.7577
- Ilmenite: 9.30632E-2
- Apatite: 7.87289E-2
- Sum: 99.0434

Wollastonite (Diopside): 0.342322
Enstatite (Diopside): 5.22457E-2
Ferrosilite (Diopside): 0.320136
Enstatite (Hypersthene): 0.246608
Ferrosilite (Hypersthene): 1.5111

*NORMATIVE RATIOS - CIPW*

- OR:AB:AN = 37.1835 62.8165 0
- Q:OR:AB = 32.9432 24.934 42.1228
- Q:OR:AB&AN = 32.9432 24.934 42.1228

NORMATIVE PLAGIOCLASE CONTENT = AN O
NORMATIVE COLOR INDEX = 2.56547

*PETROCHEMICAL INDICES*

- Alkaline Index: 42.3414
- Felsic Index: 97.754
- Mafic Index: 95.3465
- Solidification Index: 1.03775
- Differentiation Index: 91.7153
- Crystallization Index: 0.285527
- Weathering Index (Parker, 1970): 82.2913
- Alteration Index (Ishikawa, 1976): 42.1331
- Peraluminous Index: -13.1624
SAMPLE NUMBER 31

SiO2 64.2  Al2O3 16.1  Fe2O3 5.72  FeO 0
MgO 2.02  CaO 4.39  Na2O 3.61  K2O 2.73
TiO2 .11  P2O5 .35  MNO .084
MODIFIED Fe2O3 = 1.61
MODIFIED FeO = 3.69818
SUM OF OXIDES 98.9022

*NORMATIVE MINERALS*
Quartz  18.8516
Corundum  6.21714E-2
Orthoclase  16.1319
Albite  30.5446
Anorthite  19.4934
Hypersthene  10.4657
Magnetite  2.33439
Ilmenite  .208917
Apatite  .810445
SUM 98.9032

Enstatite (Hypersthene)  5.03071
Ferrosilite (Hypersthene)  5.43501

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 24.3795 46.1609 29.4596
Q:OR:AB 28.7687 24.6183 46.613
Q:OR:AB&AN 22.1727 18.9739 58.8534
NORMATIVE PLAGIOCLASE CONTENT = AN 38.9572
NORMATIVE COLOR INDEX = 13.009

*PETROCHEMICAL INDICES*
Alkaline index 43.0599
Felsic index 59.0867
Mafic index 72.4352
Solidification index 14.9554
Differentiation index 65.5281
Crystallization index 23.0191
Weathering index (Parker, 1970) 73.1969
Alteration index (Ishikawa et al, 1976) 37.2549
Peraluminous index -4.81394
SAMPLE NUMBER 41

SiO₂ 80.1  Al₂O₃ 10.2  Fe₂O₃ 1.66  FeO 0
MgO 0.2  CaO 0.12  Na₂O 3.68  K₂O 3.69
TiO₂ 0.012  P₂O₅ 0.095  MnO 0.014
MODIFIED Fe₂O₃ = 1.512
MODIFIED FeO = 0.13317
SUM OF OXIDES 99.5762

*NORMATIVE MINERALS*
ROCK CONTAINS EXCESS P₂O₅ OVER CaO 3.79182E-3
QUARTZ 44.5463
CORUNDUM 0.152253
ORTHOCLASE 21.8047
ALBITE 31.1369
HYPERSTHENE 0.049809
MAGNETITE 0.440068
HEMATITE 1.20849
ILMENITE 0.022791
APATITE 0.703288
SUM 100.065

ENSTATITE (HYPERSTHENE) 0.049809

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 41.1863 58.8137 0
Q:OR:AB 45.6942 22.3665 31.9392
Q:OR:AB&AN 45.6942 22.3665 31.9392
NORMATIVE PLAGIOCLASE CONTENT = AN 0
NORMATIVE COLOR INDEX = 1.72116

*PETROCHEMICAL INDICES*
ALKALI INDEX 50.0678
FELSPIC INDEX 98.3979
MAPIC INDEX 98.7989
SOLIDIFICATION INDEX .225132
DIFFERENTIATION INDEX 97.4879
CRYSTALLIZATION INDEX 3.4908E-2
WEATHERING INDEX (PARKER, 1970) 65.6074
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 49.4008
PERALUMINOUS INDEX -.646282
SAMPLE NUMBER 46

SI02 76  AL203 10.8  FE2O3 2.12  FEO 0
MGO  .25  CAO  .36  NA2O  4.93  K2O  3.89
TI02  .43  P2O5  .006  MNO.1
MODIFIED FE2O3 = 1.93
MODIFIED FEO = .170962
SUM OF OXIDES 98.867

*NORMATIVE MINERALS*
QUARTZ 33.9924
ORTHoclASE 22.9863
ALBITE 33.8926
ACMITE 5.58357
SODIUM METASILICATE .345075
DIOPSIDE 1.01475
HYPERSTHENE .152187
ILMENITE .574992
SPHENE .312256
APATITE 1.38933E-2
SUM 98.8682

WOLLASTONITE (DIOPSIDE) .544324
ENSTATITE (DIOPSIDE) .470426
ENSTATITE (HYPERSTHENE) .152187

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 40.4129 59.5871 0
Q:OR:AB 37.4071 25.2956 37.2973
Q:OR:AB&AN 37.4071 25.2956 37.2973
NORMATIVE PLAGIOCLASE CONTENT = AN 0
NORMATIVE COLOR INDEX = 1.74193

*PETROCHEMICAL INDICES*
ALKALI INDEX 44.1043
FELSIC INDEX 96.0784
MAFIC INDEX 89.3661
SOLIDIFICATION INDEX 2.27737
DIFFERENTIATION INDEX 90.8715
CRYSTALLIZATION INDEX 1.12137
WEATHERING INDEX (PARKER, 1970) 80.0687
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 43.9024
PERALUMINOUS INDEX -20.1394
SAMPLE NUMBER 66

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MODIFIED Fe₂O₃ = 1.98
MODIFIED FeO = 0.377916
SUM OF OXIDES 99.1959

*NORMATIVE MINERALS*

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<tr>
<td>Ilmenite</td>
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<td>Apatite</td>
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SUM 99.1975

Wollastonite (Diopside) 0.374617
Enstatite (Diopside) 0.323758

*NORMATIVE RATIOS - CIPW*

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NORMATIVE PLAGIOCLASE CONTENT = AN 0
NORMATIVE COLOR INDEX = 2.04664

*NITROCHEMICAL INDICES*

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SAMPLE NUMBER 72

SiO2 76.9  Al2O3 11.2  Fe2O3 1.86  FeO 0
MgO .05  CaO .14  Na2O 4.58  K2O 3.97
TiO2 .15  P2O5 .006  MnO .01
Modified Fe2O3 = 1.65
Modified FeO = .188958
Sum of Oxides 98.845

*Normative Minerals*
- Quartz 35.5982
- Orthoclase 23.4592
- Albite 35.5046
- Acmite 2.86073
- Wollastonite 1.29551
- Diopside 0.268606
- Magnetite 0.206884
- Hematite 0.518486
- Ilmenite 0.284887
- Apatite 1.38933E-2
Sum 98.8451

Wollastonite (Diopside) 0.144083
Enstatite (Diopside) 0.124522

*Normative Ratios - CIPW*
- Or:Ab:An 39.7858 60.2142 0
- Q:Or:Ab 37.6453 24.8083 37.5464
- Q:Or:Ab&An 37.6453 24.8083 37.5464
- Normative Plagioclase Content = An 0
- Normative Color Index = 1.27886

* Petrochemical Indices *
- Alkaline Index 46.4327
- Felsic Index 98.389
- Mafic Index 97.353
- Solidification Index .486683
- Differentiation Index 94.5621
- Crystallization Index .268595
- Weathering Index (Parker, 1970) 76.4117
- Alteration Index (Ishikawa et al., 1976) 45.9954
- Peraluminous Index -7.90974
SAMPLE NUMBER 76

SiO₂ 76.8  Al₂O₃ 10.4  Fe₂O₃ 1.76  FeO 0
MgO .03  CaO .31  Na₂O 4.76  K₂O 3.89
TiO₂ .12  P₂O₅ .008  MnO .034
MODIFIED Fe₂O₃ = 1.62
MODIFIED FeO = .125972
SUM OF OXIDES 98.098

*NORMATIVE MINERALS*
QUARTZ 36.826
ORTHOCRASS 22.9865
ALBITE 31.8353
ACMITE 4.68673
SODIUM METASILICATE .726092
WOLLASTONITE .448986
DIOPSIDE .342434
ILMENITE .22791
APATITE 1.85244E-2
SUM 98.0984

WOLLASTONITE (DIOPSIDE) .171324
ENSTATITE (DIOPSIDE) 7.47135E-2
FERROSILITE (DIOPSIDE) 9.63966E-2

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 41.9295 58.0705 0
Q:OR:AB 40.1821 25.0814 34.7366
Q:OR:AB&AN 40.1821 25.0814 34.7366
NORMATIVE PLAGIOCLASE CONTENT = AN 0
NORMATIVE COLOR INDEX = .570344

*PETROCHEMICAL INDICES*
ALKALI INDEX 44.9711
FELSIC INDEX 96.5402
MAFIC INDEX 98.3108
SOLIDIFICATION INDEX .292294
DIFFERENTIATION INDEX 91.6477
CRYSTALLIZATION INDEX .161157
WEATHERING INDEX (PARKER, 1970) 77.7687
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 43.604
PERALUMINOUS INDEX -21.197
SAMPLE NUMBER 79

SI02 77.6  AL203 10.8  FE203 1.67  FEO 0  
MGO .07  CAO .38  NA20 4.38  K20 3.73  
TI02 .13  P205 .008  MNO .024  
MODIFIED FE203 = 1.63  
MODIFIED FEO = .035992  
SUM OF OXIDES 98.788

*NORMATIVE MINERALS*
QUARTZ 37.8732  
ORTHOCLASE 22.0411  
ALBITE 34.7834  
ACMITE 2.00535  
WOLLASTONITE .472077  
DIOPSIDE .376048  
HEMATITE .936839  
ILMENITE .127336  
SPHENE .154454  
APATITE 1.85244E-2  
SUM 98.7883

WOLLASTONITE (DIOPSIDE) .201717  
ENSTATITE (DIOPSIDE) .174331

*NORMATIVE RATIOS - CIPW*
OR:AB:AN 38.788 61.212 0  
Q:OR:AB 39.9939 23.2752 36.731  
Q:OR:AB&AN 39.9939 23.2752 36.731  
NORMATIVE PLAGIOCLASE CONTENT = AN 0  
NORMATIVE COLOR INDEX = 1.44024

*PETROCHEMICAL INDICES*
ALKALI INDEX 45.9926  
FELSIC INDEX 96.252  
MAFIC INDEX 95.252  
SOLIDIFICATION INDEX .722941  
CRYSTALLIZATION INDEX .376033  
WEATHERING INDEX (PARKER, 1970) 73.197  
ALTERATION INDEX (ISHIKAWA ET AL, 1976) 44.3925  
PERALUMINOUS INDEX -10.495
SAMPLE NUMBER 84

SiO₂ 76.8  Al₂O₃ 10.9  Fe₂O₃ 1.57  FeO 0  
MgO 0.05  CaO 0.36  Na₂O 4.15  K₂O 4.52  
TiO₂ 0.11  P₂O₅ 0.008  MnO 0.014  
SUM OF OXIDES 98.482

*NORMATIVE MINERALS*
- QUARTZ 35.883
- ORTHOCLEASE 26.7093
- ALBITE 30.8997
- ACMITE 3.71229
- WOLLASTONITE 0.442797
- DIOPSIDE 0.268606
- HEMATITE 0.986822
- ILMENITE 2.29498E-2
- SPHENE 0.231227
- APATITE 1.85244E-2
- SUM 98.4822

WOLLASTONITE (DIOPSIDE) 0.144083
ENSTATITE (DIOPSIDE) 0.124522

*NORMATIVE RATIOS - CIPW*
- OR:AB:AN 46.363 53.637 0
- Q:OR:AB 38.3808 28.5685 33.0506
- Q:OR:AB&AN 38.3808 28.5685 33.0506
- NORMATIVE PLAGIOCLASE CONTENT = AN 0
- NORMATIVE COLOR INDEX = 0.585376

*PETROCHEMICAL INDICES*
- ALKALI INDEX 52.1338
- FELSIC INDEX 96.0133
- MAFIC INDEX 96.9136
- SOLIDIFICATION INDEX 0.493453
- DIFFERENTIATION INDEX 93.492
- CRYSTALLIZATION INDEX 0.268595
- WEATHERING INDEX (PARKER, 1970) 77.812
- ALTERATION INDEX (ISHIKAWA ET AL, 1976) 50.3304
- PERALUMINOUS INDEX -13.5212
APPENDIX C

PLATE I. GEOLOGIC MAP OF INDIAN SPRING, WASHOE COUNTY, NEVADA

PLATE II. GEOLOGIC CROSS SECTIONS OF THE INDIAN SPRING AREA