KIMBERLITES AND LAMPROITES OF COLORADO AND WYOMING, USA

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FIELD TRIP ITINERARY

Day 1. Monday June 16th, 2003

Overnight at airport hotel - included with the tour is dinner and breakfast. (or participants can make their own arrangements to be at hotel in AM on 17th.).

Day 2. Tuesday June 17th, 2003

Leave hotel at 8 am. 3.5 hour drive to State Line Kimberlites. Box lunch. 5pm - depart for 1 hour drive to Laramie, Wyoming. Overnight Laramie - hotel and dinner.

Day 3. Wednesday June 18th, 2003

Leave hotel 8am. 1.5 hour drive to Iron Mountain Kimberlite District. Tour all day, box lunch, hiking, and rattlesnakes provided. Drive back to Laramie. Overnight Laramie – hotel and dinner.

Day 4. Thursday June 19th, 2003

Leave hotel early 7am. 3.5 hour drive to Leucite Hills' lamproites. Tour all day, with box lunch, hiking. Overnight at Rock Springs, Wyoming - hotel and dinner.

Day 5. Friday June 20th, 2003

Leave hotel 8am. Tour Leucite Hills lamproites all day, with box lunch, hiking. Overnight at Rock Springs, Wyoming - hotel and dinner.

Day 6. Saturday June 21st, 2003

Leave early morning for flight from Salt Lake City to Victoria, Canada. Shuttle available to conference hotels.

Other comments: Participants should be prepared for significant hiking and climbing at 8000 foot elevations, rattlesnakes, strong sun, dehydration, and possibly severe afternoon thunderstorms. Foreign participants may require additional visas for entering the USA as well as Canada. Participants must arrange their own travel insurance for all parts of the tour.

FIELD EXCURSION STOPS

Day 2

Stop 1 - Chicken Park Kimberlite Complex

Sampling opportunities include fresh opaque mineral- and perovskite-rich hypabyssal kimberlite from this 614 Ma diamondiferous intrusion. Rubble of kimberlite remains from the 1981 trenching at CP-1 in this small, roughly circular pipe. Good field contacts with the country rock Sherman Granite can be seen. A southwest-trending fissure-blow system shows good kimberlite soil development, but little rock or xenolith content.

Stop 2 - Kelsey Lake Diamond Mine

Overview and tour of the Kelsey Lake Mine kimberlites and mining pits in the Kl-1 and KL-2 kimberlites. The oversize stockpiles contain abundant, although altered, mantle xenoliths including various peridotites. The oversize stockpiles also present good collecting of fairly competent samples of the various kimberlite phases encountered in the pits. Weathered volcaniclastic and hypabyssal kimberlite of various phases can be collected in pit walls of the developed pipes. Contact relationships with the country rock Sherman Granite can be seen, including a zone of contact breccia at the north end of KL-2. Pit walls show relationships between distinct phases of kimberlite. Associated fissures can be seen primarily as soil and geomorphic contrasts. Abundant mantle xenolithic material, although mostly altered, can be collected that includes large peridotites, small eclogites, and various megacrysts. The mine treatment plant includes ore preparation, concentration, recovery and tails handling sections, and may be visited as availability allows.

Day 3 - Iron Mountain Kimberlite District

This is a rare, and possibly your only, opportunity to visit this inaccessible location. You will see various outcrops of hypabyssal kimberlite showing a wide variety of textures, including some diatreme kimberlite. The hypabyssal kimberlites exhibit well-developed flow differentiation features. On the drive back to Laramie, there may be an opportunity to visit the Laramie Range anorthosite complex.

Stop 1

The Indian Guide 3 (IG-3) pipe is a small pipe with extremely altered volcaniclastic kimberlite, still showing good texture and xenocrysts. Rubble remains from 1981 trenching. This is the site of the only diamond to date from the IM District.

Stop 2

IM-27 and IM-28 have an extensive exposure and outcrop of various hypabyssal kimberlites in this fissure/sill complex.

Stop 3

IM-21 and IM-24 are small outcrops of fresh hypabyssal kimberlite showing clear textural variations and distinct flow banding and gradation of phenocryst/xenocryst size.

Stop 4

The Iron Mountain 9 and 10 (IM-9, IM-10) pipes are part of a fissure-blow complex and show excellent contact relationships with the Sherman Granite country rock, a well-developed zone of contact breccia (east end of IM-9), and kimberlitic soils and rubble with rare altered kimberlite fragments and mantle xenoliths.

Stop 5

IM-14 and IM-15 kimberlites show fissure/sill bodies with extensive exposures of altered hypabyssal kimberlite and contact breccia.

Other IM sites may be visited as access and time allow.

DAY 4

Stop 1 - Zirkel Mesa Quarry

Zirkel Mesa is the largest volcanic feature in the Leucite Hills. Ogden (1979) indicates that six centres of activity have coalesced into a single volcanic plateau. A lava cone forms the western end of the mesa. A plug dome, together with four cinder cones and associated flows, comprise the remainder of the plateau. Lava flows vary from 3 to 50 feet in thickness and are composed predominantly of diopside sanidine phlogopite lamproite. The quarry on the eastern edge of the mesa presents excellent exposures of compound lava flows erupted onto the country rocks. A discontinuous rubble zone containing xenoliths of country rock is present above which are found highly vesicular layered flows. The layering is commonly flow folded. Lava tubes are evident in the northern part of the quarry. Ascend to the plateau for views of the Zirkel Mesa cinder cones, Spring Butte, and Black Rock.

Stop 2- Black Rock

Black Rock is the eastern-most, and least understood, vent in the Leucite Hills. Essentially, it consists of discontinuous thin lava flows overlying a pyroclastic unit. The north side of the mesa consists of about 15m of poorly lithified vesicular lamproite overlain by 25m of alternating vesicular and non-vesicular lavas. These units exhibit well-defined pseudo-columnar jointing formed by vertical jointing. The vertical south and east faces of the mesa are bedded and the lavas dip ~30o to the north. They consist of pseudo-columnar jointed discontinuous layers of vesicular and non-vesicular lava. The west face consists of a poorly-exposed olivine sanidine lamproite overlain by friable rubbly lamproite capped by a wedge of interbedded fissile and vesicular lavas, which are in turn covered by vertically-jointed, northerly-dipping interbedded vesicular and massive leucite phlogopite lamproite and sanidine phlogopite lamproite lavas. The top of the mesa is depressed giving the impression that the lavas dip towards the centre of a vent. However, there is no geophysical/geological evidence for the presence of a crater/magma chamber underlying the mesa, and Ogden (1979) suggests that the depression on the top of the mesa was formed by post-extrusional compaction. Ogden (1979) further states that the presence of the pseudo-columnar jointing indicates that the entire section of lavas cooled as a single unit. Cinder cones are not present. Dunite megacrysts or xenoliths have been identified at Black Rock and single crystals of olivine are present in the anthills at the base of the western face (Hausel, 1998).

Stop 3 - Spring Butte (Formerly Orenda Mesa)

This butte is the type locality for orendite (now known as diopside sanidine phlogopite lamproite). The butte is a compound volcanic centre consisting of six cinder cones and at least six lava flows together with three minor northwest trending feeder dykes associated with the oldest flow. Flow thicknesses range from 3 - 25m. The cones consist of welded clastic flows with ribbon and bread-crust bombs. Xenoliths of country rock and basement are rarely found. Both leucite and sanidine lamproite are present. Lavas forming the second and third oldest flows of the mesa will be examined at the eastern margin of the butte.

DAY 5

Stop 1 - Steamboat Mountain

Steamboat Mountain forms a prominent plateau at the northern margin of the Leucite Hills field. Unlike other mesas in the area, the plateau is forested and, because of this and the soil cover, exposures of the lava flows are not as extensive as elsewhere. The mesa consists of numerous small flows and four lava cones. The southeast face of the plateau exposes an excellent cross-section of numerous lavas lying upon the Bridger and Green River Formations. Ogden (1979) has noted that lava tubes are extremely common on Steam Boat Mountain. These may have scoriaceous or massive cores. Tubes in some instances have broken through thin lava flows and produced dome-like protrusions. Many of the diopside leucite phlogopite lavas are amygdaloidal. Lava cones are composed of thin flows of hyalo-phlogopite lamproite interbedded with minor amounts of tephra. Pumice-like material is common.

Stop 2 - Middle Table Mountain - North Table Mountain

Middle Table Mountain is a small mesa, located 200 m south of North Table Mountain, and is the type locality for transitional diopside leucite maduptic lamproite. This occurrence consists principally of green-coloured madupitic lamproite with lesser amounts of massive-to-weakly vesicular grey leucite diopside phlogopite lamproite. The madupitic rocks are fissile and columnar-jointed. Ogden (1979) has described the occurrence as a plug-dome, on the basis of the presence of concentric vertical joints and phlogopite flow-aligned phenocrysts. However, it is also possible that the madupitic portion might represent a subvolcanic lava lake analogous to the lake found at Mt. North in the Ellendale lamproite field. In addition to their unusual petrographic character, they contain an unusual suite of accessory minerals including Sr-REE-perovskite, $K_2TiSi_3O_9$ (the titanium analog of wadeite), and Ba-Sr-apatite (Mitchell and Steele, 1992). The maduptic rocks are overlain by yellow scoriaceous phlogopite lamproite and a thin lava flow with squeeze-up spines and horizontal flow layering. North Table Mountain is a mesa capped by a single lava flow. Flow layering is exceptionally well developed in this lamproite. The layers consist of isochemical dark grey leucite phlogopite lamproite and light grey sanidine phlogopite lamproite. Squeeze-up spines and parasitic flows are common.

Stop 3 - Boar's Tusk

The Boar's Tusk is a prominent erosional remnant of a volcanic neck. The top of the neck is 110m above the surrounding surface. The lower 65m consists of Laramie age country rock covered by talus. The actual neck is a pair of spires that are separated from each other by a fault and an eroded feeder dyke. The neck consists of leucite phlogopite lamproite agglomerate and tuff. Clasts are of vesicular and massive lamproite and local country rock, including the now-eroded Green River shale. Samples that are representative of a wide range of textural types of phlogopite lamproite are best collected from the talus slope rather than the spire itself.

Stop 4 - Badger's Teeth (Twin Rocks)

This small exposure is an elongated volcanic neck and associated feeder dyke emplaced in Laramie sandstone. It consists of five projecting teeth-like masses arranged along and east-west strike. The agglomerate is formed from clasts of highly vesicular amygdaloidal leucite phlogopite lamproite and angular country rock xenoliths.

Stop 5 - Pilot Butte

Pilot Butte is a mesa consisting entirely of diopside madupitic lamproite (type locality of the former madupite) and is isolated from the main volcanic centres of the Leucite Hills field. It now consists primarily of a 20 m thick lava flow of madupitic lamproite that issued from a volcanic neck located at the western end of the mesa. Vertical flow layering in the neck becomes horizontal and like that of the main easterly-flowing lava about 10m above the neck. Jointing in the lava is parallel to the surface over which it flowed. Whilst partially solidified, the flow front was breached by material from the still fluid interior. Removal of this magma resulted in collapse of the lava surface. The lavas contain abundant xenoliths of Green River Formation that have been abraded and assimilated by the magma. A dyke exposed on the southern flanks contains globular segregation-textured lamproite.

INTRODUCTION AND GEOLOGIC SETTING, KIMBERLITES AND LAMPROITES OF COLORADO AND WYOMING

The Archean Wyoming craton, including the Proterozoic Front and Laramie Ranges (Figs. 1, 2, 3), hosts the largest fields of kimberlites and lamproites in the US (Hausel, 1998). This, coupled with a few hundred kimberlitic indicator mineral anomalies identified in stream sediment samples collected over widespread regions (Hausel et al., 1988), provides evidence of an extensive swarm of mantle-derived intrusives. To date, the State Line District Kimberlites have been the most productive region in the United States for diamonds. More than 15,000 carats of diamond have been recovered from these kimberlites (Fig. 4), including gem-quality stones weighing more than 28 carats. The Wyoming craton also hosts one of the largest lamproite fields in the world, the Leucite Hills, in southwestern Wyoming (Fig. 2). Other lamproites and lamprophyres are found in the northern portion of the Wyoming craton in Montana and to the south in Utah (Mitchell and Bergman, 1991; Hausel, 1998). One mafic breccia pipe is reported in the Greater Green River Basin in western Wyoming (Hausel et al., 1999), and one diamondiferous kimberlite is reported in eastern Montana (Pete Ellsworth, pers. comm., 2000).

The Archean Wyoming Craton

Much of Wyoming is underlain by the Archean Wyoming craton, which is the core of an ancient craton. However, only slices of this terrain are exposed at the surface in the core of several of Wyoming's mountain ranges, e.g. the Medicine Bow and Sierra Madre Mountains (Houston et al., 1979). The remainder of the craton lies under a thick layer of sediment fill in the Wyoming basins. According to Eggler et al. (1988), the Wyoming craton was established by 2.7 Ga and was subsequently affected by a regional metamorphic event at 1.9 to 1.7 Ga. At the southeastern boundary of the Wyoming Craton is a belt of Proterozoic gneisses and schists, which accreted at a south-dipping paleo-Benioff zone (Hills and Houston 1979), at about 1,770 Ma (Loucks et al., 1988). The northern edge of this belt, known as the Green Mountain terrain, is marked by a relatively wide suture zone known locally as the Mullen Creek-Nash Fork shear zone, and more generally as the Cheyenne Belt (Karlstrom and Houston, 1984), or the Wyoming shear zone.

The Green Mountain terrain forms a Proterozoic basement complex to the south of the Wyoming craton, and underlies the State Line and Iron Mountain Kimberlite Districts. This terrain consists of 1.9 to 1.6 Ga metamorphic rocks comprised of felsic to mafic gneisses and schists, intruded by the 1.4 Ga Sherman Granite. Post-Precambrian rocks are restricted to the flanks of the Front Range and consist of Pennsylvanian to Cretaceous sedimentary units. The principle structural features of the Front Range were developed during the Laramide Orogeny (Cretaceous-Tertiary), however, many structures are suspected to be older reactivated structures of Precambrian ancestry (McCallum, 1991). Pre-Pennsylvanian sedimentary rocks are absent in the region, although xenoliths and large blocks of Cambrian,

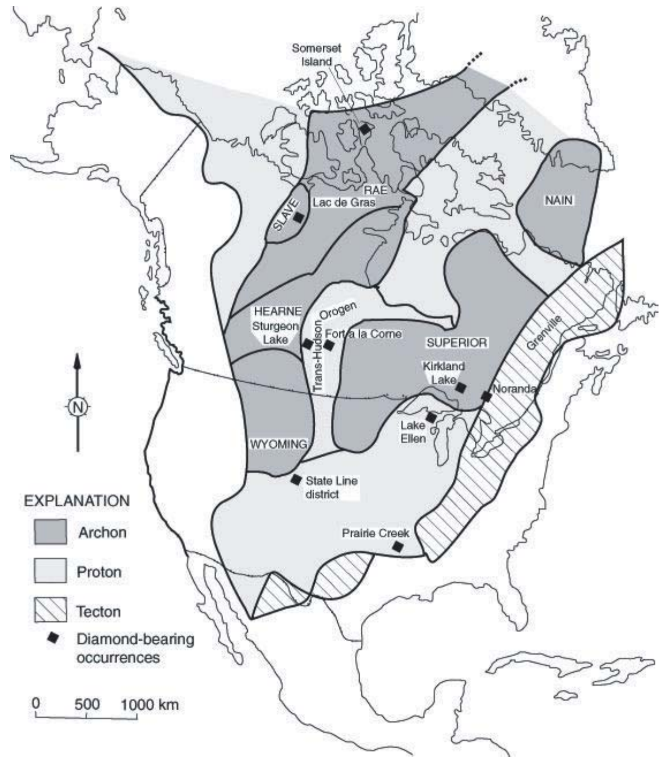

Figure 1. Location of the Archean Wyoming craton, within North American, with respect to other known Archean cratons and Proterozoic mobile belts (from Hausel, 1998).

Ordovician and Silurian sediments (limestone, dolomite, conglomerate, sandstone, etc.) do occur in the State Line and Iron Mountain District kimberlite diatremes. Therefore, emplacement of these diatremes (late Devonian) predated an extensive erosional event that removed all early Paleozoic rocks of the region.

State Line District Kimberlites

Approximately 40 occurrences of kimberlite are known in the State Line District (Fig. 3). The District contains larger, upper level diatreme pipes such as at Sloan and Kelsey Lake, lower level diatreme pipes to root zone intrusions, such as at Nix and Moen, and hypabyssal dykes such as at George Creek. Kimberlite emplacement has centered around 400 Ma and 600 Ma. Various kimberlites in the State Line District have been evaluated for diamond, with grade results ranging from zero to close to one hundred carats per hundred tons. Essentially all occurrences of kimberlite in the State Line District contain some diamond, although most are not commercial (McCallum and Waldman, 1991).

Iron Mountain District Kimberlites

Approximately 90 occurrences of Devonian kimberlite have been mapped in the Iron Mountain District, although most are quite small discontinuous fissures. Larger diatreme pipes occur primarily in the western part of the district (IM-7, 8, 42, 46 complex, IG-1-3) and locally contain Paleozoic sedimentary xenoliths. Mostly hypabyssal blows, fissures, and sills occur in the far western area (IM-1-5, IG-15) and throughout

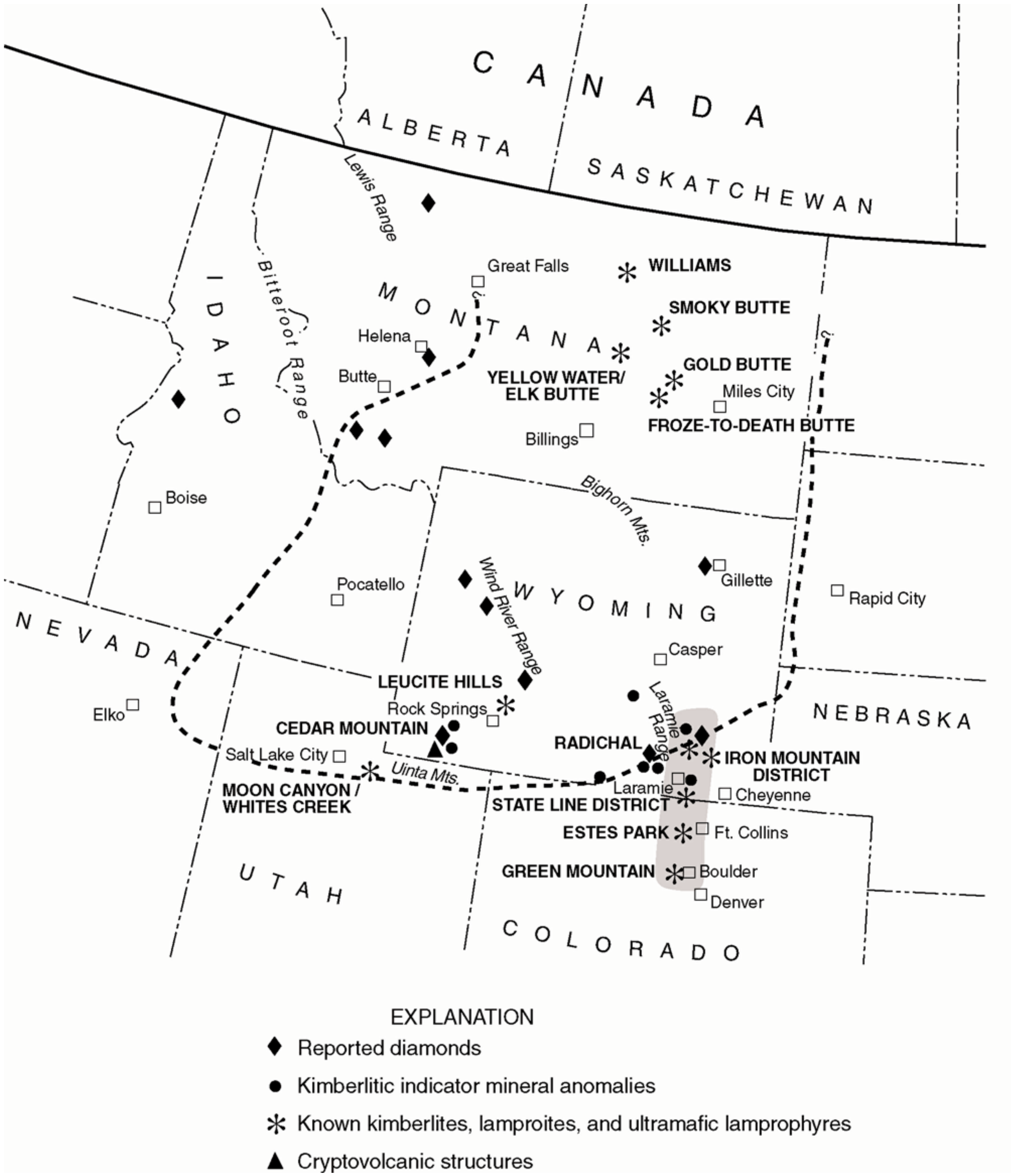

Figure 2. Generalized map of the Archean Wyoming craton (outlined by heavy dashed line) showing the locations of known kimberlites, lamproites, related rocks, and kimberlite indicator mineral anomalies (from Hausel, 1998).

the remainder of the district. Limited bulk sampling to date has produced only one diamond from Iron Mountain.

Age of Kimberlites and Lamproites in the Wyoming Craton

Kimberlites and lamproites in this region were emplaced during more than one episode. A group of kimberlitic, lamproitic, and lamprophyric intrusive events have been recognized including Late Precambrian, Early Devonian, Tertiary, and Quaternary. Ages of kimberlite in the State Line and Iron Mountain Districts are Early Devonian based on the presence of Paleozoic xenoliths (McCallum and Mabarak, 1976), fission track dating of titanite (Larson and Amini, 1981) and zircon (Naesser and McCallum, 1977), and on Rb-Sr dating

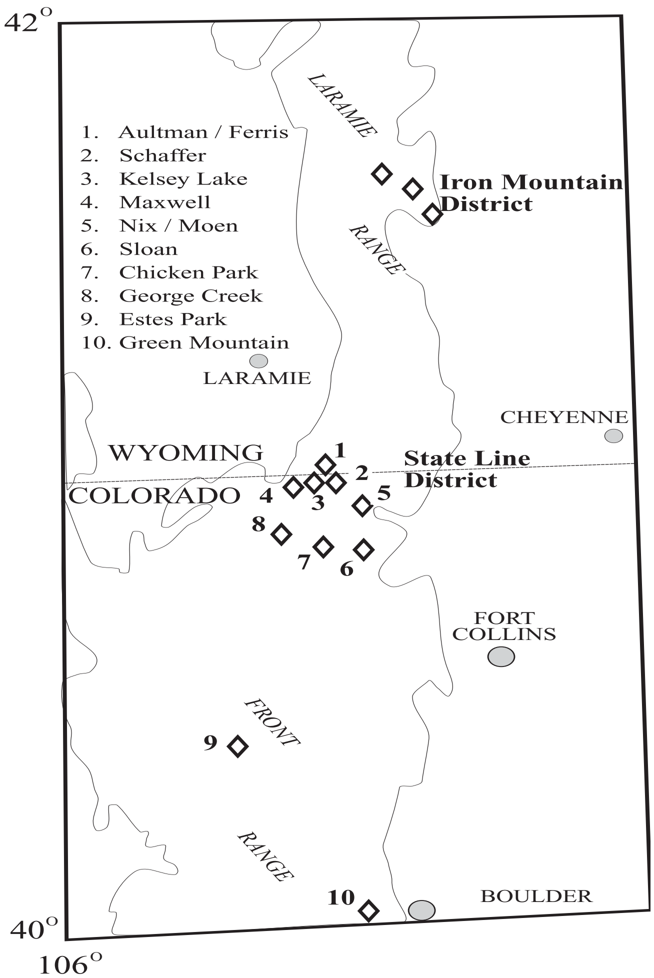

Figure 3. Location map of the State Line District kimberlites in northern Colorado and southern Wyoming (from Coopersmith, 1991).

of phlogopite (Smith, 1977, 1983). More recently, a Late Proterozoic (600 to 700 Ma) episode was also recognized in some State Line kimberlites (Carlson and Marsh, 1989; Lester and Larsen, 1996; Heaman, et al., 2003). This age is essentially equivalent to the emplacement age of 600 Ma reported for the Green Mountain kimberlite pipe, which is located in the southern portion of the Colorado-Wyoming kimberlite province adjacent to Boulder, Colorado (Larson and Amini, 1981). In eastern Montana, the Williams' kimberlites as well as lamproites and lamprophyres in the region are thought to be middle Tertiary (46-51 Ma) in age (Hearn, 1989). The age of the recently discovered diamondiferous Homestead kimberlite near Yellow Water Butte is unknown, but also assumed to be Tertiary (Pete Ellsworth, pers. comm., 2000). The Leucite Hills lamproites in southwestern Wyoming are quite young and very late Tertiary to Quaternary in age (3.0 to 0.9 Ma; Lange et al., 2000).

THE CHICKEN PARK KIMBERLITES, COLORADO

The Chicken Park kimberlites occur in the SW part of the Colorado-Wyoming State Line District (*see* Fig. 1). The initial kimberlite was discovered by a local prospector in 1980,

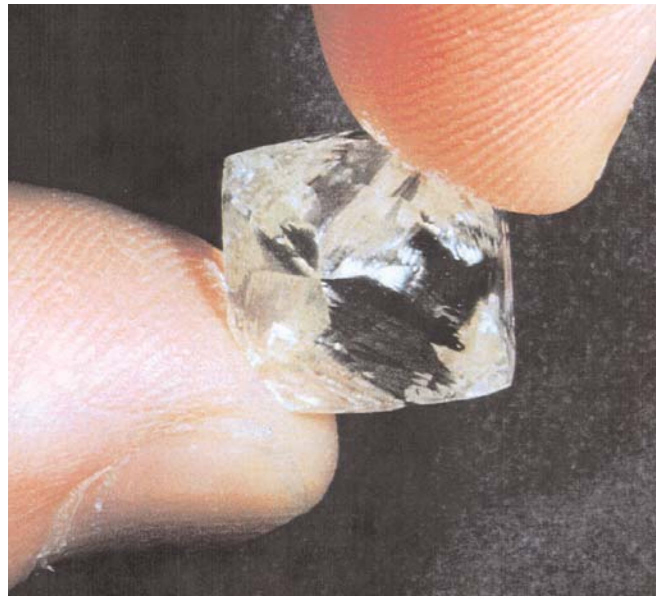

Figure 4. 14.2 carat octahedron recovered from the Kelsey Lake Diamond Mine.

with the remaining pipes discovered by H. G. Coopersmith of Cominco American Inc. Additional exploration and study was performed by Jack Rogers (1985), upon whose thesis much of this discussion relies.

The Chicken Park kimberlite complex is a fissure system along which several small pipes were intruded (Fig. 5). The kimberlite has a radiometric age of 614.5 ± 2.1 Ma (Heaman, et al., 2003), making it older than most of the kimberlite in the largely Devonian-aged State Line District. Country rock is the Precambrian Log Cabin Granite of the Sherman batholith (1.4 Ga). The largest pipe, CP-1, is less than one acre in surface area, and is the only deposit that has been trenched for bulk sample and study. The pipe consists largely of volcaniclastic phlogopite-serpentine kimberlite breccia, containing abundant cognate blocks of hypabyssal opaque-rich kimberlite. Due to the friable nature of the volcaniclastic kimberlite, only the hypabyssal blocks remain on the surface for study.

Bulk sample trenching in the early 1980's by Cominco and Superior Oil totaled about 300 tonnes. Plus 2mm diamond grade is about 7 - 8 cpht, with the largest diamond being an irregular 2.7 carat crystal. The diamonds show

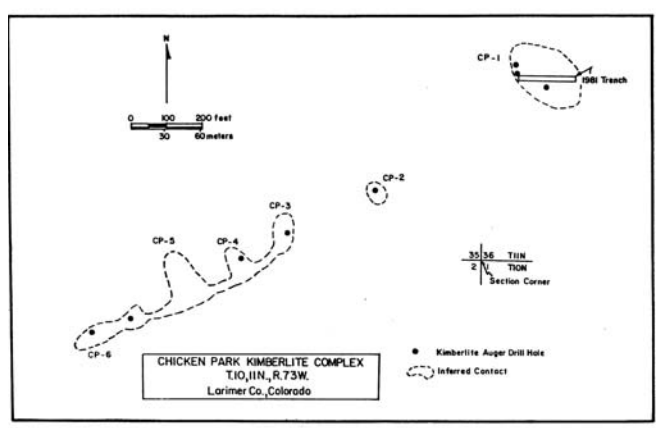

Figure 5. Map of the Chicken Park kimberlite complex.

mostly single crystal forms and most contain deformation features. Extreme stone resorption is noted, as is extreme late stage surface etching (Falk, 1992).

These kimberlites are rich in perovskite, phlogopite, macrocrystal ilmenite, and olivine (altered). Pyroxene and garnet are extremely rare. The xenolith content in the kimberlite is low, with only a few lower crustal rocks and highly altered upper mantle xenoliths present. Granitic xenoliths are most common near the contacts. No Paleozoic sedimentary xenoliths have been found, which is consistent with the Eocambrian age of emplacement.

The kimberlite at Chicken Park is highly autolithic. These autoliths, or cognate inclusions of kimberlite, occur as blocks a few centimeters to 1 meter in size. Two distinct types of kimberlite autoliths/cognate inclusions are observed. One type is generally smaller and always rounded to sub-rounded, implying that they have spent some time incorporated in a possibly fluidized diatreme matrix. This type of kimberlite is a phlogopite- perovskite-, and/or opaque mineral-rich variety of serpentine-phlogopite macrocrystic kimberlite. The second type is a serpentine kimberlite, and the blocks are larger, angular, and exhibit a brecciated texture. This type often has a reddish appearance due to hematite in the serpentine, and secondary titanium-rich minerals (‘leucoxene’) after ilmenite and perovskite can also be quite common. Less common aphanitic calcite kimberlite is nearly devoid of macrocrysts, and has a uniform groundmass of calcite and euhedral olivine microphenocrysts.

Rogers (1985) provides the following limited analyses. Olivine macrocrysts have Mg/(Mg+Fe) ratios ($Mg^{\#}$) of 0.875 to 0.919. Olivine microphenocrysts have Mg/(Mg+Fe) ratios of 0.877. Ilmenite macrocrysts and xenocrysts have low Cr_2O_3 (0.00 to 0.45 wt%) and moderate to high MgO (8.66 to 15.34 wt%). Garnet xenocrysts (peridotitic) range from 4.5 to 11.5 wt% Cr_2O_3, some being low CaO (from 3.5 wt%). Phlogopite has low Cr_2O_3 (to 0.07 wt%), low Al_2O_3 (to 14.34 wt%), high FeO (from 4.86 wt%) and K_2O from 9-10 wt%. Perovskite has consistently low Cr_2O_3, TiO_2 generally 40 to 54 wt%, and FeO generally 1-1.5 wt%. Groundmass spinels are generally chrome-rich magnesian titanomagnetite, although high-Cr chromite does occur.

McCallum (1989) further studied the oxide minerals at Chicken Park. He notes that the oxide minerals reflect a somewhat atypical Mn-rich assemblage, and that two intervals of crystallization are recognized: an early assemblage crystallized at deep levels, and a later assemblage formed in a near surface environment. This conclusion is consistent with the observed late stage diamond-etching event.

Table 1 presents major element whole rock analyses of Chicken Park kimberlite, along with representative analyses from elsewhere.

GEOLOGY AND DEVELOPMENT OF THE KELSEY LAKE DIAMOND MINE, COLORADO

Introduction

The Kelsey Lake kimberlites, a cluster of nine diamondiferous pipes, occur in the northern State Line Kimberlite District of the Colorado/Wyoming Diamond Province (Coopersmith, 1991, 1993; Fig. 3). This location is at the southern margin of the Archean Wyoming Province (Fig. 2). Three relatively large pipes and a few smaller bodies define the cluster (Fig. 6). The Kelsey Lake kimberlites have been developed as the first United States’ diamond mine. Essentially all State Line kimberlites contain diamond, but only the Kelsey Lake pipes are economic. Study, evaluation, and development have progressed since discovery in 1987. Full-scale production commenced in late spring of 1996. Mining has produced gem quality diamonds to 28.3 carats in size.

The Kelsey Lake kimberlites contain predominately volcaniclastic kimberlite, with minor hypabyssal and epiclastic kimberlite locally occurring. Alteration and weathering of the kimberlites is extensive. Petrologic study of mantle-derived xenoliths and xenocrysts indicates an underlying lithosphere whose geochemical signature is suggestive of Proterozoic deep melt and metasomatic events.

This development has concentrated on the two largest pipes. These have undergone a bulk sample evaluation after geological study (1987 onwards) identified the presence of small diamonds and mineral chemistry favorable for the presence of diamonds. A 10 tonnes per hour (tph) rotary pan plant was established on the site in 1992 for the processing of several thousands of tonnes of bulk sample material. During this phase of evaluation, diamonds to 14.2 carats in size were recovered (Fig. 4), and grade and stone values were encouraging. Early in 1995, it was decided to progress the evaluation program to trial commercial mining.

Economic development included a 195 tph process plant, ancillary water and tailings systems, and pit development. An indicated resource in excess of 22 million metric tons is outlined in two pits. The environmentally benign nature of diamond mining and processing has facilitated a relatively simple permitting process. The ore processing comprises a liberation stage, a gravity concentration stage using rotary pans, and a recovery stage using grease tables. The final product has been sold as “Colorado Diamond®” for the first time in 1996.

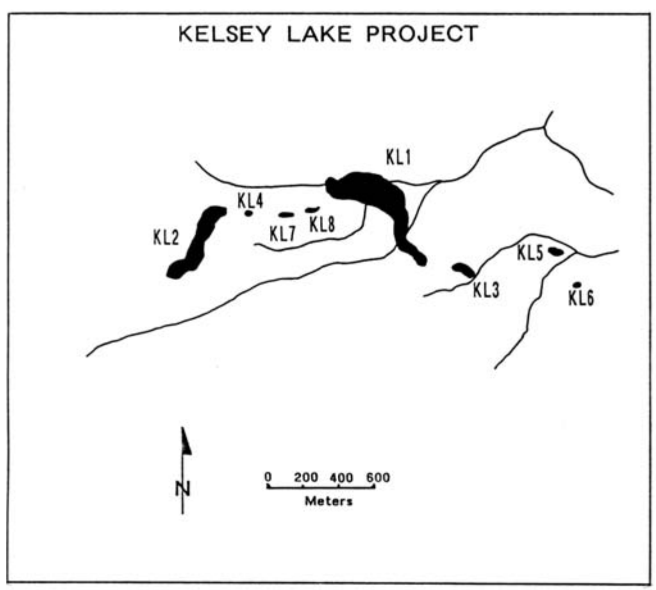

Figure 6. The Kelsey Lake kimberlite cluster.

Table 1. Major oxide whole-rock analyses (in weight percent) of kimberlites from the CP-1 pipe of the Chicken Park kimberlite complex, and average wt % of major oxides of Colorado-Wyoming and southern African kimberlites (from Rogers, 1985). Colorado-Wyoming kimberlites are from McCallum and Eggler (1971), McCallum and Smith (1978), and Smith et al. (1979). Southern African kimberlites are from Dawson (1967).

	CP1- 1	CP-2	CP-3	CP-4	CP-5	Sloan	Nix	Ferris	Iron Mtn.	Estes Dyke	Gp I	Gp II
#analyses	1	1	1	1	1	4	4	1	2	1		
SiO_2	33.7	30.3	30.1	29.8	29.9	31.6	30.3	36.3	31.6	29.6	35.2	31.1
TiO_2	2.61	3	2.95	3.08	3.07	0.86	1.13	1.9	3.5	5.2	2.32	2.03
Al_2O_3	2.94	3.01	2.84	2.92	2.59	2.26	2.85	2.9	3.4	2.7	4.4	4.9
Cr_2O_3	NR	NR	NR	NR	NR	0.14	0.13	NR	NR	NR	NR	NR
Fe_2O_3*	9.86	10.5	10.6	11.2	10.7	5.12	5.85	9	9	5.6	NR	NR
FeO	NR	NR	NR	NR	NR	1.64	1.42	0.85	2.8	5	9.8	10.5
MgO	19.4	21.1	20	21.3	20.7	27.1	27.5	32.7	25.7	23.1	27.9	23.9
MnO	NR	NR	NR	NR	NR	0.13	0.14	0.16	0.19	0.25	0.11	0.1
NiO	NR	NR	NR	NR	NR	0.1	0.11	NR	NR	NR	NR	NR
CaO	10.9	9.95	11.2	10.5	10.5	11.5	10.7	0.67	9.1	10.2	7.6	10.6
Na_2O	0.71	0.72	0.8	0.57	0.83	0.06	0.07	0.07	0.06	0.03	0.32	0.31
K_2O	1.42	2.01	1.83	1.88	1.7	0.65	0.47	0.23	1.6	0.94	0.98	2.1
P_2O_5	0.49	0.73	0.45	0.67	0.41	0.37	0.54	0.07	0.33	0.09	0.72	0.66
CO_2	NR	NR	NR	NR	NR	6.74	6.28	0	1.5	5.8	3.3	7.1
LOI	15.1	15.3	15.8	14.1	16.1	11.7	11	12.8	9.05	9.9	7.4	5.9

CP1-1, highly altered kimberlite; CP1-2, 3, and 4, altered phlogopite-serpentine kimberlite; CP1-5 Relatively fresh phlogopite-serpentine kimberlite; NR = Not Reported; *Total Fe as Fe_2O_3

Geology

The Kelsey Lake kimberlites form a small group of irregular shaped pipes and fissures (Fig. 6). The pipes consist largely of multiphase blows of volcaniclastic kimberlite with extensions of hypabyssal kimberlite. The kimberlite is altered and deeply weathered. The Kelsey Lake 1 pipe is approximately 12 acres in surface area, while the Kelsey Lake 2 pipe is approximately 10 acres. The two main pipes combined are over 20 acres in surface area, ranking them among the largest in the district. The kimberlites intrude 1.4 Ga Proterozoic granitic rocks of the Sherman batholith. A simplified geological map is presented in Figure 7. Shape is largely controlled by jointing in the country rock. The kimberlite contains sedimentary xenoliths of Cambrian to Silurian age. An apparent Devonian age of the Kelsey Lake kimberlite occurrences is in good agreement with Early Devonian (390 Ma) isotopic ages of other kimberlites in the District (Smith, 1983).

The KL-1 pipe consists of multiple phases of volcaniclastic units of diatreme kimberlite and subordinate epiclastic or pyroclastic kimberlite. Pellet-rich volcaniclastic serpentine kimberlite breccia occupies the southern fissure appendage of the main pipe. This is extremely rich in mantle xenocrysts, megacrysts, and xenoliths. The southern portion of the pipe contains pellet- and autolith-rich layered pyroclastic kimberlite, which is termed a 'sandy' tuff. The quantity of rounded quartz grains and sedimentary xenolith material varies between and within layers. Large (up to 3 meters) sedimentary blocks are present. This zone has a moderate amount of mantle xenocrystal and xenolithic material. The main pipe, which comprises the northern part of the body, contains volcaniclastic serpentine kimberlite breccia, with a moderate amount of mantle component, and locally abundant large crustal xenolithic blocks.

The KL-2 pipe is a multiphase kimberlite complex with at least four major distinct phases of volcaniclastic serpentine kimberlite breccia. These are locally rich in mantle xenoliths and xenocrysts. Sedimentary xenolith content, size, and

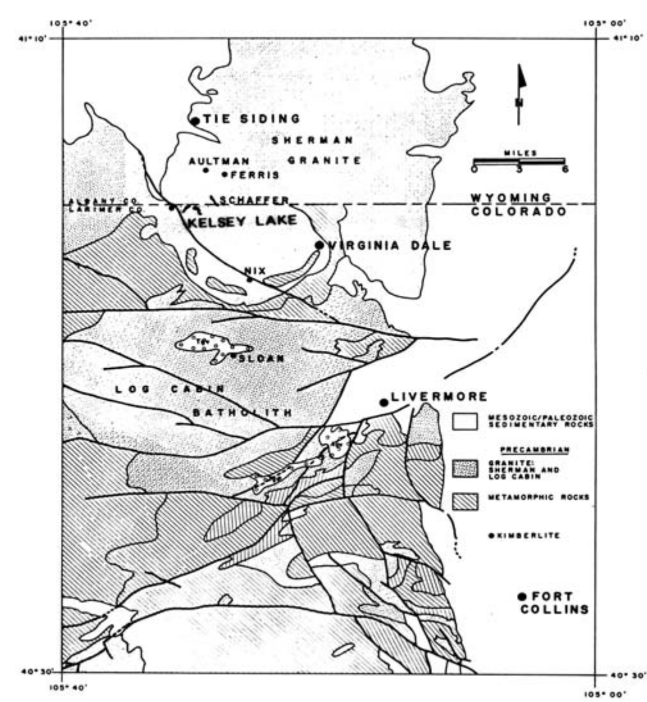

Figure 7. Simplified regional geological map of the Colorado-Wyoming State Line Kimberlite District (from Coopersmith, 1991).

preservation varies considerably between phases. Alteration and carbonatization is also variable. Locally abundant crustal xenoliths exceed one meter in size. Occurrence of a contact breccia is observed.

Late stage alteration and surface weathering has destroyed much of the primary mineral assemblage of both bodies of kimberlite. Ubiquitous pheonocrystal and macrocrystal olivine is totally replaced by serpophitic or lizardite serpentine, and commonly is carbonatized. Groundmass perovskite, apatite, opaque minerals, and diopside generally are preserved. Groundmass serpentine and calcite may be either primary or secondary. Macrocrysts and xenocrysts of Mg-ilmenite, pyrope garnet, spinels, phlogopite, and chromian diopside are generally preserved, as are megacrysts of Mg-ilmenite, Cr-poor titanian pyrope, and subcalcic diopside. The groundmass of the autoliths and pellets is relatively fresh, and generally is phlogopite-rich. Petrographically, these rocks are Group 1 kimberlites as defined by Smith (1983). Whole-rock and trace element chemical analysis of the kimberlite is presented in Table 2. These analyses show the extensively altered nature of the kimberlite. Xenolithic material in the pipes includes upper mantle peridotite and eclogite, lower crustal granulite, and crustal granitic, metamorphic and sedimentary rocks. Content and size ranges of xenolithic and megacrystal material varies widely within phases of the pipes.

Table 2. Whole rock geochemistry of the Kelsey Lake kimberlites (from Coopersmith, 1991).

Wt. %	KL1-5	KL1-6	KL1-7	KL2-1	KL2-4	KL2-10
SiO_2	36.86	44.04	41.60	41.00	38.00	39.00
TiO_2	0.58	0.24	1.40	0.55	0.81	1.13
Al_2O_3	4.71	3.62	5.40	4.85	5.07	4.08
Fe_2O_3	4.97	1.69	7.40	4.51	5.86	7.43
MnO	0.09	0.08	0.15	0.10	0.09	0.15
MgO	12.00	3.84	21.70	14.90	18.70	25.50
CaO	17.56	22.89	7.09	13.20	10.20	6.00
Na_2O	0.13	0.05	0.38	0.11	0.19	0.06
K_2O	1.27	1.51	0.76	1.35	0.49	0.35
LOI	20.30	20.46	12.17	18.15	18.27	15.24
TOTAL	99.02	98.94	98.78	99.30	98.34	99.78
C.I.*	2.87	6.95	2.04	2.61	2.20	1.65
ppm						
Ba	430	140	1100	450	1100	200
Nb	57	8	143	53	93	124
Rb	57	54	49	54	25	27
Sr	255	143	516	264	417	249
Y	10	12	15	19	17	14
Zr	115	104	153	130	147	125
Cr	101	2	868	312	693	1225
La	42	10	121	65	60	72
Ni	422	92	669	494	618	894

C.I. = Contamination Index
KL1-5 = Grey Volcaniclastic Kimberlite Breccia (F trench)
KL1-6 = Red Sandy Volcaniclastic Kimberlite (F trench)
KL1-7 = Serpentine Kimberlite Breccia (E trench)
KL2-1 = Calcite - rich Serpentine Volcaniclastic Kimberlite Breccia - contaminated (C trench)
KL2-4 = Volcaniclastic Serpentine Kimberlite Breccia (C trench)
KL2-10 = Volcaniclastic Serpentine Kimberlite Breccia (A trench)

Mantle Xenocrysts and Xenoliths

Mantle-derived material in the Kelsey Lake kimberlites includes diamonds, xenoliths of lherzolite, harzburgite, and eclogite, members of the Cr-poor megacryst suite, and various single crystal xenocrysts.

Diamonds

No diamond-bearing xenoliths have been recovered, although a diamond-bearing harzburgite has been found in the nearby Schaffer kimberlite. At Kelsey Lake, two diamondiferous garnet xenocrysts have been analyzed. These are harzburgitic garnets with 10.8 wt% Cr_2O_3, 5.0 wt% CaO, and 7.8 wt% Cr_2O_3, 5.0 wt% CaO (Pizzolato and Schulze, 1998). Aside from sulphide rosettes, syngenetic inclusions recognized include olivine, Cr-pyrope (10.5 wt% Cr_2O_3, 3.3 wt% CaO; L.A. Pizzolato, pers. comm., 2002), and eclogitic pyrope (D. J. Schulze, pers. comm., 2003), linking at least a portion of the diamond population to a harzburgite paragenesis.

The diamonds are predominately of octahedral form, showing only moderate resorption (Falk, 1992). Preservation varies from sharp octahedra (10 % of the population; notably this percentage of sharp octahedra is higher in the larger stone size classes), through transition stones to tetrahexahedroid (rounded dodecahedron). Macles are common, interpenetrant twins are rare. Broken crystals are common (old breaks). Aggregates are uncommon. The diamonds were subject to major deformation while within their host xenoliths (Falk, 1992). No late-stage etching event is indicated. Approximately one-half of the production is cuttable with very little boart. Most stones are white, colorless, with colors trending towards honey brown. Large canary yellow stones have been found, but the rare pinks and blues are very small to date. More than 25% by weight are diamonds greater than sieve size 21 (approx. 5mm round; 1ct.), while stones less than sieve size 9 (approx. 2mm round; approx. 0.05 ct.) are only a small percentage.

Peridotite xenoliths

Peridotite xenoliths are relatively abundant in the kimberlite in the mine, occurring as extensively altered rounded fragments to 30 cm in diameter. They are recognized on broken surfaces by their yellow-green color and, in many samples, the presence of purple garnet, green Cr-diopside, and/or black spinel. Olivine and orthopyroxene are not preserved, but replaced by serpentine and calcite. Some peridotites are thoroughly silicified, as are the altered peridotites at the nearby Schaffer kimberlites. Primary rock types include lherzolite and harzburgite, with or without garnet and/or spinel.

The peridotite xenoliths are classified as infertile (depleted) based on molar ratio Cr/(Cr+Al) and Mg/(Mg+Fe) of the Cr-pyropes and Cr-diopsides (Eggler et al., 1987). Eggler determined that infertile peridotites extended to depths of 200 km (Fig. 8) as residua from a Precambrian melting event involving the entire lithosphere, subsequently metasomatically enriched at shallower depths. Garnets in both lherzolite and harzburgite xenoliths are mostly lherzolitic with concentra-

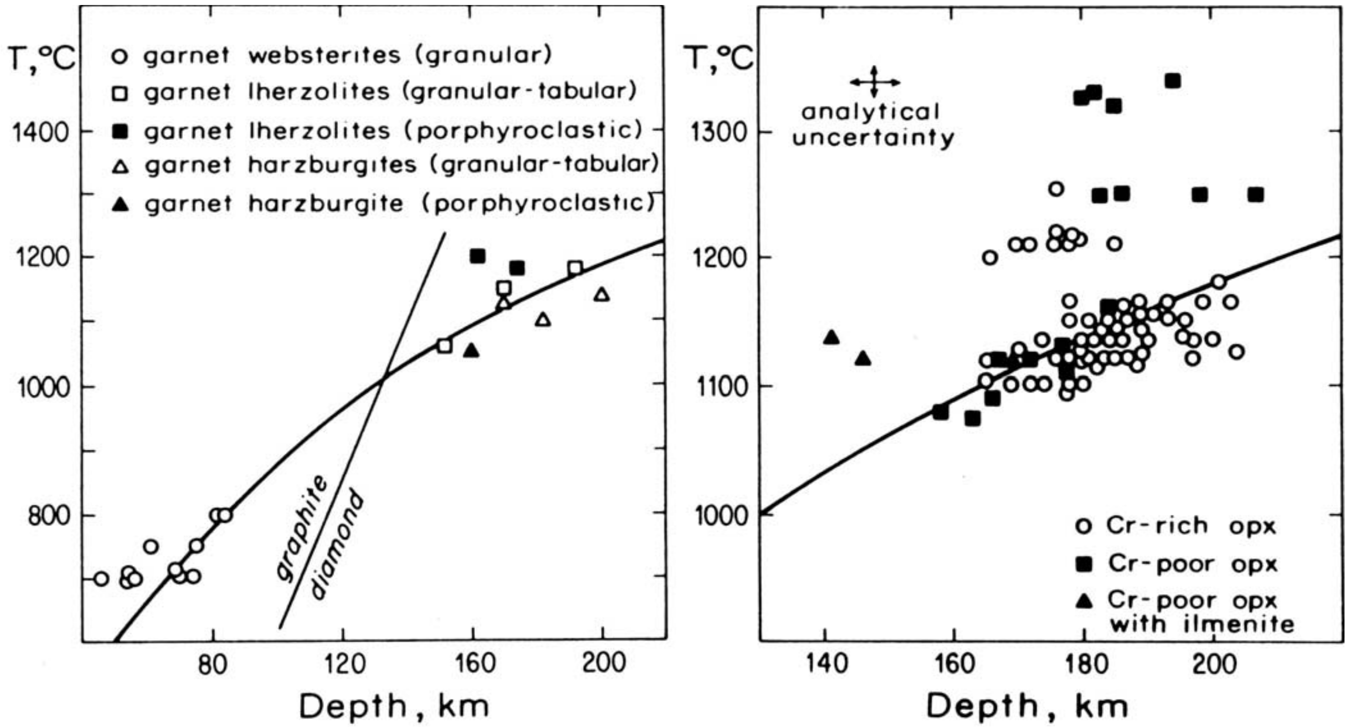

Figure 8. Geotherm based on mantle xenoliths from the Colorado-Wyoming State Line kimberlites (from Eggler et al., 1979).

tions of Cr_2O_3 ranging from 3.5- 14.7 wt%, CaO rarely lower than 4 wt% and Mg# of 81 - 86 (Pizzolato and Schulze, 1998).

Eclogite xenoliths

Small eclogite xenoliths occur in the coarse heavy mineral concentrate, but larger specimens are more rare. A variety of textures and grain sizes occur, but aside from a single Group I eclogite sample with 0.10 wt% Na_2O in garnet, all eclogites analyzed to date (Hozjan, 1996; Schulze, unpub. data) correspond to Group II eclogites of McCandless and Gurney (1989). World-wide, only Group I eclogites are known to contain diamonds, but Group I eclogites appear to be rare in the xenolith populations of all State Line kimberlites (Ater et al., 1984; McCandless and Collins, 1989; Schulze, 1992). However, diamond-bearing Group I eclogites have been found at the Sloan kimberlite (Schulze, 1992). Rutile is a common accessory mineral, and kyanite, corundum, and sanidine eclogites are known, but rare at Kelsey Lake. Preliminary chemical data indicate a restricted compositional range relative to other State Line eclogite populations (e.g. Ater et al., 1984). For example, most garnets have low grossular component (Ca/(Ca+Mg+Fe)) of 0.09 - 0.12, with a variable Mg# of 0.56 - 0.83. A single alkremite xenolith has been recovered. It is dominated by pale pink garnet with accessory black spinel. No compositional data is available for the alkremite.

Megacrysts

Coarse crystals (to several cm) of ilmenite and red-brown garnet are relatively abundant in heavy mineral concentrate. Grey-green clinopyroxene is less common. Intergrowths of phases include garnet in clinopyroxene, ilmenite in garnet, and ilmenite lamellae in clinopyroxene. The garnet megacrysts have a wide range of Cr_2O_3 concentrations (0.1-6.5 wt %) and Mg# of 0.68 – 0.83 (Pizzolato and Schulze, 1998). The higher Cr_2O_3 values relate to dark purple-black colored garnets. The Kelsey Lake megacrysts all belong to the Cr-poor suite, including the high Cr_2O_3-high Mg# examples. They are compositionally distinct from the Cr-rich suite in other State Line kimberlites analyzed by Eggler et al. (1979).

Many ilmenite macrocrysts are extensively altered, with high MnO contents (to 9 wt% MnO) and lacking ilmenite stoichiometry (Schulze et al., 1995). Phases of the kimberlites that contain such ilmenites also contain Mn-rich chromites (e.g., in KL-1, Pit 5 chromites range to 4.5 wt % MnO and ilmenites to 5.8 wt % MnO), indicating that the Mn-enrichment is unlikely magmatic in origin, but probably related to post-emplacement, near-surface groundwater alteration, restricted to certain zones in the kimberlites.

Fresh ilmenites range from 5 to 15 wt % MgO, 0.1 to 2.7 wt % Cr_2O_3. Mg-depletion and Cr-enrichment correlate with increased oxidation state (to 38 mole % hematite component). Although diamonds are thought not to occur in conjunction with oxidized ilmenite populations (e.g., Gurney, 1989), this hypothesis is not supported by the Kelsey Lake data (Schulze et. al., 1995), in which 80% of the ilmenite population has between 5 - 10 wt % MgO, and less than 10% of the population has >10 wt % MgO.

Xenocyrsts

Single crystals of garnet are extremely abundant in the fine fractions (<4mm) of the Kelsey Lake heavy mineral concentrates. Chromite and Cr-diopside grains are less abundant, as are intergrown phases (e.g., clinopyroxene or chromite in garnet). Purple and red garnets (peridotite-derived) are about 5-10 times as abundant as are orange garnets (derived from megacrysts and lesser eclogites), based on visual estimates.

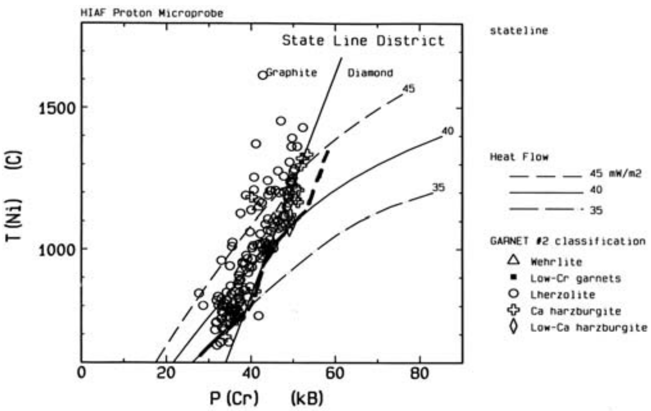

Figure 9. Garnet trace element geotherm of the Colorado-Wyoming State Line kimberlites (from Coopersmith et al., 1995).

Chemical compositions indicate that most purple garnets are derived from Iherzolite xenoliths ("G9" garnets of Gurney, 1984). Low-Ca Cr-pyropes ("G10" garnets) also occur (consistent with the presence of diamonds), with CaO contents as low as 2.4 wt %. Similarly, high-Cr chromites (Cr_2O_3 to 67 wt %), which correspond chemically to chromite inclusions in diamonds (e.g., Sobolev, 1984), are also present in the Kelsey Lake kimberlites.

Trace elements in the Kelsey Lake garnets and chromites have been analyzed using the proton microprobe at CSIRO, Sydney (Coopersmith et al., 1995). The garnet and spinel data has defined a geotherm corresponding to a 35 mW/m2 conductive model to about 40 kb. Above this the geotherm jumps to 40 mW/m2, to about 50 kb, and then further shows a deviation from the conductive model above 1100o C (Fig. 9). It appears that the mantle was strongly heated at depths below about 175 km, and this raised the geotherm in the lower part of the lithosphere. The upper mantle in this region contains only 5 - 10% harzburgite and this being Ca-rich. This is more typical of a Proterozoic lithosphere than an Archean one. This probably reflects the craton-margin setting, where a significant thickness of Proterozoic lithosphere has replaced the Archean rocks at depth. Both potassic and high-T melt-related metasomatism are noted at depth. Eggler et al. (1979) constructed a paleogeotherm based on mantle xenoliths from State Line kimberlites (Fig. 8) that indicated the base of the lithosphere at 200 km depth, consistent with the diamondiferous nature of the State Line kimberlites.

Evaluation and Development

Initial evaluation included delineation and mapping of the kimberlite deposits. Detailed petrographic study and mineral chemistry indicated a strong likelihood that the deposits would host important diamond mineralization. Microdiamond analyses have shown contents ranging from 1 stone to 8 stones per 10 kg. Small diamonds (0.01 to 0.20 ct) were recovered from small surface samples.

In 1990, approximately 1000 tonnes were processed through a nearby contract diamond processing plant. Recovery at this stage included gem diamonds in excess of 2 carats in size. In 1992, a 10 tonnes per hour test plant was constructed on site. This plant utilizes a rotary diamond pan for concentration and a vibrating grease table for recovery. Approximately 6000 additional tonnes were processed through this plant. The resulting diamond recovery included gem diamonds of 6.2 and 14.2 carats.

In 1995, it was decided to commence trial mining at the 250,000 tonnes per year rate. Permits were been upgraded and amended to accommodate the increased scale of the operation. Process and plant design and construction began in the fall of 1995. Site development and mining commenced in the fall of 1995. Construction and commissioning was completed in the early spring of 1996. Mining and treatment of the ore has taken place at the rate of 40,000 to 60,000 tonnes per month.

The ore processing facilities comprise three sections: liberation, concentration, and recovery. Gravity processes are utilized for the concentration as diamond reports to the heavy mineral concentrate. The liberation stage is critical to disaggregate the ore and release the heavy mineral grains, which will include the diamond. Liberation also completely breaks up the clay, which is critical to the process. Crushing and scrubbing sections are utilized in the liberation stage. A simplified flow sheet of the treatment plant is shown as Figure 10.

The concentration stage uses four rotary diamond pans, each 4.25 m in diameter. A gravity separation is accomplished using the naturally occurring finely ground up rock in suspension to act as the dense media. With the disaggregated ore in a slurry with the natural dense media, the heavy minerals drop out into a concentrate. Carefully controlled mass balance between ore and water maintains the desired density separation.

The recovery stage utilizes physical properties specific to the diamond. A Flow Sort x-ray sorter treats sized heavy mineral concentrate. Diamonds luminesce under x-ray excitation, allowing optical recognition and separation. Diamonds are also hydrophobic, or non-wetable. X-ray tails and audit material is passed with water over a vibrating grease table. This is coated with a thin layer of specially formulated "collector grease". As most of the concentrate has a thin film of water adhering to it, it passes over the grease table. The diamond, remaining dry, sticks to the collector grease. These methods are extremely efficient and produce a clean diamond concentrate for final hand sorting. Ore grade at Kelsey Lake is approximately 5 cpht, with an overall stone value of approximately US$120 per carat.

GEOLOGY OF THE IRON MOUNTAIN KIMBERLITE DISTRICT, WYOMING

Introduction

The Iron Mountain district is located within the Laramie Range of southeastern Wyoming 65 km north-northwest of Cheyenne and 50 km northeast of Laramie. Kimberlite was first identified in the district in 1971, and was later described as a small group of scattered dykes and blows by Smith (1977) who discovered and mapped additional bodies and studied their petrology.

Cominco American evaluated the district and identified additional kimberlite bodies in the early 1980's, following

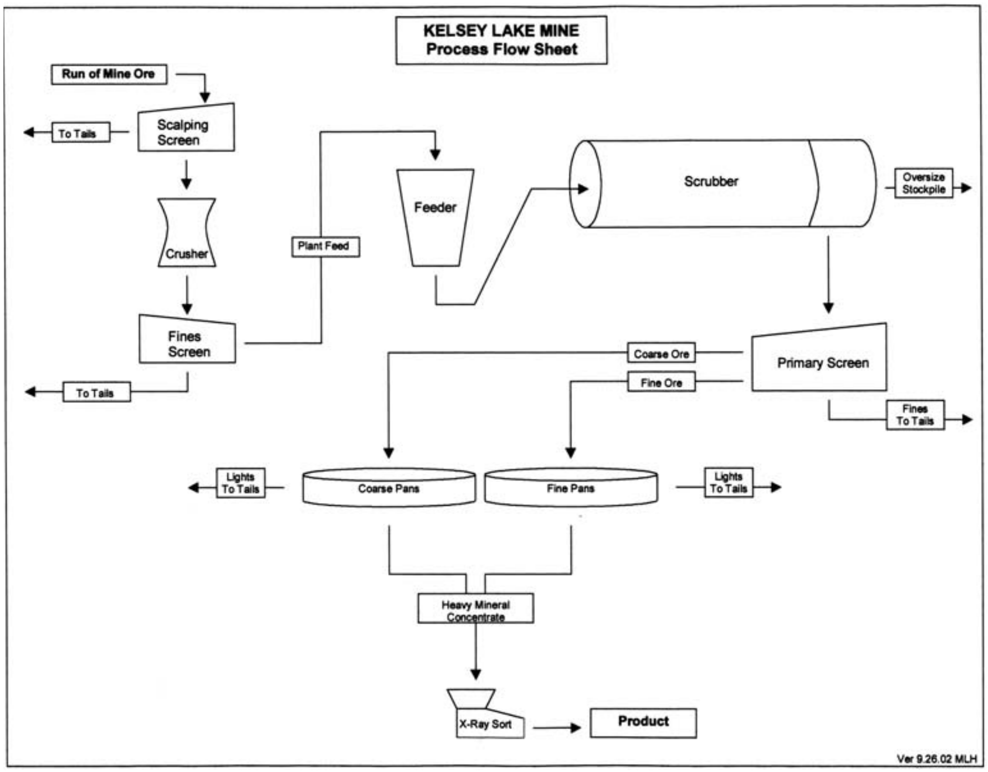

Figure 10. Schematic process flow sheet of the Kelsey Lake Mine treatment plant.

the discovery of several diamondiferous kimberlites 70 km to the south in the Colorado-Wyoming State Line district. Interest in the Iron Mountain district was limited due to the lack of reported and recovered diamonds, and due to the apparent limited volume of kimberlite. However, only a very limited bulk-sampling program evaluated a few kimberlites, and much of the complex remains untested.

The Wyoming State Geological Survey (WSGS) initiated investigations in the district in 1997 and continued in the following field season as an exercise to search for additional kimberlite and test for diamond. During this study, several previously unmapped kimberlites were discovered, as were additional targets. Samples collected from the district include kimberlitic indicator minerals with geochemical signatures characteristic of lherzolite, harzburgite, and eclogite, with a weak contribution from the diamond-stability field.

Mapping of the district identified a more extensive kimberlite complex than previously recognized, and it became apparent that the Iron Mountain district is the second largest kimberlite district in the United States, after the State Line district. The district also encloses one of the better-exposed kimberlitic root zone complexes in North America, and based on exploration in the region surrounding the Iron Mountain district, there is also potential for discovery of additional kimberlites in the surrounding region.

The Iron Mountain District

History and Location

The Iron Mountain district lies on the eastern flank of the Laramie Range north-northwest of Cheyenne (Fig. 2). The district was named after several massive and disseminated titaniferous magnetite deposits in the Laramie Range anorthosite (1.5 Ga) batholith located immediately west of the kimberlite field. Some of these deposits were mined in the 1950’s for ballast.

The district lies at an average elevation of 2,200 m and is characterized by rolling hills with sparse scattered sagebrush and local stands of coniferous trees. About 50 percent of the district is underlain by rock exposure, although large grassy fields covered with soil and regolith are prevalent in many areas, providing potential cover for undiscovered kimberlites.

W.A. Braddock and D. Nordstrom first reported kimberlite in the district in 1971. Smith (1977) later mapped the district as part of a thesis describing the ultrabasic intrusives as a complex of small, discrete, discontinuous dykes and blows that were identified by 57 different sample sites. This paper relies heavily on the detailed work of Smith (1977). Mapping by Cominco American in the early 1980’s and by the WSGS, beginning in 1997, greatly expanded the known extent of kimberlite. Based on geology and petrography, the Iron Mountain kimberlites are interpreted as a poorly-exposed, deeply-eroded, root zone to possible root to diatreme transition zone kimberlite complex. As much as 1,000 to 1,600 m of vertical column of rock may have been removed by erosion since the kimberlites were emplaced.

Age of Emplacement

Heaman et al. (2003) reports a radiometric age of 408.4 ± 2.6 Ma for an Iron Mountain kimberlite. This is similar to the 400 Ma Rb-Sr phlogopite mica age reported by Smith (1979) for an Iron Mountain kimberlite. A kimberlite in the southwestern portion of the Iron Mountain district in the SW/4 section 17 (*see* Fig. 2) encloses sedimentary xenoliths of probable Ordovician and Silurian age (Smith, 1977). The sedimentary xenoliths indicate the intrusive penetrated the former Silurian-Devonian surface and assimilated fragments of the sedimentary cover. The xenoliths establish the oldest possible age for the primary episode of eruption, and fits well with the reported age determinations.

Upper crustal xenoliths found in some of the kimberlites include quartz monzonite, anorthosite, syenite, hypersthene syenite, amphibolite, biotite schist, and fragments of mafic igneous rock. Lower crustal xenoliths include pyroxenite and garnet granulite. Mantle xenoliths include garnet and spinel peridotite, websterite, eclogite, and diopside-ilmenite intergrowths. Megacrysts include clinopyroxene, orthopyroxene, garnet, ilmenite, and rare olivine (Smith, 1977).

Geology and Structure

The Iron Mountain district lies along the eastern flank of the Laramie Range. The range was uplifted and thrust easterly during the Laramide orogeny and the district is currently surrounded on the east, south, and west by Phanerozoic sedimentary rocks, which were deformed by crustal shortening. Several broad folds, anticlines, domes, synclines, low angle thrusts, and associated tear faults are present in the adjacent Phanerozoic terrain. Precambrian deformation at Iron Mountain includes joint sets and a northeast-trending zone of cataclasis in the northwestern part of the district.

Kimberlites at Iron Mountain and in the State Line lie within the Proterozoic basement south of the Cheyenne Belt. The Iron Mountain kimberlites parallel the trend of the Cheyenne Belt, suggesting that kimberlite emplacement may have been influenced by this structure. The Cheyenne Belt is also exposed in the Sierra Madre and Medicine Bow Mountains to the west, where additional indicator minerals and a few diamonds have been found.

The Iron Mountain kimberlites (Fig. 11) form a deeply dissected feeder dyke complex with periodic blows and sills intruding Sherman Granite. The granite and kimberlites are exposed in the core of an eroded, south-plunging, anticlinorium. It is possible that the kimberlite complex continues to the east and west under the Phanerozoic cover, and the possibility of kimberlites further north and west is considered likely.

Mississippian and younger sedimentary rocks unconformably overlie the Sherman Granite and kimberlite, and dip off the core of the Iron Mountain anticlinorium to the east, south, and west. Immediately west of the district, sedimentary rocks are exposed in the asymmetrical, southerly-plunging Hay Canyon syncline. Precambrian rocks of the Laramie anorthosite-syenite batholith and titaniferous magnetite deposits crop out west of the syncline.

The oldest in situ sedimentary rocks in the area consist of thin, calcareous, arkosic sandstone with underlying dolomitic limestone. These are thought to be a southern extension of the Mississippian Madison Formation and sit on the Precambrian surface. The Madison is overlain by the Casper (Mississippian – Pennsylvanian), the Permian Minnekahta and Opeche Formations, and the Triassic Chugwater Formation.

A Tertiary conglomerate (paleoplacer) lies directly on the Sherman erosional surface in the western portion of the district. The conglomerate is unsorted, poorly consolidated, with rounded to angular boulders, pebbles, and cobbles of Precambrian igneous and metamorphic rock interspersed with Paleozoic and Mesozoic fragments and occasional kimberlitic indicator minerals. Kimberlite was traced into the conglomerate from both the east and west, and locally continues under the unit. The extent of hidden kimberlite beneath the conglomerate is unknown and considerable clay in the conglomerate masks electrical responses from any potentially buried kimberlite.

Precambrian anorthosite is found in the northwestern portion of the district, as fragments in Tertiary conglomerate, and xenoliths in some kimberlites (Smith, 1977). The anorthosite was intruded by the Sherman Granite (Peterman et al., 1968). Two varieties of granitic rocks in the area are distinguished by grain size. One is fine-grained granite in the northeast, northwest, west-central, and southeast. A coarse-grained porphyritic quartz monzonite to granite is found elsewhere. Discontinuous simple pegmatite and aplite dykes are scattered throughout the district. North- to northwest-trending Precambrian mafic dykes intrude the Sherman Granite. These are 2 to 3 m wide, nearly vertical, and form sharp contacts with the granite. Locally, some of these dykes have been cut by kimberlite.

Kimberlite

Smith (1977) conducted detailed sampling and study of the Iron Mountain kimberlites, and much of this discussion is based on his work. Kimberlites at Iron Mountain form an extensive, locally continuous, fissure complex. The complex was traced over a strike-length of 8 km within 30 km^2 and contains several enlargements, some of which are interpreted as 'blows', or the eroded remnants of former pipes. A few possible pipes were recognized in the western and northwestern portion of the district. The central portion of the complex contains a network of branching dykes and sills. The dykes range from 1 to 125 m wide and dip vertically to steeply, while the sills are shallow dipping.

A few blows were mapped where dyke enlargements coexist with kimberlite breccia, which is extensively carbonatized. Elsewhere, dyke swells contain macrocrystic hypabyssal kimberlite (i.e., SE section 3 near geophysical lines 18, 20, and 21, and in the NW section 2; Fig. 11). Pipes were also mapped in sections 6, 17 and 18, along the western margin of the district and are interpreted as diatremes that contain crustal sedimentary xenoliths and also mantle xenoliths.

A group of carbonatized breccia pipes were also mapped in sections 15 and 16. These contain abundant fragmented Sherman Granite breccia clasts with hypabyssal kimberlite xenoliths (Smith, 1977). The absence of Paleozoic xenoliths suggests these breccias may represent a degassing event of the kimberlitic magma, and are interpreted as root zones of blind diatremes.

In general, the dykes are mapped as scattered serpentinized kimberlite outcrops connected by grus-covered kimberlitic soil. In places, the kimberlitic soils are distinct, particularly where the grus is thin. These soils contain intermixed rock fragments of kimberlite and granite in blue ground (carbonated montmorillonite clay) with variable amounts of indicator minerals (notably ilmenite, less com-

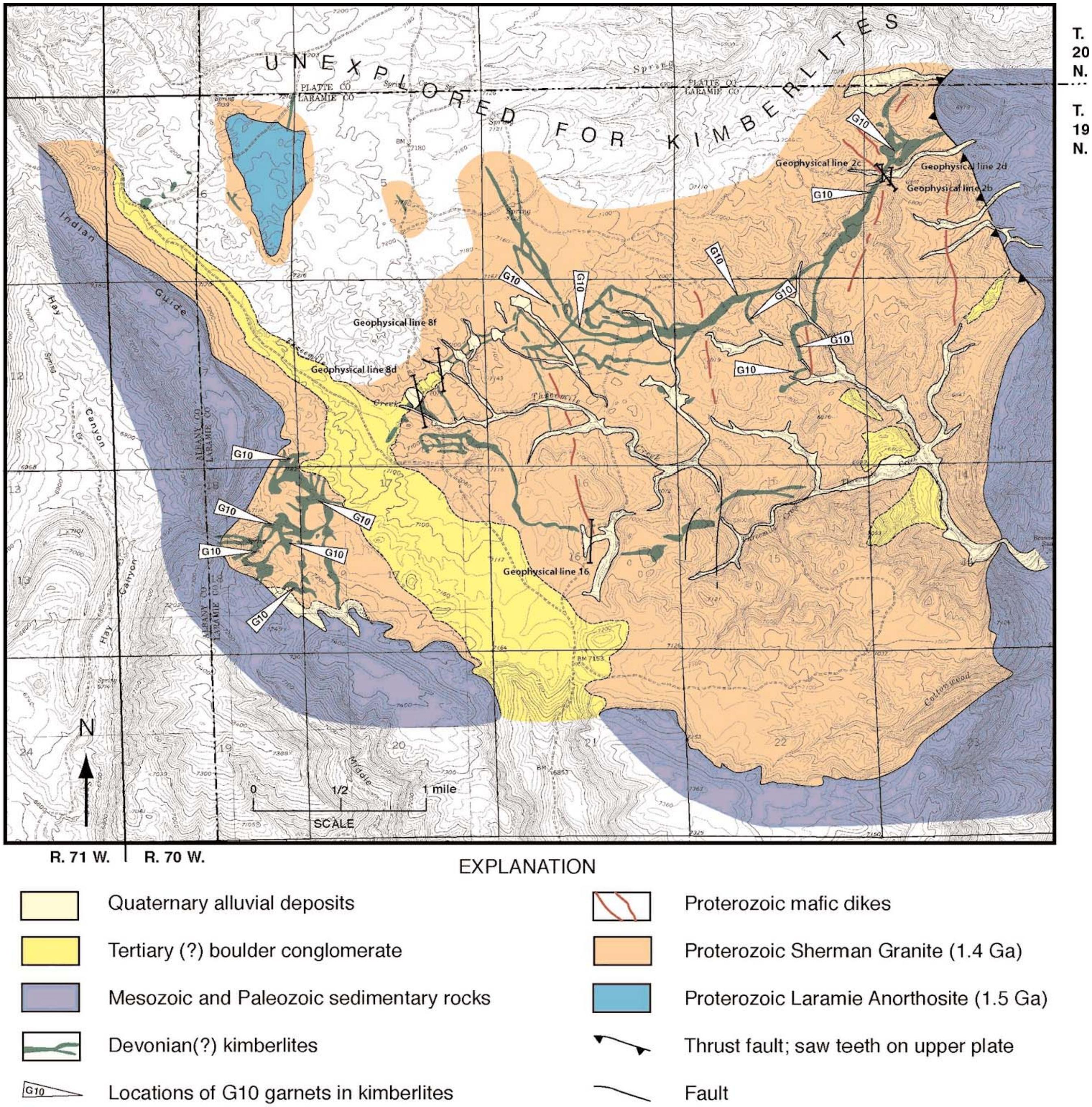

Figure 11. Geological map of the Iron Mountain kimberlite district, (geology by W. D. Hausel, unpublished) kimberlite locations from Smith (1977) and H. G. Coopersmith, pers. comm.). The G10 flags on the map are localities where sub-calcic, chrome pyropes were collected as verified by electron microprobe analysis at the University of Wyoming.

monly pyrope garnet, and rarely chromian diopside). The kimberlitic soils are outlined by distinct, mappable, vegetation anomalies. Because kimberlite erodes faster than the surrounding granite, many kimberlites are expressed by slight topographic depressions. Similar 'blue ground' has been mapped over many kimberlites in the State Line district. Vegetation anomalies associated with the blue ground include relatively lush, grassy parks devoid of trees, which are visually prominent at certain times of the growing season, such that the kimberlites can literally be mapped by the vegetation anomalies after a few weeks of rain in late May and early June. The kimberlitic soils are also attractive to burrowing animals including rattlesnakes (Billman, 1998).

Petrography

Three petrographic types of kimberlite were identified by Smith (1977):

Type I - hypabyssal ('porphyritic' to 'massive') kimberlite;
Type II - carbonatized kimberlite;
Type III- carbonatized to silicified kimberlite breccia.

All stages of gradation from one kimberlite type to another have been recognized in the district.

The hypabyssal kimberlite is a distinct green, highly serpentinized, magmatic kimberlite that is restricted to dykes and sills. This rock contains large, sub-rounded, <1 to 3 cm olivine macrocrysts, pervasively replaced by grey-black magnetite, reddish hematite, and light-green serpentine in a serpentinized groundmass. The groundmass consists of abundant, small, rounded, serpentinized olivines in a mesh of serpentine with minor interstitial to poikilitic carbonate, minor perovskite and phlogopite, and trace apatite. Locally, the kimberlite exhibits an irregular, flow texture with a rough alignment of the long axes of the macrocrysts, megacrysts, and xenocrysts. Only minor amounts of xenocrysts and xenoliths are found in this type of kimberlite. Uncommon, mantle-derived xenocrysts include pyrope garnet, chromian diopside, chromian enstatite, and enstatite. Ilmenite megacrysts are present in relatively large amounts and may form as much as 2 to 3 percent of the rock, locally. The most common xenolith is granite; eclogite and peridotite are rare. The hypabyssal kimberlite represents a magmatic dyke facies, and is the least differentiated kimberlite in the district.

The carbonatized kimberlite is dark grey to greyish-green rock with porphyritic to massive texture similar to the hypabyssal kimberlite. This kimberlite is spatially associated with blows, and is weakly to strongly carbonatized. The rock is primarily hypabyssal facies with local volcaniclastic kimberlite units. This kimberlite may contain minor to 80 percent carbonate as replacements of olivine macrocrysts in a serpentine-carbonate groundmass. Hematite mantles some macrocrysts and the groundmass includes hematite, magnetite, minor Cr-spinel, and a variety of Fe-Ti oxides. Serpentine is usually present in small amounts dispersed throughout the matrix and is intimately intermixed with carbonate. Small amounts of secondary phlogopite may also be present. The heterogeneous nature of this rock is accented by a varied group of xenoliths. In general, a greater quantity of mantle xenoliths and xenocrysts are found in this kimberlite compared to other varieties of Iron Mountain kimberlite. In the southwestern portion of the district, this kimberlite contains angular, elongate, granitic fragments that locally exhibit flow alignment.

Carbonatized to silicified kimberlitic breccia is exposed in a group of blows interpreted to represent the eroded root zones of blind diatremes. This rock is gradational to the carbonatized kimberlite. Whole rock chemistry of this contaminated rock is difficult to assess due to the abundant granitic xenoliths. These breccias are serpentine deficient relative to normal intrusive kimberlite breccia. In hand specimen, the rock is grey to black and may contain as much as 70 percent granitic fragments in a carbonate-rich matrix. The breccia exhibits varying degrees of silicification. Exposures may be expressed as saddles between silicified granitic wall rock. In thin section, granitic rock fragments are set in a finely crystalline matrix of carbonate, pulverized granitic material, cryptocrystalline to microcrystalline quartz, hematite, magnetite, and rounded carbonatized grains. Hematite commonly rims altered xenocrysts, most of which were probably olivine. Smith (1977) found rare, altered, serpentine-rich kimberlite xenoliths in this breccia.

Whole Rock Geochemistry

The mineralogy and whole rock geochemistry show the Iron Mountain kimberlites range from serpentine dominant to carbonate dominant. The Iron Mountain kimberlites bare little resemblance to their initial mantle melt due to fractionation, differentiation, and incorporation of abundant xenolithic material. Representative whole rock analyses of these rocks are difficult to assess, as the kimberlites are contaminated with appreciable foreign material incorporated in the magma as it rose from the mantle through the earth's crust. Samples of Iron Mountain Type I and II kimberlite were selected for analysis because of the lower amount of visible contaminates. All samples of the Type III kimberlite were pervasively contaminated by granitic xenoliths. Major oxide, minor and trace element concentrations of many Iron Mountain kimberlites are compatible with worldwide kimberlite averages, and to those of the State Line diamondiferous kimberlites (Table 1).

The Type I kimberlite is characteristic of a typical kimberlite containing considerable groundmass and macrocrystal olivine with minor pyroxene and ilmenite and some contaminates. The olivine throughout the samples is pervasively serpentinized, with little preserved primary olivine. Where preserved, the olivine is found in the cores of some megacrysts and groundmass grains that are enclosed in a reaction rim of serpentine. But for the most part, the grains occur as serpentine pseudomorphs after olivine. The mineralogy emphasizes a magnesium-rich chemistry.

The average chemistry of the Type I kimberlite is comparable with average Gp 1 kimberlite (Table 3). Type I kimberlites have higher average magnesium (28.6 % MgO) and lower average potassium (1.04 % K_2O) than the average Gp 1 kimberlite (27.9 % MgO; 0.98% K_2O). Magnesium content is higher and potassium content lower than the average Gp 2 kimberlite/orangeite (23.9 % MgO; 2.1 % K_2O; Table 3). Samples of the Iron Mountain Type I hypabyssal kimberlite range from 23.1 - 33.31 % MgO, and 0.18 - 1.8 % K_2O.

Carbonatized kimberlites (Type II) show a wide range in major oxide chemistry, in part due to contamination and differentiation. Carbonatization appears to have had the greatest influence on the chemistry variance. These kimberlites show a wide range of carbonatization from weakly carbonated rock where the serpentinized olivine megacrysts contain reaction rims of carbonate with some interstitial carbonate groundmass, to extreme carbonatization showing pervasive alteration of the rock. In the pervasively altered rocks, the megacrysts and groundmass appear to be completely replaced by carbonate. Samples IM7-98 and IM18-98 (Table 3) are weakly carbonatized. Whole rock chemistry shows 28.91 and 32.92 % MgO with 7.11 and 2.64 % CaO, respectively. LOI totals 12.29 and 13.38 %, much of which probably occurs as H_2O with some CO_2. Other Type II samples listed in Table 3 are pervasively carbonatized. In particular, sample IM4-98 contains 5.56 percent MgO, 39.27 % CaO, and 34.9 % LOI, and is dramatically depleted in silica (9.85 % SiO_2) and potassium (0.34 % K_2O). Based on the chemistry this sample represents extreme carbonatization with depletion of MgO. Other samples of this type also show intense carbonatization. Samples IM15-98 and IM30-98 contain serpentinized olivine megacrysts with a groundmass

Table 3. Major and trace element analyses of Iron Mountain kimberlite samples. Samples IM16-5, IM21-1, IM1-8, and IM53-1 are from Smith (1977). Average Group 1 kimberlite and average Group 2 kimberlite/orangeite are for comparison. All other sample analyses are from this study.

Massive Macrocrystic Kimberlite from Iron Mountain

	IM8-98	IIM16-98	IM21A-98	IM21B-98	IM21C-98	IM28-98	IM60-97	IM16-5	IM21-1	IM15-97	IM16-97	IM21-98	IM24-98	M27-98	IM47-98	IM51-98
SiO_2 (%)	31.67	30.86	30.2	30.93	30.44	30.08	31.76	33.8	29.9	30.2	33.48	31.93	33.01	33.2	32.36	33.29
TiO_2	2.83	3.11	2.62	2.89	2.77	2.76	2.6	3	4	2.36	2.56	2.56	2.64	2.64	2.4	2.57
Al_2O_3	3.9	3.81	2.49	2.94	2.71	2.69	2.62	2.8	4	2.34	3.08	2.54	2.91	3.18	2.85	3.8
Fe_2O_3	11.88	12.83	11.75	12.41	12.06	12.06	11.97	7.8	10.4	--	--	--	--	--	--	--
FeO	--	--	--	--	--	--	--	3.8	1.8	11.26	11.56	11.82	11.9	12.52	12.27	12.4
MnO	0.28	0.24	0.18	0.21	0.18	0.19	0.19	0.18	0.19	0.2	0.2	0.2	0.21	0.23	0.2	0.18
MgO	33.31	27.62	29.26	28.91	28.95	29.11	28.42	28.6	23.1	0.23	0.22	0.18	0.29	0.21	0.2	0.21
CaO	2.37	6.82	8.76	8.28	8.04	8.62	6.46	5.1	13.2	25.92	29.12	28.82	29.28	28.54	27.89	27.59
Na_2O	0.12	0.06	0.15	0.11	0.12	0.1	<0.01	0.05	0.07	10.11	5.28	7.72	5.32	5.2	5.72	8.88
K_2O	0.18	0.65	0.91	1.33	1.23	1.24	0.58	1.4	1.8	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P_2O_5	0.54	0.75	0.16	0.14	0.22	0.2	0.33	0.35	0.3	1.21	0.4	1.04	0.52	0.91	1.48	0.45
CO_2	--	--	--	--	--	--	--	1.7	1.3	0.78	0.41	0.21	0.58	0.36	0.63	0.32
LOI	13.4	13.08	13.68	12.22	12.86	13.44	15.57	11.3	9.9	16.01	12.74	13.29	13.67	12.1	14.39	10.73
TOTAL	100.64	100.04	100.37	100.57	99.79	100.7	100.69	99.88	99.96	100.62	100.06	100.31	100.35	99.08	100.4	100.43
Cr	787	951	912	934	1005	985	210	970	930							
Ce	290	414	334	362	377	346	--	220	390							
Eu	2.5	4.2	3.4	3.5	3.7	3.6	--	2	2.8							
La	169	238	195	212	218	203	--	98	220							
Lu	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	--	--	--							
Nd	81	120	100	110	120	100	--	80	61							
Sc	14.4	20.7	17.4	19.6	19	17.7	--	--	--							
Sm	11.4	17.3	13.8	15.1	15.5	14.3	--	--	--							
Tb	<1	1	1	2	1	1	--	--	--							
Th	28	32	25	27	29	26	--	22	36							
U	6	5	5	6	5	5	--	--	--							
Yb	1	1	<1	1	1	1	--	1.3	2.2							
Hf	3.6	5.1	5.2	5.1	4.8	4.7	--	--	--							
Cu	13	10	47	18	66	47	--	85	97							
Pb	32	41	19	19	27	20	--	13	21							
Zn	87	100	93	87	96	96	--	75	130							
Mo	1	2	1	1	2	2	--	2.6	6.8							
Ni	635	549	756	692	714	719	--	820	1100							
Co	96	88	94	97	94	93	--	69	80							
As	5	6	<5	<5	<5	<5	--	--	--							
Ba	1643	>2000	797	144	439	514	--	720	1400							
V	115	142	57	57	66	67	--	62	130							
Sr	398	658	325	332	339	311	--	320	910							
Y	14	17	13	15	15	14	--	9.7	23							
Ga	<10	<10	<10	<10	<10	<10	--	8.4	12							
Li	9	40	4	8	3	3	--	--	15							
Nb	223	245	215	240	231	227	--	100	220							
Ta	9	11	6	7	7	9	--	--	--							
Zr	123	160	178	173	163	161	--	81	250							

pervasively replaced by carbonate. These yielded 8.95 and 11.7 % MgO with 21.05 and 19.13 % CaO.

Carbonatized breccias (Type III) have been contaminated by abundant granite breccia clasts. These rocks look more like a fault breccia than kimberlite. Samples with the least amount of granitic xenoliths were selected for whole rock analysis, and show enrichment in SiO_2, Al_2O_3, K_2O as well as extreme depletion of MgO (Table 3). Only sample IM14-97 contained appreciable magnesium (4.92 % MgO). Three other samples contained 0.54 to 1.44 % MgO. These samples also show enrichment of calcium (7.55 - 18.87 % CaO) in the form of calcite. No magnesium-silicate minerals were identified during petrographic analysis of these samples, and it is possible that the rocks represent a degassing phase of a blind diatreme, where CO_2 gas exsolved from the kimberlite magma as the lithostatic pressure decreased near the surface.

Rare earth contents of the kimberlites show chondrite normalized distribution patterns that are highly fractionated toward light rare earths. La/Yb ratios range from 75 to 173, and the kimberlites from Iron Mountain (as well as the State Line district) display negative Eu anomalies. Similar patterns have been recognized in some South African and Siberian diamondiferous kimberlites (Smith, 1977).

Mantle Petrology

Smith (1977) studied the mantle petrology at Iron Mountain through examination of xenoliths. Mantle xenoliths include garnet peridotite, spinel peridotite, websterite and eclogite, as well as discrete megacrysts of garnet, diopside, ilmenite, and diopside-ilmenite intergrowths. The majority of these mantle xenoliths are intensely altered, with relict primary mineralogy including chrome diopside, garnet, and chrome spinel. Smith (1977) identified three general types of material: depleted spinel and garnet peridotite from which partial melt has been extracted; eclogite and websterite, which formed as cumulates of rising basaltic melts; and the megacryst assemblage, which crystallized from a fractionating liquid that may have been parental to kimberlite.

Smith (1977) reported the following mineral chemistry. Chrome pyrope in garnet peridotite contains Cr_2O_3 concentrations ranging from 5.8 to 10.5 wt %, CaO concentrations ranging from 5.5 to 7.5 wt %, and TiO_2 concentrations ranging from 0.03 to 1.0 wt %. Clinopyroxene in garnet peridotite contains 1.3 - 2.9 wt % Cr_2O_3, Na_2O concentrations ranging from 1.1 to 2.7 wt %, and Al_2O_3 concentrations ranging from 0.15 to 4.6 wt %. Spinel in spinel peridotite and spinel-bearing garnet peridotite contains Cr_2O_3 concentra-

Table 3. continued

	Transitional Kimberlite								Carbonatized Kimberlite Breccia						
	IM18-98	IM7-98	IM15-98	IM1-8	IM53-1	IM4-98	IIM30-98	IM16-98A I	M54-98	IM14-97	M13-98	IM14-98	IMK1-97	Gp I	Gp II
SiO_2 (%)	31.68	34.04	25.69	26	27.8	9.85	25.34	30.62	19.57	52.18	46.13	58.72	49.03	35.2	31.1
TiO_2	2.96	1.9	1.84	2.6	2.5	1.81	1.55	1.52	1.56	0.82	0.86	1.14	1.08	2.3	2
Al_2O_3	3.26	3.44	5.44	2.1	2.8	1.97	3.25	3.68	2.04	9.26	9.26	9.66	7.59	4.4	4.9
Fe_2O_3	11.96	9.84	6.72	8.8	7.5	4.74	8.12	8.64	7.84	5.54	5.81	6.98	6.37	9.8	10.5
FeO	--	--	--	0.89	2.8	--	--	--	--	--	--	--	--	--	--
MnO	0.27	0.18	0.21	0.16	0.21	0.78	0.16	0.19	0.17	0.09	0.11	0.12	0.12	0.11	0.1
MgO	32.92	28.91	8.95	12.7	12.3	5.56	11.7	8.93	13.75	4.92	0.86	0.54	1.44	27.9	23.9
CaO	2.64	7.11	21.05	20.1	11.8	39.27	19.13	18.79	23.23	7.55	15.87	7.82	15.03	7.6	10.6
Na_2O	0.1	0.12	0.08	0.05	0.07	<0.01	<0.01	<0.01	<0.01	0.11	0.15	0.22	0.02	0.32	0.31
K_2O	0.15	1.79	4.59	1	1.7	0.34	2.87	2.83	0.66	7.35	7.72	7.92	6.35	0.98	2.1
P_2O_5	0.53	0.67	1.79	0.35	0.55	0.44	0.19	1.95	0.7	0.27	0.24	0.42	0.34	0.72	0.66
CO_2	--	--	--	20.2	21.5	--	--	--	--	--	--	--	--	--	--
LOI	13.38	12.29	24.27	5.1	8.5	34.9	28.26	23.01	30.82	11.92	13.52	6.75	13.36	7.4	5.9
TOTAL	100	100.47	100.73	100.05	100.03	99.77	100.7	100.29	100.48	100.07	100.58	100.36	100.82	100.03	99.17
Cr	711	915	467	850	1000	1300	1200	1200	1300	600	232	344	700	660	610
Ce	285	358	150	480	390					--	300	251		290	660
Eu	2.3	2.9	1.7	3.5	2.5					--	2.1	2.2		2	4.1
La	169	212	121	270	190					--	160	150		120	380
Lu	<0.2	0.2	0.9	--	--					--	0.8	0.9		--	--
Nd	85	100	55	120	180					--	110	94		150	190
Sc	14.5	13.4	13	--	--					--	8.5	8.4		--	--
Sm	11.2	14	8.5	--	--					--	18.9	18.7		--	--
Tb	<1	1	1	--	--					--	2	3		--	--
Th	24	29	24	42	22					--	26	29		22	56
U	6	6	8	--	--					--	5	6		--	--
Yb	1	1	3	3	1.9					--	6	6		0.3	2.2
Hf	4	4.1	4	--	--					--	9.4	9.5		--	--
Cu	66	52	75	71	54					--	11	17		21	22
Pb	27	30	37	32	13					--	38	49		23	72
Zn	94	76	208	120	110					--	129	113		140	190
Mo	<1	1	4	7.5	<2.2					--	3	4		4.2	7.6
Ni	676	740	245	940	500					--	128	118		530	500
Co	106	75	34	79	56					--	25	26		37	28
As	<5	<5	9	--	--					--	15	18		--	--
Ba	1395	>2000	1946	1000	580					--	839	1370		650	1900
V	151	108	219	120	70					--	43	47		60	120
Sr	590	1037	1279	800	600					--	273	279		330	1300
Y	14	16	21	31	15					--	45	54		13	26
Ga	<10	<10	<10	11	11					--	13	13		5.5	8.5
Li	7	10	65	10	--					--	9	12		--	35
Nb	224	228	182	290	150					--	141	174		110	310
Ta	9	6	<5	--	--					--	<5	<5		--	--
Zr	124	132	85	290	110					--	128	159		68	280

tions ranging from 21.0 to 57.3 wt %, TiO_2 concentrations ranging from 0.04 to 0.89 wt %, and Al_2O_3 concentrations ranging from 8.2 to 45.1 wt %. P-T estimates for Iron Mountain mantle xenoliths range up to 1205 °C and 65 kb, equating to a 200 km depth. Garnet in eclogite contains Al_2O_3 concentrations ranging from 19.9 to 22.4 wt%, and Na_2O concentrations ranging from 0.0 to 0.11 wt %. Clinopyroxene in eclogite contains Al_2O_3 ranging form 3.9 to 17.8 wt%, Cr_2O_3 concentrations ranging from 0.0 to 0.66 wt %, and Na_2O concentrations ranging from 2.4 to 7.6 wt %. Rare chrome-rich garnet xenocrysts contain Cr_2O_3 concentrations of up to 12.6 wt % and 6.3 wt % CaO. Cr-pyrope xenocrysts (Fig. 12) show primarily a lherzolitic trend, but include harzburgitic garnets (10 - 11 wt % Cr_2O_3, 3 - 4 wt % CaO; Coopersmith, unpub. data; Hausel and Sutherland, 2000). Chrome-poor garnet megacrysts contain Cr_2O_3 concentrations ranging from 0.03 to 4.8 wt %, CaO concentrations ranging from 4.2 to 5.2 wt %, and TiO_2 concentrations ranging from 0.37 to 1.1 wt %. Chrome-poor ilmenite megacrysts contain Cr_2O_3 concentrations ranging from 0.01 to 2.5 wt %, FeO concentrations ranging from 23.5 to 71.1 wt %, MgO concentrations ranging from 1.5 to 12.4 wt %, and TiO_2 concentrations ranging from 30.3 to 55.6 wt %.

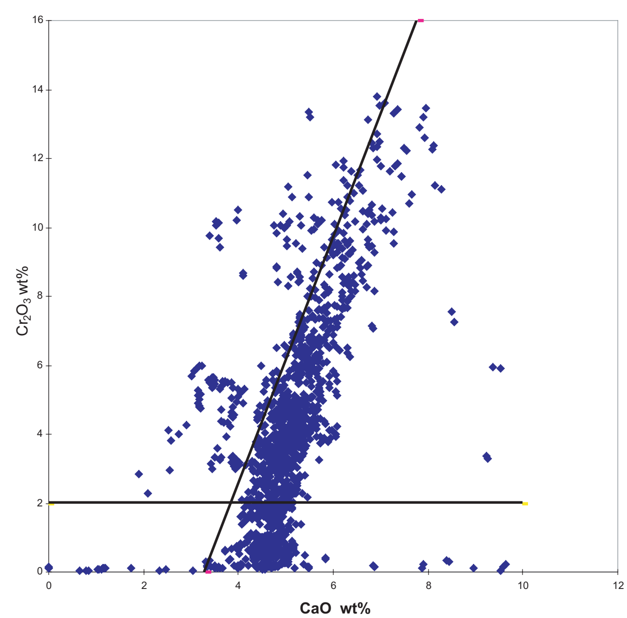

Figure 12. Biariate plot of CaO vs. Cr_2O_3 for garnets collected from Iron Mountain kimberlites. Those with compositions left of the inclined line have compositions equivalent to G10 (sub-calcic) garnets.

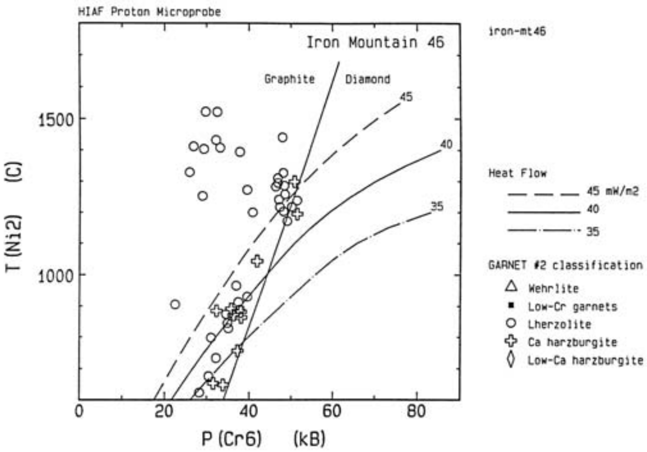

Figure 13. Iron Mountain geotherm. P-T plot based on Cr and Ni analyses in garnet for kimberlite IM-46 (from Griffin et al., 1994).

Concentrate from IM-46 has been studied by Griffin et al. (1994), utilizing the proton microprobe to analyze for trace elements. The paleogeotherm (Fig. 13) for this kimberlite is poorly constrained. An inflected steep geotherm for this area suggests only minimal sampling of the diamond stability field. The deeper mantle is strongly affected by melt-related metasomatism, and the shallower parts to a weaker extent by phlogopite-related metasomatism.

Economic Geology of Iron Mountain Kimberlites

Recent mapping has greatly increased the amount of known kimberlite in the district, much of which has not been tested for diamonds. The indicator mineral chemistry supports that much of the kimberlite in the Iron Mountain dyke complex originated just within or near the diamond-stability field.

Samples show a presence of sub-calcic, high chromian garnets with chemistry similar to G10 (diamond-stability) pyrope garnets. This data suggests that the Iron Mountain magmas may have originally entrained diamonds from a garnet harzburgite mantle. The contribution from potentially diamondierous Group I eclogites (Fig. 14) appears to be low. Ilmenite chemistry (Fig. 15), is similar to that at the Kelsey Lake kimberlites, suggesting poor diamond preservation. The ilmenite chemistry of the Kelsey Lake kimberlite shows as much as 38 % hematite component (Schulze et al, 1995; Coopersmith and Schulze, 1996). Although poor diamond preservation is predicted for Kelsey Lake, diamond production at the mine includes a large percentage of high-quality gemstones with octahedral habit. Thus the chrome/magnesian ratios and chrome depletion in ilmenites provide inconsistent information on diamond preservation (Coopersmith and Schulze, 1996).

To date, only a minor amount of material has been collected from Iron Mountain for diamond testing. Microdiamond testing has recovered only a small number of stones from a few kimberlites. During the early 1980s, Cominco American Incorporated collected small bulk samples from the IM7, IM46, and IG3 kimberlites. These were chosen based upon their size, pipe-like nature and mineral chemistry. Approximately 40 - 60 tonnes were sampled from each pipe and treated at Cominco's facility in Fort Collins. Only one diamond (>2mm) was recovered, a 0.3 carat white octahedral stone from IG-3. No further bulk sampling was performed.

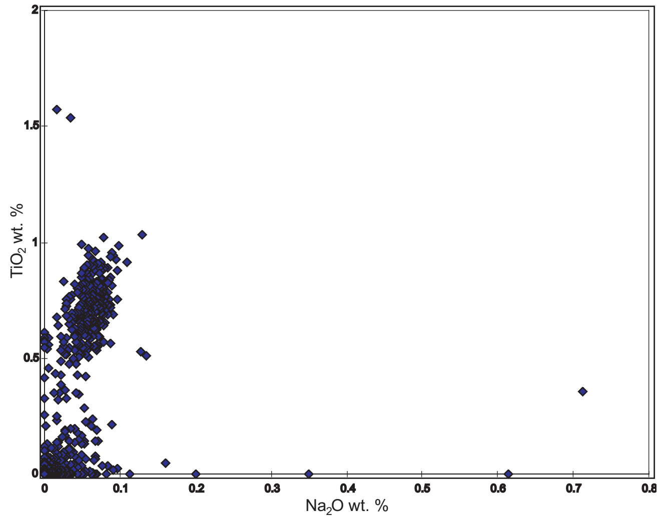

Figure 14. Microprobe analyses of eclogitic garnets from Iron Mountain show that a subset has compositions similar to diamond inclusion eclogitic garnet.

Other Anomalous Areas in Southeastern Wyoming

Approximately 1,600 stream sediment samples were collected in southeastern Wyoming by the WSGS in the mid-1980s to search for kimberlite (Hausel et al., 1988). Of these, nearly 20 % (~ 300) contained kimberlitic indicator minerals, providing evidence that the craton may have been intruded by a major, undiscovered, kimberlite swarm. Sampling by Cominco American and others showed a similar distribution of kimberlite indicators.

THE LEUCITE HILLS LAMPROITE PROVINCE, WYOMING

History of Investigations

In 1871, S.F. Emmons, while undertaking a survey of the 40th parallel in the western United States discovered the first occurrence of leucite-bearing rocks on the North American continent (Zirkel, 1876). In recognition of this discovery, the series of buttes and mesas composed of these rocks were aptly named by Emmons (1877) as the Leucite Hills. Subsequent petrographic study of the rocks by Whitman

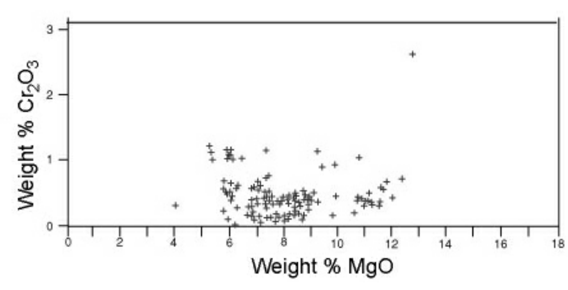

Figure. 15. Ilmenite chemistry from kimberlite at Iron Mountain

Cross (1897) resulted in the definition of three new rock types: wyomingite (after the State of Wyoming); orendite (after Orenda mesa - etymology unknown); and madupite (from the Shoshone word "madupa", meaning "sweetwater" and the name of the county in which the Leucite Hills are located). The geology and petrology of the area was initially described by Kemp (1897), Kemp and Knight (1903), and Schultz and Cross (1912). Subsequent geological studies were by Johnston (1959), Smithson (1959), Ogden (1979), and Gunter et al. (1990). The first detailed mineralogical studies of the Leucite Hills rocks using the electron microprobe were by Carmichael (1967), Kuehner (1980), Barton and van Bergen (1981), these being followed by the extensive studies of Mitchell and Bergman (1991). Other whole rock geochemical and isotopic studies have been undertaken by Kuehner (1980), Kuehner et al. (1981), Vollmer et al. (1984), Salters and Barton (1985), and Fraser (1987). Model K-Ar age determinations initially provided by Bradley (1964) and McDowell (1966, 1971) have been followed by the comprehensive $^{40}Ar/^{39}Ar$ study of Lange et al. (2000). Experimental studies using Leucite Hills' rocks as starting material have been conducted by Carmichael (1967), Sobolev et al. (1975), Barton and Hamilton (1978, 1979, 1982), Mitchell (1995), and Mitchell and Edgar (2002). Summaries of the geology and petrology of the Leucite Hills are given by Mitchell and Bergman (1991) and Hausel (1998).

It should be noted that the potassic volcanic rocks of the Leucite Hills were not strictly described as lamproites until revisions were made to the terminology of potassic alkaline rocks by Scott Smith and Skinner (1984) and Mitchell (1985). As a consequence of these revisions, the old type locality nomenclature was abandoned in favour of a mineralogical-genetic terminology, employing compound names that describe the mineralogy of the rocks (Table 4). These terminological revisions, summarized by Mitchell and Bergman (1991) are now integrated into the IUGS hierarchical systematic classification of igneous rocks (Woolley et al., 1996).

Regional Geological Setting

The Leucite Hills lamproite province consists of 14 lava-capped buttes and mesas and nine dykes (Table 5). Although these occurrences are found over an area of about 260 km^2 the actual total volume of preserved lamproite is only about 0.58 km^3 (Lange et al., 2000). The lamproites are hosted by a sequence of Lower Tertiary (Eocene and Paleocene; Fort Union, Green River and Wasatch Formations) to Upper Cretaceous (Lance, Lewis, Almond, Ericson, Rock Springs, Blair and Baxter Formations) clastic sedimentary rocks, which include sandstones, shales, siltstones, coals, and mudstones (Fig. 16). The lamproites were intruded through, and extruded onto this nearly flat lying sedimentary sequence at the northern nose of the Rock Springs uplift (Fig. 17), a doubly-plunging Laramide basement-involved anticline in the centre of the great Green River Basin in the Wyoming Basin. There is a preferred northwest orientation to the lamproite vents that parallels the Farson lineament and other buried Laramide structures. Thus, Johnston (1959) has noted that the 12 igneous bodies occurring between Zirkel Mesa and North Table Mountain are aligned at 325º to 335º (NNW). Many northeast trending normal faults cut across the Rock Springs Uplift in the vicinity of the Leucite Hills, although there is no obvious relationship between these and the locations of the lamproites.

Table 4. Nomenclature of lamproites.

Historical Name	*Revised Name*
Wyomingite	diopside leucite phlogopite lamproite
Orendite 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

All other lamproites have mineralogical-genetic names *e.g.* hyalo- armalcolite phlogopite lamproite, sanidine richterite lamproite, macrocrystal olivine lamproite. These might have received type-locality names if they had been recognised prior to revisions to lamproite terminology

In terms of their regional tectonic setting the Leucite Hills occur in the northern Colorado Plateau area midway between the Uinta Mountain Uplift (to the south west) and the Wind River Range (to the north). These two Proterozoic-to-Archean complexes were structurally inverted by thrusting in the Late Cretaceous to Palaeogene. Leucite Hills' lamproites occur less than 200 km north of the southern limit of the Archean Wyoming Craton, whose southern limit is defined by the Cheyenne Belt, a major shear zone separating Proterozoic rocks of the Colorado Province from the Archean Wyoming craton. At the time of lamproite emplacement, the area was relatively stable, having experienced regional uplift, and was relatively insulated from basin-and-range extensional faulting. The Leucite Hills are underlain by the Archean Wyoming Craton which has crystallization ages of >2.6 - 3.2 Ga (Ernst, 1988). Xenoliths of basement rock can be found in some of the lamproite vents (principally at Hatcher Mesa).

Table 5. Calculated volumes, areas, and $^{40}Ar/^{39}Ar$ ages of Leucite Hills lamproites.

Vent	Area km^2	Thickness km	Vol.lava km^3	Vol.cones km^3	Plateau phlogopite	Ages (Ma) whole rock
Zirkel Mesa	14.422	0.023	0.3317	0.0361	0.95±0.05	
Steamboat Mtn	4.018	0.017	0.0683	0.0044	1.78±0.04	1.77±0.02
Spring Butte	1.653	0.03	0.0496	0.0033	0.89±0.04	0.89±0.02
Deer Butte	1.67	0.015	0.0251	0.0028	0.91±0.03	0.96±0.03
Emmons Mesa	1.96	0.015	0.0294	0.0028		0.96±0.03
North Table Mtn	0.36	0.015	0.0054		1.47±0.05	
Hatcher Mesa	0.12	0.015	0.0018			0.92±0.02
South Table Mtn	0.1	0.015	0.0015		2.53±0.06	
Pilot Butte	0.07	0.03	0.0021			3.00±0.03
Cabin Butte	0.068	0.03	0.002			
Black Rock	0.053	0.03	0.0016			0.80±0.02
Boar's Tusk			0.0031		2.23±0.04	2.19±0.04
Middle Table Mtn		0.0011			2.03±0.03	2.02±0.04
Badger's Teeth			0.0001			
Matthews Hill			0.0001			
Other buttes			0.0003			
Total Volume			0.5232	0.0494		

All data from Lange et al. (2000), who also give total gas and isochron ages.

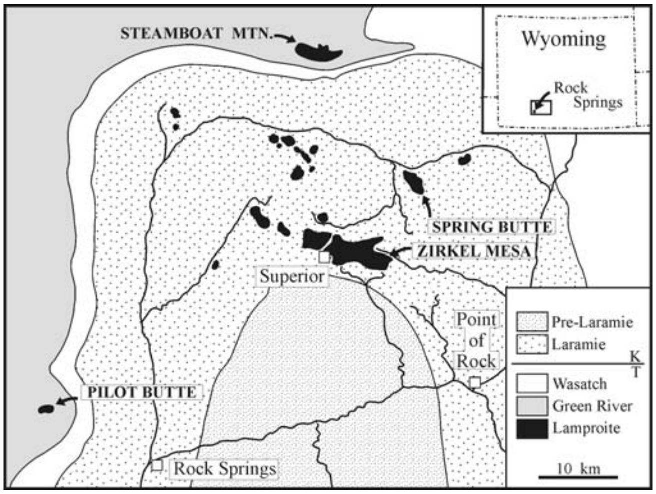

Figure 16. Regional geology in the Leucite Hills area.

Geology and Age of the Leucite Hills Lamproites

The principal lamproite occurrences of the Leucite Hills consist of fourteen lava-capped buttes and mesas (Fig. 18), with half of these also containing small cinder and lava cones. Other occurrences of lesser volumetric importance consist of volcanic necks and dykes. Table 5 lists the area, thickness, volume and $^{40}Ar/^{39}Ar$ age of individual vents (Lange et al., 2000). These vents were isolated centres of volcanic activity and it is considered that lavas never covered the entire region. The majority of the small flows appear to have originated from lava cones and "plug-like" domes.

Age

Lange et al. (2000) have shown that volcanic activity in the Leucite Hills occurred from 3.0 to 0.89 Ma. It is considered that 98 % of the lavas were erupted between 1.78 and 0.89 Ma, with approximately 84 % of the volume erupted within a 50,000 (± 40,000) interval at approximately 0.9 Ma. The eruption rate between 3.0 and 0.89 Ma is estimated by Lange et al. (2000) to be <0.15 m^3/km^2/year, and that between 0.94 and 0.89 Ma as ~5 m^3/km^2/year. Such eruption rates are exceedingly low relative to eruption rates at slow spreading mid-oceanic rates and for plateau basalts. The oldest lavas are those of South Table Mountain (2.53 Ma), with the bulk of the younger activity forming Zirkel Mesa (0.96 Ma).

Lange et al. (2000) have noted that the lamproite lavas were erupted onto an actively eroding landscape. As the volcanic cap protects the underlying sediment of the mesas, there is a correlation between the thickness of the sediments beneath the cap and the age of the lava. Thus, the difference in elevation (122 m) between South Table Mountain and North Table Mountain is not due to faulting, but reflects the significant difference (1.06 Ma) in their eruption ages. In addition, the erosion of the cinder cones originally present on the North Table Butte lavas might have taken place prior to the eruption of the Zirkel and Emmons Mesa lavas, which are associated with intact cinder cones.

The entire Leucite Hills volcanic field is considered to consist of about 50 individual lava flows, which vary from 20 cm to 15 – 21 m in thickness and are of limited aerial extent (Table 5). The average volume for a flow is 0.01 km^3, with a total volume of ~0.53 km^3. The volumes of the volcanic necks are insignificant relative to the lavas and amounts only to about <0.004 km^3 (Lange et al., 2000).

Lava Flows

The morphology of the lava flows has been described by Kemp and Knight (1903), Ogden (1979), and Gunter et al. (1990). Flows that are thicker than about 4.5 m typically consist of a basal rubble zone, an intermediate platy zone, and a central massive zone. Thinner flows consist of homogeneous vesicular lava with thin platy joints. Rubble zones are minor or absent. The rubble zone is a discontinuous autobreccia at the contact of the flow with the underlying sediments. It consists of angular blocks of lava with dense centres and scoriaceous rinds and lesser country rock xenoliths welded together in a vesicular lava matrix. The rubble zone grades sharply into a 0.3 - 1.5 cm thick, platy zone characterized by well-defined flow layering of phlogopite phenocrysts. As a consequence of this alignment the rock readily breaks into 5-7 cm thick plates. Platy zones grade into massive lava comprising 75 % or more of the flow; typically ranging from 4.5 to 18 m in thickness. Vesiculation in the massive zones ranges from 25 - 40 vol. %. At the bottom of the massive zone 0.2 - 1.0 cm vesicles are flattened parallel to the ground surface. Cooling joints are a characteristic feature of the massive flows. These joints result in fracturing of the flow into equidimensional blocks ranging in size from 1 - 6 m on edge depending on flow thickness.

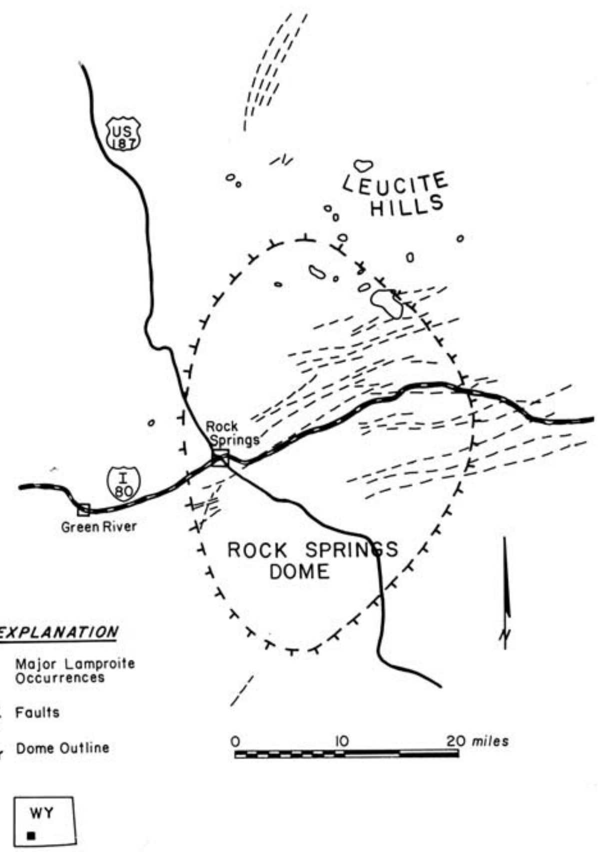

Figure 17. Major structures in the Leucite Hills area.

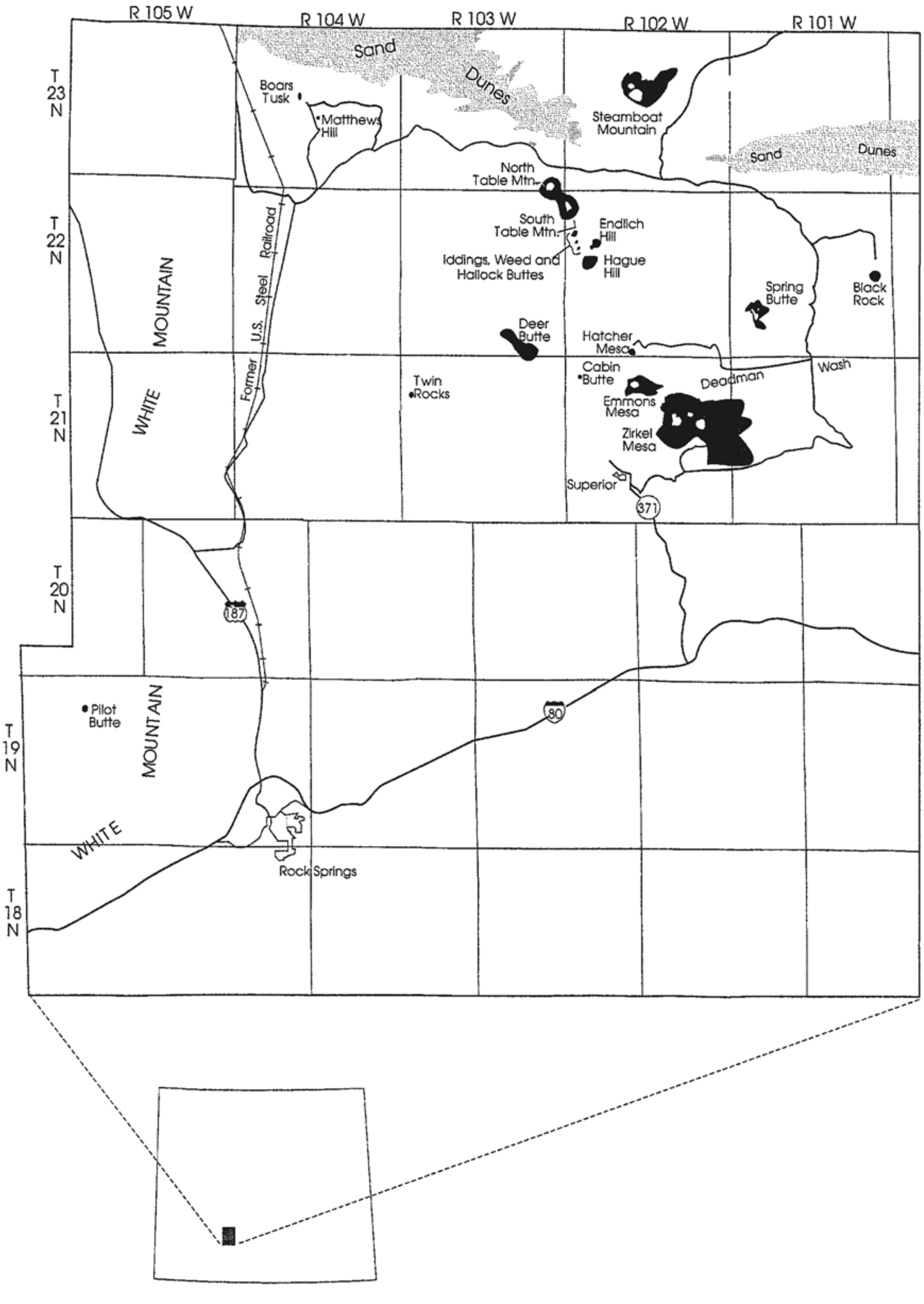

Figure 18. Lamproite localities in the Leucite Hills.

Massive zones also exhibit centimetre scale layering resulting from alternating bands (0.2 - 5 cm) of dark-coloured sanidine-bearing lamproite and light coloured leucite-bearing lamproite. This type of layering may be vertical or horizontal and is commonly "folded" due to differential flow rates at the margins and centres of a flow. Gunter et al. (1990) have shown that the light and dark coloured layers are isochemical with exception of water (see below).

The surfaces of the flows consist of smooth massive vesicular blocks of jointed lava. Scoriaceous surfaces typical of aa flows are usually absent, although these may have been removed by erosion. Squeeze-up spines ranging in height from 0.3 - 0.6 m are common. These are commonly flow-aligned.

The lavas exhibit flow morphology features that indicate transformation from pahoehoe to aa with a single flow. This transition can be due to increases in viscosity resulting from cooling or an increase in shear strain or both. Ogden (1979) considers that most of the flows advanced on broad fronts with many features typical of aa lavas. However, in many places it is evident that lavas flowed through tube-like features. The bottoms of such tubes are flattened and massive lava within the tube exhibits concentric platy joints about scoriaceous centres.

Cinder and Lava Cones

Fourteen cinder cones are associated with lavas at Zirkel Mesa (4), Emmons Mesa (2), Deer Butte (2), and Spring Butte (6). With the exception of Zirkel Mesa, cones formed contemporaneously with the lavas as they are breached by these flows. At Zirkel Mesa, cones were formed on the associated flows. The bulk off the material forming the cinder cones consists of highly vesicular scoria blocks ranging in size from 2.5 - 13.0 m. The cinder cones are small; the largest being the eastern-most cone on Zirkel Mesa, which has a basal diameter of 85 0m and is 115 m high These are similar in size to alkali basalt cinder cones. The majority of the cones are asymmetrical as a consequence of breaching or erosional modification (Ogden, 1979). The presence of scoriaceous material on North Table Mountain indicates that cinder cones were originally present here but have now been removed by erosion.

Lava cones are found on Steamboat Mountain (3) and Zirkel Mesa (1). These are asymmetrical shield-like structures composed of numerous thin flows and minor amounts of pyroclastic material. The cones range in size from 760 m x 100 m (Zirkel Mesa) to 1600 m x 75 m (Steamboat Mountain). Summit craters are not associated with the lava cones. Lava forming the cones on Steamboat Mountain is exceptionally fresh phlogopite hyalo-lamproite associated with dark coloured pumice.

Volcanic Necks/Vents

Although pyroclastic sub-aerial cinder cones are associated with many of the Leucite Hills lavas, there are few occurrences of preserved pyroclastic rocks associated with vent opening. Either these have been buried by later lavas or have been removed by erosion. The former is perhaps the more probable. The absence of base surge deposits, air-fall pyroclastics, hydroclastic breccias etc., suggests that eruption of the Leucite Hills lamproites was relatively quiescent as compared with that of the Ellendale or Argyle (Australia) or Arkansas (USA) lamproite provinces, and was not phreatomagmatic in character. A further difference with respect to the Ellendale (and Spanish) lamproites is that lava ponds of hypabyssal olivine lamproite or leucite-diopside-richterite lamproite (“wolgidite, cedricite, mamillite”) are not found in the Leucite Hills. Mitchell and Bergman (1991) have noted that the Leucite Hills volcanism is similar to that of normal sub-aerial basaltic volcanism.

Vent agglomerates have been exposed only where erosion has been extensive, i.e. the northern end of Killpecker Creek, where the Boar’s Tusk and Matthew Hill volcanic necks are located. They represent some of the earliest activity (2.23 Ma) in the Leucite Hills, and lavas or pyroclastics associated with the necks have not been preserved. The necks are filled with autolithic clasts of lamproite and crustal xenoliths derived from the Green River and Wasatch Formations set in massive-to-foliated phlogopite lamproite.

Dykes

Dykes are not a conspicuous feature of the Leucite Hills at the present level of erosion. It is not known if a swarm of feeder dykes occupies the infrastructure of the province. The dykes are present primarily as small bodies (width 0.3 - 15m; length 8 - 215 m) that typically strike 320^{o} (NNW), subparallel to the Farson lineament. The margins of some of the dykes can be occupied by an agglomeratic breccia containing country rock and autolithic clasts. This style of breccia also forms the small Iddings, Weed and Hallock Buttes, which are interpreted as incipient vents developed along a single dyke. Dykes associated with sub-volcanic lamproite necks at Boars’ Tusk, Badger’s Teeth, and Pilot Butte are t h i n (<10 m) and do not following the regional strike trend.

Plug Domes

Ogden (1979) has suggested that three volcanic plug domes formed from relatively viscous magmas occur at Middle Table Mountain, Zirkel Mesa, and Cabin Butte. The plug domes are cylindrical with flat tops and near-vertical sides. Lavas comprising the domes show very pronounced vertical flow layering and platy vertical jointing. The Middle Table Mountain dome is unusual relative to other plug domes in that it consists of sub-volcanic/hypabyssal transitional madupitic lamproite. It is older than the spatially associated lavas of North Table Mountain.

Petrographic and Mineralogical Character of the Leucite Hills Lamproites

Lamproites exhibit a mineralogy that reflects their peralkaline ultrapotassic nature. As a group they are characterized by the presence of titanian phlogopite, titanian potassium richterite [$(Na,K)(Na,Ca)(Mg,Fe,Ti)_5(Si,Ti,Al)_8O_{22}(OH)_2$], titanian tetraferriphlogopite, sodium- and aluminium-deficient leucite, iron-rich sanidine, poor-poor diopside, potassian barian titanites [priderite $(K,Ba)_{1\text{-}2}(Fe^{3+}, Mg, Cr, V,)_{1\text{-}2}(Ti)_{6\text{-}7}O_{16}$) or jeppeite $(K,Ba)_2Ti_6O_{13}$)], and potassian zirconian or titanian silicates [wadeite ($K_2ZrSi_3O_9$), shcherbakovite [$(Ba,K)(K,Na)Na(Ti,Nb,Zr,Fe)_2Si_4O_{14}$)]. Minerals that are characteristically absent from lamproites include: nepheline; melilite; kalsilite; sodium-rich alkali feldspar; plagioclase, monticellite, titanium- and zirconium-bearing garnets, and aluminium-rich augite.

Five petrographic varieties of lamproite are now recognized from the Leucite Hills Province: diopside-leucite-phlogopite lamproite (wyomingite); diopside-sanidine-phlogopite lamproite (orendite); olivine-bearing diopside-sanidine-phlogopite lamproite (olivine orendite); diopside madupitic lamproite (madupite); transitional madupitic lamproite. The terminology used to describe the rocks follows the mineralogical-genetic system of nomenclature recommended for lamproites by Mitchell and Bergman (1991), and adopted by the IUGS (Woolley et al., 1996). The older, now otiose, terminology is given above in parentheses.

Diopside-leucite-phlogopite lamproite

These vesicular rocks are characterized by the presence of phenocrysts of phlogopite set in a groundmass containing microphenocrysts of leucite and diopside. All of these minerals can be set in a glassy mesostasis with or without potassian titanian richterite. Accessory microphenocrystal phases include apatite, priderite, and wadeite. Wide variations in mode can occur and pumice consisting of phlogopite set in glass can be found.

Diopside-sanidine-phlogopite lamproite

These vesicular rocks are also characterized by the presence of phenocrysts of phlogopite. They differ from the above leucite-bearing lamproites in that sanidine is a characteristic mineral of the groundmass and that they exhibit greater modal diversity. Sanidine can coexist with leucite, diopside, and potassian titanian richterite. In contrast to the above lamproites, glass is not typically present. Accessory phases include apatite, priderite and wadeite.

Typically, leucite is enclosed by sanidine. The proportions of leucite to sanidine may vary on a centimetre scale within the same flow. Gunter et al. (1990) have demonstrated that such modally different lamproites are isochemical, with the exception that the water content of the sanidine-bearing varieties is higher than that of the sanidine-free types (Table 3).

Olivine-bearing diopside-sanidine-phlogopite lamproites

These rocks are petrographically identical to diopside-sanidine-phlogopite lamproite with the exception that olivine is present as either anhedral crystals mantled by phlogopite laths or microphenocrystal euhedral olivines. Mantled olivines are magnesian ($Mg^{\#}$ = 0.93 - 0.92; 0.30 - 0.40 wt. % NiO) relative to microphenocrystal olivines ($Mg^{\#}$ = 0.93 - 0.87; 0.25 - 0.17 wt. % NiO). The mantling micas are identical in composition to mica forming phenocrysts and have evidently formed by reaction with the magma in which they are enclosed. These olivines are considered to be mantle-derived xenocrysts. The euhedral olivines appear to be bona fide primary liquidus phases. Their presence might reflect enhanced Mg-contents resulting from dissolution of mantle xenocrysts or they might be high-pressure phenocrysts. Microphenocrystal olivine can also form as reaction rims around phlogopite phenocrysts and represent the breakdown products of primary phlogopite. Olivine bearing lamproites in the Leucite Hills are known only from North and South Table Mountain, Black Rock, and Endlich Hill. Olivine lamproites of the type found in the West Kimberley lamproite province of Australia are not present in the Leucite Hills.

Diopside madupitic lamproite

The term *madupitic* indicates that a lamproite contains poikilitic groundmass phlogopite as opposed to phlogopite lamproite in which the mica occurs as phenocrysts. Madupitic is preferred to the textural term “oikocrystal”, as the latter is used primarily for large late-forming poikilitic crystals in a wide variety of plutonic rocks. However, it is recognized, that the formation of a madupitic texture might involve similar crystallization processes as lead to oikocryst formation. Madupitic-textured lamproites are sub-volcanic-to-hypabyssal rocks.

Diopside madupitic lamproite (formerly madupite) consists of flow-aligned microphenocrysts of diopside set in glassy (commonly altered) matrix containing groundmass diopside, spinel, wadeite, perovskite, and apatite. The characteristic petrographic feature is the presence of large (up to 1 cm) optically continuous, poikilitic plates of Al-poor, Ti-rich phlogopite. These micas are considered on the basis of their compositions to be more evolved than the Al-rich, Ti-poor micas occurring as phenocrysts in phlogopite lamproites. Olivine, richterite, sanidine, and priderite are not found in these rocks and leucite is only very rarely present.

Transitional diopside madupitic lamproite

These rocks share some of the petrographic character of both phlogopite lamproites and madupitic lamproites as they contain phlogopite phenocrysts that are mantled by poikilitic micas, which are petrographically- and compositionally-identical to associated large groundmass plates. In addition to diopside, leucite is a characteristic microphenocrystal phase. Also present are poikilitic purple groundmass Sr-REE-rich perovskite, wadeite, and Sr-rich apatite.

Compositions of Leucite Hills Lamproites

All of the Leucite Hills lamproites are peralkaline with very high K_2O/ Na_2O ratios (>8). Lamproites from Steamboat Mountain represent the most potassic (12 wt.% K_2O) volcanic rocks ever described. Unlike, the Ellendale lamproite province, the Leucite Hills rocks do not exhibit a wide range in composition. Two broad groups in terms of their SiO_2 content are evident: madupitic low silica rocks and silica-rich phlogopite lamproites (Table 6). Phlogopite lamproites within and between individual vents exhibit only a limited range in composition, reflecting primarily the proportions of crystals to glass. Sanidine phlogopite lamproite and leucite phlogopite lamproite within a given flow are identical in composition (Table 3, analyses 7, 8), clearly demonstrating that they are heteromorphs. The compositions of phlogopite lamproites can be considered a representative of their parental magmas, unlike those of madupitic lamproites whose compositions appear to have been determined, in part, by crystal accumulation. Madupitic lamproites are not less-evolved variants of the magmas that formed the phlogopite lamproites. The relationship between the two types is not yet resolved, although it is clear that processes other than crystal fractionation must have played a role in their genesis as they exhibit different Sr and Nd isotopic compositions.

Table 6. Whole rock compositions of Leucite Hills lamproites.

wt%	1	2	3	4	5	6	7	8
SiO_2	50.23	51.03	55.43	54.08	55.14	53.45	56.00	55.60
TiO_2	2.27	2.67	2.64	2.08	2.58	2.14	2.40	2.40
ZrO_2	--	0.17	0.28	--	0.27	0.17	0.18	0.19
Al_2O_3	11.22	9.81	9.73	9.49	10.35	10.27	11.00	10.80
Cr_2O_3	0.10	0.07	0.02	0.07	0.04	0.08	0.03	0.03
Fe_2O_3	3.34	3.67	2.12	3.19	3.27	3.60	4.00	4.30
FeO	1.84	0.65	1.48	1.03	0.62	1.00	0.75	0.59
MnO	0.05	0.07	0.08	0.05	0.06	0.08	0.03	0.03
MgO	7.09	7.24	6.11	6.74	6.41	9.61	6.00	5.60
CaO	5.99	5.37	2.69	3.55	3.45	4.21	3.50	3.70
SrO	0.24	0.32	0.27	0.20	0.26	0.20	0.18	0.17
BaO	1.23	0.78	0.64	0.67	0.52	0.34	-	-
Na_2O	1.37	1.03	0.94	1.39	1.21	1.26	1.10	0.80
K_2O	9.81	10.61	12.66	11.76	11.77	10.62	11.60	11.40
P_2O_5	1.89	1.71	1.52	1.35	1.40	1.28	1.60	1.40
H_2O^+	1.72	2.91	2.07	2.71	1.23	--	3.40	3.00
SO_3	0.74	1.00	0.46	0.29	0.40	1.15	--	--
Cl	0.03	0.02	--	0.04	--	0.03	--	--
F	0.50	0.69	--	0.49	--	0.66	--	--

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