THE GEOLOGICAL SURVEY OF WYOMING

Daniel N. Miller, Jr., State Geologist

REPRINT No. 36

PRELIMINARY REPORT ON EXPLORATION FOR DIAMONDIFEROUS KIMBERLITES, COLORADO-WYOMING

by

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Reprinted from the Colorado Mining Association 1979 Mining Yearbook

LARAMIE, WYOMING

1979

Preliminary Report On Exploration For Diamondiferous Kimberlites, Colorado-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 (phase I) 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.

Under phase II, the surface extent of newly discovered diatremes (or dikes) is delineated. Contacts between kimberlite and enclosing host rock are rarely exposed, but may be approximately located by the presence of weathered kimberlite, abundant mantle and/or lower crustal nodules, xenoliths of Lower Paleozoic sediments, caliche, and/or 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 microdiamonds to determine if the diatreme is diamondiferous. Considering that large volumes of material must be processed to evaluate the economic grade of a diamond pipe, none of the diatremes have 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

HISTORY AND DISTRIBUTION

Recently, the interest and curiousity of scientific, industrial, and public groups were stimulated by the unique discovery of diamonds in kimberlite diatremes in the State Line District, Colorado-Wyoming (McCallum and Eggler, 1976; McCallum and Mabarak, 1976 a and b; McCallum et al., 1978). Kimberlite, although a rare igneous rock, has received much attention over the years, primarily because of its economic and scientific importance, in that it is the only known primary source rock of economical concentrations of diamond, and it contains xenoliths of lower crust and upper mantle derived material. Because of its hardness, diamond is essential for the survival of modern industrial civilizations. This fact places special importance on the State Line discovery in that this is only the second authenticated occurrence of diamonds found, in place, on the North American continent (McCallum and Mabarak, 1976 a).

The first diatremes were discovered in 1960 and 1961 by C. S. Ferris, Jr. and C. A. Aultman, respectively, in the Northern Front Range of Wyoming, approximately 2 miles north of the Colorado border. The discoverers were attracted to the occurrences because of the unusual exposure of concentric rock bodies roughly 250 feet (76 m) in diameter containing blocks of Lower Paleozoic sedimentary rocks surrounded by Precambrian granite. Similar Paleozoic rocks are not found within 90 miles (145 km) of the locality. The true nature of the diatremes was not immediately recognized, and the sedimentary rocks were assumed to be preserved in concentric grabens (Chronic and Ferris, 1963). In 1964, M. E. McCallum recognized kimberlite in a similar feature (the Sloan 1) located nearly 14 miles (23 km) south of the initial discovery, and established all three structures as diatremes (Chronic et al., 1965). The discovery of six additional pipes by D. H. Eggler in that same year confirmed the existence of a kimberlite district (Eggler, 1967; McCallum and Eggler, 1968; McCallum et al., 1975). Since the diatreme nature of the kimberlites was established, a total of more than 90 separate occurrences have been identified primarily by McCallum and Colorado State University students, C. D. Mabarak, C. B. Smith, H. G. Coopersmith, C. E. Beverly, W. W. Oriel, V. L. Leighton, and D. L. Collins. Additional discoveries have been made by W. A. Braddock, K. Nordstrom, J. C. Cole, D. H. Eggler, M. Fischer, L. K. Burns, and W. D. Hausel.

Presently, kimberlites are known to occur within the Front Range as far north as Iron Mountain, 40 miles (64 km) to the north; and as far south as Green Mountain located 70 miles (113 km) to the south of the state line. Two major kimberlite districts are recognized. The State Line District straddles the Colorado-Wyoming state line south of Tie Siding, Wyoming, and extends approximately two miles north into Wyoming, and twelve miles south into Colorado (Figure 1). Nearly 40 separate kimberlite diatremes and dikes are mapped in this district. The Iron Mountain District located 40 miles (64 km) north of the state line, marks the northernmost extent of the known kimberlites in the region. This district was discovered in 1971 by W. A. Braddock and K. Nordstrom, and to date, fifty-seven kimberlite bodies, principally dikes and blows, have been identified (McCallum et al., 1975; Smith, 1977).

Isolated kimberlite dikes, discovered by J. C. Cole, occur in the Estes Park area of Colorado, approximately 40 miles (64 km) south of the state line, and a single pipe (Green Mountain Pipe recognized by W. A. Braddock) is located nearly 70 miles (113 km) south of the State Line District (McCallum and Mabarak, 1976; McCallum and Smith, 1978).

Based upon the presence of Ordovician and Silurian sedimentary rock xenoliths in several of the diatremes, and the absence of Mississippian – Pennsylvanian rocks, some which outcrop in the near vicinity of some pipes, a Late Silurian or Early Devonian age of kimberlite emplacement has been proposed (Chronic et al., 1969; McCallum et al., 1975). Fission-track dating of zircons indicates a Devonian age (Naeser and McCallum, 1977).

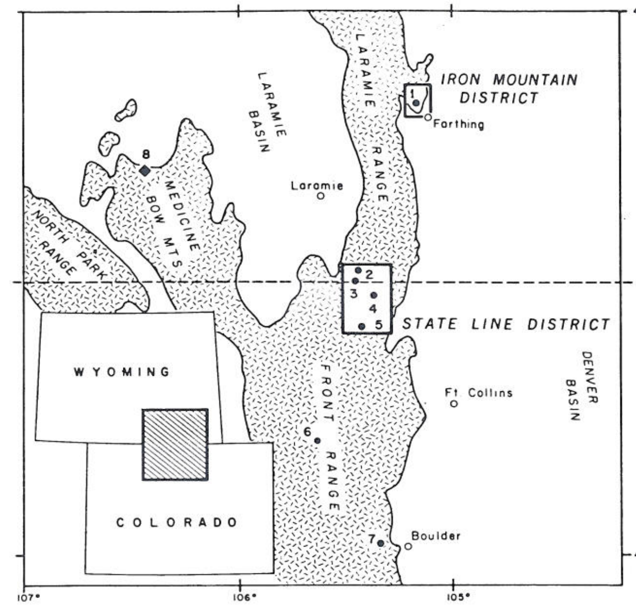


Figure 1. Index map showing general locations of kimberlite districts and the placer diamond occurrence. The numbers on the map locate the (1) Iron Mountain District kimberlites, (2) Aultman and Ferris pipes, (3) Schaffer pipes, (4) Nix-Moen pipes, (5) Sloan pipes, (6) Estes Park dikes, (7) Green Mountain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

Diamonds have only been found in kimberlites from the State Line District (McCallum et al., 1977, 1978), except for an isolated occurrence of two placer diamonds recently identified from stream sediment concentrates from the northwestern flank of the Medicine Bow Mountains, Wyoming (Hausel, 1977).

This unique discovery of diamonds in Colorado and Wyoming warrants further and continued investigation. Kimberlite exploration programs have been underway for several years at Colorado State University, and more recently, the Wyoming Geological Survey and several private exploration groups have entered into the search for kimberlite.

It is the purpose of this report to evaluate kimberlite exploration techniques and to summarize preliminary results of exploration conducted by researchers from Colorado State University and the Wyoming Geological Survey. The exploration phases are subdivided into three categories; (1) prospecting, (2) delineation, and (3) assessment.

NATURE OF KIMBERLITES

Before discussing techniques used to prospect for kimberlite in Colorado and Wyoming, it is appropriate to first review some general features related to kimberlite and its emplacement.

Kimberlite is considered to be the primary source of all economical concentrations of diamond, although many of the world's richest deposits are secondary placers. However, most kimberlites are not diamondiferous, and according to Lampietti and Sutherland (1978) only about 2% are economically mineralized. Even in the richest pipes, diamond occurs as a trace mineral that seldom attains concentrations greater than 1 ppm.

The presence of diamond in some kimberlites suggests that kimberlitic magmas were derived from a minimum depth of about 85 miles (137 km) below the earth's surface where the shield geotherm intersects the zone of graphite-diamond equilibrium. Calculations of temperatures and pressures of crystallization of ultramafic nodules found in State Line District kimberlites suggest that these kimberlites originated at depths that may have exceeded 120 miles (193 km)(Eggler and McCallum, 1976; Eggler et al., 1978; McCallum and Eggler, 1976). It should be apparent that not only are kimberlites potentially important economically, but they also provide a wealth of knowledge about the chemical and mineralogical makeup of portions of the earth's upper mantle and lower and upper 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). Kimberlites have been found only within (or marginal to) stable cratonic regions that have been free of major orogenies for a considerable period of geological history. Deep vertical fractures developed during epeirogenic disturbances appear to play an important part in the emplacement of kimberlite bodies (MacGregor, 1970). The suggestion is that the deep-seated fractures act as conduits for the rapid ascent of the magma from depth. Other igneous rocks associated with these epeirogenic events include carbonatites and alkalic assemblages. Older igneous rocks commonly occurring within kimberlite provinces include basalt, gabbro, diabase, peridotite and lamprophyres (Mannard, 1968). Kimberlite generally occurs in clusters or groups of diatremes commonly controlled by major factures. 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.

PROSPECTING (PHASE I)

REMOTE SENSING

Remote sensing imagery and aerial photography can be a valuable aid to the geologist in evaluating structural trends and major geological features. High altitude photographs and Landsat images can be used to evaluate and detect major structural features which could otherwise be missed on low altitude photographs and ground surveys. Low altitude photographs are used to define more detailed structural trends, and may even be useful in precisely locating kimberlite occurrences where the proper conditions exist.

For example, high altitude, near infrared photographs (1:192,000, U-2 project), over the State Line District clearly show the prominant concentrically banded nature of the Precambrian crystalline rocks in the Virginia Dale ring-dike complex (Eggler, 1967)(Figure 2). Fractures associated with the development of the ring-dike complex

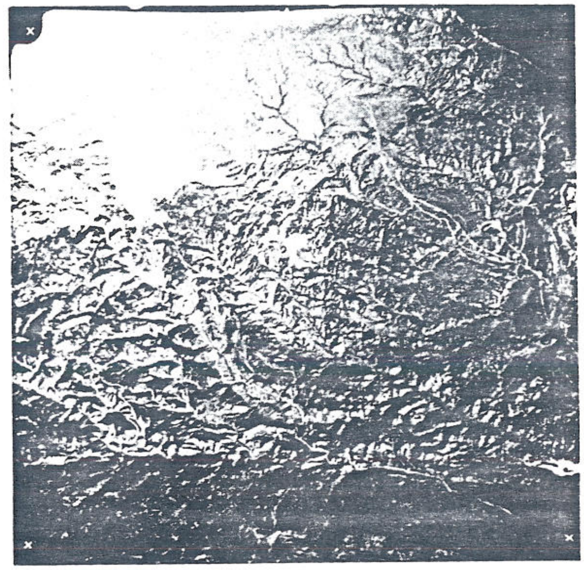


Figure 2. High altitude (U-2) photograph over the Colorado-Wyoming State Line District. A large, concentric feature approximately 9 miles (14.5 km) in diameter dominates Precambrian structures at this scale. This feature is the Virginia Dale ring dike complex (Eggler, 1967). Scale: 1:192,000.

as well as a number of late (?) Precambrian post-complex structures are also readily visible. Many diatremes show a preferential alignment along northwest trending fractures, and similar structures should be considered as primary exploration targets.

Low altitude color and black and white photographs (1:24,000), are used to examine major and minor lineations and structural trends in greater detail.

Low altitude false color infrared photography techniques have 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 forms thick layers of water-rich soil commonly exceeding ten feet (3 m) in depth over the State Line diatremes. 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 within the kimberlite soils. For example, grasses in kimberlite soils tend to be lusher and more dense than grasses developed over granites, and they are better infrared reflectors. However, trees generally do not grow in kimberlitic soils except in areas where the diatremes are blanketed by thick alluvium or colluvium.

This development of lush grassy vegetation over many kimberlite pipes 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 is at its lushest stage, false color infrared photos may show sharp contrasts between kimberlite and granite. Several known kimberlites with poorly developed soils showed 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.

Remote sensing methods have been principally used to identify target areas during the initial phases of the 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, geochemical sampling) are initiated.

GEOPHYSICAL PROSPECTING

Geophysical prospecting methods, although not widely utilized in kimberlite exploration, have met with reasonable success in some regions in the U.S.S.R. and Africa (Litinskii, 1963; Gerryts, 1967; Burley and Greenwood, 1972). In order for geophysical methods to be applicable to prospecting for kimberlite the geophysical characteristics of kimberlite versus the enclosing host rock must differ enough to be measurable. Since kimberlites intrude a variety of rock types around the world, the success of geophysical exploration differs from one kimberlite district or province to another.

In Yakutia province, U.S.S.R., magnetic surveys were used with great success in areas where differences in the magnetic susceptibility of kimberlite (susceptibility = 100 - 6000 x 10^{-6} emu/cm^3) to that of the intruded carbonates (susceptibility $\approx$ 0) were extremely high (Litinskii, 1963). Anomalies as great as 5000 gammas are reported which are successfully detected from airborne surveys (Litinskii, 1963). Equally good results were obtained from Mali in West Africa where the magnetic contrast between kimberlite and schist and sandstone countryrock 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.

Gravity surveys have been used in the U.S.S.R., Tanzania, and Lesotho with some success (Gerryts, 1967). In the U.S.S.R. gravity surveys were successful in locating kimberlite buried by trap. Strong negative anomalies as high as 6 milligals produced from the contrasting densities of the pipe rock and that of the sedimentary host were observed in Tanzania (Gerryts, 1967). However, in Lesotho, only the largest pipes were recognized on gravity surveys, and these anomalies (1-2 milligals) were quite small due to 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. However, 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 can be useful in identifying kimberlite.

Gerryts (1967) discusses some resistivity surveys in Africa. These surveys show that there are distinct conductive differences between weathered kimberlite and most host rocks. In the Congo, kimberlite displays an average resistivity low of 65 ohm-feet (20 ohm-m) compared to 1300 ohm-feet (400 ohm-m) in the host Precambrian limestone. In South Africa, resistivity differences were small, however, a kimberlite dike produced a 10 to 13 ohm-feet (3-4 ohm-m) reading compared to 40 to 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 countryrock. The apparent resistivity of weathered kimberlites in Lesotho is reported to vary between 48 ohm-feet to 350 ohm-feet (15-110 ohm-m) as compared to 800-4800 ohm-feet (245-1465 ohm-m) in contrasting basalts (Burley and Greenwood, 1972).

Seismic exploration for kimberlite in Lesotho showed that basalt, in general, has a higher velocity than kimberlite, thus seismic refraction does not appear to be useful for exploration in that terrane (Burley and Greenwood, 1972).

In general, kimberlites and the Precambrian crystalline rocks of Colorado and Wyoming have similar geophysical properties making it very difficult, if not impossible to prospect for kimberlite by geophysical techniques. Geophysical surveys have been used almost exclusively in the refining of diatreme contacts in the Colorado-Wyoming region.

ALLUVIAL SAMPLING FOR HEAVY MINERAL INDICATORS

It has been our experience in Colorado and Wyoming that once a target area is identified, a program should be initiated to sample alluvial drainages for kimberlite derived heavy mineral indicators (i.e. chrome diopside, pyrope garnet and magnesian ilmenite). This may not be the next phase of exploration in other kimberlite provinces, because of differing environment and geological conditions, but in the Colorado-Wyoming province it is one of the most efficient methods tested.

At the beginning of a stream sediment sampling program, collection sites are located on topographic maps with the aid of aerial photography prior to entering the field. In a new target area, stream sediment samples are collected in a systematic pattern with a spacing of 0.5 or 1.0 miles (0.8-1.6 km) along significant drainages. Areas with known kimberlites, such as the State Line District, are sampled in greater detail with as many as 10 to 20 samples taken per square mile (2.6 km^2), in an effort to locate additional kimberlites.

Approximately 6-10 pounds (2.7-4.5 kg) of alluvial material was collected at each station. In the lab, the samples are washed and sieved and separated into size fractions. At Colorado State University, sample splits of 1-2 pounds (0.5-0.9 Kg) were removed and retained for possible future geochemical analysis: the bulk of each sample was passed through a sluice after the coarse fraction (>3.3 mm) had been removed. The coarser splits are examined visually. After the removal of strongly magnetic mineral constituents (mainly magnetite and ferro-ilmenite) from the finer splits, the samples are examined with a binocular microscope for the presence of kimberlite indicator minerals. Suspect garnets are examined for refractive index with immersion oils, 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. All positive shows are followed by detailed ground surveys in an attempt to locate sources. A number of new kimberlites were discovered during the follow up studies, however, 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 site density 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 man power. 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 the heavy minerals around kimberlite pipes and the distances that the heavy minerals chrome diopside, pyrope, and magnesian ilmenite can be transported in streams has not been determined for the Colorado-Wyoming environment. However, a limited study by Leighton and McCallum (1979) in the area including and proximal to the Sloan diatremes indicates minimum 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 was never encountered more than one-quarter mile from a kimberlite source. These observations are 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 (Figure 3) indicate that the ilmenite halo is most extensively developed, followed by pyrope garnet, and chrome diopside. The rarity of chrome diopside in alluvial

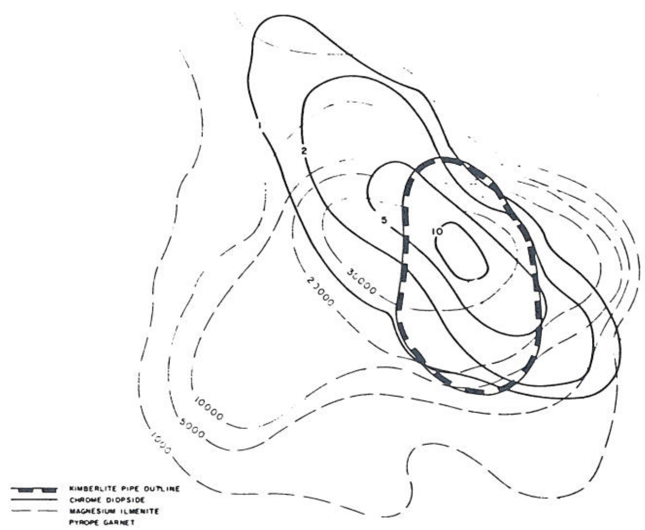


Figure 3. Heavy mineral haloes developed around the Manyu North Pipe in Tanzania. Similar heavy mineral haloes should be expected around the Colorado-Wyoming pipes (After Mannard, 1968, Figure 4, p. 20).

deposits results from the breakdown of the pyroxene during transport because of well developed [110] and [001] cleavage and parting, respectively. 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.

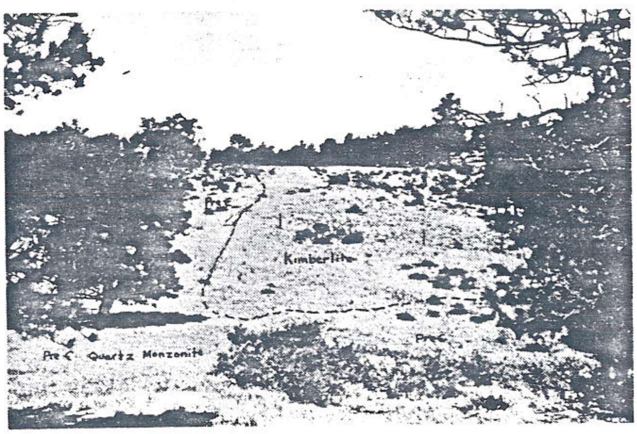
Under different environmental conditions, the maximum transport distance of heavy minerals varies. Satterly (1971) points out that in the subarctic glacial environment of Siberia, chrome diopside, pyrope garnet, and magnesian ilmenite are reported as far as 30 miles (48 km), 95 to 125 miles (153-200 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, sepentine, talc, magnesian vermiculite, and calcite, whereas granitic soils are generally yellow-brown to brown and contain abundant quartz, feldspar and kaolinite. Kimberlite soil profiles may exceed 10 feet (3 m) in thickness as opposed to granitic soils which are seldom more than one

a



b

Figure 4. (a) The Schaffer 15 kimberlite pipe shows distinct vegetative differences as compared to the enclosing granitic rocks. The pipe is outlined (b) by a more lush vegetation.

foot (0.3 m) 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 and/or lower crustal rocks and several kimberlites were located by the presence of abundant upper mantle megacrysts of magnesian ilmenite and pyrope garnet as much as several inches (cm) across. 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/or significant concentrations of caliche in eluvial material.

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

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.

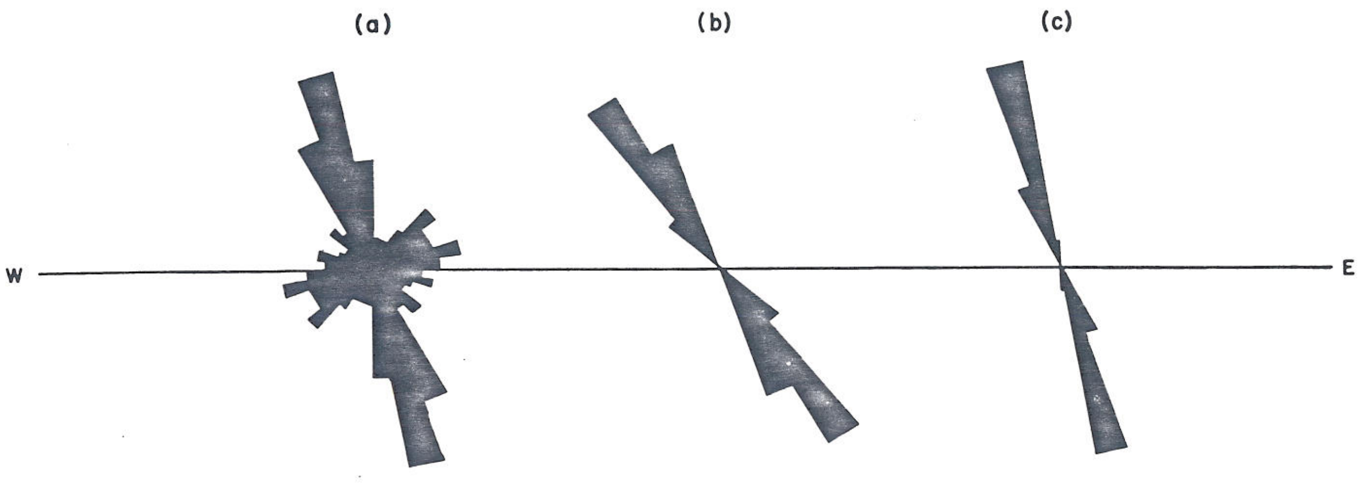
GEOCHEMICAL PROSPECTING

Geochemical exploration techniques have not been widely used in the search for kimberlites because heavy mineral sampling procedures generally are 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, 1963; Kosolopova and Kosolopov, 1962; and Gregory and Tooms, 1969), and preliminary studies on the effectiveness of geochemical exploration in the State Line District are being conducted (McCallum, In press).

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 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 limtied 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 Ba, Nb, and cettain rare earth elements.

STRUCTURAL TRENDS

Following the discovery of new kimberlites, detailed ground surveys are initiated within the immediate area of the new occurrence. These surveys place special emphasis on structural relationships, especially any associated linear trends 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 5). The Sloan diatremes in Colorado are fault controlled, the Sloan 1 pipe outcrops at the intersection of the Prairie Divide Fault with the Copper King Fault, and the Sloan 2 diatreme is exposed to the north of the Sloan 1 on the Prairie Divide Fault (McCallum et al., 1977). Emplacement of the Nix diatremes was also apparently fault related.



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

Figure 5

Figure 5. 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 dominantly trend several degrees off strike from Precambrian trends and suggest that Precambrian structures probably had very little control on the emplacement of kimberlite magma. 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 dike may have played an important part in the emplacement of that pipe.

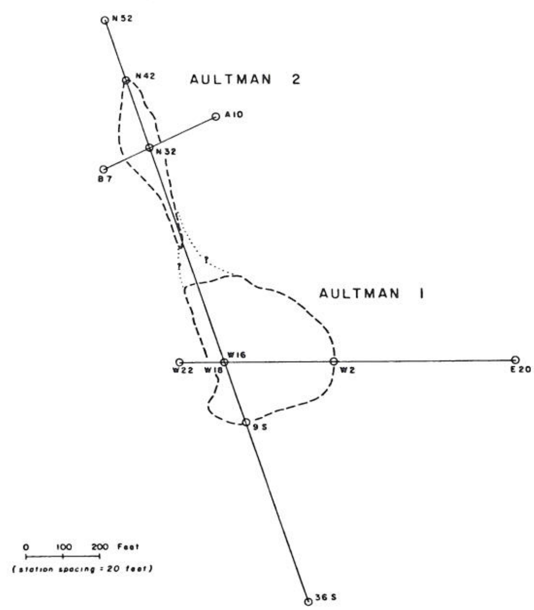
In the Iron Mountain District kimberlite distribution reflects an overall northeast trend that is believed to be controlled by pervasive jointing (Smith, 1977). The joint trends are extremely variable and are reflected in the variable trend of the kimberlite dikes and blows.

DELINEATION (PHASE II)

Kimberlites in Colorado and Wyoming have been truncated by multiple erosion surfaces and generally show no appreciable topographical relief. A few kimberlite outcrops have positive relief (e.g. Nix 1 & 2 pipes), and at some sites in the Iron Mountain District; wall rock immediately adjacent to kimberlite. However, the majority of kimberlite show little to no relief. The boundaries of the kimberlite bodies generally are defined by the distribution of kimberlitic eluvial material; namely weathered kimberlite (blue ground), xenocrysts, megacrysts, and xenoliths. At many sites, kimberlite contacts are difficult to establish accurately because of blanketing alluvial and colluvial covers.

Geophysical surveys were initially tested to determine their potential application in kimberlite exploration in the granitic terrane of Colorado and Wyoming (Puckett, 1971; Puckett, et al., 1972). However, results of those studies as well as our more recent evaluations indicate that the main application of geophysical surveys in this region is to help define the extent of newly discovered kimberlite bodies.

Geophysical surveys were conducted across several diatremes in Wyoming. Resistivity surveys were most successful and the detection of small magnetic anomalies across some pipes and not across others suggest that magnetics could have limited use. Seismic refraction surveys and resistivity soundings were attempted over some



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

Figure 6a. Outline of the Aultman 1 and 2 pipes showing locations of geophysical lines.

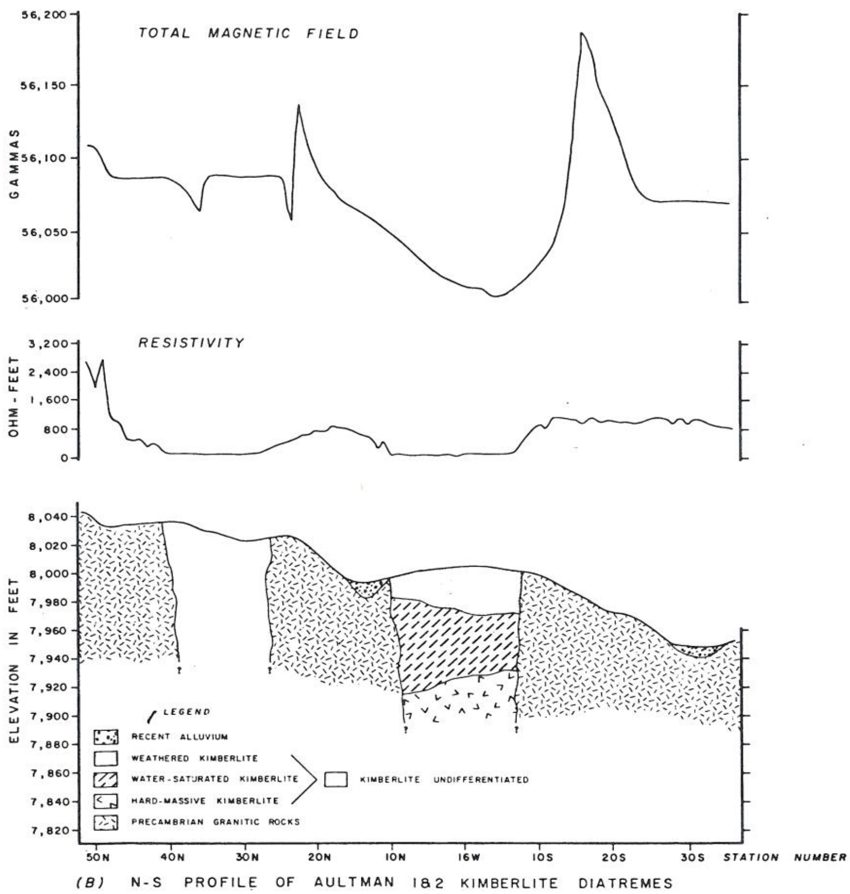


Figure 6b. Cross-sectional (N-S) interpretations of the Aultman 1 and 2 pipes based on geophysical studies.

kimberlites to determine if vertical variations in pipe structure could be detected. No gravity anomalies were realized.

ELECTRICAL RESISTIVITY SURVEYING

The contacts of several diatremes were mapped based on soil coloration and vegetation changes, prior to the use of electrical resistivity surveying, to compare results of geological mapping to that of the various geophysical surveys. Stations were spaced every 30 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.

A Wenner arrangement of 20 foot (6.1 m) spacing between potential electrodes was used in the resistivity profiling measurements (horizontal profiling), and the same arrangement with progressively expanding equal spacing between the current and potential electrodes was also used across the Aultman 1 diatreme for resistivity sounding measurements (vertical profiling). The horizontal profiling data show that kimberlite is more highly conductive than the host granites (Figures 6 and 7). The apparent resistivity of weathered kimberlite ranges between 80 to 250 ohm-feet (24-76 ohm-m) compared to 500-7400 ohm-feet (150-2250 ohm-m) for granite. resistivity profiling measurements were used successfully to define the kimberlite/granite contacts. These results are in good agreement with those of Pucket (1971) and Ray (1963). Puckett observed resistivity values ranging between 80 to 100 ohm-feet (24-30 ohm-m) over the Sloan 1 diatreme in Colorado, and Ray observed low values over the Ferris 1 diatreme in Wyoming.

Resistivity sounding across the Aultman 1 diatreme suggests the presence of 3 layers of differing conductivity (Figure 8). The surface layer is fairly conductive and represents a layer that consists of a mixture of Lower Paleozoic carbonate rocks, organic-rich debris, weathered kimberlite and grus. Beneath the surface layer is a several foot thick (1+ m) highly conductive layer of 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 as compared to the upper layers; however, it was not accurately defined because the required extended electrode

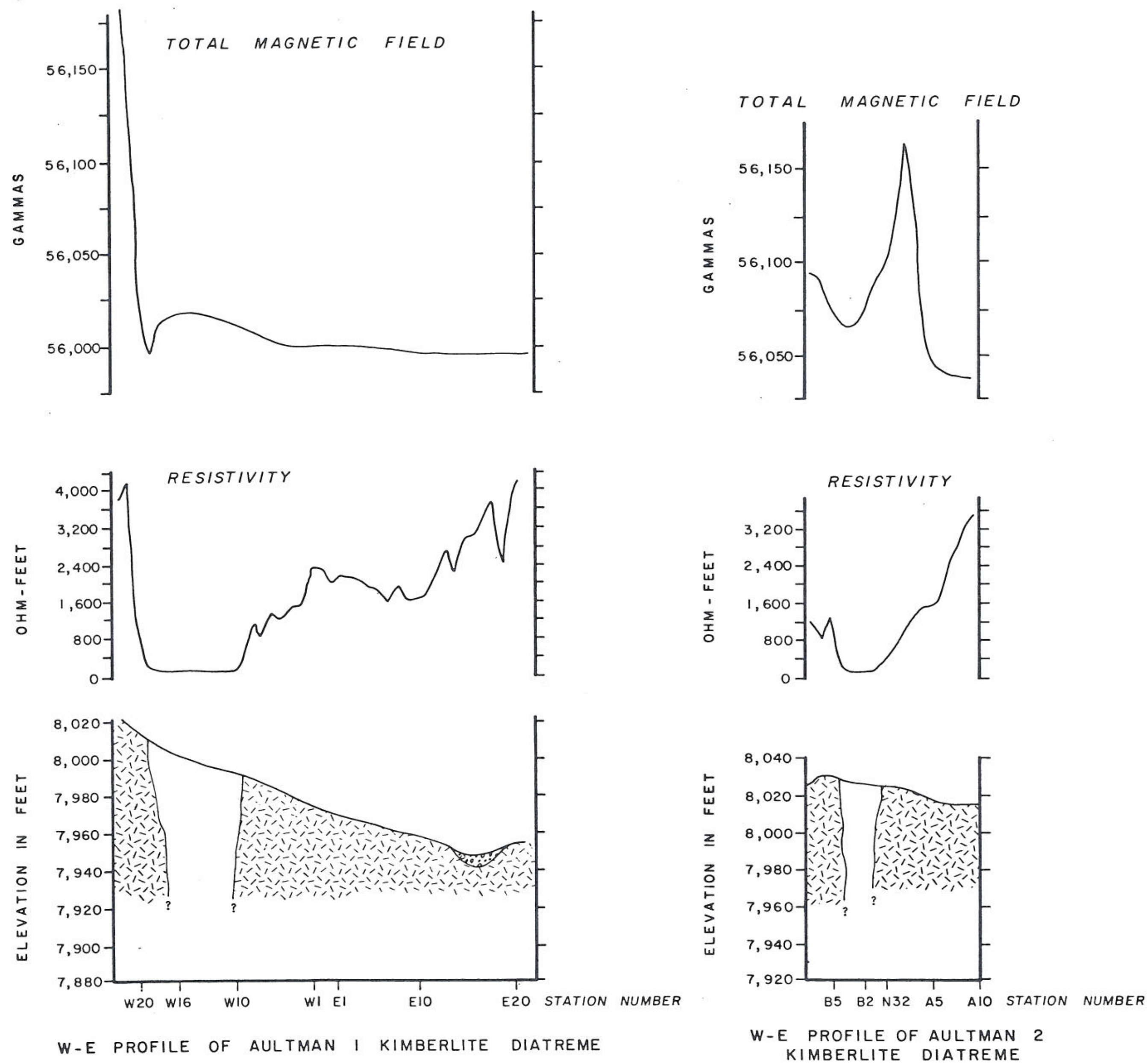


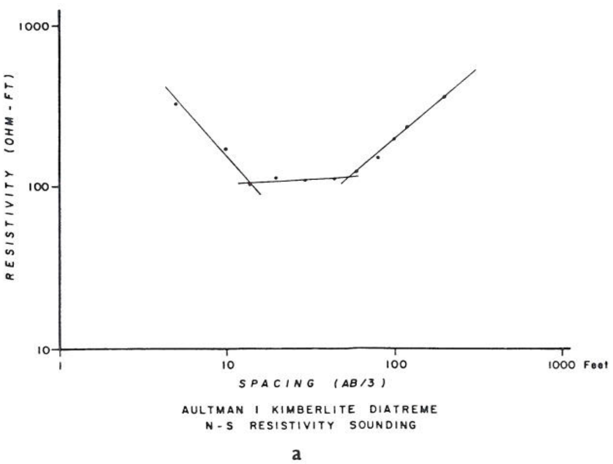
Figure 7. Cross sectional W-E interpretations of the Aultman 1 and 2 pipes based on geophysical studies.

separation was not achieved thus apparent resistivity of this layer was not obtained. Based on current knowledge of the structure of kimberlite diatremes, it is suggested that this layer is dense, unweathered kimberlite.

Resistivity surveys in the State Line District show that the conductive properties are highly contrasted between weathered kimberlite and the host granites. However, the use of resistivity prospecting offers little promise because of the irregular terrane and the relatively small size of the conductive targets. The use of resistivity surveys has been limited to defining kimberlite boundaries, but the method may be applicable to locating shallow blind diatremes along established structured trends.

MAGNETIC SURVEYS

Magnetic measurements over the kimberlite diatremes were recorded with a Geometrics G816 proton magnetometer which has an accuracy of plus or minus 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 at the State Line District are only slight if remnant magnetism is considered negligible and varies from station to station as



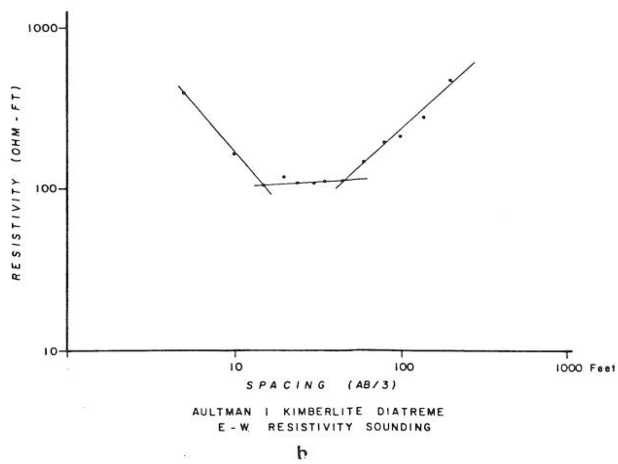


Figure 8. (a) North-South and (b) East-West resistivity sounding plots in the Aultman 1 pipe. Apparent resistivity sounding surveys were conducted using a Wenner configuration with inter-electrode spacing ranging from 5 to 200 feet (1.5-61 m). The plots are consistent with a simple dipping layer model. Apparent resistivities are approximately 650 ohm-ft (200 ohm-m) for the top, 115 ohm-ft (35 ohm-m) for the middle, and greater than 650 ohm-ft (200 ohm-m) for the bottom layer.

the sine of the inclination of the earth's total field. The inclination at the State Line area is approximately 71 degrees.

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 in the measurements. All data were smoothed using a 3 point weighted running average to reduce the effects of magnetic noise.

Figures 6 and 7 show the magnetic profiles across the Aultman 1 and 2 diatremes. These diatremes produced only weak anomalies compared to the host granitic rocks. The magnetic results at the Aultman diatremes are comparable to results of similar measurements obtained on the Sloan 1 (Puckett, 1971), Schaffer 3 and 15 diatremes which in general exhibited 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

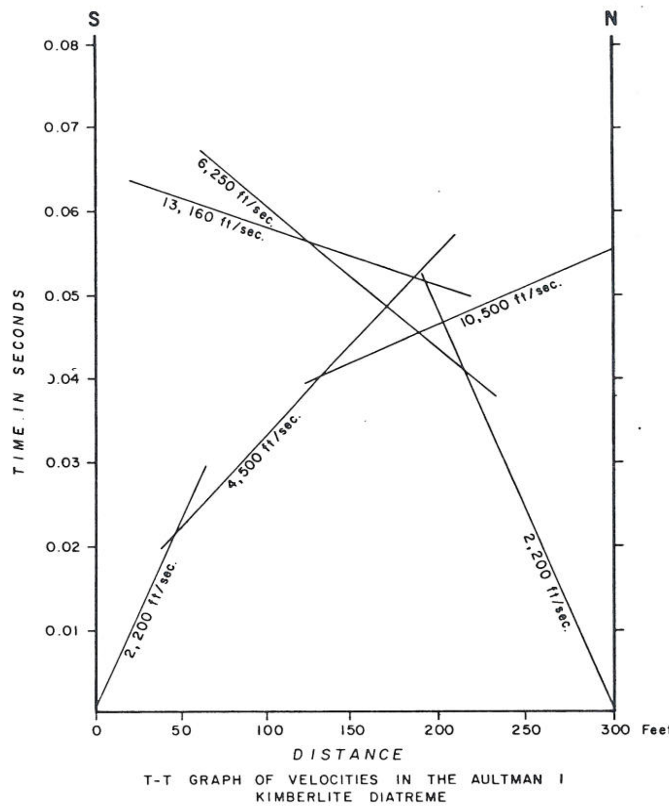


Figure 9. Seismic velocity plot across the Aultman 1 diatreme. The seismic data are in good agreement with the resistivity sounding plot. Three dipping layers are interpreted from the data.

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, In prep.) 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 and/or the localization of abundant spinels in the kimberlite matrix.

The small magnitude of the magnetic anomalies related to most kimberlite diatremes in the State Line area implies that magentic surveys would probably be of only limited value in prospecting for kimberlite within the Precambrian terrane of Colorado and Wyoming.

SEISMIC SURVEYS

Seismic refraction surveys were conducted across the Aultman 1 diatreme. The seismic survey results indicate three distinguishable dipping layers (Figure 9). The top layer varies from 13 feet (4 m) to 38 feet (11.5 m) thick and has an average seismic velocity of 2200 ft/s (670 m/s). The intermediate layer varies in thickness from 53 feet (16 m) to 74 feet (22.5 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 are similar to 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 (2133.5 m/s) to 16,000 ft/s (4877 m/s). These data suggest that seismic prospecting in the Precambrian terrane of Colorado and Wyoming will not uniquely differentiate kimberlite from granite.

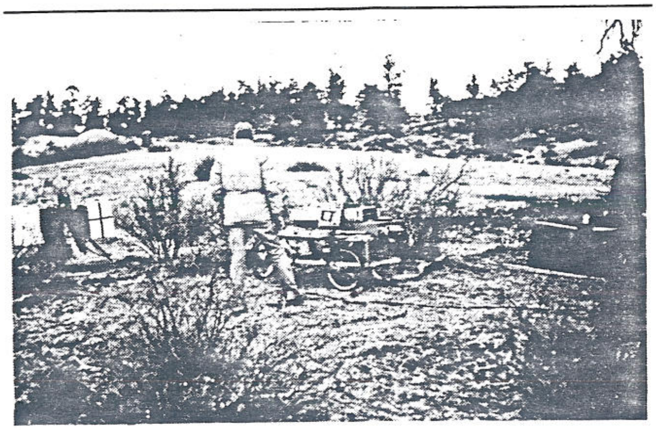


Figure 10. Microwave sounding on the Schaffer 3 pipe, Wyoming.

GRAVITY SURVEYS

Gravity surveys were conducted over several of the kimberlites in the State Line District. Gravity anomalies should be expected over rocks with such contrasting densities that are normal for granitic versus ultramafic compositions. However, the high serpentine and carbonate content of most kimberlites result in density values that are lower than expected, and which are comparable to those of granitic rocks in the area. Consequently, thus gravity surveys appear to have little potential as a tool in kimberlite exploration in Colorado and Wyoming.

MICROWAVE SOUNDING

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 the appearance of kimberlite versus granite (Figure 10). This testing is only preliminary and we have no results to date.

ASSESSMENT (PHASE III)

The final phase of kimberlite exploration involves assessment of the diamond potential. During this phase, 100 to 200 pound samples of weathered kimberlite are collected from each diatreme to be tested for microdiamonds. Diamond testing of the State Line kimberlites has been conducted at Colorado State University, and to date, more than 90 microdiamonds have been recovered (McCallum, et al., 1978).

Processing involves size separation 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 placed in a 52% 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, 1976).

Diamonds were first discovered in a serpentinized garnet peridotite collected from the Schaffer 3 pipe on Wyoming School Section 16 (McCallum and Eggler, 1976). Since that discovery, diamonds have been recovered from the Schaffer 3, 10, 15, 16, and 19 pipes; the Aultman 1 pipe; two out of four of the Nix pipes; and the Sloan 1 and 2 pipes. The largest reported diamond recovered from the Sloan 2 pipe, weighs 11.8 mgs (0.059 carat or 5.9 points – A metric carat equals 200 mg, and one point is equal to 0.01 carats) and

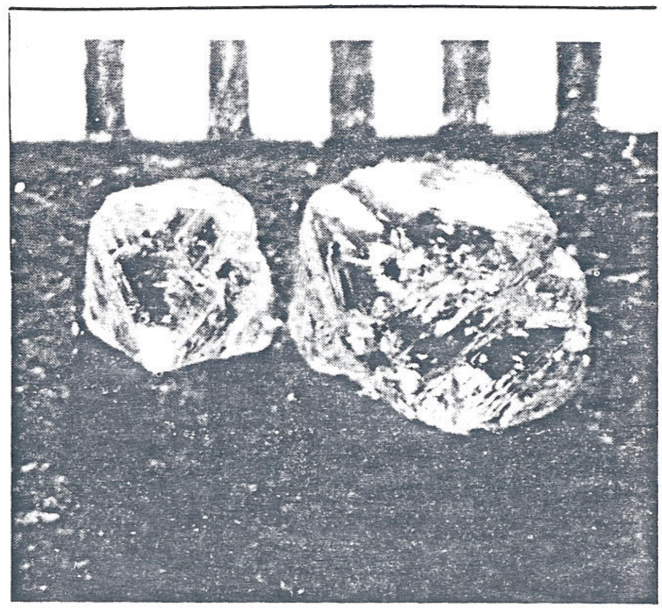


Figure 11. Placer diamonds from Wyoming. The diamond on the right is the largest reported diamond found in Wyoming.

measures approximately 1.3 x 1.75 x 2.8 mm (McCallum et al., 1977, 1978).

Diamonds have not been found in the Colorado-Wyoming province in kimberlites other than those of the State Line District. Kimberlites at Iron Mountain were examined for diamond, however, the nature of the occurrences suggests that if diamonds are present they probably are not sufficiently abundant to constitute a commercial deposit. Exposures at Iron Mountain are small and apparently represent deeply eroded remnants or "root zones" of diatremes. In general, 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, especially if one or more of the diatremes are shown to contain economical diamond concentrations.

Placer diamonds were identified from stream sediment concentrates extracted nearly 70 miles (113 km) to the west of Iron Mountain on the northwestern flank of the Medicine Bow Mountains. Two octahedrons were recovered and tested for hardness and X-ray characteristics. The smaller of the two crystals measures approximately 1.5 mm in diameter and weighs 6.94 mg (3.47 points). The larger crystal measures 3 mm in diameter and weighs 20.03 mg (10.015 points)(Figure 11)(Hausel, 1977).

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 (1609 km) from their source at Kimberley, South Africa (Lampietti and Sutherland, 1978), and many of these crystals are preserved as excellent good quality octahedrons with no hint of transport (A. E. Waters, Jr., personal communication 1978).

ECONOMIC ASSESSMENT

Determining the grade of diamond-bearing kimberlite rock is not a simple task principally because the diamond, is present only as a trace mineral that seldom exceeds concentrations of 1 ppm. McCallum and Mabarak (1975) report that average kimberlite ore runs at about 0.25 carat/ton or about one part diamond per 20 million parts waste rock (0.00000005 percent). In order to adequately test diatremes for ore potential, the kimberlite must be drilled to depths of several hundred feet (meters) and several thousand tons of rock (10,000 to 50,000 tons) must be processed from each pipe to determine the grade.

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 due to the large bulk samples that are required for testing. Because of these restrictions, 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 State Line District. Actual assessment of the diatremes will probably take several years to determine the economic potential of the diamond-bearing kimberlites.

ACKNOWLEDGMENTS

The authors wish to extend sincere appreciation to the students at Colorado State University and the employees at the Wyoming Geological Survey who assisted in various aspects of the data gathering process. Special thanks are given to R. DeBruin, V. Harder, A. VerPloeg, T. Stephenson, C. Mabarak, R. Filson, and V. Leighton for there help on the ground surveys. Valuable suggestions on the geophysical surveys were received from Professor R.B. Johnson of Colorado State University, and D. L. Campbell of the U. S. Geological Survey, were very helpful in the interpretation of the seismic and resistivity sounding data. We also extend our thanks to H. G. Coopersmith, C. D. Mabarak and Frank Yaussi for their helpful suggestions and comments, and to Paul Boden who was very helpful in gathering data on the Medicine Bow Mountains diamonds. Daniel N. Miller, Jr., suggested the subject of the manuscript and provided some valuable ideas and criticisms. We also appreciate the help and cooperation of the landowners and the many ranch employees who made it possible for the authors to collect the needed information. Partial financial support was provided to T. Woodzick by the Wyoming Geological Survey. Much of the mineralogical and chemical data reported herein was derived from work done by McCallum and others that was supported by the Earth Sciences Section, National Science Foundation (Grants DES74-13078 and EAR74-13078 A01) and the U. S. Geological Survey.

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