THE GEOLOGICAL SURVEY OF WYOMING
Daniel N. Miller, Jr., State Geologist

REPORT OF INVESTIGATIONS No. 19

EXPLORATION FOR DIAMOND-BEARING KIMBERLITE IN COLORADO AND WYOMING: AN EVALUATION OF EXPLORATION TECHNIQUES

By W.D. Hausel, M.E. McCallum, and T.L. Woodzick

LARAMIE, WYOMING
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Front cover photographs: *Upper left*, kimberlite outcrop and tallus on the Sloan 1 pipe, Colorado. *Upper right*, diabasic dike in the Trail Creek Granite, Wyoming. *Lower left*, Medicine Bow placer diamond. This is the largest authenticated diamond found to date in the Colorado-Wyoming region, and weighs about one-tenth carat. *Lower right*, electrical resistivity survey on the Aultman 1 pipe, Wyoming

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ABSTRACT

More than 90 separate occurrences of kimberlite are known in the Colorado-Wyoming State Line District and the Iron Mountain District of Wyoming. One isolated kimberlite pipe occurs west of Boulder, Colorado, and a kimberlite dike has been found near Estes Park, Colorado. To date, diamonds have been recovered only from the State Line kimberlites. An isolated occurrence of placer diamonds was recently identified in stream sediment concentrates from the Wyoming Medicine Bow Mountains, but no associated kimberlite has been located.

Several kimberlite exploration programs have been initiated in the State Line District since the discovery of diamonds there in 1975. Exploration for new kimberlites falls into three categories or phases: prospecting, delineation, and assessment.

Prospecting is initiated by selection of favorable target areas. Geologic maps, aerial photos, and all available remote sensing imagery (e.g. LANDSAT, false color IR, thermal IR, etc.) are evaluated for structural trends, and any areas showing apparent relationships or similarities to known kimberlite districts are given highest priority, especially those in close proximity to known kimberlite occurrences. Drainages of target areas are systematically sampled for heavy minerals, and kimberlite indicator mineral "trains" are traced upslope to potential kimberlite sites. Detailed ground surveys are conducted over several miles around all new discoveries, and special emphasis is placed on any associated linear trends (faults, dikes, joints, etc.). Heavy mineral soil sampling has not been utilized to date, but where interfluves are extensively developed this method may be effective. Limited geochemical sampling of both soil and alluvial material has been used with variable success.

During the delineation phase, the surface extent of newly discovered diatremes (or dikes) is mapped. Contacts between kimberlite and enclosing host rock are rarely exposed, but may be approximately located by the presence of weathered kimberlite, abundant mantle or lower crustal nodules, xenoliths of Lower Paleozoic sediments, caliche, and vegetation changes. Geophysical Surveys in conjunction with soil and vegetation mapping are used to further define contacts. Resistivity and magnetic surveys appear to be most useful.

The final exploration phase involves the assessment of diamond potential. Small samples (approximately 100-200 pounds) of weathered kimberlite are examined for diamonds to determine if the diatreme is diamondiferous. Since large volumes of material must be processed to evaluate the economic grade of a diamond pipe, none of the diatremes has been properly assessed to date. However, this phase of exploration is scheduled to be conducted on several pipes in Wyoming by Cominco American Incorporated, under an assessment permit granted by the State of Wyoming and Rocky Mountain Energy Company.

INTRODUCTION

The presence of kimberlite in the Front Range of Colorado and the Laramie Range of Wyoming was first recognized by M.E. McCallum in 1964, based upon results of preliminary mineralogical and petrographic studies of rock exposed in the Sloan 1 diatreme in the Prairie Divide region of Colorado (Chronic et al., 1965; McCallum and Eggler, 1968; 1971). Eleven years later, diamonds were discovered in a serpentinized garnet peridotite nodule during thin section preparation at the U.S. Geological Survey rock preparation lab in Denver (McCallum and Eggler, 1976; McCallum and Mabarak, 1976a). The nodule was collected from the Schaffer 3 diatreme, in Wyoming, one of several kimberlite pipes on State School Section 16 located just north of the Colorado-Wyoming state line (McCallum and Mabarak, 1976a). Shortly following the discovery of the diamondiferous peridotite, diamonds were recovered from weathered kimberlite at the Sloan 1 and 2 pipes in Colorado (McCallum and Mabarak, 1976a & b). These discoveries represent only the second authenticated occurrence of diamonds found in their primary source rock in North America. Subsequent testing throughout the Colorado-Wyoming State Line District has led to the recovery of more than 90 small diamonds (McCallum et al., 1979). These important discoveries led Colorado State University and the Geological Survey of Wyoming personnel to test exploration methods suitable for prospecting for additional kimberlite occurrences in Colorado and Wyoming.

History and Distribution

In 1960 and 1961, C.S. Ferris, Jr., and C.A. Aultman located two occurrences of Lower Paleozoic sedimentary rocks completely surrounded by Precambrian granites in the Sherman Mountains of Wyoming's Laramie Range, south of Tie Siding (Figure 1). Both features were recognized to be roughly elliptical to circular in plan and reported to be a few hundred feet (tens of meters) across (Chronic and Ferris, 1963). These features were referred to as the Ferris and Aultman "outliers." The Paleozoic rocks, found to occur in the "outliers" are mostly fossilized carbonates of Ordovician and Silurian age, chaotically distributed across the structures. Sandstones of Cambrian age have also been recognized (R.J. Ross, Jr., personal communication, 1979).

No *in place* Lower Paleozoic rocks are known to exist in this region. For example, the nearest outcrops of similar Silurian rocks are more than 300 miles (480 km) from these Paleozoic "outliers" (Chronic et al., 1969). The oldest, *in place*, sedimentary rocks in the area are arkosic sediments of the Pennsylvanian Fountain Formation that outcrop about 2 miles (3.2 km) north, east, and west of the "outliers."

Electrical resistivity profiling and sounding surveys were conducted across the Ferris "outlier" by Ray (1963), and his data were interpreted as indicating a 6.5 to 10.5 foot (2-3.2 m) thick layer of overburden overlying an 11.5 to 27.5 (3.5-8.4 m) thick layer of limestone bottoming out in Precambrian granite. This feature was interpreted as a concentric graben (Chronic and Ferris, 1963; Ray, 1963).

A third occurrence of Lower Paleozoic sedimentary rocks was recognized by M.E. McCallum in 1964 at a site on the Sloan Ranch in Colorado located approximately 14 miles (22.5 km)

Figure 1. The Ferris "outlier," so termed by Chronic and Ferris in 1963, was later established (in 1964) by M.E. McCallum to be a diatreme. The abundant Lower Paleozoic carbonates completely surrounded by Precambrian granite led to its discovery by C.S. Ferris, Jr., in 1960.

south of the Ferris and Aultman "outliers" (Chronic et al., 1965). Here, blocks of Ordovician and Silurian carbonates occur in a green, serpentine-rich breccia that apparently had been prospected on a number of occasions for copper and was quarried intermittently for curios, terrazzo, and building stone. Earlier prospecting activity on the Sloan property included a cross cut tunnel about 135 feet (41 m) in length and a shaft about 75 feet (23 m) in depth. In 1959, Sterling Sand and Gravel Company quarried rock from the Sloan property for use as a decorative building stone, processed by the Wyoming Tile and Terrazzo Company in Cheyenne, Wyoming. It is reported that quarrying operations terminated in 1960 when the tile company refused to purchase rock from the Sloan property because of damage to the carborundum wheel used in the processing (Frank Yaussi, personal communication, 1978). Four years later, in 1964, the serpentine-rich breccia on the Sloan property was recognized as kimberlite by M.E. McCallum and the Sloan, Ferris, and Aultman features were established as diatremes (Chronic et al., 1965).

Since the kimberlitic diatreme nature of the three Lower Paleozoic "outliers" was established, approximately 90 separate occurrences have been identified in the Front Range and Laramie Range of northern Colorado and southern Wyoming (Figure 2). The northernmost district, the Iron Mountain District, is located 40 miles (64 km) north of the Colorado-Wyoming border near the town of Farthing, Wyoming. This district is represented by 57 separate kimberlite dikes and blows (McCallum et al., 1975; Smith, 1977; Smith et al., 1979). The State Line District, which contains the first kimberlite discovery, straddles the Colorado-Wyoming border, reaching about 2.5 miles (4 km) into Wyoming and extending 12 miles (19 km) into Colorado, and includes nearly 40 diatremes and dikes (McCallum et al., 1975; 1977). A Kimberlite dike has been recognized in the Estes Park area of Colorado, nearly 40 miles (64 km) south of the state line, and a single pipe, the Green Mountain pipe, occurs west of Boulder, Colorado, nearly 70 miles

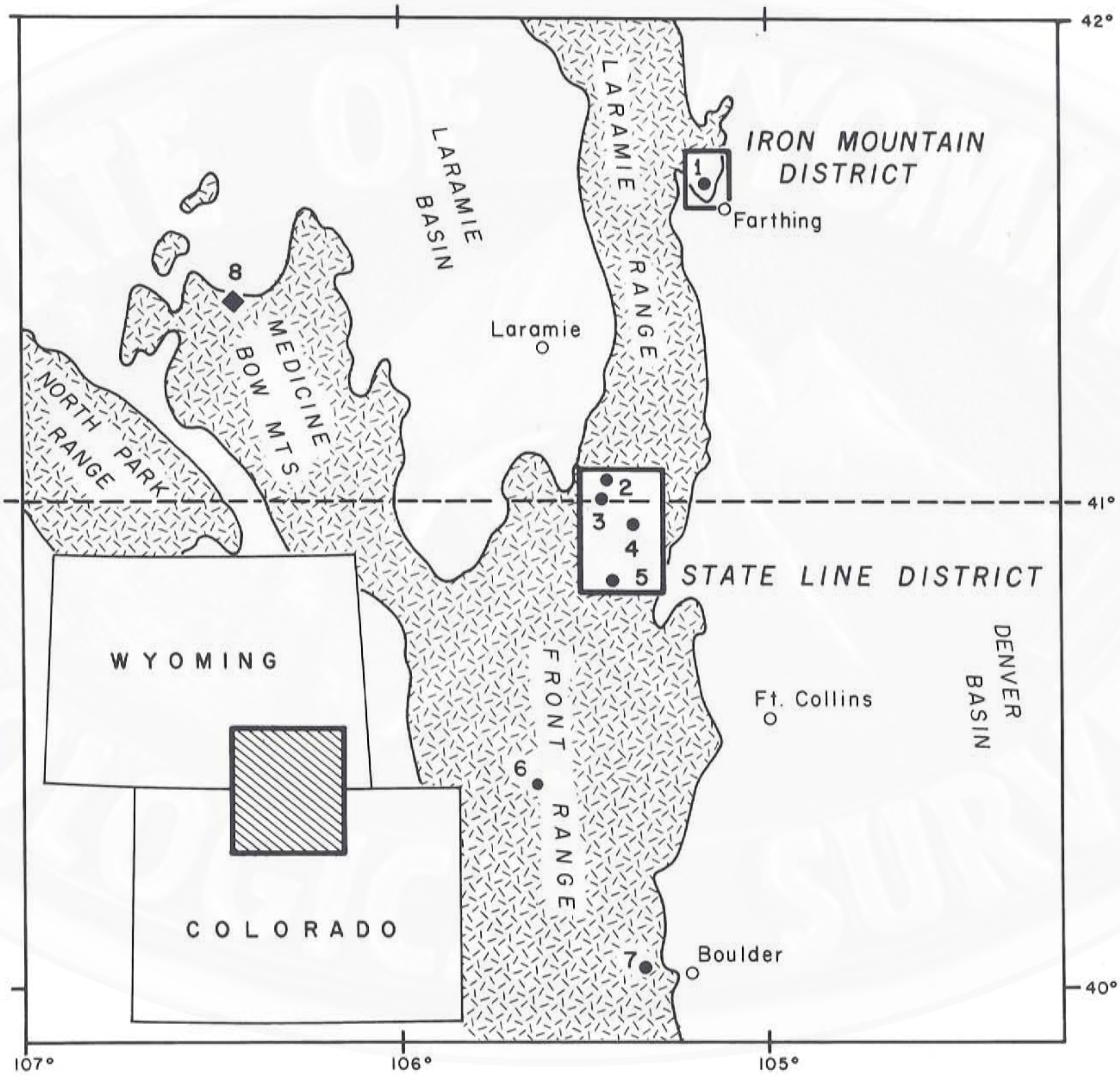


Figure 2. Index map showing general locations of kimberlite districts and the placer diamond occurrence. The numbers on the map refer to the (1) Iron Mountain District kimberlites, (2) Aultman and Ferris pipes, (3) Schaffer pipes, (4) Nix-Moen pipes, (5) Sloan pipes, (6) Estes Park dike, (7) Green Mountain pipe, and (8) Placer diamond occurrence. (Modified from McCallum and Smith, 1978.)

(113 km) south of the Colorado-Wyoming border (McCallum et al., 1975; 1977; McCallum and Mabarak, 1976b). Neither of these two latter districts is formally named.

The possibility of kimberlite occurrences, or rock of kimberlite affinity, existing at two additional localities in Wyoming is currently being investigated. Two small octahedrons positively identified as diamond using X-ray techniques (Hausel, 1977), were reportedly recovered from stream sediment concentrates in the Medicine Bow Mountains from a placer mining operation in the Mullison Park area nearly 50 miles (80.5 km) northwest of the State Line area (Paul Boden, personal communication, 1977). The drainage in this area is underlain by undifferentiated Tertiary sediments and by Precambrian crystalline rocks. Preliminary stream sediment sampling has revealed no kimberlite indicator minerals (other than the two diamonds) (Hausel, 1977; Hausel et al., 1979a). The presence of diamond as the only kimberlite indicator mineral may not be indicative of close proximity to a kimberlite source, as diamond can readily survive transport distances in excess of 1000 miles (1600 km) (Arnold Waters, Jr., personal communication, 1978).

Recently, chrome diopside and pyrope garnet, both potential indicator minerals of kimberlite, were discovered in ant hills within the Green River Basin of Wyoming (Tom McCandless, personal communication, 1979). These minerals may indicate the presence of kimberlite, but they could be disaggregation products of garnet peridotite, and considerably more detailed work must be done to determine the origin of these minerals.

Age of Kimberlite Emplacements

A Late Silurian to Early Devonian age of emplacement of the Colorado-Wyoming Front Range and Laramie Range kimberlites has been proposed (Chronic et al., 1969; McCallum and Eggler, 1971; McCallum et al., 1975). This age determination is based on the presence of Ordovician and Silurian sedimentary rock xenoliths in several diatremes, and on the absence of Mississippian and Pennsylvanian rocks that crop out in the near vicinity of some pipes (Chronic et al., 1969; McCallum et al., 1975). The age of the sedimentary xenoliths was determined by identification of abundant diagnositc fossils (Chronic et al., 1969). More recent work has established a Devonian age of emplacement. Devonian ages have been obtained both by fission-track dating of kimberlitic zircons (Naeser and McCallum, 1977), and by Sr-Rb dating of phlogopite (C.B. Smith, personal communication, 1979).

No age is available for the Medicine Bow diamonds, but presumably they were reworked from the undifferentiated Tertiary strata that laps onto the Archean granites of the Medicine Bow Mountains. The ultimate source of the diamonds is not known, and a realistic appraisal must await a more detailed investigation of the area. Age relationships for a source rock of the chrome diopsides and pyrope garnets in the Green River Basin area are equally speculative and must also await more detailed investigations.

Nature of Kimberlite

Kimberlite is considered to be the primary source of all economic concentrations of diamond, although many of the world's richest deposits are secondary placers, such as the De-Beers Consolidated Diamond Mines on the coast of Southwest Africa which produces about 1.6 million carats of high quality gems annually (Lampietti and Sutherland, 1978). However, most kimberlites are not diamond-bearing and, according to Lampietti and Sutherland (1978), only about 2 percent are economically mineralized. Even in the richest pipes, diamond occurs only in traces seldom attaining concentrations greater than 1 ppm.

The presence of diamond in some kimberlites indicates that these magmas were derived from depths in excess of about 85 miles (140 km) below the earth's surface, where the shield geotherm intersects the zone of graphite-diamond equilibrium (Clark and Ringwood, 1964). Calculation of temperatures and pressures of crystallization of ultramafic nodules found in State Line District kimberlites suggests that these kimberlites originated at depths that exceeded 120 miles (190 km) (Eggler and McCallum, 1976; McCallum and Eggler, 1976; Eggler et al., 1979). As kimberlite magmas migrate upward, they pick up fragments of wall rock that are carried to the earth's surface. Therefore, kimberlites are not only potentially important economically, but they also provide a wealth of chemical, mineralogical, and petrological knowledge of the makeup of portions of the earth's upper mantle and lower crust.

Kimberlites are relatively rare worldwide. Only about 5000 occurrences are known, and these range in surface area from a few square feet (meters) to 361 acres (146 hectares) (Brummer, 1978). Typically, kimberlites are found primarily within or marginal to stable cratonic regions that have been free of major orogenic activity for a considerable period of geologic history. Deep vertical fractures developed during epeirogenic disturbances appear to play an important part in the emplacement of kimberlite bodies (MacGregor, 1970). Deep-seated fractures apparently serve as conduits for the rapid ascent of the magma from depth. Other igneous rocks associated with these epeirogenic events include carbonatites and various alkalic assemblages. Older igneous rocks commonly occurring within kimberlite provinces include basalt, gabbro, diabase, peridotite, and lamprophyres (Mannard, 1968). Kimberlites generally occur in clusters or groups of diatremes fed from one or more feeder dikes commonly controlled by major fractures. The importance of structural control during emplacement is readily observed in the State Line District, where many pipes are aligned along major joints and faults.

EXPLORATION FOR KIMBERLITE

Various techniques have been tested in the exploration for kimberlite intrusions throughout the world, and depending upon the nature of the kimberlite and the type of rock intruded by the kimberlite, the methods of exploration have had differing degrees of success. In our studies of the Colorado-Wyoming kimberlites, we have conducted a variety of geological, geophysical, and geochemical surveys in an attempt to determine the most efficient method to isolate kimberlite intrusives. Generally, any exploration program can be subdivided into three categories: (1) prospecting, (2) delineation, and (3) assessment. In that the assessment phase of kimberlite research involves the processing of large volumes of material (10,000 tons or more for a thorough evaluation), only the first two phases of exploration were emphasized in our work.

Remote Sensing

Remote sensing imagery and aerial photography can be valuable aids in evaluating structural trends and regional zones of crustal weakness that may be favorable to the emplacement of kimberlite. High altitude photographs and LANDSAT images can be used to detect and evaluate major structural features which could otherwise be missed on low altitude photographs or during ground surveys. More detailed structural trends may be defined on low altitude photographs, and in some areas they may even be useful in precisely locating kimberlite occurrences where the proper conditions exist.

Air photographs and remote sensing imagery may be effectively used for outlining target areas during the initial phases of exploration, and they are commonly consulted throughout the investigation as additional information is acquired. For example, Barygin (1962) and Jones (1970) discuss exploration programs for kimberlite in which air photos were utilized in the initial phases of research. Magnetic data were accumulated in subsequent surveys, and kimberlites were identified by combining the magnetic and air photo information.

Air photography and remote sensing imagery were used to examine known kimberlite locations in the State Line area. The purpose of examining known kimberlites on available remote sensing imagery and aerial photography was to identify photographic characteristics common to the kimberlite that could be used in future exploration efforts. High altitude, near-infrared photographs (1:192,000, U-2 project), clearly show the prominent concentrically banded nature of the Precambrian crystalline rocks in the Virginia Dale ring dike complex (Eggler, 1967) (Figure 3), as well as associated fractures and a number of late(?) Precambrian post-complex joints and faults.

Many diatremes in the State Line District show preferential alignment along northwest trending fractures that probably developed during the initial phases of the epeirogenic movement which resulted in the uplift of this region by Mississippian time. Some of the diatremes were emplaced along Precambrian fractures that were apparently reactivated during epeirogenic uplift. As an example, the Ferris 1 diatreme shows a definite relationship to a north trending Precambrian dike suggesting that the Ferris 1 pipe was emplaced along the same fracture that contains the Precambrian dike. Similar northwest trending fractures are considered as primary exploration targets.

Low altitude color and black-and-white photographs (1:24,000) are useful for examining structural trends in greater detail, especially major and minor lineaments. Some diatremes are evident on the low altitude color photographs, whereas a number of others are inferred. The Ferris 1 and Aultman 1 diatremes are relatively obvious in that the abundant gray to white Lower Paleozoic xenoliths exposed at the surface contrast with the surrounding reddish granite (Figure 4).

Low altitude false color infrared photography has been tested as a potential tool for kimberlite exploration in the State Line District, and preliminary results are encouraging (McCallum, 1974). Kimberlite is less resistant to weathering than the surrounding granite and commonly is covered by several feet of water-rich soils. By contrast, thin, water-poor soils develop over the more resistant granites except in areas of thick alluvial or colluvial cover. This difference in soil development results in a healthier growing environment for certain types of vegetation rooted in kimberlite soils. For example, grasses in kimberlitic soils tend to be lusher and more dense than grasses developed over granites, and are better infrared reflectors.

Tree growth is not favored in kimberlitic eluvium in the State Line District. This may be due to the presence of abundant clays that form during the weathering of kimberlite. In areas where thicker layers of colluvium and alluvium cover the kimberlites, trees may be abundant. For example, in the Daldyn region of the U.S.S.R., dense stands of alder and larch are observed growing in kimberlitic soils (Jones, 1970).

The development of lush grassy vegetation over many kimberlite pipes in the Colorado-Wyoming kimberlite province provides an ideal situation for low altitude infrared prospecting. A number of known kimberlites in the State Line District have been photographed with Kodak 35 mm color infrared film both at low altitudes (McCallum, 1974) and on the ground. If the photographs are taken when vegetation differences are accentuated (e.g. late Spring, early Fall), false color infrared photos may show sharp contrasts between kimberlite and granite (Figure 5). Several known kimberlites with poorly developed soils show little to no contrast. However, the technique does offer a potential means of rapid assessment of suspected kimberlite localities, particularly during periods when moisture and vegetative contrasts are emphasized. Studies are currently being conducted to determine when such periods occur.

In practice, remote sensing methods are used principally to identify target areas during the initial phases of an exploration program and to continually search for additional structures that might have controlled kimberlite emplacement. Once a target area is identified, ground surveys (mapping, alluvial sampling, geophysical prospecting, and geochemical sampling) are initiated.

Geophysical Prospecting

Geophysical prospecting surveys were tested in the Colorado-Wyoming State Line District to determine the effectiveness of geophysical surveys in locating kimberlite in granitic terrane, but gave only very limited successes. Geophysical surveys in this area are apparently better suited to refining the extent of a diatreme after it has been discovered by some other prospecting method. Therefore, detailed discussion of the geophysical surveys used in our investigations is included in a later section on delineation.

Geophysical prospecting methods have been reasonably successful in some regions in the U.S.S.R. and Africa (Litinskii, 1963a,b; Gerryts, 1967; Burley and Greenwood, 1972). In order for geophysical methods to be applicable to prospecting for kimberlite, the geophysical characteristics of kimberlite and enclosing host rock must differ enough to be measurable. Since kimberlites around the world intrude a variety of rock types, the success of geophysical exploration procedures differs from one kimberlite district, or province, to another.

In the Yakutia province, U.S.S.R., magnetic surveys were used with great success in areas where differences between the magnetic susceptibility of kimberlite (susceptibility = 100-600 x 10^{-6}emu/cm^3) and that of the intruded carbonates (susceptibility about 0) were extremely high (Litinskii, 1963b). Anomalies as great as 5000 gammas, which are successfully detected from airborne surveys, are reported (Litinskii, 1963b). Equally good results were obtained from Mali in West Africa, where the magnetic contrast between kimberlite and schist-and-sandstone country rock produced 2400 gamma anomalies (Gerryts, 1967). In Lesotho, anomalies are reported to be comparable to those in the Yakutia province (Burley and Greenwood, 1972). Magnetic surveys in the United States have had limited success in kimberlite exploration. In the Prairie Creek District in Arkansas, a magnetic anomaly exceeding 2000 gammas over the Prairie Creek kimberlite pipe was recorded by Stern (1932); however, later surveys over nearby diatremes failed to show any anomalies. Brookins (1970) reported large positive (550-5000 gamma) and negative (0-2800 gamma) anomalies over kimberlites in Kansas. Kimberlites in the Colorado-Wyoming State Line District, in general, show only small dipolar anomalies (50-150 gammas), with the exception of two isolated anomalies of 250 and 1000 gammas (Hausel et al., 1979a; Puckett et al., 1972; Woodzick et al., 1980). A major problem with using magnetics in the State Line District is that disseminated magnetite in the host granite produces readings that are similar to the readings over the kimberlite diatremes. Thus, a lack of magnetic contrast, except in rare instances, hampers the approach.

Gravity surveys have been used in the U.S.S.R., Tanzania, and Lesotho with some success. In the U.S.S.R., gravity surveys were successful in locating kimberlite buried by trap. Strong negative anomalies as great as 6 milligals produced from contrasting densities of the kimberlite and surrounding sedimentary host rocks were observed in Tanzania (Gerryts, 1967). However, in Lesotho, only the largest pipes were recognized by gravity surveys, and these anomalies (1-2 milligals) were quite small because of the density similarities of kimberlite and the host basalts (Burley and Greenwood, 1972).

Very little information is available concerning resistivity and seismic surveys for kimberlite. The data that are available indicate that marked differences exist in the conductive properties and density between kimberlite and many host rocks. In regions where there are no marked contrasts between the magnetic susceptibilities and densities of diatremes and their enclosing hosts, resistivity may be useful in identifying kimberlite.

Gerryts (1967) discusses some resistivity surveys in Africa which show that there are distinct conductive differences between weathered kimberlite and most host rocks. In the Congo, kimberlite displayed an average resistivity low of 65 ohm-feet (20 ohm-m) compared to 1300 ohm-feet (396 ohm-m) in the host Precambrian limestone. In South Africa, resistivity differences were small; however, one kimberlite dike produced a 10 to 13 ohm-feet (3-4 ohm-m) reading compared to 40-50 ohm-feet (12-15 ohm-m) in surrounding shales and diorites. Tanzanian kimberlite is reported by Gerryts (1967) as 5 to 10 times more conductive than the granitic country rock. The apparent resistivity of weathered kimberlites in Lesotho is reported to vary between 48 to 350 ohm-feet (15-107 ohm-m) as compared to 800 to 4800 ohm-feet (244-1463 ohm-m) in contrasting basalts (Burley and Greenwood, 1972). Colorado-Wyoming kimberlites are, in general, 2 to 25 times more conductive than the host granites (Hausel et al., 1979a; Woodzick et al., 1980). This conductive difference indicates some promise for prospecting by electrical methods in Colorado and Wyoming, particularly in interfluve areas where the alluvial cover is relatively thin.

Seismic exploration for kimberlite in Lesotho shows that basalt generally has a higher velocity than kimberlite, so seismic refraction does not appear to be useful for exploration in that terrane (Burley and Greenwood, 1972). Seismic velocities in the Colorado-Wyoming State Line kimberlites are roughly equivalent to those in the granitic country rock; thus, seismic surveys are essentially useless for prospecting in this area (Hausel et al., 1979a; Puckett, 1971).

The physical properties of the kimberlites and their host Precambrian crystalline rocks in the Colorado-Wyoming State Line District are too similar to allow successful utilization of geophysical techniques in prospecting for kimberlite in this area. However, selected geophysical surveys can be used quite effectively in establishing kimberlite contacts in the Colorado-Wyoming State Line District.

Alluvial Sampling for Heavy Mineral Indicators

Once a general target area is identified, a stream sediment sampling program is initiated in an effort to recover kimberlite heavy mineral indicators (e.g. chrome diopside, pyrope garnet, magnesian ilmenite) (Figure 6). This phase of exploration is widely used in exploration for kimberlite and is probably the single most effective technique for locating kimberlites.

The first phase of alluvial sampling in the Colorado-Wyoming kimberlite province involves the location of potential sample sites on topographic maps (with the aid of aerial photographs) prior to entering the field. In new target areas, stream sediment samples are collected in a systematic pattern with a spacing of approximately 0.5 to 1.0 miles (0.8 - 1.6 km) along significant drainages. If indicator minerals are identified, additional samples generally are needed to isolate sources, and as many as 10 supplementary samples may be collected per square mile (2.6 km^2). This sample distribution provides for excellent representation of a large area.

Where water is available at or near the sample sites, each sample is panned in the field to reduce bulk and to increase heavy mineral content. Approximately 5 to 10 pounds (2.3 - 4.5 kg) of panned material is collected or, where no water is available, about 10 to 20 pounds (4.59 kg) of material is collected, at each sample site. The samples are washed and sieved and separated into major size fractions in the laboratory. (At Colorado State University, sample splits of 1 to 2 pounds (0.45 - 0.9 kg) were removed and retained for possible future geochemical analysis.) The bulk of each sample is passed through a sluice after the coarse fraction (greater than 3.3 mm) has been removed and examined visually (this fraction is removed in the field where collection sites are less accessible). After the removal of strongly magnetic mineral constiuents (mainly magnetite and ferro-ilmenite) from the sluice concentrates, the samples are examined with a binocular microscope for the presence of kimberlite indicator minerals. Suspect pyrope garnets are examined for refractive index (IR = 1.705 - 1.755) with immersion oils and checked for specific gravity (S.G. = 3.5 - 3.8), and magnesian ilmenites are isolated by magnetic means (Leighton and McCallum, 1979). The presence of chrome diopside is obvious because of its characteristic emerald green color and excellent parting and cleavage. All positive shows are followed by detailed ground surveys in an attempt to locate sources. Several new kimberlites were discovered during the follow-up studies; but a few anomalies have not led to discoveries, and additional ground surveys are planned for these areas.

It should be emphasized that alluvial sampling for heavy mineral indicators utilizing the moderate density sampling program described may miss some kimberlites. The presence of the Sloan 3 diatreme, which was established by Mabarak (1975) as a result of a close-spaced high density stream sediment sampling program, was not revealed in a lower density sampling program recently completed by Leighton and McCallum (1979).

Sampling interfluves for heavy minerals has not been utilized appreciably to date, primarily because of lack of personnel. However, we plan to employ this method more in the future, especially in areas where anomalies have not led to kimberlite by other ground survey techniques.

The distribution of heavy minerals around kimberlite pipes and the distances that the diopside, pyrope, and magnesian ilmenite can be transported in streams has not been determined for the Colorado-Wyoming province. However, a limited study by Leighton and McCallum (1979) in the area including and proximal to the Sloan diatremes suggests limited stream transport distances of kimberlite indicator minerals in that area. Pyrope was detected as far as 1.5 miles (2.4 km) from its source, magnesian ilmenite 2.5 miles (4 km), and chrome diopside never more than one-quarter mile from a kimberlite source. Leighton's and McCallum's results are in good agreement with a sample survey conducted by Hausel et al. (1979b) in the vicinity of the Schaffer, Aultman, and Ferris pipes. These observations are also similar, in general, to those reported by Mannard (1968) in eastern, western, and southern Africa. Heavy mineral halos developed in soils around the Manyu North Pipe in Tanzania indicate that the ilmenite halo is most extensively developed, followed by pyrope garnet and chrome diopside. The rarity of chrome diopside in alluvial deposits results from the breakdown of the pyroxene during transport because of well developed (110) cleavage and (001) parting. Mannard (1968) indicates that chrome diopside is rarely found more than one mile from its source, whereas garnet persists for a few miles, and magnesian ilmenite is carried several miles from its source.

Under different environmental conditions, the maximum transport distance of heavy minerals varies. Satterly (1971) points out that in the subarctic glacial environment of Siberia, chrome diopside, pyrope garnet, and magnesian ilmenite are reported as far as 30 miles (48 km), 95 to 125 miles (153 - 200 km), and greater than 125 miles (200 km) from the kimberlite source rocks, respectively.

Environmental conditions occurring in Colorado and Wyoming compare more favorably with those in South Africa than Siberia, and this is reflected by indicator mineral transport distances that are more in accord with those reported by Mannard (1968) for the African kimberlite districts.

Eluvial Indicators of Kimberlite

The eluvial material over kimberlites in Colorado and Wyoming is distinct from weathered material covering Precambrian granitic host rocks. The soils developed over kimberlite are typically light blue to grey (blue ground) and are rich in montmorillonite, chlorite, serpentine, talc, magnesium vermiculite, and calcite, whereas granitic soils are generally yellow-brown to brown and contain abundant quartz, feldspar, and kaolinite (McCallum, 1974). Kimberlite soil profiles may exceed 10 feet (3 m) in thickness as opposed to granitic soils, which are seldom more than one foot thick. The greater thickness of kimberlite soils is ideal for the activity of badgers and other burrowing animals that commonly bring diagnostic kimberlitic material to the surface, even in areas where masking covers of granitic alluvium or colluvium are present.

Many kimberlitic eluvial deposits contain abundant rounded nodules of mantle or lower crustal rocks, and several kimberlites were located by the presence of abundant upper mantle megacrysts of magnesian ilmenite and pyrope garnet up to several inches (several cm) in maximum dimension (Figure 7, 8). Megacrysts and xenocrysts of the deep green chromium-rich and the light olive green to blue-grey chromium-poor diopsides occur in lesser concentrations than ilmenites and garnets, but have been important in some pipe discoveries. Also useful in locating kimberlites in the Colorado-Wyoming State Line District is the presence of Lower Paleozoic sedimentary xenoliths and significant concentrations of caliche on eluvial material.

Types of deep-seated nodules that have been found in eluvial deposits over diatremes include: (1) mantle derived peridotite, eclogite, carbonatite, and monomineralic nodules, and (2) lower crustal granulite, pyroxenite, and altered basalt(?) (Eggler and McCallum, 1973; 1974; McCallum and Mabarak, 1976a; McCallum et al., 1977). Peridotite nodules commonly are silicified, and are characterized by pronounced boxwork structures on their surfaces (Figure 9).

Nodular material has been found several hundred yards downslope or downstream from its kimberlite source, and a few pipes were located by tracing the nodules upslope to their source.

Geochemical Prospecting

Geochemical exploration techniques have not been widely used in the search for kimberlites because heavy mineral sampling procedures are generally considered to be quicker and more effective (Lampietti and Sutherland, 1978). However, the potential of geochemical methods has been suggested by a number of workers (e.g. Holman, 1956; Webb, 1956; Alcard, 1959; Litinskii, 1961; 1963a; Kosolopova and Kosolopov, 1963; and Gregory and Tooms, 1969), and preliminary studies on the effectiveness of geochemical exploration in the State Line District are being conducted (McCallum, 1979).

Kimberlites, like all ultramafic rocks, are enriched in Mg, Fe, Mn, Ni, Co, Cr, and Ti; however, they also contain significant concentrations of Ca, Ba, Sr, Rb, P, Nb, Zr, and rare

Figure 3. High altitude (U-2) air photograph over the Colorado-Wyoming State Line District. A large, concentric feature about 9 miles (14.5 km) in diameter dominates Precambrian structures at this scale. This feature is the Virginia Dale ring dike complex, which may be a deeply dissected Precambrian caldera (Eggler, 1967). Scale is 1:192,000.

Figure 4. Low altitude color photograph (U.S. Forest Service photo, scale 1:24,000) over the Ferris 1 and 2 pipes. The Ferris 1 pipe is the white to light-gray concentric feature lying immediately north of the "triple junction" formed by Night Creek and its tributary (right center). At its maximum dimension, the Ferris 1 pipe measures approximately 300 feet (100 m) across. The Ferris 2 pipe, about 550 feet (150 m) southeast of the Ferris 1, cannot be seen on the photograph. The white coloration reflected from the Ferris 1 pipe is principally due to the abundant Lower Paleozoic carbonate xenoliths exposed at the surface.

A

B

Figure 5. (A) Color oblique photo, and (B) false color infrared oblique photo, of the Schaffer 15 pipe. Oblique photos of the Schaffer 15 kimberlite pipe taken from a nearby ridge during the Fall of 1978. These photos demonstrate that the kimberlite eluvium is distinctly outlined by a thick, lush, grassy vegetation. The pipe occurs as an elongated feature (in the center of the photographs) and is completely barren of tree growth although this region is moderately forested. The fence dividing the pipe trends east-west.

Figure 6. Heavy mineral indicators used to prospect for kimberlite. The two small deep green crystals near the center of the pan with distinct cleavage and parting are chrome diopside. Magnesian ilmenite occurs as bluish-black metallic nodules, and pyrope garnet is the deep red to purple nodular material. The base of the pan is 8.25 inches (20.96 cm) in diameter.

Figure 7. A kyanite eclogite nodule from the upper mantle. Centimeter scale.

Figure 8. Pyrope garnet megacryst collected from a drainage immediately east of the Schaffer 19 and 20 pipes in Wyoming; cm scale.

Figure 9. Silicified peridotite nodule with boxwork structure collected on the Schaffer 15 pipe, Wyoming. It measures 11.5 centimeters across in its maximum dimension.

earth elements (Gregory and Tooms, 1969). In terranes where other ultramafic or mafic rocks are absent, anomalous levels of Ni and/or Cr in stream sediments or soils might be indicative of kimberlite, but these elements have limited use to exploration in the State Line District, as basaltic to andesitic dikes and mafic metamorphic rocks are abundant locally. Elements with greatest geochemical potential for locating kimberlites in the Colorado-Wyoming districts appear to be Nb and certain rare earth elements (McCallum, 1979).

Structural Trends

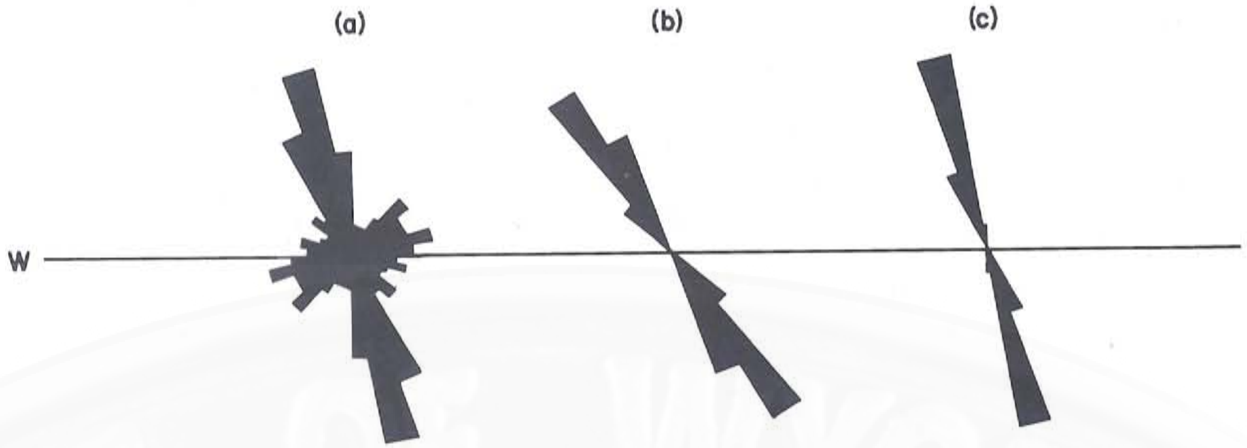
Following the discovery of new kimberlites, detailed ground surveys are initiated within the immediate area of each new occurrence. These surveys place special emphasis on structural relationships, especially linear trends associated with the diatremes. For example, the trend of many kimberlite pipes in the State Line District is northwest, and the diatremes generally have surface outlines that are elongated in the direction of alignment. This trend roughly parallels prominent joint sets and trends of many Precambrian porphyritic diabasic dikes (Figure 10). The Sloan 1 and 2 diatremes in Colorado are fault controlled: the Sloan 1 pipe crops out at the intersection of the Prairie Divide Fault with the Copper King Fault, and the Sloan 2 diatreme is exposed to the northwest of the Sloan 1 on the Prairie Divide Fault (McCallum et al., 1977). Emplacement of the Nix diatremes is also apparently fault related.

In the Iron Mountain District, kimberlite distribution reflects an overall northeast trend that is believed to be controlled by pervasive jointing (Smith, 1977). The joint trends are extremely variable and are reflected in the variable trend of the kimberlite dikes and blows.

DELINEATION

Kimberlites in northern Colorado and southern Wyoming have been truncated by multiple erosion surfaces and generally show no appreciable topographical relief. A few kimberlites are characterized by prominent positive relief resulting from silicification of wall rock immediately adjacent to the kimberlite. This relationship is most prevalent in the Iron Mountain District (Smith, 1977). Boundaries of many kimberlite bodies commonly can be defined by the distribution of kimberlitic eluvial material; namely weathered kimberlite (blue ground), xenocrysts, megacrysts, and xenoliths, and by vegetative changes (Figure 11). At many sites, kimberlite contacts are difficult to establish accurately because of blanketing alluvial and colluvial covers. This is especially true where pipe surfaces are sloping.

Geophysical surveys were conducted over several diatremes in Colorado and Wyoming, and results indicate that such surveys may be useful in defining the boundaries of the kimberlite. Resistivity surveys were most successful, and the detection of small magnetic anomalies over some pipes suggests that magnetics might have limited use. Seismic refraction surveys and resistivity soundings were attempted over some kimberlites to determine if vertical variations in pipe structures could



Trend diagram of (a) 744 joints (b) six? kimberlite lineaments (c) twenty-five "andesitic" dikes in the Wyoming State Line District

Figure 10. The trend of joint sets in granite and of the diabasic ("andesitic") dikes in the State Line District suggest that dike emplacement was controlled by pervasive jointing. Kimberlite pipe alignments dominately trend several degrees from the Precambrian trends and suggest that Precambrian structures probably had very little control on these kimberlite emplacements. However, some Precambrian structures appear to be important in the emplacement of a few diatremes. For example, the Ferris 1 pipe straddles a Precambrian diabasic dike and this relationship suggests that the fracture containing the dike may have played an important part in the emplacement of the Ferris 1 pipe, and Smith (1977) suggests that the emplacement of the Iron Mountain kimberlites was controlled by pervasive jointing in that district.

be detected. No gravity anomalies were realized. Cursory scintillometer surveys produced no radiation levels detectable above background over any of the examined kimberlites.

The contacts of several diatremes were mapped on the basis of differences in soil coloration and vegetation. Some of these diatremes were selected as sites to compare the results of geological mapping with those of the various geophysical surveys tested in this investigation. Stations were established every 20 feet (6.1 m) along sets of three traverses across the Aultman 1, Aultman 2, Schaffer 3, and Schaffer 15 diatremes and were surveyed for elevation. The stations were fixed with wooden stakes so that several geophysical surveys could be tested across the same profiles. Furthermore, base stations were established to correct for natural variations in the earth's geophysical parameters.

Electrical Resistivity Surveys

A Craelius ABEM Terrameter model G-2698 low frequency AC resistivity meter was used in a Wenner arrangement with 20 foot (6.1 m) spacing between electrodes for the resistivity profiling measurements (horizontal profiling), and the same arrangement with progressively expand-

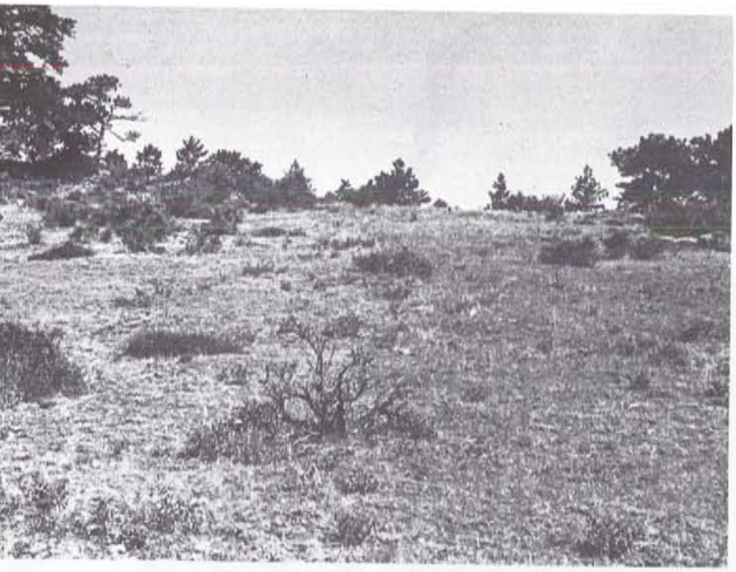


Figure 11. The Wyoming Schaffer 15 pipe shows a distinct contact between granitic soils (left) and kimberlitic soils (right) as outlined by vegetation.

ing equal spacing between the current and potential electrodes was also used across the Aultman 1 diatreme for resistivity sounding measurements (vertical profiling). It was assumed that the depth of current penetration was approximately equal to the electrode separation in the resistivity interpretations. The horizontal profiling data show that kimberlite is more highly conductive than the host granites (Figure 12). The apparent resistivity of weathered kimberlite is between 80 and 250 ohm-feet (24-76 ohm-m) compared to 500 to 7400 ohm-feet (152-2256 ohm-m) in the granite. Resistivity profiling measurements were used successfully to refine the kimberlite/granite contacts. These results are in good agreement with Puckett (1971) and somewhat in agreement with Ray (1963). Puckett observed resistivity values ranging between 80 and 100 ohm-feet (24-30 ohm-m) over the Sloan 1 in Colorado, whereas Ray observed apparently erroneous low values over the Ferris 1 diatreme in Wyoming.

Results of resistivity soundings across the Aultman 1 diatreme suggest the presence of 3 layers of differing conductivity (Figure 13). The surface layer is a fairly conductive 10 to 20 foot (3.0 - 6.1 m) layer with an apparent resistivity of approximately 650 ohm-feet (200 ohm-m) that is interpreted to represent a mixture of Lower Paleozoic carbonate rocks, organic-rich debris, weathered kimberlite, and grus. (Although not detected, the upper layer of Aultman 1 pipe may consist of the two separate layers as suggested by Puckett's (1971) seismic survey across the Sloan 1 pipe.) Beneath the surface layer is a 30 to 50 foot (9.1 - 15.2 m) thick highly conductive layer with an apparent resistivity of approximately 115 ohm-feet (35 ohm-m) that is interpreted to be weathered kimberlite. The highly conductive properties are believed to be the result of water saturation associated with montmorillonitic clays. The third layer is highly resistive 650 ohm-feet (greater than 200 ohm-m) as compared to the upper layers; however, it was not precisely defined in that the required extended electrode separation was not achieved. Based on current knowledge of the structure of kimberlite diatremes, it is suggested that this layer is dense, partially weathered to unweathered kimberlite.

Results of resistivity surveys in the State Line District indicate that the conductive properties are highly contrasted between weathered kimberlite and the host granites. However, the routine use of resistivity prospecting offers little promise because of the relatively small size of the conductive targets. The use of resistivity surveys has been limited to defining kimberlite boundaries of newly discovered diatremes and providing some idea of vertical variations within larger occurrences. Such surveys may also be applicable to locating shallow blind diatremes along known structures.

Magnetic Surveys

Magnetic measurements over kimberlite diatremes in the State Line District were taken with a Geometrics G816 proton magnetometer which has an accuracy of ± one gamma in weak to moderate magnetic gradients. Anomalies measured over the diatremes are weak but should be correct within the accuracy range of the instrument. The proton magnetometer measures the total magnetic field, as opposed to other instruments such as fluxgate magnetometers which measure the vertical component of the magnetic field. Differences between total and vertical magnetic fields in the State Line District are only slight if remnant magnetism is considered negligible, and varies from station to station as the sine of the inclination of the earth's total field. The inclination at the State Line area is approximately 71°

Magnetic surveys were conducted along the same profile stations that were established for resistivity surveys. A base station was established on each diatreme and during the course of each survey was reoccupied several times so that the diurnal effects of the earth's magnetic field could be recorded and corrected for in the measurements. All data were smoothed using a 3 point weighted running average to reduce the effects of magnetic noise.

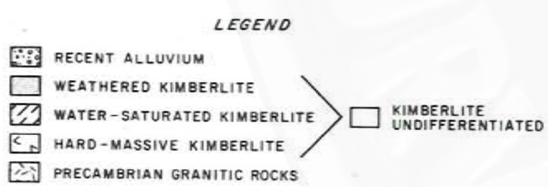
Figure 12 shows the magnetic profiles across the Aultman 1 and 2 diatremes. The Aultman 1 and 2 diatremes produced only weak anomalies, compared to the host granitic rocks. These data are comparable to results obtained on the Sloan 1 (Puckett, 1971) and on the Schaffer 3 and 15 diatremes which, in general, exhibit weak magnetic highs displaced slightly south of the southern granite/kimberlite contact. For example, the Aultman 1 shows a weak magnetic high of approximately 50 to 60 gammas over the granite at the southern boundary of the pipe, and the Aultman 2 shows a similar high of about 20 to 30 gammas. Most of the diatremes also exhibit magnetic lows of 10 to 50 gammas below background over the pipe proper, although magnetic highs are evident over some pipes (e.g., 1000 gammas at the Nix 2; Woodzick et al., 1980) and at isolated sites within pipes (e.g., 250 gammas within the Sloan 1 pipe; Puckett, 1971). The local presence of magnetic highs in the State Line kimberlites is probably due to local concentrations of ultramafic nodules, finely disseminated magnetite in serpentinized iron-rich olivines or the localization of abundant spinels in the kimberlite matrix (Puckett, 1971).

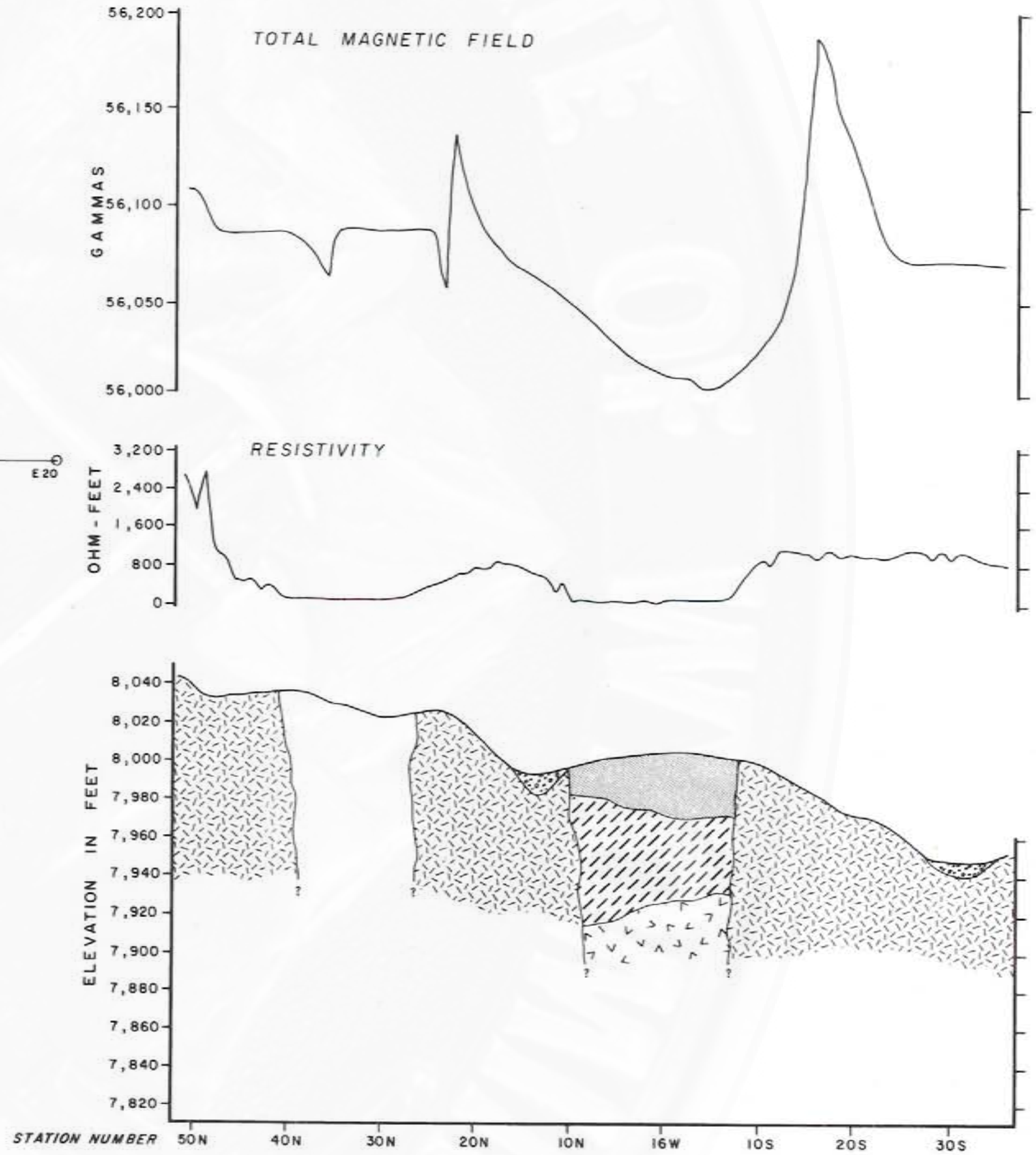
The small magnitude of the magnetic anomalies related to most kimberlite diatremes in the State Line area implies that magnetic surveys should probably be of only limited value in prospecting for kimberlite within the Precambrian terrane of Colorado and Wyoming. If the magnetic anomalies were projected upward, it would be highly unlikely that these anomalies would continue to any great distance above the ground level; i.e., airborne magnetic surveys would probably not "see" kimberlite related magnetic anomalies.

Seismic Surveys

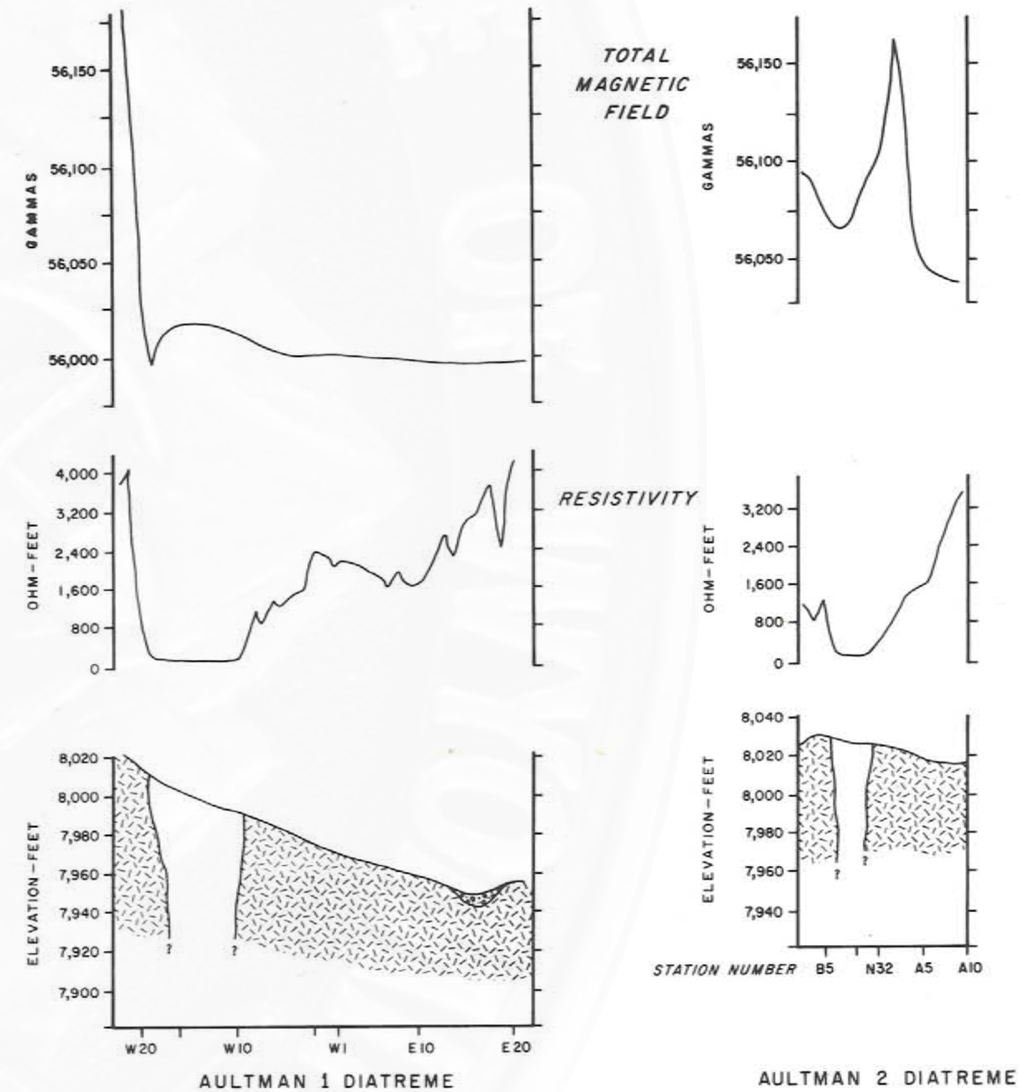
Seismic refraction surveys were conducted using a Huntec Model FS-3 portable facsimile seismograph over the Aultman 1 diatreme. The seismic survey results indicate three distinguishable dipping layers (Figure 14). The top layer varies from 13 to 38 feet (4 - 11½ m) thick and has an average seismic velocity of 2200 ft/s (670 m/s). The intermediate

PLAN VIEW OF AULTMAN 1&2 KIMBERLITE DIATREMES BASED ON GEOLOGY





(B) N-S PROFILE OF AULTMAN 1&2 KIMBERLITE DIATREMES



(A) W-E PROFILE OF AULTMAN 1 & 2 KIMBERLITE DIATREMES

Figure 12. (A) West-east and (B) north-south apparent resistivity and magnetic interpretations of the Aultman 1 and Aultman 2 pipes. The kimberlites are 2 to 25 times more conductive than the enclosing granite. Magnetic anomalies are commonly small, usually less than ±100 gammas. The cross section interpretation of the Aultman 1 pipe (B) shows three distinctive electrical and seismic layers.

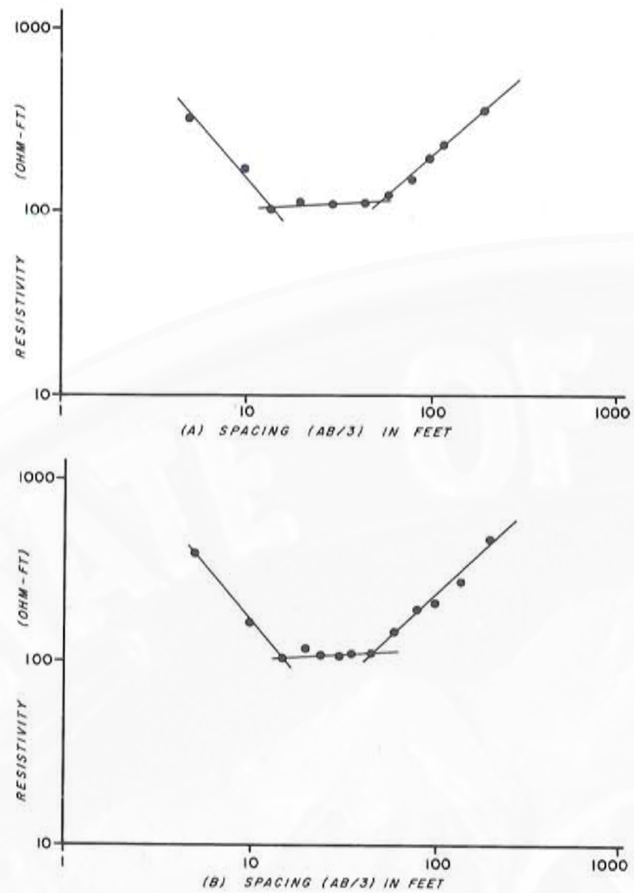


Figure 13. (A) North-south and (B) east-west resistivity sounding plots in the Aultman 1 pipe. Apparent resistivity sounding surveys were conducted using a Wenner configuration with inter-electrode spacing ranging from 5 to 200 feet (1.5 - 61 m). The plot is consistent with a simple dipping layer model. Apparent resistivities are approximately 650 ohm-feet (200 ohm-m) for the top layer, 115 ohm-feet (35 ohm-m) for the middle layer, and greater than 650 ohm-feet (200 ohm-m) for the bottom layer.

layer varies in thickness from 53 to 74 feet (16-22½ m) and has an average seismic velocity of 5218 ft/s (1590 m/s). The higher velocity, dense kimberlite lies below the intermediate layer, and its average velocity is 11,578 ft/s (3529 m/s).

Our results compare favorably with those of Puckett (1971), who observed a 4-layer case in the Sloan 1 pipe. Puckett was able to differentiate a composite upper layer consisting of two separate soil horizons which were not differentiated at the Aultman 1. Seismic velocities over the granites range from 7000 ft/s (2135½ m/s) to 16,000 ft/s (4877 m/s). These data suggest that seismic prospecting in

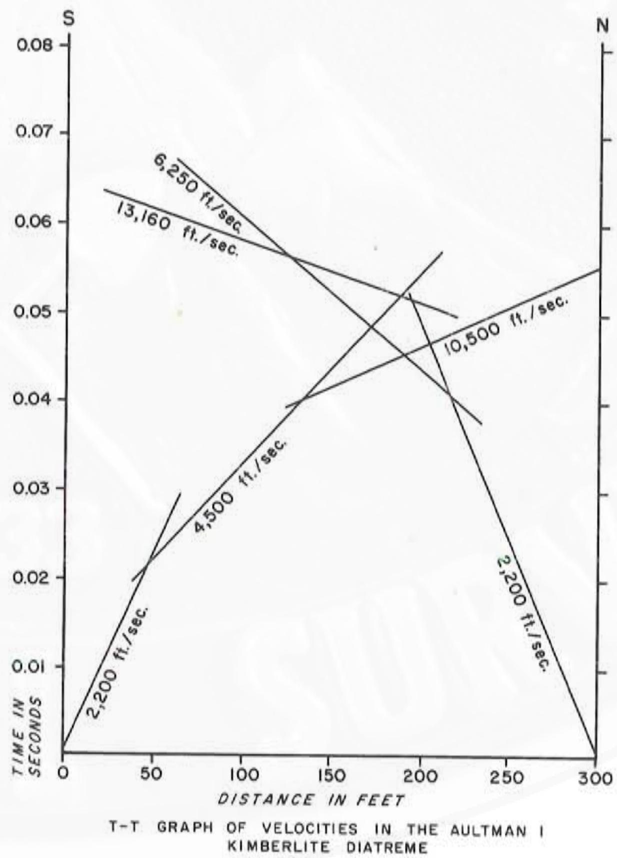


Figure 14. Seismic velocity plot across the Aultman 1 diatreme. The seismic data are in good agreement with the resistivity sounding plot. Three dipping layers are interpreted from the data.

the Precambrian terrane of Colorado and Wyoming will not uniquely differentiate kimberlite from granite.

Gravity Surveys

Gravity surveys were conducted over several of the kimberlites in the State Line District using a Worden gravity meter. Gravity anomalies should be expected over rocks with densities as contrasting as those of granitic and ultramafic rocks. However, the high serpentine and carbonate content of most kimberlites contribute to density values that are lower than expected, and which are comparable to those of the granitic rocks of the area (McCallum and Eggler, 1971). Consequently gravity surveys appear to have little potential as a tool in kimberlite exploration in the region.

Miscellaneous Surveys

A McPhar scintillometer Model TV-1A was used to examine several diatremes for scintillation counts. Brookins et al. (1977) report that several kimberlites in the United States are enriched in uranium compared with other ultrabasic and ultramafic rocks, and they report an average of 5.25 ppm uranium content for a Colorado kimberlite. However, scintillation counts here showed no observable change from background over the kimberlites, which would be expected in a granitic terrane where average background counts from the granites are comparatively higher than the average background from more basic igneous rocks. Several pegmatites in the immediate area gave counts of 2 to 3 times background.

A new technique using a portable microwave instrument was tested on the Schaffer 3 diatreme by Belsher and McLaughin of the U.S. Bureau of Standards in an attempt to differentiate kimberlite from granite. This testing is only preliminary and no definite results are available, to date.

ASSESSMENT

The final phase of kimberlite exploration involves assessment of the diamond potential. During this phase, 100 to 200 pound (45.4 - 90.7 kg) samples of weathered kimberlite are collected from each diatreme to be tested for diamonds. Diamond testing of the State Line kimberlites has been conducted at Colorado State University, and, to date, more than 90 small diamonds have been recovered (McCallum et al., 1979). Additionally, the Wyoming Geological Survey is presently testing several pipes for diamonds.

Processing involves size separation of weathered kimberlite by sieving and concentration of the heavy minerals in a sluice. Material larger than 3.3 mm is examined visually. The smaller sized splits are processed in a sluice with a water flow rate adjusted to concentrate minerals with a specific gravity greater than 3.0. The sluice concentrates are dried and, after removal of magnetite with a hand magnet, are placed in a 52 percent hydrofluoric acid bath for two to four weeks to digest the majority of the heavy minerals. Following the acid bath, most of the paramagnetic minerals are removed from the residual fraction in a Franz magnetic separator. The remaining concentrate is examined through binocular and polarizing microscopes, and suspect crystals are tested for hardness and index of refraction (McCallum and Mabarak, 1976a and b).

Diamonds were first discovered in a serpentinized garnet peridotite nodule collected from the Schaffer 3 pipe on Wyoming School Section 16 (McCallum and Eggler, 1976). Since the discovery, diamonds have been recovered from twelve separate pipes in the State Line District which include the Schaffer 3, 10, 13, 15, 16, and 19 pipes; the Aultman 1 pipe; the Ferris 1 pipe; two of the four Nix pipes; and the Sloan 1 and 2 pipes. The largest reported diamond was recovered from the Sloan 2 pipe and weighs 11.8 mg (0.059 carat or 5.9 points*) (McCallum et al., 1977; 1979).

Diamonds have not been found in the Colorado-Wyoming province in kimberlites other than those of the State Line District. Kimberlites in the Iron Mountain District have been examined for diamond, but without success. However, the nature of these occurrences suggests that, if diamonds are found, they probably are not present in commercial quantities, at least not in the kimberlites. Exposures at Iron Mountain are small and apparently represent deeply eroded remnants or "root zones" of diatremes (McCallum et al., 1977). In general, the diamond content of known producing diatremes decreases with decreasing size and increasing depth, and small blows and dikes are typically diamond poor (Smith, 1977).

If it can be shown that the Iron Mountain kimberlites are diamond-bearing, then the main thrust of exploration in that district should be centered on the location of placer deposits. Similar exploration would be recommended in the State Line District, since several hundred vertical feet of pipe have been removed by erosion.

Figure 15. These two diamonds were recovered by Paul Boden from a placer mining operation in the Mullison Park area of the Medicine Bow Mountains. The crystals were positively identified using hardness and X-ray techniques at the Wyoming Geological Survey (Hausel, 1977). Millimeter scale.

Placer diamonds have been identified (Hausel, 1977) in stream sediment concentrates reportedly extracted nearly 70 miles (112 km) to the west of Iron Mountain on the northern flank of the Medicine Bow Mountains (Paul Boden, personal communication, 1977) (Figure 15). Two crystals were recovered and tested for hardness and X-ray characteristics. Both crystals exhibit good octahedral habit and show no sign of damage from transport; however, lack of damage is no indication of a nearby source. Diamonds from the South West African placer deposits are believed to have been transported some 1,000 miles (1610 km) from their source at

*A metric carat equals 200 mg, and one point is equal to 0.01 carats.

Kimberley, South Africa (Lampietti and Sutherland, 1978), and many of these crystals are preserved as excellent, good quality octahedrons with no hint of transport damage (A.E. Waters, Jr., personal communication, 1978).

Economic Assessment

Determining the grade of diamond-bearing kimberlite rock is not a simple task, principally because diamond, when present in kimberlite, is only a trace mineral, seldom in concentration greater than 1 ppm. McCallum and Mabarak (1976) report that average kimberlite ore runs at about 0.25 carat/ton, or about one part diamond per 20 million parts waste rock (0.000005 percent). In order to test for these small diamond concentrations in kimberlite and determine economic ore grade, the diatremes should be drilled to several hundred feet depth to determine dimensions and attitudes, and several thousand tons of rock (at least 10,000 tons) should be processed from each pipe.

The State Line District kimberlites cannot be properly assessed as to their economic potential by personnel at Colorado State University or the Wyoming Geological Survey because of the large bulk samples that are required for testing. Because of this restriction, the State of Wyoming and Rocky Mountain Energy Company (landowners) decided to grant an assessment permit to a mining company with experience in diamond exploration and assessment. Cominco American Incorporated, was granted an exploration permit by the Wyoming Department of Environmental Quality in the Fall of 1978 to collect test samples in the Wyoming portion of the State Line District. Actual assessment of the diatremes to determine the economic potential of the diamond-bearing kimberlites will probably take several years.

COLORADO-WYOMING DIAMONDS

More than 90 diamonds have been recovered from weathered kimberlitic material in Colorado and Wyoming. They range in size from 0.2 mm to 2.0 mm in average diameter and weigh less than 0.25 to 5.0 points (0.5 - 10 mg). The largest authenticated stone recovered from these kimberlites is a distorted octahedron from the Sloan 2 which measures 1.3 x 1.75 x 2.8 mm and weighs 11.8 mg or nearly 6/100's of a carat (McCallum et al., 1977; 1979). The recovered diamonds are predominantly aggregates and octahedrons with some octahedral-dodecahedral transitionals, rhombic dodecahedra, flattened dodecahedra, and macles. These diamonds are predominantly colorless to glassy with a few white, light brown, and light yellow to nearly black crystals. Many of the crystals show pronounced fluorescence in ultraviolet light. Many of the diamonds also contain abundant inclusions (McCallum et al., 1979).

The two placer diamonds recovered from the Medicine Bow Mountains are both octahedral crystals showing well developed triangular growth platelets on the octahedral 111 faces. The crystals measure approximately 1.5 mm and 3 mm in diameter, and weigh 3.47 and 10.015 points (6.94 - 20.03 mg), respectively. Neither crystal fluoresces under ultraviolet light; the smaller crystal is colorless to glassy and the larger is pale yellow. Both crystals contain inclusions that are observable under a 10X lense (Hausel, 1977).

CONCLUSIONS

More than 90 Devonian kimberlites are known to occur in four separate districts in the Front Range and Laramie Range of Colorado and Wyoming. Twelve diatremes within the State Line District are known to be diamond bearing; however, no kimberlites in any of the other districts have been found to contain diamonds. Many of the kimberlites in the Colorado-Wyoming State Line District were tested by various remote sensing, sediment sampling, and geophysical techniques to determine the most efficient method of kimberlite prospecting in the area. Infrared remote sensing surveys show very promising potential, in that the method records variations in vegetation growing in kimberlitic versus host rock granitic soils. Electrical resistivity surveys are very useful in defining kimberlite contacts because of the abundance of water in the near-surface weathered kimberlite. Magnetic surveys gave only small dipolar anomalies, with the exception of 250 and 1000 gamma anomalies over the Sloan 1 and Nix 2 pipes, respectively. The most promising method of rapid exploration is sampling alluvial drainages for the heavy mineral indicators chrome diopside, pyrope garnet, and magnesian ilmenite. Chemical analysis of heavy minerals from stream sediment and soil samples for selected elements (e.g. Nb) might also be a valuable aid to kimberlite prospecting.

Two diamonds were reported from a placer mining operation on the northern flank of the Medicine Bow Mountains, more than 70 miles (112 km) west of the Iron Mountain District. These diamonds may reflect proximity to a new kimberlite district, but it is more likely that they have been reworked from nearby Tertiary sediments. No kimberlitic material or heavy mineral indicators (other than the diamonds) have been recognized in this area.

Chrome diopside and pyrope garnet were reported in ant hills in the Green River Basin. These minerals may be indicative of a nearby kimberlite source, but an equally reasonable interpretation is derivation from garnet peridotite.

Considerable additional work is necessary to properly assess all known Colorado-Wyoming kimberlite occurrences for diamonds, and extensive exploration will be required to locate undiscovered kimberlites and placer deposits. The number of recent discoveries of kimberlite made during the course of systematic exploration surveys suggests that many additional kimberlites still remain to be located, and this will best be achieved by initiation of more regionally focused prospecting programs.

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