DIAMOND DEPOSITS OF THE NORTH AMERICAN CRATON – AN OVERVIEW

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ABSTRACT

Diamonds have been found in placers in North America derived from unknown sources. Others were recovered from glacial deposits from distant lands. The number of placer diamonds found in North America indicates that several source deposits would be discovered.

Some discoveries initially led to developments of small mines in Murfreesburo, Arkansas (Prairie Creek) and the Colorado-Wyoming State Line district (Kelsey Lake). However, world-class diamond deposits have eluded the United States to date, but have now been found in Canada that led that nation to becoming a major source of gem-quality diamonds over a very short period of time. Canada now ranks as the third largest diamond producer of gem-quality diamonds in the world, which followed the development of their first mine (Ekati) in 1998 and second mine (Diavik) a few years later. A third mine was recently dedicated (Jericho) and two additional mines are under development – all world-class deposits! With thousands of additional discoveries, other diamond mines will be developed in the future of Canada. The timing of this diamond boom and rush occurred at a promising time, when major diamond mines in Africa, Australia and Russia were showing declining production.

Even though favorable Cratonic (Archon) basement rocks extend south of Canada under large portions of the United States, essentially all meaningful exploration has been confined to Canada over the past 25 years. Reports of hundreds of diamonds along with hundreds of kimberlitic indicator mineral anomalies, kimberlites, lamproites, lamprophyres and some distinct geophysical anomalies in the US, would lead one to anticipate that exploration could result in significant discoveries in the US – however, the political climate in the US remains archaic at best for exploration.

The favorable Cratonic terrains in Canada that are host for some very impressive diamondiferous kimberlites does not stop at the Canadian border but continues southward into the Great Lakes region (Superior Province) and into Wyoming and Montana (Wyoming Province). One should anticipate that major swarms of mantle-derived intrusives continue southward into Montana, Wyoming, Colorado, Michigan, Wisconsin, and Montana and that this terrain could potentially become an important source for diamonds in the future – a scenario that is unlikely unless there is modernization of exploration regulations and removal of bureaucrats in government agencies.

This craton and cratonized margin has been intruded by widespread swarms of these mantle-derived magmas. The North American craton is predicted to become the principal primary source of gem and industrial quality diamonds in the near future and for decades to come.

This paper is dedicated to the memory of three wonderful friends and geologists; John Dooley, Ray Harris and Robert Lyman. It is difficult to lose a friend so early in life, but three in their prime!

INTRODUCTION

There are many deposits of diamond that are found throughout the world: some are the classical kimberlite- and lamproite-hosted deposits; others are placers derived from the erosion of these rocks, and still others are classified as unconventional and include a whole variety of deposits, some of which may someday be found to host commercial amounts of diamonds. Most notably are some lamprophyres. Still, the search for commercial diamond deposits continues to focus on kimberlite and less often on lamproite.

Commercial diamond deposits are extremely rare. In the richest primary mines, diamond is found in concentrations considerably less than 1 ppm (Lampietti and Sutherland, 1978). Most primary diamond deposits are found within thermally stable Archean cratons that have relatively thick cratonic keels (termed Archons) and in cratonized Proterozoic belts accreted to the margins of the Archons (termed Protons), and with the discovery of many unconventional diamondiferous host rocks in recent decades, a new exploration philosophy is necessary, as some of these host rocks have significant numbers of diamond (Hausel, 1996; Erlich and Hausel, 2002). In the past, unconventional host rocks have only been cursory sampled or ignored by exploration groups and little effort is made to evaluate these deposits (Erlich and Hausel, 2002). Even so, significant amounts of diamond can be expected in some unconventional host rocks, in particular, those associated with subduction tectonics (Erlich and Hausel, 2002; O'Neill and Wyman, 2006), where one might expect significant organic carbon in diamond formation, as well as stressed diamonds potentially producing higher percentages of valuable pink diamonds.

The world's natural diamond deposits are mostly mined from a small group of primary and secondary deposits that have operating lives of 10 to 30 years. A notable exception is the South African Premier mine, the source of many of the world's largest gem diamonds including the 3,106 carat Cullinun, the largest ever recovered. The Premier mine operated for more than 100 years. Another exception is the marine placers along the western coast of Africa, which have been productive for decades. Nearly all exploration companies spend their efforts searching for world-class diamond deposits and ignore smaller, yet potentially productive minor deposits, such as those mined at Kelsey Lake, Colorado and Murfreesburo, Arkansas. This archaic philosophy has left the door open to smaller companies to search for small to medium size diamond deposits.

The top natural diamond producers in the world, based on total carats recovered (gems plus industrial stones) are: Botswana, Russia, Canada, Congo, South Africa, Australia and Angola (Hausel, 2006). Notably absent from this list is the US, even though large parts of the United States are underlain by a cratonic basement terrain suitable for the discovery of diamond. Canada, which became a major diamond producer in 1998, will remain in the forefront of diamond production and exploration for decades to come. Not only is the Canadian Shield favorable for discovery of significant diamond deposits, but the various Provincial and Territorial governments provide exploration and investment incentives unmatched. There is a perceived negative business climate for exploration in the US that is supported by little to no research funding. As a result, nearly all North American exploration activity and investment for diamonds has focused on Canada. This philosophy has led to the discovery of >500 Canadian kimberlites and dozens of unconventional host rocks over the past 2 decades - nearly half of which are diamondiferous (Kjarsgaard and Levinson, 2002). These discoveries are unfortunately restricted to political boundaries and continuation of diamond discoveries to the south of the Canadian border has been almost nonexistent in the past decade due to gothic politics on the state level.

Research

Grassroots exploration for diamond deposits in the United States is almost unheard of. This is partially the result of an archaic system of exploration regulations and laws that favor a plethora of government agencies. The North American Craton is represented by a very old continental core that provides a favorable geological environment for the discovery of diamonds. It is also the largest craton in the world with vast regions available for diamond exploration (Figure 1). This cratonic basement projects south from Canada into the Wyoming Province and the Superior Province. The older (>2.5 Ga) region of the craton (known as Archons) have the highest potential for discovery of commercial diamond deposits associated with kimberlite. The more favorable terrains for diamond exploration in the US extend under Montana, South and North Dakota, Colorado and Wyoming as well as into the Great Lakes region of Michigan, Wisconsin and Minnesota. Even with these favorable protrusions of cratonic basement into the US, the political climate has been less than favorable south of the border. As an example, investment in exploration and research in Wyoming Province – the most favorable extension of the North American craton in the US, amounted to considerably <0.01% of investments in Canada over the past decade.

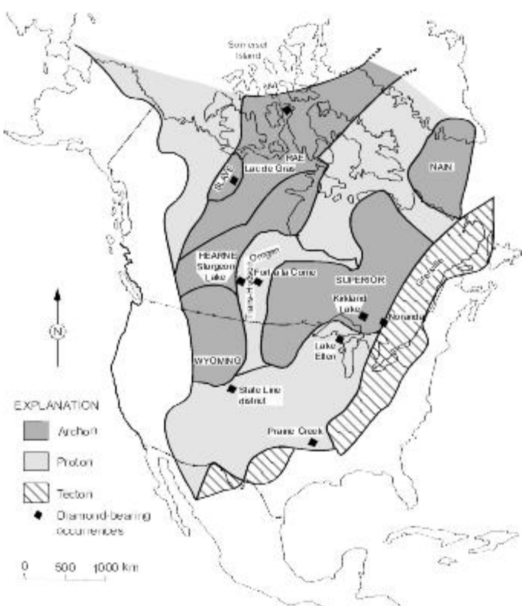


Figure 1. The North American craton. The older cratonic cores, referred to as Archons (>2.5 Ga), have the highest potential for discovery of conventional diamondiferous host rocks. The Proterozoic basement terrains (<2.5 Ga; >1.6 Ga) referred to as Protons, are thought to have moderate potential, and Tectons (<1.6 Ga; >0.6 Ga) have low potential (after Janse, 1994).

A comparison of the research expenditures invested by the State of Wyoming (about \$100,000) over the past 10 years to exploration, research and capital investments of Alberta (>\$70 million) and the Northwest Territories (>\$2.0 billion), it should be clear that the State of Wyoming is under-explored (Table 1) and that the government has not made a realistic commitment to search for diamonds in the Wyoming craton. Even with little to no support over the past few decades, the Wyoming Geological Survey identified hundreds of anomalies – anyone of which could lead to a major discovery. These included >300 kimberlitic indicator mineral anomalies, >100 vegetation anomalies typical of those associated with many kimberlites, and geological maps produced of the two largest kimberlite districts in the US and the largest lamproite field in North America (Hausel and others, 1981; 2003; Hausel, 2006). In the past few years, this trend of funding has taken a turn for the worse (if that were possible) with no support from the agency's director and legislature.

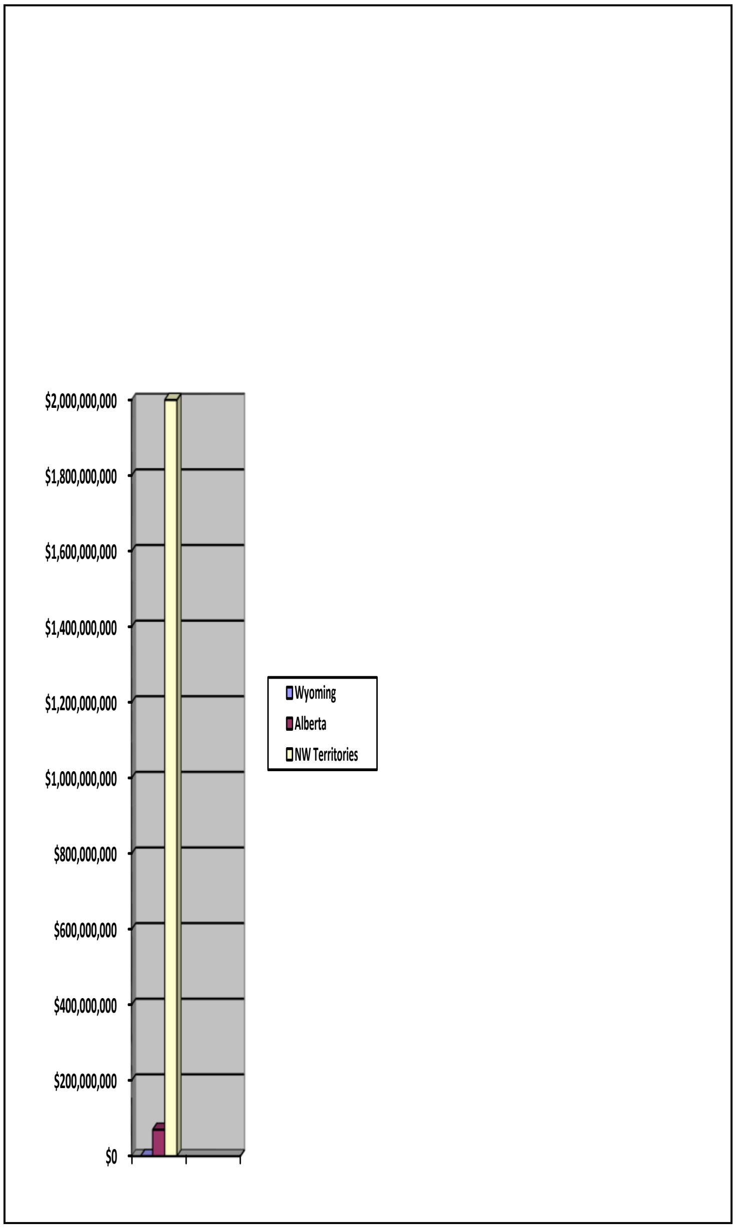


Table 1. Comparison of financial investments for diamond exploration and development between Wyoming, Alberta, and the NWT. Wyoming dramatically falls short of having a serious research program to find commercial diamond deposits. Much of the problem results from a poor performance of directors from the Wyoming Geological Survey who have continued in recent years to support personal agenda and ignore projects of merit that could generate jobs and considerable money for the state.

Many diamond exploration projects in Canada are well funded and significant discoveries have now been made in every province and territory. In contrast, little effort has been made by the government in the United States in the search for diamonds and other gemstones.

South of the Canadian border, detrital diamonds, hundreds of kimberlitic indicator mineral anomalies (KIMs), dozens of vegetation anomalies, circular geomorphic and vegetation anomalies, geophysical anomalies, known kimberlites and the largest field of lamproites in North America have been identified. Many diamonds and diatremes have been discovered throughout various regions of the US, both within the cratonic environments and also in unconventional terrains (Hausel, 1996; 1998). Some of the more notable terrains in the US include the Appalachian Uplift, the Arkansas Proton, Superior Province, the Wyoming Craton and the California Sierra Nevada and coastal mountain terrains.

Diamond Mineralogy & Geochemistry

Both gem and industrial diamonds have been created in the laboratory (Hazen, 1999), but the value of synthetic gem diamonds falls short of natural gem diamond. And some natural diamonds represent the most valuable commodity on earth based on price per unit weight (Hausel, 2006).

Native carbon occurs as one of three polymorphs: (1) diamond, (2) graphite, and (3) lonsdaleite (Erlich and Hausel, 2002). The physical differences between these are related to the bonds between carbon atoms. The crystalline cell of diamond approximates a cube with sides of 3.56Å and coordination of carbon atoms in diamond is tetrahedral such that each atom is held to four others by strong covalent bonds that results in the extreme hardness, incompressibility and thermal conductivity associated with diamond.

In its simplest form diamond forms a cube. Even so, cubic habits are uncommon, and when found, diamond cubes are characteristically frosted industrial stones. Many diamond cubes have been found in placer deposits in Brazil and a significant percentage of the diamonds recovered from the Snap Lake kimberlites in Canada also have cubic habit (Pokhilenko and others, 2003). A more common habit for diamond is that of an octahedron (Figure 2). Partial resorption of the octahedron can result in a rounded (12-sided) dodecahedron with rhombic faces. Many dodecahedrons develop ridges on the rhombic faces to produce a 24-sided crystal known as a trishexahedron. Four-sided tetrahedral diamonds are distorted octahedrons (Bruton, 1979; Orlov, 1976; Shafranovsky, 1964).

A tetrahedron by definition is a four-faced polyhedron in which each face forms a triangle (Bates and Jackson, 1980). Twinning in diamond commonly follows the spinel law to produce a flat triangular macle.

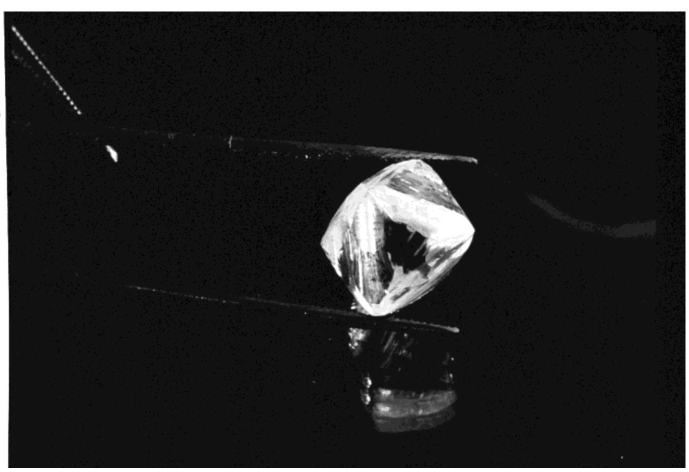


Figure 2. A flawless, 14.2-carat octahedron from the defunct Kelsey Lake diamond mine, Colorado (photo courtesy of Howard Coopersmith).

Diamonds recovered from lamproites often exhibit resorbed habits: octahedrons are typically less common in lamproite than in kimberlite. The many resorbed diamond textures associated with lamproite are a result of diamond instability in relatively hot lamproitic magma as compared to kimberlite. In particular, the slower rate of rise of lamproite magma through the graphite stability field, coupled with high magmatic temperatures in an oxygen-rich environment provides conditions that favor diamond resorption. Similar resorbed habits are found in many diamonds recovered from lamprophyres as well as many kimberlites that exhibit geochemical evidence of eruption as an oxidizing magma. Diamondiferous lamproites also tend to produce a large percentage of industrial to gem diamonds and often many fancy gem diamonds. Some fancy diamonds appear to be associated with deformation in diamond (such as the pink diamonds) and are often found near subduction zones.

Industrial stones may be classified as bort (a poor grade diamond that is used as industrial abrasive) and carbonado (an opaque, black to grayish, fine-grained aggregate of microscopic diamond, graphite, and amorphous carbon with or without accessory minerals) (Erlich and Hausel, 2002). Even though diamond is extremely hard and resistant to compression, it is brittle and will break to yield a conchoidal to hackly fracture along with smooth cleavage surfaces. Diamonds exhibit perfect cleavage in four directions parallel to the octahedral faces: thus an octahedron can be fashioned from an irregular shaped diamond simply by cleaving (Kukharenko, 1954; Orlov, 1977). Natural diamonds contain tiny mineral inclusions along cleavage planes. These provide important data on the origin of diamond and some inclusions can be used for age determinations. The mineral inclusions typically form assemblages that are characteristic of peridotite or eclogite. Some rare inclusions have been identified that are characteristic of very deep mantle sources and interpreted as ultra-high pressure diamonds that originated within the lower mantle (Erlich and Hausel, 2002).

The specific gravity for diamond (3.516 to 3.525) is high enough that it will concentrate in stream, river or marine placers with *'black sand'* heavy minerals. This density is surprisingly high given the fact that diamond is composed of such a light element (carbon). Compared to graphite (2.2), diamond is twice as dense due to the close packing of atoms from high pressures within the earth's mantle (Harlow, 1998). The depth of erosion of many diamondiferous kimberlites in Wyoming and Colorado led Hausel (2004) to conclude that placer diamonds are likely common within and surrounding the Colorado-Wyoming State Line district. Diamonds have been found in black sand concentrates in at least three drainages in the district, even though there has never been any concerted effort to search for placer diamonds. The largest diamond recovered from a drainage in the district was a 6.2 carat stone found in Fish Creek in Wyoming (Howard Coppersmith, personal communication)..

Diamond has greasy to adamantine luster. The luster is distinctive and due to the mineral's high refractive index, this results in a gemstone of unparalleled beauty with extraordinary fire. Diamonds also occur in a variety of colors from white to colorless, gray to black, and shades of yellow, red, pink, orange, green, blue, violet and brown. Strongly colored diamonds are termed fancies and many have extraordinary beauty and sell for premium prices. As an example, in 1989 a 3.14-carat Argyle pink diamond sold for US$1,510,000. More recently, a 0.95-carat fancy purplish-red Argyle diamond sold for nearly US$1 million. Thus, these diamonds are many thousands of times more valuable than an equivalent weight of gold.

The color in most gemstones is due to trace impurities of transition metals. However, the color in diamond is often caused by trace nitrogen, boron or structural defects. Pink diamonds in particular, are thought to result from structural defects. Diamonds may be red, pink, purple, orange, yellow, green, blue, white, black, gray or brown. The most common color is brown. Prior to the development of the Argyle mine in Australia in the 1980s, brown diamonds were considered unattractive and typically classified as industrial stones. But due to Australian marketing strategies, some brown stones are now highly prized gems. Lighter brown diamonds are quite variable and have color tones that range from very light brown, light (champagne) brown, medium brown, dark brown to very dark brown. Color saturation is also variable resulting in bright brown and dark (cognac) brown colors. In particular, champagne and cognac gem diamonds are in high demand due to marketing.

Pink, red and purple diamonds are rare with the colors concentrated in tiny lamellae in an otherwise colorless diamond (Harlow, 1998). The color lamellae are interpreted to be a result of micro-deformation possibly resulting from stresses applied to diamond while crystallizing within an active subduction zone. Areas in North America, such as the Sierra Nevada of California, the State Line district of Colorado-Wyoming, and the Cordillera of British Columbia may be good targets to search for fancy diamonds due to the presence of active a paleo-subduction. At any rate, pure pink diamonds are extremely rare. Most green diamonds have a thin surface coating that is removed during faceting – thus natural faceted green diamonds are rare. The green color results from natural irradiation, while others may result from the presence of hydrogen. The rarest color is orange, for which the coloring agent has yet to be identified in diamond. The range of tones in orange is quite variable in lightness and saturation resulting in pale orange, bright orange, dull orange and deep orange. One of the most exquisite colors for all orange diamonds is a pumpkin orange.

Black diamonds result from the presence of graphite inclusions, which not only color diamond, but also make the diamond an electrical conductor. Individual colors can vary from pale charcoal black, dull ink black, to bright gun metal black, all with weak saturation. Gray diamonds are hydrogen rich and their color is related to light absorption by hydrogen defects. Opalescent or fancy milky white diamonds are the result of numerous mineral inclusions (and possibly nitrogen defects) (Harlow, 1998).

Diamond's high index of refraction (2.4195) is a result of density. High density diminishes light velocity (77,000 mi/sec in diamond) to less than half the velocity of light in a vacuum (Harlow, 1998). Diamonds are four times as thermally conductive (5 to 25 watts/cm/^{o}C) as copper at room temperature. Unlike copper, diamond is also an electrical insulator (0 to 100 ohm/cm at 300^{o}K). Because of its high thermal conductivity, diamond feels cool and the gem will conduct heat away from one's lips, which is why diamonds are sometimes referred to as *"ice"*. Hand-held diamond detectors are designed to measure its unique thermal conductivity. Diamonds are relatively unaffected by heat except at high temperature. Without the presence of oxygen, diamond will transform to graphite residue at 1900°C. When heated in oxygen, diamond will burn to CO_2 at much lower temperatures ($\geq$690^{o}C). Diamonds are unaffected by acids.

Diamonds repel water and are hydrophobic (non-wetable) and attract grease. Even though they are 3.5 times heavier than water, diamonds can be induced to float. Oxygen atoms in water and in a given material tend to link and thus water will adhere to materials that contain oxygen making them wetable, but diamond contains no oxygen. Hydrocarbons such as grease have affinities for material without oxygen. This property is used effectively in grease tables, where tables are coated with grease to attract non-wetable diamonds, while wetable oxygen-bearing minerals tend to wash over grease plates (Erlich and Hausel, 2002).

GEMOLOGY

There are four general types of commercial natural diamonds: (1) *gem* (well-crystallized, transparent, flawless to nearly flawless), (2) *bort*, (3) *ballas* (spherical aggregates formed by many small diamonds), and (4) *carbonado* (opaque, black to gray, tough and compact industrial diamond). Gem diamonds may be further subdivided into *gem* and *near-gem* (lower-quality gemstones).

Rough gem diamonds have values as much as 10 to 100 times greater than industrial diamonds. Gem diamonds, when cut and polished, will fetch values 5- to 100- times that of the rough stone particularly when they are displayed in jewelry. The extreme value of diamond as a gem is due to its mystique, rarity, extreme hardness, preparation, beauty, high refractive index and dispersion that produce brilliant faceted gems with distinctive *'fire'*.

Top cutters in the world produce beautiful gems from rough material and may require considerable pragmatic crystallographic research to determine location of cleavage, fractures, pits, curves, protrusions, inclusions, and color inconsistencies. Some of the more valuable diamonds have been studied and mapped by cutters as much as a year prior to faceting. Since 1981, lasers, and since 1988, computer modeling and scanning, have become an integral part of diamond fashioning. A rough diamond can now be modeled with a computer and scanner to determine the optimum faceted stone using virtual 3D models to display positions of mineral inclusions and virtual saw planes.

The size and shape of rough diamond, the number and location of imperfections and inclusions, and the direction of cleavage (referred to as “grain” by cutters) are considered prior to creating a gem. In the past, many large diamonds were pre-shaped by cleaving. The cutter selected the octahedral cleavage by cutting a small groove in the octahedral plane with a sharp-edged diamond chip, and a steel knife was placed in the groove and struck to create enough force to cleave the stone (laser kerfing may now be used to mark a notch that is burned into the stone).

If the cleavage was improperly identified, the diamond shattered into pieces. Conventional primary shaping is done by cutting the stone with a diamond saw. In the past, diamond is either cut parallel to the cube or to the dodecahedron with a rapidly rotating blade impregnated with diamond powder. Because of hardness, it took 4 to 8 hours to complete a cut through a 1-carat diamond of only 6 to 8 mm in diameter (Hurlbut and Switzer, 1979)! With the use of lasers, this process requires less time. With the desired cut preprogrammed in a computer, a platform moves the diamond through the laser. At the point where the beam is focused, the temperature is extremely high and the molecular structure of diamond is converted to graphite on the first pass. The graphite is then "burned off" on the return pass. Diamond combustion occurs at 690^{o}C to 875^{o}C. Representative cutting time using a laser would be approximately eight hours for a 10-carat crystal (Baker, 1981).

Faceting is completed by grinding and polishing the diamond on a revolving horizontal lap impregnated with diamond powder. In a standard, round, brilliant diamond, as many as 58 facets are cut and polished. The optimum directions for conventional polishing are parallel to the crystallographic axes. Because the cubic faces of the diamond are parallel to axes, they are easiest to polish. Those that lie nearly parallel to an optic axis are more favorable to polish because of lower hardness.

The octahedral face is the hardest on a diamond and lies at the greatest angle from the crystallographic axis. If the plane of the cut or facet varies more than a few degrees from a cubic face, it is nearly impossible to saw. In this case, a laser is necessary to produce cuts and facets.

Tiny inclusions of diamond may be scattered within a host diamond. With conventional methods, the diamond inclusions must be avoided during sawing since vibrations produced when a blade contacts the included diamond can cause the host to shatter. If the stone does not shatter, the cutting time may increase 2 to 3 times and extend cutting many days or even weeks. With laser technology, this problem is resolved and may take only a matter of hours. A laser also includes the ability to produce new fancy shapes that were not formerly possible, such as horse-heads, oil wells, stars, butterflies, initials, etc. Many diamonds with distorted growth, such as twinning, were virtually impossible to cut by conventional means because of cleavage changes. However, these stones can now be cut by laser without regard to grain (Baker, 1981).

The finished gem is judged by *"four Cs"*—cut, clarity, carat weight and color. The cut of a diamond can increase its value enormously - the better proportioned, polished and faceted, the greater the value of the finished stone. With diamonds of similar quality, those of greater size can dramatically increase in value with increased carat weight. When the girdle (base) and table of the diamond are correctly proportioned, the diamond will exhibit greater fire and brilliance. Gem diamonds include fancy (colored) and white (colorless) stones. Colorless diamonds range from colorless (white) and blue-white to pale yellow (Bruton, 1978). One of the more common systems for evaluating diamonds is that of the Gemological Institute of America's (GIA) color grading system which ranges from D (colorless) to X (light yellow). Each letter of the alphabet from D to X shows a slight increase in yellow tinge (Hurlbut and Switzer, 1979).

A visual appraisal is done in a well-lighted room using natural north window light. Appraisals compare the stone to a master set of instrument-graded diamonds. The instrument used in color grading is a colorimeter, which quantitatively measures the degree of yellowness (Hurlbut and Switzer, 1979). Clarity is determined by the presence or absence of blemishes, flaws and inclusions. Many grading systems in use have descriptive terms such as flawless (F)or imperfect (I) and terms that denote intermediate grades such as very slightly imperfect (VSI).

Economic Value

Diamond deposits can provide significant economic boosts to local economy and even national economies. Many diamond mines host from $500 million to $75 billion in raw stones. Rough gem diamonds may be valued at only $50 to as much as $400 per carat.

Faceted stones are typically valued at 10 to as much as 100 times the raw stone depending on the placement of the stone in jewelry. Diamond mines typically have lives of a decade to 100 years.

The recent discoveries of commercial deposits in and near the arctic north in Canada have resulted in dramatic costs for capitalization of mines. Additionally, spring and summer thaw of the ice roads for mine supplies result in increases in cost of mining, as much of the materials and fuel for the mines have to be flown in at a very high cost. The discovery of commercial diamond deposits further south in Alberta, Montana and Wyoming could provide more favorable capitalization start-ups due to the presence of more favorable infrastructure.

GEOLOGY

Commercial amounts of diamond have only been found in rare magmatic rocks (kimberlite and lamproite) and in placers presumably derived from these igneous rocks. Even so, diamonds have been identified in other igneous rock types (i.e., alkali basalts, lamprophyres, ultramafics, etc) and in some ultra-high pressure metamorphic rocks (Hausel 1996; Erlich and Hausel, 2002). Primary commercial diamond deposits so far have been restricted to ancient stabilized cratons and cratonized margins that include Archons (cratons of Archean age) and Protons (cratonized belts of Early to Middle Proterozoic age). Nearly all modern exploration ventures focus on a search for diamondiferous kimberlite in cratonic terrains.

Primary magmatic diamond deposits are limited to a few rock types that originally formed under extreme pressure and temperature at great depth beneath the lithosphere. The most notable magmatic diamond deposits are associated with kimberlite, lamproite and some lamprophyres. Many diamondiferous kimberlites, lamproites and lamprophyres tend to occur in small or large clusters of a few to more than 100. The clusters can be related to distinct structural control. As a result, more than one intrusive is often found along the same fracture or orientation, or along parallel or cross fractures. Several favorable structural orientations are typically recognized within a given district and most individual structures responsible for the control of the diamond deposits typically have very limited strike lengths. Larger, more distinct structures may occur near some districts and may in some way be related to kimberlite emplacement or a more regional scale (Hausel and others, 1979).

Detailed mapping of smaller linear structures responsible for orientation of kimberlites may lead to discovery of additional hidden to poorly exposed kimberlite (Hausel and others, 1979; 1981; 2000). The emplacement of kimberlite in the Iron Mountain district of Wyoming is thought to have an association with the nearby Cheyenne Belt suture zone (Hausel and others, 2003). This suture is interpreted to represent a paleo-Benioff zone marking the break between the Wyoming (>2.5 Ga) Province to the north, from the Colorado (1.8 -1.6 Ga) Province to the south (R.S. Houston, personal communication, 1996). The suture lies 6 mi (10 km) north of the known kimberlites at Iron Mountain while the Iron Mountain kimberlites tend to occur along fractures that parallel the projected suture. However, 60 miles further south, kimberlites of the State Line district show primarily north-northwesterly trends with some east-west cross-trends but no evidence of control by major structures (Hausel and others, 1981).

Kimberlite magmas tend to erupt as diatremes (pipes) at the earth's surface. These erupt with considerable latent energy ejecting pyroclastic material into the air (referred to as crater-facies kimberlite) and disrupting and incorporating blocks of country rock to produce a volcaniclastic rock (Figure 3). The resulting breccia, referred to as diatreme-facies kimberlite, exhibits fragments of kimberlite along with crustal xenoliths and cognate mantle nodules within a serpentinized peridotite matrix. Kimberlite diatremes typically exhibit more than one episode of magma intrusion and often suggest several episodes of intrusion within the same pipe as well as within the same district. For instance six-different kimberlite facies were mapped within the Sloan 1 and 2 kimberlite complex in Colorado (McCallum and Mabarak, 1976).

Diatremes are vertical pipes that taper at depth to steeply incline cylindrical bodies that grade into a root zone and dike complex. The average angle of wall inclination at the Wesselton, DeBeers, Kimberley and Dutoitspan pipes in South Africa is 82° to 85°. Ideally, such pipes form circular or ellipsoidal cross sections in the horizontal plane filled with kimberlitic tuff or tuff-breccia. In a vertical plane, the ideal cross-section is carrot-shaped. Most pipes taper from the surface to depths of 0.6 to 2 miles (1-3.2 km) where they pinch to narrow root zones that originate from a feeder dike beneath the root (Kennedy and Nordlie, 1968). At the feeder dike, the kimberlite is massive porphyritic (root-zone or hypabyssal-facies) peridotite rather than a breccia. The porphyry typically has considerable olivine or serpentinized olivine phenocrysts with minor pyroxene in a fine-grained serpentine matrix typical of peridotite.

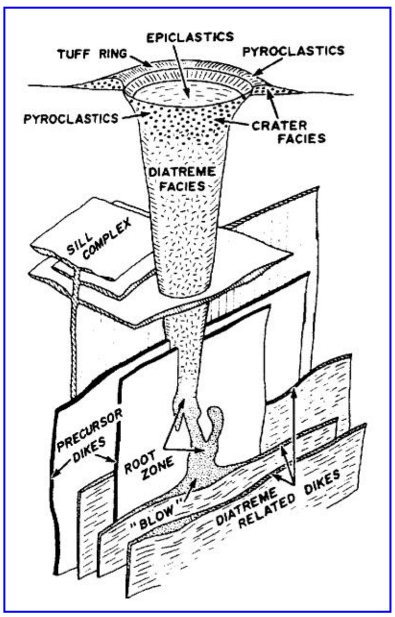


Figure 3. Cross-section of kimberlite pipe showing different facies and the characteristic carat-shaped diatreme (after Mitchell, 1986).

Diamondiferous kimberlite was initially identified in 1870 at the Jagersfontein and Dutoitspan pipes in South Africa. The diamonds were found in deeply-weathered, oxidized kimberlite (referred to as *'yellow ground'*) that graded into less intensely weathered kimberlite (referred to as 'blue ground'). The blue ground is formed of carbonated montmorillonite clay with scattered rounded country rock boulders and mantle nodules. As the kimberlite was mined to greater depth, hard, serpentinized rock was intersected. H.C. Lewis introduced the term *"kimberlite"* in 1887 for diamondiferous rock at the type locality near Kimberley, South Africa that was defined as a porphyritic mica-bearing peridotite.

The magma temperature of kimberlite is hot at depth, but at the point of eruption is strikingly cool. Watson (1967) suggested an emplacement temperature of <1100°F (<600^{o}C) was necessary to produce coking effects on coal intruded by kimberlite. A much lower temperature of emplacement is supported by the absence of visible thermal effects on country rock adjacent to most kimberlite contacts. Davidson (1967) suggests that the temperature of emplacement may be as low as 390°F based on the retention of argon. Hughes (1982) argues that near-surface temperatures of the gas-charged kimberlite melt may be as low as 32°F (0^oC) owing to the adiabatic expansion of CO_2 gas during eruption at the surface and supports that emplacement velocity of gasses and magma which produced the diatreme breccias and crater facies pyroclastics at the surface could have been as high as Mach 3 (2,282 mph)!

Lamproite, another host for diamond, became of major interest following the discovery of a world-class diamond deposit in olivine lamproite in the Kimberley region of Western Australia in 1979. This discovery led to the development of the Argyle mine. Several other diamondiferous lamproites have been described in Australia, Canada, Zambia, Ivory Coast, India, Russia and the United States (Mitchell and Bergman, 1991). Lamproites are known in more than 25 provinces or fields in the world (Mitchell and Bergman, 1991; Coopersmith and others, 2003). Altered diamondiferous leucite lamproite had been described as early as 1967 near Seguela, Ivory Coast (Dawson, 1967). More than a century earlier (in 1827), diamonds had been found in the Majhgawan lamproite in India. Diamonds had also been identified in the Prairie Creek lamproite in Arkansas as early as 1906 (Scott-Smith, 1986, 1989).

Olivine lamproites typically yield higher ore grades than leucite lamproites. But for the most part, lamproites have very low ore grades such as the Mahjgawan olivine lamproite (1.14 Ga) (10 cpht) and the Prairie Creek olivine lamproite (11 cpht) (cpht=carats per hundred tonnes). The Zhenyuan lamproites of the Yangtze craton, China, grade at only 25 cpht (Mitchell and Bergman, 1991). However, there is one very notable exception - the extraordinarily rich Argyle olivine lamproite that yielded some bulk samples as high as 2,000 cpht (carats per hundred tones)!

The pipe morphology of lamproite contrasts with typical kimberlite. Instead of pipes with steep walls that slowly diminish in width with increasing depth, lamproites are characterized by champagne glass-shaped vents filled by tuffaceous rocks often with massive volcanic rock in the core. Many lamproites form distinct cinder cones, flows, and/or maar-like volcanoes (Mitchell and Bergman, 1991). It is important to note that there is a qualitative correlation between diamond and olivine in lamproite. This is seen most everywhere and supported by the Ellendale and Kapamba districts, where diamond grades are consistently higher in olivine lamproites compared to leucite lamproites.

Because of a relatively slow magma ascent rate, diamonds in lamproite often show a variety of morphologies suggestive of resorption and large diamonds are uncommon. At Argyle, for instance, more than 60% of the recovered diamonds were irregular-shaped and included macles, polycrystalline forms and rounded dodecahedrons (Shigley and others, 2001). Some diamonds also exhibit evidence of shearing or deformation: ore grades are essentially restricted to preserved pyroclastics in a given vent where magma temperatures declined rapidly following eruption (Scott-Smith, 1986). A potential for substantial ore tonnage exists where there is flaring of the vent. This is well illustrated at the Argyle lamproite in Australia.

Argyle Lamproite. At Argyle (AK1), early reserve estimates of 94 million tons of ore at an average grade of 750 cpht led to its classification as a world-class deposit. At the end of 2004, the reserves at the AK1 pipe were reported at 136.5 million tonnes (290 cpht) and resources at 160.4 million tonnes (270 cpht). Considerable numbers of diamond were found in the adjacent Smoke Creek drainage where mining began in alluvial material in 1983, and the adjacent open pit operation being later commissioned in 1985. The open pit operations are expected to end in 2008 with mining progressing underground for another decade.

Many fabulous gemstones were recovered from Argyle, but a large portion of the diamonds were graphitized and/or partially resorbed, while the largest recovered diamond weighed only 42.6 carats. Overall, the average size of the diamonds are <0.1 carat. Even so, at one point, Argyle's annual production totaled 40% of the world's production with >670 million carats recovered since mine operations began.

Most lamproite-derived diamonds are relatively small and many exhibit *'fancy'* colors. Overall, diamonds from Argyle and Ellendale are relatively small. Macrodiamonds (>1 mm) from Ellendale are dominantly yellow dodecahedra, whereas microdiamonds (<1 mm) are colorless to pale-brown, frosted, unresorbed step-layered octahedra. The Argyle diamonds are mostly irregularly shaped, fractured, strongly resorbed dodecahedra or combinations of octahedra and dodecahedra. Almost 80% of Argyle diamonds are brown and many of the remaining 20% are yellow to colorless. Significant, but rare, are the economically important pink diamonds of which Argyle has accounted for more than 90% of the world's *'pinks'.*

A variety of lamprophyres have similarities to kimberlite and lamproite. Some of the lamprophyres have yielded diamond and these potassic rocks are becoming of greater and greater interest for diamonds. Erlich and Hausel (2002) predicted that some lamprophyres would most likely be found that contain commercial amounts of diamond. With greater and greater interest in diamondiferous rocks, a large number of diamondiferous lamprophyres are now being found particularly in Canada.

GENESIS

The majority of diamonds are interpreted to represent xenocrysts derived from disaggregation of mantle fragments trapped within a magma. Kimberlites and some lamprophyres will sometimes contain rounded diamondiferous hand-specimen to boulder-size nodules of peridotite (garnet and chromite harzburgites and less commonly lherzolites) and eclogites. These are residual fragments of the mantle that were sampled by the kimberlitic, lamproitic and lamprophyric magmas. During transport to the earth's surface, many of the nodules were disaggregated and if diamonds were present, the diamonds and kimberlitic indicator mineral content were scattered throughout the hybrid magma, although many mantle nodules survive in tact. Some diamondiferous eclogite nodules recovered from kimberlite have been very diamond-rich yielding ore grades as high as 20,000 to 30,000 carats/tonne. Some diamondiferous peridotite nodules have yielded grades 2 to 4 orders of magnitude lower than the richest eclogites, or a much as 3 orders of magnitude greater than host kimberlite ores. Bulk samples of kimberlite and lamproite range from 15 to 2000 carats/100 tonne.

Peridotite is thought to be the most common rock type in the upper mantle in cratonic keels, and pyrope garnets derived from disaggregation and also from intact diamondiferous peridotites often have unique geochemistry. Many of these pyropes (one of the suite of kimberlitic indicator minerals used in searching for kimberlite) are designated as G10 that have chemical affinities for subcalcic harzburgite with relatively low Ca/Cr ratios compared to lherzolitic pyropes (Gurney, 1989). Calcic chrome-rich pyrope garnets designated as G9 have affinity for lherzolite. Lherzolite is thought to have much less potential for diamond. Even so, some lherzolites are diamondiferous!

Eclogite occurs as nodules in kimberlite and is interpreted to represent xenoliths unrelated to kimberlite. They are assumed to either be cumulates of garnet peridotite melts or subducted oceanic crust. Mantle garnets of eclogitic paragenesis have been designated as either Group I or Group II. Diamondiferous eclogites belong to Group I which contain almandine-pyrope with $\geq$0.07% Na_2O, low levels of Cr_2O_3 (<0.05 wt.% Cr_2O_3) and CaO in the range of 3.5 to 20 wt.%. Group II eclogitic pyropes have <0.07% Na_2O. Low-Cr garnets with less than 3.5% CaO are probably derived from crustal rocks (Helmstaedt, 1993).

Many diamonds in kimberlite and lamproite form at depth within the diamond-stability field defined by a unique set of high P and T within the earth's lithosphere (non-convecting uppermost portion of the mantle). The top of this zone corresponds to graphite transition to diamond: the bottom corresponds to the maximum thickness of the lithosphere. Graphite transforms to diamond at a depth of 90 to 125 miles (45 to 55 kbar) and 1920-2190^{o}F within cratonic keels.

There is also a very minor contribution of diamond from sub-lithospheric depths within the convecting portion of the mantle to depths of 420 miles. These ultra-high pressure diamonds are transported to the lithosphere by convection within the earth's asthenosphere and contain mineral inclusions suggestive of very high pressure and temperature (Erlich and Hausel, 2002). Such ultra-high pressure diamonds contain mineral inclusions that support derivation at depths of >185 miles where garnet and pyroxene are unstable and transform to stable sub-calcic, high-chrome majorite garnet (Stachel and others, 2005).

Other diamond deposits have been recognized that do not fit traditional models. These unconventional deposits include rare metamorphics, meteorites, lamprophyres, peridotites and eclogites (Hausel, 1997; Erlich and Hausel, 2002). Unconventional deposits would also include those formed above Benioff zones where diamond is postulated to form in cold subducting slabs along some continental margins. Some research has postulated that such diamondiferous slabs may be generated at depths of only 50 to 56 miles (22 to 25 kbar) and 390-750^{o}F.

Some interesting unconventional source rocks include Archean rocks of komatiite affinity. One komatiite in South America is described as a diamondiferous lamprophyre of komatiitic affinity. Ayer and Wyman (2003) suggest the South American rocks originated at only 50 miles depth. Similar hosts are under investigation in an Archean greenstone belt in the Wawa area, Ontario, Canada (Ayer and Wyman, 2003; Kaminsky and others, 2003). Another similar diamond occurrence was discovered in volcaniclastic komatiite in the Dachine region of the Inini greenstone belt of the Guyana shield of French Guyana (Capdevila and others, 1999). This komatiite was suggested by Capdevila and others (1999) to have originated at depths of >155 miles. Bulk samples of the rock yielded <1 to 35 diamonds/pound. Using a cut-off size of 1 mm, sample grades varied from 0.06 to 10.48 carats/100 tonnes. The largest stones ranged from 1.7 to 2.36 mm across. Colors varied from white to light brown and rarely greenish/yellow and were translucent to transparent but often masked by large quantities of inclusions. The dominant shapes are irregular with few cubic and octahedral stones. The diamonds are for the most part intensely resorbed (press release, 10/12/2000, Global Infomine website).

Indicator minerals associated with komatiites are rare, and are essentially restricted to Mg-Cr garnets and chromite. The garnet population is characteristic of lherzolite with some subcalcic harzburgitic (G10) pyrope and eclogitic garnet. Other kimberlitic indicator minerals (Mg-ilmenite, chromian diopside, and perovskite) are absent. Chromite cores are poorer in Ti and richer in Mn that those typically associated with kimberlite and lamproite. These are similar to spinels found in similar rocks in other greenstone belts.

When found, the komatiites are highly altered and form finely foliated albite-carbonate-chlorite-talc schists, actinolite-chlorite schists, and primary volcanic textures are preserved in some outcrops. Concentrations of immobile elements are very low similar to other komatiites, yet distinct from kimberlite and lamproite. It is thought that the komatiite formed by melting of a hot, deep, mantle source, and that the diamonds were transported as xenocrysts from depths >95 miles. Capdevila and others (1999) suggest a depth of genesis for the Al-depleted magma at >160 miles.

In one test, samples collected from 8 outcrops at Wawa Ontario, Canada yielded 231 diamonds. The diamonds were found in a narrow 3 to 30 foot wide actinolite-rich ultramafic dike crosscutting metasedimentary and metavolcanic rocks of a greenstone belt. In another sample 363 pounds of rock were taken from a road cut along the Trans-Canada Highway north of Wawa and yielded 95 diamonds. The samples suggest an average grade of 25 carats/100 tonnes, potentially within limits of a commercial deposit, depending on the size and clarity of the stones!

Diamonds were also discovered in 2.67 Ga lamprophyres in the Michioicoten and Abitibi greenstone belts. These apparently represent the oldest known primary host rocks for diamonds. They were intruded late in the evolution of the greenstone belts and the chemistry of the lamprophyres suggest that the diamonds originated from spinel lherzolite mantle at depths of less than <50 miles, whereas the diamond stability field is interpreted to lie at >95 miles. The probable absence of a thick cratonic root beneath the Michioicoten, Abitibi and Wawa greenstone belts at the time of eruption indicates a variant of a subduction diamond model applied to Phanerozoic terrain in southeastern Australia may be appropriate. Most likely these diamonds formed at relatively shallow depths 48 miles in a subduction zone and were generated in a low-temperature environment located in a subducted or underplated oceanic crust (Ayre and Wyman 2003). These are notable discoveries since most greenstone belts in the world have thin to thick successions of komatiites and very few have been sampled for diamond.

EXPLORATION METHODS

In diamond exploration, a region is selected that may have good potential for the discovery of commercial diamond deposits based on the tectonics as well as the basement terrain. Since kimberlite and lamproite have been important sources for diamond, most prospecting has focused on finding these types of rocks. Typically, Archons have high priority. In these regions, areas are examined by aerial photography for vegetation and topographic anomalies that might be indicative of kimberlite as well as detailed INPUT airborne geophysical surveys. This data is examined along with stream sediment sampling designed to find kimberlitic indicator mineral anomalies (chromian diopside, pyrope garnet, picroilmenite, diamond and chromite). Once anomalies are identified, additional surveys are conducted to find the source of the indicator minerals and to investigate any aerial photo anomalies.

Airborne geophysical surveys are typically flown over regions where kimberlites have been found, or where distinct indicator mineral anomalies have been identified. INPUT surveys (combined EM and magnetics) are used to focus on geophysical anomalies and to search for distinct bull's-eye anomalies. These anomalies may be drilled. Once a kimberlite, lamproite or lamprophyre is discovered, structural mapping and aerial photo mapping may reveal controlling structures which can lead to the discovery of additional kimberlite pipes. In glaciated areas, mapping of tills and paleo-glacier trends are necessary, and some mapping of paleo-drainages will also be necessary in other non-glaciated regions. Additional information on exploration techniques used for kimberlite is presented by Erlich and Hausel (2002).

Cost figures for annual diamond exploration amounts to tens of millions of dollars. Regional circumstances will dictate which exploration method will need to be used; however, when an exploration program is initiated, priority is given to areas of favorability for finding 'traditional' diamondiferous host rocks. For example, commercial diamondiferous kimberlites are considered to be restricted to cratonic regions that have been relatively stable for about 1.5 Ga. Janse (1984, 1994) suggested that cratons be separated into areas of favorability known as Archons, Protons and Tectons. This method for outlining regions of favorability provides an excellent first option priority list.

Archons are considered to have high potential for discovery of commercial diamond deposits hosted by kimberlite and possibly by lamproite and lamprophyre. Proterons (Early to Middle Proterozoic [2.5–1.6 Ga]) have moderate potential for commercial diamond deposits in kimberlite and high potential for commercial diamond deposits in lamproite and possibly lamprophyre. Tectons (Late Proterozoic [1.6 Ga–600 Ma] basement terrains) are considered to have low potential for commercial diamondiferous host rock. Unconventional diamond deposits (such as high-pressure metamorphic complexes, astroblemes, subduction-related complexes and volcaniclastics) may occur in tectonically active terrains, but the methods for exploration for these, are not well defined.

Following selection of a favorable terrain, topographic and geological maps, aerial and satellite imagery, and aerial geophysical data are examined. Unusual circular depressions, circular drainage patterns, noteworthy structural trends and vegetation anomalies are noted. Geophysics is used to search for distinct conductors and magnetic anomalies. Geochemical data are examined for Cr, Ni, Mg, and Nb anomalies (Hausel and others, 1979).

Stream sediment sampling. One of the primary methods used in diamond exploration is stream sediment sampling programs designed to search for ‘kimberlitic indicator minerals’ (pyrope garnet, chromian diopside, chromian enstatite, picroilmenite, chromian spinel, and of course diamond). Diamond targets are small and may range from diatremes of several acres to narrow dikes and sills. Diamond-bearing kimberlites and lamproites typically contain abundant soft serpentine with resistant mantle-derived xenocrysts and xenoliths. The serpentine matrix tends to decompose releasing distinct mantle-derived ‘kimberlitic indicator minerals’ into the surrounding environment. The indicator minerals may be carried downstream for hundreds of yards, or a few or many miles depending on the climatic and geomorphic history of the region. Diamonds however, are thought to be carried considerable distances – in some cases, hundreds of miles. The indicator minerals may provide a trail leading back to the source.

In the planning stages of stream-sediment sampling, proposed sample sites are initially marked in prominent drainages on a topographic map using a sample spacing designed to take advantage of the region. In arid regions, sample spacing should take advantage of relatively short transport distances of the indicator minerals. In subarctic to arctic areas (i.e., Canada, Sweden, Russia, etc) sample density may be considerably lower owing to the greater transport distance and the logistical difficulties of collecting samples. Anomalous areas are then re-sampled at a greater sample density.

The traditional kimberlitic indicator minerals are rare to non-existent in lamproite, thus other minerals (zircon, phlogopite, K-richterite, armalcolite, priderite) may be considered that unfortunately have low specific gravity, poor resistance, and are potentially difficult to identify. The better indicators for diamondiferous lamproite have been diamond and magnesiochromite.

To take advantage of the dispersion of kimberlitic indicator minerals, the size of samples are determined based on the environment. For example, where there is a general lack of active streams, much larger samples are taken compared to regions with active drainages. In areas with juvenile streams, samples are often panned on site to recover a few pounds of sample concentrates. Recovered indicator minerals are tested for chemistry using an electron microprobe to identify those that have higher probability of originating from the diamond stability field. The data are plotted on maps to facilitate evaluation.

Geomorphology. Kimberlite and olivine lamproite are often pervasively serpentinized, making outcrops the exception rather than the rule. In many cases, geomorphic expressions of pipes are subtle to unrecognizable. The Kimberley pipe in South Africa was expressed as a slight mound, but nearby pipes (i.e., Wesselton pipe) were expressed as subtle depressions. Others produced subtle modifications of drainage patterns (Mannard, 1968). In the subarctic, where glaciation has scoured the landscape, some kimberlites produce noticeable depressions filled by lakes. In the semi-arid region of Wyoming and Colorado, a few kimberlites are expressed as slight depressions, but most blend into the surrounding topography and may or may not have a subtle vegetation anomaly.

In the Ellendale field, Western Australia, serpentinized diamondiferous olivine lamproites lie hidden under a thin layer of soil in a field of well-exposed leucite lamproite volcanoes. The Argyle lamproite and diamondiferous lamproites in the Murfreesburo area of Arkansas were also hidden by a thin soil cover. Several kimberlites in the Colorado-Wyoming region, exhibit, slight depressions with distinct vegetation anomalies.

Lineaments. Many kimberlites and lamproites are structurally controlled (Hausel and others 1979; 1981; Erlich and Hausel, 2002). Controlling lineaments and fractures may be indicated by alignment of a cluster of intrusives or by the elongation of a pipe. In Lesotho, South Africa, Dempster and Richard (1973) reported a close association of kimberlite with lineaments: 96% of kimberlites were found along WNW trends, and many pipes were located where the WNW trends intersected WSW fractures.

Lamproites in the Leucite Hills, Wyoming are found on the flank of the Rock Springs uplift where distinct E-W fractures lie perpendicular to the axis of the uplift (Hausel and others, 1995). In the West Kimberley province of Western Australia, some lamproites are spatially associated with the Sandy Creek shear zone, a Proterozoic fault. In the Ellendale field, several lamproites lie near cross faults perpendicular to the Oscar Range trend, even though the intrusions do not appear to be directly related to any known fault. The Argyle lamproite to the east has an elongated morphology suggestive of fault control, and intrudes a splay on the Glenhill fault (Jaques and others, 1986).

Remote Sensing. Kingston (1984) reported remote-sensing techniques are widely used to search for kimberlite: these include conventional and false color aerial photography, LANDSAT multispectral scanner satellite data, and airborne multispectral scanning.

Many pipes and dikes possess distinct structural qualities or vegetation anomalies that may allow detection on aerial photographs (figure 11). Many kimberlites have been identified on aerial photographs on the basis of vegetation anomalies, circular depressions or mounds, and/or tonal differences (Hausel and others 1979, 2000, 2003).

Figure 4. Aerial view of the Sloan 5 kimberlite, Colorado-Wyoming State Line district, showing distinct vegetation anomaly (high growth of grass and no trees) along a distinct lineament (photo by Hausel).

Geophysical Surveys. Geophysical exploration has been used successfully in the search for hidden kimberlite and lamproite (Litinskii, 1963a, b; Gerryts, 1967; Burley and Greenwood, 1972; Hausel and others, 1979, 1981; Patterson and MacFadyen, 1984; Woodzick, 1980), particularly in districts where kimberlites have previously been discovered. Contrasting geophysical properties are often favorable for distinguishing kimberlite, lamproite and minette from country rock.

INPUT™ airborne surveys are effective in identifying both serpentinized and weathered kimberlite owing to the combination of conductivity and magnetics used in INPUT™. Rock exposures of kimberlite may yield magnetic signatures but are poorly conductive, while deeply weathered kimberlites are conductive but poorly magnetic.

Because of the relatively small size of the diamond host rock, close flight-line spacing is required. In an airborne INPUT™ survey over the State Line district, Wyoming, a flight-line spacing of 640 feet effectively detected several kimberlites and identified distinct magnetic anomalies interpreted as blind diatremes (Patterson and MacFayden, 1984). An aeromagnetic survey flown over parts of northeastern Kansas identified several anomalies, some of which were drilled resulting in the discovery of previously unknown kimberlites (i.e., Baldwin Creek, Tuttle, and Antioch kimberlites) (Berendsen and Weis, 2001). Flight line spacings of 160 to 320 feet were used for INPUT™, magnetics and radiometrics in the Ellendale field, Australia (Atkinson 1989; Janke 1983; Jaques and others, 1986). The olivine lamproites yielded distinct dipolar magnetic anomalies.

Most kimberlites in the Colorado–Wyoming State Line district yielded small complex dipolar anomalies in the range of 25 to 150 gammas, with some isolated anomalies of 250 and 1,000 gammas (Hausel and others, 1979). Blue ground kimberlite tends to mask magnetic anomalies. In the Iron Mountain district, where much of the kimberlite is relatively homogeneous, massive hypabyssal-facies kimberlite, only weak to indistinct magnetic anomalies were detected (Hausel and others, 2000).

Resistivity of weathered lamproite may be lower than that of country rock, owing to the conductive nature of smectitic clay relative to illite, kaolinite and other clay minerals (Gerryts, 1967; Janke, 1983). However, the Argyle olivine lamproite yielded moderate to strong resistivity anomalies (40-100 ohm/m) compared to the surrounding country rock (200 ohm/m) (Drew, 1986). Seismic and gravity surveys are essentially useless in the search for kimberlite (Hausel and others, 1979).

Biogeochemical and Geochemical Surveys. Kimberlite and lamproite are potassic alkalic ultrabasic igneous rocks with elevated Ba, Co, Cr, Cs, K, Mg, Nb, Ni, P, Pb, Rb, Sr, Ta, Th, U, V and light rare earth elements (LREE). The high Cr, Nb, Ni, and Ta may show up in nearby soils (Jaques, 1998), but dispersion of these metals in soils is not extensive.

Bergman (1987) suggested that olivine lamproites are generally enriched in compatible elements relative to leucite lamproites as a result of the abundance of xenocrystal olivine in the former. Barren lamproites contain elevated alkali and lithophile contents (K, Na, Th, U, Y, and Zr) relative to diamondiferous (olivine) lamproites. Diamondiferous lamproites possess twice the Co, Cr, Mg, Nb, and Ni, and half the Al, K, Na and as barren lamproites (Mitchell and Bergman, 1991), and lamproites have anomalous Ti, K, Ba, Zr, and Nb compared to most other rocks. These components may favor the growth of specific flora or may stress local vegetation (Jaques, 1998). The Big Spring vent, West Kimberley, Australia, is characterized by anomalous faint pink tones that reflect the growth pattern of grass on the vent (Jaques and others, 1986).

Many kimberlites in the Colorado–Wyoming State Line district will not support growth of woody vegetation resulting in open parks over kimberlite in otherwise forested areas.

These same kimberlites may support a lush stand of grass delineating the limit of the intrusive. Distinct grassy vegetation anomalies over kimberlites in the Iron Mountain district were used successfully to map many intrusives (Hausel and others, 2000). The anomalies are especially distinct following a few days of rain in the late spring.

Vegetation over the Sturgeon Lake kimberlite in Saskatchewan was tested for 48 elements; the kimberlite showed a consistent spatial relationship with Ni, Sr, Rb, Cr, Mn and Nb, and to a lesser extent with Mg, P and Ba, and relatively high Ni concentrations occurred in dogwood twigs. In hazelnut twigs, Cr levels were greater than 15 ppm near the kimberlite but only 5 to 8 ppm elsewhere, and Nb was higher in hazelnut twigs. Sr and particularly Rb were relatively enriched in some plant species on kimberlite. The Sr was probably derived from the carbonates associated with the kimberlite, whereas the Rb was derived from phlogopite. Ni, Rb and Sr distribution and Cr enrichment associated with Mn depletion in the twigs could be used to identify nearby kimberlite.

NORTH AMERICAN DIAMOND DEPOSITS

Diamonds mined from North America prior to 1998 was restricted to minor production from two small operations at Murfreesburo, Arkansas and Kelsey Lake, Colorado. But due to extraordinary exploration efforts, Canada is now a world power in diamonds surpassing South Africa and ranks as the number 3 producer in the world following only Botswana and Russia. It is likely that Canada will soon become the number 2 source of diamonds based on the number of discoveries and exploration expenditures and investments.

The great Ekati diamond mine opened in 1998, and encloses some of the richest kimberlites in the world (Figure 4). But, just after 3 years of operation, the Diavik mine, which opened about 4 years after the Ekati, became Canada's top diamond producer after recovering just under 20 million carats of rough (Robertson, 2006). Canada currently has three major diamond mines in operation - Diavik, Ekati and Jericho, while others are under construction and permitted including Snap Lake, Gahcho Kue and Victor and still other properties in the feasibility stage.

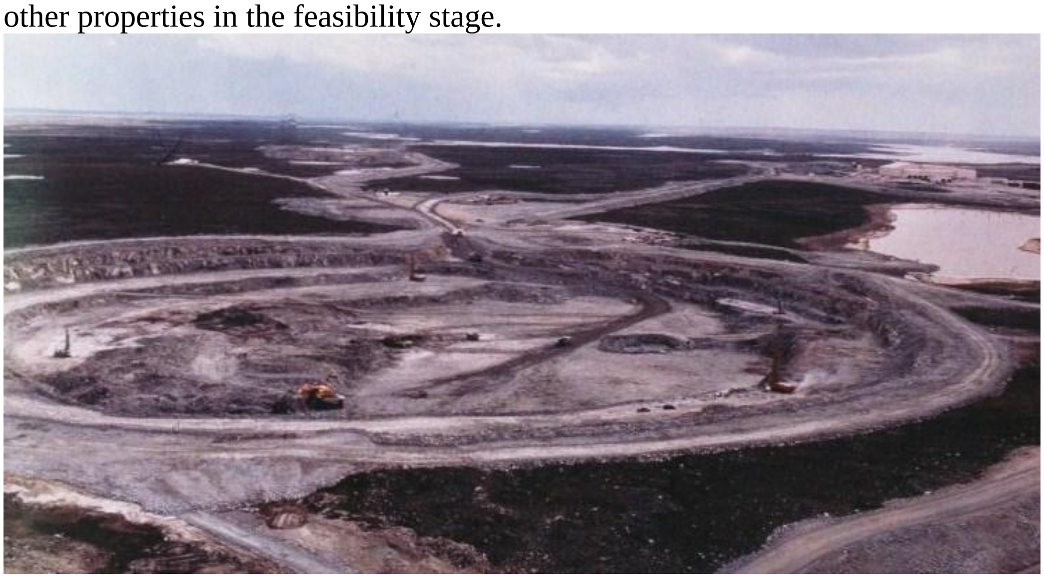


Figure 5. Ekati mine, Northwestern Territories.

Even though large regions of the United States have potential to host significant diamond deposits, the US will remain unproductive unless effort is made to devote research funding in search of diamond deposits. According to Kjarsgaard and Levinson (2002), exploration over the past several years resulted in the discovery of more than 500 kimberlites (including some unconventional host rocks) in Canada, of which nearly half are diamondiferous. The number of discoveries is now more than double. Some unconventional host rocks include actinolite schist (metamorphosed komatiite? or lamprophyre?) at Wawa, Canada, as well as diamondiferous lamprophyres found elsewhere.

Numerous anomalies have also been identified in the US (Figure 5). In the Wyoming Province (>2.5 Ga) and portions of the Colorado Province (<2.5-1.6 Ga) collectively referred to as the Wyoming Craton, >150 kimberlites and dozens of lamproites and lamprophyres have been found surrounded by vast regions of kimberlitic indicator mineral anomalies and more than 100 structurally-controlled geomorphic depressions with vegetation anomalies of unknown origin. The Wyoming Craton underlies nearly all of Montana and Wyoming, and a portion of northern Colorado. A few dozen kimberlites and lamprophyres have also been found in the Superior Craton in the Great Lakes region of Michigan, Wisconsin and Illinois.

More than 30% of kimberlites found in the Wyoming Craton are known to be diamondiferous, although even though many of the remaining yield favorable geochemistry for diamonds, most have not been tested. Twenty-two *in situ* diamond deposits have been identified in Wyoming; and 20 diamondiferous kimberlites have been found in Colorado (Hausel, 1998) with one described in Montana (Ellsworth, 2000). Diamondiferous host rocks have also been found in the Great Lakes region where as many as 26 kimberlitic and lamprophyric intrusives were discovered in the Michigan-Wisconsin-Illinois region. Eight (~30%) of the kimberlites yielded diamond (Cannon and Mudrey, 1981; Carlson and Floodstrand, 1994). A diamondiferous lamprophyre was also discovered in southeastern Wisconsin (Carlson and Adams, 1997) and a small group of diamondiferous lamproites have been known in Arkansas for nearly 100 years (Hausel, 1995).

Diamonds were recovered on a small scale at two US localities: Arkansas and Colorado. Diamonds were initially mined at Murfreesboro, Arkansas in the early 1900s from olivine lamproite (~10 cpht). In the State Line district, two kimberlites were mined in 1996 at Kelsey Lake (Schaffer complex kimberlites) and some attractive diamonds were recovered including two stones >28 carats in weight and one fragment from a stone estimated to be 3 to 4 times greater in size. The grade was reported at ~15 cpht (Coopersmith and others, 2003). Other kimberlites mined in the district included the George Creek dikes (yielded bulk sample grades >135 cpht and averaged 31 to 46 cpht) and the Sloan Ranch kimberlites (9 to 15.5 cpht). Detrital diamonds have been found scattered throughout the US. Most have had little to no follow-up studies and many kimberlites, lamproites and lamprophyres have also been described in the US (Hausel, 1995, 1998).

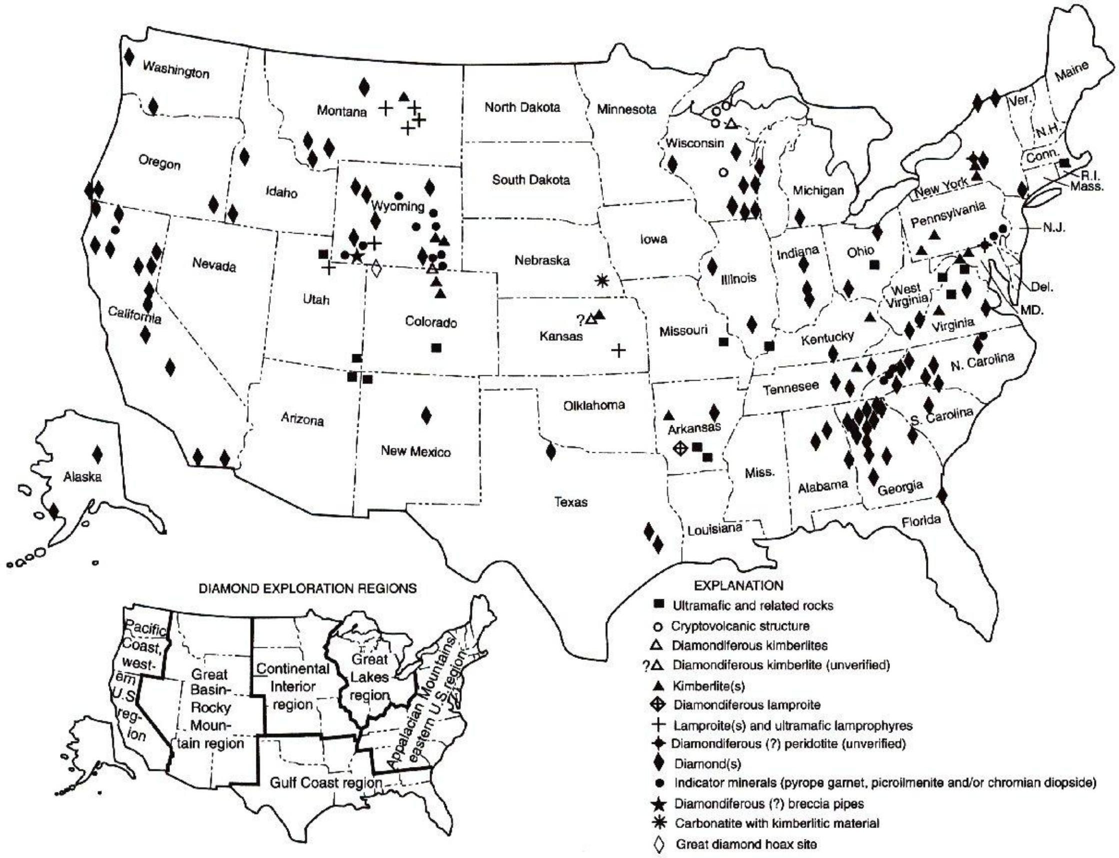


Figure 6. Kimberlite, lamproite, reported diamonds and other anomalies in the US (after Hausel, 1998).

United States

Alaska. Three detrital diamonds were found in Alaska between 1982 and 1986 in a gold placer on Crooked Creek in the Circle mining district northeast of Fairbanks. The Circle district lies near the fragmented northern margin of the North American craton. No kimberlitic indicator minerals were identified in the placer suggesting that the gems may have originated from lamproite or lamprophyre, or from a distal source. A distal source is supported by the percussion marks and fractures in the diamonds suggesting that the stones had a complex alluvial history (Forbes and others, 1987).

The area in which the diamonds were found is a Tertiary basin. Material in the basin is derived from Late Proterozoic through Late Paleozoic sedimentary and metamorphic rock from the Crazy Mountains to the north and Paleozoic to Precambrian metamorphic and Late Cretaceous granitic plutonic rocks from the Yukon-Tanana region to the south. Some alkalic igneous rocks are also reported to the south although no kimberlites or lamproites have been identified (Forbes and others, 1987).

More recently, diamonds were described *in situ* in a diamond-bearing tuffaceous maar near Shulin Lake north of Anchorage. However, this occurrence remains to be verified (Casselman and Harris, 2002). Golconda Resources Ltd. and Shear Minerals Ltd. announced that they had recovered 15 microdiamonds and one macrodiamond from 22 pounds of drill core on their Shulin Lake property. The mineralized interval was described as interbedded volcaniclastic and tuffaceous rocks containing olivine and pyroxene (Shear Minerals Press Release, July 8, 2002). The property is located 45 miles (72 km) north of Anchorage (Casselman and Harris, 2002).

Arkansas. Portions of the Gulf Coastal region of Arkansas and Texas are underlain by an Early to Middle Proterozoic basement considered to have low to moderate favorability for diamondiferous lamproite, kimberlite, and lamprophyre. Some diamondiferous lamproites are known in this region. Most notable is the Prairie Creek olivine lamproite located along the edge of the Ouachita Mountains uplift. This lamproite was the site of North America's first diamond mine following a diamond discovery in 1906 near the mouth of Prairie Creek, southeast of Murfreesboro. The pipe yielded more than 90,000 diamonds including the largest diamond found in the United States (40.42 carats), and was later incorporated into the Crater of the Diamonds State Park.

Diamonds recovered from Prairie Creek include 30% gems: there has been little attempt to recover microdiamonds (Sinkankas, 1959). Some large diamonds from the property include the Uncle Sam (40.42 carats), the Star of Murfreesboro (34.25 carats), the Amarill Starlight (16.37 carats) and the Star of Arkansas (15.24 carats). Most diamonds are white, yellow or brown, and the most common habit is a distorted hexoctahedron with rounded faces (Bolivar, 1984; Kidwell, 1990). The area is underlain by Cretaceous sedimentary rocks that dip gently to the south (Meyer and others, 1977) that were intruded by the lamproite at 106 Ma (Late Cretaceous) (Gogineni and others, 1978). The pipe covers an area of approximately 73 acres (30 ha) and consists of breccia, tuff and hypabyssal olivine lamproite (Miser and Ross, 1922; Bolivar, 1984). Nearly all diamonds have been recovered from breccia facies lamproite, whereas the other magmatic facies are diamond poor. Gogineni and others (1978) report pyrope compositions to be equivalent to G9 calcic-chrome pyropes and Fipke and others (1995) identified only one sub-calcic G10 pyrope from the lamproite. None of the chromite analyses from the pipe yielded favorable geochemistry for diamonds. Thus based on the indicator mineral geochemistry, this would be considered as a very poor target for diamonds, if considered at all. Even so, the pipe has been more productive than what the geochemistry would suggest.

Five other lamproites have been reported nearby and due to very thick vegetation and a long history of erosion the probability of other undiscovered and hidden lamproites is likely. Other lamproites found 2 miles (3 km) north of Prairie Creek include the Kimberlite, American, Black Lick, Twin Knobs and Twin Knobs 2 intrusives (Krol, 1988; Mike Howard, written communication, 1996). Both the Kimberlite lamproite and the American lamproite have yielded some diamonds (Miser, 1914; and Miser and Ross, 1922).

Other ultramafic rocks of lamproitic or lamprophyric affinity have been reported a few miles east of Prairie Creek and about 3 miles (5 km) south of Corinth. Another intrusive of possible interest is the Blue Ball kimberlite dike located 24 miles (38 km) southwest of Danville (Salpas and others, 1986; Hausel, 1998). Little information is available on this intrusive.

Wyoming Craton. Diamonds were found *in situ* in the Colorado-Wyoming region in 1975 in a Wyoming kimberlite (McCallum and Mabarak 1975). Since 1975, essentially every kimberlite in this district has yielded diamond. Even so, some kimberlites still have not been bulk sampled and several geophysical anomalies interpreted as blind diatremes remain inexplicably unexplored. Another group of blind diatremes were found a short distance further south along the border also using an airborne geophysical survey (Tony Barringer, personal communication).

Of the bulk samples taken in the district, grades ranged from <0.5 to 135 cpht with 30 to 50% gemstones with >130,000 diamonds recovered. The 135 cpht bulk sample had been contaminated by considerable granitic country rock, thus the true ore grade of the kimberlite could have been considerably higher. Two episodes of kimberlite magmatism was recognized (Early Cambrian & Early Devonian) along a region extending 3 miles (5 km) north into Wyoming and at least 10 miles (16 km) south into Colorado (Hausel, 1998) and possibly more.

The most productive property to date was the Kelsey Lake mine in Colorado. Commercial production began in 1996 with a mill capacity of only 25,000 carats/year. The mine was developed on two Kelsey Lake kimberlites (KL1 and KL2) which had been initially mapped as the Schaffer 1, 2, 6, 7, 8, and 9 by Eggler (1967). The kimberlites are irregular-shaped pipes and fissures with diatreme facies kimberlite and zones of hypabyssal facies and minor crater facies. An apparent Devonian age on the Kelsey Lake kimberlites is in agreement with Early Devonian and/or Cambrian isotopic ages for most other pipes found in the Colorado-Wyoming kimberlite province (Coopersmith, 1993, 1997; Hausel, 1998).

The mine yielded many high-quality diamonds macrodiamonds. Some of the larger stones included 6.2, 9.4, 10.48, 11.85, 14.2, 16.9, 28.18, and 28.3 carat gems. One broken fragment was estimated to have fragmented from a larger stone of 80 to 90 carats (Howard Coopersmith, personal communication, 1999). The diamonds exhibit predominantly octahedral habit and are colorless with some honey-brown gems (Coopersmith and Schulze, 1996). The 28.18 carat diamond was cut to produce in the largest faceted diamond found in the US. The finished stone weighed 16.8 carats and had an estimated value of >US$250,000 (Denver Post, September 25, 1997). A 28.3 carat diamond, also recovered from Kelsey Lake, was cut into a 5.39-carat gemstone that sold for $87,000 (Paydirt, 1996).

Two open pits were developed to 125 feet (38 m) deep. The ore averaged only about 5 to 15 cpht (Coopersmith and others, 2003), but the high diamond value and relatively low capitalization costs allowed the operation to apparently start out favorably until operations terminated due to legal problems. The property was later reclaimed in 2005.

The Kelsey Lake kimberlites are not mined out and considerable unmined ore remains in place. Resources were established at 16.9 million tonnes to a depth of 320 feet (100 m) (Coopersmith, 1997). The mill was also inefficient as it rejected an unknown amount of diamonds to its tailings including everything >40 carats in weight! During later testing of the mine tailings by Roberts Construction Company, the very first sample yielded diamonds up to 6 carats in weight. Thus the possibility that even much larger diamonds were lost during the operation is likely.

Kimberlites in the State Line district surrounding mine show distinct structural control. Thus exploration for additional kimberlites is enhanced by field mapping of structural trends. All kimberlites in the district have been deeply eroded such that diatreme and hypabyssal facies kimberlites are exposed at the surface. This implies that a very large diamond budget was carried downstream during periods of erosion (Hausel, 2004). The probability that diamond placers have been overlooked is highly likely. For example, detrital diamonds including a 6-carat stone was found in Fish Creek, Wyoming, and smaller diamonds were found in placers south in Colorado. There has been very little to no exploration of placers or paleoplacers, and absolutely no systematic sampling.

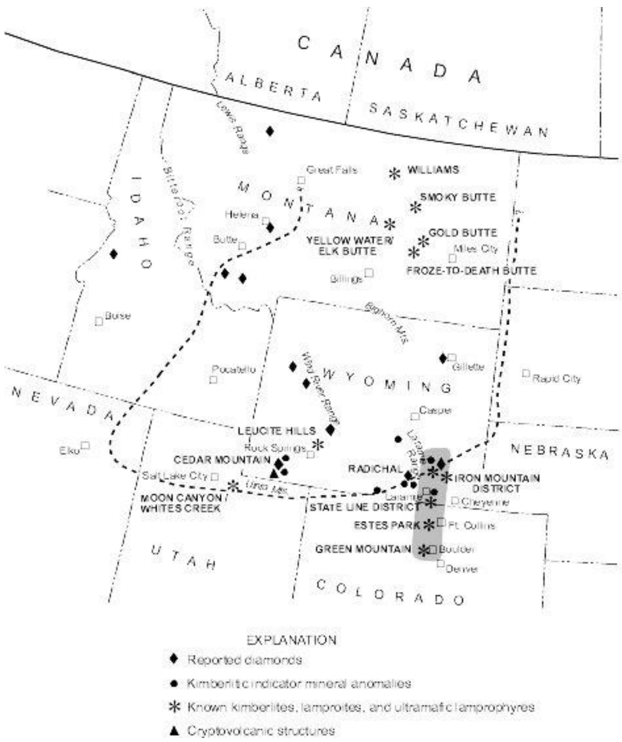


Figure 7. The Wyoming Province Archon within dashes surrounded by Proterozoic accreted terrains as well as locations of anomalies of interest (i.e., kimberlites, lamproites, indicator mineral anomalies, etc., after Hausel, 1998). Very large regions of the Archon remain unexplored including regions considered to have high potential for significant diamond occurrences, such as the older core of the craton in the vicinity of the Granite and Wind River Mountains.

Iron Mountain district. A second major kimberlite district lies 45 miles north of Cheyenne near Chugwater, Wyoming (Figure 6). This district, known as Iron Mountain includes the nearby Indian Guide kimberlites. The district forms a large cluster of kimberlite dikes, sills, blows, structurally controlled depressions and other anomalies in the Sherman granite (1.4 Ga) and Laramie Range anorthosite (1.5 Ga). The kimberlites form continuous anatomizing (Early Devonian) dikes with some blows. Portions of the dike complex were mapped over a strike length of 5 miles (8 km) prior to the kimberlites disappearing under Phanerozoic and Quaternary sediments at either end of the complex. Thus the complex extends for an unknown distance beyond both extremities under younger sedimentary rock (Hausel and others, 2000). There is also considerable Quaternary (Tertiary?) boulder conglomerate cover within the district and kimberlites were mapped to the edge and presumably continue under the conglomerate.

Farther west is a group of structurally controlled depressions along strike that are possibly additional kimberlites (Hausel and others, 2003). These remain unexplored for diamonds. Much of the kimberlite in the district is hypabyssal with some diatreme facies and a group of kimberlites in the northwestern portion of the district, known as the Indian Guide kimberlites, yielded some diamonds including a 0.3 carat stone (Coopersmith and others, 2003). Essentially, all kimberlites in this district yielded diamond stability minerals (Hausel and others, 2003), and in many cases the geochemical signatures are essentially the same as that for the Kelsey Lake diamond mine.

Middle Sybille Creek. Northwest of the Iron Mountain district is the Middle Sybille Creek district where a single kimberlite blow (Radichal) was found in 1980 (Hausel and others, 1981). The kimberlite is surrounded by >4 dozen strong kimberlitic indicator mineral trails that provide evidence for other hidden kimberlites in that region. One of the anomalies (referred to as the *Grant Creek anomaly*) lies along Grant Creek at the eastern edge of the district where a few hundred indicator minerals were recovered from stream sediment samples that suggest a proximal source. Nearby, a limestone xenolith (?) was identified in the Laramie anorthosite (1.5 Ga). This limestone is either out-of-place or represents a Paleozoic outlier similar to those found in the State Line district in the early 1960s that were later proven to be kimberlite. This is referred to this as the ‘Grant Creek outlier’.

Eagle Rock-Happy Jack district. The Eagle Rock-Happy Jack district was discovered by the WSGS during stream sediment sampling between Laramie and Cheyenne (Hausel and others, 1988). Dozens of indicator minerals were recovered along several drainages indicating the presence of hidden kimberlites. To the south, the author recently discovered a group of circular depressions containing considerable carbonate-rich sediment enclosed by Sherman Granite (1.4 Ga).

Indicator mineral anomalies (pyrope garnet, chromian diopside, picroilmenite, chromite, and/or diamonds). Between the Iron Mountain and State Line districts, as well as several miles north and along the eastern flank of the Medicine Bow Mountains, >300 kimberlitic indicator mineral anomalies were discovered: very few have ever been traced to their source (Hausel and others, 1988). Numerous other KIM anomalies were identified by Cominco American in the same region (Howard Coopersmith, personal communication, 1990).

KIM anomalies are widespread and have been identified in the Laramie, Hartville, Sierra Madre and Seminoe Mountains and in the Greater Green River Basin in southern Wyoming, and in the Bighorn Basin, the southern Bighorn and Owl Creek Mountains, and the Powder River Basin of northern Wyoming. KIM anomalies are also reported in the Front Range of northern Colorado, in the Uintah Mountains of northeastern Utah and in the Sweet Grass Hills of Montana. The presence of several hundred KIM anomalies along with geophysical and remote sensing anomalies support that the Wyoming Craton has been intruded by major swarms of kimberlitic and related intrusives.

Green River Basin. One of the major KIM anomalies was described McCandless and others (1995) in the Green River Basin of Wyoming. Five diamonds were found in the early 1980s in a drainage running from the flank of Cedar Mountain within this region. Later, a group of 10 mafic lamprophyric breccia pipes and dikes were discovered in this drainage, and many others were mapped in the region by Amselco. The pipes lie along a 5- to 10-mile-long (8-16 km), northerly-trending lineament in the Bridger Formation (Eocene). Samples recovered from the pipes yielded some diamonds (Hausel and others, 1999) and Guardian Resources later reported the discovery of two additional breccia pipes nearby (Press Release, Guardian Resources, 1997). Diamonds were also recovered by Anadako from these intrusive.

Several alluvial diamonds were found in a nearby drainage (Guardian Resources Press Release, Sept. 24, 1996). The Cedar Mountain pipes and dikes contain numerous KIMs that are geochemically similar to those in the Bishop Conglomerate (Oligocene) and in anthills to the north, many of which are gem quality. The pipes only account for a small portion of the indicator minerals in this region.

Leucite Hills lamproites. The largest lamproite field is northeast of Cedar Mountain and north of the towns of Superior and Rocks Springs. Twenty-two lamproites were mapped in this area and the field remains unexplored for diamonds. Some gem-quality peridot was found in the northeastern portion of the volcanic field, along with some diamond-stability chromites (Hausel, 2006). The possibility of hidden, diamondiferous olivine lamproite in the Leucite Hills needs to be investigated.

Many other anomalies have been identified in Wyoming including KIM anomalies in the Seminoe Mountains and the Bighorn Basin, and in the Medicine Bow Mountains. One very interesting anomaly identified by the WSGS several years ago is a Tertiary-Quaternary conglomerate along the north flank of the Seminoe Mountains. This conglomerate has occasional pebbles of tawny-colored banded iron formation typical of that found at the western edge of the Seminoe Mountains greenstone belt (Hausel, 1993). Panned samples of the dry conglomerate in the flats near the Miracle Mile yielded gold as well as pyrope garnet. Samples from both sides of the North Platte River yield lilac to purplish garnets that were tested for geochemistry. All pyrope analyses have yielded diamond-stability geochemistry typical of sub-calcic chrome pyropes (G10). The possibility of finding diamonds in this region is very high.

Montana. Detrital diamonds have been found in Montana in the northern portion of the Wyoming craton, along with numerous potential host rocks (alnöite, peridotite, monchiquite, lamproite and kimberlite) (Figure 5). Several potential host rocks are found within the central alkalic province in eastern Montana, and a few lamproites are reported in western Montana including the Ruby Slipper (Pete Ellsworth, personal communication, 1996). Two diamonds were found in gravels of the Etzikom Coulee in the Milk River drainage north of the Sweet Grass Hills in northern Montana (0.14 and 0.17 carats) (Lopez, 1995). The occurrence lies near a buried magnetic anomaly aligned with presumed kimberlitic rocks in Alberta.

This extensive field of lamproites, lamprophyres and kimberlites in eastern Montana have trace amounts of KIMs (Fipke and others, 1995). Some interesting targets in this region include a belt of ultramafic lamprophyre and kimberlite diatremes in the Grassrange Field, east-central Montana. The area was highly recommended (Hausel, personal field notes, 1994) as having high potential for diamonds and within a few years following this recommendation, the Homestead kimberlite was discovered and proven to be diamondiferous (Ellsworth, 2000). This kimberlite sits near an extensive breccia pipe known as Yellow Water Butte that is formed of massive to brecciated olivine-phlogopite-diopside-carbonate lamprophyre with massive hypabyssal olivine lamprophyre facies (Doden, 1996).

Hypabyssal facies kimberlites are found near Landusky north of the Grassrange Field. These include four closely-spaced diatremes in the eastern part of an east-northeasterly trending swarm of ultramafic alkalic diatremes, dikes and plugs (46 to 51 Ma) in the

Missouri Breaks area of north-central Montana that are referred to as the Williams kimberlites. Analyses of garnets from the kimberlites indicate compositions equivalent to G-9 (Hearn and McGee, 1983) and P-T estimates from co-existing orthopyroxene-clinopyroxene pairs in some of the peridotite nodules indicate some nodules may have originated from the diamond stability field (Fred Barnard, written communication, 1994).

West Coast. The west coast of the US and Canada may provide some very interesting unconventional targets for diamonds. Many diamonds were found in the past during gold placer mining in California, Oregon and Washington. California, in particular, was a good source for diamonds in the gold rush days. Some historical gold placer mines north of Oroville, California in the Round Mountain area yielded diamonds as a by-product of gold mining between 1853 and 1918. About 400 diamonds and 600,000 ounces of gold were recovered on the Feather River (Hill, 1972). Kunz (1885) reported diamonds were found in all of the northern counties of California drained by the Trinity River in the vicinity of Coos Bay, Oregon; and on the banks of the Smith River of Del Norte County, California. Five diamonds were also recovered from a tributary of the Trinity River in Hayfork Creek. One found in 1987 weighed 32.99 carats (Kopf and others, 1990). Sinkankas (1959) reported that microdiamonds were found in the black sands of the Trinity River near its junction with the Klamath River, and pyrope garnet and chromian diopside were described from the Trinity River (Kopf and others, 1990). Chromian diopside-bearing serpentinites were later discovered in this area (Hausel, personal field notes 1995).

The presence of an active Benioff zone in California provides a mechanism to develop over-pressurized magmas at depth and possibly provide a source for the diamonds. Breccia pipes from such magmas may have been found at Leek Springs and at another undisclosed locality in the Sierra Nevada of California. Both pipes contain some diamond-stability minerals. The possibility of other breccia pipes in this region needs to be considered.

Diadem Resources reported discovery of a cluster of dikes including a 1,875 by 188 m (6000 x 600-ft-wide) 'dike' after following an indicator mineral trail upstream from a historic diamond placer at Leek Springs (Northern Miner, 1/29/96). Drill cuttings from a 120 foot (37 m) zone of 'lamproite' yielded 235 diamond fragments (Northern Miner, 4/20/96). At another breccia pipe in the Sierra Nevada, the diatreme has clasts of serpentinite along with some diamond-stability indicator minerals typical of mantle peridotite (Lynn O'Rouke, personal communication).

Great Lakes Region. A group of kimberlites in the Michigan-Illinois area in the Great Lakes region intrude the Superior Province, which is an Archean craton underlying much of Minnesota and eastern South and North Dakota continuing north into Canada. The Superior Province is bounded on the west by the Trans-Hudson Orogen and a Proton of Early to Middle Proterozoic basement rock to the east and south suggesting this region to have moderate potential for diamond discoveries.

The Early to Middle Proterozoic basement along the margin of the Superior Archon is bounded by Late Proterozoic rocks of the Grenville Tecton further to the east. The Grenville Tecton extends into eastern Michigan and Indiana. Several diamonds (including some sizable stones) were recovered from the Great Lakes region (Hausel, 1995, 1998). These were thought to have been transported from Canada by continental glaciers during a past ice age. This assumption has come under question since the discovery of several post-Ordovician kimberlites in Michigan. A few dozen kimberlites and lamprophyres have also been described within the Superior Craton in Michigan, Wisconsin and Illinois. Eight kimberlites in Michigan yielded diamond (Cannon and Mudrey, 1981; Carlson and Floodstrand, 1994) and a diamondiferous ultramafic lamprophyric breccia was discovered in southeastern Wisconsin (Carlson and Adams, 1997). At least 26 kimberlites have been found in Michigan, Wisconsin and northern Illinois. Eleven magnetic anomalies were also detected that are suggestive of buried diatremes. Michigan also has some Paleozoic outliers that are completely surrounded by Proterozoic rocks that are interpreted as cryptovolcanic structures that are possibly kimberlite pipes.

One kimberlite found near Crystal Falls, Michigan, lies one mile (1.6 km) west of Lake Ellen near the Wisconsin border. This kimberlite (Lake Ellen pipe), is poorly exposed but yields a strong positive magnetic anomaly that suggests the presence of a 650 to 950 feet (200-290 m) diameter kimberlite with a surface area of 20 acres (8.1 ha). The kimberlite was emplaced in Proterozoic volcanic rocks and has abundant Ordovician(?) dolomite xenoliths. Diatreme facies kimberlite at Lake Ellen contains olivine, pyroxene, mica, pyrope and magnesian ilmenite in a fine-grained serpentine matrix (Cannon and Mudrey, 1981). Another kimberlite (Michgamme), lies a short distance northwest of the Lake Ellen intrusive along the Michgamme Reservoir shoreline (Carlson and Floodstrand, 1994).

Northwestern Wisconsin is underlain by basement rocks of the Superior Province while Proterozoic age rocks underlie the remainder of the state. Since 1876, 25 diamonds were found in southern and central Wisconsin. All were found in Pleistocene glacial deposits or Holocene river gravel. Other diamonds were recovered in a diamondiferous ultramafic lamprophyre (melnoite) known as the Six-Pak diatremes that was discovered by Ashton with airborne magnetics. The diatreme was drilled: it has 50 acre (20 ha) surface area and consists of hypabyssal facies lamprophyre with a typical kimberlitic mineral suite including calcic pyrope garnet (G9). Several small diamonds were recovered from the intrusive. The intrusive lies in the outskirts of Kenosha in southeastern Wisconsin (Carson and Adams, 1997). Many other kimberlites, lamproites and lamprophyres have been identified in the US. The reader is referred to Hausel (1995, 1995a, 1998) for these.

Canada

Canada is undergoing a major economic evolution. Many kimberlites and other potential diamondiferous host rocks have been identified over large regions of the North American Craton in Canada (Figure 7). Most of the discoveries have been made since the early 1990s. The number of discoveries and the variety of host rocks as well as the incredible capital investment will change fundamental concepts on diamond exploration. The scenario has resulted in one of the greatest economic evolutions in history. Within a very short period, Canada became the world's number three producer of gem-quality diamonds. Prior to 1998, Canada did not produce a single commercial natural diamond. Today, only Namibia and Russia out-pace Canada. But within the next decade, Canada is expected to become the number two diamond producer in the world and may even surpass Namibia within the foreseeable future.

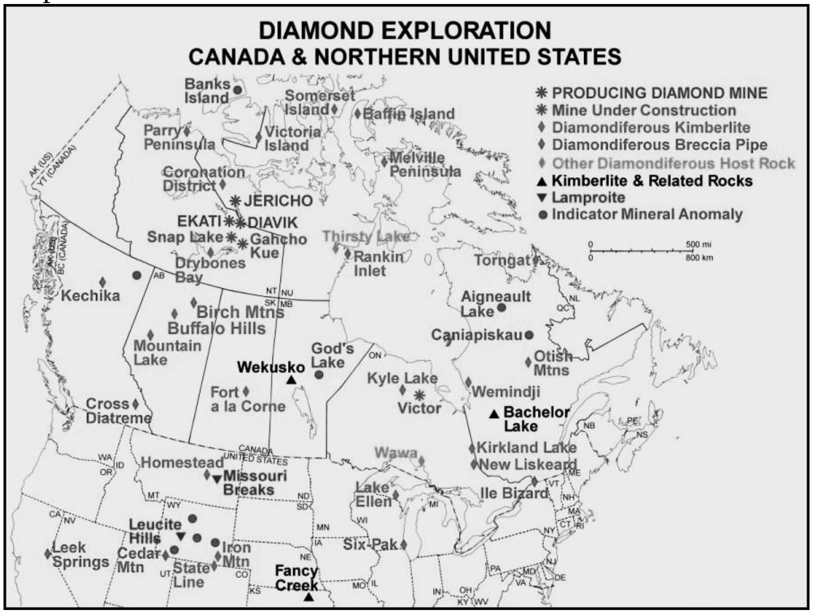


Figure 8. Location of principal diamond districts, fields and anomalies in North America (compiled by Wayne M. Sutherland and the author).

The diamond discoveries span the North American craton from one end of Canada to the other. One interesting anomaly is that the discoveries essentially end at the US border. This is a political anomaly, not a geological phenomenon.

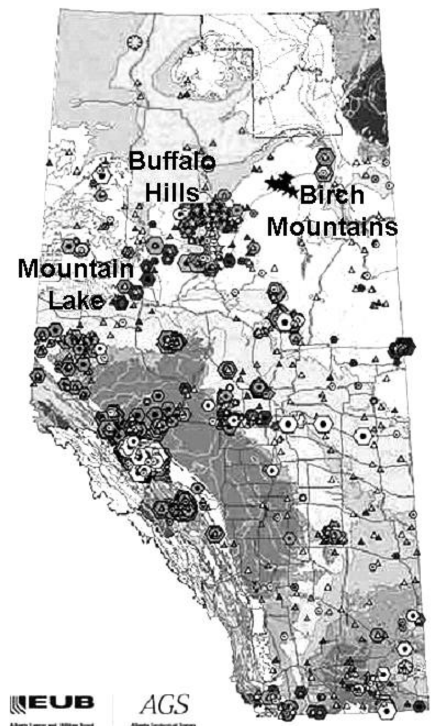
Alberta. Exploration in Alberta resulted in the discovery of several kimberlites, lamprophyres, widespread KIM anomalies and magnetic anomalies. Both magnetics and electromagnetics have proven invaluable in the search for hidden kimberlite in this region. Widespread KIMs have been identified in Alberta. The Alberta Geological Survey reports widespread anomalies from the Canadian-Montana border northward to the Northwest Territories, with extensive anomalies in the central portion of the Province (Alberta Geological Survey, 2004). The data suggests the presence of hidden kimberlites and related host rocks.

One group of kimberlites were discovered along a northeasterly trend paralleling two major shear structures near the north-central portion of the province. These occur at (1) Mountain Lake northeast of Grande Prairie, (2) Buffalo (Head) Hills northeast of Mountain Lake and (3) in the Birch Mountains further to the northeast. Many of the kimberlites in northern Alberta yield 70 to 85 Ma ages (Simandl and others, 2005).

At (1) Mountain Lake, the diatremes are lamprophyres. The Mountain Diatreme was discovered in 1973 and initially interpreted as kimberlite. However, recent analyses suggest it is a hybrid with geochemical affinities for basanite (olivine potassic basalt), olivine minette, alnöite and melilitite. Compared to the Buffalo Hills and Birch Mountains kimberlites, the Mountain Lake diatreme has higher SiO_2, Al_2O_3, Na_2O, K_2O, Na_2O/K_2O, Ga, Rb and peralkalinity index, and lower MgO, Nb, LREE, and Sr. The chemistry implies high potassic, alkali, ultramafic rock (Eccles, 2002).

In 1983, a sample of the lamprophyre taken by Superior Minerals yielded two microdiamonds from a 77-lb (35 kg) sample and 8 or 9 microdiamonds were recovered from crater facies outcrops at the surface (Casselman and Harris, 2002).Two pipes are known in this area. The Mountain Lake diatreme is 118 miles (190 km) southwest of Norman Wells, Northwest Territories in the Mackenzie Fold Belt. It forms a 1,970-foot (600 m) diameter pipe that intrudes Upper Cambrian to Middle Ordovician limestone. The diatreme contains picroilmenite, pyrope and chrome-diopside xenocrysts similar to the DK pipes at Cedar Mountain in the Green River Basin of the Wyoming Province. The Mountain diatreme has a central core of dark green autolithic breccia with lesser country rock xenoliths. The matrix is composed of chlorite, phlogopite and carbonate with minor serpentine, tremolite and opaques. K-Ar dating of phlogopite returned a 445 Ma age for the intrusive.

Figure 9. Location of principal diamond districts in Alberta including known KIM trails and anomalies (circles). Modified from the Alberta Geological Survey).



The Buffalo Hills cluster to the northeast are of current interest due to discovery of 36 diamondiferous pipes within a cluster of 38 kimberlites. Three (K14, K91 and K252) have yielded bulk sample tests of >11 cpht and the K252 kimberlite yielded an initial test of 55 cpht and is of potential economic interest (Alberta Geological Survey, 2004; Cummings, 2006). The Buffalo Head Hills are underlain by Early Proterozoic crystalline basement with possibly some Archean basement of the Buffalo Head Craton. The regional setting was favorable for emplacement of kimberlite during periodic tectonic activity associated with movement along the Peace River Arch (Alberta Geological Survey, 2004; Cummings, 2006).

Samples from the region yielded significant numbers of KIMs including olivine, pyrope garnet, chromite and picroilmenite. Some of these were collected well north of the northernmost known Buffalo Hills kimberlite indicating a strong likelihood that undiscovered kimberlites lie to the north. In addition, some geophysical anomalies within the cluster are characteristic of hidden kimberlite.

At least three distinctive volcaniclastic units are recognized in the Buffalo Hills kimberlites, two are primary pyroclastic deposits that are not normally preserved in most kimberlites. The pipes are distributed over a 2,300 mi^2 (6,000 km^2) area and intrude Proterozoic Buffalo Head Terrain. The kimberlites erupted through Proterozoic basement, Devonian sedimentary and Cretaceous sedimentary rock, but were covered by Quaternary till (Boyer and others, 2005).

Volcaniclastic crater facies kimberlite in the district indicates very little erosion has occurred since diatremes emplacement. The crater facies includes well-sorted, ash-size fine-grained, olivine-rich layers interbedded with lapilli-size fragment-rich layers. Cross-stratified and finely bedded deposits are similar to those formed by basal surge and pyroclastic ash fall. Some accretionary fragments with multiple magmatic rinds thought to have formed during a series of eruptions are typical of proximal crater-fill and pyroclastic ash falls. Some poorly-sorted, subtly bedded, crystal-rich kimberlite is depleted in fine-grained matrix material (Boyer and others, 2005).

The Buffalo Head Hills and Birch Mountain diatremes are chemically similar to Group I kimberlites. Of the two, the Buffalo Hills kimberlites have the highest MgO, Cr, and Ni, the lowest Al_2O_3, SiO_2, V, Y, Pb, Sr and Ga content, and have geochemical signatures similar to primitive kimberlite in the Northwest Territories. In addition, a high proportion of the Buffalo Head Hills kimberlites are diamondiferous (Eccles, 2002).

Diamonds recovered from the K11, K91 and K252 kimberlites in the Buffalo Hills cluster are mainly colorless and transparent: most have resorbed octahedral habits. The garnet, olivine and pyroxene inclusions indicate a presence of both eclogitic and peridotitic diamonds. The data supports that a lithospheric mantle beneath Buffalo Hills is dominated by an eclogitic component similar to many younger diamond-bearing areas around the world. The presence of rare majoritic garnet inclusions in some diamonds supports that some diamonds were formed in very deep mantle source region (Eccles, 2002).

At least nine kimberlites have been identified in the Birch Hills cluster northeast of the Buffalo Head Hills: two of which have yielded diamonds. The Birch Mountains kimberlites are more evolved than the Buffalo Hills kimberlites and have lower SiO_2, Ni and MgO and higher Fe_2O_3, TiO_2, Nb, V, Sc, Zr, Hf, Y, Ba, Rb, LREE, Ga and Pb. Hence, whole-rock geochemistry of these kimberlites is similar to Group IB South African kimberlite. One kimberlite, known as the Legend, is a 1,640 to 2,625-foot (500-800 m) diameter multiphase kimberlite. The Legend Kimberlite lies beneath 42 feet (12.8 m) of overburden. Four microdiamonds were recovered from an 896-lb (406 kg) sample (Eccles, 2002).

British Columbia. Much of British Columbia is underlain by an unconventional terrain for primary diamond deposits. However, recent studies in the extreme northeastern portion of the province suggest that part of that region may be underlain by a structurally disturbed fragment of the North American Craton. Even though much of British Columbia is considered unfavorable for *in situ* diamond deposits based on traditional diamond exploration concepts, diamonds have been recovered from a group of breccia pipes, many with classical KIMs. These intrude the Cordilleran belt along a NNW-trend. Lithologies include alkalic basalts, and alkalic and ultramafics lamprophyres. Only a few true kimberlites are reported in British Columbia. Even so, microdiamonds have been recovered from some pipes.

Many anomalies have been identified near the Alberta border north of Montana and further north in northern British Columbia. The known kimberlites and lamprophyres have yielded age dates of 391 to 410 Ma for the HP pipe to 240 Ma for the Cross diatreme (Simandl and others, 2005). Of 58 samples of alluvium, regolith and bedrock collected in extreme northeastern British Columbia in the Etsho plateau near Ft. Nelson and Dawson Creek, 38 contained kimberlitic indicator minerals supporting a likelihood of hidden pipes. Some indicator minerals yielded diamond-stability geochemistry and one

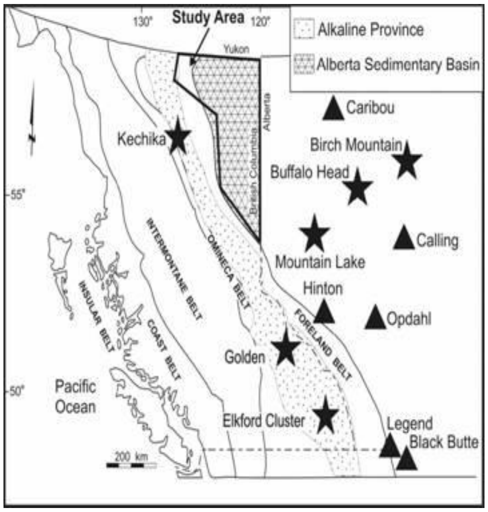


Figure 10. Diatremes (stars) in British Columbia and Alberta (from Simandl and others, 2005).

contained an enclosed microdiamond inclusion.

Nearly all of diatremes lie along a north-south 54 by 12 mile (87 x 19 km) trend within the Rocky Mountains Uplift. This region is remote and rugged supporting that other discoveries will likely be made with continued exploration (Roberts and others, 1980; Grieve, undated). Many of the diatremes were emplaced in Cambrian to Permian carbonate and clastic sedimentary rocks of the Foreland and Intermontane Belts near the west coast of Canada (Simandl, 2003). This area is characterized by thrusts and associated folding. All of the diatremes were emplaced in Middle Devonian and older strata while the Cross diatreme in the Elkford cluster in the southeastern corner of the province was emplaced in Permian bedrock. The terrain is not what would be anticipated for primary conventional diamond models that require cool, stabilized, cratonic cores (Archons) with thick keels. Instead, this region is geologically unstable and has been subjected to considerable deformation with displaced and accreted terrains.

Kechika Group. The Kechika River group includes the Xeno pipe that lies at the northern end of Dall Lake in the Kechika Range of the Cassiar Mountains. The property was originally acquired for rare earths associated with a mafic alkalic igneous complex that is underlain by quartzite of the Lower Cambrian Atan Group, chlorite-sericite schist, phyllite, marble and dolomite of the Cambrian-Ordovician Kechika Group, and by siliceous tuff, chert, sandstone and argillite of the Ordovician to Silurian Sandpile Group. The rare earths are hosted by alkalic igneous complex that forms a west-northwest trending belt of cogenetic syenites, trachytic volcanics and carbonatites that have been traced for 12.5 miles (20 km) along strike and is a few hundred feet to a few miles wide. At the southern end of this belt, a diatreme was discovered with a variety of igneous and sedimentary (quartzite and carbonate) xenoliths and chrome-spinel xenocrysts in a pale green, carbonate-rich tuffaceous matrix. Exploration in 2002 identified a nearby lamprophyre dike that varies in width from a few to over 160 feet (49 m) exposed intermittently along a 1.6 mile (2.6 km) strike length. A 70-lb (32 kg) sample collected from the dike yielded a transparent, green microdiamond (0.38 x 0.30 x 0.25 mm). The Kechika River diatreme within the Kechika Range lies west of the Rocky Mountain trench has geochemically affinity for alkalic lamprophyre.

The Ospika pipe to the south of Kechika River (north of Mackenzie) is complex breccia with at least 5 intrusive events. The breccias has xenoliths, cognate nodules and phlogopite, titaniferous augite, rare altered olivine and bright green diopside in aphanitic carbonate matrix. The pipe is classified as an ultramafic lamprophyre (aillikite) based on petrography and whole rock geochemistry (Ijewliw and Pell, 1996). A microdiamond was reportedly recovered from breccia in a carbonatite complex in the Kechika area.

Golden Field. A group of diatreme breccias and dikes are reported at five localities further south, in the Golden field. These are located at Bush River, Mons Creek, Valenciennes River (Mark diatremes), Lens Mountain (Jack diatreme) and Campbell. The Bush River breccia and dikes have been classified as olivine kersantites (calc-alkalic lamprophyres) based on mineralogy, although they have an affinity for more alkaline chemistry. Diatremes and dikes in the Mons Creek and Valenciennes River are altered with pseudomorphs of serpentine after olivine, clinopyroxene, biotite and plagioclase and are classified as camptonites (alkalic lamprophyres). The Lens Creek diatreme may be lamproitic, and the HP pipe south of the Campbell Ice field consists of limestone clasts, quartzite, clasts of plutonic rock with autoliths, megacrysts and phenocrysts of clinopyroxene (chrome diopside), melanite garnet, biotite spinel and apatite in a groundmass of calcite, chlorite, serpentine, talc and pyrite and is classified as aillikite (Ijewliw and Pell, 1996). Simandl (2003) reports that diamonds were recovered from samples from the Jack (Lens Mountain) and Mark (Valenciennes River) diatremes.

Bull-Elk Creek Field. Another 40+ breccia pipes and dikes are found south-southeast of the Golden Field near Cranbrook in the Bull-Elk Creek field. These are primarily tuffaceous intrusives with vesicular lapilli, clinopyroxene, olivine, calcite, and spinel in a groundmass of carbonate, chlorite, talc and minor plagioclase.

Summer diatremes. The Summer diatremes 24 miles (38 km) northeast of Cranbrook, lie near the intersection of Galbraith and Summer Creeks. One known as the Quinn diatreme lies near the head of a tributary of Quinn Creek, 36 miles (58 km) northeast of Cranbrook. This diatreme intrudes Ordovician-Silurian Beaverfoot-Brisco Formation carbonates and has gray-green matrix with small clasts and phenocrysts of olivine and spinel (<5 mm). In thin section, angular quartz and feldspar, volcanic fragments, carbonate, argillaceous material and serpentine occur in carbonatized groundmass. Xenoliths in the breccia include well-rounded limestone, argillite, quartzite, granite and rare ultrabasics (Grieve, undated). Simandl (2003) reported that macrodiamonds were extracted from the Cranbrook cluster, the Bonus and the Ram 5 and 6 diatremes. The Ram 6 is located north of Elkford and reported to be diamondiferous and possibly kimberlitic (Allan, 1999).

Elkford kimberlites. The Cross diatremes in southeastern British Columbia is located near Elkford (Figure 7). This diatreme was initially reported in 1957 on the north side of

Crossing Creek valley. It covers a surface area of 225 by 190 feet (69 x 58 m) and is composed of intrusive breccia in a shear zone in Permian Rocky Mountain Group shale, limestone and chert. No thermal metamorphism is visible along the intrusive contact. The breccia matrix is a bluish-green, calcareous groundmass enclosing phenocrysts and megacrysts of phlogopite, altered olivine, hematite, calcite, chromian diopside and reddish-brown pyrope-almandine garnet with rounded to subangular xenoliths of limestone, argillite, serpentinite and peridotite. Reconnaissance exploration was not initiated until after the Cross diatreme was described as kimberlite in 1976. Geochemical analyses support that it is kimberlite, and four other kimberlites are apparently found in the region (Ijewliw and Pell, 1996).

Portions of the field are underlain by blueschist and eclogite facies rocks interpreted as subducted-related. Some diatremes in British Columbia are weakly diamondiferous possibly from sampling material from a paleo-subduction zone. The breccia matrix or magma type for the British Columbia breccia pipes is not well defined, similar to the subduction related breccias identified in California. The majority of diatremes in British Columbia are ultramafic lamprophyres while the Cross is kimberlitic (Grieve, Undated).

Labrador. At least four areas in northern Labrador within the Nain Province (Archean) have been identified that have rocks of apparent kimberlitic to lamprophyric affinity. These include (1) Capes Aillik-Makkovik dikes and pipe, (2) the Ford's Bight diatreme, (3) the Saglek dikes and pipes, and (4) the Torngat Mountains dikes. Groups 1, 2, and 3 are described as kimberlites, and number 4 includes both kimberlites and ultramafic lamprophyres (melilitites and or aillikites). The Torngat dikes are affiliated with the Abloviak shear zone and several are diamondiferous (Wilton and others, 2002).

Manitoba. Exploration in Manitoba resulted in discovery of the Wekusko kimberlite dike north of Lake Winnipeg. Research by the Canadian Geological Survey resulted in the identification of numerous indicator mineral trains in the Gods Lake-Knee Lake area near the Snow Lake-Flin Flon area. The indicator mineral trains suggest the presence of several hidden, mantle-derived pipes in eastern Manitoba.

Northwest Territories (NWT) – Nunavut. Diamond deposits have been discovered at numerous locations in the Canadian far north. Some of the more important are: (1) Lac De Gras (NWT & Nunavut), (2) Thirsty Lake (Nunavut), (3) Parry Peninsula (Darnley Bay) (NWT), (4) Victoria Island cluster (NWT- Nunavut), (5) Somerset Island cluster (Nunavut), (6) Rankin Inlet cluster (Nunavut), (7) The Melville Peninsula (Nunavut), (8) Baffin Island (Nunavut), (9) Dry Bones Bay (NWT) and (10) Coronation Bay (Nunavut).

(1) *Lac De Gras region*. A major kimberlite district was discovered in the Slave Province northeast of Yellowknife in the Northwest Territories in the early 1990s. Several commercial pipes and sill have been identified in this region that include the Ekati group, Diavik group, Snap Lake, Gahcho Kue (formerly Kennady Lake) and Jericho (Figure 8). There are many other kimberlites in this region such as those at Carp Lake, Hardy Lake and others, but only the commercial deposits are described.

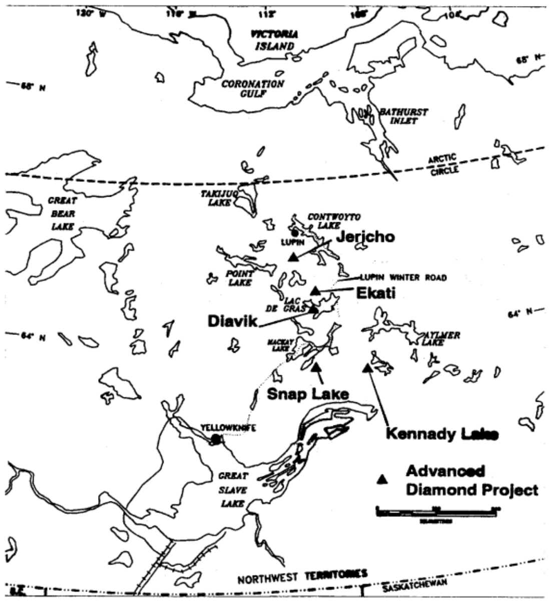


Figure 11. Northwest and Nunavut diamond mine localities.

One of the great exploration success stories in history was the discovery of diamonds in the Canadian Northwest Territories, which sparked the largest claim staking rush in history (Krajick, 2000). Within a few years, capitalization of the *Ekati mine* resulted in the first Canadian diamond mine. Production began in 1998. Since mine operations started, other commercial properties have been identified that include the Snap Lake dike and the Diavik pipes. A fourth commercial diamond prospect in Canada, *Jericho*, is located in Nunavut 100 miles (160 km) north of Ekati and 250 miles (400 km) NNE of Yellowknife. Of these four commercial operations Ekati is by far the largest operation. Most kimberlites in the Northwest Territories were emplaced at 45 to 75 Ma (Simandl and others, 2005).

Kimberlites at Ekati are located nearly 180 miles NE of the town of Yellowknife. Several pipes were discovered lying under a group of shallow lakes in the Lac de Gras region in the early 1990s. A short time following the discovery, Canada's first diamond mine was commissioned by BHP in late 1998. This world-class mine includes a cluster of 121 kimberlite intrusives (52-65 Ma) and reserves established for the Fox, Leslie, Misery, Koala, Koala North, Panda, Beartooth, Sable and Pigeon kimberlite pipes on the Ekati property: other kimberlites are being evaluated and the mine has an anticipated minimum life of 25 years.

In 2001, three years after the mine opened, the Ekati produced 3.7 million carats. In 2003, production increased to 6.96 million carats (EMJ, 2004). Open pit operations on the Panda pipe reached maximum economic depth in 2003, five years after mining was initiated. Declining production from the Panda open pit has been replaced by production from the nearby Misery and Koala open pits. The Panda mine life will be extended by underground mining, and the kimberlite is being developed by sublevel retreat mining. Underground mining was previously initiated at the adjacent Koala North pipe in 2002. The Panda underground mine is expected to produce 4.7 million carats over an operating period of 6 years: production was scheduled in 2005 followed by full production in 2006. Ekati production for the first quarter of 2004 totaled 1.27 million carats, which was a 40% decline from the previous quarter. For the first 9 months of fiscal year 2004, the Ekati mine produced more than 5.3 million carats.

On June 30th, 2003, it was reported that the Ekati mine had 47.7 million tonnes of reserves averaging 80 cpht (36.6 million carats of recoverable diamonds) based on a 2 mm cutoff size (the size that distinguishes macrodiamonds from microdiamonds is 2 mm, although some companies use a 1 mm diameter cutoff size). Measured, indicated, and inferred kimberlite resources stood at 127.9 million tonnes of ore with an estimated 171.2 million carats (Robertson, 2004)! As exploration continues on the property, reserves should increase (Hausel, 2006).

The Panda kimberlite is small, steeply-dipping carat-shaped pipe that is 640 feet (195 m) across and roughly circular in plan covering a surface area of only 7.4 acres (3 ha). The fault-controlled pipe is slightly asymmetrical in vertical section. Panda has been delineated to depths of 1,800 feet where it tapers to a narrow 64 foot wide blow. The structure is filled with a complex mixture of volcaniclastic kimberlite containing variably carbonized wood fragments and mudstone that are locally abundant in bedded material at depth. Primary diatreme-facies kimberlite is present in the lower portions of Panda (>1,150 feet below surface) and minor intrusions of hypabyssal-facies kimberlite occur as occasional narrow peripheral dikes (McElroy and others, 2003).

The Misery Main pipe is an even smaller intrusive of only 3.7 acres (1.4 ha). It is elongated and steep-sided with dimensions of 295 by 574 feet at the surface. According to Mustafa and others (2003), the pipe transects a contact zone between Archean granite and metagreywacke with its location corresponding to the intersection of this contact with a narrow, N-S trending shear. The Misery Main pipe ranges from ash- to mud-rich phases to coarse-grained, olivine-rich volcaniclastic kimberlite. In places, fine-scale bedding is defined by abundance variations and grain size of olivine. Numerous other kimberlite intrusives occur in the immediate vicinity of the Misery Main kimberlite. The Misery Main pipe is largest in this local cluster while the others include narrow hypabyssal dikes that radiate out from the pipe, pipe-like hypabyssal intrusions, and small pipes with diatreme-facies kimberlite (Mustafa and others, 2003).

Diavik mine. Production at the Diavik mine began in 2003. The Diavik pipes are located west of Ekati and are operated by Diavik Diamond Mines: a joint venture between Rio Tinto (60%) and Aber Mines (40%). Rio Tinto assumed responsibility from their subsidiary Kennecott Canada Exploration. Fifty-five kimberlites occur on the Diavik property of which 25 are diamondiferous and at least four are commercially mineralized. The mine is estimated to contain 138 million carats in four kimberlites (A154S, A154N, A418, A21). Of these, the A154S kimberlite is one of the richest in the world with a reserve of 11.7 million carats at an average grade of 520 cpht.

Operations currently focus on the A154S and A154N, with production scheduled to reach 6 to 8 million carats/year. The mine has resources to sustain an operation for 16 to 22 years. In 2004, the mine produced 7.6 million carats including some large stones that weighed up to 151 carats. The property lies on a 7.7 mi^2 island known as East Island located 180 miles NE of Yellowknife. The Diavik kimberlites (55 Ma) intrude the Precambrian Slave basement complex (2.5 to 2.7 Ga) and several underlie lakes. Capitalization to initially open the mine were on the order of \$1.3 billion, but the mine made up for high capitalization by surpassing the 20,000,000 carat production mark at the end of 2005!

Snap Lake mine. This mine is scheduled to begin diamond recovery from a kimberlite sill 60 miles SSE of Ekati and 130 miles NE of Yellowknife. The sill dips under adjacent Snap Lake and has a strike length of 2 miles and 15^o dip with dip length of at least 1.9 miles. DeBeers began mine construction in 2006 and anticipates full production in 2008. The ore will be mined entirely underground from rock estimated to contain 38.8 million carats in 22.8 million tonnes (146 cpht) (Robertson, 2004). The mine life is anticipated for 22 years. Snap Lake is one of three properties under developed by DeBeers. The other two are Gahcho Kue east of Snap Lake and Victor in the James Bay Lowlands of northern Ontario.

Gahcho Kue (formerly Kennady Lake) mine. The Gahcho Kue property lies south of Lac de Gras, 50 miles SE of Snap Lake near Ft. Defiance and 186 miles NE of Yellowknife. At least 8 diamondiferous kimberlites lie on this property including sills and dikes. Inferred and indicated resources for three pipes are 31.4 million carats averaging 148 cpht with reserves averaging 167 cpht. Estimates suggest a potential tonnage of at least 20 million tonnes of ore in the 5034, Hearne and Tuzo pipes. Gahcho Kue is being developed by joint venture (Mountain Lake Resources and DeBeers) (EMJ, 2004). The mine is anticipated to have a life of 15 years and produce 3 million carats annually when in full production.

Jericho mine. The Jericho mine includes six diamondiferous kimberlites. During bulk sampling of one pipe by Tahera Exploration, a decline was driven to obtain a 9,435 tonne bulk sample which yielded 10,539 carats at a cutoff size of 1 mm. The stones included 44 diamonds between 5 and 10 carats and 23 stones >10 carats: the largest weighed 40 carats. Production at Jericho began in January of 2006. The mine lies south of Carat Lake within the Nunavut Territory 260 miles NE of Yellowknife, about 106 miles north of the Ekati mine near Echo Bay's Lupin gold mine. The principal Jericho kimberlite (172 Ma) is a multiphase intrusive measuring 960 by 120 feet and is on dry land. The pipe has an indicated and inferred resource of 7.1 million tonnes averaging 84 cpht with an estimated resource of 6 million carats that will be recovered over 9 years. Reserves of 2.6 million tonnes at 120 cpht have been established (EMJ, 2004).

About 8 miles west of Jericho is the Muskox pipe. This kimberlite has twice the surface area as the Jericho pipe and may considerably extend the life of the Jericho mine. Bulk samples from the Muskox pipe have yielded grades from 26 cpht to 142 cpht (Northern Miner, 2006, 92:6, p 1-2).

(2) *Thirsty Lake lamprophyre*. The Thirsty Lake dike is part of the Akluilak dike system in the central Churchill Province of the Northwest Territories along the northwestern margin of Hudson Bay. The dike system lies west of the Rankin Inlet kimberlites. Kaminsky and others (1998) interpret the dike as a metaminette. Similar to some ultrahigh pressure metamorphosed diamond deposits in the Kazakhstan region, this deposit is very rich in microdiamonds (Hausel, 1996; Erlich and Hausel, 2002). A small 44 pound sample collected from the dike yielded >1,700 diamonds, but the sample lacked macrodiamonds (MacRae and others, 1995).

The Thirsty Lake North and South dikes comprise a zone with a strike length >9 miles. Diamonds recovered from the property are strongly colored yellow and brown diamonds with cubo-octahedral and cubic forms and lesser dodecahedral habits. Nitrogen aggregations of the diamonds are comparable to those of the Kokchetav massif diamonds in Kazakhstan (Chinn and others, 2000). The Kokchetav diamonds are believed to have formed during an ultrahigh metamorphic event (DeCorte and others, 1998; Erlich and Hausel, 2002). A similar event is not recognized at Thirsty Lake.

The chemistry of mineral inclusions in the microdiamonds suggests the Thirsty Lake stones grew metastably within the graphite-stability field similar to those in Kazakhstan. According to Chinn and others (2000), the diamonds exhibit elevated hydrogen which has been connected to nucleation processes for synthetic diamonds. The presence of the high volatiles (H and N) associated with these diamonds may have been responsible for metastable growth of microdiamonds at pressures below the diamond-stability field. The high hydrogen abundance is thought to explain the high nucleation rate for microdiamonds and the lack of macrodiamonds in this deposit (Chinn and others, 2000).

(3) *Parry Peninsula.* Along the Parry Peninsula to the NNW of Ekati, adjacent to Darnley Bay in the Amundsen Gulf north of the Arctic Circle, exploration was initiated over the strongest isolated gravity anomaly in North America in a search for ultramafic-hosted nickel and platinum-group mineralization. During exploration in 1997, an aeromagnetic survey flown over the anomaly identified several characteristic 'bulls-eye' mag-anomalies typically associated with diatremes. Many of these were evaluated and 12 were drilled resulting in the discovery of kimberlite (270 Ma) at 10 anomalies: diamonds were recovered from 6 of the intrusives.

(4) *Victoria Island cluster (Nunavut)*. The Victoria Island cluster lies east of the Parry Peninsula and a considerable distance north of Yellowknife. The Snowy Owl kimberlite within this cluster consists of hypabyssal-, diatreme- and crater-facies kimberlite. Initial samples (966 lbs) yielded 785 microdiamonds with 4 macrodiamonds. The nearby Longspur kimberlite yielded 36 microdiamonds and 3 macrodiamonds from a 198-lb sample, and the Golden Plover kimberlite yielded 41 microdiamonds and 3 macrodiamonds from a 397-lb sample of crater and hypabyssal facies kimberlite.

(5) *Somerset Island cluster (Nunavut)*, located 200 miles east of Victoria Island within the Arctic Circle. A cluster of 36 kimberlites on Somerset Island show strong NE-, NW- and also N-S structural controls that parallel basement foliation. A few kimberlites (88 to 105 Ma) appear to be weakly mineralized with microdiamonds. The Somerset Island kimberlites lie to the west of the Brodeur Peninsula kimberlites along the NW extent of Baffin Island. Diapros established a 1-ton/hr processing facility in the vicinity of the Batty kimberlites in the summer of l972 and processed 262.3 tons of kimberlite. An additional 215.1 tonnes were processed from the Diapron, Batty, Nord, Oucat, Ham and Elwin kimberlites. Diamonds were recovered from Nord.

The kimberlites have hypabyssal and diatreme facies (105 Ma). The transition from lithosphere to asthenosphere at depths of 87 miles beneath Somerset Island is suggested. The presence of diamonds indicates that the kimberlites tapped the lithosphere within the diamond stability field, although the lithospheric root is believed to be thinner under Somerset Island than in the central Slave craton.

Other notable diamondiferous occurrences are located within the Nunavut Territory. Exploration continues in the Tomgas region of southeastern Nunavut and the north coast of Baffin Island. Further to the southeast, the Torngat dikes (346 Ma) are analogous to the kimberlite dikes of west Greenland. The extent of Proterozoic metasomatism within the lithosphere beneath the western Churchill Province is still poorly documented and its effects on diamond stability are not understood (Armstrong, 2000).

(6) *Rankin Inlet*. Much of this region is underlain by the Churchill Province. These kimberlites were emplaced in the Archean Rankin Inlet group of metamorphics. The kimberlites lie about 75 miles ESE of the Thirsty Lake (Parker Lake) diamondiferous minette dike that is believed to be associated with the magmatic event responsible for the Christopher Island Formation (Proterozoic). Past exploration in the region was largely for gold and base metals and systematic exploration for diamonds has been limited. Some kimberlite dikes (192-214Ma) were intersected during drilling at the Meliadine gold deposit. In 2003, Cumberland and Comaplex announced the discovery of 11 new kimberlites, and the Geological Survey of Canada reported numerous kimberlite float occurrences along the Meliadine trend. These provide evidence for multiple kimberlitic sources in the Churchill region.

Exploration resulted in the recovery of 145 KIMs from 183 till samples. About 46% of the pyropes were G10 (garnets that are chemically similar to diamond-inclusion garnets) subcalcic pyropes (Gurney, 1984). The indicator mineral results define several corridors of interest on the property that were followed up in 2003 with >1,800 till samples and a high resolution airborne magnetic survey identified 226 priority targets. In 2003 a follow-up line identified more than 100 additional high priority targets including a cluster of 29 magnetic lows. The geophysical evidence suggests that a kimberlite cluster of more than 100 pipes may be present at the Churchill property!

Ground geophysics completed on 58 targets resulted in 29 being selected to drill and resulted in discovery of 16 kimberlite pipes. This cluster occurs over a spatially large area measuring 37 by 30 miles. The kimberlites were initially recognized as magnetic highs and lows with some correlating EM signatures. Nine kimberlites yielded diamonds (Strand, 2004).

(7) *Melville Peninsula*. The Melville Peninsula is located along the edge of the RAE craton, north of the Arctic Circle adjacent to the Foxe Basin and south of Baffin Island. A group of 9 diamondiferous kimberlites known as the Aviat kimberlites were discovered in this region as well as till samples with diamond-stability (G10) pyrope garnets. These kimberlites lie NE of another group of kimberlites referred to as the Wales Island kimberlites. Based on a 10.4 tonne sample, the AV-1 kimberlite yielded a preliminary ore grade of 83 cpht. The Wales Island kimberlites to the southwest include a group of 10 kimberlites.

(8) *Baffin Island*. Results from an aeromagnetic survey led to the staking of approximately 75,000 acres in the south central region of Baffin Island. One of the three claim blocks contains 14 discrete geophysical anomalies that vary in size from 410 to

2,625 feet in diameter. All of the anomalies are within a single cluster and in an area considered to be structurally favorable for kimberlite intrusion.

The Jackson Inlet kimberlite on the West Coast of the Brodeur Peninsula of Baffin Island is centered 2 miles south of Jackson River. The Brodeur Peninsula is bounded by Admiralty Inlet, Lancaster Sound and Prince Regent Inlet. Flat-lying Ordovician and Silurian carbonates are exposed along the steep coastline of the Brodeur Peninsula and in the deeply incised river gorges. Between these gorges, the land surface forms an undulating plateau. Except at the crests of some hills, a thick blanket of glacial till was deposited by a small ice cap centered on the peninsula during the last glaciation and beyond the northern limit of the continental glacier which covered much of Canada.

Although isolated gneissic erratics provide evidence of earlier more extensive glaciation, the till consists mainly of carbonate blocks in a matrix of pulverized carbonate that supports very sparse vegetation. From the air and on aerial photographs, evidence of the Jackson Inlet cluster of kimberlites is manifested as three dark brown circular patches within a 1,640 by 1,970 foot halo of tan coloration. Within the halo are patches of darker tan color. The surrounding Ordovician-Silurian limestone is grey and the tan color of the halo is interpreted as a result of limestone weathering, which was dolomitized by introduction of magnesium from the kimberlitic magma.

(9) *Drybones Bay kimberlites (NWT).* At least 3 diamondiferous kimberlites have been found in the Drybones Bay area along the north shore of the Great Slave Lake to the east of Yellowknife.

(10) *Coronation Gulf*. The Coronation Gulf area, located 70 miles NNW of the Jericho mine, includes a group of more than 11 diamondiferous kimberlites. The Knife Pipe, under exploration by DeBeers, is described as being significantly diamondiferous. Ashton Mining reported highly encouraging results from caustic fusion analyses of kimberlite from their nearby Potentilla, Stellaria and Artemesia pipes. Samples of the Potentilla kimberlite include hypabyssal and diatreme facies with an estimated grade of 17.5 cpht.

Ontario. North of the Great Lakes in Ontario, a number of kimberlites, some lamprophyres, and a group of diamondiferous actinolite schists are recognized. To date, the most notable appear to be the Attawapiskat cluster and the Wawa dikes. Other discoveries in Ontario include kimberlites at Kyle Lake, Kirkland Lake, Keith Township, New Liskeard and others. Only the principal occurrences are described: (1) The *Attawapiskat cluster* includes several well-mineralized kimberlites including the Victor pipe in the tundra near Hudson Bay; (2) The *Kyle Lake kimberlite cluster* about 60 miles west of the Attawapiskat cluster; (3) The *Kirkland Lake cluster* along the eastern Ontario border adjacent to Quebec; (4) The *Keith Township kimberlite*; and unconventional host rocks of great interest known as (5) the *Wawa cluster* on the northeastern shore of Lake Superior.

(1) The *Attwapiskat cluster* includes 20 kimberlites (155 to 170 Ma) near the Attwapiskat River in the James Bay lowlands along a distinct NNW trend. One commercial pipe has been identified within this field. The project, operated by DeBeers, encloses 18 kimberlite pipes, 16 of which are diamondiferous. The Victor Main and Victor Southwest

pipes are two pipes that coalesce at the surface and have a combined area of 37 acres. The composite pipe is formed of pyroclastic crater, diatreme and hypabyssal facies kimberlite with highly variable diamond grades. The pipe averages 33 cpht with an average value of $154/carat. Plans are to develop an open pit with an expected 12-year mine-life and total project life of 17 years. The Victor mine would be supported by a plant with a designed capacity of 2.5 million tonnes/year.

In 2003 and 2004, airborne magnetic signatures were evaluated within the Attwapiskat cluster and 5 previously unknown kimberlite pipes were found in the MacFayden group. The interpretation of the magnetic total field showed distinct circular magnetic isograds along a prominent NNW magnetic trend interpreted as a buried kimberlite dike. This trend continues for about 11 miles or more. This group is situated along the bank of the Attwapiskat River. The Victor pipe, 5 miles to the SSE, lies along the same trend.

The *Kyle Lake kimberlite cluster* 60 miles west of the Victor pipe, includes a group of 5 Precambrian kimberlites. Preliminary tests of the Kyle Lake #1 kimberlite yielded an average grade of 60 cpht. Several phases were mapped in the kimberlite including one that yielded an ore grade as high as 800 cpht! The surface area of the kimberlite is only 6.2 acres, but it has an ore resource of 14.5 million tonnes to a depth of 1,670 feet. The recovered diamonds show little resorption and have distinct octahedral habit. The Kyle Lake #3 kimberlite lies near the confluence of the Attwapiskat and Muketei rivers. This is a vertical dike with average width of 82 feet and a blow at one end that increases the width to 410 feet. The dike has been traced to more than 1475 feet along strike, and has an even greater strike length based on ground magnetic surveys. The average grade based on limited sampling was 92 cpht.

The *Kirkland Lake* group includes two clusters within the Kirkland Lake mining district. The Kirkland Lake district is a well-established gold mining camp underlain by Archean rocks (2.5 to 2.7 Ga) of the Superior Province. Proterozoic rocks of the southern Cobalt Group of the Huron Supergroup (2.5 to 2.2 Ga), Grenville Province metamorphics (1.1 Ga) and Phanerozoic sedimentary rocks also underlie the region. The Kirkland Lake kimberlites (150-159 Ma) include a cluster of 10 pipes in the Kirkland Lake area as well to the south near Cobalt in the New Liskeard area near Lake Timiskaming, along with 11 dikes in the Kirkland Lake area. Some of these are weakly mineralized and the geochemistry supports that the kimberlites should only be weakly mineralized. The kimberlites in the New Liskeard area continue from Ontario into Quebec along a northeasterly trend (Schulze, 1996).

Wawa cluster. The Wawa deposits are similar to deposits in the Akwatia field, Ghana. The Wawa discovery is significant: these are the oldest diamond deposits ever found and they occur as stratiform, metamorphosed schists within an Archean greenstone belt. The host rock precursors remain an enigma, and have been interpreted as metamorphosed lamprophyre, metamorphosed crater facies kimberlite, lahar, breccia, conglomerate and even komatiite. It may be some time before the origin of these hosts is known. At any rate, the discovery provides a whole new concept in exploration for diamonds worldwide.

The host rocks are Archean (2.7 Ga) diamondiferous ultramafic breccias and schists. Limited sampling of some breccias yielded grades ranging from 6 to 262 cpht (Wilson, 2004). The largest diamond found to date is 1.39 carats.

The deposits occur within the western Michipicoten greenstone belt of the Wawa subprovince of the Superior craton and have been metamorphosed and deformed during 4 episodes of deformation with little evidence of their precursor being preserved. Two types of diamond-bearing rocks are described: both have been metamorphosed to upper greenschist facies and are described as a younger lamprophyre(?) and a volcaniclastic breccia. Both the lamprophyre and breccia are intercalated with 2.7 Ga felsic to intermediate metavolcanics, intermediate to mafic metavolcanics and mafic intrusive rocks.

The matrix- to clast-supported breccia forms ~200 to 230 foot thick units. It contains dominantly angular, granular to large boulder-sized fragments with a wide variety of igneous lithologies including metamorphosed ultramafic rocks with high Cr and Ni. The breccias are interpreted as volcaniclastic debris flows based on stratigraphy, the wide range in fragment lithologies, crude bedding, poor sorting, and lack of sedimentary structures. The fine-grained breccia matrix is comprised of upper greenschist to epidote-amphibolite mineral assemblages, which includes 50-75% actinolite, 1-20% epidote, 1-20% titanite 1-10% quartz/feldspar, 0-20% biotite, 0.5-15% hornblende, and 0-10% chlorite, with minor calcite, albite, opaques and rutile.

The rock may occur as dikes and appear to cross-cut the metavolcanic sequences and breccia. In some areas the relationship between the lamprophyre(?) and breccia, and the lamprophyre(?) and metavolcanics is unclear. The lamprophyre overlies these rocks along straight, long, parallel contacts that may be depositional in origin with 5-10% fragments of surrounding country rock, occasional altered ultramafic mantle xenoliths, and rare breccia. The lamprophyre is weakly foliated as defined by faint alignment of actinolite and biotite grains.

Whole rock compositions of breccia matrix, juvenile clasts and lamprophyre show no major systematic differences between compositions of the breccia, its juvenile clasts and the lamprophyre. This may be interpreted as a complete obliteration of primary magmatic compositions by metamorphism, or as a reflection of similar compositions of the protoliths. The rocks are alkaline to sub-alkaline based on (Na_2O + K_2O) vs. SiO_2. Major element compositions show a better fit to calc-alkaline lamprophyre and lamproite of Rock (1987, 1991).

Bulk rock compositions cannot be used since the rocks are hybrids with incorporated mantle xenoliths. They may have experienced additional compositional changes during metamorphism. Some phenocrysts may provide clues. Hornblende phenocrysts retain relict magmatic compositions as they display concentric oscillatory zoning rarely found in metamorphic rocks. Assuming that Mg-hornblende, tschermakite, edenite and pargasite retained original magmatic compositions, their protoliths could be similar to calc-alkaline lamprophyre. The hornblende compositions are not compatible with orangeites (kimberlites) and lamproites; the latter containing Ti- and K- richterites. Hornblende the Wawa lamprophyre and volcaniclastic breccia could have crystallized from calc-alkaline lamprophyre.

Diamonds are found in both breccia and lamprophyres. Both have metamorphosed ultramafic mantle xenoliths. The presence of these xenoliths and diamonds is evidence for preservation and incorporation of mantle material into the lamprophyric magma. The diamond population from the polymictic volcaniclastic breccia is dominated by microdiamonds. The majority of macrodiamonds are colorless, have non-uniform color, or are yellow and show very little resorption and are dominated by pristine octahedrons. They form single crystals and aggregates with predominant octahedral and occasional cubic morphology. Many diamonds have experienced breakage and late etching (Lefebvre and others, 2003). Of the microdiamonds, some colored stones suggest possibilities for fancy stones including pink, rose, amber, green, yellow and brown (White-Kirkpatrick, 2003).

The two types of diamondiferous rocks from Wawa have been interpreted as metamorphosed polymictic volcaniclastic breccia and lamprophyre based on field observations, petrographic studies, and mineral chemistry. The matrix of the breccia, the juvenile material and the lamprophyre have similar mineral assemblages, bulk rock compositions and mineral chemistry which suggests they may have formed from a similar type of magma. This primary magma was likely to have had calc-alkaline affinity based on the chemistry of hornblende. The magma must have originated with the diamond stability field, as it incorporated diamond-bearing mantle material upon ascent to the surface. It erupted during the Archean to produce volcaniclastic deposits and later was intruded as dikes. A highly explosive eruption style that produces volcaniclastic rocks is not characteristic of lamprophyric magmas that commonly intrude as dikes. Thus, the Wawa diamondiferous rocks could be one of few known lamprophyric volcanoes (Lefebvre and others, 2003).

Similar examples have been described in Namibia, New Mexico and southern Alberta. The Wawa lamprophyres belong to a greenstone belt volcanic sequence and formed in a subduction-related tectonic setting. The presence of diamond in subduction-related magmatic rocks suggest that diamonds may have already formed at earlier stages of subduction, well before later incorporation in subcratonic eclogites. Thus, similar rocks in similar geological environments should be considered as potential targets for diamond exploration (Lefebvre and others, 2003). During the mapping and sampling of Wyoming’s greenstone belts in the past, the search for similar lamprophyres as well as diamondiferous komatiites was not considered at Elmers Rock (Graff and others, 1982), Rattlesnake Hills (Hausel, 1996), Seminoe Mountains (Hausel, 1994) or South Pass (Hausel, 1991).

The Wawa deposits have similarities to diamondiferous metakomatiites described in the Akwatia diamond field within Birimian (Early Proterozoic), where kimberlitic indicator minerals were lacking. In the Akwatia field, the diamond deposits represent some of the oldest diamond deposits that have been found, and the rocks occur in arc sediments not associated with an Archon. The diamondiferous rocks are actinolite/ tremolite schists and actinolite rocks with little or no schistocity and distinctive clastic texture with clasts of phyllite and carbon. The clastic units are elongate and contained within the actinolite schist. Major and trace element analysis of these rocks suggest a suite of rocks similar to the diamond-bearing volcaniclastic komatiites of French Guiana and/or the metamorphosed suit of komatiite/ boninite type rocks of the Wawa (Superior Province) greenstone belts (Canales and Norman, 2003).

Quebec. Diamond has been found in both kimberlite and in some unconventional host rocks in Quebec: both kimberlites and ultramafic lamprophyres have been discovered. Some deposits include: (1) *Torngat district* which encloses the Abloviak kimberlites and/or lamprophyres along the edge of Ungava Bay in extreme northern Quebec, the (2) *Wemindji kimberlite* on the shoreline of Hudson Bay, (3) *Otish Mountains district* (Renard and Indicator Lake kimberlites) in central Quebec, (4) the *Bachelor Lake* kimberlite cluster north of Val-Dor, (5) the *New Liskerd* cluster on the western border of Quebec north of Sudbury, and (6) an unconventional host (alnöite) *at Ile Bizard* near the US border along the St. Lawrence River east of Ottawa (Erlich and Hausel, 2002; DeBeers, 2003).

(1) Torngat district. The Torngat district lies adjacent to the Ungava Bay region in Quebec. It consists of a group of olivine-rich hypabyssal facies rock (550 Ma) known as the Abloviak dikes that intrude Paleo-Proterozoic paragneiss and metasedimentary rock along the Abloviak shear zone. The dikes are 6.5 feet wide and have been traced from a few feet to more than 1.8 miles along strike. They were emplaced in brittle fractures that cut foliation and mineralogically consist of anhedral olivine, pyrope, phlogopite and ilmenite macrocrysts in fine-grained phlogopite, olivine, spinel and carbonate matrix. Pyrope compositions match calcic pyrope-almandine, calcic chromian pyrope, and subcalcic chromian pyrope. Rock compositions have high K_2O/Na_2O, high Mg#, low SiO_2, low Al_2O_3 and elevated TiO_2 suggesting affinity to aillikitic lamprophyre or Group I kimberlite.

In addition to the Abloviak dikes, the kimberlite and aillikite dike swarms in the Holsteinsborg, Safartoq and Sukkertoppen regions of Greenland are thought to be an extension of the Abloviak dike complex. The age and geological setting of the Greenland and Quebec dikes suggest similar genesis (Digonnet and others, undated). Some high-quality diamonds were recovered from low grade ore in the complex (Cumming, 2006).

(2) Wemindji. Kimberlite was discovered near Wemindji in the Quebec lowlands on the east shore of James Bay in early 2002. The Wemindji area lies at a junction of two major Proterozoic structures; the Wemindji-Caniapiscau corridor and the NE extension of the Kapuskasing structural zone. The basement rocks are Archean (2.8 Ga) and part of the Superior Craton with remnants of a Mesoarchean Craton.

Kimberlite was discovered by drilling at the head of a 1.2 mile long KIM dispersion train. The hole intersected sub-horizontal 6.4 foot thick kimberlite at depths of 12.8 to 105 feet. The geometry suggests a shallow-dipping folded and faulted sill or stacked sills. Indicator minerals are dominated by abundant picroilmenite, secondary garnet, and uncommon chromite and chrome diopside. Mineral compositions indicate that ilmenites and approximately 50% of garnets and clinopyroxenes from samples of the Wemindji pipe are megacrysts. The remaining garnets are predominantly lherzolitic with subordinate wehrlitic population and rare harzburgitic grains. Only a very small proportion of the clinopyroxenes recovered were derived from garnet lherzolite (Letendre and others, 2003).

Otish Mountains district. The Superior Craton hosts a variety of mantle-derived rocks that include kimberlite and ultramafic lamprophyre of varying compositions (Birkett and others, 2003). To date, several pipes, some sills, and several geophysical anomalies typical of hidden diatremes have been found in the Otish Mountains district. Many of the intrusives were tested with poor results, with one exception: the Renard intrusives on the Foxtrot property in LaBelle Province east of James Bay. The Renard intrusives yielded one 459-carat parcel of diamonds from a 664-tonne sample collected from four intrusives. The largest diamond weighed 4.3 carats (Cumming, 2006). At least 11 intrusives have been identified in this cluster. Small bulk sample tests have yielded grades of 134 cpht for the Renard 3 to 65 cpht for the Renard 2.

The host rocks may be kimberlite; however, preliminary mineralogical and geochemical tests suggest these rocks have melnoite affinities. In spite of the high temperatures of emplacement and significant incorporation of country rock into the host rocks, some Renard intrusives potentially have commercial grades and diamonds of commercial size (Birkett and others, 2003).

Kimberlitic and lamprophyric intrusives of the Renard, Tichégami River and Beaver Lake areas lie at the southern end of the Mistassini-Lemoyne structural zone. This zone extends over 405 miles NNE of the Mistassini Basin to the Labrador Trough, in the Cambrian Lake region and possibly into the Lemoyne Lake region. From south to north it includes the Beaver Lake kimberlites (551 Ma), the Tichégami River intrusives, the Renard region, the Archean Niaux nepheline syenite suite and Proterozoic Castignon Lake (1.88 Ga) and LeMoyne carbonatites (<1.87 Ga) of the Labrador Trough (Moorhead and Houle, 2002).

The area west of Matagami, in the northwestern part of the Archean Abitibi greenstone belt, became a target for diamond exploration in Québec following discovery of KIMs in glacial debris. The surface textures of several grains suggested a proximal kimberlite source. The first discovery of dikes of kimberlite in the Abitibi greenstone belt occurred in 1955 in the Desmaraisville area, in the north-central part of the subprovince, during exploration for gold. In 1992, a diamond-bearing kimberlite pipe was found in the same region. The Desmaraisville kimberlite field contains 5 weakly diamondiferous hypabyssal pipes and several dikes. It is located in the Waswanipi-Saguenay structural zone, which forms the NW-extension of the Saguenay Rift (Doucet, 2002).

Ile Bizard. The Ile Bizard intrusion is one of several diatremes within the Oka carbonatite complex west of Montreal. In the 1960s, a sample from the diatreme yielded 10 microdiamonds, although there was concern of possible contamination in the diamond mill in Johannesburg. It is not known if the diatreme has been resampled. The host rock has been described as alnöite, although work by Raeside and Helmstaedt (1982) suggest that the intrusive lacks characteristics of alnöite and may best be classified as a lamprophyre until further work can be completed.

Saskachewan. A major kimberlite district known as Fort a la Corne was discovered near the town of Smeaton. This district has attracted considerable attention due to the number of kimberlites and the large size of the intrusives. The Fort a la Corne project, 30 miles NE of Prince Albert includes more than 70 large kimberlites ranging in area from 6 to 318 acres that typically lie under 320 feet of glacial cover (Robertson, 2004). The kimberlites are thought to have laterally extensive sub-horizontal lenses of crater facies kimberlite that are as much as 6,400 feet in diameter and in some cases are as much as 320 feet thick. Kimberlites were discovered in this region by follow-up drilling projects into circular to sub-circular complex magnetic anomalies.

The Fort à la Corne kimberlite field consists of Cretaceous volcaniclastic-dominated crater-facies kimberlites that are highly variable in size, complexity and diamond content. They vary from small simple to large, very complex, multi-phase kimberlites with as many as 6 eruptive phases. Furthermore, each eruptive phase may have various sub-facies. The largest kimberlite has about 675 million tonnes and is comparable to the largest kimberlites in the world. Since their initial discovery in 1988, over 75% of the kimberlites have proven to be diamondiferous; approximately 50% have yielded macrodiamonds (Harvey, 2004).

The Fort à la Corne field is one of the largest in the world and consists of two clusters along with many isolated intrusives. The main Fort à la Corne cluster forms a NNW-trending 22 mile long trend that is 6 miles wide. Surrounding the main cluster, the Snowden cluster to the NE is aligned along a NNW-trend with the Foxford and Birchbark kimberlites further NW, the Weirdale kimberlites to the west and the Candle Lake kimberlites to the north. In total, over 75% of kimberlites in the Fort à la Corne field have been verified as diamondiferous. Close to 70% of recovered macrodiamonds are gem quality (Harvey, 2004).

Yukon. Exploration in Yukon by Patrician Diamonds reports discovery of KIMs with some diamonds in an undisclosed drainage. Reported lamprophyres of kimberlitic affinity may lead to some additional exploration in the Yukon as well as Alaska.

Some rocks of interest include the Early Cambrian Quartet Mountain lamprophyres. These are ultramafic alkaline dikes emplaced in the Wernecke and Mackenzie Mountains supergroups in the Wernecke Mountains of northern Yukon. The Quartet Mountain lamprophyres are porphyritic with phenocrysts of phlogopite ± diopside ± olivine in dark-gray aphanitic groundmass and are suggested to have arisen from depths >56 miles. One lamprophyre has abundant olivine xenocrysts pseudomorphs along with crustal and mantle xenoliths. The dike resembles kimberlite due to abundance of mantle xenoliths and xenocrysts but differs from kimberlite in abundance of phlogopite phenocrysts. It has been described as an ultramafic lamprophyre of kimberlitic affinity.

Many other deposits have been found in Canada since the 1990s in the Northwest Territories, Nunavut, Alberta, Ontario, Quebec, and Saskatchewan (Olson, 2001). According to EMJ (2004), Canada is currently supplying about 15% of the world's diamonds and is expected to show dramatic production increases in the future. In 2002, the Canadian diamond industry produced nearly 5 million carats. In 2003, production increased to 11.2 million carats, and it is estimated that essentially 50% of the world diamond exploration funding is focused on Canada.

In addition to the commercial properties, many other successes have been made. DeBeers alone reported the discovery of more than 219 kimberlites in 12 different regions of Canada, of which more than half are diamondiferous. Typically, only one in every 200 kimberlites will contain sufficient numbers of diamond of high enough value to open a commercial mine (Hausel, 2006).

CONCLUSIONS

With the current trend of investment, exploration, and progressive pro-mining atmosphere, it is anticipated that Canada will remain as a leading diamond producer for decades to come. The sheer size of the North American Craton allows one to predict Canada will someday soon become the world's number 2 source for diamonds. Unless there is a major change in attitude in the US, little will be produced in the way of diamonds, as diamond exploration requires considerable risk but the rewards are very high. Parts of the US (i.e., Superior and Wyoming Provinces) are underlain by favorable terrains for gemstones and could become a source for gemstones with reasonable exploration investments.

Exploration, research and development investment for diamonds in Canada amounts to billions of dollars. Exploration and research investments in the search for diamonds in the US is more on the order of hundreds of thousands of dollars. With such poor investment by state governments, the US will continue to lag behind Canada in major diamond discoveries.

The Wyoming Craton in particular has yielded hundreds of anomalies based on past research projects completed at the Wyoming Geological Survey. These projects were always underfunded, but successful only due to the efforts of a few driven individuals. Presently such projects are nonexistent and have been replaced by projects of little value that are designed to benefit bureaucrats with personal agenda. Such gothic politics are unfavorable for Wyoming's future economic health and need to be investigated by the legislature.

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Glossary

Aillikite. A variety of carbonate-rich lamprophyres that are abundant in the Aillik Bay area of Labrador. These rocks lack melilite and thus can not be classified as alnöite. Aillikites are carbonate-rich ultramafic lamprophyres characterized by olivine and phlogopite macrocrysts and/or phenocrysts, and a groundmass of primary carbonate, phlogopite, spinel, ilmenite, rutile, perovskite, Ti-rich garnet and apatite.

Alnöite is used to describe melilite-bearing ultramafic lamprophyres. Melilite-free ultramafic lamprophyres are split into aillikite and damtjernite. Alnöites are melilite-bearing ultramafic lamprophyres characterized by olivine, phlogopite and clinopyroxene macrocrysts and/or phenocrysts, and groundmass melilite, clinopyroxene, phlogopite, spinel, ilmenite, perovskite, Ti-rich garnet, apatite and minor primary carbonate. Monticellite may occur in rare instances.

Camptonites are alkalic lamprophyres with olivine, clinopyroxene, biotite and plagioclase.

*Kersantite*s are calc-alkalic lamprophyres based on mineralogy.

*Kimberlite*s are volcanic or subvolcanic rocks composed largely of serpentinized olivine with variable amounts of phlogopite mica, orthopyroxene, clinopyroxene, carbonate and chromite. Characteristic accessory minerals include pyrope garnet, rutile, monticellite and perovskite, and in some cases diamond. Two types of kimberlite include Group I and Group II (Orangeite). Kimberlites are volatile-rich (CO_2) potassic rocks with macro/megacrysts of olivine, ilmenite, pyrope, enstatite, and/or chromite in fine-grained matrix of montecellite, phlogopite, perovskite, spinel, epidote, serpentine and rutile.

*Komatiite*s are high magnesium volcanic flows that crystallized at high temperaturee. They commonly display spinifex texture consisting of intergrown skeletal and bladed olivine and pyroxene crystals in a glassy groundmass. Most are Archean in age, fine-grained, SiO_2 <53% , Na_2O+K_2O <1% , MgO >18% , TiO_2 <1%.

*Lamproite*s are volcanic or subvolcanic rocks enriched in potassium and magnesium that are composed of unusual rare minerals such as K-Ti-richterite, priderite, wadeite, jeppeite, Fe-orthoclase and leucite. Olivine lamproites are often diamondiferous.

Lamprophyre: a name for a group of subvolcanic rocks that are strongly porphyritic in mafic minerals such as biotite, amphiboles and pyroxenes in a groundmass of feldspar. They commonly occur as dikes.

Melilitite. Rocks with >10% modal melilite. A definition based on rock chemistry is desirable, but unfortunately cannot be used to distinguished adequately from other volcanic rocks. The presence of melilite in more than trace modal amounts results in the formation of larnite (or calcium orthosilicate) in the CIPW norm, and this can be used as a potential discriminant.

There is a continuous series from melilitite through melilite nephelinite to nephelinite which is problematic. Investigation of this problem indicates that a reasonably clear discriminant between melilitite and melilite nephelinite is normative larnite.

Minette. Exotic crystalline intrusive/extrusive melano-mesocratic panidiomorphic lamprophyre with orthoclase>plagioclase, predominant mafic minerals, phenocrystic biotite+diopsidic augite +/- olivine; felspathoids, Ti-rich augite, amphibole and rare to absent melilite.

Melonite. An acronym (melilite plus alnöite) that refers to all ultramafic lamprophyres. It is a collective term used by exploration geologists for potentially diamondiferous igneous rocks other than kimberlite and lamproite. However, because melnoite implies ‘melilite-bearing’, which is not true for many carbonate-rich or feldspathoid-bearing ultramafic lamprophyres, it is suggested that the widely used collective term ‘ultramafic lamprophyre’ be used for this group name of genetically related rock types.

Monchiquite. An exotic crystalline intrusive/extrusive melano-mesocratic panidiomorphic rock; with a glass or foid matrix, dominant mafic minerals, phenocrystic barkevikite, kaersutite, Ti-rich augite, olivine, biotite, diopsidic augite, and hornblende.