WYOMING STATE GEOLOGICAL SURVEY

OVERVIEW OF THE SLOAN 1 & 2 DIAMONDIFEROUS KIMBERLITES, COLORADO-WYOMING STATE LINE DISTRICT

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INTRODUCTION

On Sunday, May 19th, the 1996 Industrial Minerals Forum will travel to the Sloan ranch in the southern portion of the Colorado-Wyoming State Line diamond district to examine two of six diamondiferous kimberlite intrusives within the Sloan cluster. These two intrusives, the Sloan 1 and 2 pipes, are just two of the more than 40 known kimberlites in the Colorado-Wyoming State Line district (McCallum, 1991).

Total diamond production from the State Line district, to date, has included more than 120,000 diamonds. The diamonds have ranged from microdiamonds to a 14.2 carat gemstone octahedron. Cumulative production from the Sloan 1 and 2 kimberlites has totaled 30,580 diamonds, or about 1/4 of the total production in the district. The Sloan diamonds have ranged from microdiamonds to a 5.51 carat gemstone (Hausel, 1995).

While in the field, please do not enter the Sloan 2 adit. It is also advised to check for ticks and WATCH OUT FOR RATTLESNAKES!!!

Acknowledgements and Access

I would like to thank Frank Yaussi, Prairie Divide Corporation, and Cominco American Incorporated for permission to visit the Sloan 1 and 2 kimberlites. The kimberlites are located in the S/2 section 10, T10N, R72W in Larimer County, Colorado, at an elevation of about 7,250 feet. The pipes can be reached from U.S. Highway 287 which runs between Laramie and Fort Collins. From Laramie, the pipes are accessible by driving 40 miles south along Highway 287 to the Larimer County Road 80C (Cherokee Park Road) turnoff. From that point, travel west 8 miles to the Larimer County Road 82E junction. Turn left on County Road 82E and continue west another 4.5 miles. The pipes lie south of the county road adjacent to a large, blue, metal building which houses the Dia Met diamond processing facility. An overview of the plant was published by Waldman (1991).

This field trip summary is an overview of several publications listed in the references cited section at the end of the paper. Much of this compilation was taken from papers by M.E. McCallum and K.C. Shaver.

HISTORY

Diamonds were first discovered in the Colorado-Wyoming State Line district in 1975. The lack of historical discoveries in this region is curious especially when one considers that the district hosts several deeply eroded diamondiferous kimberlite intrusives. And in all probability, some drainages in the district contain placer diamonds.

The lack of historical placer discoveries may be due to two reasons. (1) The "1872 Great Diamond Hoax" was located just 180 miles due west of the State Line district (see: Hausel and Stahl, 1995). The "hoax" was of such magnitude that few people would have believed diamonds could be found anywhere in Colorado or Wyoming for many decades to come. (2) Much of the State Line district is underlain by relatively unmineralized granite, thus very little gold prospecting has ever occurred in the district. The general lack of placer gold activities probably contributed to the lack of placer diamond discoveries.

Kimberlite was first identified in the district in 1964, by Dr. M.E. McCallum from samples collected from a small terrazzo quarry along the western edge of the Sloan 1 diatreme. Diamonds were later discovered in 1975 during routine thin-section preparation of a serpentinized garnet peridotite nodule collected from the Schaffer 3 kimberlite in Wyoming. During the preparation of the section, Florian Nowacki and Ross Jensen of the U.S. Geological Survey noted deep scratches were cut into a carborundum grinding plate. Upon examination of the nodule, a small white crystal was isolated that was confirmed as diamond by x-ray diffraction analysis by T. Botinelly and B.F. Leonard of the U.S. Geological Survey. Other small diamonds were subsequently recovered from the nodule (McCallum and Mabarak, 1976).

Commercial interest in the Colorado-Wyoming State Line district was later initiated in 1979 after the State of Wyoming, in cooperation with Rocky Mountain Energy Company (Union Pacific), issued a call for exploration proposals for the Wyoming portion of the State Line district. Cominco American Incorporated submitted the successful bid and explored the Schaffer and Aultman kimberlites in Wyoming. The results of bulk sample tests by Cominco American were discouraging as only subeconomic grades (0.5 to 1.0 carats/100 tonnes) were detected. The largest diamond recovered in these tests was a 0.86 carat gemstone.

Interest in the Sloan 1 and 2 kimberlites was initiated by Superior Minerals in the following year in 1980. This was followed by a Superior-Lac joint venture in 1983, and in 1984, the property was quit-claimed back to the owners. This latter event coincided with a scheduled advanced royalty payment, and the purchase of Superior Minerals by Mobil Oil Company. Mobil eventually disposed of all of Superior's mineral interests while Lac Minerals was entering into litigation in Canada concerning its control of the Hemlo Gold mine (Oliver, 1990). The most recent exploration on the Sloan property resulted in a 700 foot adit driven into the Sloan 2 kimberlite by Royalstar Ltd. in 1994.

GEOLOGIC SETTING

The Colorado-Wyoming State Line district lies within the southern Laramie Range of Wyoming and continues south into Colorado along the eastern flank of the northern Front Range (Figure 1). Geographically, the Laramie and Front Ranges are a continuous mountain range. This range was uplifted during the Laramide orogeny and its core was exposed following several million years of erosion. The core of range in the vicinity of the State Line district consists of Proterozoic crystalline rock. The Proterozoic basement continues north, where in the vicinity of the Sheep Rock area, the Cheyenne Belt separates the Proterozoic basement from an Archean basement farther to the north. The Archean core consists of Archean gneisses, schists and granites of the Wyoming Province. Thus in terms of cratonic environments, an Archon lies north of the Cheyenne Belt, and a Proton consisting of a Proterozoic mobile belt, lies to the south.

Precambrian exposures in the vicinity of the State Line district consist of 1.9 to 1.7 Ga metamorphic rocks of the Colorado Province that are disconcordantly intruded by 1.4 Ga granitic rocks. The metamorphic rocks are amphibolitic, quartzofeldspathic, and pelitic gneisses and schists (McCallum and others, 1977) that are part of a island arc succession which collided with the Archean craton of the Wyoming Province nearly 1.7 Ga ago. This collision boundary is marked by a major suture referred to as the Cheyenne Belt (Karlstrom and Houston, 1984). Even though the district lies 50 to 70 miles south of the Wyoming Province, Shaver (1988) suggested that the Proterozoic rocks of the Colorado Province may have thrust over the Wyoming Province and an Archean fragment may lie at depth in the district.

The dominant regional structure in the district is the Virginia-Dale ring dike complex, a circular granitic pluton of nearly 9 miles in diameter. The ring-dike intrudes 1.4 Ga Sherman Granite and the older metamorphic rocks (Eggler, 1968). The complex is interpreted as a phase of the Log Cabin batholith located to the south.

The only post-Precambrian rocks found *in situ* in the district are arkosic sedimentary rocks of the Pennsylvanian Fountain Formation (McCallum and others, 1979). *In situ* Lower Paleozoic rocks do not occur in the district, although some Cambrian, Ordovician, and Silurian sedimentary xenoliths are found in some kimberlite diatremes. It was the presence of these sedimentary xenoliths that first attracted the curiosity of geologists to the diatremes in the early 1960s (see: Chronic and Ferris, 1961).

The age of the kimberlites in the Colorado-Wyoming kimberlite province, which extends as far south as Boulder, Colorado, and as far north as Sybille Canyon in the central Laramie Range (Figure 1), were assumed to be early Devonian based on the presence of Paleozoic xenoliths in some of the intrusives. Fission track dating of sphene (Larson and Amini, 1981) and zircon (Naesser and McCallum, 1977), and Rb-Sr dating of phlogopite (Smith, 1979, 1983) has since established a late Devonian age for many of the kimberlites.

The Green Mountain pipe located 50 miles south of the district near Boulder, Colorado, recently yielded paleomagnetic, K-Ar, Ar^{40}-Ar^{39}, and Rb-Sr ages between 600 to 700 Ma. Additionally, Ar^{40}-Ar^{39} and Rb-Sr data also indicate a Proterozoic age for one of the Chicken Park kimberlites located in the district, just five miles west of the Sloan kimberlites (Alan P. Lester, written communication, 1996). These dates provide further evidence of the several episodes of kimberlite and lamproite magmatism

in the Wyoming craton (Hausel, 1996) *[the Wyoming craton is here defined to include both the Wyoming Province (Archon) and the Colorado Province (Proton)]* (Figure 2).

Kimberlites in the region occur as diatremes (pipes), related plugs or blows, and dikes. Intrusive breccia (tuffisitic kimberlite breccia) predominates in the diatremes, whereas massive porphyritic kimberlite (hypabyssal facies) is dominant in dikes and blows. Kimberlite is typically intensely serpentinized, carbonated, and locally silicified and/or fenitized (McCallum and Eggler, 1971; Smith and others, 1979).

Diatreme facies kimberlite consists of abundant subrounded to angular rock fragments along with serpentinized macrocrysts of olivine and lesser enstatite, Cr-rich and Cr-poor pyropic garnet and diopside, picroilmenite, clinopyroxene-ilmenite intergrowths, and phlogopite in a finely crystalline matrix of serpentine, carbonate, olivine, diopside, picroilmenite, phlogopite, perovskite, magnetite, Cr-rich spinels, hematite, apatite, and zircon (Rogers, 1985; McCallum, 1991).

Hypabyssal facies kimberlite occurs in dikes, sills, and small plug-like bodies that most likely represent root zones of deeply eroded pipes. Kimberlite and kimberlite breccia both occur, although kimberlite breccia is common only locally. Xenolithic fragments rarely exceed a few percent (unlike the diatreme facies) and are typically moderately well-rounded upper mantle and lower crustal nodules. Aphanitic hypabyssal kimberlite devoid of macrocrysts is rare. The mineralogy of the hypabyssal kimberlite is essentially the same as for the diatreme facies. However, globular, emulsion-like segregations of serpentine and calcite are more abundant in hypabyssal types (Rogers, 1985).

The State Line district has been truncated by late Tertiary to Pleistocene erosion. The kimberlites are generally poorly exposed, have negligible relief, and are deeply weathered. Geophysical surveys suggest weathering continues to depths of at least 100 feet below the surface (Hausel and others, 1979), although moderately fresh exposures are present at some sites. Most kimberlites are covered by alluvium and or colluvium, and some have been recognized by the presence of grey, weathered ("blue-ground"), kimberlitic soil that is commonly associated with lush, grassy, vegetation, animal burrows, and/or cliche. Other sites are recognized by the presence of Lower Paleozoic xenoliths as well as mantle and lower crustal xenoliths and nodules of peridotite, pyroxenite, eclogite, granulite, and/or megacrysts of pyrope, ilmenite, or diopside (McCallum and Eggler, 1979).

GEOLOGY OF THE SLOAN RANCH KIMBERLITES

The Sloan cluster consists of six kimberlites near the southern margin of the Colorado-Wyoming State Line district (Figure 3). The field trip attendees will visit only the Sloan 1 and 2.

The Sloan 1 consists of diatreme-facies kimberlite, and the Sloan 2 consists of hypabyssal- and transitional-facies kimberlite (Shaver, 1994). The Sloan 1 has an aerial extent of 500 by 1,800 feet while the Sloan 2 is 200 by 2,000 feet. These two pipes have yielded a significant number of subcalcic 'G10' harzburgitic pyropes (McCallum, 1991).

(author's note: *Many peridotitic garnets found in kimberlite have been designated as 'G10' or 'G9'. These were derived from the peridotite xenoliths sampled by the kimberlite during ascent from the upper mantle. The peridotites are Cr-rich*

ultramafic rocks with olivine (>40%) and pyroxene and minor plagioclase that are subdivided on the basis of pyroxenes. For example, lherzolites are peridotites that have both clinopyroxene and orthopyroxene. Wehrlites contain clinopyroxene but lack orthopyroxene. Harzburgites have orthopyroxene but no clinopyroxene.

Diamonds are found in some garnet peridotites. Most peridotitic diamonds occur in garnet-bearing harzburgite: diamondiferous pyrope-lherzolites are uncommon. Pyrope garnets from disaggregated peridotite have been designated by Gurney (1989) as either 'G10', derived from low-Ca garnet harzburgites, and 'G9' derived from the more calcic lherzolites. This suggests that a kimberlite with abundant 'G10' pyropes should be predicted to be diamondiferous as long as the magma was reducing. Reducing conditions can be predicted on the basis of MgO:Cr_2O_3 ratios of picroilmenite. The ratios provide an indication of the oxygen fugacity and the favorability of diamond preservation. In addition to G10 garnets, eclogitic garnets also are important in appraising the diamond potential of a kimberlite. Eclogitic garnets with Na_2O contents >0.09% are indicative of a diamondiferous source terrane).

A significant number of peridotitic garnets from the Sloan 1 and 2 kimberlites were reported by McCallum and Waldman (1991) to be subcalcic chromian garnets with G10 compositions indicating a low to moderate grade of diamonds from a harzburgitic source. The TiO_2:Na_2O plots for the eclogitic garnets indicated a low potential for a eclogitic diamond source. Ilmenite Cr_2O_3:MgO compositions indicated that reducing conditions prevailed in the kimberlite magmas suggesting that diamond preservation was favorable (McCallum and Waldman, 1991).

The emplacement of the Sloan 1 and 2 kimberlites was structurally controlled. The Sloan 1 was emplaced along the Copper King fault while the Sloan 2 was emplaced along the Prairie Divide fault in the Log Cabin granite (McCallum, 1976).

Typically, kimberlite erodes faster than the adjacent granite which results a slight topographic depression. Both pipes continue under Tertiary gravels in the North Fork of Rabbit Creek to the north (McCallum, 1991). The extent of kimberlite under the surficial cover is unknown (Oliver, 1990).

Geologists from Superior Minerals Company concluded that both Sloan pipes were emplaced during separate events and were later eroded. McCallum (1976; 1991) however, concluded that both pipes were emplaced during the same event, and interpreted the Sloan 2 to be a blind diatreme. The evidence cited by McCallum supports that the Sloan 2 is a blind diatreme, in that no Paleozoic xenoliths have been found in the pipe indicating the kimberlite did not penetrate the Paleozoic cover during the Devonian. Whereas, the Sloan 1 contains abundant Paleozoic xenoliths along its western flank.

The kimberlites are ultrabasic intrusive rocks that have been extensively altered through carbonatization and serpentinization. Minor phlogopite, mantle megacrysts, and cognate and xenolithic nodules from the mantle and crust occur in the kimberlites. The Sloan 1 is dominated by tuffisitic kimberlite breccias typical of diatreme facies, whereas the Sloan 2 is more characteristic of macrocrystic kimberlite breccia typical of hypabyssal facies (McCallum, 1991)(Figure 4). The following descriptions are based on reports by McCallum (1991) and Shaver (1994).

Sloan 2

DK1 (Sloan 2 phase): As we walk up the side of the hill from the vehicles towards the Sloan 2 adit, numerous fresh samples of DK1 phase kimberlite are scattered around the mine dump. These rocks were exposed by mining operations, as kimberlite did not crop out on the surface of the Sloan 2. The pipe was discovered following heavy mineral sampling (McCallum and Mabarak, 1976).

The DK1 phase is a pale-green to black, phlogopite, monticellite, calcite, serpentine, macrocrystic hypabyssal-facies kimberlite breccia, with a phlogopite-serpentine groundmass. Locally, opaques (mostly spinel), perovskite, and apatite may be abundant. Olivine macrocrysts are pervasive and range from fresh to partially altered to completely serpentinized and locally carbonatized rounded grains. Macrocrysts of picroilmenite, pyrope garnet, and chromian diopside are abundant as are mantle and lower crustal xenoliths. This phase forms the northwestern two-thirds of the dike.

DK4 (Light-green spotted phase): Samples of the DK4 phase can be found farther up the hill near the contact with the Sloan 1. This is a pale-green, locally pelletal, lithic tuffisitic transitional phase kimberlite breccia with a serpentine-clay-carbonate matrix. Some light green spots in this phase are the result of calcite-serpentine pools. Macrocrysts of serpentinized olivine are ubiquitous and macrocrysts of picroilmenite, pyrope, chromian diopside, phlogopite, and orthopyroxene are present. Crustal and mantle xenoliths are abundant. Carbonatite xenoliths are also common in this phase, and some are phlogopite-rich sovites. Some of the nodules contain barite. This phase occurs at the southeastern end of the Sloan 2.

Sloan 1

Three major diatreme facies kimberlite phases were described by McCallum (1991) and Shaver (1994) in the Sloan 1.

DK 2 (Black border phase): This is a distinctive, grey to black, tuffisitic kimberlite breccia with a serpentine matrix scattered around some reclaimed pits along the eastern margin of the Sloan 1 pipe. Serpentinized olivine macrocrysts are abundant and locally characterized by a reddish coloration due to finely disseminated hematite after magnetite produced during the serpentinization process of the olivines. Xenocrysts of pyrope, picroilmenite, and chromian diopside are relatively common, and phlogopite and orthopyroxene occur locally. Small xenoliths of Proterozoic granite are abundant, and fragments of Paleozoic sediments are ubiquitous.

DK3 (eastern green phase): This phase forms much of the Sloan 1 diatreme and can be found near some old reclaimed bulk sample pits. It is a pale-green tuffisitic kimberlite breccia containing abundant secondary serpentine, talc, clay, and carbonate. Unaltered minerals are rare, and macrocrysts and microcrysts of picroilmenite, pyrope, and chromian diopside are widely dispersed. Lower Paleozoic limestone and some granitic and metamorphic xenoliths are common.

DK5 (Quarry phase): Located along the western flank of the Sloan 1 diatreme at the site of the old terrazo quarry. This is a dark-green, pelletal, tuffisitic kimberlite breccia with a serpentine matrix. The groundmass includes fine-grained prisms of diopside, phlogopite, and irregular pools of calcite and minor apatite. The abundant pelletal lapilli gives this phase a pseudo-conglomeratic appearance. Serpentinized olivine macrocrysts are abundant and macrocrysts of picroilmenite, pyrope, chromian diopside, and phlogopite are present. Pelletal lapilli vary from a few inches across and are cored with

serpentinized olivine, Paleozoic carbonate, or Proterozoic crystalline rock clasts. Kimberlite in the lapilli is generally relatively fresh compared to the kimberlite matrix. Paleozoic carbonate and Proterozoic granite xenoliths can be found. The Paleozoic xenoliths are abundant and vary in size from inches to many feet across.

DK6 : Several dikes (< 6 feet wide) of brown, black, to green macrocrystic hypabyssal-facies kimberlite with a serpentine matrix cut the kimberlite breccias.

DIAMONDS

The stability of diamond is constrained by pressure, temperature, and the oxygen fugacity of the host magma. Minimum depths of genesis of diamond-bearing kimberlites are estimated at 95 miles.

Most, if not all diamonds from kimberlite are interpreted as xenocrysts derived from the disaggregation of diamondiferous mantle xenoliths during the ascent of the kimberlite. The most important xenoliths are eclogite and garnet-bearing peridotites. Some nodules are very rich in diamond: a hand-specimen of eclogite collected from the Sloan 1 diatreme yielded a grade of 2,100,000 carats/100 tonnes (Schulze, 1992). Typical kimberlite and lamproite ore may only average 10 to 680 carats/100 tonnes.

Eclogite consists of clinopyroxene (omphacite) and yellow-orange garnet (almandine-pyrope) with the possible addition of accessory rutile, kyanite, corundum, and coesite. Eclogites are assumed to be cumulates of melts of garnet peridotite or possibly derived from subducted oceanic crust.

Some eclogites represent primary host rocks for diamond. This is not only supported by the presence of very rich diamondiferous eclogites, but also by the common occurrence of E-type (eclogitic) diamonds containing eclogitic mineral inclusions in kimberlite groundmass. Such diamonds may contain sodic clinopyroxene and garnet with rutile, kyanite, corundum, and coesite. A genetic relationship between eclogite and inclusion minerals is corroborated by the elevated sodium and potassium contents in garnets and clinopyroxenes, respectively (Helmstaedt, 1993).

Most peridotitic diamonds are formed in garnet-bearing harzburgite. Diamondiferous pyrope-lherzolites are uncommon. Diamond grades in the peridotite xenoliths are up to three orders of magnitude higher than the host kimberlites, but are still 2 to 4 orders of magnitude lower than those in the eclogite xenoliths (Helmstaedt, 1993).

The majority of the diamonds in the Sloan Ranch complex are E-type diamonds. A parcel of 153 diamonds from the Sloan 1 and 2 yielded 74% E-type diamonds (Otter and Gurney, 1989). Thus, any attempts made to predict the diamond content of these kimberlites based on their G10 pyrope geochemistry would be invalid as the G10 pyropes are only indicative of the garnet harzburgites (Shaver, 1994). The diamonds range from well-perserved octahedra to highly resorbed tetrahexahedra with colors ranging from D to E to some that are very dark brown-yellow (Dummett and others, 1988).

Diamonds from the Sloan pipes range from microdiamonds to a 5.51 carat gemstone (Bernie Free, personal communication, 1994). The 5.51 carat diamond was sent to a cutter and two small 'windows' were polished on its surface. Based on the

'windows' the cutter estimated the diamond would produce a clear, white, brilliant-cut stone weighing at least 2 carats (Shaver, 1994).

In a recent test, Royalstar Resources recovered a 3,300 tonne sample from a 700 foot adit driven into the Sloan 2 kimberlite. The Sample yielded 9,034 diamonds larger than 1 mm with a combined weight of 342.17 carats for an average grade of 12.68 carats/100 tonnes (Shaver, 1994). Individual samples ranged from 7.2 carats to 21.63 carats/100 tonnes (Oliver, 1990). The sample was processed in the Dia Met mill east of the Sloan 1 kimberlite. The mill was constructed by Superior Minerals in 1982 with a rated capacity of 50 tonnes/day.

Resources: The Sloan 1 pipe is estimated to contain a resource of 15,300,000 tonnes of kimberlite at an average grade of 6.1 carats/100 tonnes. The Sloan 2 is estimated to contain a resource of 8,400,000 tonnes at an average grade of 17.1 carats/tonne. A transitional phase along the contact between the Sloan 1 and 2 contains 3,800,000 tonnes at an average grade of 12.5 carats/100 tonnes (Oliver, 1990).

All three resource estimates were made to a depth recoverable by open-pit mining (i.e., to a depth 400 feet). Based on the grades, the Sloan 2 kimberlite represents a potential resource of 1.4 million carats of contained diamonds, and the Sloan 2 (including the transitional phase) represents a potential resource of 1.9 million carats of contained diamonds (Oliver, 1990).

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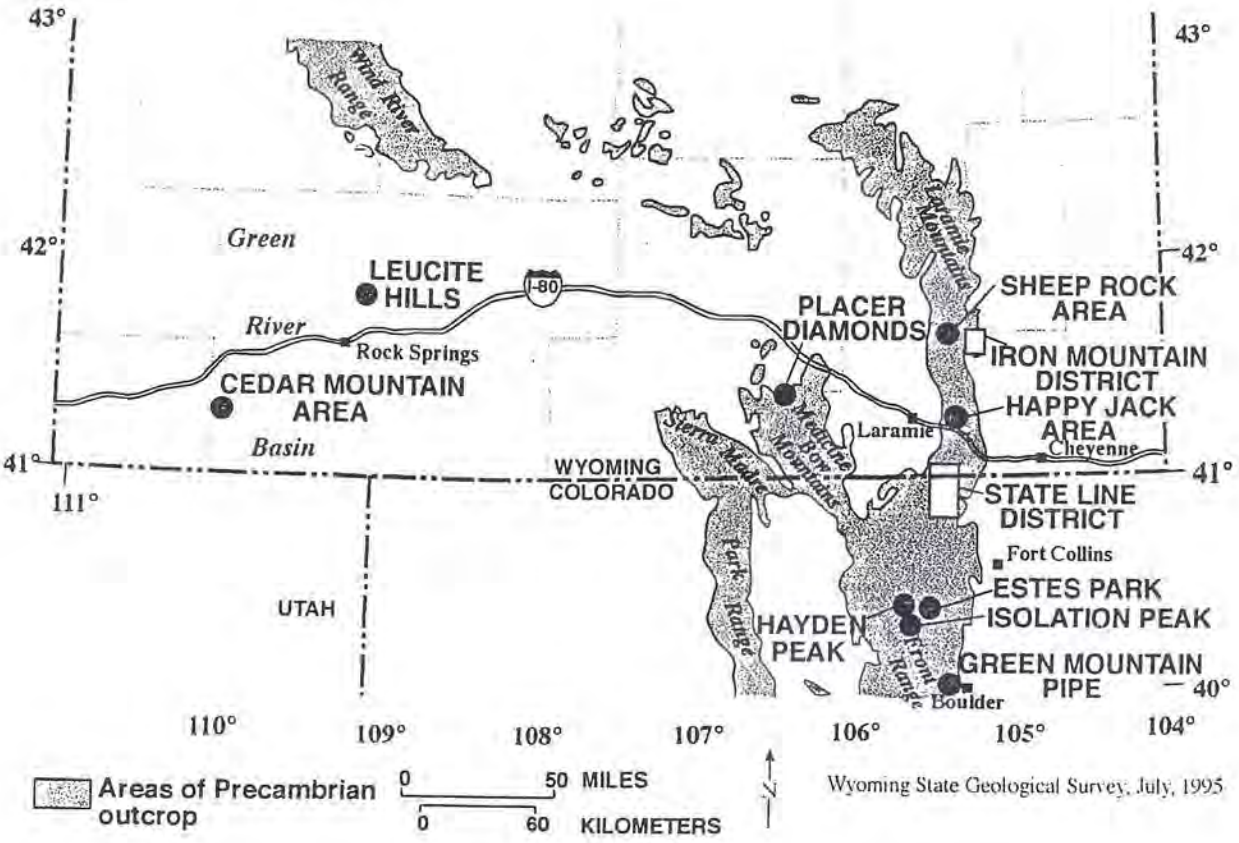

Figure 1. Generalized map showing the location of the Colorado-Wyoming State Line diamond district. Areas of interest include the Iron Mountain kimberlite district, the Sheep Rock and Happy Jack anomalous areas; the Estes Park, Isolation Peak, Hayden Peak, and Green Mountain kimberlites; the Leucite Hills lamproites; and the Cedar Mountain anomalous area (The Cedar Mountain area contains widespread 'kimberlitic' mineral indicators as well as the recent discovery of 10 breccia pipes and a dike complex hosting eclogite xenoliths. A 200 pound core sample from one of the pipes recently was reported to have yielded two diamonds).

Figure 2. Kimberlite, lamproite, diamond, and kimberlitic indicator mineral anomaly map of the Wyoming craton. The approximate boundary of the Wyoming (Archean) Province lies within the dashed line. Diamond symbols are areas were detrital diamonds have been reported. Dots are locations of indicator mineral anomalies, and stars represent sites of kimberlite and lamproite occurrences, districts, and related rocks.

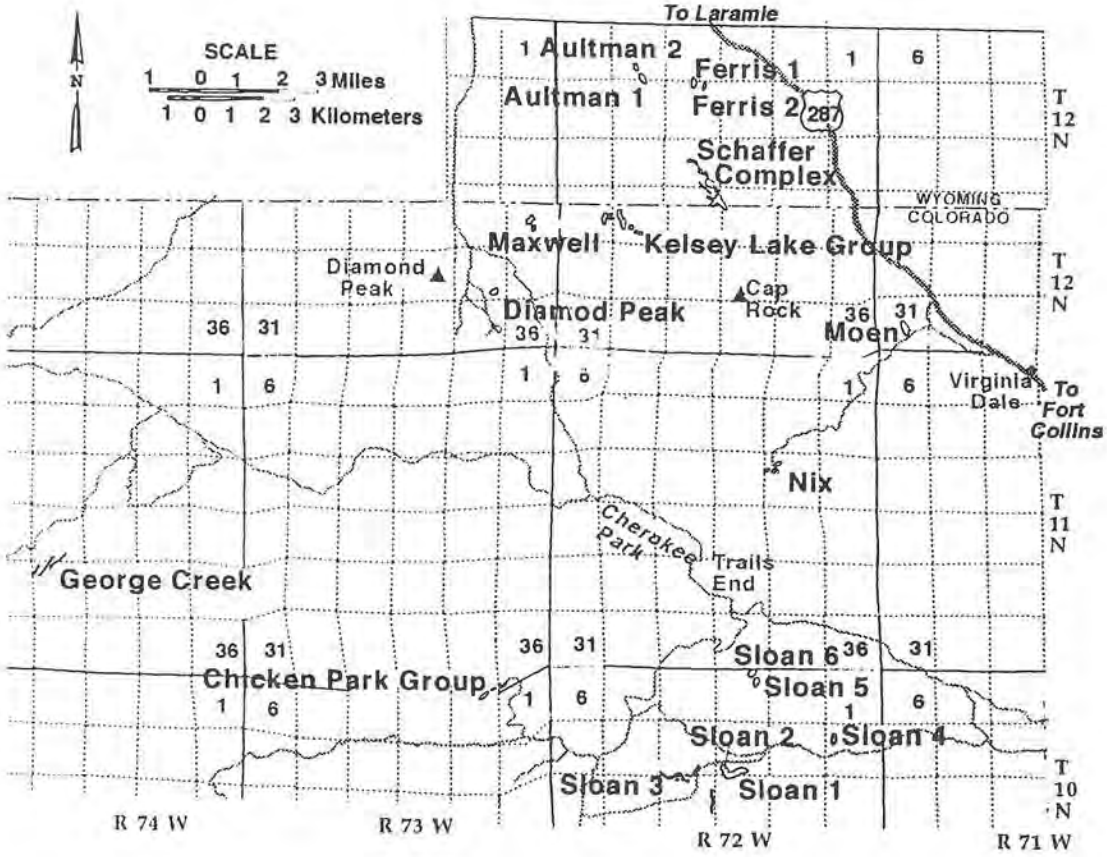

Figure 3. Kimberlite localities of the Colorado-Wyoming State Line district.

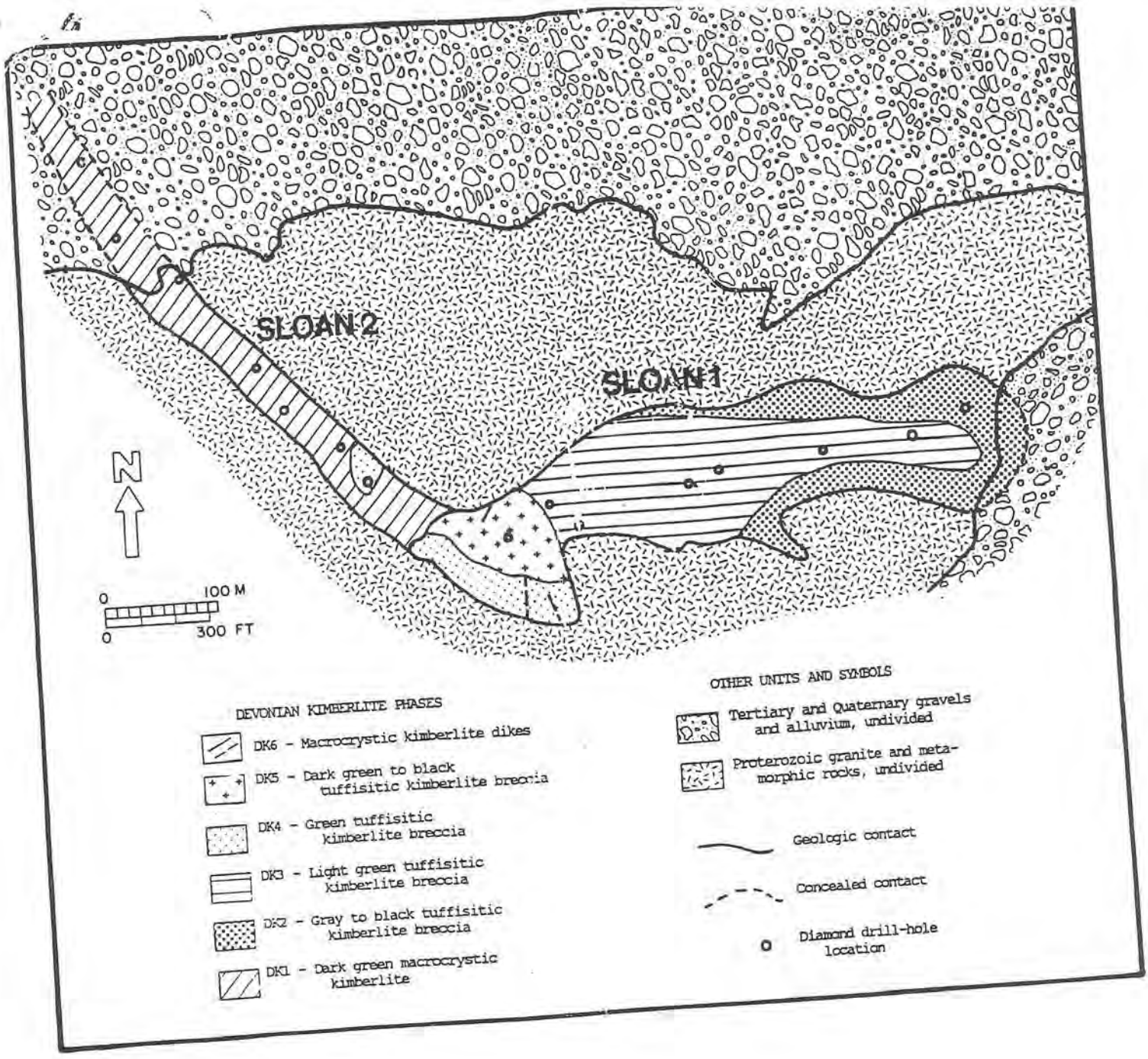

Figure 4. Geologic map of the Sloan 1 and 2 kimberlites (from McCallum, 1991).