THE GEOLOGICAL SURVEY OF WYOMING

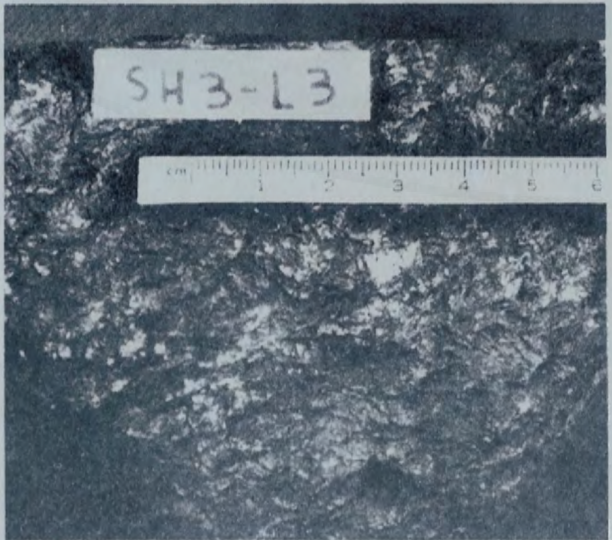
Daniel N. Miller, Jr., State Geologist

REPORT OF INVESTIGATION NO. 12

DIAMOND IN STATE-LINE KIMBERLITE DIATREMES ALBANY COUNTY, WYOMING LARIMER COUNTY, COLORADO

BY M.E. McCALLUM AND C.D. MABARAK

SEPTEMBER, 1976



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BOX 3008, UNIVERSITY STATION
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Cover--Kimberlite diatreme on State Section 16 where diamond was first discovered in Wyoming. Lower left: diamond-bearing Garnet peridotite nodule. Lower right: octahedral diamond embedded in peridotite matrix.

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ERRATA

Page 2, paragraph 1, last sentence should read,"A more comprehensive report on the Colorado diamonds by McCallum and Mabarak appears in vol. 4 of Geology (1976)."

Page 6: Kimberlite occurrences along the Missouri River in north-central Montana were inadvertently omitted from Figure 5.

Page 13, Table 2, augite-granulite under Lower Crustal Group at bottom of table: augite composition should read ($Ca_{45}Mg_{35}Fe_{20}$).

Page 31, footnote 80 should read, "Bruton, 1971, p. 274."

DIAMOND IN STATE-LINE KIMBERLITE DIATREMES, ALBANY COUNTY, WYOMING AND LARIMER COUNTY, COLORADO

By

M. E. McCallum* and C. D. Mabarak°

INTRODUCTION

A number of kimberlitic diatremes penetrate Precambrian crystalline rocks near the Wyoming-Colorado state line, south of Tie Siding, Wyoming, and north of Prairie Divide, Colorado (Fig. 1). These diatremes or pipes originated in the Earth's upper mantle and transported deep-seated ultramafic material to the surface. In addition to xenoliths of mantle material, the pipes also contain crystalline rocks of crustal origin and xenoliths of Lower Paleozoic sedimentary units which once covered the region.

Initial discoveries of diatreme sites in Wyoming were made in 1960 and 1961 by C.S. Ferris, Jr. and C.A. Aultman, respectively. They found fragments and blocks of Lower Paleozoic rocks in the Precambrian crystalline terrane. These anomalous occurrences were originally interpreted as "graben" features[1] however, at the time, the diatreme nature was suggested by Ogden Tweto[2] Discovery of the Sloan pipe in Colorado by M.E. McCallum in 1964 and of several additional pipes by D.H. Eggler in Colorado and Wyoming in the same year established the features as kimberlitic diatremes[3] Subsequent finds in the State-Line district have been made by McCallum, Eggler, L.K. Burns and Colorado State University students C.E. Beverly, W.M. Oriel, C.D. Mabarak, D.L. Collins and H.G. Coopersmith. Several discussions of the geology of the diatremes and mineralogy, petrology and chemistry of the kimberlite and included nodules are available[4]

Diamonds were discovered in the State-Line diatremes in June, 1975. During thin section preparation of a serpentinized garnet peridotite nodule, Florian J. Nowacki and Ross Jensen of the Analytical Branch of the U.S. Geological Survey in Denver, Colorado, noticed deep scratches on a grinding plate and isolated a small white crystal (approximately one millimeter in diameter). X-ray diffraction analysis by T. Botinelly and B.F. Leonard (U.S. Geological Survey), utilizing a Gandolfi camera, confirmed the diamond identification. Subsequent examination of the nodule revealed three small diamonds imbedded in the peridotite. Other small crystals were recovered when chips of the nodule were dissolved in hydrofluoric acid.

The odds against finding a diamond during thin section preparation are astronomical. Davidson (in von Eckerman, 1967, p. 312) has stated that "the richest kimberlites . . . carry one part diamond in 10^7 of rock, and the average is one in 10^{10} or less. So the chances of finding a diamond in a thin section are somewhat around the cube of the probability of finding the needle in the haystack." The odds should be raised several more orders of magnitude for finding diamonds in the Wyoming peridotite nodule, as it is only one of a very few occurrences of a diamond-bearing nodule of its type in the world. A diamond-bearing garnet peridotite nodule from the Mothae kimberlite pipe in northern Lesotho was recently described by Dawson and Smith (1975), and Sobolev and others (1969) have described diamond from five garnet serpentine nodules (probably altered garnet peridotite) from the Aykhal kimberlite diatreme in Siberia. The diamonds in the State-Line nodule also represent the first authenticated occurrence of diamond in Wyoming and the second known occurrence of diamonds from a kimberlite pipe in North America; the other is at Murfreesboro, Arkansas, where diamonds were discovered in 1906 and recovered commercially until 1919[5]

Following recognition of diamonds in the Wyoming nodule, a program was initiated to evaluate weathered kimberlite in the State-Line district for diamonds. Research priority has been given to the evaluation of pipes on lands controlled by the State of Wyoming, although several of the Colorado pipes are also being studied as part of a National Science Foundation and U.S. Geological Survey project.

In July, 1975, several diamonds were recovered from weathered kimberlite at the Sloan diatremes in northern Colorado. The discovery was noted in a U.S. Geological Survey July project progress report by

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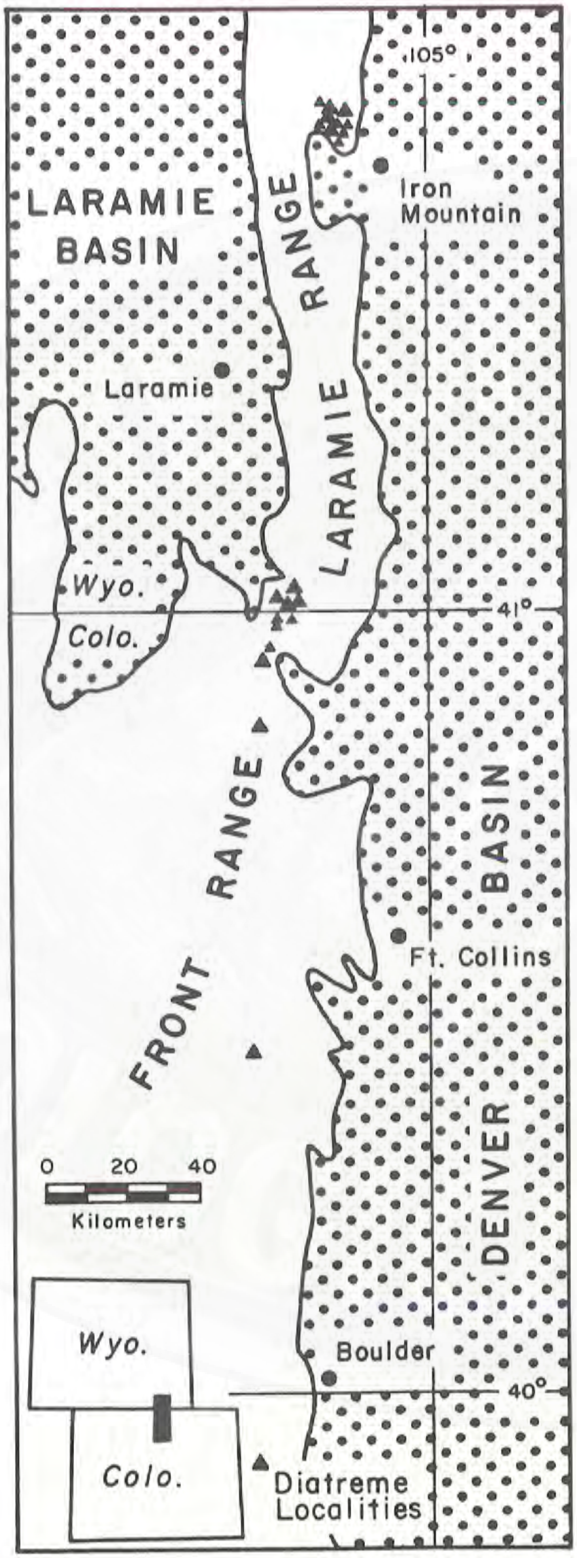


Figure 1 – Location map of kimberlite diatremes in northern Colorado and southern Wyoming. Stippled areas are underlain by sedimentary rocks; unshaded areas by Precambrian crystalline rocks.

McCallum (on file at the Branch of Central Mineral Resources, Denver, Colorado). A more comprehensive report on the Colorado diamonds by McCallum and Mabarak in Vol. 4 of Geology (1976).

Recovery of the first diamonds from the Wyoming State-Line pipes was made in September 1975. At the time of writing, diamonds have been recovered from six diatremes located on lands owned by the State of Wyoming. Kimberlite from other pipes in the area is now being evaluated and a systematic search for additional pipes is underway.

GENERAL GEOLOGY

The State-Line kimberlitic diatreme district encompasses approximately 50 square miles and extends across the boundary between Wyoming and Colorado (Fig. 1). The diatreme sites define a roughly north-south trend and locations range from about 12 miles south to two miles north of the state line. Other kimberlite in the region occurs in a single pipe (Green Mountain diatreme) west of Boulder, Colorado, approximately 70 miles south of the state line,[6] in dikes in the Estes Park, Colorado, area about 40 miles to the south,[7] and in pipes and dikes near Iron Mountain (Farthing), Wyoming, about 40 miles north-northeast of the State-Line district.[8] Distribution of the kimberlite roughly parallels the eastern edge of the Front Range in northern Colorado and southern Wyoming. Emplacement may have been controlled by a deep-seated fracture system that later dominated the structural evolution of the Front Range.[9]

All of the diatremes in the State-Line district penetrate a crystalline sequence of Precambrian igneous and metamorphic rocks. The district is dominated by the Virginia Dale ring-dike complex which is a roughly circular granitic feature about nine miles in diameter.[10] The complex is a part of the large Sherman granite batholith that discordantly intrudes a sequence of metamorphic rocks. Eggler (1968, p. 1546) divides the complex into four zones: an outer ring-dike of biotite-hornblende granite, a composite zone of diorite, andesite and metamorphic rocks, and two inner zones

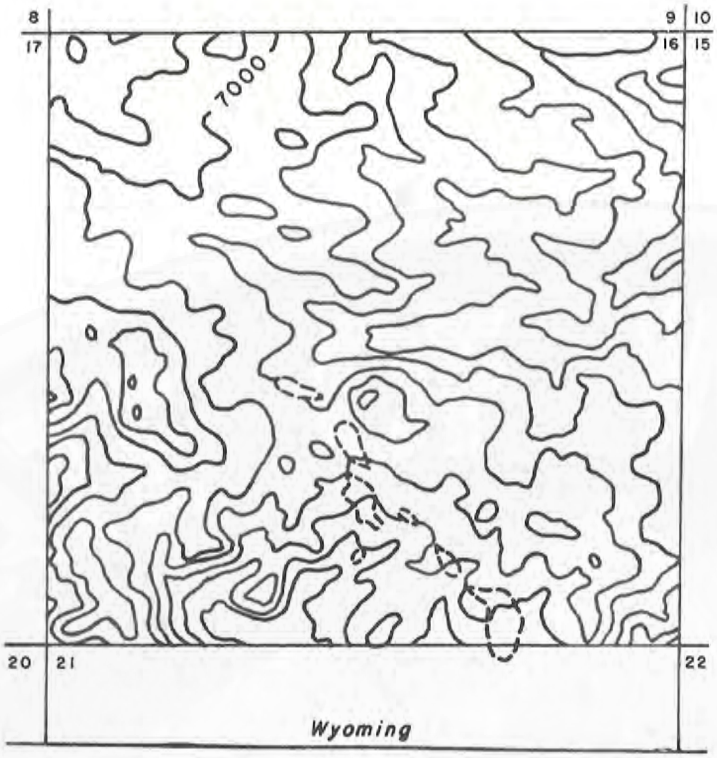


Figure 2 – Topographic map of 16 T. 12N., R. 72W. showing locations of kimberlite diatremes. Note the linear alignment of pipes and elliptical to subelliptical surface outlines.

of biotite quartz monzonite which are younger than the granite. The ring-dike complex merges with the main body of the Sherman batholith to the north and to the south with granite of the Log Cabin batholith.[11] The Log Cabin granite is prominent in the southern part of the State-Line diatreme district where the Sloan pipes are located.[12]

Granite of the Log Cabin batholith is slightly younger than the Sherman granite and, according to Eggler (1968, p. 1549), may be distinguished from the latter by "its finer grain size, primary muscovite and the abundant small bodies and dikes of pegmatite and aplite within and, especially, immediately outside the batholith." Peterman and others (1968) have established essentially equivalent radiogenic Sr-Rb ages for granites of the Sherman and Log Cabin batholiths (1.41 ± 0.003 b.y. and 1.42 ± 0.003 b.y. respectively); however, crosscutting field relationships indicate that, at least locally, the Log Cabin phase is younger.[13] Metamorphic rocks in the area give Sr-Rb ages of approximately 1.75 b.y.[14]

Numerous dikes of biotite and hornblende quartz monzonite, alaskite and porphyritic andesite cut the batholithic and metamorphic rocks of the district. They are especially abundant in the vicinity of the state line. In general, the dikes are either strikingly linear, reflecting a joint controlled emplacement, or parallel to the curved contacts of the granitic units of the ring-dike complex. All dikes were apparently emplaced during the Sherman-Log Cabin igneous event[15] and a date of 1.42 b.y., established by Ferris and Krueger (1964) on a porphyritic andesite dike, supports this.

No *in situ*, post-Precambrian, sedimentary rocks are exposed in the State-Line diatreme district; however, arkosic sediments of the Pennsylvanian Fountain Formation do outcrop about two miles north where sediments of the Laramie Basin overlap Precambrian rocks. Early paleogeographic interpretations suggested that the general region was a low, stable landmass where no sediments were deposited during Early Paleozoic time. Blocks and fragments of limestone, dolomite, dolomite breccia and small amounts of flat pebble conglomerate and sandstone of Ordovician and Silurian age are found in a number of the diatremes. They indicate that Early Paleozoic seas repeatedly covered the region.[16] Extensive Late Silurian or Early Devonian erosion apparently removed the Lower Paleozoic sedimentary rock cover. Blocks of Ordovician and Silurian sediments preserved in kimberlite provide the sole remaining record of Early Paleozoic sedimentation in the Northern Front Range of Colorado and Wyoming.[17] Emplacement of diatremes must have predated the extensive erosional episode that stripped the Lower Paleozoic rock cover, and a very late Silurian or Early Devonian age of kimberlite intrusion is postulated.[18]

Although the general structural fabric of the district is dominated by the circular ring-dike complex, prominent joint sets and faults apparently played a more important role in the emplacement of the diatremes. Some of the diatremes are closely associated with fault zones (*e.g.* the Nix pipes in Colorado);[19] the Sloan 1 and 2 pipes, near the southern end of the district in Colorado, are clearly fault controlled.[20]

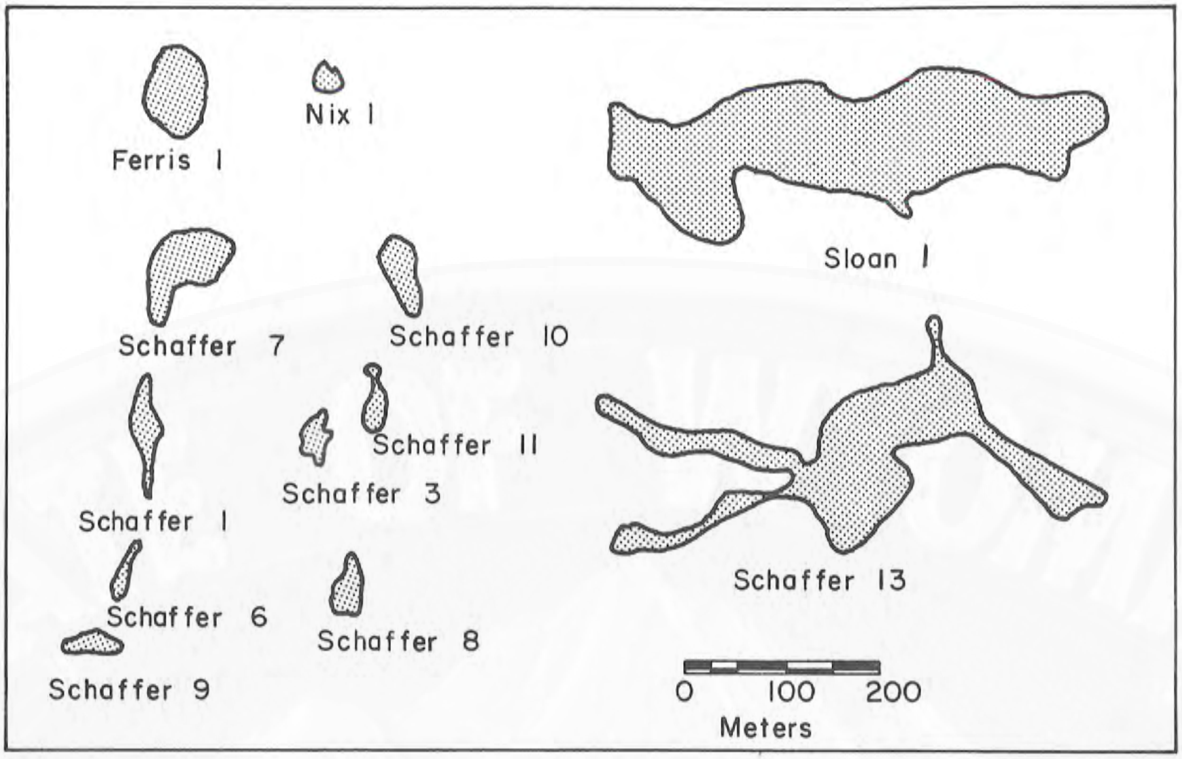


Figure 3 – Surface plans of several State-Line district diatremes (after McCallum, *et al.*, 1975, p. 151).

Figure 4 – Photographs of kimberlite diatremes. A) Schaffer 15 pipe on Wyoming State Section 16. The pipe underlies lighter grassy area beyond the fence-line. B) Nix 1 pipe showing kimberlite exposed in positive relief.

Many of the diatremes have a roughly linear alignment, apparently controlled by major joint sets (Fig. 2). North-northwest and north-northeast trending joints appear to have been most important in pipe distribution. Planar structural controls apparently account for the strongly elliptical to sub-elliptical surface planes of many of the pipes (Figs. 2 and 3).

The State-Line diatreme district is characterized by an upland erosion surface (Sherman surface), that is increasingly more dissected to the south. Maximum cutting apparently occurred in Late Tertiary and Pleistocene time, and most of the truncated diatremes have negligible relief and are poorly exposed. Kimberlite at all of the known pipes on Wyoming state land is deeply weathered, although unweathered kimberlite is present at two nearby Wyoming diatremes. Unweathered kimberlite also outcrops at several of the pipes in the Colorado portion of the district. Land surfaces over most of the diatremes generally show little difference from the surrounding granitic terrane (Fig. 4a), although in a few pipes kimberlite is exposed in positive relief (Fig. 4b). Typically, the pipes are covered with thin veneers of weathered granite (grus) derived from the breakdown of adjacent rocks. Where grus covers are thin or where weathered kimberlitic material has been brought up in animal burrows, gray to gray-green soils containing montmorillonite, chlorite, serpentine and calcite characterize the pipe. Many of the pipes were discovered by the presence of carbonate rock or peridotite xenoliths and/or megacrysts (rounded crystals generally larger than one centimeter) of pyrope garnet and magnesian ilmenite in grus.

KIMBERLITIC DIATREMES

Significance and Distribution

Kimberlitic diatremes have been found in many parts of the world. They have long been a subject of interest because kimberlite is the primary source of diamonds; its potential economic importance has been accepted for years.

More recent studies of kimberlitic pipes have taken on added significance of a petrological, geophysical and geochemical character. Xenoliths or nodules of deep-seated rocks typically occur in kimberlite, thus the researcher is provided a rare opportunity to study samples from lower crust and upper mantle sources (down to depths greater than 100 miles). Such studies permit construction of petrologic models that aid in interpreting the nature and origin of deep crustal and mantle rocks that underlie stable continental areas.[21]

Some diatremes are known to contain low-grade deposits of uranium although many of these are not kimberlitic in composition.[22] Some kimberlite pipes in the Colorado Plateau district are uranium-bearing[23] and some production of U_3O_8 was realized in the 1950's.[24] Uranium deposits are restricted chiefly to diatremes that contain bedded carbonate rocks,[25] although uranium-vanadium-copper minerals are found as a cement or as vein fillings in the Navajo sandstone along pipe and dike contacts at the Garnet Ridge, Arizona, kimberlite site.[26]

The most famous kimberlitic diatreme locality is the "type section" in South Africa where diamonds have been mined from pipes since 1870.[27] In addition, pipes are widely distributed throughout central and northwest Africa although the production of diamonds from kimberlite is significant only in Tanzania, Zaire, Angola and Botswana.[28] Lesotho, Sierra Leone, West Africa and Rhodesia also show minor production from kimberlite pipes.

The second most important kimberlite locality is in the USSR, where the rock was first recognized in dikes in 1940. An important district of diamond-bearing pipes was discovered in the province of Yakutia in 1954,[29] although diamond was not actually found in the bedrock until 1961.[30] Locations of many hundreds of kimberlitic dikes and pipes are now known throughout the Siberian platform. Although accurate production figures are not available, the Yakutia district accounts for a significant percentage of the world diamond output.[31] Kimberlitic pipes and dikes have been reported from a number of other localities worldwide, although none are noted for their diamond production.[32]

Kimberlite is widely distributed throughout North America but diamond-bearing localities are quite rare. Except for the Wyoming–Colorado State-Line district, diamonds have only been found in North American pipes at the Murfreesboro district in Pike

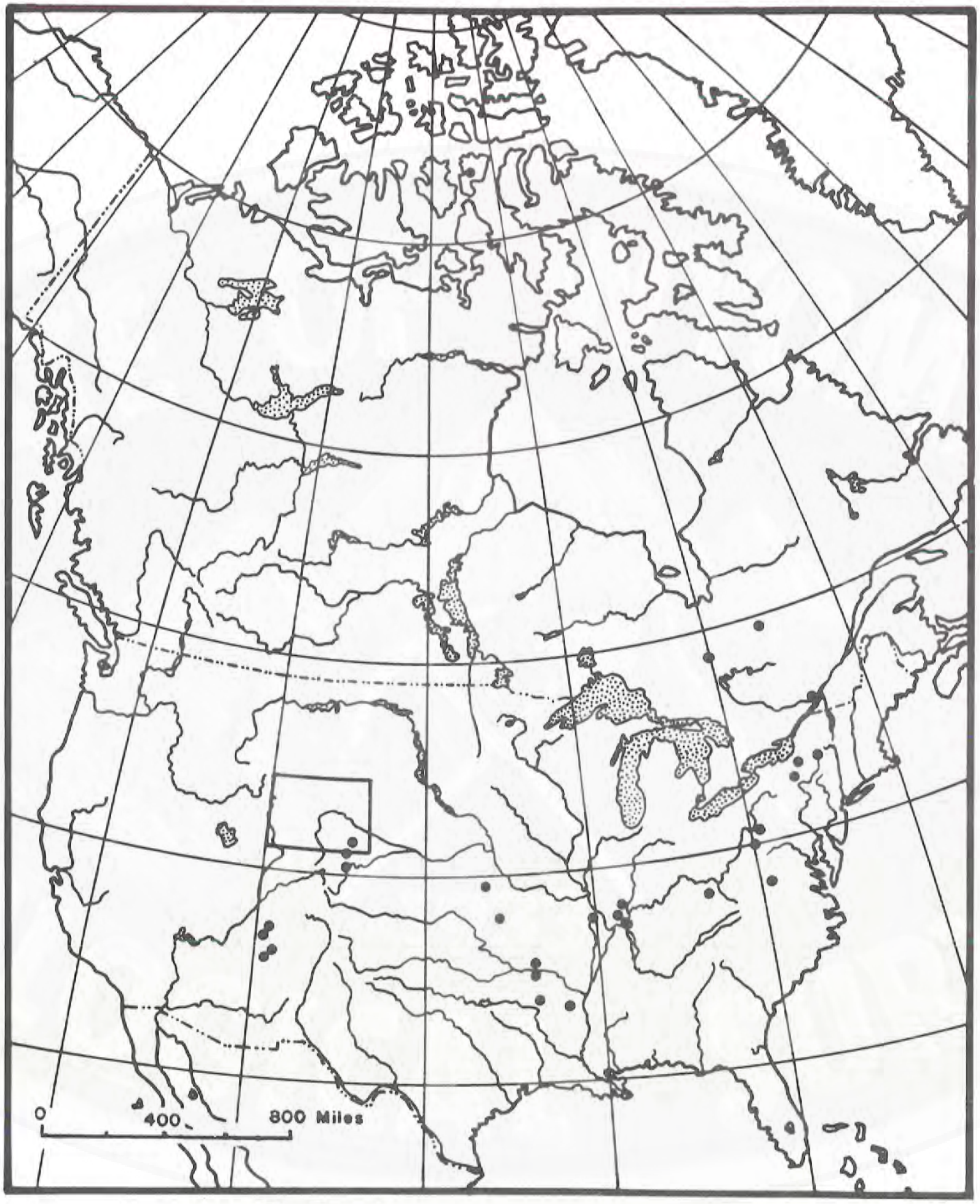


Figure 5 – Occurrences of kimberlite and related rocks in North America.

County, Arkansas[33]. The kimberlite occurrences can be conveniently assigned to four general provinces: 1) the Appalachian province which includes dikes in the Ithaca, New York, area, dikes in southwestern Pennsylvania, northern Virginia and eastern Kentucky and pipes in eastern Tennessee; 2) the Central province which includes dikes in western Kentucky and southern Illinois, diatremes and dikes in southeastern Missouri and southern Arkansas and diatremes in eastern Kansas3)Rocky Mountain-Colorado Plateau province which includes diatremes in north-central Montana and dikes and pipes in northeast Arizona, northwest New Mexico, southeast Utah and the Colorado–Wyoming Front Range; 4) the Canadian province which includes pipes and dikes in Quebec, Ontario and Somerset Island, Northwest Territory.

For a more comprehensive discussion of the various kimberlite localities in the United States, the reader is referred to a paper by H.O.A. Meyer of Purdue University. The paper, titled "Kimberlites of the Continental United States –A Review," is currently in press in the **Journal of Geology**.

Nature and Emplacement

Diatremes have been described by Holmes (in Trowbridge, 1957, p. 81) as volcanic vents or pipes drilled through the enclosing rock by the explosive energy of gas charged magma. More recent workers distinguish diatremes from the more common volcanic vents by the identification of the brecciated nature of the included material as opposed to the molten liquid form seen in volcanic vents[34]. More specifically, brecciated country rocks are almost invariably admixed with juvenile, magmatic materials in kimberlitic diatremes[35]. Diatremes are apparently formed by fluidized gas-solid magmas in which denser solid particles are distributed within a rising gas phase[36]. These magmas intrude along fracture systems and produce cylindrical, pipe shaped vents at upper levels (Fig. 6). Circulating fluidization cells in the pipes are responsible for the subsidence of surface and near surface materials to depths that may exceed 1000 m[37].

Diatremes that break through to the surface may produce tuff rings, tuff cones or maars[38]; those failing to reach the surface are called blind diatremes (the Sloan 2 pipe in Colorado may be such a feature). Diatremes range in diameter from a few meters to more that 1500 m[39]. They may be nearly circular to elliptical or highly irregular in surface plane (Figs. 2 and 3). The pyroclastic or breccia fillings of many diatremes have a crude, roughly concentric zoning and, at some localities[40], pyroclastic fillings are well bedded.

Only those diatremes containing kimberlite are

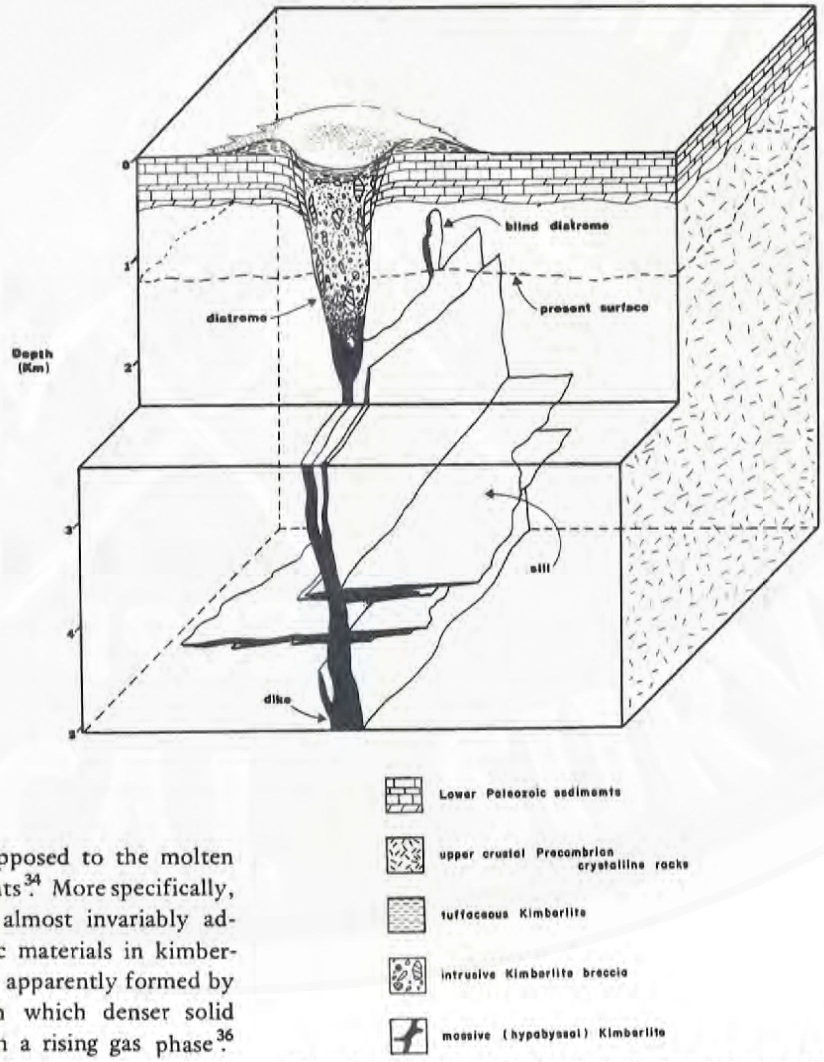


Figure 6 – Diagrammatic sketch of diatremes showing dike and sill system.

economically significant, although, as previously mentioned, some non-kimberlitic breccia pipes that may be diatremes have been known to contain uranium[41]. Also, a few peridotite pipes in South Africa contain platinum[42]. Kimberlitic diatremes apparently originate from dikes at depth (Fig. 6). Many of the mined-out kimberlite pipes in South Africa taper into dikes (*e.g.* the Kimberley pipe), and many kimberlite dikes exposed at the surface are characterized by randomly spaced small "blows" or pipes (*e.g.* Bellsbank, South Africa) that apparently represent the lower portions of larger diatremes, mostly removed by erosion. Kimberlite dike systems in the Iron Mountain, Wyoming, district also contain "blows" and the pronounced linear alignment of some diatremes in the Colorado–Wyoming State-Line district might be the result of dike control (Fig. 2).

According to Dawson (1971), kimberlite magma migrates rapidly upward as a hot fluid (mostly gas-solid mixture) along major, deep-seated fractures. It picks up xenoliths and xenocrysts of upper mantle and lower crustal material enroute and, in part, crystallizes as dikes and sills in upper crustal areas. Some included rock fragments from depth and from host rocks adjacent to the exposed dikes show moderate thermal effects, although of much lesser intensity than would be the case if the magma were liquid. When the fluid or crystal mush has penetrated to within a few kilometers of the surface, the pressure of gas phases in the magma approaches that of the overlying rock column and rapid expansion of the gases results. The expanding gases (H_2O and CO_2 are apparently most abundant) move upward along zones of weakness, stopping and drilling with a "sand blasting" effect, utilizing joints and faults. If the gas content of the magma is relatively low and overlying rocks are moderately to highly porous, the volatiles may escape without appreciable stopping. However, in most situations, explosive breakthrough probably occurs with associated development of a flared, cone-shaped conduit formed by a gas-solid fluidization process. The explosive vent is enlarged with continued fluidization and is infilled by ash fall material and blocks of country rock that subside along conduit margins. All of these materials, along with xenoliths from below, may be circulated repeatedly in fluidization cells. The resulting abrasion may account, in part, for much of the characteristic rounding and polishing of included nodules. Rounded nodules, present in the deeper dikes where the fluidization process was not active, were probably shaped, at least to a degree, by some form of magmatic corrosion. Many diatremes contain multiple generations of breccia or tuff, emplaced by later gas surges. Some contain dikes, sills or plugs of massive kimberlite or peridotite that apparently were intruded relatively slowly as gas poor magmas[43].

The lack of appreciable thermal effects on xenoliths included in diatremes or on the adjacent wallrocks has prompted most workers to advocate a "cold intrusion" mechanism of emplacement[44]. Strong adiabatic cooling would be expected to accompany rapid expansion of gases at shallow depths and significant thermal effects in the diatremes would be precluded[45]. Dawson (1971) has suggested that gas expansion, and thus initiation of diatreme formation, would occur at depths of approximately two to three kilometers (~ 1.2 to 1.8 miles) below the original land surface (see Fig. 6). This estimate is based on a calculated depth of 2.4 km (~ 1.5 miles) for the original point of expansion of mined out diatremes at Kimberley, South Africa, coupled with the fact that "P-V-T relationships of water indicate considerable expansion, at all temperatures, at pressure equivalent to 2-3 km[46]."

In summary, diatremes are conical shaped breccia or tuff filled vents that apparently rose above the general level of "feeder" dike intrusions (Fig. 6) and were emplaced at low temperatures (less than 500°C) by a fluidization process. Diatremes that breached the surface were probably expressed as maar volcanoes or craters with tuff cones or rings composed of fragmental kimberlite.

KIMBERLITE PETROGRAPHY AND MINERALOGY

Kimberlite in diatremes of the State-Line district is of fairly uniform type and composition. It is similar mineralogically and chemically to kimberlite from a variety of world-wide sites. The term kimberlite was proposed by Lewis (1887) to describe the diamond-bearing ultramafic breccia found in volcanic vents in the Kimberley area of South Africa in 1870. Although Lewis included diamond as an essential constituent of kimberlite, most workers no longer do so. Many "mica peridotites" and "lamprophyric" rocks are now considered as kimberlite. A widely accepted definition, proposed by Dawson (1971, p. 188), is:

"Kimberlite is a very rare, potassic, ultrabasic, hybrid igneous rock that occurs in small diatremes, or dikes, or sills of limited extent. It has an inequigranular texture, the porphyritic aspect being due to megacrysts of olivine, enstatite, chrome-diopside, pyrope, picro-ilmenite and phlogopite, set in a finer-grained matrix of which serpentine, carbonates, phlogopite, magnetite and perovskite form the major part. Many of the megacrysts are derived from fragmentation of mantle-derived garnet lherzolite (blocks of which are embedded in the kimberlite) and are in various stages of reaction with the kimberlite matrix. The matrix may, or may not contain diamonds; even in the most diamondiferous kimberlites diamond is a very rare and widely dispersed mineral."

Most of the pipes in the State-Line district are characterized by deeply weathered profiles. Unweathered kimberlite is intensely serpentinized and has been observed at only two of the Wyoming sites, although it is relatively common in many of the Colorado pipes. Fresh kimberlite containing unaltered to moderately altered olivine and orthopyroxene has been observed at only one pipe in Colorado.

The predominant type of kimberlite in the area is an intrusive breccia (Figs. 7A, 8A, and 8B). The breccia is light to dark green, gray green or greenish black. It consists of abundant subrounded to angular clasts in a finely-crystalline matrix of serpentine, calcite, dolomite, phlogopite, magnetite, perovskite, chlorite, talc and hematite. Rock clasts include both upper

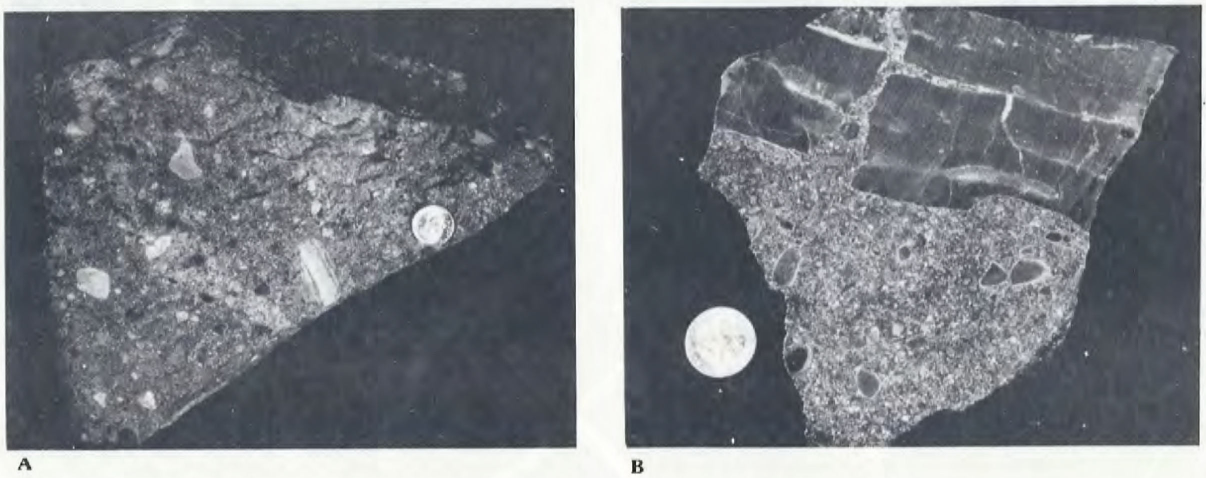
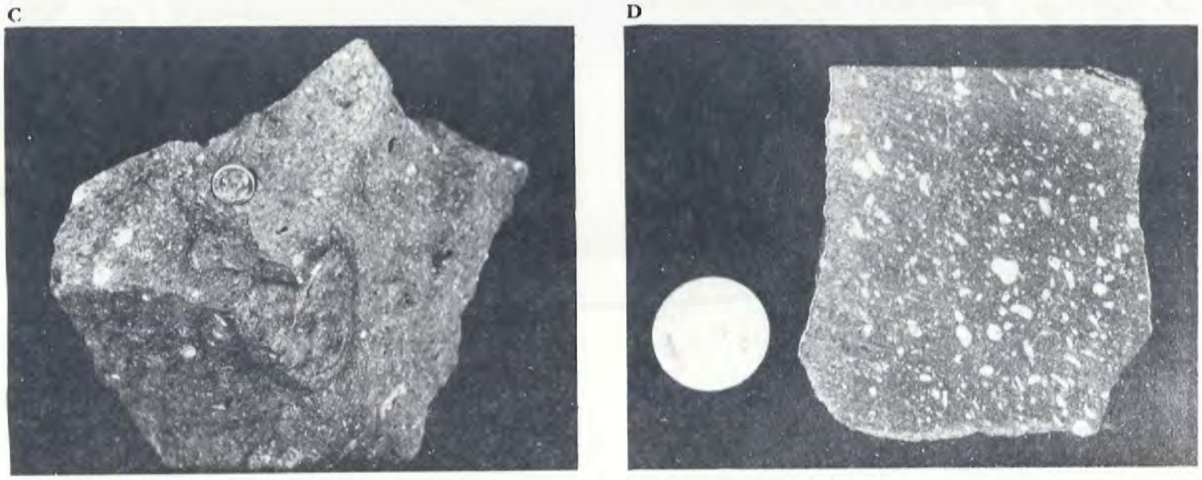


Figure 7 – Kimberlite samples. A) Kimberlite breccia, light colored fragments are mostly sedimentary carbonates and igneous carbonatites. B) Angular block and several small rounded fragments (gray) of Lower Paleozoic limestone in kimberlite breccia. C) Rounded, serpentinized spinel lherzolite nodule in kimberlite breccia. D) Sawed slab of massive porphyritic kimberlite; rounded to subrounded phenocrysts are mostly serpentine pseudomorphs of olivine and enstatite.



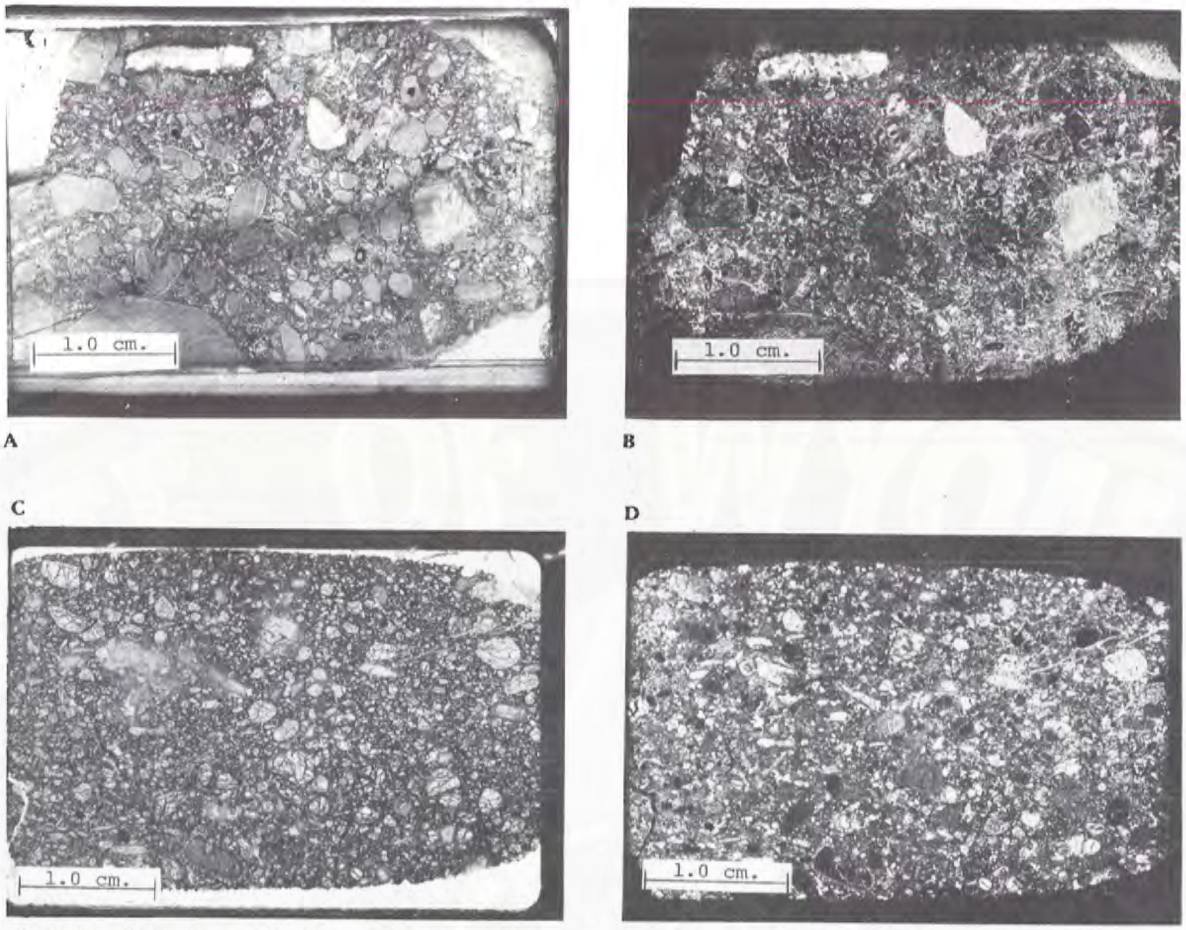


Figure 8 – Photomicrographs of kimberlite. A) Kimberlite breccia showing angular and rounded nature of clasts. The angular fragments are mostly Paleozoic sedimentary rocks and upper crustal Precambrian plutonic rocks; rounded fragments are chiefly serpentine pseudomorphs after olivine and enstatite; matrix is primarily serpentine, calcite, dolomite and phlogopite. Opaque grains are ilmenite and chromite-picotite, "rimmed" grains are pyrope surrounded by kelyphite. Plane light. B) Sample in A under crossed nicols. Note the typical mottled to wormy fabric of the serpentine and light colored angular xenoliths (rock fragments). C) Massive porphyritic kimberlite showing abundant fresh to only slightly serpentinized olivine (subrounded grains with irregular fractures) and orthopyroxene (more tabular to blocky grains without diagnostic fractures). The matrix is similar to that in kimberlite breccia of A. Plane light. D) Sample in C under crossed nicols.

and lower crustal Precambrian crystalline units (granite, gneiss and schists—granulite, pyroxenite and basalt?). Lower Paleozoic sedimentary units (limestone, dolomite and rare flat pebble conglomerate and sandstone; Fig. 7B) and nodules of cognate kimberlite and upper mantle carbonate (sovite), spinel and garnet lherzolite (Fig. 7C), dunite, harzburgite, garnet websterite and clinopyroxenite, and eclogite. Mineral clasts include picro-ilmenite (magnesium-rich), garnet (mostly pyropic, both chrome-rich and chrome-poor), chromian diopside, low-chrome diopside, enstatite, olivine (rare), diopside-garnet intergrowths (rare), phlogopite, biotite, chromite-picotite, magnetite, perovskite, zircon, apatite (rare) and abundant serpentine pseudomorphs after olivine and enstatite.

A massive, porphyritic variety of kimberlite (Figs. 7D, 8C and 8D) occurs locally at a number of the Colorado and Wyoming pipes. The massive kimberlite is relatively free of fragmental inclusions, contains up to 60 percent olivine and orthopyroxene xenocrysts (generally serpentinized but approximately Fo91 and En91 respectively where fresh) and typically has a dense, fine-grained matrix similar in composition to the brecciated variety. Varying amounts of euhedral to subhedral phlogopite and perovskite with subhedral to anhedral grains of magnesian ilmenite, pyrope, chromian diopside, chromite and magnetite are also present. Crude flow textures, defined by tabular phenocrysts and xenocrysts, have been observed at several of the pipe localities. The massive kimberlite is considered to be characteristic of dikes, sills and lower parts of diatremes.[47] One of the sample sites appears to be a dike-like zone connecting two elliptically shaped pipes. Two other occurrences of the massive rock type are in very small diameter pipes that probably represent "root zones" of once more extensive diatremes.

Massive kimberlite has been subdivided into "basaltic" and "micaceous" varieties. In the basaltic type, olivine or serpentinized olivine is the dominant phenocryst mineral, while in the micaceous variety, mica forms greater than five percent of the phenocrysts or comprises a large part of the groundmass.[48] Because the two varieties may be gradational and no sharp distinctions can commonly be drawn between them, some workers suggest that the terms be dropped. However, in areas where distinctions are possible, retention of the terms seems useful. Kimberlite in the State-Line district generally has a low phlogopite content and appears to be predominantly "basaltic" in nature.

Both brecciated and massive varieties of kimberlite are characterized by intense alteration of constituents. As previously mentioned, most olivine and orthopyroxene have undergone complete serpentinization, a process that may have proceeded rapidly following intrusive breakthrough to the surface.[49] Dikes, sills or "blind" pipes that failed to penetrate the surface would more likely contain fresh olivine and orthopyroxene. Some irregular masses of perovskite appear to be secondary products after ilmenite. Some ilmenite may break down into complex mixtures of hematite, rutile and unidentified microcrystalline material. Garnets are generally rimmed by kelyphite (Fig. 8A) and, locally, may be completely replaced by the same alteration mixture (microcrystalline mixture of biotite, spinel, pyroxene, amphibole and plagioclase?). Many xenocrysts of both fresh and serpentinized material have rinds or rims consisting of a mixture or intergrowth of serpentine and carbonates (chiefly dolomite) (Figs. 8A and 8B). Some carbonate xenoliths have a thin rind of fine-grained dolomite that has replaced the more calcic parent material.[50] Peridotite and eclogite nodules also show varying degrees of serpentinization, carbonation and/or silicification. Lath-like carbonate pseudomorphs in the matrix of some massive kimberlite have been interpreted by some workers as pseudomorphs after melilite.[51] According to Milashev (1965), these secondary minerals probably form at temperatures of less than 450°C. Montmorillonite, Mg-vermiculite, chlorite and talc are present in the weathered profile of some pipes. They probably represent products of low temperature weathering processes rather than autometamorphic reactions.

KIMBERLITE CHEMISTRY

Kimberlite is an undersaturated, ultrabasic rock that varies widely in composition, reflecting its hybrid origin.[52] In essence, it may be referred to as "garnet peridotite + matrix" and, relative to other ultrabasic rocks (peridotites), it is enriched in TiO_2, Al_2O_3, Fe_2O_3, Cr_2O_3, MnO, CaO, K_2O, P_2O_5, H_2O and CO_2, and deficient in SiO_2 and MgO (Table 1). Ratios of K_2O:Na_2O and Fe^{3+}:Fe^{2+} are unusually high and the Mg:Fe ratio is low.[53] Furthermore, kimberlite is enriched in the minor elements Li, B, F, Sc, V, Cu, Ga, Rb, Si, Y, Zr, Nb, Cs, Ba, La, Ta, Pb, Th and U,[54] and in rare earth elements.[55]

Dawson (1967b, p. 272) has shown that although no sharp chemical distinction can be drawn between "basaltic" and "micaceous" types of kimberlite, general differences are evident. According to Dawson (1967b, p. 272), "basaltic kimberlites tend to contain higher SiO_2, MgO and H_2O, whereas micaceous kimberlites contain more Al_2O_3, CaO, K_2O and CO_2 . . . ." Kable, *et al.*, (1975) have further noted that micaceous kimberlites are characterized by higher concentrations of Nb, Ta, Zr, Hf, Sc, P, Sr, Th, U and rare earth elements (REE).

Although no kimberlite samples from the Wyoming pipes in the State-Line district have been analyzed, two whole rock analyses of samples from the Sloan 1 pipe in Colorado show low SiO_2, Al_2O_3 and K_2O and high MgO and H_2O (Table 1) indicating a "basaltic" kimberlite affinity.[56]

DEEP-SEATED NODULES IN KIMBERLITE

Kimberlite throughout the world is noted for its content of ultramafic and basic rock xenoliths derived from the mantle and lower crust. These xenoliths give researchers many of the samples that are available to evaluate the petrologic nature of mantle and lower crust in continental plates.

Deep-seated nodules are very abundant in kimberlite from several of the State-Line district diatremes. Mantle derived garnet and spinel lherzolite, garnet clinopyroxenite and websterite, spinel websterite, harzburgite, dunite, carbonatite (sövite), eclogite and discrete mineral nodules (Table 2, Figs. 9

Table 1. Chemical compositions of kimberlites (weight percent).

	Breccia Sloan 1 pipe Colo.-a	Massive Sloan 1 pipe Colo.-a	Average basaltic kimberlite-b	Average basaltic kimberlite-c	Average micaceous kimberlite-b	Average micaceous kimberlite-c	Average Lesotho kimberlite-d	Average Yakutian kimberlite-e	Average S. African kimberlite-f
SiO_2	31.42	32.24	35.02	35.20	36.33	31.10	33.21	27.64	36.36
TiO_2	0.85	1.08	1.22	2.32	1.89	2.03	1.97	1.65	0.98
Al_2O_3	2.20	3.05	3.90	4.40	5.09	4.90	4.45	3.17	5.13
Cr_2O_3	0.15	0.16	-----	-----	-----	-----	0.17	0.14	0.22
Fe_2O_3	5.58	7.41	5.15	9.80*	7.43	10.50*	6.78	5.40	7.71*
FeO	1.58	1.09	4.14		3.40		3.43	2.75	
MnO	0.13	0.15	0.06	0.11	0.10	0.10	0.17	0.13	0.16
MgO	27.94	27.13	31.29	27.90	26.63	23.90	22.78	24.31	17.43
CaO	9.92	8.63	6.80	7.60	6.78	10.60	9.36	14.13	11.16
Na_2O	0.10	0.06	0.34	0.32	0.37	0.31	0.19	0.23	0.42
K_2O	1.27	0.84	1.05	0.98	2.43	2.10	0.79	0.79	1.52
H_2O^+	10.42	9.74	7.43	7.40	7.25	5.90	8.04	7.89	-----
H_2O^-	2.23	2.65	-----	-----	-----	-----	2.66	-----	-----
P_2O_5	0.42	0.54	0.87	0.72	0.66	0.66	0.65	0.55	0.55
CO_2	5.84	5.20	2.73	3.30	1.64	7.10	4.58	10.84	-----

a) Kimberlite breccia (sample 3-23b) and massive porphyritic kimberlite (sample 3-500), Sloan 1 pipe, Colorado, State-Line diatreme district. McCallum and Eggler, 1971.
b) Average basaltic kimberlite (ten analyses) and average micaceous kimberlite (four analyses). Nockolds, 1954.
c) Average basaltic and micaceous kimberlite. Dawson, 1967.
d) Average Lesotho kimberlite (25 analyses). Gurney and Ebrahim, 1973.
e) Average Yakutian kimberlite (623 analyses). Ilupin and Lutz, 1971.
f) Average South African kimberlite (80 analyses). Gurney and Ebrahim, 1973.
*) Total Fe as FeO

and 10) are included in the nodule assemblages. Compositional ranges of members of the peridotite nodule assemblage are shown in Figure 11. Lower crustal nodules (Table 2) include hypersthene granulite, charnockitic granulite, augite granulite, garnet kyanite granulite (Fig. 9E), pyroxenite, altered basalt (?) and numerous intensely carbonated and fenitized rocks of unknown original composition. The nodules are generally well rounded and are commonly rimmed by thin rinds of finely-crystalline serpentine-carbonate mixtures. Most of the xenoliths show varying degrees of alteration (usually intense), ranging from the pervasive serpentinization of peridotites to carbonation, silicification, fenitization and combinations thereof.

For more comprehensive discussions of the nodular assemblages the reader is referred to recent papers by Eggler and McCallum (1973, 1974a), McCallum, *et al.* (1975) and McCallum and Eggler (1976).

UPPER MANTLE-CRUSTAL MODEL FOR STATE-LINE AREA

At a number of classic kimberlite sites in other parts of the world, the compositions of the nodules of deep-seated origin have been used to construct models of the crust and upper mantle.[57] By comparing mineral phase chemistry in the nodules with equilibration data established from synthetic (laboratory) systems, estimates of the temperature and pressure of their crystallization can be made.

Estimates of temperature and pressure of formation can be used to calculate the depth at which the mineral suites crystallized. Equilibration data calculated from State-Line nodules have been compared with those from the construction of models elsewhere, and preliminary upper mantle-crustal models for northern Colorado and southern Wyoming at the time of diatreme emplacement have been developed.[58]

The crustal thickness shown in the model (Figure 12) is based upon the 50 km present thickness beneath the Front Range estimated by Pakiser and Zeitz (1965) from seismic evidence.

The precise amount of erosion since kimberlite emplacement in Devonian (?) time is highly uncertain but the removal of 1-2 km of material (including all of the Lower Paleozoic sedimentary sequence) is suggested.

Upper crustal rocks presently cropping out at the surface are Precambrian granites and gneisses and these units are found as inclusions in the kimberlite; the lower crust apparently consists of granulites, pyroxenites and basaltic units as these rock types are also present in relative abundance as inclusions (Table 2). At the time of kimberlite eruption, the upper mantle consisted of spinel and garnet peridotite which, through episodes of partial melting, had been

Table 2: Composition and Abundance of Nodules in State-Line Kimberlite Diatremes

	Nodule Type	Mineral Composition	Alteration and Abundance
Peridotite Group	Spinel lherzolite (residual)*	Olivine (Fo_{89-93}), enstatite (En_{91-93}), Cr-rich diopside (ave. 0.8% Cr_2O_3), and low Cr-high alumina and high Cr-low alumina spinels (12% Cr_2O_3: 54% Al_2O_3 and 28% Cr_2O_3: 41% Al_2O_3).	Olivines and enstatites generally serpentinized. Relatively abundant; fresh nodules very abundant at two pipes in Colorado
	Garnet lherzolite (residual)*	Olivine (Fo_{89-93}), enstatite (En_{91-93}), Cr-rich diopside (1.0-2.2% Cr_2O_3), Cr-rich pyrope garnet (4-11% Cr_2O_3), Cr-rich alumina-poor spinel (50-60% Cr_2O_3: 7-12% Al_2O_3) and native metal (CuNi and Zn--McCallum and Eggler, 1976.	Generally intensely altered to serpentine, hematite, carbonates and locally quartz and talc. Garnet diopside and spinel commonly less altered to unaltered. Altered nodules rare (common in only one pipe in Colorado--Sloan 2 pipe)
	Garnet websterite group (includes garnet websterite and clinopyroxenite and chemically related garnet lherzolite)	Olivine (Fo_{92-94}) (generally minor), enstatite (En_{93-94}), diopside (higher Ca and Na_2O and lower Cr_2O_3 content than in residual lherzolite), garnet (lower Cr_2O_3 and TiO_2 content than in residual lherzolite).	Moderately to very fresh where recognized. Abundant at only one pipe in Colorado--Sloan 2 pipe
	Dunite	Olivine--bimodal distribution; either Fo_{88-89} or Fo_{91-92}, minor spinel	Commonly serpentinized. Present at several pipes but abundant at only one pipe in Colorado--Sloan 2 pipe
Misc. Upper Mantle Group	Eclogite	Garnet (40-62 mole % pyrope), omphacitic clinopyroxene (10-50 mole % jadeite), kyanite and rutile (common), corundum, orthoclase, quartz and Mg-ilmenite (rare).	Slightly to intensely altered to amphibole, mica, chlorite and finely crystalline aggregates of unidentified material. Minor grain boundary alteration most common. Moderately abundant in several pipes.
	Carbonatite (sövite)	Carbonates (calcite, dolomite and magnesite?), biotite, phlogopite (?), barite and minor fine grained accessories (e.g. apatite, monazite and zircon).	Generally unaltered. Present in several pipes but abundant in two of the Colorado pipes (Sloan 1&2).
	Monomineralic nodules (megacrysts--generally 1 cm)	Mg-ilmenite (range from 25-50 mole % $MgTiO_3$, more Mg-rich also enriched in Cr_2O_3-up to 3.0%) Cr-rich assemblage: Cr-rich pyrope garnet (6.5-11.5% Cr_2O_3, moderate Ca, low Fe and TiO_2 content), Cr-rich diopside (1.0-1.6% Cr_2O_3, moderate Ca, low Fe and TiO_2 content), chromium enstatite (0.25-0.50 Cr_2O_3 and moderate Ca content, En_{91-93}), olivine (Fo_{92}). Cr-poor assemblage: Cr-poor pyrope garnet (0.6-1.6% Cr_2O_3, lower Ca, higher Fe and TiO_2 than Cr-rich pyrope) and Cr-poor diopside (0.2-0.5% Cr_2O_3, lower Ca and higher Fe and TiO_2 content than Cr-rich diopside).	Generally unaltered to only slightly altered. Mg-ilmenite and garnet are very abundant in most pipes, Cr-rich diopside is abundant. Cr-poor diopside and enstatite are moderately abundant in some pipes.
Lower Crustal Group	Hypersthene granulite	Hypersthene, plagioclase (An_{34-37}), microcline, magnetite and apatite; or hypersthene, plagioclase (An_{54}) and magnetite.	Commonly intensely carbonated and/or fenitized. Original material replaced by carbonate (calcite), biotite, muscovite, apatite, serpentine, amorphous silica and fine-grained aggregates and films of sphene-leucoxene-calcite. Altered lower crustal nodules abundant in many pipes, fresh nodules relatively rare except for one Colorado pipe--Sloan 2.
	Charnockitic granulite	Microcline, hypersthene, plagioclase (An_{36-40}), and magnetite	
	Augite-granulite	Augite ($Co_{45}Mg_{35}Fe_{20}$), plagioclase (An_{41}), microcline and magnetite	
	Garnet kyanite granulite	Garnet, kyanite, augite plagioclase (An_{55}), rutile.	
	Pyroxenite	Augite, hypersthene, phlogopite and magnetite	
	Basalt (?)	No primary minerals preserved but relict texture suggests a basaltic material	

*Referred to as residual lherzolite because they are considered to represent primitive mantle that was depleted by previous partial fusion (Eggler and McCallum, 1974a, p. 298). Evidence for depletion is low to negligible clinopyroxene content, high Cr_2O_3 content of spinel and garnet and Fo_{90-93} olivine.

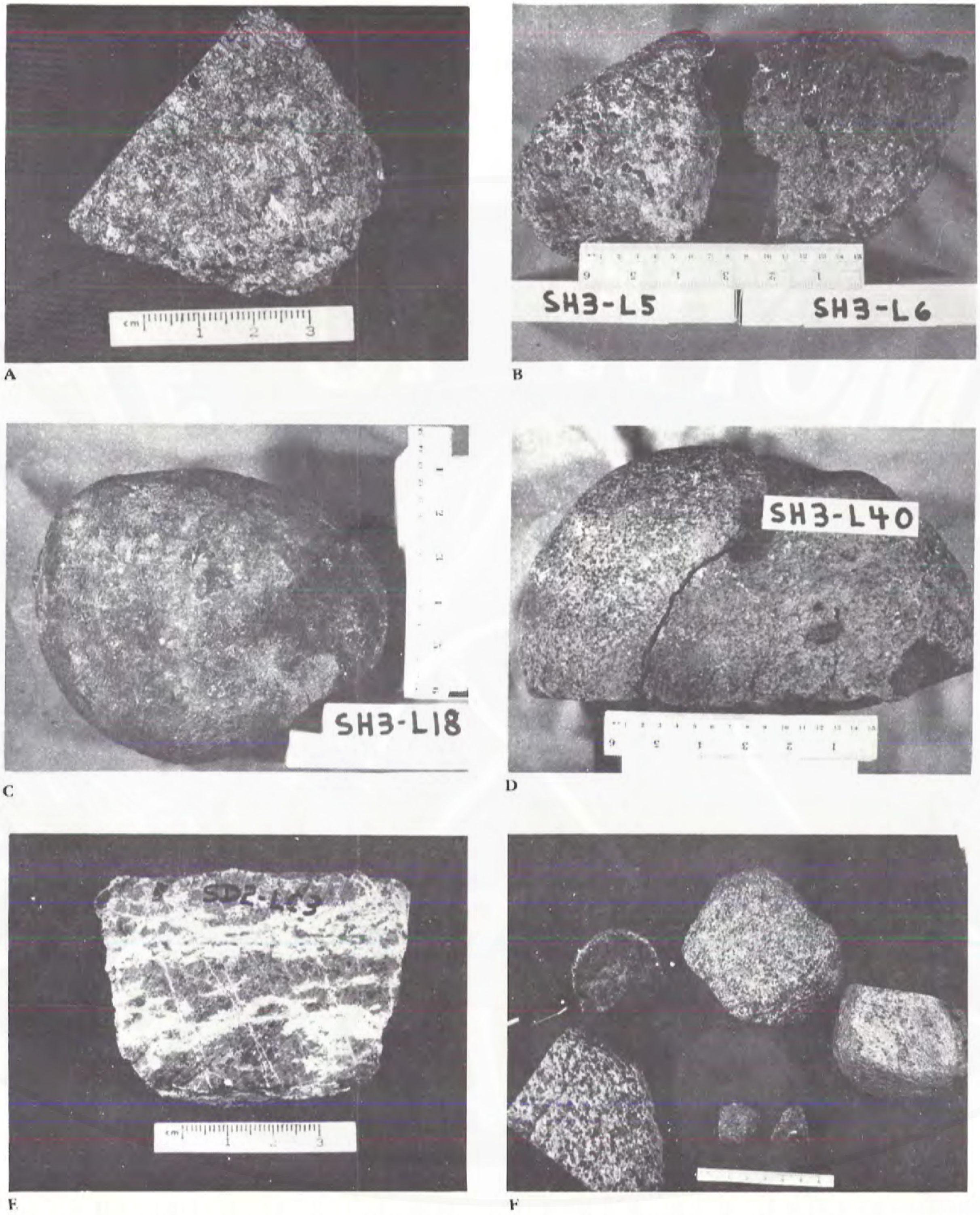
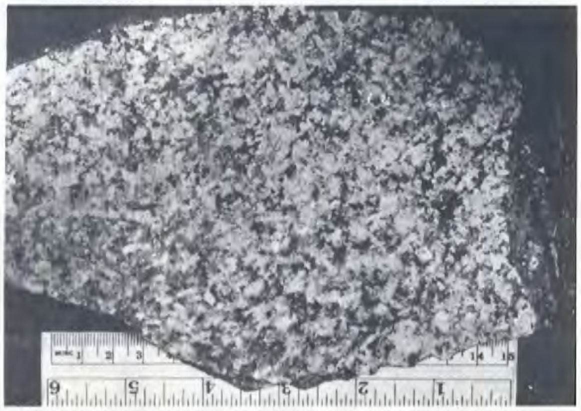


Figure 9 – Deep-seated nodules from State-Line kimberlite: spinel and garnet lherzolite, granulite, eclogite and carbonatite (sövite). A) Spinel lherzolite nodule. B) Garnet lherzolite nodules (dark rounded grains are garnets: six inch-15 cm scale). C) Serpentinized and silicified garnet lherzolite nodule (six inch-15 cm scale). D) Completely serpentinized and silicified lherzolite nodule (six inch-15 cm scale). E) Garnet-kyanite-augite granulite nodule showing well-developed layering. F) Assorted eclogite nodules. See next page – G) Eclogite nodule. H) Slabbed phlogopite (?)-barite carbonatite (sövite) nodule (six inch-15 cm scale).

G



H

depleted of less refractory elements and enriched in more refractory elements such as Mg and Cr.[59] Spinel peridotite apparently is restricted to the uppermost mantle zone of 50 to 65 km, whereas the Mg- and Cr-enriched garnet peridotite extends from a depth of 65 km to at least 180 km. Rocks of the garnet websterite group (garnet clinopyroxenites, garnet websterites, garnet olivine websterite and chemically related garnet lherzolite) occur as lenses or pockets in the peridotite at depths of 50-75 km. This mode of occurrence is suggested by the presence in a few peridotite nodules of small lenses (up to one centimeter thick) of garnet-pyroxene aggregates with chemical composition similar to that of websterite.

Eclogite nodules show a wide range of accessory minerals, chemical compositions and equilibration temperatures. They are believed to have been derived from pockets within the peridotite mantle at depths of approximately 75-130 km. The megacryst assemblages (Cr-rich and Cr-poor orthopyroxene, clinopyroxene, garnet and associated ilmenite) indicate depth ranges of approximately 165 to 200 km, the Cr-deficient crystals coming from greatest depths. The megacrysts of the State-Line kimberlites are very similar to those from the Lesotho pipes. For the latter occurrences, Boyd and Nixon (1973) suggest that the Cr-poor varieties originate in relatively undepleted, deeper mantle peridotite. These megacryst nodules of deeper origins exhibit sheared textures. In the State-Line district, only depleted peridotite nodules originating from probable depths of less than 180 km have been recognized. Many nodules from the district exhibit pervasively sheared textures somewhat similar to those described by Boyd and Nixon (1973) as characteristic of deep, undepleted peridotite; unfortunately, these are all intensely altered with the original minerals completely converted to serpentine, hematite, calcite and quartz.

The petrogenic model presented in Figure 12 should be considered as a "working model" or "reasonable approximation" in light of current knowledge. It is emphasized that construction of such models must rely heavily upon a myriad of assumptions (and conflicting opinions) regarding the experimental systems which provide the basis for all P-T equilibration estimates. Limitations on model construction are also imposed by the fragmentary and incomplete nature of samples brought to the surface in the diatremes and by geologic processes that may have changed the mantle since the time of kimberlite emplacement.[60]

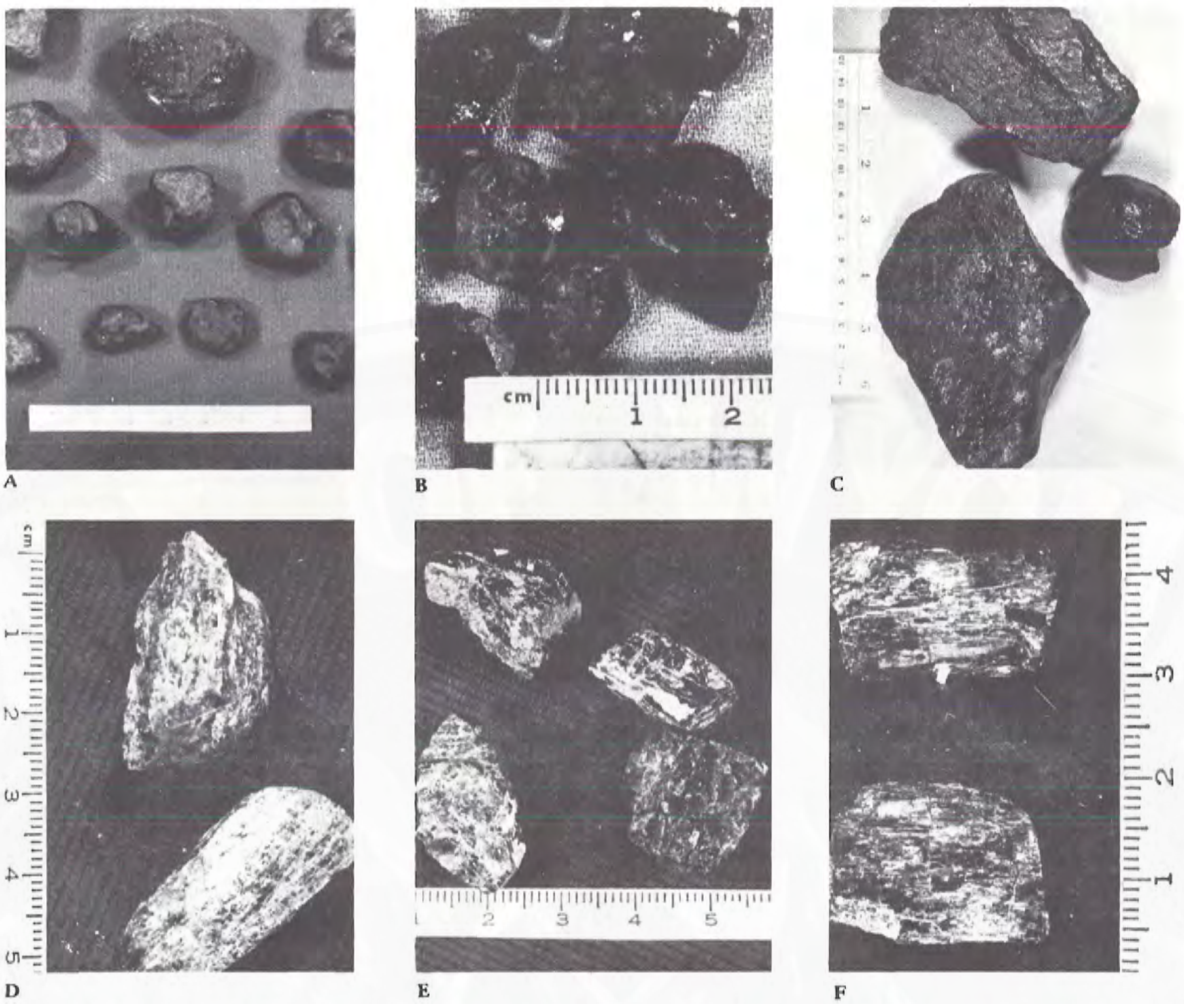


Figure 10 — Deep-seated discrete mineral nodules (megacrysts) from State-Line kimberlite. A) Mg-ilmenite nodules (six cm scale). B) Cr-poor pyrope garnet nodules. C) Cr-rich pyrope garnet (upper center, rounded specimen) and Cr-poor pyrope garnet nodules (other two specimens) (six inch-15 cm scale). D) Enstatite megacrysts. E) Cr-rich diopside megacrysts. F) Cr-poor diopside megacrysts.

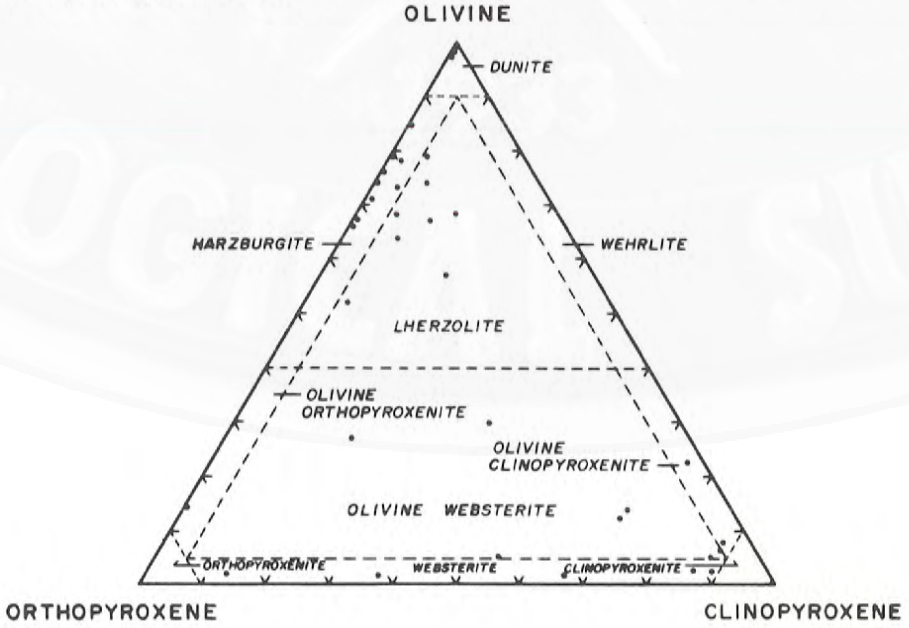


Figure 11 — Triangular diagram of compositions of some peridotite nodules from State-Line diatremes.

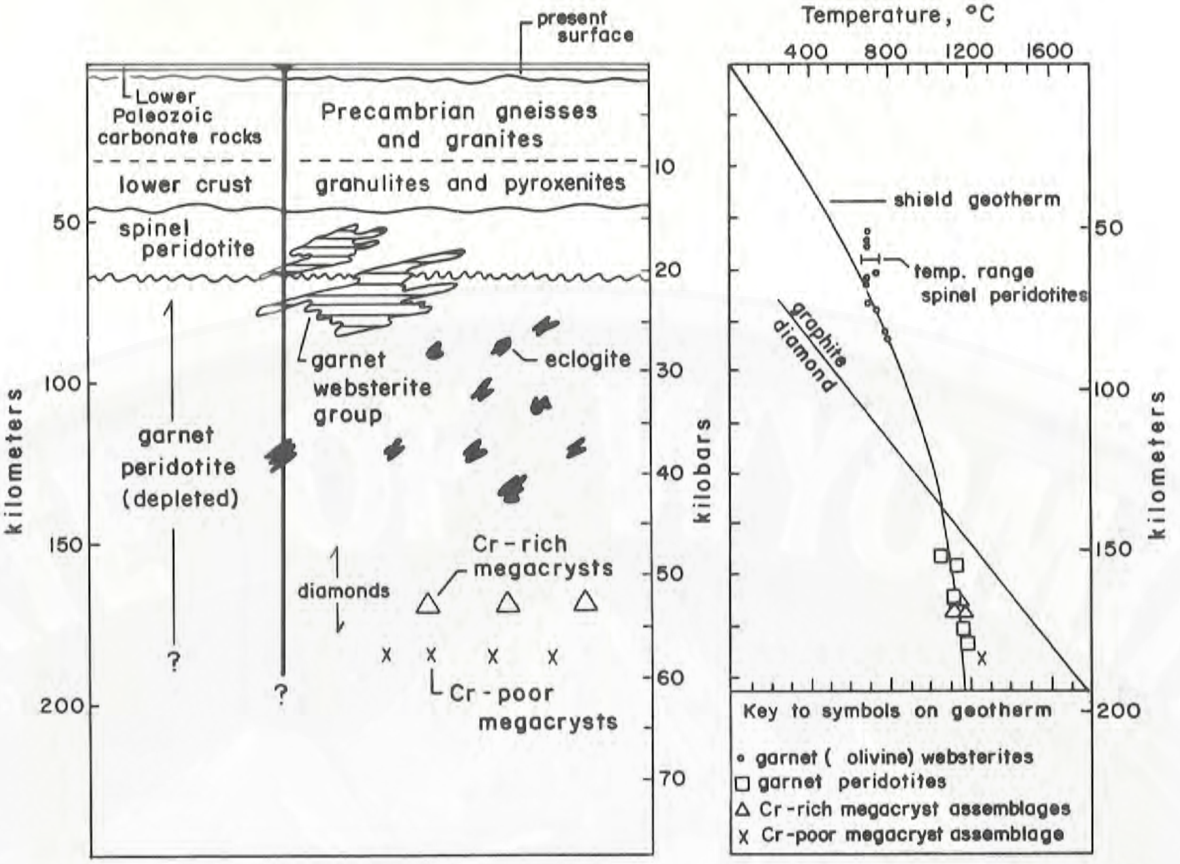


Figure 12 – Diagrammatic model of the upper mantle and crust beneath the Front Range of Colorado and Wyoming at the time of kimberlite emplacement (Devonian?). It was constructed from equilibration data established from nodules in State-Line kimberlite pipes. The shield geotherm is based on that computed by Clark and Ringwood (1964). (Model from McCallum and Eggler, 1976).

DIAMOND OCCURRENCES IN NORTH AMERICA

Although there is no current production of natural diamond in North America, diamonds have been reported from many locations. Most of the diamonds were found while panning or sluicing stream gravels for gold; a number of stones have been recovered from stream sands along the eastern slope of the Appalachian Mountains, from Virginia to Georgia, and from gold sands of northern California, southern Oregon, western Idaho and western Montana.[61]

More important discoveries have been made from glacial drift, principally in the Great Lakes area. The diamonds were apparently derived from pipes in the Canadian Shield to the north and northeast. Gunn (1967) reported that 82 diamonds had been recovered since 1863 from drift in the area, and listed the discoveries as follows: 34 in Indiana, 16 in Wisconsin, 25 in Illinois, two in Michigan, two in Ohio, two in New York and one in Ontario. Of 48 documented stones, most weigh from less than a carat to five carats. Two from Wisconsin and one from Michigan weigh 21.25, 15.37 and 10.8 carats, respectively.[62]

The only commercial natural diamond production in North America came from the Murfreesboro kimberlite pipe in Pike County, Arkansas. It is the first authenticated occurrence of *in situ* diamonds on this continent. Following the initial discovery in 1906, diamonds were mined from the site until 1919.[63] Over 40,000 stones were recovered; the largest weighed 40.23 carats.[64] The property is now a tourist attraction where people are allowed to work the weathered kimberlite and alluvium on a daily basis.

The recent discovery of diamonds in a serpentinized garnet peridotite nodule from a Wyoming kimberlite pipe in the State-Line district represents the second authenticated occurrence of *in situ* diamonds.[65] Subsequent evaluation of weathered kimberlite from several pipes in the district has led to the recovery of a number of small diamonds from sites in both Wyoming and Colorado.[66] A fairly intensive evaluation of the entire area is currently underway.

Table 3. North American Kimberlites and Principle References

Locality	References
APPALACHIAN PROVINCE	
Central New York (Ithaca)	Martens, 1924; Watson, 1967a; Foster and Reitan, 1972
Southwestern Pennsylvania (Masontown)	Kemp, 1907; Kemp and Ross, 1907; Honess and Graber, 1924, 1926
Northern Virginia (Mt. Horeb)	Young and Bailey, 1955; Johnson and Milton, 1955; Sears and Gilbert, 1973
Eastern Kentucky (Elliot Co.)	Diller, 1885, 1887, 1889; Crandall, 1887; Koenig, 1956; Hunt, et al., 1971; Bolivar, 1972
Eastern Tennessee (Norris Lake)	Gordon, 1927; Hall and Amick, 1944; Meyer, 1975
CENTRAL PROVINCE	
Western Kentucky and Southern Illinois	Diller, 1892; English and Grogan, 1948; Koenig, 1956
Southeastern Missouri (Avon)	Spurr, 1926; Weller and St. Clair, 1928; Tarr and Keller, 1933; Rust, 1937; Kidwell, 1947; Mansker, 1973
Southern Arkansas (Murfreesboro)	Miser and Ross, 1922a, 1922b; Miser and Purdue, 1929; Ross, et al., 1929; Moody, 1949
Eastern Kansas (Riley Co.)	Ross and Brookins, 1966; Brookins, 1970a, 1970b; Brookins and Naeser, 1971; Meyer and Brookins, 1971a, 1971b
ROCKY MOUNTAIN-COLORADO PLATEAU PROVINCE	
Colorado-Wyoming Front Range	McCallum and Eggler, 1968, 1971, 1976; Chronic, et al., 1969; Kridelbaugh, et al., 1972; Kridelbaugh and Meyer, 1973; McCallum, et al., 1973, 1974, 1975; McCallum, Smith, et al., 1975; Eggler and McCallum, 1973, 1974a, 1974b, 1975
North-central Montana	Hearn, 1968; Hearn and Boyd, 1975
Colorado Plateau (NE Ariz., NW New Mex., SE Utah)	Balk, 1954; Balk and Sun, 1954; Malde, 1954; Malde and Thaden, 1963; O'Sullivan, 1964; Watson, 1967b; McGetchin, 1968, 1969; McGetchin and Silver, 1970; McGetchin, et al., 1973; Stuart-Alexander, et al., 1972; Smith, 1974
CANADIAN PROVINCE	
Quebec (Lesueur Township)	Watson, 1955; 1967a, 1973; Gittins, et al., 1975
Ontario (Gauthier, Keith and Michaud Townships	Satterly, 1948, 1971; Brown, et al., 1967; Lee, 1965; Lee and Laurence, 1968; Watson, 1973
Northwest Territory (Somerset Island)	Mitchell and Fritz, 1973; Clark and Mitchell, 1975

WYOMING-COLORADO DIAMONDS

Diamond in Peridotite

The diamond-bearing peridotite nodule that led to active evaluation of kimberlite pipes in the State-Line area was collected in December, 1974, from one of the diatremes in Wyoming School Section 16 near the Colorado border (cover photo and Fig. 2). As previously mentioned, the presence of diamond in the nodule was recognized during preparation of a thin section in June, 1975. The original diamond of the discovery is approximately one millimeter in diameter. It is embedded in a slabbed portion of the nodule in Figure 13. The largest crystal observed in the nodule is approximately 1.0 x 1.5 mm and is cleaved along a (111) plane. Two other diamonds embedded in the nodule and the several crystals that were isolated from peridotite matrix by hydrofluoric acid digestion range from 0.1 to 1.0 mm.

Most of the diamonds show at least some well developed octahedral faces and growth forms range from simple (cover photo and Figs. 14A and B) to complex (Figs. 13 and 15)[67]. The crystals are described according to the morphological classification of Whitelock (1973) and include aggregates (multiple crystals and interpenetrant twins), a regular octahedron and a flattened octahedron. Some of the crystals have rounded and pitted surfaces (*e.g.* Fig. 13). Octahedral faces are commonly composed of superimposed lamellae of progressively smaller size producing a stepped or terraced appearance. Small, triangular shaped growth platelets may be present (Fig. 16). The lamellar buildup of platelets of progressively decreasing size on octahedral faces of the small (0.2 mm), nearly perfect, regular planar octahedron shown embedded in serpentinized garnet peridotite in Figure 14A and B has caused the formation of incipient striated dodecahedral faces[68].

Aggregate crystals are characterized by re-entrant angles marking contact where smaller crystals have grown together (Fig. 15) or composition surfaces of interpenetrant twins (Fig. 13). Octahedral forms dominate in the multiple crystal aggregates and interpenetrant twins appear to be controlled by several twin laws; (111) twins are present in at least one crystal.

The diamonds are predominantly colorless to white, although the small regular octahedron (Fig. 14) is grayish black. The dark color in the octahedral crystal is caused, in large part, by the presence of small graphite (?) platelets and grains within the crystal that probably reflect alteration along cleavage planes. Several ridges of graphite (?) are also present along the stepped surfaces of the dodecahedral faces. Small inclusions of unknown minerals are present in several of the diamonds (*e.g.* Fig. 15).

The peridotite nodule containing the diamonds is rounded and oblate with dimensions of 9 x 11.5 x 12.5 cm (cover photo). Although the nodule has been intensely serpentinized and silicified, the original dominantly tabular texture (terminology after Boullier and Nicolas, 1975), is readily recognizable (Fig. 17). Narrow zones with porphyroclastic to mosaic texture, apparently formed by shearing, parallel the long dimensions of the nodule.

The olivines, orthopyroxenes and clinopyroxenes which originally comprised most of the nodule are completely converted to serpentine and locally replaced by carbonate, quartz and/or talc. However, the mineral's pseudomorphs display characteristics reflecting their parentage. Serpentine (antigorite) after olivine shows an irregular grain pattern that reflects the irregular fracture pattern typical of olivine; bastite after orthopyroxene reflects the

Figure 13 — Original diamond discovered during thin section preparation. It is embedded in a serpentinized garnet peridotite; note rounding of edges and interpenetrant twinning.

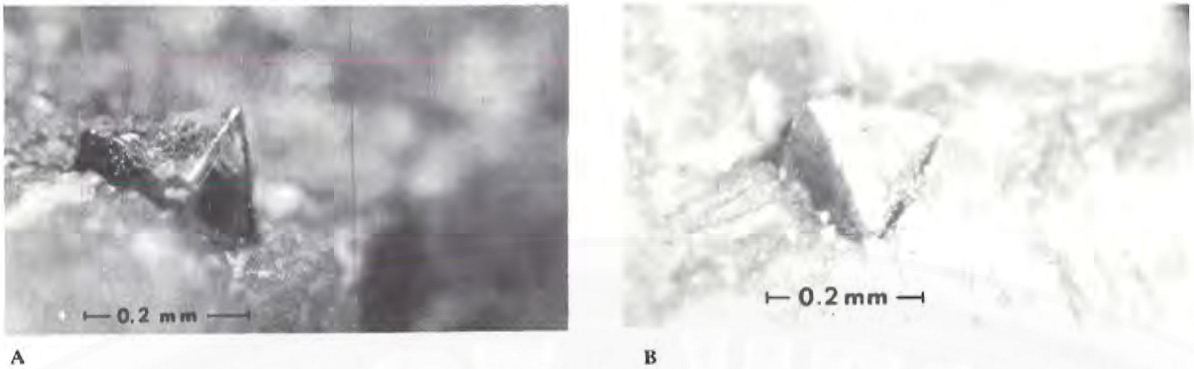


Figure 14 – Simple planar octahedral diamond crystal embedded in peridotite. It shows weak development of narrow dodecahedral faces by incipient lamellar growth on(111)faces. A) Tetrad view. B) Diad view.

primary pyroxene cleavage; the serpentine-talc-quartz aggregate pseudomorphs after clinopyroxene retain the characteristic green color of the parent chrome diopside as opposed to the yellow-brown and pale brown of the olivine and orthopyroxene pseudomorphs[69]. Pseudomorphs after olivine and orthopyroxene range up to 0.5 cm long and are generally equant. Pseudomorphs after clinopyroxene (which comprised less than ten percent of the nodule) occur chiefly as stringers and porphyroclastic aggregates. They are predominantly confined to zones of shear. The only unaltered primary minerals present are garnet and spinel (chromite) (Fig. 15). Garnet occurs as rounded grains up to three millimeters in diameter; spinel grains are generally highly irregular in shape and occupy interstitial sites. Numerous small, irregular grains (up to one millimeter) of copper-zinc alloy and nickel metal are also present[70].

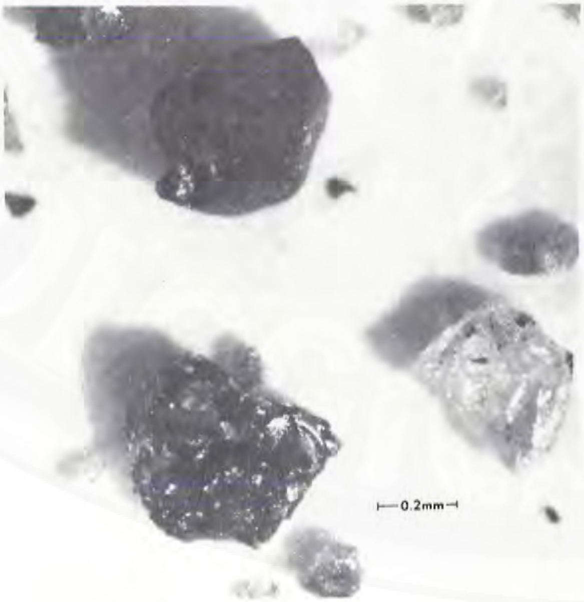


Figure 15 – Diamond (right), pyrope garnet (lower left) and spinel (upper left) isolated from peridotite matrix by hydrofluoric acid digestion. The diamond shows aggregate development of octahedral forms and contains abundant tiny inclusions of dark colored minerals.

Figure 16 – SEM micropraph of flattened octahedral crystal isolated from peridotite nodule showing lamellar buildup and development of triangular shaped growth platelets on octahedral faces.

Despite the degree of most mineral phases' alteration in the nodule, there is little doubt that the nodule was originally a depleted garnet lherzolite[71], based on the petrographic evidence and electron microprobe analyses of garnet and spinel (Sample 1117, Table 4). Garnet composition falls within the ranges established for garnet lherzolites from pipes in the area[72]. Although intense alteration of the pyroxene phases precludes calculation of equilibration conditions for the diamond-bearing nodule, other peridotite nodules from the same pipe contain similar Cr-rich garnet but also have unaltered clinopyroxene. For this unaltered clinopyroxene, a temperature of formation of 1050°-1150°C has been established, corresponding to a depth of 130-180 km, and pres-

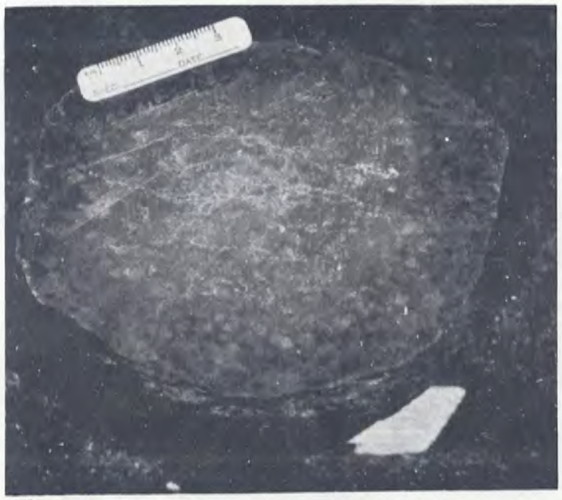


Figure 17 – Slabbed surface of serpentinized diamond-bearing garnet peridotite nodule showing dominantly tabular texture with narrow zones of porphyroclastic to mosaic texture. A) Entire nodule. B) Enlarged portion of surface.

Table 4. Electron microprobe chemical analyses* of mineral assemblages of selected nodules from State-Line kimberlites.

Sample	Spinel lherzolite (NX2-2)				Garnet lherzolite (S2-L102)+					Serpentinized garnet lherzolite (1040)+	
Mineral	Olivine	Opx	Cpx	Spinel	Olivine	Opx	Cpx	Garnet	Spinel	Cpx	Garnet
SiO_2	41.1	56.7	53.2	0.11	41.0	57.4	54.7	41.5	0.14	55.3	41.2
TiO_2	---	---	0.07	0.01	---	0.04	0.07	0.16	0.8	0.26	0.6
Al_2O_3	---	2.6	4.3	48.4	0.02	0.7	1.9	19.5	11.8	2.0	17.4
Cr_2O_3	---	0.24	0.88	16.3	---	0.3	2.0	5.1	55.3	2.3	7.4
Fe_2O_3	---	---	---	---	---	---	---	---	3.1	---	---
FeO**	9.3	6.4	1.98	13.6	8.1	4.8	2.3	7.2	14.6	2.6	6.5
MnO	0.14	0.16	0.10	0.16	0.12	0.13	0.12	0.36	0.31	0.11	0.38
MgO	50.7	35.3	16.6	19.0	50.7	35.8	17.3	20.7	12.6	18.0	20.6
NiO	0.4	0.05	0.06	0.3	0.35	0.06	0.05	---	---	0.01	---
CaO	0.02	0.23	21.9	---	0.04	0.53	19.7	5.2	---	18.1	5.7
Na_2O	---	0.02	1.18	---	---	0.07	1.7	0.05	---	1.73	0.05
K_2O	---	---	---	---	---	---	---	---	---	0.01	---
Totals	101.66	101.70	100.27	97.88	100.33	99.83	99.84	100.77	98.65	100.42	99.83

Sample	Serpentinized diamond-bearing lherzolite (1117)+		Garnet websterite (SD2-L45)			Garnet clinopyroxenite (SD2-L29)		Kyanite eclogite (SD2-E3)		
Mineral	Garnet	Spinel	Garnet	Opx	Cpx	Garnet	Cpx	Garnet	Cpx	Kyanite
SiO_2	40.8	0.32	42.5	58.3	54.0	43.2	55.6	40.5	55.3	37.9
TiO_2	0.09	0.3	0.14	0.07	0.4	0.18	0.29	0.10	0.29	0.04
Al_2O_3	14.3	7.5	23.1	0.88	3.33	23.57	3.43	22.2	12.0	61.0
Cr_2O_3	12.3	61.1	0.82	0.12	0.56	0.30	0.26	0.05	0.05	0.06
Fe_2O_3	---	3.7	---	---	---	---	---	---	---	---
FeO**	6.0	11.3	7.79	4.39	1.96	10.27	2.74	15.3	2.64	0.37
MnO	0.38	0.27	0.36	0.08	0.06	0.43	0.06	0.38	0.03	---
MgO	21.4	14.2	21.3	37.0	15.84	20.63	16.3	9.03	9.58	0.03
NiO	---	0.07	---	0.05	0.07	---	0.05	---	0.01	0.01
CaO	4.7	0.01	4.64	0.2	21.33	3.89	20.0	13.5	15.7	---
Na_2O	0.03	0.04	0.05	0.03	1.92	0.07	2.41	0.01	5.05	0.02
K_2O	---	---	---	---	---	---	---	---	---	---
Totals	100.00	98.81	100.70	101.12	99.47	102.54	101.14	101.07	100.65	99.43

*All analyses done by D.H. Eggler at the Carnegie Institution of Washington using methods described by Finger and Hadidiacos (1971).

**Total Fe as FeO unless otherwise indicated.

+Analyses from McCallum and Eggler, 1976.

sures of approximately 40-55 kbar (Fig. 12).[73] Equilibration calculations based on analyses of completely unaltered lherzolite nodules containing garnet and spinel, chemically similar to those from the diamond-bearing nodule, yield pressure-temperature values that fall within the same range as given above. By analogy, it is suggested that the diamond bearing nodule may have equilibrated within the range of 1050°-1150°C and 40-55 kbar which corresponds to a 130-180 km depth (Fig. 12).[74]

Diamonds in Weathered Kimberlite

Several hundred pounds of deeply weathered kimberlite have been collected from diatremes in both Wyoming and Colorado and processed for diamonds. Initially, approximately 50 pounds of material was taken from each pipe to be tested and, to date, additional samples have been collected and processed only from those pipes that showed maximum promise (*e.g.* Sloan 1 and 2 pipes in Colorado and one of the School Section 16 pipes in Wyoming). The weathered kimberlite samples, along with variable amounts of weathered host granitic material, were sieved through 3.3 mm and 1.5 mm screens. The 1.5-3.3 mm and less than 1.5 mm splits were run separately through a sluice to concentrate the heavy mineral fraction. Material larger than 3.3 mm was examined visually, but no diamonds were recovered. In earlier work on material from the Sloan pipes in Colorado, only material of less than 1.5 mm size was sluiced; all larger material was examined by rapid scan under a binocular microscope, without success.[75]

The sluice used for the separation of heavy minerals is six feet long and contains riffles spaced one inch apart. Slope angle of the sluice and water flow rate were adjusted to obtain maximum concentration of minerals with specific gravity greater than 3.0. More effective concentration was facilitated by gently shaking the sluice. For each 50 pounds of sample processed, approximately seven pounds of material was recovered. The percentage of minerals with specific gravity of greater than 3.0 remaining after sluicing was not determined, but an estimate of more than 50 percent is reasonable. Splits of the sluice concentrates were dried and placed in 52 percent hyrdofluoric acid for periods of two to four weeks. The acid was changed approximately every four to five days. After four weeks of treatment, most of the heavy silicates were digested and only about one percent of the original sample volume remained. The residual, acid-insoluble fraction was run through a Franz magnetic separator using a side slope setting of 20 degrees, a front slope setting of 23 degrees and an amperage setting of one. This effectively removed most of the more paramagnetic minerals and reduced substantially the amount of final concentrate. Utilizing both regular binocular and polarizing microscopes, the remaining heavy mineral material was examined and all suspected diamonds were checked for hardness and refractive index. A few of the first recovered diamond crystals were subjected to x-ray diffraction analysis[76] and many were examined morphologically under the scanning electron microscope. Other minerals in the residual concentrates were identified by optical and x-ray techniques. Zircon is most abundant and occurs in euhedral to well rounded crystals, some of which fluoresce in ultraviolet light. They range in color from clear to yellow-brown. The zircons almost certainly are of varied origins; many came from the kimberlite, but others came from the Precambrian, crystalline, host rocks. Angular to rounded fragments of purple, lavender and orange pyrope are second in abundance, even though most of the grains were destroyed in the digestion process. Grains of spinel (chromian?), rutile, barite, pyrite and minor native metals are usually also present in variable percentages.

Figure 18 – Distorted octahedral diamond from the Sloan 2 kimberlite pipe. It is the largest diamond recovered to date from the State-Line district.

Table 5. Descriptions of selected diamonds recovered from weathered kimberlite from the State-Line District

Pipe	Sample Number	Type	Size in mm	Weight in mg	Color	Fluorescence	Comments
St. Sec. 5	AD1-X1	Aggregate	0.3x0.6x0.9	<0.5	Clear-glassy to white	-----	Multiple octahedron and interpenetrant twins
St. Sec. 16	SH10-X1	Macle	0.55x1.1x1.25	1.95	Grayish white	-----	Growth lamellae prominent, abundant inclusions
St. Sec. 15	SH15-X1	Flat	0.125x0.3x0.3	<0.5	Clear to glassy	-----	Octahedral faces, trigons
St. Sec. 16	SH16-X1	Aggregate	0.2x0.3x0.5	<0.5	Gray-white	-----	Flattened
St. Sec. 16	SH16-X2	Irregular	0.2x0.25x0.3	<0.5	Clear-glassy	-----	Rounded surface, conchoidal fracture, abundant inclusions
St. Sec. 19	SH19-X1	Irregular	0.2x0.25x0.4	<0.5	Glassy to white	-----	Curved fragment, possibly from rounded octahedron
Sloan 1	SD1-X1	Aggregate	0.9x1.85*	3.0	Clear-glassy	Yellow	High brilliance, abundant inclusions
Sloan 1	SD1-X2	Irregular	1.2x1.6*	3.3	Clear-glassy locally pale brown	Yellow	Abundant growth pits
Sloan 1	SD1-X3	Dodecahedron	1.2x1.2*	2.3	Clear-glassy	Blue-white	Evolved from octahedron, poorly developed tetrakis hexahedron
Sloan 1	SD1-X4	Flat	0.65x0.8x1.3	1.5	Clear-glassy	Very weak pale orange	Octahedral faces, abundant trigons
Sloan 1	SD1-X5	Aggregate	0.9x1.2*	1.9	Clear to gray	Pale orange	Interpenetrant twins, octahedra, abundant inclusions
Sloan 1	SD1-X6	Laminated octahedron	1.1x1.1*	2.0	Clear to orange brown	Pale yellow (non uniform)	Distorted, well developed triangular platelets
Sloan 2	SD2-X2	Flat	0.8x1.15x1.35	1.8	Pale orange	Bright yellow	High brilliance, parallel growth lamellae
Sloan 2	SD2-X8	Aggregate	0.9x0.9*	0.65	White	-----	Multiple octahedron
Sloan 2	SD2-X9	Macle	0.25x0.5x0.6	<0.5	White	-----	Triangular growth platelets, abundant inclusions
Sloan 2	SD2-X13	Distorted octahedron	1.3x1.75x2.8	11.8	Glassy to white	Yellow	Lamellar buildup, internal fracture along cleavage, inclusions

*Essentially equi-dimensional

At the time of writing some 27 micro-diamonds have been recovered from weathered kimberlite from several pipes. Most of these stones were extracted from samples collected from the Sloan 1 and 2 pipes in Colorado;[77] six diamonds were recovered from pipes on state owned land in Wyoming. Most of the diamonds are extremely small, measuring less than 0.7 mm in diameter and weighing less than one milligram. The largest crystal recovered to date, taken from the Sloan 2 pipe, weighs 11.8 mg (0.059 carat) and is approximately 1.3 x 1.75 x 2.8 mm in size (Table 5 and Fig. 18). A tabular crystal (macle) measuring 0.55 x 1.1 x 1.25 mm and weighing 1.95 mg (0.0098 carat) is the largest stone recovered from a Wyoming pipe (in State Section 16). Figure 19 shows six of the larger diamonds, all from the Sloan 1 pipe in Colorado, that have a cumulative weight of 14.0 mg (0.07 carat).

The diamonds have been described utilizing the morphological classification established by Whitelock (1973). They include eight octahedra (laminated and deformed), one dodecahedron, three flats (flattened dodecahedra), two macles (111 contact twins), four irregular shapes (formless crystals and broken fragments), and nine aggregates (multiple crystals and interpenetrant twins). Most of the diamonds are characterized by the presence of at least a few octahedral faces and, in octahedron and aggregate types, these faces are generally well developed. Dodecahedral faces, although present locally, are markedly subordinate to the octahedral forms. Lamellar buildup of (111) surfaces is very prominent (Figs. 20A, B and C) and triangular shaped growth platelets (Figs. 20A and B), depressions (trigons) (Figs. 20A, C and D) and natural etch pits (Fig. 20D) that may give surfaces a corroded appearance, are commonly abundant.

Figure 19 — Six diamonds recovered from weathered kimberlite from the Sloan 1 pipe in Colorado; total weight 14.0 mg (0.07 carat). Types are as follows; top row left to right—aggregate (SD1-X5), laminated octahedron (SD1-X6) and aggregate (SD1-X1); bottom row left to right—flat (SD1-X4), dodecahedron (SD1-X3) and irregular (SD1-X2).

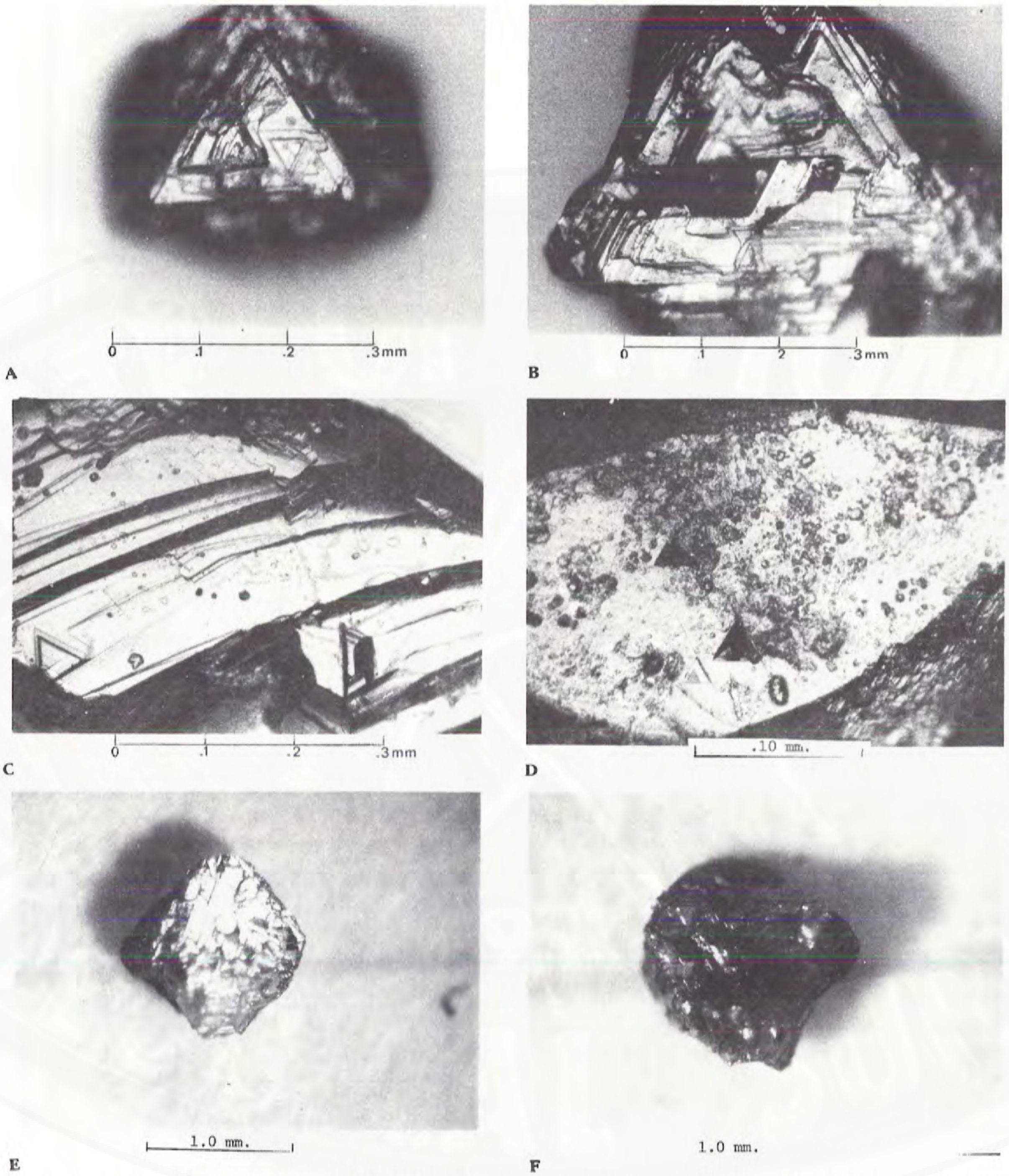


Figure 20 — Lamellar buildup and surface features of (111) faces of diamonds from the Sloan 1 and 2 pipes (Colorado). A) Pronounced triangular platelets and trigons on built-up (111) face of a laminated octahedron (SD2-X7). B) Triangular laminations on (111) face of a complex, distorted laminated octahedron (SD2-X3). C) Laminations and trigon (lower left corner) on (111) face of a flattened dodecahedron (flat) (SD2-X2). D) Trigons and natural etch pits on (111) face of the flattened dodecahedron in C (SD2-X2). E) Regular laminated octahedron (SD1-X6). F) Laminated octahedron of E (SD1-X6) showing back side with abundant small platelets of graphite (?) along cleavage planes imparting a dark gray color to crystal.

Most of the octahedra exhibit very pronounced lamellar buildup on (111) surfaces (Figs. 20A, B, E and F). Both distorted and regular laminated crystals have been recovered. Some of the crystals have a rounded appearance caused by the progressive decrease in platelet size on octahedral surfaces (Figs. 20E and F). The octahedra are generally colorless to white, but one crystal is partially pale orange-brown while another is partially dark gray because of abundant small graphite(?) platelets along some cleavage surfaces (Fig. 20F).

One regular dodecahedral diamond (SD1-X3; Fig. 21D) was recovered from the Sloan 1 pipe in Colorado. Although the crystal was broken in half, a good, rounded, complex dodecahedral form is evident. The dodecahedral faces apparently evolved from an octahedron; fine ridges are present along the short diagonal of the rhombic faces producing a poorly developed tetrakis hexahedron similar to those discussed by Whitelock (1973, p. 129). Although the presence of octahedral faces is still evident, the crystal is classed as a dodecahedron based on the more pronounced development of faces of the latter form, in accord with the procedure adopted by Whitelock (1973). The crystal is clear to glassy and contains numerous complex growth lamellae.

In addition to graphite(?), the crystals commonly contain numerous minute, lighter colored mineral inclusions of unknown composition and a few dark, rounded grains that may be spinel. The octahedra range in size from approximately 0.2 to 2.8 mm (Table 5). Graphite(?) inclusions all appear to be concentrated near the surface of crystals along fractures or cleavage planes and are probably the result of graphitization of the diamond along planes of weakness (stress planes).

The three flats or flattened dodecahedra are characterized by rounded edges and curved to irregular elongated faces that locally are conchoidally fractured and pitted. Growth lamellae are present on some surfaces and are accompanied by minor triangular growth depressions (Fig. 21A). Two of the crystals are clear to glassy, one is pale orange. All of the crystals show considerable brilliance and contain abundant minute clear to white inclusions. The two flats from Colorado are among the largest stones recovered to date; 0.9 x 1.3 mm—1.8 mg (SD1-X4, Fig. 19) and 1.0 x 1.3 mm—1.3 mg (SD2-X2, Fig. 21A). The single flat recovered from Wyoming kimberlite is quite small; 0.125 x 0.3 x 0.3 mm—$<$0.5 mg (SH15-X1, Fig. 21B).

Two crystals have been tentatively identified as macles; one from the Sloan 2 pipe in Colorado and the other from a pipe in Wyoming State Section 16. The Colorado macle is 0.25 x 0.5 x 0.6 mm and weighs $<$ 0.5 mg. It is tabular triangular in shape, has slightly curved faces that slope toward the (111) twin plane along which the crystal has been cleaved and the large octahedral face paralleling the twin plane has abundant triangular growth plates and laminations.[78] The Wyoming macle is 0.55 x 1.1 x 1.25 mm and weighs 1.95 mg. It is broken along a highly irregular curved fracture that reveals both sides of the contact twin plane. Only two of the octahedral faces are well preserved and lamellar growth buildup is evident. The Colorado macle is clear to glassy with a pale orange zone near one side, whereas the Wyoming stone is grayish-white. Both crystals contain numerous minute black to colorless mineral inclusions.

The four irregularly shaped diamonds (two from Colorado, two from Wyoming—Table 5) are rounded to angular and have no or only a few isolated, poorly developed crystal faces (Figs. 21B, C and D). Growth lamellae, triangular platelets and pyramidal etch pits are present on some surfaces. The crystals range from 0.2 x 0.25 x 0.3 mm to 1.2 x 1.6 mm; the largest stone (SD1-X2 from Colorado—Table 5, Fig. 21C) weighs 3.3 mg (0.0165 carat). Two of the "irregulars" are angular fragments; one (SD1-X8) appears to be a fragment of a flattened dodecahedron while the other (SH19-X1, Fig. 20B) is a chip from a rounded octahedron. The crystals are glassy-clear to white with the exception of a pale brownish zone in one. Minute mineral inclusions, similar to those previously described for other samples, are present in all of the irregular diamonds.

Aggregate diamonds (Figs. 19, 21 and 22) are comprised of small crystals that have grown together, some quite complexly. All specimens contain at least some lamellar buildup on (111) surfaces; triangular platelets, trigons and etch pits are locally abundant. Intergrowths of octahedra (*e.g.* Fig. 22A) predominate but dodecahedral forms are also common, generally in combination with the octahedra (Fig. 22B).

Many of the octahedra intergrowths are controlled by interpenetrant twin laws. Most common are parallel interpenetrant growth types in which individual crystals have mutually parallel "a" axes. A rarer twin type, shown in Figure 22C, is the simple penetration growth of two planar octahedra about an inclined "a" axis. This twinned crystal (Fig. 22C) is 0.5 x 0.5

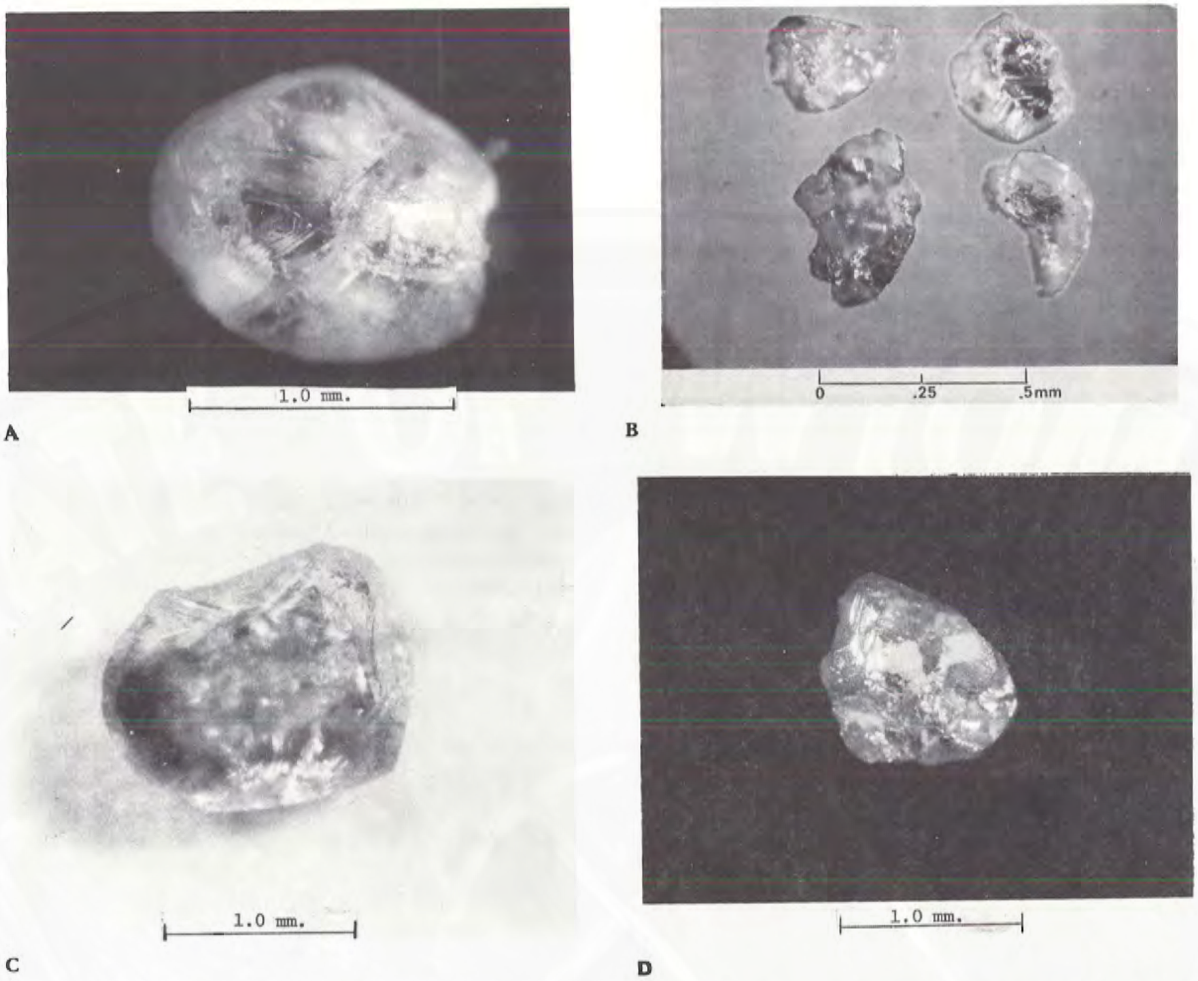


Figure 21 – Diamond types from the State-Line kimberlite pipes: flats, dodecahedron, aggregates and irregular shapes. A) Flattened dodecahedron from the Sloan 2 pipe showing growth lamellae (SD2-X2). B) Irregular, flat and aggregate diamonds from Wyoming pipes: upper left–irregular (SH16-X2); upper right–flat (SH15-X1); lower left–aggregate (SH16-X1); lower right–irregular (fragment of rounded octahedron) (SH19-X1). C) Irregular diamond from Sloan 1 pipe (SD1-X2). D) Dodecahedron developed from octahedron from Sloan 1 pipe (SD1-X3).

x 0.8 mm and is part of the first diamond recovered from a Colorado pipe (the stone was originally about 50 percent larger but was broken during testing).[79] The aggregate diamonds range from 0.3 x 0.4 mm to 0.9 x 1.85 mm. They all contain variable amounts of unidentified mineral inclusions. Most are colorless to white although a few are grayish-white and part of one is pale brown.

Many of the diamonds show a pronounced fluorescence in ultraviolet light. Weak to bright yellow colors are most common, but one crystal fluoresced blue-white and another was essentially non-fluorescent (extremely weak pale orange) (Table 5).

At the time of writing, alluvial micro-diamonds have been recovered from seven pipes in the State-Line district (two pipes in Colorado and five in Wyoming). Considerable amounts of heavy mineral concentrates from other pipes in the district are currently being processed, and the likelihood of further recoveries is high.

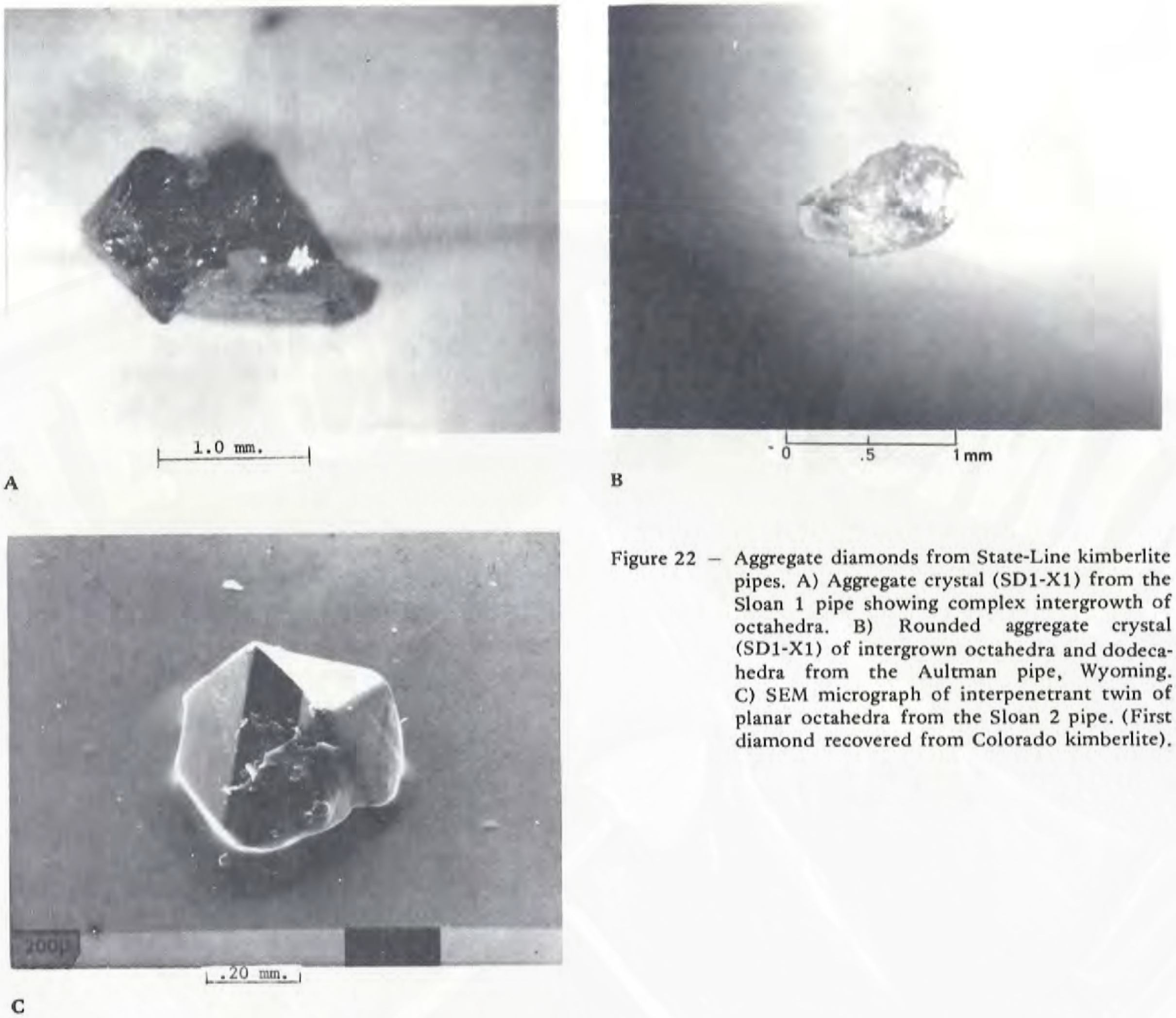


Figure 22 – Aggregate diamonds from State-Line kimberlite pipes. A) Aggregate crystal (SD1-X1) from the Sloan 1 pipe showing complex intergrowth of octahedra. B) Rounded aggregate crystal (SD1-X1) of intergrown octahedra and dodecahedra from the Aultman pipe, Wyoming. C) SEM micrograph of interpenetrant twin of planar octahedra from the Sloan 2 pipe. (First diamond recovered from Colorado kimberlite).

ECONOMIC POTENTIAL

The discovery of diamonds, like that of gold, immediately conjures visions of booms, rushes and riches in the minds of many. Before one mortgages away home and family possessions, however, it would be wise to consider the production potential of a property (or district) and the economics involved in exploration and development. Since diamonds represent one of the lowest yield commodities in terms of material that must be processed for units of product, the costs leading up to and included in production are understandably high.

The concentration of diamond in a rich kimberlite ore (*e.g.* at the Premier pipe in South Africa) is approximately one carat per ton (0.2 gm/ton) or one part diamond per 4.5 million parts of waste rock which constitutes a grade of approximately 0.00000022 percent. Average kimberlite ore runs about 0.25 carat per ton or approximately one part diamond per 20 million parts waste rock (0.00000005 percent). Alluvial diamond ores generally return one part diamond for every 15 to 30 million parts of waste material (0.3 to 0.15 carat/ton).

Clearly, large tonnages of material must be processed to recover such a low concentration product and the "less than obvious" presence of diamonds in a district necessitates considerable exploration and testing expense. Furthermore, the profitability of mining ore in such low concentrations is dependent on the value of the recovered diamonds. A property producing only industrial quality stones would obviously require larger concentrations of diamond per ton than one producing gem quality stones before production is profitable. Industrial diamonds average approximately $3.00-$5.00 a carat and require high concentrations to be economic; a handful of good quality gem stones could underwrite the entire cost of a single operation. It is apparent that, for most operations to be successful, at least some sizable gem quality stones must be recovered.

Pipe erosion is another factor to be considered in evaluating a kimberlite property. It has been demonstrated that diamond sizes and yields diminish with depth in pipes[80]. If only the pipe "roots" are preserved in a district, the potential for economic development of kimberlite is quite low. However, alluvial possibilities should be evaluated in such areas.

Bruton (1971, p. 274) sites two classic South African examples in which diamond yields in pipe mines decreased substantially with depth. At the Bulfontein mine yields at upper levels averaged approximately 0.525 carat per ton, while at the 1000 foot level average yield diminished to 0.386 carat per ton. Decreasing yield values are even more dramatic for the Premier Mine where surface blueground operations produced about 1.0 to 1.6 carats per ton compared with 0.236 carat per ton between the 410 and 510 foot levels.

Most kimberlite pipes in the State-Line district do not appear to be eroded to "root" levels, thus the potential for significant concentrations of diamonds is at least reasonable from a depth standpoint. Compared to major producing kimberlite districts, however, the regional geologic framework is less favorable. Most worldwide diamond-bearing kimberlites are confined to older cratons (3+ b.y.) where ancient rocks have persisted in relatively undeformed states[81]. Crustal rocks in the Wyoming-Colorado Rocky Mountains are considerable younger (less than 1.85?b.y.) and have been subjected to multiple episodes of orogeny, the 1.75±b.y. deformational event having been very severe. According to Dawson (1970, p.333), the higher degree of crustal rigidity beneath ancient shields coupled with cooler mantle below these areas would favor the formation and preservation of diamonds. Dawson suggests that cooler mantle zones would be favorable to accumulation of the high amounts of volatiles which appear to be necessary for diamond formation. He notes that the high strength of crustal rocks would be sufficient to retain enough pressure within the intruding dikes and pipes to retain levels of stability necessary for diamond preservation. Diamond-bearing kimberlite intruding orogenic belts would be expected to encounter planes of weakness such as faults, fractures and foliations along which magmatic gases could escape. This would lower the pressure within the ascending kimberlite magma, "promoting inversion or resorption of the diamonds[82]."

Such a mechanism may have been responsible for the apparent development of graphite(?) observed as platelets along outer cleavage planes and as minor surface coatings on some of the State-Line district diamonds. The majority of the crystals show little to no evidence of graphitization, thus Dawson's suggested process for "inversion" of diamonds in orogenic belts clearly is not completely applicable to the area. However, if such a process operated even in part and was responsible for the destruction of appreciable percentages of diamonds during emplacement of the kimberlite, the viability of economic development of the district would be diminished accordingly. A positive factor supporting evaluation of the district is the large size of some pipes. It has been apparent for years that the most diamond-rich pipes are also the largest (*e.g.* Premier, Mwadui, Williamson, Orapa, Kimberley, Wesselton). Dawson (1970, p.332) points out that "the high diamond content and the large size of the diatremes are both a reflection of the extremely high pressures in the sub-diatreme dikes." At least three pipes in the State-Line district are comparable in size to the Kimberley and Wesselton pipes of South Africa.

At present, no quantitative figures are available regarding diamond concentrations in the Wyoming-Colorado pipes. As previously mentioned, the kimberlite has been tested only for presence of diamond and not for "ore grade." Even though nearly two dozen micro-diamonds have been recovered from the Sloan 1 and 2 pipes in Colorado, considerably less than 1000 pounds of material has been processed and available data in no way constitutes a valid test of diamond concentration. The required tests for evaluation of economic potential necessitate processing several thousand tons of material or, in essence, the establishment of a field concentration operation or small "pilot plant" on properties to be tested.

It should be pointed out that the costs of properly testing and developing a property are substantial. For example, the total cost of bringing the Orapa pipe in Botswana into production in 1971 was $34,250,000[83]. The deposit was discovered in 1967

Table 6. World production of diamonds (data in thousand metric carats).

Country	Gem diamonds					Industrial diamonds								
	++1967	++1968	++1969	++1970	++1971	++1967	++1968	++1969	++1970	++1971	**1972	**1973	‡1974	‡1975
AFRICA:														
Angola	*1,000	1,250	1,311	1,344	1,455	*300	417	706	896	970	539	531		
Botswana	----	----	----	54	82	----	----	----	490	743	2,043	2,054	2,300	2,000
*Central African Republic	260	183	263	193	172	260	426	264	289	258	178	129		
+Congo (Brazzaville)	300	400	100	na	na	5,000	6,000	1,400	na	na	na	na		
Ghana	254	612	830	175	174	2,283	1,835	3,312	2,697	2,676	2,393	2,085	2,300	2,000
*+Guinea	20	25	25	22	----	50	75	75	52	----	55	55		
*Ivory Coast	105	75	120	128	240	70	112	120	85	160	200	180		
*Lesotho	na	6	15	15	7	na	6	15	2	1	8	9		
+Liberia	353	300	212	350	344	197	450	640	203	196	350	370		
Sierra Leone	*600	609	600	1,616	1,802	*800	913	1,337	431	473	1,080	1,000		
South Africa	*2,100	3,196	3,073	2,602	2,314	*4,900	4,238	4,789	5,559	5,267	4,025	4,117	4,100	4,000
South-West Africa	*1,700	1,636	1,923	1,679	1,482	*200	86	101	186	167	80	80		
Tanzania	494	351	389	284	264	494	351	388	424	396	325	290		
*Zaire	263	250	310	350	340	12,890	12,162	15,155	17,150	16,600	12,051	11,646	11,900	12,000
Total Africa	7,449	8,893	9,171	8,812	8,676	27,444	27,171	28,302	28,464	27,907	23,327	22,546		
OTHER COUNTRIES														
*Brazil	160	175	160	95	80	160	175	160	95	80	155	160		
Guyana	38	32	31	24	24	57	33	21	36	35	29	31		
India and Indonesia	8	21	20	25	40	2	8	5	6	10	3	3		
*USSR	1,400	1,600	2,500	2,700	2,700	4,800	5,600	7,500	9,300	9,300	7,350	7,600	7,900	8,000
Venezuela	38	57	118	112	163	32	57	76	388	487	315	537		
Other Free World	----	----	----	----	----	----	----	----	----	----	na	na	3,000	4,000
Total Other Countries	1,644	1,885	2,829	2,956	3,007	5,051	5,873	7,762	9,825	9,912	7,855	8,334		
Total World Production	9,093	10,778	12,000	11,768	11,683	32,495	30,049	36,064	38,289	37,819	31,182	30,880	31,500	32,000

*)Estimate
+)Exports
‡)From Clarke,1976
**)From U.S. Bureau of Mines, 1975
na)Not available
++)From Linari-Linholm, 1973

after 12 years of prospecting by DeBeers at a cost of $1,500,000. Economic evaluation of the pipe ran about $750,000 and plant construction was an additional $24,750,000.[84]

Based on the results of our preliminary studies, a more comprehensive evaluation of the Wyoming-Colorado pipes is definitely warranted. Although there appears to be little likelihood that the district would ever become another "Kimberley" or "Yakutia" field, the presence of even trace amounts of a strategic commodity requires that proper evaluations be conducted. Considering that there is currently no domestic source of natural diamonds, any possibility of local production should be pursued.

Major world production of natural diamonds is largely from African countries and the USSR (Table 6). The leading exporters of industrial diamonds are Zaire, South Africa, Angola, Ghana, Botswana and the USSR. The principal producers of gem diamonds are South Africa, the USSR, Sierra Leone, South West Africa and Angola (Table 6). Synthetic diamonds now compete favorably in the industrial market and, in addition to domestic production by the General Electric Corporation, significant quantities are produced in Canada, South Africa, the Irish Republic and the USSR (Table 6).

In 1975, the United States imported 14,290,391 carats of synthetic and industrial diamonds worth $53,316,686 and 4,607,580 carats of gem diamonds valued at $730,405,306. Total 1975 United States production of synthetic diamonds was 19,000,000 carats.[85]

RECOMMENDATIONS AND EXPLORATION PROCEDURES

The authenticated presence of any strategic mineral resource warrants follow-up investigations. Levels of concentrations and distribution of mineralization should be evaluated in order to establish development potential. Several of the larger existing pipes showing maximum promise should be tested by large volume heavy mineral separation procedures. Since some initial exploratory work has already been conducted at the Sloan 1 and 2 pipes in Colorado and both pipes are readily accessible, these sites are ideally suited to the preliminary large volume tests that should be conducted. If these pipes show potential for diamond production, other large pipes in the district should be tested by the same procedures.

A systematic exploration program designed to find additional pipes is currently underway at Colorado State University, and this program is being supported by the Wyoming Geological Survey, the National Science Foundation, the U.S. Geological Survey and several private companies. Expanded levels of exploration will automatically be pursued if preliminary large volume tests at the Sloan pipes are successful.

Stream sediment sampling techniques similar to those developed in Africa for finding kimberlite pipes are being employed. According to Gold (1968) nearly three-quarters of the kimberlite pipes known throughout the world have been found in this fashion. Samples are collected systematically over an area from stream beds and the sediment is sieved and panned or sluiced for its heavy mineral content. Heavy mineral fractions are examined visually and microscopically for pyrope garnet, magnesian ilmenite and chrome diopside, all of which are "indicator" minerals of kimberlite. Upon recognition of indicator minerals in samples, the target areas in the vicinity of sample sites are carefully field checked and the source pipes can generally be located. Approximately 50-100 pounds of weathered kimberlite is collected from the new pipes and processed for diamond content.

Aerial false color infrared techniques of pipe exploration have been examined on a preliminary basis and this and related aerial (remote sensing) methods show promise[86]. More extensive evaluation of several remote sensing techniques is planned.

Geophysical methods of exploration have also been examined on a preliminary basis and, thus far, they appear to have only limited application[87]. Airborne surveys would be most useful, but small target size and generally low contrast in geophysical properties recorded by airborne instruments seriously limit the potential of such surveys. However, once target areas have been located by other methods, geophysical ground surveys may be applicable to the location of pipes or, more specifically, to the delineation of pipe boundaries. Resistivity methods are especially effective and magnetic and seismic surveys are useful over some pipes.

In summary, since the potential mineral resource of concern is a strategic commodity, the careful evaluation of known pipes is definitely warranted and exploration for new pipes should be continued at an accelerated pace.

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FOOTNOTES

1. Chronic and Ferris, 1961, 1963.
2. Personal communication, 1965.
3. Chronic, *et al.*, 1965; Eggler, 1967; McCallum and Eggler, 1968.
4. Chronic, *et al.*, 1969; Eggler and McCallum, 1973, 1974a, 1974b; McCallum, 1974; McCallum and Eggler, 1968, 1971, 1976; McCallum, *et al.*, 1973, 1974, 1975; McCallum, Smith, *et al.*, 1975.
5. Miser and Ross, 1922a, p. 318; Hurlbut, 1971, p. 241.
6. Kridelbaugh, *et al.*, 1972; McCallum, *et al.*, 1975.
7. W.A. Braddock, personal communication., 1975.
8. McCallum, *et al.*, 1973, 1975; McCallum, Smith, *et al.*, 1975.
9. McCallum, *et al.*, 1975, p. 150.
10. Eggler, 1968.
11. Boos and Boos, 1933.
12. McCallum and Eggler, 1971; McCallum, *et al.*, 1975.
13. Eggler, 1968, p. 1549.
14. Peterman, *et al.*, 1966.
15. Eggler, 1968, p. 1560.
16. Chronic, *et al.*, 1969, p. 154.
17. Chronic, *et al.*, 1969; McCallum and Eggler, 1971.
18. Chronic, *et al.*, 1969; McCallum and Eggler, 1971; McCallum, *et al.*, 1975.
19. *e.g.* the Nix pipes in Colorado—Eggler, 1967; McCalsum, *et al.*, 1975.
20. McCallum and Eggler, 1971; McCallum, *et al.*, 1975.
21. Boyd, 1973; Boyd and Nixon, 1973; Brookins and Meyer, 1974; Eggler and McCallum, 1974a; McCallum and Eggler, 1976; Hearn and Boyd, 1975; MacGregor and Basu, 1974; McGetchin and Silver, 1972; Nixon and Boyd, 1973.
22. *e.g.* rhyolite breccia pipes at Majuba Hill, Nevada—Trites and Thurston, 1958; Walker, 1963; diatremes filled with alkalic basalt tuff and related pyroclastic and sedimentary rock debris in the Hopi Buttes area of Arizona—Lowell, 1956; Shoemaker, 1955; Shoemaker and Moore, 1956; Shoemaker, *et al.*, 1962.
23. Shoemaker, 1955; Shoemaker, *et al.*, 1962; Gavasi and Kerr, 1968.
24. Shoemaker, *et al.*, 1962, p. 349.
25. Shoemaker, *et al.*, 1962, p. 348.
26. Gavasi and Kerr, 1968, p. 870.
27. Bruton, 1971, p. 34.
28. Linari-Linholm, 1973.
29. Davidson, 1957; Tomkeieff, 1958; Smirnov, 1959; Wilson, 1960; Frantesson, 1970; Satterly, 1971.
30. Davidson, 1967.
31. Linari-Linholm, 1973; Bruton, 1971, p. 69.
32. *e.g.* Brazil—Draper, 1911, 1923; Rimann, 1915, 1931. Borneo—Van Bemmelen, 1949, p. 343. Czechoslovakia—Kopecky, 1960, 1968; Kopecky, *et al.*, 1967. Greenland—Andrews and Emeleus, 1971, 1975; Emeleus and Andrews, 1975. India—Mathur, 1962; Rao and Phadtare, 1966. Malaita, Solomon Islands—Allen and Dears, 1965. Norway—Saether, 1957; Griffen and Taylor, 1975. Sweden—von Eckermann, 1964, 1967.
33. Miser and Ross, 1922a.
34. Challinor, 1967, p. 72.
35. Lorenz, *et al.*, 1970, p. 12.
36. See Woolsey, *et al.*, 1975, for a more comprehensive discussion of the fluidization process.
37. Hearn, 1968; Stuart-Alexander, *et al.*, 1972; Woolsey, *et al.*, 1975.
38. Lorenz, *et al.*, 1970; Lorenz, 1973, 1975; Hawthorne, 1975.
39. *e.g.* Buell Park diatreme, Arizona—Watson, 1967b. Orapa pipe, Botswana—Hawthorne, 1975. Mwadui pipe, Tanzania—Hawthorne, 1975.
40. *e.g.* Black Butte diatreme, Montana—Hearn, 1968. Fife pipes of Scotland—Francis, 1962.
41. Shoemaker, 1955; Shoemaker, *et al.*, 1962.
42. Wagner, 1929.
43. *e.g.* Black Butte diatreme, Montana—Hearn, 1968.
44. *e.g.* Cloos, 1941; Dawson, 1962, 1967a, 1971; Lorenz, 1975; McCallum and Eggler, 1971; McGetchin, 1968; Sobolev, 1960.
45. Dawson, 1971, p. 202.
46. Dawson, 1971, p. 202.
47. Dawson, 1971, p. 193.
48. Dawson, 1967a, p. 244.
49. Dawson, 1967a, p. 247.
50. McCallum, *et al.*, 1975.
51. Dawson, 1971, p. 195.
52. Dawson, 1971, p. 196.
53. Dawson, 1967b, p. 272; 1971, p. 196.
54. Dawson, 1967b, 1971.
55. Burkov and Podporina, 1966; Frey, *et al.*, 1971; Philpotts, *et al.*, 1972; Mitchell and Brunfelt, 1975.
56. McCallum and Eggler, 1971, p. 1738; McCallum, *et al.*, 1975, p. 152.
57. *e.g.*, Lesotho—Boyd and Nixon, 1973; Nixon and Boyd, 1973. South Africa—MacGregor and Basu, 1974; MacGregor, 1975. Colorado Plateau—McGetchin and Silver, 1972. Kansas—Brookins and Meyer, 1974. Montana—Hearn and Boyd, 1975.
58. Eggler and McCallum, 1974a; McCallum, *et al.*, 1975; McCallum and Eggler, 1976.
59. Boyd and Nixon, 1973; McCallum and Eggler, 1976.
60. Eggler and McCallum, 1974a, p. 300.
61. Sinkankas, 1959; Gold, 1968; Hurlbut, 1971.
62. Satterly, 1971, p. 26.
63. Miser and Ross, 1922a, p. 318.
64. Copeland, 1966; Hurlbut, 1971, p. 241.
65. McCallum and Eggler, 1976.
66. McCallum and Mabarak, 1976.
67. McCallum and Eggler, 1976.
68. McCallum and Eggler, 1976.
69. McCallum and Eggler, 1976.
70. McCallum and Eggler, 1976.
71. McCallum and Eggler, 1976.
72. McCallum and Eggler, 1976.
73. McCallum and Eggler, 1976.
74. McCallum and Eggler, 1976.
75. McCallum and Mabarak, 1976.
76. McCallum and Mabarak, 1976.
77. McCallum and Mabarak, 1976.
78. McCallum and Mabarak, 1976.
79. McCallum and Mabarak, 1976.
80. Bruton, 1971, p. 264.
81. Clifford, 1966; Dawson, 1970.
82. Dawson, 1970, p. 333.
83. Satterly, 1971, p. 35.
84. Satterly, 1971.
85. Personal Communication, R.G. Clarke, U.S. Bureau of Mines, April 1976.
86. McCallum, 1974.
87. Puckett, *et al.*, 1972.

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