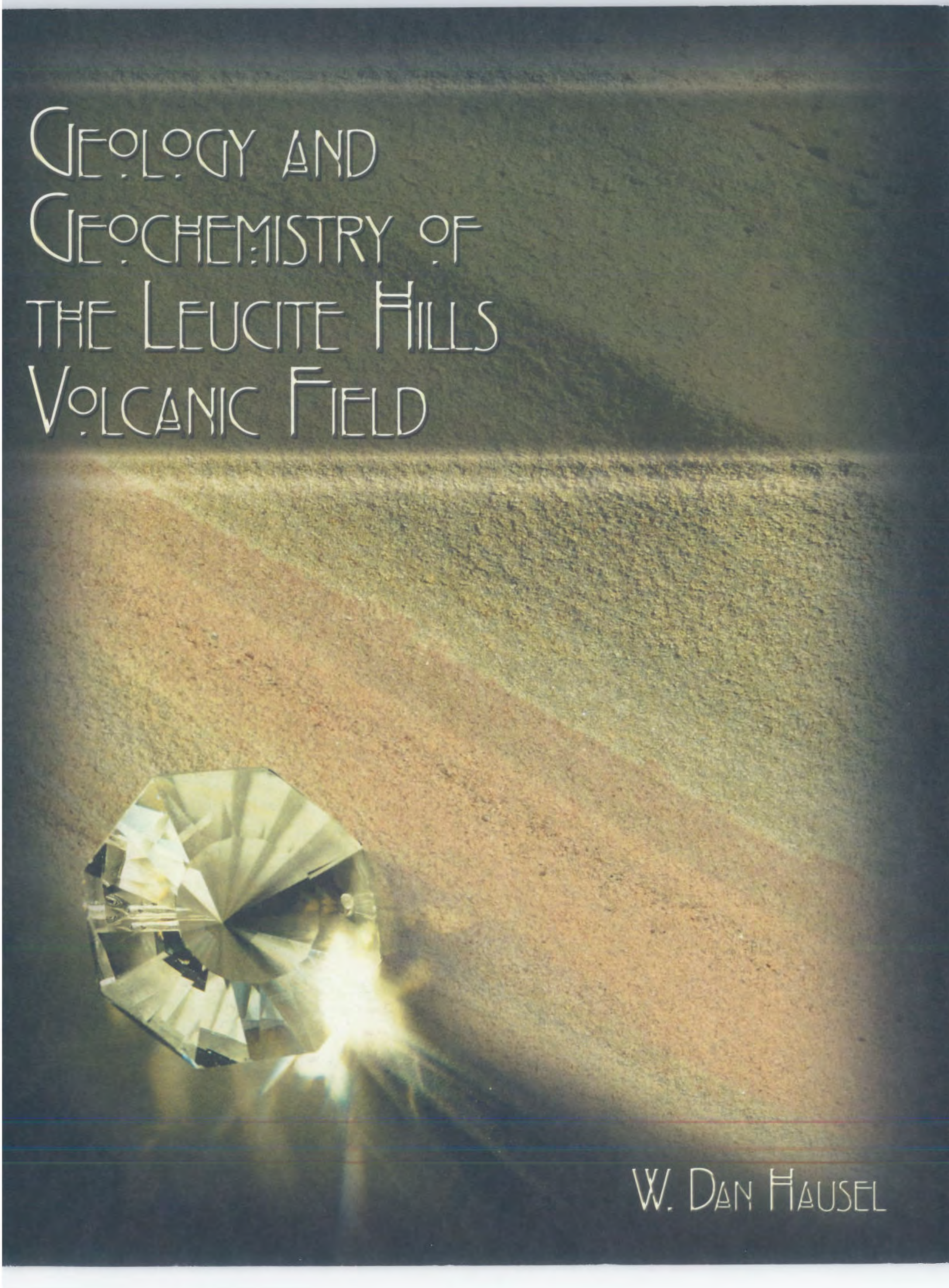
Geology and Geochemistry of the Leucite Hills Volcanic Field



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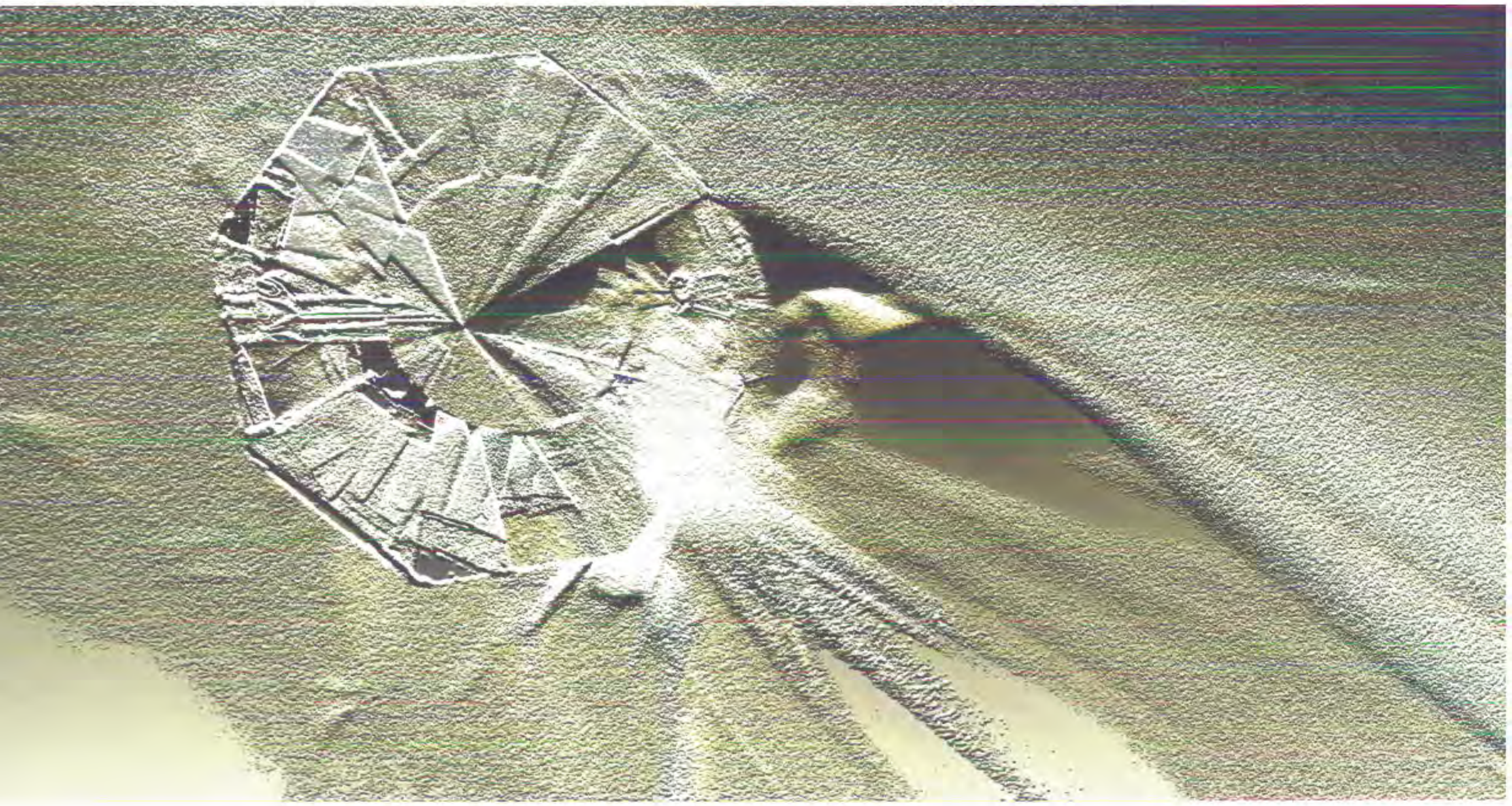

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W. Dan Hausel

TABLE OF CONTENTS

ABSTRACT

The Green River Basin of southwestern Wyoming encloses one of the largest lamproite fields in the world. This field, known as the Leucite Hills, contains some of the rarest rock types on the surface of the earth. These ultrapotassic, mafic volcanic rocks form a group of 22 flows, plugs, volcanic necks, and dikes located north of Rock Springs and Superior. For the most part, they form leucite-orthoclase phlogopite lamproites that range in age from approximately 1-3 million years old. Olivine is found in a few of the lamproites in the northeastern part of the field. The volcanic rocks include several classical volcanic features such as cinder cones, volcanic necks, flows, volcaniclastics, and basal rubble zones.

The Leucite Hills lamproites have been the subject of several research studies and are considered possible sources of potassium and decorative rock. Since 1967, these rocks have been considered similar to kimberlite, and are regarded as a possible source of diamond. Other lamproites have been identified in the United States at Kamas, Utah; Middle Park, Colorado; the Missouri Breaks of Montana; Hills Pond, Kansas; and Murfreesburo, Arkansas. Only those at Murfreesburo have been shown to contain diamonds.

5

INTRODUCTION

The Leucite Hills volcanic field lies north of Rock Springs and Superior in southwestern Wyoming (**Figure 1**). Although Interstate 80 runs a few miles south of the southernmost volcano in the Leucite Hills, a few of the lamproitic volcanoes are visible to the north from various points along the highway near Superior and Rock Springs.

This volcanic field consists of a group of ultrapotassic mafic volcanoes formed from lamproites, some of the rarest rock types on the surface of the earth. The Leucite Hills are one of the largest lamproite fields in the world.

Similar rocks are found in only a few other places, including Spain, India, Australia, and Antarctica. In the U.S., lamproites occur not only in Wyoming, but also in Montana, Utah, Kansas, Colorado, and Arkansas (Mitchell and Bergman, 1991; Hausel, 1995; Hausel, 1998a; Thompson and others, 1997). Lamproites have also been reported in California and South Carolina.

During the past two decades, the Wyoming State Geological Survey (WSGS) conducted limited-reconnaissance investigations in the Leucite Hills designed to investigate the potential for gemstones in the volcanic field. The investigations were initially stimulated by Carmichael's 1967 descriptions, which suggested that the Leucite Hills lamproites were similar to kimberlites in general and diamondiferous rocks at Murfreesburo, Arkansas in particular. A few years after Carmichael's discussion, diamonds were discovered in lamproites in the Ellendale field and at Argyle in Western Australia. Following these discoveries, the diamondiferous rocks at Murfreesburo, Arkansas and Majhawan, India were reappraised and reclassified as olivine lamproites (Mitchell and Bergman, 1991).

Samples collected by the WSGS from the Leucite Hills were used for petrologic studies and a few samples were also collected to test for diamond. Not enough material was collected for practical diamond testing. However, restrictions were necessary due to limitations of both the WSGS laboratory and project funding.

Brief reconnaissance excursions into the Kilpecker dune field were conducted along the northern margin of the Leucite Hills. This area is thought to have potential for hidden olivine lamproite. However, the dune field is too difficult to prospect by ground and is better suited for airborne geophysical surveys. The dunes cover an extensive shear zone which has been traced both west and east of the Leucite Hills (Gordon Marlatt, personal communication, 1999).

The accompanying map of the Leucite Hills (**Plate 1**) was compiled from previous mapping by Roehler (1977) and Odgen (1979) and supplemented by aerial photography interpretations and limited-reconnaissance field mapping by the author. During mapping, several faults were identified which control the positions of the volcanic orifices. This suggests that a search for hidden lamproites may prove effective if it focuses on these and other structures with similar orientations, and on fractures lying nearly perpendicular to the faults.

Lamproites are of potential economic interest because some are a source for diamonds, others have been mined for decorative rock, and a few have been mined for potassium, which is used as a fertilizer additive.

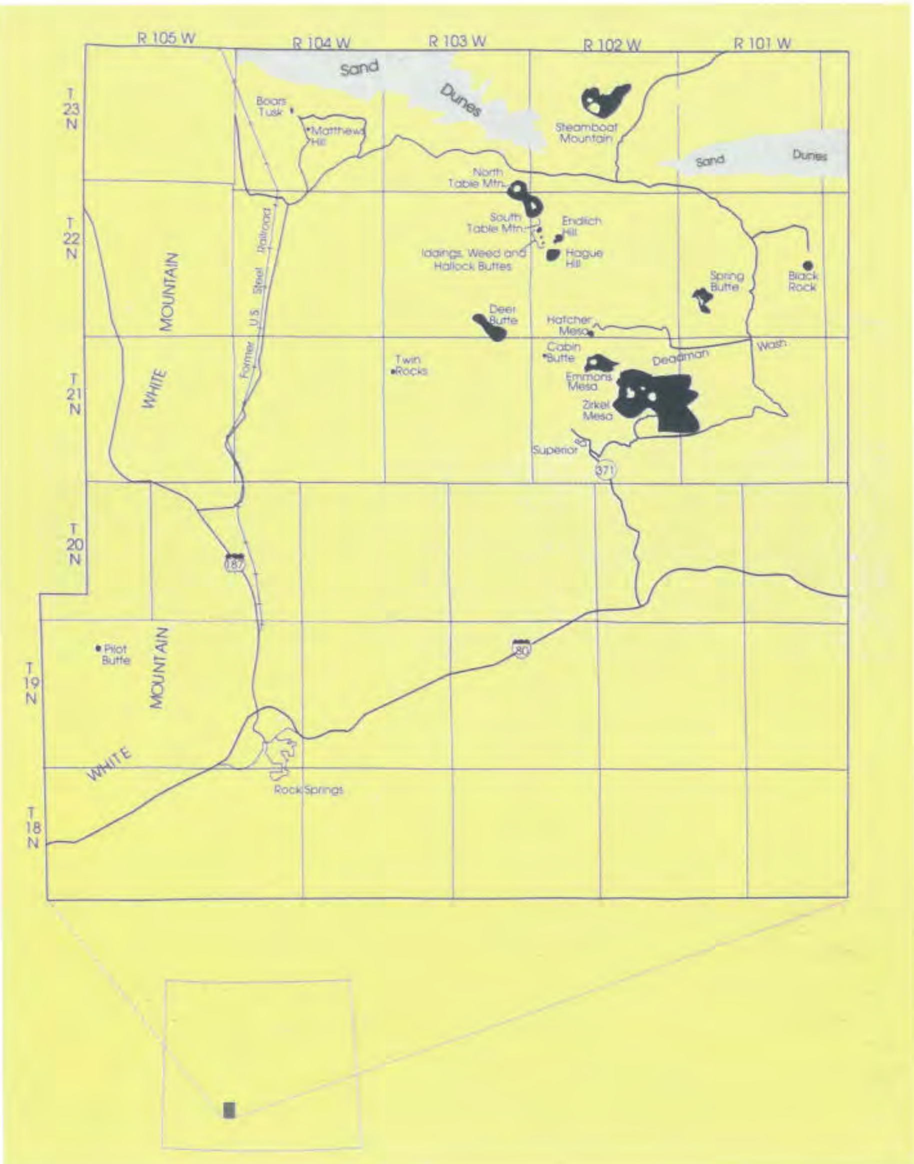


Figure 1. Index map of the Leucite Hills volcanic field, southeast Wyoming.

HISTORY OF INVESTIGATIONS

The volcanic rocks of the Leucite Hills were described by Samuel F. Emmons of the 40th Parallel Survey (1867-1873) (Emmons, 1877). Emmons explored the volcanic field in 1871 and provided samples to Professor Ferdinand Zirkel of the University of Leipzig in Germany for petrographic analysis. During these initial studies, Zirkel recognized leucite in several specimens. This may have been the first report of leucite-bearing rock in North America (Kemp and Knight, 1903).

Six years after Emmons' excursion into the Leucite Hills, F.M. Endlich of the Hayden Survey mapped the northern part of the Leucite Hills (Endlich, 1879). John Powell of the United States Geological Survey (USGS) visited the volcanic field at about the same time (between 1868 and 1875) and collected samples from Pilot Butte at the extreme western margin of the Leucite Hills (**Figure 2**). Powell's samples were examined by Whitman Cross of the USGS along with other samples collected by Cross in 1884.

Cross (1897) published a detailed petrographic study on the volcanic field and noted the presence of primary phlogopite phenocrysts. Cross also noted an unusual mineral, which in his words formed small, pale yellow amphibole prisms with "...optical characters...unlike any of which I can find on record." This rare amphibole was identified years later as potassium-titanium-richterite and is es-

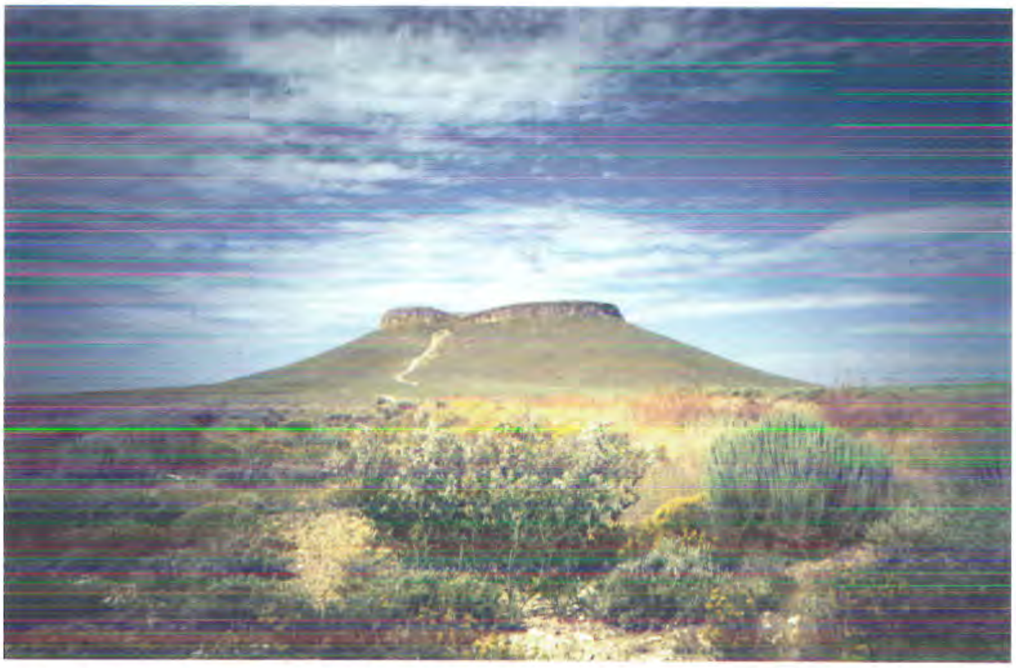


Figure 2. Pilot Butte lamproite flow. Note that near the center of Pilot Butte, a road leads to a v-cut in the lamproite. This is the topographic low of the butte such that both the east and west ends of the butte dip toward the center. This topographic low is interpreted as a fault.

sentially restricted to lamproite petrogenesis (Mitchell and Bergman, 1991). The petrographic and chemical studies by Cross (1897) resulted in the recognition of three new rock types that were called wyomingite, orendite, and madupite.

In 1896, J.F. Kemp visited the Leucite Hills and noted the presence of olivine in some of the lamproites (Kemp, 1897). In 1902, he teamed up with Wilbur C. Knight of the University of Wyoming and revisited the volcanic field (Kemp and Knight, 1903). In 1967, Carmichael (of the University of California–Berkeley) completed cursory petrographic studies of these rocks and recommended that a fourth rock type, which he called olivine orendite, be recognized based on the presence of olivine. During field reconnaissance in 1998, W.D. Hausel collected two anthills near Black Rock for olivine and recovered 13,000 carats of industrial and gem-quality olivine (peridot) (Hausel 1998b). This was the first known report of peridot in Wyoming.

Some additional mapping of the Leucite Hills occurred in the early part of the 20th century. Under the direction of Alfred Schultz, the USGS mapped the lamproites from 1907-1908 during a regional study of coal deposits of the Rock Springs uplift. Schultz and Cross (1912) later evaluated the volcanics as a potential source of potash. During World War I, a quarry was developed on Zirkel Mesa to mine lamproite for potash (**Figure 3**).

Geologic investigations were later completed by Smithson (1959) and Johnston (1959). Ogden (1979) completed the most detailed study of the physical geology and geochemistry of the Leucite Hills lamproites as part of a Ph.D. dissertation at the University of Wyoming. Ogden's research recognized many classical volcanic features associated with lamproites, including basal rubble zones, ropy lava, lava tubes, spines, dikes, cinder cones, plug domes, and lava rings (**Figure 4**).

In the 1960s, the petrogenesis of the Leucite Hills became a topic of interest due to the mantle signatures of the rocks. Yagi and Matsumoto (1966) discussed some possible petrogenic aspects of the Leucite Hills, while Carmichael (1967) examined the mineralogy and geochemistry establishing liquidus and solidus temperatures for the magmas. Powell and Bell (1970) later published a rubidium-strontium isotope age analysis of the rocks, which supported a mantle origin for the magmas. Sobolev and others (1975) studied fluid inclusions to determine the crystallization temperature of the wyomingites, while Barton (1976) and Barton and Hamilton (1978, 1979) completed high-pressure experimental studies on similar melts. Kuehner (1980) later completed his thesis on the genesis of the Leucite Hills lamproites, and indicated a mantle origin for these rare rocks.

In the early 1980s, the author initiated field reconnaissance in the Leucite Hills to study the region for diamond potential based on Carmichael's (1967) conclusion that there was a petrogenic link between kimberlite and the volcanics in the

Figure 3. Quarry on Zirkel Mesa in ultrapotassic scoria (top). View of two of the seven cinder cones on Zirkel Mesa from the quarry (bottom).

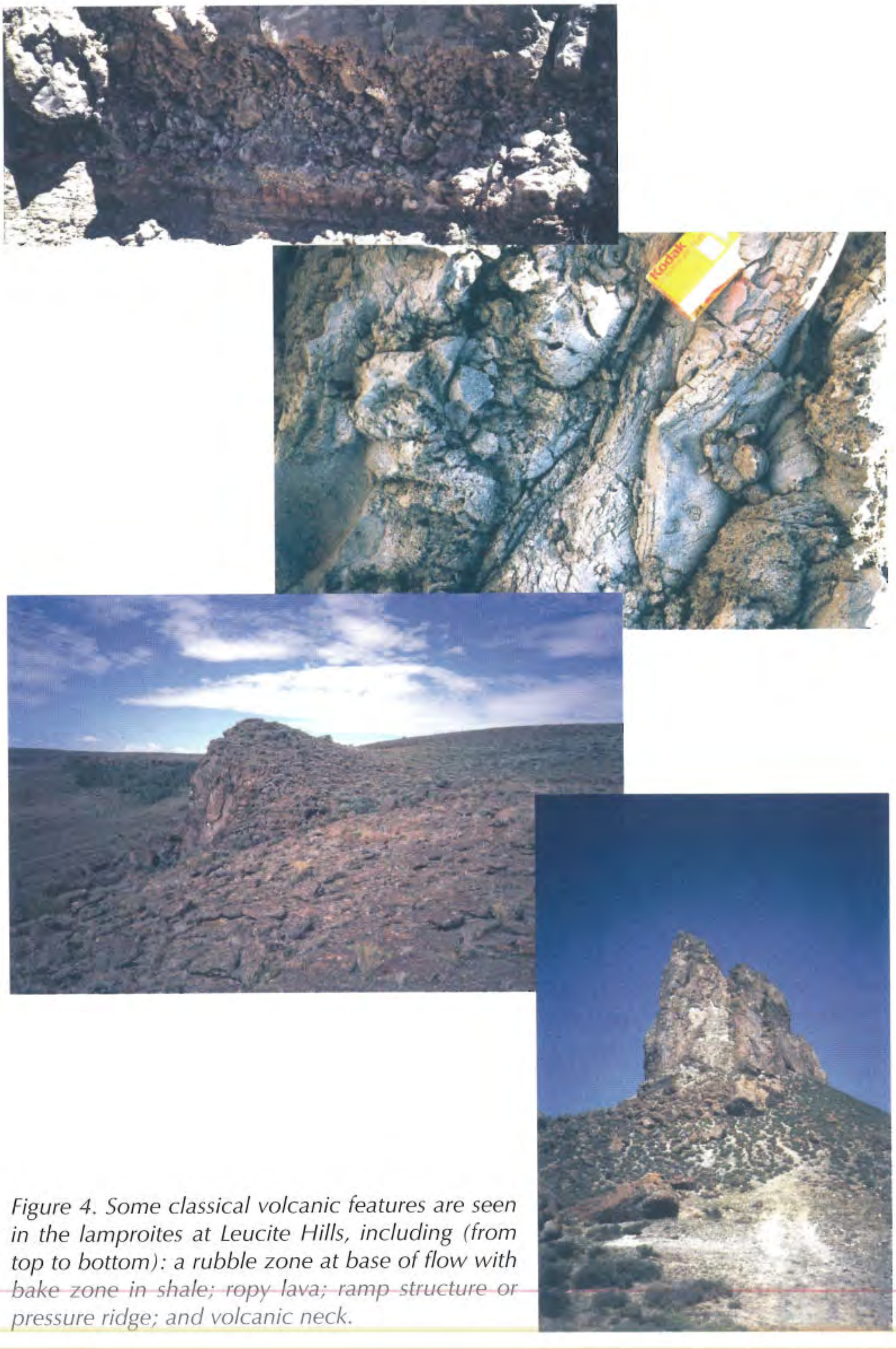


Figure 4. Some classical volcanic features are seen in the lamproites at Leucite Hills, including (from top to bottom): a rubble zone at base of flow with bake zone in shale; ropy lava; ramp structure or pressure ridge; and volcanic neck.

Leucite Hills. However, the apparent high temperature of the lamproite flows caused concern about whether diamonds could survive in such hot magmas. For this reason, a test was conducted to determine the probability of diamond surviving in hot magma. A small (approximately 0.1 carat) industrial diamond burned completely to carbon dioxide and carbon in an oxidizing Bunsen burner flame within a few minutes.

Therefore, it was assumed that the likelihood of finding preserved and non-resorbed diamonds that erupted in hot ultrapotassic lavas in an oxidizing atmosphere is dramatically diminished where temperatures remained hot for a significant time after the eruption. Accordingly, it was thought that possible diamond targets were limited to volcaniclastics, tuffs, and other phases that potentially cooled more quickly after eruption into the oxidizing atmosphere. Shortly after this experiment, it was reported that diamonds had been discovered in similar rocks in northern Australia.

The Australian diamonds were primarily found in olivine lamproites. Current thinking indicates that olivine lamproites are the most likely lamproite sources of diamond because they are interpreted to be relatively reduced magmas that may have cooled rapidly due to serpentinization. Because of serpentinization, these rocks generally erode more rapidly than the phlogopite-leucite lavas, and most probably lie hidden under thin layers of soil (**Figure 5**).

A small bulk sample of volcaniclastics from Endlich Hill was collected by Union Pacific Resources and transported to the WSGS for testing. No diamonds were found, but the test was considered insufficient (Hausel and others, 1992, 1994). The highest priority targets in the Leucite Hills are considered to be potentially hidden olivine lamproites.

Figure 5. Mount North (Ellendale Field, Kimberley Province, Australia) in the background with a termite mound in the foreground (top). Phlogopite-leucite lamproites like this one typically form distinctive positive hills (geochemically, many lamproites of the Kimberley Province are similar to those of the Leucite Hills, although the compositional range of the Leucite Hills lamproites is not as great). The diamondiferous olivine lamproites, typically formed of softer and more easily eroded material, lie hidden in the center of the lamproite field (bottom), such as the Ellendale 9 lamproite exposed in a bulldozer cut.

LAMPROITES

The term lamproite was introduced by Niggli (1923) for a clan of unusual leucite-bearing rocks known to occur only in Wyoming and Spain. Lamproites were later found elsewhere in the world, and are now known in more than 25 provinces or fields (Mitchell and Bergman, 1991). Interest in these rocks has intensified since the discovery of a world-class diamond deposit in olivine lamproite at Argyle, Western Australia. This single deposit generated as much as 30% of the world's annual diamond production over a period of several years. With additional exploration and research, other lamproites will undoubtedly be found. Of the known varieties of lamproite, olivine lamproite offers the best potential for discovery of significant diamond mineralization (Atkinson, 1989).

Geochemistry

Lamproites are extremely rare igneous rocks and have geochemical signatures similar to those of kimberlite. These similarities have resulted in some lamproites being misidentified as kimberlite. Kimberlites and lamproites are distinctly different rock types, even though there is some overlap in chemical composition between micaceous kimberlites and some lamproites (Helmstaedt, 1993).

In general, lamproites are mafic, peralkaline, ultrapotassic igneous rocks enriched in the trace elements Zr, Nb, Sr, Ba, and Rb relative to kimberlite (Kirkley and others, 1991). Although some are quartz normative, lamproites are generally silica-poor. Compared to other mafic alkaline igneous rocks, they are distinguished by high weight percents of K_2O (3-13%), TiO_2 (1-7%), P_2O_5, MgO, and F, and low weight percents of Al_2O_3 (<12%), CaO (<13%), and CO_2 (<1%). Lamproites exhibit molar $K_2O/Na_2O>5$ (ultrapotassic); molar $K_2O/Al_2O_3>6.8$ (commonly >1; perpotassic); and molar $K_2O + Na_2O/Al_2O_3>1$ (peralkaline). Lamproites are typically enriched in light rare earth elements (LREE), in incompatible elements such as Ba (>5000 ppm), Rb (>150 ppm), Sr (>1000 ppm), Zr (>500 ppm), La (>200 ppm), and in compatible elements such as Cr and Ni (Kirkley and others, 1991; Scott-Smith, 1996).

Based on chemistry, lamproites have elevated compatible Ni, Cr, Co, V, Sc, and elevated incompatible Rb, Sr, Ba, Zr, Hr, Ti, P, Nb, LREE, Y, Th, and U compared to average crustal rocks. Seemingly paradoxical, these rocks have silica contents that range from ultrabasic to intermediate in composition and are enriched in K, Rb, and Ba, elements normally concentrated in crustal-derived igneous rocks. Ni and Cr, which are depleted in crustal igneous rocks, typically occur in high average abundances in lamproite and other mantle-derived rocks (Scott-Smith and Skinner, 1982).

Mineralogically, lamproites may contain diopside, phlogopite, K-Ti-richterite, leucite, sanidine, wadeite, priderite, and/or olivine, with minor apatite, perovskite, ilmenite, and spinel (Mitchell and Bergman, 1991). The typical 'kimberlitic indicator' minerals (pyrope garnet, chromian diopside, and picroilmenite) are rare to absent in lamproite.

Scott-Smith (1996) subdivided lamproites into two general groups: (1) phlogopite-leucite-lamproites; and (2) olivine-lamproites. Olivine lamproites were defined to have >20% MgO, <45% SiO_2, and 7% K_2O, and abundant serpentine pseudomorphs after olivine. It should be noted that the olivine orendites described by Carmichael (1967) from the Leucite Hills contain higher SiO_2 (51-53.5%), lower MgO (9-11.2%), and higher K_2O (8-11.5%) than the olivine lamproites defined by Scott-Smith (1996). These rocks also lack serpentinization.

In the past, researchers provided local geographic names for lamproites. In Wyoming, Cross (1897) introduced three rock types for the Leucite Hills volcanics and Carmichael (1967) proposed a fourth type years later for the olivine-bearing flows at South Table Mountain and North Table Mountain (olivine also occurs at Wortman dike, Endlich Hill, and Black Rock). This system of using local names resulted in lamproites of similar chemistry and mineralogy from different parts of the world receiving more than one name. For example, wyomingites from the Leucite Hills are equivalent to fitzroyites in Western Australia. For this reason, Mitchell and Bergman (1991) suggested that lamproite nomenclature be modernized using descriptive mineralogical classifications to eliminate confusion generated by the type-locality nomenclature (**Table 1**).

Unfortunately, the type-locality nomenclature is so ingrained in the literature that it will take time to replace. In some cases, it is useful to refer to type-locality names in the Leucite Hills. Therefore, both type locality and mineralogical names are used interchangeably in the following discussions.

Wyoming lamproites

Geochemistry

Wyoming lamproites are ultrapotassic, basic to ultrabasic, volcanic and subvolcanic rocks with the following geochemical variations: SiO_2 (42.65-56.34%), K_2O (2.52-12.66%), and MgO (5.8-12.75%). They are enriched in the trace elements Rb, Ba, Sr, Nb, Zr, and P (Carmichael, 1967) and generally exhibit extreme enrichment of LREE, K, Zr, Sr and Ba (Kuehner, 1980; Ogden, 1979). They are also fairly enriched in Ni, Cr, and Sc (Vollmer and others, 1984) and form a bimodal suite with respect to silica resulting in a petrographic division into madupitic and wyomingite-orendite lamproites (Mitchell and Bergman, 1991).

The madupitic lamproites are low in silica, slightly peraluminous ($K_2O + Na_2O \leq Al_2O_3$), and found primarily as hypabyssal plugs and dikes at Pilot Butte, Middle Table Mountain, and Twin Rocks (locally known as Badger's Teeth). Geochemically, the madupitic lavas have lower SiO_2,

Table 1. Historical lamproite nomenclature and mineralogy.

Historical name	Mineralogical description
Wyomingite	Diopside-leucite-phlogopite lamproite
Orendite	Diopside-sanidine-phlogopite lamproite
Olivine orendite	Olivine-diopside-sanidine-phlogopite lamproite
Madupite	Diopside-madupitic lamproite
Cedricite	Diopside-leucite lamproite
Mamilite	Leucite-richterite lamproite
Wolgidite	Diopside-leucite-richterite madupitic lamproite
Fitzroyite	Leucite-phlogopite lamproite
Verite	Hyalo-olivine-diopside-phlogopite lamproite
Jumillite	Olivine-diopside-richterite madupitic lamproite
Fortunite	Hyalo-enstatite-phlogopite lamproite
Cancalite	Enstatite-sanidine-phlogopite lamproite
Gaussbergite	Olivine-diopside-leucite lamproite

Al_2O_3, and K_2O and higher MgO, CaO, and Fe relative to wyomingite and orendite.

The wyomingite-orendite lamproites have whole rock compositions that are indistinguishable and overlap (some overlap also occurs between madupite and wyomingite), and wyomingite often forms chilled margins in orenditic lavas (Vollmer and others, 1984). This led Ogden (1979) to suggest that the mineralogical differences in these rocks was due to the cooling rate of the respective flows rather than the SiO_2 content. For instance, sanidine (in orendite) is favored over leucite (in wyomingite) when the cooling rate is relatively fast, or is a function of local differences in PH_2O (sanidine is more stable in higher PH_2O). Kuehner and others (1981) suggested that many of the differences could instead result from depth of crystallization.

Similar chemical analyses between different rock types imply a similar petrogenic history for the rocks. In addition, the mode of emplacement and geographic distribution of the rocks also support similar petrogenetic histories.

Madupites are enriched in Ba, Sr, Th, LREE, have a higher La/Yb ratio, and are depleted in Ni with a lower K/Rb ratio than wyomingite and orendite. Higher LREE abundance coupled with a lower Ni concentration confirms that madupite cannot be parental to wyomingite and orendite. Conversely, the madupitic lamproites may be derivatives of wyomingite and orendite (Mitchell and Bergman, 1991). However, Ogden (1979) reported that the variation in bulk chemistry of the lamproites showed a linear range in major element composition from most to least silicic rocks. This linear range suggests that all of the lavas may be petrogenically related.

It is evident that individual vents in the Leucite Hills differ only slightly in overall composition. These differences possibly reflect minor magma differentiation and/or small changes in the source composition along with the degree of melting. Wyomingite and orendite from South Table Mountain are more MgO-rich by virtue of the presence of phenocrystal and xenocrystal olivine. Madupitic lamproite from Pilot Butte and Middle Table Mountain differ in composition but are both SiO_2-poor and MgO-rich compared to other lamproites in the field. Lamproites from Middle Table Mountain are richer in SiO_2 than are those from Pilot Butte. As a result, the Middle Table Mountain lamproites contain more groundmass leucite, diopside, and wadeite.

Olivine orendites have more MgO than orendite and wyomingite. Orendites tend to have more SiO_2 and less CaO than wyomingite and olivine orendite (Kuehner, 1980). Wyomingite and orendite are peralkaline ($K_2O + Na_2O < Al_2O_3$) with high K_2O/Na_2O (>8) (Ogden, 1979; Mitchell and Bergman, 1991).

Lavas from Steamboat Mountain are thought to be the most potassic volcanic rocks in the world (Carmichael, 1967; Ogden, 1978). Overall, the K_2O content of lavas in the Leucite Hills varies from a low of 2.52% at Pilot Butte to a high of 12.66% at Steamboat Mountain (**Appendix 2**).

Lamproites in the Leucite Hills do not exhibit as great a compositional range as lamproites in the Kimberley Province of Western Australia. The Wyoming lamproites are notably poorer in TiO_2 than the Australian lamproites. They form a bimodal suite with respect to silica and include madupitic lavas low in silica as well as the relatively higher-silica, perpotassic hyalo-phlogopite lamproite lavas (Mitchell and Bergman, 1991).

As a group, lamproites are mineralogically characterized by Ti-phlogopite, Ti-K-richterite (amphibole), Ti-tetraferriphlogopite, Na- and Al-deficient leucite, Fe-rich sanidine, Al-poor diopside, K-Ba-titanates (priderite and jeppeite), and K-Zr- or Ti-silicates (wadeite, davanite, and shcherbakovite) (Mitchell and Bergman, 1991).

Geology and structure

The Leucite Hills volcanic field consists of 22 known lamproite flows, dikes, necks, plugs, cinder cones, and pumice cones. Radiometric dating indicates volcanic activity commenced approximately 3.1 Ma (million years ago) and continued until approximately 1.1 to 0.9 Ma (Bradley, 1964; McDowell, 1966, 1971). A timeline of volcanic activity shows a progression of eruptions beginning in the northwest and continuing to the southeast. Even though none of the volcanoes in the field are currently active, the range of ages and the amount of time between each eruption indicate future eruptions could occur to the southeast.

The volcanic field and the Greater Green River Basin overlie the Wyoming Province, which is an Archean craton stabilized between 3.2 Giga-annum (Ga) and 2.5 Ga (Peterman, 1979). Eggler and others (1988) more specifically suggest cratonization occurred at approximately 2.7 Ga. The Wyoming craton includes a thick, cool, Archean lithospheric mantle keel. Eggler and others (1988) and Eggler and Furlong (1991) suggest that this mantle keel has been preserved under the Leucite Hills throughout geologic time, supporting the idea that this region may have potential for diamonds.

A positive Bouguer gravity anomaly associated with the Rock Springs uplift was interpreted by Vollmer and others (1984) to be due to dense, lower crustal material lying beneath the uplift, or possibly to a mantle salient. Mitchell and Bergman (1991) reported that the Leucite Hills lies within an area of intense gravity low (-100 to -150 milligal), and noted that all North American lamproites occur in areas with regional negative magnetic anomalies with slight to intense regional gravity lows.

Other lamproites in the Wyoming craton have also been identified in the Missouri Breaks in western Montana and in the Kamas area of Utah (Mitchell and Bergman, 1991; Hausel, 1998b). These all erupted long after termination of Laramide deformation and during a period or orogenic relaxation (Mitchell and Bergman, 1991).

The Leucite Hills lamproites lie along the northern flank of the Rock Springs uplift, a doubly plunging asymmetrical anticline Late Cretaceous to Paleocene in age. Rock exposures in the anticline include the Cretaceous Baxter Shale in the core of the anticline, which is flanked by progressively younger Cretaceous rocks; the youngest exposed Cretaceous sedimentary unit in the map area is the Lance Formation (**Plate 1**). The Cretaceous rocks are unconformably overlain by Tertiary-age rocks of the Fort Union and Wasatch Formations, and intruded by volcanic rocks of the Leucite Hills, which erupted through the Cretaceous and Tertiary units.

The age of deformation, which affected the Rock Springs uplift, is based on an unconformity at the top of the Lance Formation. Curry (1973) suggested the principal deformation of the uplift occurred between the deposition of the late Cretaceous Lance Formation and the deposition of the early Paleocene Fort Union Formation. Basement involvement in the uplift is indicated by a gravity anomaly centered on the uplift.

Lamproites have deep-seated origin, similar to that of kimberlite, and originate within the upper mantle requiring deep-seated fractures to provide conduits to the earth's surface. Mitchell and Bergman (1991) suggested that the Leucite Hills were located along the continental extension of the east-trending Mendicino Transform Fault.

According to Ogden (1979), the distribution of cinder cones and associated flows in the Leucite Hills was controlled by a northwest-trending fissure zone. This is probably the Farson lineament described by Blackstone (1972). The lamproite dikes are predominantly oriented to the northwest (N40°W), parallel to this lineament.

During mapping, the author identified several east-northeast-trending fault zones and fractures that project into the majority of the eruptive centers. These may have been controlled and possibly represent a surface expression of the Mendicino Transform Fault. Based on the style of volcanism, these fractures are interpreted to originate at depth. These potentially intersect the Farson lineament and may provide foci for the eruptions. Another major lineament lies along the northern edge of the Leucite Hills and trends east-west, essentially parallel to controlling fractures. This is a relatively young lineament and continues to the west from the Leucite Hills into the Overthrust Belt and east to the Laramie Range (Gordon Marlatt, personal communication, 1998).

Volcanic Morphology

The volcanic centers in the Leucite Hills include vesicular lavas, scoria, autolithic intrusive breccias, lapilli tuffs, tuff breccias, and agglomerates. Although vents have been found associated with most flows, vent facies breccias are inconspicuous at South Table Mountain, North Table Mountain, Black Rock, and Hatcher Mesa (Coopersmith and others, 2003). Either these vents were removed by erosion, or most likely, the vents were buried by later flows (Ogden, 1979).

Individual flows are limited in extent and vary from 48 to 68 feet thick to as thin as 8 inches locally. One flow on the northwest margin of South Table Mountain was ponded at the time of eruption and resulted in a 122-foot-thick flow (Ogden, 1979).

Many of the flows are simple flows with basal autobreccia rubble zones overlain by dense, nonvesicular, platy lavas characterized by a well-developed flow layering accented by abundant mica phenocrysts (**Figure 6**). These platy zones grade upward into massive lava that has a marked increase in vesiculation and common orthogonal cooling joints with flow layering. Much of the layering is due to contrasting layers of vesicular and nonvesicular rock, light and dark lavas, and alternating layers of contrasting mineralogy (Ogden, 1979). The alternating centimeter scale bands of vesicle-rich sanidine-phlogopite-lamproite and vesicle-poor leucite-phlogopite-lamproite may result from different water contents of the magmas. A slight difference in volatile content may also explain contrasting stability of sanidine and leucite at atmospheric pressure (Mitchell and Bergman, 1991).

Flow tops are scoraceous and squeeze-up spines protrude above preserved flows. Concentric flow ridges have been recognized at some localities (Ogden, 1979). Vesicular lavas, scoria, autolithic intrusive breccias, lapilli tuffs, tuff breccias, and agglomerates have been mapped in the field. The bulk of the material comprising the 14 cinder cones in the Leucite Hills consists of highly vesicular blocks of scoria.

Ogden (1979) suggested that as much as 50% of the original flows were removed by erosion during the past 1 to 3 million years. Explaining the removal of such a massive amount of rock in such a short geologic time span is difficult, especially since no active streams currently exist in the volcanic field.

Crater facies volcanics include pyroclastic eruptions associated with cinder cones, volcanic necks, and vents (**Figure 7**). The cinder cones are composed of highly vesicular cinders (lapilli), ribbon bombs, spindel bombs, and welded blocks of lamproite scoria. Most of the cinder cones erupted after massive vesicular lava flows, although a few erupted at the same time as the flows (Emmons Mesa, Deer Butte, and Spring Butte). Evidence for vents at Steamboat and Black Rock consists of cylindrical reentrants exposed in the walls of eroded mesas. Pyroclastic debris (cinders and ribbon bombs) line the reentrants (Ogden, 1979).

Other crater facies lithologies include tuff breccias, lapilli tuffs, and agglomeratic rocks found at Matthews Hill, Boar's Tusk, Twin Rocks, and Iddings, Weed, and Hallock Buttes. These fragmental rocks contain a wide range of xenoliths: some are composed almost entirely of cognate, comagmatic fragmental clasts in a tuffaceous matrix. At Iddings, Weed, and Hallock Buttes, massive nonvesicular phlogopite-leucite-diopside-lamproite intrudes marginal tuffaceous rocks. These consist of autobrecciated vesicular pyroclasts, country rock xenoliths, and scoria set in a lamproite tuff matrix. At Twin Rocks, exposures consist mostly of autobrecciated lamproite with very minor amounts of massive, dense lava restricted in the core. At Boar's Tusk, vesicular to dense autobreccia lavas form portions of xenolithic tuff breccias and lapilli tuffs that have lithologies similar to those of the West Hill tuff at Crater of Diamonds (Prairie Creek) Arkansas, Calwynyardah (West Kimberley) Australia, and Cerro de Monagrillo (Murcia-Almeria) Spain. However, the Leucite Hills tuffs lack the abundant quartz grains derived from disaggregated country rock seen in many West Kimberley, Argyle, and Prairie Creek crater facies lithologies (Mitchell and Bergmann, 1991).

Hypabyssal facies lamproites are dominantly massive, dense, holocrystalline rocks formed by the crystallization of intrusive lamproite magma. These are found in volcanic necks and dikes in the Leucite Hills. Dikes in the Leucite Hills are

Figure 6. Flow layering is visible to the left of geologist Jay Roberts at Zirkel Mesa.

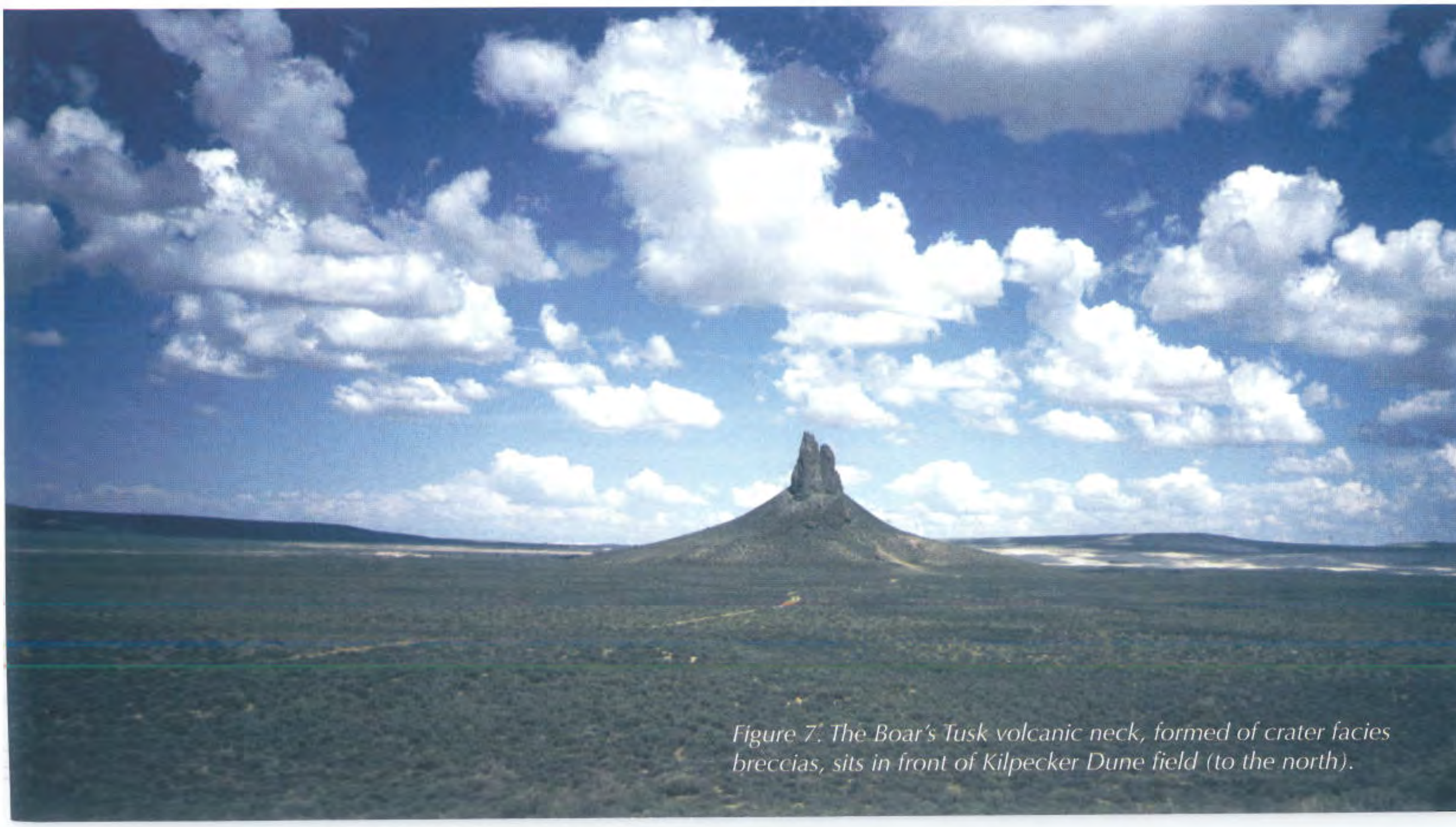


Figure 7. The Boar's Tusk volcanic neck, formed of crater facies breccias, sits in front of Kilpecker Dune field (to the north).

typically less than 150 feet long; however, Wortman dike is approximately 650 feet long. Ogden (1979) found that the widest dikes (25-35 feet wide) exhibit breccia zones with rounded lava and sedimentary rock fragments in a volcanic matrix.

Mineralogy and Petrology

Mitchell and Bergman (1991) stated: "The mineralogy of the lamproite clan is perhaps one of the most exotic of all alkaline rocks. The perpotassic and peralkaline traits of the magmas lead to a distinctive mineral assemblage that is virtually unparalleled."

The Leucite Hills may represent the best type locality for lamproites in the world (Mitchell and Bergman, 1991). The four rock types found in the field include: (1) madupite, a diopside-rich glassy volcanic rock with poikilitic phlogopite phenocrysts enclosing diopside in a groundmass of leucite, diopside, apatite, and glass; (2) wyomingite, an ultrapotassic mafic volcanic rock with microphenocrysts of phlogopite and diopside in a groundmass of leucite, diopside, apatite, and rare glass (the glass may be replaced by chlorite (many wyomingites have an extremely fine-grained vesicular groundmass with little glass)); (3) orendite; and (4) olivine orendite. Olivine orendites are distinguished from orendite by higher MgO and normative olivine. Petrographically, these rocks are identical and have microphenocrysts of phlogopite and diopside in a groundmass of ±olivine, leucite, apatite, magnophorite, and richterite with considerable sanidine and rare glass (or its alteration product). Petrographically, the presence of sanidine in orendite distinguishes orendite from wyomingite. Olivine orendites are less magnesian than true olivine lamproites (>20% MgO). Classical olivine lamproites have not yet been found in the Leucite Hills.

Carmichael (1967) reported that Wyoming madupites are distinct and have no counterpart in Western Australia and also indicated that, "The diagnostic texture of the madupites of phlogopite enclosing diopside, together with small crystals of magnetite and perovskite is identical to that found in the Arkansas kimberlite; olivine or its pseudomorph has never been found in a madupite, however." (Author's note: the kimberlite described by Carmichael is now known to be olivine lamproite). The Prairie Creek lamproites are petrographically similar to madupites (Mitchell and Bergman, 1991). Olivine lamproites contain much primary phenocrystal olivine, but some lamproites contain common xenocrystal olivine and are hybrids; their compositions do not reflect the nature of the derivative liquid from which they formed.

Petrographic studies show the Leucite Hills lamproites are similar to other lamproites in the world and contain diopside, phlogopite, titanian-potassium-richterite, leucite, sanidine, wadeite, priderite, and/or olivine, with minor apatite, perovskite, and spinel.

Typical kimberlitic "indicator" minerals are rare in lamproite. None of the classical indicator minerals have been reported in the Leucite Hills except for rare chrome spinel and a sample concentrate collected in a drainage along the northern margin of Endlich Hill, which yielded one pyrope garnet from an unknown source (W.D. Hausel, personal field notes, 1984).

Minerals indicative of lamproite include Ti-rich phlogopite, K-Ti richterite, low-Al diopside, chrome spinel, forsterite, perovskite, priderite, wadeite, and shcherbakovite. Other minerals may include diamond, rare G9 (chrome-pyrope), and eclogitic (G3, G6) garnets (Mitchell and Bergman, 1991).

Major minerals

Phlogopite

The Greek root for lamproite means "glistening" which reflects the abundant phlogopite mica seen in lamproite (Scott-Smith, 1996b). Phlogopite is a ubiquitous phenocryst in the Leucite Hills. Both Ti-rich phlogopite and Al-rich phlogopite have been identified. The alumina phlogopite probably represents a high-pressure mineral phase (Mitchell and Bergman, 1991). Phenocrystal phlogopite is titanian (2-10% TiO_2) and aluminum poor (5-12% Al_2O_3). Groundmass phlogopite is titanian (5-10% TiO_2) tetraferriphlogopite. Some of the phlogopite phenocrysts may be completely resorbed. Sagenitic grids of priderite indicate their former presence. Olivine may also replace phlogopite along cleavage planes in a few lamproites (Kuehner, 1980).

Groundmass phlogopite occurs as poikilitic subhedral plates enclosing earlier phases such as diopside, leucite, priderite, apatite, and spinel. The rims of many resorbed phlogopite phenocrysts are mantled by discrete overgrowths of mica that have compositions similar to groundmass phlogopite. Commonly, these mantles are euhedral to subhedral and contain abundant euhedral inclusions of priderite, wadeite, and apatite in contrast with the inclusion-free phlogopite cores. The mantles exhibit stronger pleochroism than the cores. Rocks containing mantled phlogopite are referred to as transitional madupitic lamproites and have been recognized at Mount North (Australia), Middle Table Mountain, Twin Rocks, and Iddings Butte in the Leucite Hills (Mitchell and Bergman, 1991).

Single crystals of anhedral olivine and some spinel are characterized by coronas of interlocking laths of phlogopite (Carmichael, 1967). The phlogopite in the coronas appears to have nucleated preferentially upon olivine rather than resulting from the reaction between olivine and the magma. Phlogopites from the Leucite

Hills have compositions similar to groundmass micas reported in some kimberlites (Mitchell and Bergman, 1991).

Amphibole

Cross (1897) noted K-Ti-richterite (also known as magnophorite) was found in several lamproites in the volcanic field. Richterite exhibits extreme pleochroism ranging from reddish brown or pink to lemon yellow. Typically, the adsorption is X = colorless to pale yellow or lemon yellow, Y = salmon pink, reddish, or pinkish brown, and Z = yellow, lemon yellow, or greenish yellow. Groundmass plates may be zoned from pale yellow-pink cores through reddish pink regions to dark red-brown margins. Where found, richterite occurs principally as groundmass poikilitic plates and is one of the last phases to crystallize. In coarser-grained samples, it may poikilitically enclose leucite (Kuehner, 1980). K-Ti-richterite is titanium-rich (3-5% TiO_2) with potassium (4-6% K_2O) in excess of sodium (Mitchell and Bergman, 1991). At Hague Hill, the K-Ti-richterite occurs as small euhedral prisms lining vesicles.

Pyroxene

Both orthopyroxene and clinopyroxene have been found in the Leucite Hills. Orthopyroxene does not occur as a primary phase and has only been reported as xenocrysts and in some xenoliths (Kuehner, 1980; Barton and van Bergen, 1981). Where found, orthopyroxene occurs as faint green enstatite with phlogopite reaction rims (Kuehner, 1980).

The compositions of clinopyroxene range from titan-augite to nearly pure diopside. The diopsides are colorless to very pale green and are weakly pleochroic. They may have thin, bright green, strongly pleochroic mantles of aegerine-augite on substrates (Carmichael, 1967; Barton and van Bergen, 1981). Diopside is rarely found as a phenocryst, but where found in the groundmass it has an unusual elongate habit and is rarely twinned (Carmichael, 1967). Colorless augite is also found in olivine-biotite-pyroxenite inclusions (Mitchell and Bergman, 1991), and aegirine has been identified in wyomingite at Spring Butte and Hatcher Mesa.

Salitic pyroxenes at Hatcher Mesa occur as megacrysts that are wholly or partially surrounded by thin diopside rims. They are also found in cores of diopside phenocrysts and in clinopyroxene-rich xenoliths, and are relatively iron-rich (Barton and van Bergen, 1981). Salitic pyroxene $\{Ca(Mg,Fe)Si_2O_6\}$ has a composition similar to that of diopside and is thought to have originated from the disaggregation of ultramafic xenoliths. The green salitic pyroxenes are found in wyomingite and orendite at several locations and appear to be particularly abundant at Hatcher Mesa, where a number of mafic and ultramafic xenoliths are found.

Olivine

Two morphological varieties of olivine have been recognized in the Leucite Hills (Cross, 1897; Carmichael, 1967: anhedral xenocrysts with reaction rims and subhedral to euhedral microphenocrysts and groundmass grains. The latter grains exhibit no evidence of instability.

The primary euhedral microphenocrystal olivines crystallized after phlogopite. This is the reverse sequence from most other lamproites elsewhere in the world (Mitchell and Bergman, 1991). Olivine grains from Hatcher Mesa are unzoned and characterized by high $Mg/(Mg^{+}\sum Fe^{2+})$ and Ni. In this respect, they are comparable to olivines from lherzolite and harzburgite mantle nodules found in kimberlite (Barton and van Bergen, 1981) and suggest a deep-seated origin.

Olivine occurs in the groundmass in orendites and olivine orendites. Some of the olivine-sanidine-phlogopite lamproites in the northeastern Leucite Hills have some olivine that represents a third paragenesis. This olivine consists of partially resorbed and embayed anhedral olivine mantled by phlogopite laths that are in disequilibrium with the host magma and thought to represent upper mantle xenocrysts. These olivine grains are chemically similar to olivines found in peridotites (Kuehner, 1980).

Leucite

Leucite ($KAlSi_2O_6$) is a common constituent in many lamproites in the Leucite Hills and may even occur in some of the silica-saturated rocks. Leucite, however, is uncommon to absent in true olivine lamproites. The leucite occurs as subhedral phenocrysts and as anhedral groundmass grains with icositetrahedral habit and typically forms small, isotropic, and untwinned grains (Mitchell and Bergman, 1991).

Sanidine

Sanidine is the only primary feldspar found in lamproite. It occurs as euhedral-to-subhedral prismatic microphenocrysts, as groundmass poikilitic plates, and as pseudomorphs after leucite. It is very pale yellow, water-clear, and usually has poorly developed cleavage (Carmichael, 1967). Twinning is often absent, although Kuehner (1980) noted Carlsbad, Baveno, and penetration twinning in some feldspars from Zirkel Mesa.

Accessory minerals

Anacite

Anacite is a minor constituent of lamproite (Henage, 1972). Where found, it occurs as rounded to anhedral, isotropic microphenocrysts with radial glass inclusions. Its similarity to leucite often leads to misidentification, and confirmation by electron microprobe analysis is usually necessary.

Spinel

Primary spinels are reported in olivine lamproites in the Ellendale field of West Kimberley, Australia, in olivine-bearing madupitic lamproites from the Leucite Hills, at Prairie Creek, Arkansas, and at Murcia-Almeria, Spain (Mitchell and Bergman, 1991). Spinels are absent in phlogopite lamproites in which the primary oxide phase is priderite, armalcolite, and/or ilmenite. In general, chrome spinels are generally not present in lamproites with less than 8 to 10% modal olivine (Jaques and others, 1986).

A few spinels found in the madupitic lavas at Pilot Butte have been chrome-poor (>1% by weight Cr_2O_3), magnesian (<5% by weight MgO), titaniferous (>10% by weight TiO_2) magnetites, unlike the chrome spinels (9-58% by weight Cr_2O_3) found in the diamondiferous lamproites in Western Australia and Murfreesburo, Arkansas.

Kuehner (1980) reported two varieties of chromite in orendite at the Leucite Hills. One formed dark red grains and the other was opaque. A third type was recovered by the WSGS during diamond testing in the early 1980s. This spinel was extracted on a grease table and was a translucent octahedron. X-ray precession diffraction completed in the University of Wyoming's Physics Department confirmed the mineral to be spinel.

A rare accessory mineral found in wyomingite is green spinel (Yagi and Matsumoto, 1966). This iron spinel is dark green, irregularly shaped, and typically enclosed by phlogopite. It appears to be more common in rocks with abundant green-cored diopside (Kuehner, 1980).

Chrome spinel is found in some orendites and wyomingites in the Leucite Hills and typically has a reaction rim of phlogopite (Carmichael, 1967). Robert Kirkwood (personal communication) reported a chrome spinel extracted from lamproite in the Leucite Hills that displayed chemistry (high chrome, high-magnesian) similar to that of diamond-stability chromites. A similar chrome spinel was later identified by Robert Gregory at the WSGS (personal communication). The composition of these spinels suggests that the magmas originated within the upper mantle.

Priderite

Priderite is a key mineral in the recognition of lamproite because its occurrence is essentially restricted to this paragenesis, although rare priderite has been reported in kimberlite and carbonatite (Mitchell and Bergman, 1991).

Priderites are K-Ba-Ti-hollandites with the general composition $(K,Ba)(Ti, Fe^{3+})_8O_{16}$. They form small, opaque, elongate acicular tetragonal prisms with tetragonal bipyramids, and are often mistaken for rutile (Carmichael, 1967). Priderite has high relief, high birefringence (0.04), and may be virtually opaque or exhibit pleochroism in shades of yellow-orange, orange-red, or deep red. The color is often unevenly developed and alternating bands of different hues give the crystal a barred or striped appearance. In reflected light, well-developed cleavage may be evident by characteristic etch pits. Kuehner (1980) noted sagenitic grids of priderite occurred along the (001) planes of partially resorbed phlogopite phenocrysts in sanidine-bearing lamproites.

Magnetite

Magnetite is fairly abundant in madupite and is absent in wyomingite and orendite. The only reported iron-titanium oxide in the Leucite Hills is found in madupite, and is a titaniferous magnetite (Carmichael, 1967).

Wadeite

Wadeite ($K_2ZrSi_3O_9$) occurs as poikilitic groundmass grains in virtually all rocks in the Leucite Hills, although it is only common in madupite. Wadeite was initially identified in the West Kimberley lamproites in Australia and was later recognized in the Leucite Hills by Carmichael (1967). At Middle Table Mountain, wadeite forms hexagonal, poikilitic groundmass crystals that commonly exhibit characteristic rectangular cross-sections with high birefringence, resembling apatite in both relief and habit (Kuehner, 1980; Mitchell and Bergman, 1991).

Apatite

Most apatite is found as microphenocrysts in the groundmass of orendite and olivine orendite. They are clear with euhedral to rounded, hexagonal habit. The apatites generally have low BaO (0.16-0.4%) (Carmichael, 1967). However, Ba-rich and Sr-rich apatites were found mantling two apatites at Middle Table Mountain.

Perovskite

Perovskite is reported in lavas at Pilot Butte, Twin Rocks, and Middle Table Mountain. The perovskite from these areas is enriched in iron compared to perovskite found in lamproites elsewhere, and is also rich in LREE. The iron content of this perovskite is also higher than that of perovskites from kimberlite, and rare earth element (REE) content is comparable (Mitchell and Bergman, 1991).

Shcherbakovite

Shcherbakovite, a K-Ba-titanosilicate, occurs as small, euhedral, blue-green pleochroic prisms lining the walls of vesicles in association with potassium richterite (Mitchell and Bergman, 1991).

Secondary minerals

Secondary minerals include chalcedony, carbonate, chlorite, zeolite and strontiobaryte. Zeolites have been reported as fillings in some amgydules at Twin Rocks, and carbonates are uncommon accessory minerals found in vugs in some lavas in the Leucite Hills. The carbonates include calcite and less commonly witherite (Mitchell and Bergman, 1991).

Xenoliths and xenocrysts

A variety of xenoliths and xenocrysts have been identified in the Leucite Hills lamproites. The majority of the material is derived from disaggregation of Phanerozoic rocks underlying the Green River Basin. Lesser amounts of lower crustal and upper mantle xenoliths and xenocrysts have been identified in the lamproites.

Cognate xenoliths include lamproitic fragments formed of coarse-grained intergrowths of phlogopite, diopside, apatite, priderite, and magnophorite with ocelli texture.

Crustal xenoliths include arkose, tuffaceous sandstone, argillite, siltstone, shale, quartzite, limestone, dolomite, and chert. The limestone and chert are thought to have originated from the underlying Paleozoic rocks, while the quartzites and sandstones probably originated from the Nugget Sandstone and/or Ericson Sandstone. The remaining sandstones and shales were most likely derived from underlying Cretaceous and Tertiary sediments (Speer, 1985). Some of the more common xenoliths found in the Leucite Hills were derived from the Green River Formation.

Lower crustal granitic rocks are the next most common of the xenoliths. These include granite, quartz diorite, granitic gneiss, diorite gneiss, and quartz diorite gneiss (Speer, 1985). Granulitic and anorthositic xenoliths are believed to be derived from the lower crust. Some of the granitic xenoliths are highly vesiculated scoriaceous masses of feldspar in which much of the quartz has been removed.

Barton and van Bergen (1981) also identified phlogopite-chromite harzburgite, orthopyroxene amphibolite, clinopyroxene-rich pyroxenites, mica pyroxenite, and mica-rich xenoliths.

The clinopyroxenite xenoliths are comprised of green, euhedral to subhedral, weakly pleochroic clinopyroxene, rare euhedral apatite, and rare, rounded grains of iron-titanium oxide. These mineral phases are identical to the green pyroxene, apatite, and Fe-Ti oxide megacrysts found in the lava. One orthopyroxene-amphibole xenolith was described as a mosaic of anhedral grains of orthopyroxene, amphibole, and minor Fe-Ti oxide (Barton and van Bergen, 1981).

Ogden and others (1978) also described dunite and peridotite xenoliths. These included phlogopite-chromite harzburgite (peridotite). The phlogopite in the harzburgite is weakly pleochroic and strongly corroded, while the olivine forms colorless, corroded, grains with rims of a deep red color. Large crystals show evidence of strain and often contain inclusions of enstatite and chromite. The smaller olivine crystals are anhedral and almost completely replaced by a deep red-brown material.

The dunite xenoliths contain olivine similar to olivine phenocrysts at Black Rock and South Table Mountain. These phenocrysts are composed of Fo90 and have a calcium content of 0.3%. They commonly have a reddish reaction rim. Other olivine phenocrysts are reported to have similar compositions (Fo80 and 0.2% Ca) (Speer, 1985).

Phlogopite-apatite-glass inclusions found at Hatcher Mesa, Zirkel Mesa, Middle Table Mountain, and Black Rock (Speer, 1985) were thought to represent an immiscible magmatic liquid phase (Carmichael, 1967). These may also represent glomeratomorphs, or clots of crystals selectively combined during flow within the melt.

Pyroxene-plagioclase-phlogopite-amphibole xenoliths are found at Deer Butte, Spring Butte, and Zirkel Mesa (Speer, 1985). Similar xenoliths have been reported in other highly potassic volcanic fields, suggesting that these xenoliths are commonly associated with rare potassic volcanic rocks.

Xenocrysts identified in the lamproites include some augite, barkevikitic amphibole, orthoclase, some phlogopite-rimmed olivine, chromite with similar reaction rims, and green spinel (Carmichael, 1967). The xenocryst suite also includes magnesian chromites found in the olivine orendites, and pleonaste and salite found in wyomingites (Kuehner, 1980).

Age

The Leucite Hills lies within the Archean (>2.5 Ga) part of the Wyoming Craton, more than 100 miles north of the southern boundary of the Wyoming Province. Cratonized Proterozoic basement rocks attached to the southeastern part of the Wyoming Province have been intruded by a large swarm of diamondiferous kimberlites. The kimberlites are located in southeast Wyoming. Some mafic to ultramafic mantle-derived diamondiferous breccias are found southwest of the Leucite Hills along the edge of Cedar Mountain and also intrude the Archean Craton (Hausel and others, 1999).

The lamproites of the Leucite Hills intrude Phanerozoic sedimentary rocks of the Rock Springs uplift. These include rocks of the Fort Union, Rock Springs, Lance, Almond, and Ericson formations, all of which lie on top of the buried Wyoming

Craton. Based on the geomorphology of the Leucite Hills volcanics and the rock units intruded, the lamproites appear to be geologically very young.

Reported radiometric dates for the Leucite Hills lamproites include a K-Ar date on phlogopite indicating an age of 1.1 ± 0.4 Ma (McDowell, 1971). Other K-Ar ages of phlogopite from five volcanic centers are 1.4 Ma for Emmons Mesa, 1.6 Ma for Zirkel Mesa, 2.2 Ma for Spring Butte, 2.4 Ma for Steamboat Mountain, and 3.1 Ma for Boar's Tusk (Bradley, 1964; McDowell, 1966, 1971). Based on these dates, the lamproites initially erupted in the extreme northwest part of the field and progressed southeast through time.

Petrogenesis

Lamproites are confined to continental areas, appear to be post-tectonic, and are found on Archean cratons or within accreted Proterozoic mobile belts. Hypotheses for the origin of these lavas include the melting of a metasomatized upper mantle, crystal fractionation of an ultramafic magma (Wade and Prider, 1940), and incongruent melting of phlogopite (Heanage, 1972).

The wide variety of lamproites in the world suggests derivation from a variety of mantle sources, or that the magmas are subjected to petrographic processes (Scott-Smith, 1996b). Lamproites have Sr isotopic compositions greater than and Nd isotopic compositions less than those of bulk Earth at their time of emplacement. Such rocks are interpreted to have sources within nonconvecting metasomatized lithosphere.

Lamproites may have originated by partial melting under H_2O-rich conditions in ancient metasomatized lithospheric mantle. Mitchell and Bergman (1991) suggested that the occurrence of rapidly emplaced batches of magma of similar composition (those with intermediate SiO_2 values) and identical, early-formed phlogopite phenocrysts (with little or no olivine) over a wide area in the Leucite Hills indicates that these lavas may be parental magmas.

The origin of olivine lamproites is a different issue entirely. Many olivine lamproites have no simple differentiation relations with phlogopite lamproites. The presence of diamond in some olivine lamproites found elsewhere in the world suggests rapid emplacement from the mantle with little modification en route to the surface (Scott-Smith, 1996b).

The initial $^{87}Sr/^{86}Sr$ ratios (0.7055-0.7070) are quite primitive for the Leucite Hills and suggest that crustal contamination of the lamproitic magmas has been minimal. This is consistent with partial melting of a primitive mantle source (Ogden, 1979).

Carmichael (1967) drew comparisons between the Leucite Hills lamproites and kimberlites, and suggested that such highly potassic volcanic rocks may have developed by fractionation of a kimberlitic liquid. According to Carmichael and others (1974), the geochemical similarities (i.e., enrichment of K, Rb, Ba, Sr, Zr, and Nb) between kimberlites and lamproites relate to their source region in the upper mantle. The madupitic lavas, in particular, may have originated by high-pressure fractional crystallization of a liquid produced by fusion of garnet peridotite. Similar conclusions were drawn by Wade and Prider (1940) for the lamproites in the Kimberley Block of Western Australia, which may have differentiated from mantle peridotite.

Ogden (1979) and Kuehner and others (1986) considered the madupitic rocks to be derived from Si-poor, Mg-rich, mantle-derived primitive liquid. High-pressure experimental studies in the system $KAlSiO_4$-MgO-SiO_2-H_2O-CO_2 indicated that a liquid similar in composition to madupite could be generated under 26 kb pressure (approximately 56 miles below the surface). The same liquid, rising diapirically, will again generate a liquid similar in composition to orendites and wyomingites at 19 kb (41-mile depth). Sobolev and others (1975) indicated that the Leucite Hills phlogopite lamproites would undergo complete crystallization at approximately 1,000°C.

Ogden (1979) suggested that the lamproites originated from a phlogopite-rich source in the mantle. The composition of the phlogopite micas supports crystallization from a MgO-TiO_2-rich, H_2O-F-bearing magma. Mitchell and Bergman (1991) noted that the madupitic lamproites from the Leucite Hills are enriched in Ba, Sr, Th, and REE, depleted in Ni, and have lower K/Rb ratios than the associated phlogopite lamproites. This observation suggests that madupitic lamproites are derivatives of phlogopite lamproites (counter to the scenario proposed by Kuehner, 1980).

The above data suggest that all of the lavas in the Leucite Hills are petrogenically related, and that the mineralogical differences between the orendites and the wyomingites may be due to an interval of high-pressure crystallization in the former (Kuehner, 1980). In addition, the similar compositions of the phlogopites in the Leucite Hills suggests that the lamproites were derived from a common magma at depth (Mitchell and Bergman, 1991).

It has also been suggested that lamproites result from partial melting under reduced H_2O-rich volatile conditions of ancient harzburgitic sources. Such primitive magma, from which lamproites are derived by fractional crystallization or contamination, is relatively rich in silica (52-55%) and magnesian (7-10%). Olivine lamproites are hybrid rocks whose compositions do not represent those of their parental magmas.

In contrast, Foley (1993) postulated that olivine lamproites represent primary magmas. Leucite lamproites are unlikely to originate by partial melting of garnet peridotite, but could instead come from a phlogopite-bearing source free of garnet and clinopyroxene. Foley suggested that the Leucite Hills lamproite compositions correspond to depths of origin of only 10 to 15 kbar.

Mitchell and Bergman (1991) do not believe lamproites are related to kimberlite. They interpret lamproites as melts derived from subcontinental mantle lithospheric sources, and kimberlites as relatively oxidized, CO_2-dominated asthenospheric melts.

Kuehner (1980) suggested that wyomingites are not related to orendites or olivine orendites by fractional crystallization based on differentiation indexes. Orendites are more differentiated than olivine orendites, evidenced by higher Al_2O_3, K_2O, and SiO_2 and lower MgO in orendite. This suggests that olivine orendites and orendites may be related by crystal fractionation.

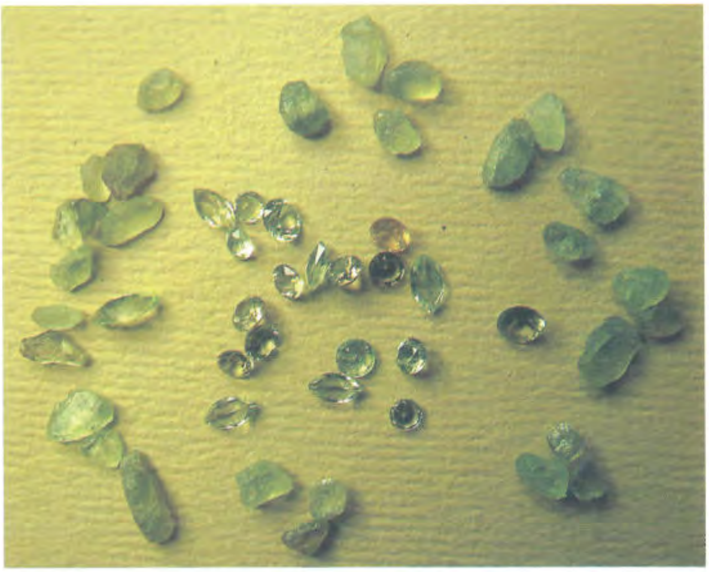
Consistent Nb, Zr, Y, Rb, and Pb values between the wyomingites, orendites, and olivine orendites suggest that they may have a common origin. Olivine, biotite, and pyroxene concentrate ^{16}O relative to ^{18}O. Therefore, the crystallization of these minerals will result in a liquid slightly enriched in ^{18}O. If these minerals settle to the bottom of a magma chamber, the resulting cumulate rock will be isotopically lighter than the original liquid. Phlogopite crystallized in a fluid with $^{18}O = 11.6$, and the whole rock has $^{18}O = 9.06$. The lower isotopic value is consistent with major elemental chemistry suggesting a cumulate origin for the olivine orendite (Kuehner, 1980).

Economic Geology

Some lamproites have served as sources for industrial and decorative stone. Others have been exploited for potash. However, the rare olivine lamproites from which diamonds are recovered are the most valuable.

Lamproites in Arkansas, India, and Australia have produced industrial and gem-quality diamonds. For several years, the olivine lamproite at Argyle, Western Australia has produced more than 30% of the world's diamonds annually, including some of the most valuable gemstones on earth. Pink diamonds known as Argyle pinks have sold for as much as $1 million/carat.

The recent identification of peridot (gem-quality olivine) associated with the Black Rock lamproite in the northeastern part of the Leucite Hills has generated some interest in this gemstone. Several thousand carats of transparent, light green, yellow-green, and reddish green peridot have been recovered from nearby anthills and adjacent soils (**Figure 8**).



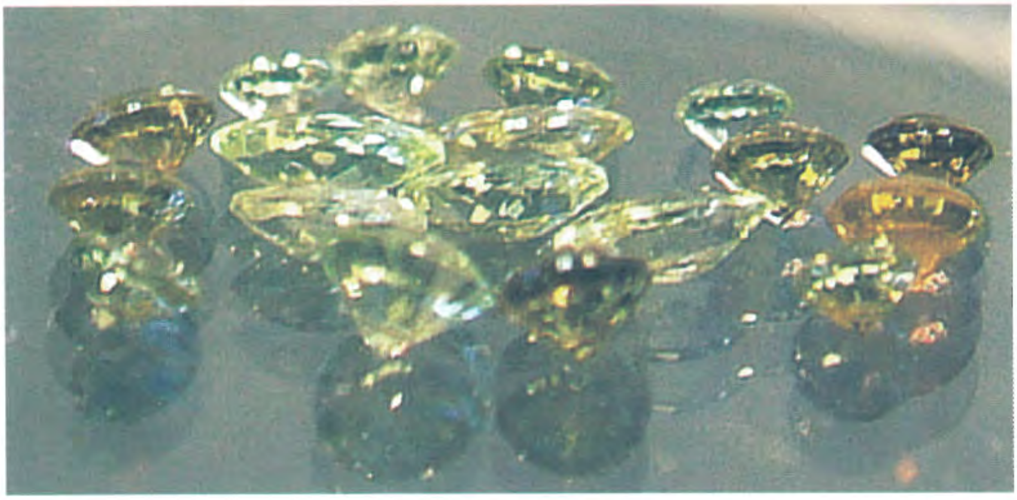


Figure 8. Rough olivine recovered from anthills in the Leucite Hills surrounding faceted olivine gems (peridot) from the same locality (top). Faceted transparent gem-quality peridot collected from the Black Rock area of the Leucite Hills (bottom, photograph by Robert W. Gregory).

EXPLORATION

Mitchell and Bergman (1991) suggested that diamondiferous lamproites are restricted to craton margins in crustal domains that experienced Proterozoic to Archean accretional and/or other orogenic events.

Many diamondiferous lamproites are geochemically and mineralogically similar to kimberlite. Important similarities include high modal olivine, Cr-rich spinel, and similar enrichments in Cr, Ni, and other incompatible elements. The classical kimberlitic indicator minerals used in the search for kimberlite are notably absent in lamproite. In particular, sub-calcic, chrome-rich pyropes (G10) typical of diamondiferous kimberlites are absent in the Prairie Creek and Argyle diamondiferous lamproites. Such garnets are also extremely rare in the Ellendale 7 and 9 diamondiferous olivine lamproites in the Kimberley block of Western Australia (Mitchell and Bergman, 1991).

Consequently, the general exploration methods used to search for lamproite differ from those used for kimberlite. Due to the lack of kimberlitic indicator minerals, other mineral trains have been used. These include phlogopite, chrome-spinel, and diamond. However, diamond may not be the best pathfinder because it has been reported to travel more than 1,000 miles from its source rock in rivers (Arnold Waters, Jr., personal communication, 1979).

Lamproites, like kimberlite, are emplaced along deep-seated fractures that potentially extend deep into the keel of the craton. When these fractures are recognized, they may provide unique orientations. A variety of remote sensing imagery equipment may be used to search regions for geomorphic features characteristic of lamproite flows and plugs, and to identify the controlling structures for potentially hidden lamproite. Once controlling structures are identified, field reconnaissance is necessary to search for poorly exposed lamproites and hidden lamproites along these structures.

Due to serpentinization, olivine-rich lamproites are susceptible to erosion and tend to be buried by thin veneers of soil or regolith, making these rocks more difficult to find than olivine-poor and olivine-barren lamproites. In many localities, diamondiferous olivine lamproites are hidden under soil while adjacent phlogopite lamproites stand as distinct volcanoes. As such, phlogopite lamproites can sometimes serve as pathfinders to olivine lamproites.

Weathering of lamproite will produce an exotic suite of secondary minerals, including nontronite, smectite, and barite, and the host rock will contain anomalous amounts of Ti, K, Ba, Zr, and Nb compared to most other rocks. The chemistry and mineralogy of lamproite may favor the growth of plants different from the surrounding vegetation community, and could cause stressed plants. The Big Spring vent in West Kimberley, Australia is characterized by anomalous faint pink tones that reflect the growth pattern of grasses on the vent (Jaques and others, 1986).

Magnetic surveys

The magnetic susceptibility of lamproite is controlled by the abundance of Ti-magnetite, other spinels, and Fe- and Ti-oxides. Because madupitic lamproites contain magnetite, they often yield distinct detectable anomalies while other lamproites may yield only weak magnetic anomalies. Serpentinization of olivine in olivine lamproites may result in the some secondary magnetite. Overall, lamproites display a wide range of magnetic susceptibilities depending on the abundance of these phases and the amount of weathering and serpentinization. For most olivine-barren lamproites to be detected, the surrounding country rock must have a simple magnetic signature. Flight-line spacing and elevations of regional aerial magnetic surveys are typically 750 feet and 150-300 feet, respectively (Mitchell and Bergman, 1991).

Janke (1983) and Jaques and others (1986) indicated that several lamproites were detected within the Ellendale field, Western Australia using aerial magnetics. The olivine lamproites, in particular, yielded dipolar anomalies. In addition, an airborne electromagnetic survey system (INPUT) has also been used successfully in the Ellendale field (Atkinson, 1986).

Magnetic surveys have been used successfully to delineate and locate lamproite in the Prairie Creek field, Arkansas (Waldman and others, 1987; Bolivar and Brookins, 1979), southeastern Kansas (Coopersmith and Mitchell, 1989), and West Kimberley, Australia (Jaques and others, 1986; Atkinson, 1989). The olivine lamproite at Prairie Creek produced a distinct dipolar anomaly (Bolivar and Brookins, 1979). Atkinson (1986) reported that the tuff phases of the Argyle olivine lamproite in Western Australia are only weakly magnetic. Because it occurs within a Precambrian belt that has a complex magnetic signature, the Argyle olivine lamproite yields a non-distinct magnetic signature (Drew, 1986).

Electrical Methods

Electrical methods can also be used to detect and characterize lamproite. Some lamproites may yield conductivity anomalies due to their clay content or weathering, and they may potentially be detectable by airborne INPUT surveys (conductivity-magnetic) and ground-based electromagnetic (EM) surveys. Due to the conductive nature of some lamproites, electrical resistivity surveys may also be used to delineate their extent.

The electrical resistivity of weathered lamproite is generally less than that of most country rocks, owing to the conductive nature of smectitic clay associated with lamproite relative to illite, kaolinte, or other clay minerals (Gerryts, 1970; Jenke, 1983). Fresh lamproite may also show higher resistivity than many country rock types. Lamproite vents, such as Argyle, possess moderate to strong resistivity anomalies (40 to 100 ohms/m) compared to the surrounding country rock (200 ohm/m) (Drew, 1986). Coopersmith and Mitchell (1989) also showed that the Hills Pond and Rose olivine lamproites in Kansas could be delineated with ground-based EM surveys.

Geochemical Surveys

Lamproites contain elevated compatible (Ni, Cr, Co, V, and Sc) and incompatible (Rb, Sr, Ba, Zr, Hr, Ti, P, Nb, REE, Y, Th, and U) metals. Even so, stream sediment geochemistry does not appear to be useful in locating lamproite due to dispersion of these metals in the stream sediments. A similar problem exists in soils. Gregory and Tooms (1969) investigated the Prairie Creek lamproite and found that Mg, Ni, and Nb anomalies did not extend more than 0.6 miles past the vent, which greatly limited the usefulness of geochemistry. Similarly, Haebid and Jackson (1986) noted that soil geochemical anomalies (Ni, Co, Cr, and Nb) were developed in sand and soil overburden immediately above lamproite vents in the West Kimberley province, Australia, but did not extend any distance from the vents.

Lithochemistry may help identify lamproite. This technique is used where rocks have been weathered or are recovered in drill cuttings. Gregory (1984) used lithochemistry to map complex lamproite intrusions and distinguished olivine lamproite from leucite lamproite based on Mg, Ni, Cr, and Co ratios.

Bergman (1987) suggested that olivine lamproites are generally enriched in compatible elements compared to leucite lamproites, primarily due to the abundance of xenocrystal olivine in the former. Barren lamproites (i.e. phlogopite lamproites) contain elevated alkali and large ion lithophile elements (LILE: K, Na, Y, U, Th, Zr) compared to diamondiferous varieties. Despite wide variances, diamondiferous lamproites contain twice the Mg, Ni, Cr, Co, and Nb and half the K, Na, and Al of barren lamproites. Mitchell and Bergman (1991) emphasize that "recognition of olivine lamproite is the only guide to the possible presence of potentially diamondiferous rocks".

Heavy mineral exploration

The kimberlitic indicator minerals Cr-pyrope (G9), Cr- spinel, diamond, G3, and G6 eclogitic garnets have been reported in trace amounts in some lamproites, and megacrystal/macrocrystal Ti-Cr pyrope (G1, G2) and Mg-Cr-rich ilmenite are rare to nonexistent in lamproite (Mitchell and Bergman, 1991). Lamproite indicator minerals include Ti-rich phlogopite, K-Ti richterite, low-Al diopside, chrome spinel, forsterite, perovskite, priderite, wadeite, and shcherbakovite. The latter three minerals are very rare, yet highly diagnostic of lamproite.

Stream sampling has been used successfully to locate some lamproites in West Kimberley, Australia (Jaques and others, 1986; Atkinson, 1989). Because of its high abundance and distinctive composition, chromite was the most useful indicator for olivine lamproite in the Ellendale field, Australia (Mitchell and Bergman, 1991).

Spinels recovered from madupitic lavas at Pilot Butte in the Leucite Hills are chrome-poor (<1% by weight Cr_2O_3), magnesian (<5% by weight MgO), titaniferous (>10% by weight TiO_2) magnetites, unlike the chrome spinels (9-58 % by weight Cr_2O_3) found in the diamondiferous lamproites in Western Australia and Murfreesburo, Arkansas. The lack of chrome spinel at Pilot Butte suggests this lamproite is a poor target for diamond.

Chrome spinel containing reaction rims of phlogopite was reported in many orendites and wyomingites in the Leucite Hills (Carmichael, 1967). These spinels were not analyzed. However, Robert Kirkwood (personal communication) reported the presence of chrome spinel in a sample from the Leucite Hills.

Diamond Exploration in the Leucite Hills

Teleseismic tomographic studies of the Wyoming craton in the vicinity of the Leucite Hills indicate the presence of a 150- to 200-km-thick lithosphere (Humphreys and Dueker, 1994). However, the petrogenic model of Kuehner (1980) suggests that lamproites were derived from relatively shadow depths (41 to 56 miles) with only 19 to 26 kb pressure, too low for diamond genesis. However, the presence of rare Cr-Mg-rich chromites and olivine orendites in the northeastern part of the field may indicate greater depths of derivation for these magmas, as well as a potential for hidden olivine lamproite in this region. This region of the Leucite Hills should be searched for hidden pipes by airborne INPUT geophysical surveys.

POTENTIAL RESOURCES

Potash

The Leucite Hills contains some of the more potassic volcanic rocks in the world. Schultz and Cross (1912) evaluated the volcanics as a potential source for potash, as the U.S. depended entirely on Germany for potash before World War I. An estimated 940 million tons of lamproite was identified at Zirkel Mesa with an estimated resource of 94 million tons of potash and an equal amount of alumina. The estimate for the entire volcanic field was approximately 2 billion tons of rock with 200 million tons of potash and 200 million tons of alumina.

Because of the study, Liberty Potash Company developed a quarry on Zirkel Mesa during World War I. The quarried rock was crushed, loaded into aerial tram buckets, and transported 1.5 miles to a storage bin at the end of a railroad spur near Superior. From the spur, the rock was hauled to a plant at Green River where potassium chloride was manufactured for use in fertilizer (Thoenen, 1932).

Diamonds

Olivine lamproites offer potential for significant diamond mineralization (Atkinson, 1986). Where found, economic amounts of diamond appear to be confined to crater-facies volcaniclastic olivine lamproites. Magmatic olivine lamproites and magmatic and volcaniclastic leucite lamproites have so far not yielded economic amounts of diamond anywhere in the world (Scott-Smith, 1996).

Diamondiferous lamproites have been known for many years, but these rocks did not attract serious attention until the initiation of an exploration program in Western Australia. Based on the concept that lamproites were differentiates of kimberlite, as proposed by Carmichael for the Leucite Hills (Prider, 1960), this program led to the discovery of diamondiferous lamproite in the Ellendale field in the Fitzroy Basin in 1976-1977. In 1978, the program resulted in the discovery of diamondiferous olivine lamproite at the Argyle vent in the East Kimberleys (Mitchell and Bergman, 1991).

Following these discoveries, other 'kimberlitic' rocks around the world were re-evaluated, and some were found to actually be diamondiferous lamproites. These include the Majhgawan olivine lamproite in India that had been discovered and mined for diamonds as early as 1827 (long before diamonds had been found in kimberlite in South Africa in 1866), and the Prairie Creek olivine lamproite in Arkansas, which was mined for diamonds as early as 1842 (Scott-Smith, 1989).

Other diamondiferous lamproites have now been found in Kapamba, Zambia, Aldan in Russia, and Bobi on the Ivory Coast. Currently, there are several known diamondiferous lamproite provinces, fields, or occurrences in the world, including the Ellendale field and Argyle lamproite in Western Australia; the Prairie Creek, American, and Kimberlite lamproites in Murfreesburo, Arkansas (United

States); the Bobi lamproites near Seguela on the Ivory Coast, Africa; the Kapamba lamproite field in Eastern Zambia, Africa; the Majhgawan vent in India; and the Coromendel lamproites in the Minas Gerais region of Brazil. They range in age from Proterozoic (1.2 Ga) to Miocene (20-22 Ma) (Mitchell and Bergman, 1991). Other altered olivine lamproites have been reported at Hills Pond, Kansas and Enoree, South Carolina. Although these lamproites are currently mined for vermiculite and fertilizer, no diamonds have been reported (Bergman, 1987).

Kimberlites and lamproites are distinctly different rock types, although the chemical compositions of micaceous kimberlite and lamproite overlap (Helmstaedt, 1993; Peterson, 1996). Lamproites can be subdivided into two general groups: phlogopite-leucite lamproites, which have little economic value; and olivine lamproites with >20% MgO, <45% SiO_2, and approximately 7% K_2O that may be good targets for diamond (Scott-Smith, 1996).

Where mineralized, diamond xenocrysts in lamproite are primarily restricted to the pyroclastics in olivine lamproite. The magmatic phases (and sills) are notoriously diamond-poor. Therefore, the available minable tonnage is limited to the vent facies rocks. Typically, diamond grades are higher in olivine-lamproites than in leucite-lamproites.

Diamondiferous lamproites possess high amounts of modal olivine, Cr-rich spinels, and similar enrichments in Cr, Ni, and incompatible elements. Some petrologists now recognize Group II kimberlites (orangeite), as chemically overlapping olivine lamproites. Group II kimberlites have been a significant source of gem diamonds (Peterson, 1996).

Average ore grades from the Argyle olivine lamproite in Australia are reported at 680 carats/100 tonnes, with some ore as rich as 1,000 carats/100 tonnes–more carats per tonne than any other primary commercial diamond deposit in the world. The Argyle mine produces many diamonds, including relatively common colored stones and the rare pink diamonds. Some 1-carat brilliant cut "Argyle Pinks" have been valued at $1 million (Rock and others, 1992).

Altered olivine-phlogopite lamproite dikes have also yielded diamonds on the Ivory Coast and in Gabon (west Africa). These rocks are devoid of the usual kimberlitic indicator minerals and appear as talc or phlogopite schists. The Bobi lamproite dike on the Ivory Coast is locally very diamond-rich, with grades nearing 1,000 carats/100 tonnes (Helmstaedt, 1993). Altered diamondiferous leucite lamproite (fitzroyite) had been described as early as 1967 near Seguela, Ivory Coast by Dawson (1967).

On average, diamonds from commercial lamproites are much smaller than those from commercial kimberlites. The average size of Argyle diamonds is less than 0.1 carat, while those from Ellendale are 0.1 to 0.2 carat. The largest reported stones from these locations are 6 and 16 carats, respectively (Mitchell and Bergman, 1991). The largest reported diamond from Prairie Creek, Arkansas is 40.42 carats. Kimberlites have produced some very large diamonds, including the famous Cullinan Diamond that weighed just more than 3000 carats.

Lamproites also produce many frosted diamonds with resorbed textures that are, for the most part, of poorer quality than kimberlitic diamonds. The majority of the diamonds are grey, brown, yellow, and mostly of industrial quality. Both P-type and E-type diamonds are recognized in lamproites.

Diamond Testing

Because diamond has a greater affinity for olivine lamproite, sampling of the Leucite Hills was primarily confined to the olivine-bearing lamproites. Samples collected by the WSGS during initial field reconnaissance were volcaniclastic rocks from Endlich Hill. These were processed for diamond using skin-flotation recovery at the WSGS. The concentrates yielded one possible transparent, clear, white, octahedral microdiamond, which proved to be spinel.

In 1991, samples of lamproite were collected from South Table Mountain and Endlich Hill (Hausel and others, 1992, 1994). In 1992, two samples (LH1-92 and LH2-92) of fragmental olivine-bearing lamproite were taken from Endlich Hill in section 8, T22N, R102 W, one sample was taken from Wortman dike (sample LH3-92), and a fourth sample (LH4-92) of olivine-bearing magma was collected from Black Rock in section 13, T22N, R101W.

Samples (UP1-93, UP2-93, UP3-93, UP4-93, **Appendix 2**) of volcaniclastic olivine lamproite were selected for testing. The samples were reduced in jaw and roll crushers to less than 16 mesh (1.0 mm) and passed over a side-shaking grease table. The grease table concentrates were then placed in a hydrofluoric acid solution and the residue was examined microscopically for diamonds.

No diamonds were identified in any of the concentrates, but because of the small sample volume, the results were not considered diagnostic. Larger sample volumes will be necessary for effective diamond testing.

Based on the similarities between lamproite and kimberlite, the Leucite Hills are considered a potential source of diamond. Diamonds are interpreted to crystallize at minimum depths of 90 to 120 miles (1,050 to 1,200°C, 45 to 55 kb) at the base of thick, cool, Archean or Proterozoic cratonic lithospheres. From these depths, they are transported as accidental xenocrysts to the surface.

The data available (see section on petrogenesis) suggest that the lithosphere under the Leucite Hills is sufficiently thick. However, genesis of the madupitic and wyomingite lavas appears to be too shallow to favor diamond sampling based on experimental data. The better targets in the region are potentially hidden olivine lamproites within the volcanic field.

CONCLUSIONS

The eruptive centers of the Leucite Hills are located along the northern flank of the Rock Springs uplift. The uplift is an anticline cored by shallow-dipping Cretaceous strata and lies within the Greater Green River Basin. This seemingly simple topographic and structural basin contains one of the largest lamproite fields in the world, along with mafic breccia pipes containing eclogitic xenoliths and mantle-derived xenocrysts, and extensive regions of scattered, mantle-derived, detrital kimberlitic indicator minerals (McCandless and others, 1995; Hausel, 1998; Hausel and others, 1999). The presence of lamproites, breccia pipes, and widespread indicator mineral anomaly to the southwest implies that several fractures penetrated deep into the earth's crust and upper mantle, providing favorable terrain for diamond occurrences.

Other ultrapotassic lavas and alkalic magmas extend from Kamas, Utah through the Green River Basin to the Black Hills of northeastern Wyoming, perpendicular to the Farson lineament. The possibility of additional discoveries of similar rocks is highly probable along this trend.

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ROAD LOG

Stops and Descriptions

Cumulative mileage from Rock Springs	Description
0	Bureau of Land Management (BLM) parking lot on the north end of Rock Springs, Highway 191.
8	Approximately 8 miles north of the BLM office, you will come to the Tri-territory road #216. Turn east.
9	Cross old railroad grade and turn north. This old grade was a captive railroad spur of U.S. Steel Corporation, which used the spur to ship about 5 million tons of taconite pellets per year from the Atlantic City iron mine near South Pass at the south end of the Wind River Mountains to the Geneva Steel blast furnaces near Provo, Utah. The mine and spur were active from 1962 to 1983.
12	Continue left at "Y" in road.
22	***Stop 1. Fifteen Mile Knoll***
	Fifteen Mile Knoll is a low-lying hill located north of the road intersection. Pediment gravels consisting of cobbles and pebbles of quartzite, schist, sandstone, metagabbro, epidotite, jasper, and agate cap the hill. North of Fifteen Mile Knoll is a prominent volcanic neck known as the Boar's Tusk. Matthews Hill, another volcanic neck, forms a low-lying hill to the right of Boar's Tusk.
	Behind the Boar's Tusk on the horizon are the Wind River Mountains. The dunes of the Kilpecker Dune field, which lie primarily on Wasatch Formation sediments, are directly behind the Boar's Tusk. The Nitch Gulch oil field is visible northeast of the dunes, and a little farther to the northeast is Steamboat Mountain. The mountain has a visible cinder cone and lies on Green River Formation rocks.
	Approximately due east are North Table Mountain and South Table Mountain, lamproites located on Fort Union Formation shales and sandstones along the

Cumulative mileage from Rock Springs	Description
	northeast flank of the Rock Springs uplift. South of Table Mountain, Endlich Hill and Hague Hill lie on Almond Formation (Cretaceous) sediments. Endlich Hill is composed of olivine orendite and was selected by the WSGS for diamond testing (no diamonds were recovered). Both flows and volcaniclastics of Endlich Hill have more than one population of olivine. In addition to anhedral xenocrysts and subhedral to euhedral microphenocrysts, the olivine-sanidine-phlogopite lamproites enclose anhedral olivine mantled by phlogopite laths in disequilibrium with the host magma that may represent upper mantle derived xenocrysts.
	To the east, Cretaceous rocks of the Rock Springs uplift are visible. To the west, the prominent, white, Green River Formation-supported cliffs of White Mountain are clearly visible. Pilot Butte, the westernmost lamproite in the Leucite Hills volcanic field, can barely be seen rising above White Mountain at approximately 15° west of south. Madupitic lavas from Pilot Butte are silica-poor and magnesian-rich compared to other lavas in the Leucite Hills. The madupitic lavas are enriched in Ba, Sr, Th, and REE, are depleted in Ni, and have lower K/Rb ratios than phlogopite lamproites, which suggests the madupitic lamproites at Pilot Butte were derivatives of phlogopite lamproites. Spinels found in the madupitic lavas at Pilot Butte are chrome-poor (<1 wt% Cr_2O_3), magnesian (<5 wt% MgO), titaniferous (>10 wt% TiO_2) magnetites, unlike the chrome-spinels (9 to 58 wt% Cr_2O_3) found in the diamondiferous lamproites in Western Australia and Murfreesburo, Arkansas. The lack of chrome spinels at Pilot Butte may suggest this lamproite Is a poor exploration target for diamond.
25	Take the east fork of the Y prior to turning north at the first trail to Boar's Tusk. On the right is Matthews Hill. Matthews Hill is a remnant of a volcanic neck that

Cumulative mileage from Rock Springs	Description
	forms a low, rounded knoll rising 40 feet above the surrounding terrain.
28	***Stop 2. Boar's Tusk***
	Boars Tusk forms a prominent volcanic neck of wyomingite (phlogopite-leucite-lamproite) rising more than 300 feet above the valley floor. The neck is an agglomerate composed of abundant Green River and Wasatch Formation xenoliths (shales, siltstones, breccias) and autobreccia fragments of lamproite. In addition to the sedimentary xenoliths, some granitic xenoliths are also present. Continue east toward Table Mountain.
37.5	Continue straight past the Westpine Canyon oil field turnoff on the right, and continue past Table Mountain on the south. Table Mountain consists of North Table Mountain, Middle Table Mountain, and South Table Mountain. North Table Mountain is a volcanic mesa capped by a single flow that exhibits well-developed flow layering.
	The layers consist of light grey orendite and dark grey wyomingite. Vents are not conspicuous on South Table Mountain or North Table Mountain. On the south margin of North Table Mountain is a small volcanic plug known as Middle Table Mountain. It consists of greenish layers of madupite alternating with dark grey to brownish layers of wyomingite on a centimeter scale.
	South Table Mountain is the prominent mesa behind (southeast) North Table Mountain. South Table Mountain is predominantly orendite with some wyomingite. Olivine phenocrysts in the rock led Carmicheal to propose the name olivine orendite.
	The phlogopite lamproites from South Table Mountain are comparatively MgO-rich due to the presence of phenocrystal and xenocrystal olivine. Small inclusions of dunite have been reported at South Table Mountain.

Cumulative mileage from Rock Springs	Description
	Madupitic lavas from Middle Table Mountain are silica-poor and magnesian-rich relative to other lavas in the Leucite Hills. The madupitic lavas are enriched in Ba, Sr, Th, and REE, are depleted in Ni, and have lower K/Rb ratios than the phlogopite lamproites, which suggests the madupitic lamproites are derivatives of phlogopite lamproites. Shale xenoliths at Middle Table Mountain are surrounded by green reaction rims 1 to 2 cm wide. Inclusions composed of some phlogopite-apatite-glass are reported at Middle Table Mountain.
48	Turn left onto County Road 83 to Steamboat Mountain.
51	***Stop 3. Steamboat Mountain*** Overlook of Leucite Hills. Looking south, from left to right, are Black Rock, Spring Butte (in the distance is Black Butte), Zirkel Mesa with its five cinder cones, Hatcher Mesa (flat top butte in front of Emmons Mesa) and Deer Butte on the skyline (Aspen Mountain lies between Emmons and Deer Butte). Emmons Mesa is made up of a cone and at least two flows with an overlapping flow that predates the cone. Pyroxene-plagioclase-phlogopite rocks, amphibolites, anorthosites, granulites, granites, and sedimentary rocks are found as xenoliths in the cone, while the flow contains only sedimentary and granite xenoliths. Rocks from Steamboat Mesa consist of aphanitic vesicular flows. Xenoliths are uncommon, and only sedimentary xenoliths have been found here. A glassy sample of wyomingite collected from this mesa yielded 12.66% K_2O, indicating that this lava is one of the most potassic lavas in the world. Backtrack down the mountain and turn east (left) on Tri-territory Road.
56.5	Intersection, turn east.
59	Turn on jeep trail to right towards Black Rock.

Cumulative mileage from Rock Springs	Description
60	***Stop 4. Black Rock***
	Black Rock marks the easternmost extent of the Leucite Hills volcanic rocks. Black Rock consists of a basal pyroclastic olivine orendite tuff overlain by a lava flow. The upper 80 feet of the mesa consists of alternating layers of vesicular and nonvesicular lava. In all probability, the mesa is a lava flow that obscures hidden vent facies lamproites.
	Small nodules of dunite have been identified at Black Rock. Olivine phenocrysts are associated with the lavas. One generation of olivine has a calcium content of 0.3%, is Fo90, and has red reaction rims, while another generation has 0.2% CaO and is Fo86. Inclusions composed of phlogopite, apatite, and glass are found at Black Rock. These are highly vesiculated with the vesicles possibly filled with zeolites. Backtrack on jeep trail.
61	Turn west (left) on Tri-territory road and continue south past Spring Butte. Spring Butte is considered the type locality for orendite and was originally named Orenda Mesa. Flow thicknesses at Spring Butte range from 10 to 77 feet. The butte is a compound volcanic center with six cinder cones, at least six flows, and three dikes. The cones consist of welded clastic flows with ribbon and breadcrust bombs. Fort Union Formation sandstones with some rare anorthosites were found as xenoliths at Spring Butte.
71	Deadman Gulch. Turn right towards Hatcher Mesa. Caution, this is a jeep trail!
79	***Stop 5. Hatcher Mesa***
	Hatcher Mesa is an eroded remnant of a small ponded lava flow. The center of the mesa is 6 feet lower than the edges, indicating the surface sagged and the lava flowed back into the vent. The vent is not conspicuous.

Cumulative mileage from Rock Springs	Description
	Composed mainly of orendite, the mesa contains the most abundant and diverse assemblage of xenoliths and xenocrysts in the Leucite Hills. Hatcher mesa consists of light grey to brownish grey vesicular lava with small 2 mm phlogopite grains and black to dark green 2.5 mm clinopyroxene grains. Petrographically, these rocks consist of microphenocrysts of clinopyroxene, phlogopite, apatite, and iron-titanium oxide with uncommon grains of olivine, in a groundmass of leucite, clinopyroxene, potassium richterite, apatite, priderite, wadeite, and glass. The absence of sanidine in these rocks distinguishes them as wyomingites. Whole rock analyses show the rocks contain relatively high K_2O, BaO, SrO, P_2O_5, and ZrO, and relatively low Na_2O and Al_2O_3 compared to the typically mafic volcanic rock (Barton and Bergen, 1981). Xenoliths from this locality include rocks of mafic and ultramafic affinity. Xenoliths include granite, norite, and mica schist. Olivine grains from Hatcher Mesa are unzoned and characterized by high $Mg/(Mg^{+}\sum Fe^{2+})$ and Ni. In this respect, the olivines are comparable to olivines in lherzolite and harzburgite mantle xenoliths found in kimberlite. Inclusions composed of phlogopite, apatite, and glass similar to those at Black Rock are also found at Hatcher Mesa. These are highly vesiculated (the vesicles could be filled with zeolites), easily weather out, and are found as talus at the base of Hatcher Mesa.
84	Return back to the Superior Road. Turn south toward Zirkel Mesa.
94	Turn north on jeep road leading to south flank of Zirkel Mesa.

Cumulative mileage from Rock Springs	Description
96	***Stop 6. Zirkel Mesa Quarry***
	Highly vesicular pumaceous leucite lamproite is exposed in the quarry showing flow banding with common country rock xenoliths. Locally, the lava has a ropey appearence.
	Zirkel Mesa is the largest of the lamproite exposures in the Leucite Hills and is composed primarily of orendite. Flow thicknesses vary from less than 3 feet to as much as 50 feet.
	The mesa consists of six cinder cones which rise more than 240 feet above the mesa surface. These cones coelesce into a single, volcanic-capped plateau. K-Ar dates for two phlogopites from the mesa indicated an age of 1.25 Ma.
	An estimated 197 million tons of potash was reported available in the Leucite Hills in 1912. Following this report, the Liberty Potash Company quarried wyomingite from Zirkel Mesa during World War I and operated a plant in Green River to produce KCl for fertilizer.
	At Zirkel Mesa, a cone postdates a flow. The flow has a xenolith assemblage of pyroxene-plagioclase-phlogopite-amphibole, anorthosite, granulite, granite, and sedimentary rocks, while the cone contains only sedimentary xenoliths. The earlier eruption of the flow carried the most diverse assemblage, while the settling of xenoliths may have occurred prior to the eruption of the cone. This suggests that the magma chamber possibly shifted to a higher stratigraphic depth, or that the last of the magma stalled in the magma chamber for a sufficient length of time to allow for the settling of its lower crustal xenolith content.

APPENDIX 1: LAMPROITE LOCALITIES

Black Rock (Black Rock Mesa)

Black Rock forms the easternmost extent of the Leucite Hills volcanic field. Cross (1897) and Cross and Schultz (1912) interpreted Black Rock to represent a volcanic plug based on the lack of an exposed contact between the volcanic rock and adjacent sediments.

Mapping by Ogden (1979) showed Black Rock to consist of a 120 foot section of volcanic rock. The lower 45 feet is friable, poorly-lithified, basal pyroclastic overlain by 75 feet of lava with alternating vesicular and non-vesicular texture. The presence of columnar jointing along the northwestern margin of the mesa, and the lack of volcaniclastics supports that the exposed portion of Black Rock represents a flow rather than a plug. The mesa is depressed at its center, and the low point of the depression is thought to mark the location of a hidden vent flooded by the terminal flow.

The lava forming Black Rock is an olivine-leucite-diopside-sanidine-phlogopite lamproite. The presence of sanidine indicates the rock to be a olivine orendite. Petrographically, samples of the lava contain microphenocrysts of partially resorbed phlogopite mica, euhedral diopside, minor subhedral to anhedral K-Ti-richterite, anhedral sanidine, and two generations of olivine lying in an aphanitic groundmass. The groundmass contains some recognizable leucite grains and sanidine laths.

Inclusions consisting of phlogopite, apatite, and glass are also found in the Black Rock lamproite. These are highly vesiculated with vesicles filled with zeolite. According to Carmichael (1974), the inclusions represent cognate xenoliths interpreted as an immiscible liquid magma phase.

The olivine in the Black Rock lamproite, occurs as anhedral xenocrystal olivine enclosed by a reaction rim of phlogopite, and as primary euhedral olivine. The anhedral olivine is a xenocryst that was out-of-equilibrium with the lamproitic magma. According to Carmichael (1967) one generation of olivine found in the Leucite Hills has a calcium content of 0.3% and a composition of Fo_{90}, while a second generation of olivine has 0.2% CaO with a composition of Fo_{86}. In addition to primary and xenocrystal olivine, some dunite nodules are found (Speer, 1985).

Olivine collected from anthills surrounding Black Rock includes cloudy, olive-green and uncommon reddish orange olivine with relatively well-developed cleavage, and transparent olive green crystals that lack well-developed cleavage. A sample collected along the western margin of Black Rock from two ant hills was concentrated and yielded 13,000 carats of olivine and transparent peridot in grains that ranged from 1 to 8 mm in length (the maximum size that could be carried by ants) (Hausel, 1998). Samples of transparent olivine more than 1 inch across, have also recovered from outcrops from Black Rock. Black Rock and the surrounding soils represent a potential source for both industrial and gem-quality olivine.

Boar's Tusk (Sentinel and Rock Point)

Boars Tusk was originally identified as the Sentinel on Hayden Survey maps, and as Rock Point and by F. M. Endlich (Kemp and Knight, 1903).

Boars Tusk forms a prominent volcanic neck which lies along a north-trending dike composed of diopside-leucite-phlogopite lamproite (wyomingite). The neck rises more than 300 feet above the Killpecker valley floor, and consists of agglomerate and tuff with abundant shale, siltstone, and breccia xenoliths of the Green River and Wasatch Formations with autobreccia fragments of lamproite.

The volcanic neck consists of two spires. The southern spire is zoned, and has an outer zone of dense, non-vesicular lava with abundant country rock xenoliths ranging from microscopic to 2 inches in size. The outer zone contains an inner zone of dense lava with fewer xenoliths. In addition, patches of volcanic agglomerate occur on the southern spire with xenoliths of country rock and autobrecciated fragments of lava. The autobrecciated fragments range in size from microscopic to about 6 inches (Ogden, 1979).

Samples of the lamproite contain microphenocrysts of strongly aligned, prismatic phlogopite. These occur with uncommon diopside with pseudo-hexagonal cross-sections, and some colorless leucite with pseudo-cubic cross sections in an opaque, aphanitic groundmass. The groundmass is dull-greenish, and its mineralogical composition is indeterminable with a petrographic microscope.

Cabin Butte (Osborn Mesa)

Originally named Osborn Mesa by Kemp and Knight (1903). Cabin Butte consists of an orendite lava flow with a volcanic plug dome along its northern edge (Ogden, 1979). Petrographically, the rock is very fine-grained with aphanitic groundmass. Mineralogically, the rock contains sanidine, minor leucite, diopside, K-Ti richterite, and phlogopite. Kemp and Knight (1903), also reported the presence of rutile.

Deer Butte (Cross Mesa)

Deer Butte is a remnant of a composite volcanic center which includes two cinder cones, three separate lava flows, and a vent exposed in its southern wall. The scoria of Deer Butte is composed of wyomingite, while the lava is predominately orendite (Ogden, 1979). The orendite has micro-porphyritic texture with microphenocrysts of tetragonal richterite, phlogopite, priderite, and diopside, in a fine-grained groundmass containing prismatic laths of sanidine and leucite trapazoids.

Some richterite exhibits the distinct pale-yellow to reddish-brown pleochroism as described by Cross (1897). The scoria from the cinder cone is sanidine-poor and is predominately wyomingite (Kemp and Knight, 1903). Richterite may occur in optically continuous plates (up to 0.5 mm) enclosing euhedral crystals of leucite, diopside, apatite, wadeite, and priderite in the coarse-grained rocks at Deer Butte (Mitchell and Bergman, 1991).

Emmons Mesa

Emmons Mesa is formed predominately of orendite (however, Kemp and Knight, 1903, suggest the rock is wyomingite). It includes a large cinder cone that rises above the mesa that is visible for several miles, a small cinder cone that rises only about 8 to 9 feet above the surface of the lava flow, and at least two flows including a third overlapping flow that predates the cone.

The cone contains xenoliths of a rock formed of pyroxene, plagioclase, and phlogopite, as well as fragments of amphibolite, anorthosite, granulite, granite, and sedimentary rocks; whereas the flow only contains granites and sedimentary xenoliths (Ogden, 1979). Xenoliths of colorless anhedral augite intergrown with olivine and phlogopite, are reported at the mesa (Mitchell and Bergman, 1991).

In thin section, samples exhibit porphyritic texture with microphenocrysts of phlogopite, common tetragonal prisms of richterite, and some priderite in a crystalline groundmass of leucite trapazoids, diopside, and uncommon sanidine laths. Based on the presence of sanidine, the rock is orendite.

Endlich Hill

Endlich Hill and nearby Hague Hill, consist of fragmented blocks of lamproite that resulted from the removal of underlying, supporting, sediments during erosion. Breakage of the blocks was controlled by cooling joints in the lava (Odgen, 1979).

Rocks from Endlich Hill are olivine orendites and are found in the form of scoria, lava, and volcaniclastics. Samples contain phlogopite, leucite, sanidine, richterite, and olivine. Olivine is not common, and more than one generation has been recognized (Cross, 1897; Carmichael, 1967). In addition to anhedral xenocrysts and subhedral to euhedral microphenocrysts, the lamproites enclose anhedral olivine mantled by phlogopite laths in disequilibrium with the host magma. These olivine grains probably represent upper-mantle derived xenocrysts. The primary microphenocrystal olivines in these rocks crystallized after phlogopite, which is the reverse sequence found in most other lamproites (Mitchell and Bergman, 1991).

Hague Hill

Hague Hill forms a low-lying hill south of Endlich Hill. The lavas at Hague Hill are composed of orendite (Ogden, 1979). Samples contain uncommon xenocrysts of olivine mantled by a phlogopite reaction rims. Some minor olivine occurs in a groundmass with sanidine, diopside, leucite and uncommon richterite. According to (Mitchell and Bergman, 1991), potassium richterite is found in small euhedral prisms lining vesicles.

Hatcher Mesa

According to Ogden (1979), Hatcher Mesa is an eroded remnant of a small ponded lava flow. The center of the mesa is depressed by 6 feet relative to the edges indicating the surface sagged as the lava flowed back into the vent. The vent is not conspicuous. According to Smithson (1959), Hatcher mesa is composed primarily of orendite with some wyomingite at the basal part of the flows.

The mesa is composed of light grey to brownish grey vesicular lava. In-hand samples of the lava are light grey to brownish grey vesicular rock with crystals of red-brown phlogopite and black to dark green clinopyroxene (Barton and van Bergen, 1981). Petrographically, the lava contains microphenocrysts of clinopyroxene, phlogopite, apatite, and iron-titanium oxide with uncommon grains of olivine in a groundmass of leucite, clinopyroxene, potassium richterite, apatite, priderite, wadeite, and glass. The absence of sanidine distinguishes the rocks as wyomingite. Whole rock analyses show the rocks contain relatively high K_2O, BaO, SrO, P_2O_5, and ZrO, and relatively low Na_2O and Al_2O_3 compared to a typical mafic volcanic rock (Barton and Bergen, 1981).

The lavas contain the most abundant and diverse assemblage of xenoliths and xenocrysts in the Leucite Hills. Xenoliths from this locality include rocks of both mafic and ultramafic affinity. According to Smithson (1959) the xenolith assemblage includes granite, norite, and mica schist.

Olivine grains from Hatcher Mesa are unzoned and characterized by high $Mg/(Mg+\sum Fe^{2+})$ and Ni. In this respect, the olivine is comparable to olivines in lherzolite and harzburgite mantle xenoliths found in kimberlite (Barton and van Bergen, 1981). Inclusions composed of phlogopite, apatite, and glass similar to those at Black Rock, are also found at Hatcher Mesa. These are highly vesiculated with the vesicles filled with zeolites. These easily weather out and are found as talus at the base of Hatcher Mesa.

Pyroxenes at Hatcher Mesa include green salites as single crystals mantled by diopside. The salites are thought to be derived from the disaggregation of ultramafic xenoliths (Barton and van Bergen, 1981). Green salitic pyroxenes are wholly or partially surrounded by thin rims of diopside, and occur as cores of diopside phenocrysts. Colorless anhedral augites are intergrown with olivine and phlogopite in xenoliths (Mitchell and Bergman, 1991).

Matthews Hill

Matthews Hill is a remnant of a volcanic neck that forms a low, rounded, knoll rising 40 feet above the surrounding terrane. It lies about a mile southeast of Boar's Tusk. On the crest of the hill, a narrow dike, about 180 feet in length trends northeast. This is separated from a small dike with nearly perpendicular strike to the first dike by 15 feet of sandstone.

A short distance beyond the cross-dike, two other dikes strike N10°W. The first dike has a length of 60 feet and is separated by 10 feet of shale from the second dike. The dikes show distinct strong fabric, and occasional pieces of agglomerate are also found. Matthew Hill represents a deeply dissected volcanic neck. Samples of the orendite contain abundant phlogopite, some diopside and sanidine.

Middle Table Mountain (South Table Mountain)

Located along the southern margin of North Table Mountain is a small volcanic plug known as Middle Table Mountain. Kemp and Knight (1903) referred to it as South Table Mountain. It has greenish layers of madupite alternating with grey to brownish layers of wyomingite (Odgen, 1979). Samples from Middle Table Mountain contain madupitic phlogopite in a groundmass of leucite, diopside and apatite.

The madupitic lavas at Middle Table Mountain are silica-poor and magnesian-rich relative to many other lavas in the Leucite Hills. Shale xenoliths in the lavas are surrounded by green reaction rims approximately 1 to 2 cm wide (Speer, 1985). Some phlogopite-apatite-glass inclusions are reported at Middle Table Mountain.

North Table Mountain

North Table Mountain is a volcanic mesa capped by a single flow that exhibits well-developed flow layering. The layers consist of light-grey orendite and dark-grey wyomingite. Samples were reported to contain a "pecular yellow hornblende" (possibly richterite) along with diopside by Kemp and Knight (1903). Vents are not conspicuous at North Table Mountain nor at the adjacent South Table Mountain.

Pilot Butte

Pilot Butte is the westernmost lamproite in the Leucite Hills, and lies on a high plateau formed of Green River shales about 12 miles northwest of Rock Springs. It forms a volcanic neck with a single lobate lava flow. The lavas contain abundant green River Formation xenoliths. Two small dikes are exposed on the southwest flank of the butte.

The madupitic lavas at Pilot Butte are silica-poor and magnesian-rich relative to other lavas in the Leucite Hills. They are enriched in Ba, Sr, Th and REE and are depleted in Ni with lower K/Rb ratios than most phlogopitic lamproites (Mitchell and Bergman, 1991). Spinels from the lavas at Pilot Butte are chrome-poor (>1% by weight Cr_2O_3), magnesian (<5% by weight MgO), titaniferous (>10% by weight TiO_2) magnetites, that are unlike the chrome-spinels (9-58% by weight Cr_2O_3) found in the diamondiferous lamproites in Western Australia and Murfreesburo, Arkansas. The lack of chrome spinels at Pilot Butte suggests this lamproite may be a poor exploration target for diamond.

In addition to spinel, the Pilot Butte lavas contain poikalitic phlogopite enclosing diopside in a matrix of greenish-brown glass. The diopside grains are euhedral to subhedral, colorless, with uncommon twinning. Phlogopite is the last mineral phase to crystallize in the madupite. Accessory minerals found in abundance in the groundmass include perovskite and wadeite (Kuehner, 1980).

South Table Mountain (North Pilot Butte, Black Butte)

Referred to as North Pilot Butte by Kemp and Knight (1903), and as Black Butte by Endlich. South Table Mountain forms a prominent mesa adjacent to North Table Mountain, and consists of olivine orendite with some wyomingite. Kemp and Knight (1903) reported that the rock contained phlogopite, diopside, and apatite, with some leucite and possible glass. Some samples were also described to contain yellow hornblende (possibly richterite).

The presence of olivine phenocrysts in the rock led Carmichael (1967) to propose the name olivine orendite for the rock. The flows on South Table Mountain are relatively MgO-rich due to the presence of phenocrystal and xenocrystal olivine. Small dunite xenoliths have also been found in these rocks. The xenocrystal olivine exhibits olivine enclosed by a reaction rim of phlogopite. The phlogopite is often surrounded by crowns and borders of deep mahogany red rutile (Kemp and Knight, 1903. Leucite is rare in these rocks with abundant sanidine.

Spring Butte (Orenda Mesa)

Spring Butte is considered the type locality of orendite. Flow thicknesses at Spring Butte range from 10 to 77 feet. The butte is a compound volcano with six cinder cones, at least six flows, and three dikes. The cones consist of welded clastic flows with ribbon and breadcrust bombs (Ogden, 1979). Smithson (1959) reported Ft. Union Formation sandstones with some rare anorthosites were found as xenoliths at Spring Butte. Samples of the magma are predominately orendite, although some wyomingite occurs. The orendite contains aligned microphenocrysts of phlogopite and K-richterite in a fine-grained groundmass dominated by leucite with some diopside and sanidine.

Steamboat Mountain (Essex Mountain)

Steamboat Mountain was originally named Essex Mountain by F.M Endlich of the Hayden Survey. Rocks from Steamboat Mountain consist of aphanitic vesicular flows. Xenoliths are uncommon and only sedimentary xenoliths have been found. According to Carmicheal (1967), a glassy sample of wyomingite collected from this mesa yielded 12.66% K_2O making this one of the most potassic lavas in the world. These rocks are predominately orendite and contain phenocrysts of phlogopite and some priderite in a groundmass of leucite, sanidine, diopside, and apatite. Kemp and Knight (1903), report some amgydules are lined with crusts of chalcedony.

Twin Rocks (Badger's Teeth)

Twin Rocks form five small projections of xenolith-rich lava that rise from an inverted cone. The projections occur along an east-west trend. These are part of a volcanic neck conduit which rose as apophyses from a subsurface dike. The bulk of the neck is formed from autobrecciated agglomerate.

Texturally these rocks are wyomingites, but chemically they are similar to madupite (Odgen, 1979). Phlogopite is found as microphenocrysts in the lava, and in the groundmass. Some of the groundmass phlogopite encloses diopside, perovskite, and apatite. Analcime occurs as pseudomorphs after leucite (Keuhner, 1980). Euhedral opaque minerals occur in the rims of phlogopite microphenocrysts. Some of the diopside exhibits simple twinning and is enclosed in a groundmass of yellow-green glass. Kemp and Knight (1903) also reported uncommon sanidine.

Wortman Dike (Iddings, Weed, and Hallock Buttes)

These occur as three small volcanic necks of wyomingite lava and agglomerate lying along a N40°W trend between Hague Hill and South Table Mountain. The buttes are apophyses originating from a dike in the subsurface. Iddings Butte is zoned and is formed of dense lava with an exterior of volcanic agglomerate (Ogden, 1979). Phlogopite is the most prominent mineral present and forms phenocrysts in a dense groundmass of phlogopite, diopside, leucite, apatite, and glass (Kemp and Knight, 1903).

According to Kemp and Knight (1903), the rock at Iddings butte is a dark gray orendite marked by schistose-like texture produced from parallel alignment of phlogopite. Microscopically, the rock contains leucite, much sanidine, considerable diopside, and abundant phlogopite. The agglomerate contains common sedimentary xenoliths.

Zirkel Mesa

The largest lamproite exposure in the Leucite Hills is Zirkel Mesa. This mesa is composed primarily of orendite with abundant phlogopite in a groundmass of sanidine with lesser leucite. Flow thicknesses vary from less than 3 feet to as much as 50 feet (Kuehner, 1980). Highly vesicular pumaceous leucite lamproite is exposed in a quarry along the eastern edge of the mesa which exhibits flow banding and common country rock xenoliths. Locally, the lava has a ropy appearance (Hausel and others, 1995).

Ogden (1979) reported six cinder cones rose more than 240 feet above the mesa surface. The cones are formed of cinders, while one is made up of dense lava (Smithson, 1959). These cones coelesce into a single, volcanic-capped plateau. K-Ar dates from two phlogopites yielded 1.25 Ma ages (Bradley, 1964).

At Zirkel Mesa, one cone postdates a flow. The flow has an xenolith assemblage of pyroxene-plagioclase-phlogopite-amphibole, anorthosite, granulite, granite, and sedimentary rocks, while the cone only contains sedimentary xenoliths. The interpretation is that the earlier eruption of the flow carried the most diverse assemblage, while the settling of xenoliths may have occurred prior to the eruption of the cone. This suggests the possibly that the magma chamber shifted to a higher stratigraphic depth, or that the last the magma stalled in the magma chamber for a sufficient length of time to allow for the settling of the lower crustal xenoliths. The rock is dominated by orendite with some wyomingite and includes K-richterite, leucite, diopside, phlogopite, sanidine, apatite, and rutile.

APPENDIX 2

Whole rock analyses of lamproites from the Leucite Hills

Data includes both published analyses and analyses completed for this study.

	1	2	3	4	5	6	7	8
SiO_2	46.5	50.23	55.14	43.56	51.03	52.98	51.57	54.86
TiO_2	2.30	2.30	2.58	2.31	2.67	2.55	2.42	2.52
ZrO_2	0.19	0.25	0.27	0.27	0.17	0.17	0.17	0.18
Al_2O_3	11.5	10.15	10.35	7.85	9.81	10.49	10.10	10.80
Fe_2O_3	5.3	3.65	3.27	5.57	3.67	2.64	2.85	3.00
Cr_2O_3	-	0.06	0.04	0.04	0.07	0.06	0.08	0.06
FeO	0.14	1.21	0.62	0.85	0.65	1.94	1.63	0.96
MnO	0.09	0.09	0.06	0.15	0.07	0.07	0.08	0.05
MgO	8.06	7.48	6.41	11.03	7.24	7.23	7.78	6.65
CaO	7.63	6.12	3.45	11.89	5.37	4.31	5.03	3.57
SrO	0.41	0.32	0.26	0.40	0.32	0.22	0.26	0.20
BaO	0.62	0.61	0.52	0.66	0.78	0.60	0.73	0.52
Na_2O	2.88	1.29	1.21	0.74	1.03	1.29	1.31	1.24
K_2O	10.4	10.48	11.77	7.19	10.61	11.15	11.32	10.70
P_2O_5	1.81	1.81	1.40	1.50	1.71	1.37	1.61	1.32
SO_3	-	0.35	0.40	0.52	1.00	-	-	0.37
H_2O	-	3.43	1.84	4.98	2.91	-	-	-
LOI	2.80	-	-	-	-	2.86	2.79	3.24
TOTAL	100.6	99.83	99.59	99.51	100.05	99.93	99.74	100.15

1. Chemical analysis of wyomingite from Hatcher Mesa (Barton and van Bergen, 1981); 2. wyomingite (LH-1) (Carmichael, 1967); 3. orendite (LH12) (Carmichael, 1967); 4. madupite (LH16) (Carmichael, 1967); 5. wyomingite (Kuehner, 1980); 6. wyomingite (Kuehner, 1980); 7. wyomingite (Kuehner, 1980); 8. orendite (Kuehner, 1980).

	9	10	11	12	13	14	15	16
SiO_2	53.45	42.71	46.44	43.10	43.16	54.17	54.08	58.6
TiO_2	2.14	2.40	2.61	2.32	2.35	2.67	2.08	4.9
ZrO_2	0.17	0.17	-	0.17	0.16	0.22	-	-
Al_2O_3	10.27	7.67	8.32	8.58	8.37	10.16	9.49	7.0
Fe_2O_3	3.60	4.72	5.90	5.34	4.85	3.34	3.19	-
Cr_2O_3	0.08	0.08	-	0.09	0.06	0.05	0.07	-
FeO	1.00	1.46	0.62	0.80	0.84	0.65	1.03	4.5
MnO	0.08	0.14	-	0.13	0.14	0.06	0.05	0.05
MgO	9.61	11.75	12.75	11.60	8.21	6.62	6.74	3.8
CaO	4.21	13.13	14.26	10.71	12.84	4.19	3.55	9.6
SrO	0.20	0.58	-	0.38	0.57	0.18	0.20	0.2
BaO	0.34	0.91	-	0.48	1.38	0.59	0.67	1.1
Na_2O	1.26	0.50	0.54	0.93	2.23	1.21	1.39	0.7
K_2O	10.62	2.52	6.68	8.53	4.31	11.91	11.76	8.0
P_2O_5	1.28	1.60	1.70	2.13	2.55	1.59	1.35	0.06
SO_3	-	-	-	0.50	0.50	0.16	0.29	-
H_2O	1.15	-	-	3.87	4.65	1.53	3.50	-
LOI	-	9.44	-	-	-	-	-	-
TOTAL	100.42	99.78	100.00	100.55	100.33	100.05	99.75	98.5

9. olivine orendite (Kuehner, 1980); 10. madupite (Kuehner, 1980); 11. madupite (Kuehner, 1980); 12. madupite (Kuehner, 1980); 13. transitional rock (Kuehner, 1980); 14. orendite, North Table Mountain (Cross, 1897); 15. orendite, Zirkel Mesa (Cross, 1897); 16. Glassy wyomingite lava, Steamboat Mountain (Carmichael, 1967).

	17	18	19	20	21	22	23	24
SiO_2	53.07	51.07	42.65	42.82	47.54	50.23	53.70	55.43
TiO_2	2.41	2.13	1.64	2.39	2.60	2.27	1.92	2.64
ZrO_2	0.26	-	-	1.60	0.43	-	-	0.20
Al_2O_3	8.96	9.93	9.14	8.14	11.28	11.22	11.16	9.73
Fe_2O_3	3.86	2.72	5.13	5.89	4.96	3.34	3.10	2.12
Cr_2O_3	0.08	-	0.07	-	-	0.10	0.04	0.02
FeO	0.91	1.19	1.07	0.70	0.96	1.84	1.21	1.48
MnO	0.08	-	0.12	0.14	0.03	0.05	0.04	0.08
MgO	11.17	10.31	10.89	10.83	7.84	7.09	6.44	6.11
CaO	3.56	4.87	12.36	12.42	9.31	5.99	3.46	2.69
SrO	0.27	-	0.33	-	-	0.24	0.19	0.27
BaO	0.34	-	0.89	0.96	0.56	1.23	0.62	0.64
Na_2O	1.15	0.82	0.90	0.54	0.81	1.37	1.67	0.94
K_2O	10.72	9.92	7.99	6.56	9.08	9.81	11.16	12.66
P_2O_5	1.24	1.53	1.52	1.39	0.72	1.89	1.75	1.52
SO_3	0.16	0.33	0.58	0.60	-	0.74	0.06	0.46
H_2O+	1.16	4.23	2.18	3.00	3.78	1.72	2.61	2.07
H_2O-	0.40	-	2.04	-	-	0.93	0.80	0.61
F	-	-	-	-	-	0.50	0.44	-
Cl	-	-	0.03	-	-	0.03	0.03	-
TOTAL	99.80	99.66	99.90	97.99	99.90	100.40	100.20	99.75

17. olivine orendite, South Table Mountain (Carmichael, 1967); 18. olivine orendite, Hallock Butte (Schultz and Cross, 1912); 19. madupite, Pilot Butte (Cross, 1897); 20. madupite, Pilot Butte (Smithson, 1959); 21. transitional rock, Middle Table Butte (Johnson, 1959); 22. wyomingite, Boar's Tusk (Cross, 1897); 23. wyomingite, Zirkel Mesa (Cross, 1897); 24. wyomingite, Steamboat Mountain (Carmichael, 1967).

	25	26	27	28	29	30	31	32
SiO_2	48.94	52.64	50.20	51.0	52.4	51.1	52.5	51.2
TiO_2	1.76	1.73	2.30	2.4	2.3	2.7	2.4	2.4
ZrO_2	-	-	-	-	-	-	-	-
Al_2O_3	12.44	13.38	11.39	8.9	10.7	9.7	9.1	10.0
Fe_2O_3	4.28	5.19	4.23	4.9	3.8	4.9	4.9	5.4
Cr_2O_3	0.09	0.03	-	-	-	-	-	-
FeO	3.71	1.63	0.57	-	-	-	-	-
MnO	0.10	0.09	0.07	0.71	0.056	0.068	0.066	0.08
MgO	5.84	4.40	7.23	9.2	6.5	7.2	7.3	7.4
CaO	4.77	3.16	6.00	4.6	4.5	4.9	4.9	7.2
SrO	0.38	0.22	-	0.3	0.4	0.32	0.29	0.42
BaO	0.81	0.37	-	0.5	0.6	0.6	0.7	0.9
Na_2O	2.17	2.22	0.86	2.9	1.6	1.5	1.3	2.0
K_2O	11.01	11.96	10.19	8.1	11.0	11.4	9.9	10.5
P_2O_5	0.47	0.44	-	1.9	1.8	1.4	1.7	1.9
SO_3	0.44	0.09	-	-	-	-	-	-
H_2O+	1.43	1.87	3.54	1.6	0.8	-	-	1.2
H_2O-	0.54	0.44	-	-	-	-	-	-
F	0.71	0.53	-	-	-	-	-	-
Cl	0.05	0.03	-	-	-	-	-	-
TOTAL	99.69	100.10	98.52	98.4				100.6

25. wyomingite, Emmons Cone (Yagi and Matsumoto, 1966); 26. wyomingite, Emmons Cone (Yagi and Matsumoto, 1966); 27. wyomingite, Boar's Tusk (Barton and Hamilton, 1978). 28. average of five samples from Black Rock (Ogden, 1979); 29. average of 2 orendite samples from Cabin Butte (Odgen, 1979); 30. average of 8 samples from Deer Butte (Ogden, 1979); 31. average of 8 samples from Emmons Mesa (Ogden, 1979); 32. Hatcher Mesa (Ogden, 1979).

	33	34	35	36	37	38	39	40
SiO_2	47.0	55.0	43.9	52.6	52.2	55.3	46.9	52.0
TiO_2	2.5	2.6	2.3	2.3	2.5	2.6	2.5	2.3
ZrO_2	-	-	-	-	-	-	-	-
Al_2O_3	8.7	10.3	8.0	9.2	9.5	10.5	8.2	9.4
Fe_2O_3	5.9	4.2	6.5	4.9	4.8	4.1	5.4	5.1
Cr_2O_3	-	-	-	-	-	-	-	-
FeO	-	-	-	-	-	-	-	-
MnO	0.103	0.05	0.116	0.061	0.068	0.044	0.079	0.027
MgO	9.1	6.2	10.3	9.4	7.5	5.8	8.7	9.5
CaO	8.6	3.4	11.3	3.7	5.1	2.8	10.4	3.6
SrO	0.39	0.2	0.46	0.23	0.22	0.21	0.6	0.25
BaO	0.8	0.7	1.0	0.5	0.7	0.6	1.2	0.7
Na_2O	0.9	1.0	0.9	1.2	1.3	1.2	1.8	0.6
K_2O	7.7	11.3	6.3	10.0	11.0	12.1	6.1	10.0
P_2O_5	0.27	0.22	2.2	1.3	1.7	1.6	2.1	nd
H_2O+	-	-	-	-	-	-	2.7	1.8
TOTAL							96.7	95.3

33. Average of 11 samples, Middle Table Mountain (Ogden, 1979); 34. Average of 8 samples, North Table Mountain (Odgen, 1979); 35. Average of 5 madupite samples, Pilot Butte (Ogden, 1979); 36. Average of 11 samples, South Table Mountain (Ogden, 1979); 37. Average of 2 wyomingite samples, Spring Butte, (Ogden, 1979); 38. Average of 20 samples, Steamboat Mountain (Ogden, 1979); 39. Twin Rocks (Ogden, 1979); 40. Wyomingite, Wortman dike (Ogden, 1979).

	41	42	43	44	45	46	47
SiO_2	51.4	53.7	51.41	53.14	71.60	56.34	51.32
TiO_2	2.5	1.92	1.92	2.26	0.91	1.94	2.20
Al_2O_3	9.9	11.16	11.00	9.46	10.48	9.67	9.25
Fe_2O_3	4.7	3.10	3.10	4.61	1.13	2.96	3.66
FeO	-	1.21	1.21	0.13	2.25	1.42	1.35
MnO	0.059	-	-	0.06	0.04	0.06	0.07
MgO	6.3	6.44	8.35	10.02	3.30	8.62	11.11
CaO	4.6	3.46	6.07	3.84	2.11	3.83	4.88
SrO	0.28	-	-	-	-	-	-
BaO	0.8	-	-	-	-	-	-
Na_2O	1.3	1.67	1.40	1.43	1.03	0.81	1.39
K_2O	11.3	11.16	11.40	10.99	4.75	9.11	8.11
P_2O_5	1.5	1.75	1.20	1.09	0.56	1.31	1.44
H_2O	-	3.41	-	-	-	-	-
H_2O+	-	-	-	0.92	0.65	1.60	2.16
SO_3	-	0.06	0.31	-	-	-	-
CO_2	-	-	0.24	-	-	-	-
CO_3	-	-	-	0.27	0.07	0.25	0.15
F	-	0.44	-	-	-	-	-
LOI	-	-	2.79	1.97	0.90	2.39	3.86
TOTAL	-	-	100.4	99.11	99.34	98.68	98.90
Ba (ppm)	-	-	-	2906	1594	4664	5428
Nb (ppm)	-	-	-	37	18	36	44
Rb (ppm)	-	-	-	227	128	165	153
Sr (ppm)	-	-	-	1775	658	1693	>2000
Zr (ppm)	-	-	-	1926	619	1586	1893
Cr (ppm)	-	-	-	497	252	446	610
Ce (ppm)	-	-	-	283	120	245	320
Eu (ppm)	-	-	-	3.4	1.6	2.8	3.5
La (ppm)	-	-	-	149	64	128	177
Lu (ppm)	-	-	-	<0.2	0.3	<0.2	<0.2
Nd (ppm)	-	-	-	120	50	100	120
Sc (ppm)	-	-	-	11.8	8.5	10.9	12.3
Sm (ppm)	-	-	-	15.7	7.9	13.7	16.3
Tb (ppm)	-	-	-	<1	<1	<1	<1
Th (ppm)	-	-	-	16	12	16	20
U (ppm)	-	-	-	5	5	5	4
Y (ppm)	-	-	-	27	32	27	25
Yb (ppm)	-	-	-	1	2	1	1
Ni (ppm)	-	-	-	460	131	358	480

41. Average of 9 samples, Zirkel Mesa (Ogden, 1979); 42. Wyomingite from Zirkel Mesa (Wells, 1916); 43. Wyomingite, Zirkel Mesa (McCarthy and others, 1944); 44. Wyomingite (Hausel and others, 1994) Endlich Hill; 45. Volcaniclastic (Hausel and others, 1994), Endlich Hill; 46. Orendite (Hausel and others, 1994), Endlich Hill; 47. Orenditic volcaniclastic (Hausel and others, 1994) Endlich Hill.

	48	49	50	51	52	53	54	55
SiO_2	52.47	51.49	54.33	50.87	50.92	53.82	53.21	51.28
TiO_2	2.28	2.06	2.35	2.36	2.13	2.37	2.22	2.20
Al_2O_3	9.15	9.90	10.91	9.90	11.28	10.28	9.84	9.41
Fe_2O_3	4.87	4.72	3.80	4.64	8.68	4.55	4.95	5.18
Cr_2O_3	0.06	0.05	0.05	0.05	0.07	0.05	0.06	0.08
FeO	1.42	0.13	0.84	1.03	0.64	0.96	0.77	1.86
MnO	0.07	0.07	0.05	0.07	0.07	0.06	0.07	0.07
MgO	9.20	7.09	6.60	7.67	10.71	7.39	8.22	11.14
CaO	4.27	5.93	4.27	6.10	4.46	4.37	4.64	4.56
Na_2O	1.36	2.05	0.97	0.85	1.23	0.72	1.18	0.76
K_2O	11.55	9.56	11.83	10.60	10.60	11.31	10.31	9.59
P_2O_5	1.54	1.80	1.52	2.01	1.20	1.48	1.26	1.38
LOI	1.77	3.48	1.97	3.97	2.35	2.50	2.55	2.27
TOTAL	99.40	99.17	99.68	100.24	98.22	99.80	99.25	98.83
Ba (ppm)	4544	6443	6498	7112	4357	5516	3906	5494
Sr (ppm)	2185	2005	2417	3078	2332	2120	2082	2185
Zr (ppm)	1463	1178	1376	1329	1308	1375	1308	1386

48. Olivine lamproite from Black Rock; 49. Boar's Tusk; 50. Cabin Butte; 51. Deer Butte (Hausel and others, 1994); 52. Vesicular lamproite, Endlich Hill; 53. Phlogopite lamproite scoria, Emmons Mesa; 54. Hague Hill; 55. Aphanitic phlogopite lamproite, Wortman Dike.

	56	57	58	59	60	61	62	63
SiO_2	48.90	50.73	47.08	53.80	54.49	40.98	51.11	52.76
TiO_2	2.17	2.20	2.36	2.46	2.50	2.19	2.34	2.25
Al_2O_3	10.10	10.68	9.03	10.23	9.20	7.47	8.70	9.60
Fe_2O_3	5.51	4.84	5.52	3.75	3.45	5.87	4.23	4.77
Cr_2O_3	0.06	0.05	0.06	0.04	0.03	0.08	0.05	0.07
FeO	0.90	1.42	0.96	0.64	0.71	1.42	0.71	1.48
MnO	0.09	0.06	0.10	0.05	0.05	0.12	0.06	0.06
MgO	7.87	7.18	9.20	6.39	5.67	11.61	7.32	10.36
CaO	7.47	5.49	8.95	3.96	3.48	13.15	5.98	3.95
Na_2O	1.33	0.58	0.79	2.98	0.51	0.88	0.73	1.43
K_2O	9.76	8.94	7.22	7.22	9.70	3.16	9.60	10.26
P_2O_5	1.88	1.89	1.02	1.66	1.57	1.79	1.71	1.62
LOI	1.96	4.65	6.51	5.99	3.79	8.70	3.06	2.36
TOTAL	98.27		99.01	98.89	95.30	97.57	95.76	100.21
Ba (ppm)	7212	>10000	7753	5928	5510	8766	5755	3381
Sr (ppm)	3241	2150	2431	1814	1741	5638	2294	2129
Zr (ppm)	1205	1363	1476	1451	1427	1353	1310	1503

56. Xenolith-rich lamproite, Hatcher Mesa; 57. Lamproite flow, Matthew's Hill; 58. Phlogopite lamproite, Middle Table Mountain; 59. Phlogopite lamproite, North Table Mountain; 60. Lamproite scoria, Steamboat Butte, Emmons Mesa; 61. Aphanitic lamproite, Pilot Butte; 62. Spring Butte; 63. Lamproite, South Table Mountain.

	64	65	66	67	68	69	70
SiO_2	43.01	51.56	47.6	53.6	55.5	42.83	47.54
TiO_2	2.20	2.35	2.4	2.3	2.5	2.39	2.6
ZrO_x	-	-	-	-	-	1.6	0.43
Al_2O_3	8.4	9.71	8.1	10.4	11.1	8.14	11.28
Fe_2O_3	5.50	4.61	-	-	-	5.89	4.96
Cr_2O_3	0.07	0.05	-	-	-	-	-
FeO	0.58	0.90	5.0	4.3	4.0	0.07	0.96
MnO	0.10	0.06	0.1	0.1	-	0.14	0.03
MgO	9.10	7.34	8.8	6.0	6.2	10.83	7.84
CaO	11.96	4.86	8.3	4.1	2.8	12.42	9.31
Na_2O	1.87	1.12	-	1.3	1.3	0.54	0.81
K_2O	2.86	11.15	8.8	12.1	12.7	6.56	9.08
P_2O_5	3.08	1.93	3.0	3.0	1.8	1.39	0.72
SrO	-	-	0.3	0.2	0.2	-	-
BaO	-	-	0.9	0.7	0.6	0.96	0.56
SO_3	-	-	-	-	-	0.6	-
H_2O+	-	-	4.3	1.4	-	3.0	3.78
LOI	10.57	2.88	-	-	-	-	-
TOTAL		98.77	97.7	99.5	98.7	97.99	99.9
Ba (ppm)	>10000	7088	-	-	-	-	-
Sr (ppm)	5239	2935	-	-	-	-	-
Zr (ppm)	1391	1328	-	-	-	-	-

64. Phlogopite-poor, aphanitic lamproite flow, Twin Rocks; 65. Lamproite flow, Zirkel Mesa; 66. Middle Table Mountain madupitic lamproite (Ogden, 1979); 67. Zirkel Mesa (Ogden, 1979); 68. Steamboat Mountain (Ogden, 1979); 69. Madupite (Smithson, 1959); 70. Transitional lamproite (Johnston, 1959).

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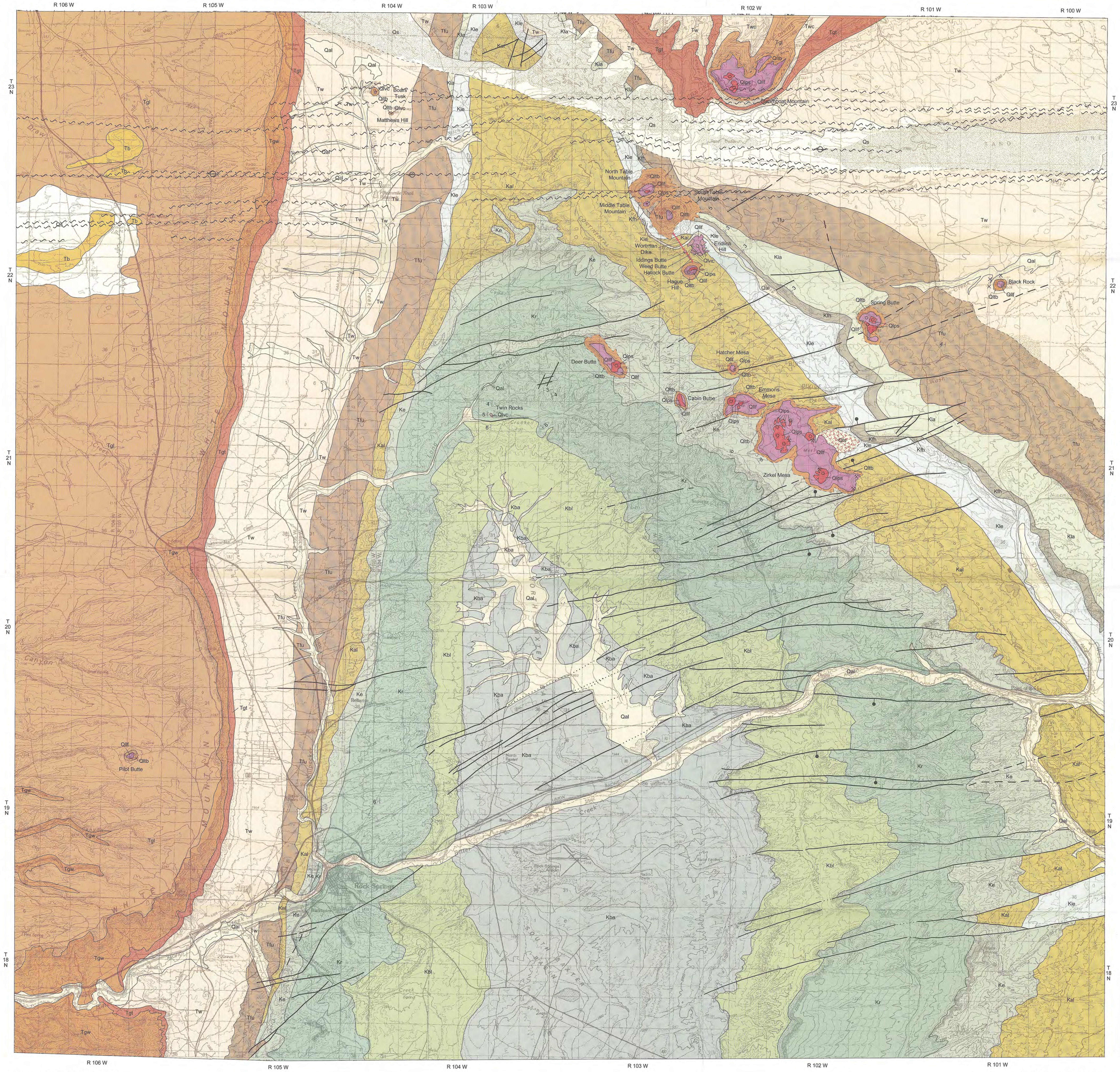
WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie Wyoming

Geology - Interpreting the past to provide for the future

REPORT OF INVESTIGATIONS 56, PLATE 1

Geologic map of the Leucite Hills lamproite fields, Rock Springs Uplift, southwest Wyoming



EXPLANATION

CORRELATION OF MAP UNITS

Qs	Sand dunes	Pleistocene and Holocene	QUATERNARY
Qal	Alluvium		
Qls	Landslide		
Unconformity			
Qltb	Lamproite talus and autobreccias	Volcanic flows, dikes, necks, plugs, cinder cones, and pumice cones from 3.1 Ma to 0.9 Ma — Pliocene and Pleistocene	QUATERNARY AND TERTIARY
☼	Lamproite cinder cones		
Qlps	Lamproite pumice and scoria		
Qlvc	Lamproite volcaniclastics		
Qllf	Lamproite lavas and flows		
Unconformity			
Tgl	Laney Shale Member of the Green River Formation	Eocene	TERTIARY
Twc	Cathedral Bluffs Tongue of the Wasatch Formation		
Tgw	Wilkins Peak Member of the Green River Formation		
Tgt	Tipton Shale Member of the Green River Formation		
Tw	Main body of the Wasatch Formation		
Tfu	Fort Union Formation	Paleocene	
Unconformity			
Kl	Lance Formation	Upper Cretaceous	MESOZOIC
Kfh	Fox Hills Sandstone		
Kle	Lewis Shale		
Kal	Almond Formation (Mesaverde Group)		
Ke	Ericson Sandstone (Mesaverde Group)		
Kr	Rock Springs Formation (Mesaverde Group)		
Kbl	Blair Formation (Mesaverde Group)		
Kba	Baxter Shale		

MAP SYMBOLS

- Contact, dashed where inferred
- Fault, dashed where inferred, dotted where concealed; ball and bar on downthrown block
- Lamproite dike
- Peridot sample sites
- Mine or quarry
- Strike and dip of beds; symbols without values show approximate direction of strike and dip
- Killpecker shear system (Gordon Marlatt, personal communication, June, 2005) — vertical shear zone that affects bedrock units and can be seen on aerial photographs and imagery. Apex of triangle points toward center of shear zone; circle with horizontal line indicates probable center of shear zone; location uncertain where obscured by surficial deposits

Base map from parts of the U.S. Geological Survey 1:100,000 - scale metric topographic maps of the Red Desert Basin (1980) and Rock Springs (1981), Wyoming 30 x 60 minute quadrangles

Digital Cartography by Robin Lyons

0 1 2 4 6 8 10 12 14 16 18 20 KILOMETERS

0 1 2 4 6 8 10 12 MILES

SCALE 1:100,000
Contour Interval 20 meters

0 2,000 4,000 6,000 8,000 10,000 12,000 14,000 16,000 18,000 20,000 Meters

0 5,000 10,000 15,000 20,000 25,000 30,000 35,000 40,000 45,000 50,000 55,000 60,000 65,000 Feet

GEOLOGIC MAP OF THE LEUCITE HILLS LAMPROITE FIELD, ROCK SPRINGS UPLIFT, SOUTHWEST WYOMING

Compiled by
W. Dan Hausel
2005