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GEOLOGICAL, GEOCHEMICAL AND GEOPHYSICAL EXPLORATION FOR DIAMONDS IN YUKON

By

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YUKON DIAMOND EXPLORATION -A

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1. INTRODUCTION

1.1 Scope

This report is a modified version of notes distributed at a short-course seminar given at the Yukon Geoscience Forum in Whitehorse on 25 November 1992. Against the background of Canada's first major diamond exploration rush, its aim is to serve as a source of general information on diamond geology, and geological, geophysical and geochemical methods of diamond exploration, with reference to their application in Yukon. Most of the material is taken directly from published scientific and exploration literature. The information is presented at a level that assumes a basic understanding of geology but no specific knowledge of diamond geology on the reader's part. The report includes a reference list of major or recent publications relevant to diamond geology and exploration, providing the option of obtaining further details for all subjects presented.

The world production of diamonds in 1990 was more than 100 million carats (metric carats, or CM; 1 carat = 0.2 grams), compared to 75 million in 1985, and 15 million in 1950. This represents a more than 14% per year growth rate. The value of 1990 production was about US$4.5 billion (1992 US$), and diamond is the fourth-ranked commodity in the world in terms of value, after Fe, Au, Cu and Zn. Primary sources of diamonds are the mantle-derived igneous rocks eclogite and peridotite, brought to the surface by rare ultrabasic magmas, kimberlite and lamproite being the most common. Secondary diamond deposits, such as the marine deposits of southwest Africa, are derived from primary sources by weathering processes that acted for several million years to transport and concentrate diamonds at favourable localities.

Of approximately 5,000 known kimberlites world-wide, fewer than 50 are or have been mined successfully. There have been fewer than 15 major producers (more than 3 million carats/year), with only 6 major discoveries made in the last 50 years. The Point Lake pipe, the first discovered in the Lac de Gras kimberlite field in Canada's NWT, is potentially another major producing pipe. The Point Lake discovery is a clear success story in diamond exploration, and as such it is given a brief review here. As the surrounding kimberlite field is still undergoing exploration, the information available is incomplete, and estimates of the importance of the diamond deposits are preliminary. However, initial results at the time of writing indicate strong potential for one or several diamond mines to be developed in the NWT.

Why explore for diamonds in North America? The following 10 reasons were given by Jennings (1990):

- North America has the largest craton and stable platform area in the world.
- Relative to Siberia and South Africa, hundreds of kimberlites remain to be discovered.
- North America is underexplored for diamonds.

- Large, gem diamonds have been found as alluvials in North America.
- Several areas are known to have favourable mineral chemistry.
- Operating costs of open-pit kimberlite mines are very low.
- Capital costs are similar to other mines; tailings are non-acid generating, and no strong chemicals are used during extraction.
- Transport costs for final products are negligible.
- Diamond prices generally increase at a level that keeps pace or exceeds inflation.
- The occasional large diamond found during production can be regarded as a bonus (a 100-carat flawless gem can be sold for about US$1.7 million).

1.2 Diamonds in Canada's NWT: The Point Lake story

The following paragraphs present an account of the discovery of the first Lac-de-Gras (Point Lake) pipe. It is adapted from summaries by Credit Lyonnais Laing (1992), Richardson Greenshields (1992), and corporate news releases.

The history of the Point Lake discovery began with the exploration for indicator minerals along the Mackenzie River, near Blackwater Lake, some 12 years ago by Diapros Canada Ltd., at the time the Canadian subsidiary of De Beers Consolidated Mines, and by Falconbridge Limited. Important indicator minerals for kimberlite were discovered but their bedrock source was not located. Four years ago, Dia Met Minerals, under the direction of C. Fipke (founder and chairman of the company), initiated a heavy mineral sampling program east of the Mackenzie River, and through some difficult years financially, traced the indicator minerals by systematic sampling of glacial deposits (eskers, till, and beach sands). The trail of heavy minerals such as ilmenite, chrome diopside and pyrope garnet, led eventually up-ice to the Lac de Gras area.

In 1989, C. Fipke started to acquire ground in the Lac de Gras area, eventually staking approximately 350,000 hectares (3,500 km^2) for Dia Met Minerals. In early 1990, Dia Met discovered a structure that showed all the signs, through geophysics and indicator minerals, of being a kimberlite pipe. The target was located at Pointe de Misère at Lac de Gras, about 200 kilometres northeast of Yellowknife, under a small lake known as Point Lake (which is not the (large) Point Lake due north of Yellowknife).

> "We were right at the end of budget; we had two days of flying and then we were out of money. I was in the front seat navigating the helicopter and we were stopping at each place to put our pegs, our staking pegs, and I just happened to look out the side of the window and the wind had blown the snow off the outcrops sort of on the south side and the north side, and this was broken by this hole, so I made a note of it and we kept on staking and then that evening I decided to cancel the staking, and go to this lake. The ground was all frozen so we had to chip through and just take these

pieces of soil, glacial till, and while we were doing it, my son Mark discovered a chrome diopside." (Charles Fipke: CBC News – November 1992)

Later in 1990, Dia Met entered into a joint venture with BHP Minerals, the North American arm of BHP (Australia), in which BHP Minerals would take the project through exploration and feasibility study and, if viable, find financing for mine construction costs up to CAD$500 million. In return, BHP Minerals would earn a 51% interest in Dia Met's Lac de Gras holdings. BHP soon began further exploration and drilling at Point Lake.

A single, small-diameter hole was drilled in September 1991. The core was analyzed at the laboratory of C.F. Mineral Research Ltd. in Kelowna, B.C. (owned by C. Fipke). On November 5, 1991, the BHP/Dia Met joint venture announced that:

> "Core hole PL91-1 at Point Lake intersected kimberlite from 455 feet to the end of the hole at 920 feet. A 59 kg sample of the kimberlite yielded 81 small diamonds, all measuring less than 2 mm in diameter. Some of the diamonds are of gem quality ... These results are sufficiently encouraging that the operator BHP Minerals is planning to add to the exploration program the bulk sampling this winter of 200 tonnes of the kimberlite...".

In February and March of 1992, BHP Minerals drilled 37 reverse-circulation holes from the ice on Point Lake, and the bulk sample was trucked to Dia Met's pilot mill diamond recovery plant at Sloan Ranch near Fort Collins, Colorado, the only plant in North America capable of easily processing up to 75 tonnes per day with > 99% recovery. The plant contains the most advanced equipment, including crushers, a trummel-scrubber, bandelari jig, heavy-media cyclone separator, vibrating diamond grease tables, an X-ray Sortex unit, and a microscope diamond sorting room. On May 19, 1992, BHP and Dia Met announced the preliminary results of the bulk sample. On June 25, 1992, the results were confirmed in the following announcement:

> "...The final weight of the diamonds recovered from the 160 tonne sample is 101 carats. About a quarter of the diamonds are of gem quality. This fraction excludes any stones commonly referred to as near-gems. A few of the stones are in the one to three carat range.
>
> BHP has completed its spring airborne geophysical survey and the results of this program, combined with the results of last summer's geochemical survey, confirm that the joint venture has located several possible pipes, some apparently of larger surface dimensions than the Point Lake pipe..."

After the bulk sample from the Point Lake kimberlite pipe, the 1992 summer season operations led to the following announcement on September 15, 1992:

> "Since the beginning of the 1992 summer season, joint venture operations have identified by drilling and mapping a total of nine new kimberlites in

> addition to the pipe at Point Lake. Core samples and small bulk samples from these kimberlites are now being tested for diamond content and the results of these tests are expected later in the year. At least 10 microdiamonds and one macrodiamond were recovered from an initial 40 kg sample taken from one of the new kimberlites..."

After the stock market closed in Vancouver on December 8, 1992, Dia Met Minerals issued the following press release:

> "BHP Minerals has released the following results from core and surface samples from nine new pipes located during the summer season of 1992... Drilling was restricted to those pipes that are believed to be as large or larger in surface area than the pipe at Point Lake.

Kimberlite	Sample type	Sample weight	Macrodiamonds	Microdiamonds
92/A	Surface	40.0 kg	2	10
92/B	Surface	72.2 kg	23	117
92/C	Core	161.4 kg	10	28
92/D	Soil	25.7 kg	2	2
92/E	Core	69.9 kg	11	36
92/F	Core	23.2 kg	1	12
92/G	Core	122.0 kg	8	45
92/H	Core	60.0 kg	1	7
92/I	Core	122.4 kg	55	132

> By way of explanation, under the column "sample type", core means samples of the drill core, surface means kimberlite from the surface rock which probably overlies a pipe, and soil means soil which probably overlies a pipe. Macrodiamonds are those diamonds greater in diameter than 0.5 mm. All core samples results reported to date include only diamonds from kimberlite and specifically exclude diamonds from drill bits. The result from pipe 92/A was part of the news release of September 14, 1992. Gem quality diamonds in variable proportions are present in each pipe."

In the world of diamond exploration, these were extremely promising results. Plans for further testing of these targets in 1993 have been announced. The total area of land staked by other companies, both majors and more than 50 juniors, exceeded 8 million hectares by the end of 1992. At least 16 other kimberlites in the field have been confirmed by diamond drilling, of which at least 10 are diamondiferous. The number of unqualified geophysical targets identified on staked land is in the hundreds, and the reports of (yet to be microprobed) garnets, diopsides and ilmenite indicator minerals from glacial debris sampling are increasing regularly, leading to a processing bottleneck in the sample analysis in 1993.

The Lac de Gras exploration itself will take several years to be completed, and has rekindled diamond exploration activity in Saskatchewan, Alberta, parts of Manitoba, northern Ontario and the Hudson Bay Lowlands region of Quebec. For example, diamondiferous kimberlites have been identified in north-central Saskatchewan at Sturgeon Lake and near Fort a la Corne, about 35 km northwest and 60 km east of Prince Albert, respectively. Past and potential future areas of diamond production were recently reviewed by Levinson et al (1993).

2. ORIGIN OF DIAMONDS

2.1 Properties and classification of diamonds

Gem diamonds have a density of 3.53, but the tough, black coke-like borts or aggregates of industrial diamond have a density as low as 3.15. Diamond is the hardest known substance, followed by a synthetic boron nitride (Borazon, synthesized by GE), boron carbide, silicon carbide, tungsten carbide and aluminum oxide.

Because these substances are all crystalline, the bonds between atoms are arranged in definite patterns. Certain planes and directions across a crystal surface have greater concentrations of bonds than others. Therefore, hardness varies with the direction of abrasion. Diamond crystals can be cut only by diamond dust on a lap, when the softer directions of the diamond crystal are presented to the diamond particles that attack it. In the random distribution of diamond dust on a lap, some particles will present their hardest directions to the diamond that is being cut.

Diamond slowly burns to CO_2 in air at a temperature as low as 900°C, and slowly inverts to graphite at temperatures as low as 1,000°C. At higher temperatures, conversion of diamond to graphite can be exceedingly rapid or even explosive. The rate of graphitization is greatly accelerated when the diamond is in contact with any of the Group VIII chemical elements or with alloys of Fe, Ni or Co.

Diamond has the highest thermal conductivity of any known substance. The thermal conductivity of pure diamond at room temperature is approximately five times that of copper. The points of diamond used as cutting tools do not become hot owing to this extreme thermal conductivity. This property contributes greatly to their usefulness in diamond-drilling.

The recovery of diamonds from ore is a relatively simple process. Diamonds are hydrophobic, or resistant to being wetted, while the host kimberlite will disaggregate and break down during crushing and washing. Diamonds also stick to grease. To take advantage of these properties, kimberlite is crushed in a primary crusher to about 6 inches in size. The rock is then fed through a secondary crusher with water added to help the breakdown of the host rock. The kimberlite, water and diamonds are passed over a grease table; the diamonds stick to the grease while the water and waste rock wash off. The grease is melted and poured off periodically, leaving behind the diamonds.

The principle of the grease table is used in small recovery plants today, in some cases updated to moving grease belts which cross the stream of rocks and water, picking up diamonds as they go. However, the largest and most modern diamond recovery plants make use of another property of the stones: diamonds fluoresce under X-rays. These plants use SORTEX units, in which photoelectric cells spot the fluorescence of a diamond under X-rays and trigger a blast of air to blow the stone off the moving belt.

In terms of classification, rough diamonds can be broken down into three broad categories (ultimately, the Central Selling Organization (see below) sorts the stones into around 3,000 categories). The three broad categories are gem stones; near-gem; and industrial diamonds. The ultimate value of a polished stone is dependent on "The Four C's" – carat, colour, clarity and cut. The best stones, classed as gems, are suitable for cutting and polishing as high-quality jewellery on all these criteria.

The next rank of stones, near-gems, are diamonds with substantial impurities or other defects which can still be cut, depending on economics, to produce small, cheaper jewellery stones. In cutting and polishing near-gems, about 75-80% of the rough diamond is lost compared to an average of just over 50% for gem stones. The economics of diamond cutting are one reason why near-gems are often referred to as "Indian goods". A diamond cutter in Bombay, the major centre for cutting near-gems, is paid around US$600/year, compared to around US$15,000/year for a cutter in Tel Aviv, and more than US$25,000/year in Antwerp and New York. The Indian cutting industry can process the poorer-quality near-gems profitably, while only gems can be economically treated in the other cutting centres.

Finally, industrial diamonds are classed as the balance of the rough stones, not suitable for cutting as gems or near-gems. Natural industrial-grade diamonds have competition in the form of synthetic stones, which now account for around 80% of the world market for industrial diamonds, about 250 million carats/year. Natural stones have kept some market share as they are still superior to synthetics for some uses and, as a by-product of gem diamond cutting, they have negligible production cost and can thus undercut synthetic stones on price.

Alluvial diamonds are the result of the erosion of a diamond-bearing rock by water, ice or wind. The stones may be carried by rivers for hundreds of kilometres, during which the poorer-quality stones tend to be broken up and worn away. As a result, alluvial deposits generally contain higher-quality diamonds than the original kimberlite pipe(s). One of the richest sources of gem diamonds has been the west coast of South Africa and Namibia. Stones were carried hundreds of kilometres from the interior by the Orange River and deposited along ancient beaches by river and tidal action. As a result of this considerable water action eroding the poorer stones, these deposits contain around 95% gem stones. Over the past 70 million years, the river mouth moved several hundred kilometres along the coast, and the sea level and beaches varied by hundreds of metres in height (see Gurney et al., 1992). Diamonds have been mined from the presently exposed beaches for the past 80 years, but exploration in recent years offshore on the continental shelf has shown that there are probably more diamonds in the ancient beaches that are now covered by the sea.

2.2 Origin of diamonds

Scientific advances in the past decade have led to a clearer understanding of the age and origin of diamonds. The following summary is taken from a review by Kirkley et al. (1991). The age dating of diamonds has been made possible by the new ability to date mineral inclusions separated from diamonds, which has existed only in the last decade. As a generalization, most diamonds formed more than 990 million years ago, within the mantle, from either of two rock types, peridotite and eclogite. Diamonds were stored below the base of cratons for varying periods of time, some as long as 3,200 million years, before being transported to the surface. Diamonds are generally much older than the volcanic rocks (kimberlite and lamproite) that transport them to the surface, are not genetically related to these volcanic rocks, and have crystallized, possibly episodically, during a large part of Earth's history.

Kimberlite and lamproite (see below) are only the transporting mechanisms for bringing diamonds to the surface and are not genetically related to diamond. Xenoliths (foreign rock fragments) in kimberlite and lamproite are usually rounded, especially if they originate at great depths. Xenoliths that contain diamonds record the pressure, temperature and chemical characteristics of crystallization of diamond. Eclogite and peridotite are the predominant xenoliths found to contain diamond. During transport of both peridotitic and eclogitic xenoliths within kimberlite or lamproite, fragmentation of the xenoliths takes place, adding smaller xenoliths or even xenocrysts (single crystals or grains) to the transporting magma. This is the explanation for the occurrence of diamond xenocrysts and crystals of other minerals (garnet, chromite, etc.) in kimberlite and lamproite.

Eclogite is a rare, coarse-grained ultramafic rock consisting of an aggregate of garnet (almandine-pyrope) and pyroxene (omphacite), with minor amounts of rutile, kyanite, corundum and coesite. Eclogite forms in high-pressure environments, consistent with the environment of diamond formation. Peridotite, likely the most abundant rock type in the Earth's mantle, occurs as several varieties of coarse-grained ultramafic rock consisting mainly of olivine, with or without pyroxene. Garnet and spinel are common accessory minerals in peridotite. Most peridotitic diamonds are formed in garnet-bearing harzburgite, with minor amounts formed in lherzolite (Gurney, 1989). Diamondiferous eclogite xenoliths are relatively common but diamondiferous peridotite xenoliths are rare, and typically extensively altered. More than 100 diamond-bearing eclogites have been described in detail in the literature, but there are fewer than 20

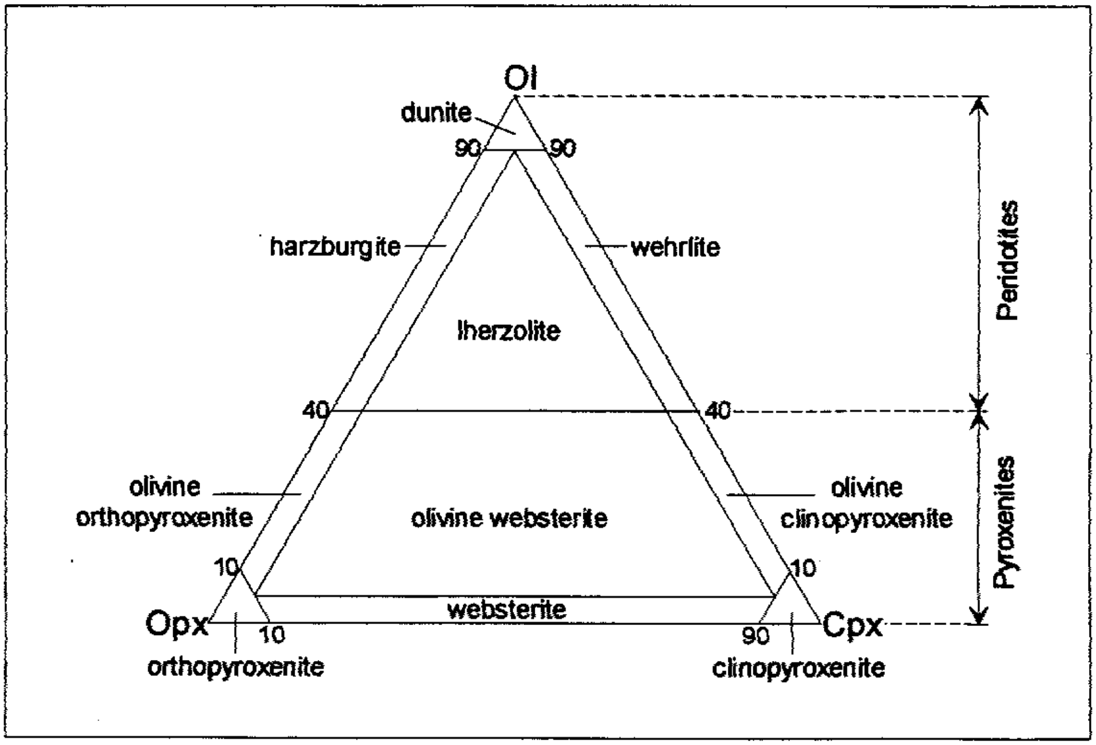


Figure 2.2 Classification of Ultramafic rocks (IUGS). Modal proportions in volume %.

comparable descriptions of diamondiferous peridotite xenoliths. However, from diamond type, harzburgite (see Fig. 2.2) is probably the source of most of the diamonds in kimberlite, and it is likely that diamond-bearing peridotite xenoliths are disaggregated by one or several processes within the mantle (Gurney, 1989).

From the study of inclusions in diamonds, it is possible to characterize with confidence 98% of all diamonds as either peridotitic (mainly harzburgitic) or eclogitic. They are referred to as "P-type" and "E-type" diamonds, respectively. The assumption is made that, in order for inclusions of single minerals (e.g. garnet) or of aggregates of minerals (e.g. minute eclogite or peridotite aggregates) to be included as intergrown crystals with another mineral (i.e. diamond), both the inclusion and host must have formed at the same time, and both have a common origin. Thus, if the inclusions are of the peridotitic assemblage, it follows that the diamond formed within peridotite host rock. The mineral inclusions in one type of mineral assemblage chemically will not be the same as those in the other type, and they are mutually exclusive except in very rare cases.

As noted, diamondiferous xenoliths of E-type are relatively abundant, while diamondiferous P-types are very rare. Yet, P-type inclusions (i.e., P-type diamonds) are much more common than the E-type. It is clear that once mineral inclusions are encapsulated within diamond, they are protected from reactions with the surrounding magma, or from disaggregation, as occurs with diamond-bearing peridotite xenoliths. Although estimates vary, peridotite-type inclusions outnumber eclogite-type inclusions by a ratio of 3:1. P-type diamonds are particularly more abundant in smaller sizes. Lamproite diamonds apparently have more eclogitic inclusions than kimberlite diamonds, but do not have characteristics that differentiate them unambiguously from kimberlite diamonds (Mitchell and Bergman, 1991).

From a review by Meyer (1985), there have been many determinations of the pressures and temperatures at which mineral inclusions in diamond (and, hence, diamond) crystallized. The peridotitic type of inclusions crystallized in the temperature range 900°C to 1,300°C, and pressure from 45 to 60 kbar (1 kbar is equal to approximately 3.3 km of depth in the Earth). Considering the geothermal gradient under continental areas (rate at which temperature increases with depth), the estimated depth of formations of P-type diamonds is in the range 150-200 km, which is within Earth's upper mantle. Eclogitic-type inclusions fall in the same or higher temperature range, and appear to have crystallized at possibly even greater depths. It is clear that diamond cannot form at the surface of the Earth, and that all diamonds present at the surface are thermodynamically metastable.

3. KIMBERLITES AND LAMPROITES

3.1 Kimberlite

Kimberlite is the main source of diamonds. Kimberlite is a complex dark-coloured (dark blue-grey when fresh) ultramafic rock that is volatile-rich and ultrapotassic, derived from deep in the Earth. It occurs in the upper 2 to 3 kilometres of the crust as small volcanic pipes, dikes and sills. At the surface, kimberlite is weathered and oxidized to a hydrated "yellow ground" that grades at depth to fresher "blue ground" (and "hardebank" in South Africa, resistant kimberlite outcrops that do not disintegrate upon exposure). It is composed principally of olivine both as phenocrysts and in groundmass, with lesser amounts of phlogopite, diopside, serpentine, calcite, garnet, ilmenite, spinel and other minor minerals. Diamond is not a primary constituent. It commonly contains fragments of deep-seated, high-temperature eclogite and peridotites and upper-crustal wall rocks. Its megacrysts (coarse, single crystals; both phenocrysts, related to the magma, and xenocrysts) have commonly reacted metasomatically with the lower-temperature volatile rich matrix and with high-level groundwater during intrusion. It occurs most commonly as diatremes, which are pipes emplaced by gas-driven explosion and filled with brecciated autoliths and wall rock fragments (see below).

The volatiles are mainly CO_2 (around 8%) and H_2O (7%). The K_2O content (0.6%-2.0%) is high for ultramafic rocks, and total SiO_2 is extremely low (25%-35%)

Table 3.1 The chemical composition of "average kimberlite" compared with that of "average ultramafic rock". From Middlemost, (1986).

Element in p.p.m.	Average kimberlite (K)	Average ultramafic rock (U)	K/U
Li	25	2	12.5
Be	~1	~0.4	~2.5
B	36	7	5.1
C	16,200	100	162
F	1,900	97	19.6
Na	2,030	2,230	0.91
Mg	160,000	247,500	0.64
Al	18,900	14,300	1.3
Si	147,000	203,300	0.72
P	3,880	220	17.6
S	2,000	~4,000	0.5
Cl	300	110	2.7
K	10,400	390	26.7
Ca	70,400	27,200	2.6
Sc	15	15	1.0
Ti	11,800	780	15.1
V	120	50	2.4
Cr	1,100	3,090	0.36
Mn	1,160	1,040	1.1
Fe	71,600	64,830	1.1
Co	77	110	0.7
Ni	1,050	1,450	0.72
Cu	80	47	1.7
Zn	80	56	1.4
Ga	~10	2.5	~4
Ge	~0.5	1	~0.5
Se	0.15	0.02	7.5
Rb	65	1.2	54.1
Sr	740	22	33.6
Y	22	2.88	7.6
Zr	250	16	15.6
Nb	110	1.3	84.6
Mo	~0.5	0.2	~2.5
Pd	0.053	0.01	5.3
Cd	0.07	0.06	1.2
Sn	15	0.52	28.8
Cs	2.3	0.006	383
Ba	1,000	20	50
La	150	0.92	163
Ce	200	1.93	104
Pr	22	0.32	68.8
Nd	85	1.44	59
Sm	13	0.40	32.5
Eu	3.0	0.16	18.8
Gd	8.0	0.74	10.8
Tb	1.0	0.12	8.3
Ho	0.55	0.016	3.4
Er	1.45	0.40	3.6
Tm	0.23	0.067	3.4
Yb	1.2	0.38	3.2
Lu	0.16	0.065	2.5
Hf	7	0.61	1.7
Ta	9	≤0.01	≥90
Pt	0.19	0.06	3.2

(Mitchell, 1989). There are also unusually high concentrations, for ultramafic rocks, of certain trace elements: Nb, Zr, Sr, Ba, Rb and Ce. Although all of these occur in amounts of less than 0.1%, this is geochemically significant and anomalous concentrations of these elements are important indicators of the presence of kimberlite in exploration samples (Table 3.1).

Kimberlites are divided into Group 1 megacryst-bearing olivine-rich kimberlites and Group 2 micaceous kimberlites. Group 1 kimberlites have a megacryst assemblage of picroilmenite (Mg-rich ilmenite), Cr-poor Ti-bearing pyrope and subcalcic diopside as well as phlogopite and spinels. Chrome-diopside, chrome-pyrope and Mg-rich chromite are abundant, and are the best heavy mineral tracers in their detection (see below). Group 2 kimberlites, known until now only in South Africa, have little or no megacrysts. They occur dominantly as dikes with very high diamond grades. The absence of ilmenite makes their detection by heavy mineral sampling more difficult.

Detailed discussions of the petrology of kimberlite have been given by Mitchell (1986, 1989).

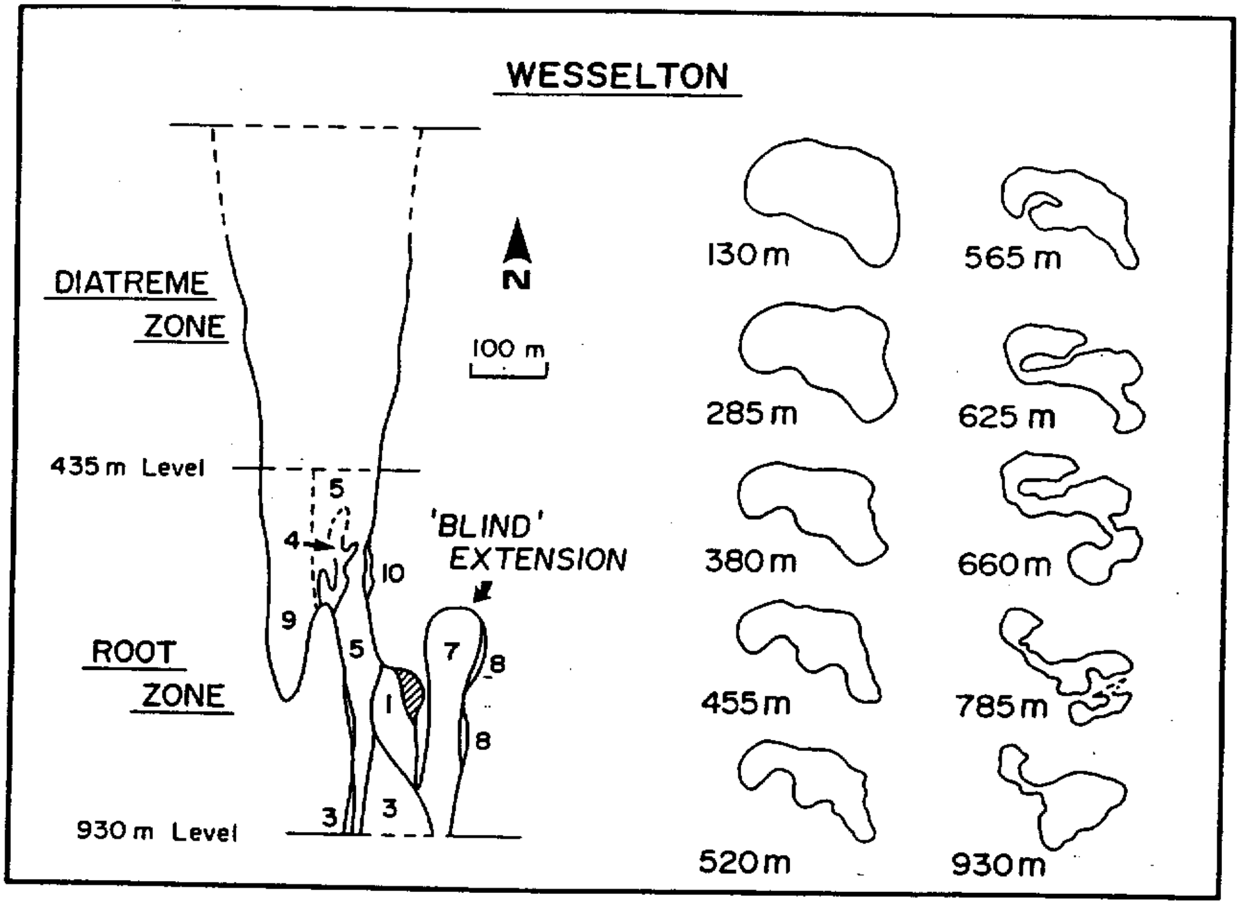


Figure 3.2.1 Diatreme-root zone relationships, Wesselton Mine, South Africa. From Mitchell, (1989).

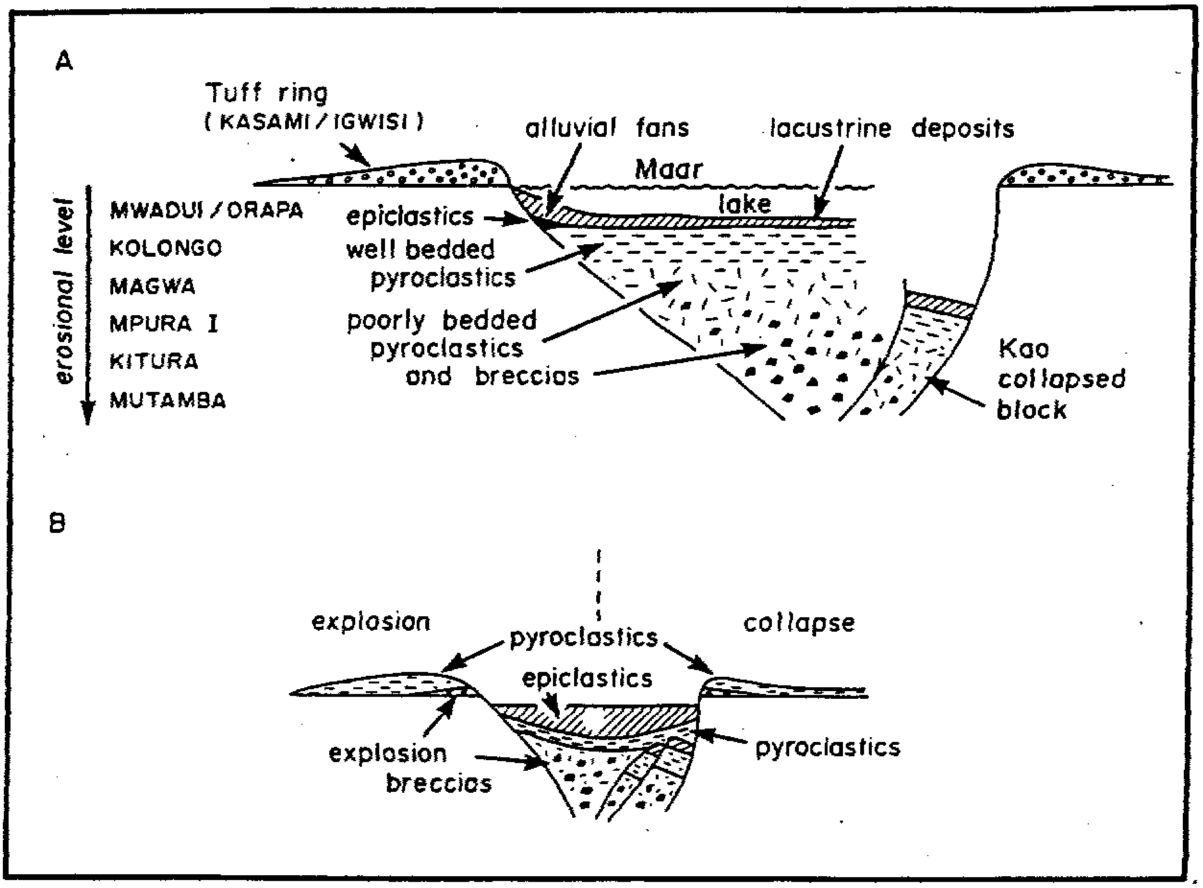


Figure 3.2.2 Schematic cross-section of kimberlitic volcanic vent. From Mitchell, (1986).

3.2 Configuration of kimberlite diatremes

The term diatreme is synonymous with breccia pipe: it is a general term for a volcanic pipe that is emplaced in rocks by gaseous explosion, and is filled with angular broken fragments (breccia). The characteristic features of kimberlite diatremes are their general shape and their three distinct depth zones (root, diatreme, crater).

The root zone is the deepest part of the pipe. It has an irregular outline and numerous intrusive phases of kimberlite and hypabyssal features, and extends about 0.5 km vertically about 2 to 3 km below the surface. It contains crystallized kimberlite magma. It grades downward into individual feeder dikes of kimberlite which extend downward for great distances, but probably not continuously, as the fractures along which the magmas moved probably opened and then closed after magma passed through. Root zones and feeder dikes may contain diamonds among the xenocrysts, but they have been mined only on a small scale because of their limited volume. Economic mining is also limited by the width of the dikes, which are usually only about 60 cm wide, although locally they reach 10 m wide in "blow" zones.

The diatreme zone (as distinct from diatreme = pipe) is the most important source of diamonds because of its volume. It ranges from 1 to 2 km in height and

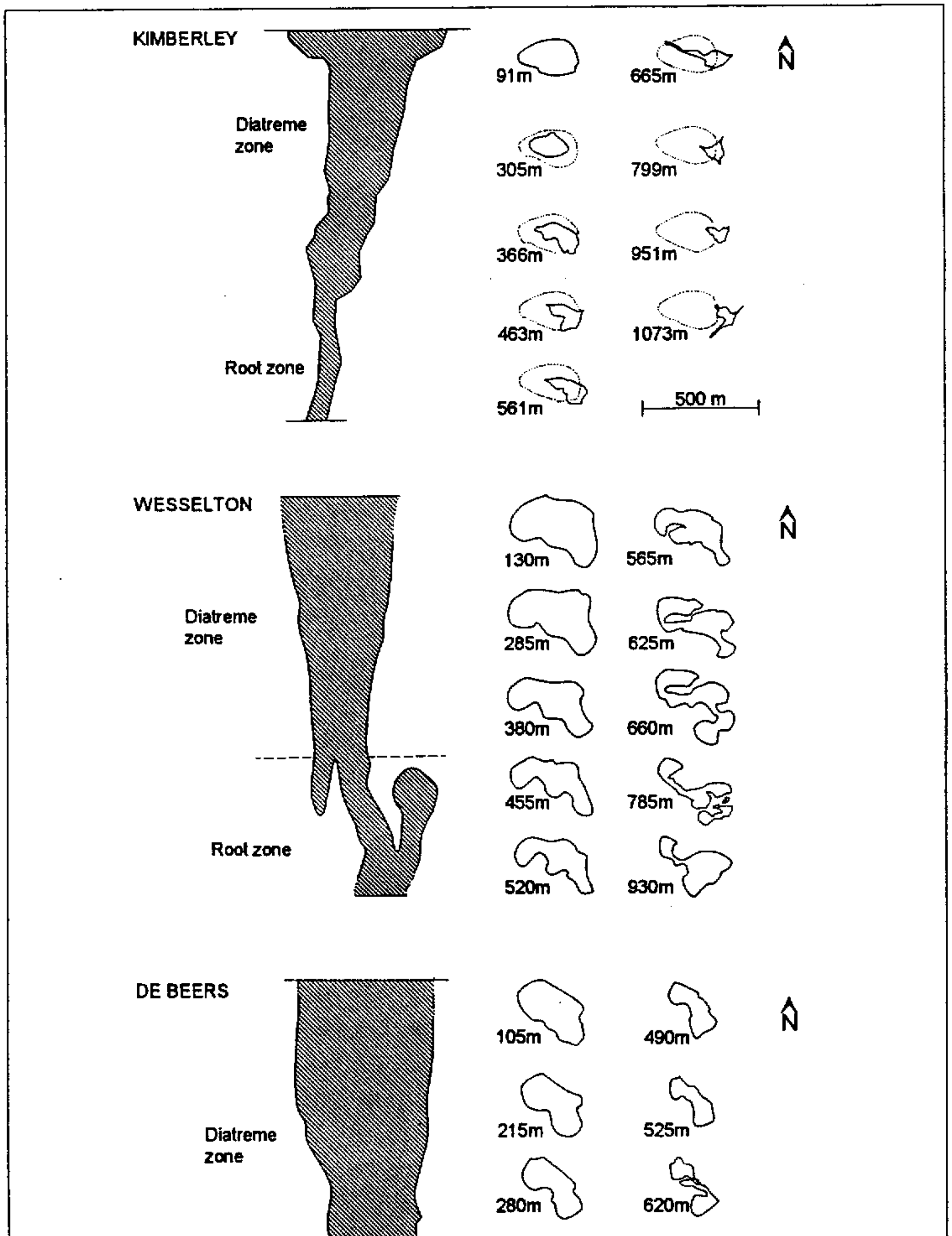


Figure 3.2.3 Vertical and horizontal cross-sections of the Kimberley (Williams, 1932), Wesselton (Clement, 1982) and De Beers (Clement, 1982) diatremes. Reproduced from Mitchell (1986).

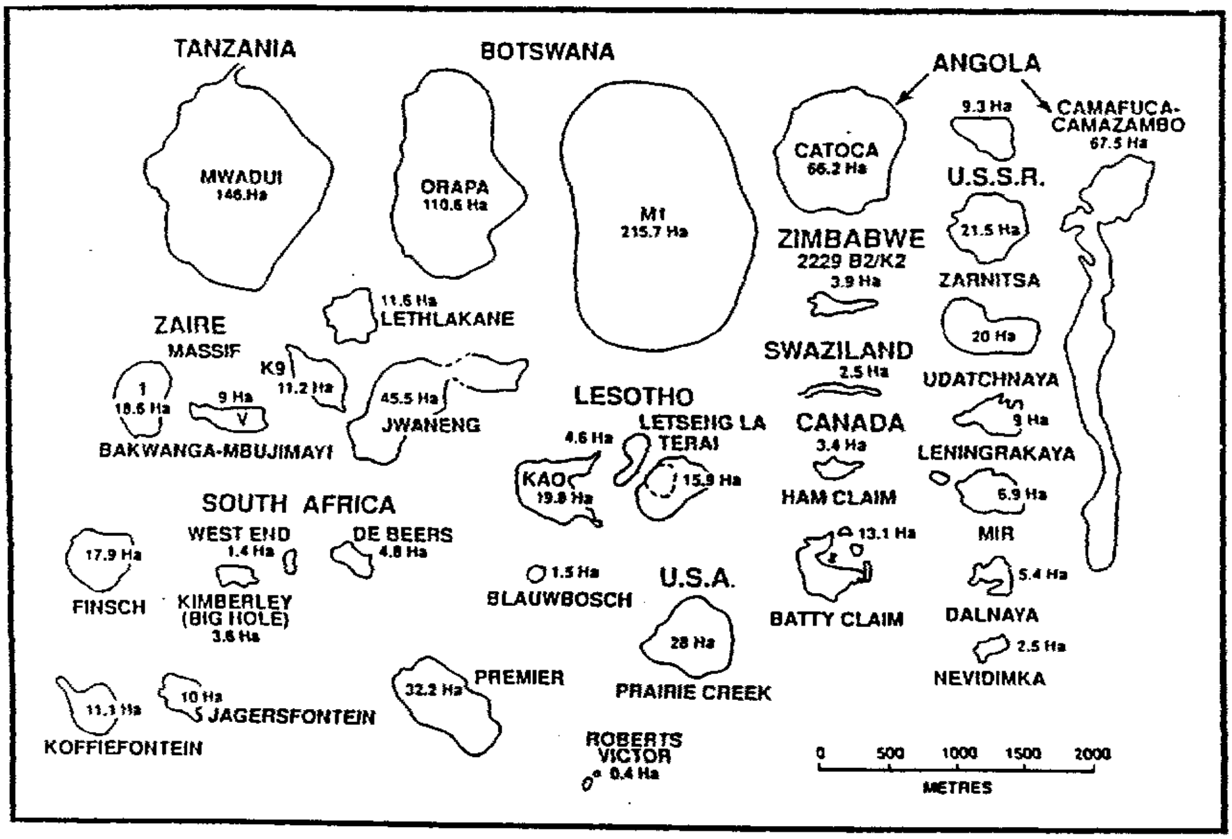


Figure 3.2.4 Shapes and sizes of diamond pipes. From Jennings (1990).

extends to within 300 m of the surface, before erosion. It contains the xenoliths and xenocrysts from the mantle, as well as rock fragments incorporated during ascent through the crust. The main characteristics of the zone are kimberlite breccias and other fragmental rocks (e.g. tuffs) associated with explosive magmas. Diatreme zones may separate into discrete, root-like bodies. Upwardly-terminating bodies or "blind" pipes may also occur (Fig. 3.2.1).

The crater zone occupies the upper 300 m of a typical kimberlite diatreme, which, during emplacement, is a volcano. Most volcanoes erupt molten lava, but kimberlite and lamproite eruptions probably do not. This is because, by the time the magma has passed through the diatreme zone, it is no longer molten and does not flow. It erupts as hot pyroclastic material, probably reacting with local groundwater. The cool groundwater turns to steam, the eruption becomes even more volatile, and extremely violent explosions can occur. Although kimberlite or lamproite volcanoes have never been observed to explode, in Tanzania, Mali, Botswana and Australia, there are examples of the surface expression of this phenomenon that have not yet been eroded away. These include maars (low-relief volcanic craters, sometimes water-filled, surrounded by crater rings) and tuff rings (wide, low-rimmed accumulations of pyroclastic debris of tuff or lapilli, slightly larger than the associated maar) (Fig. 3.2.2). It is likely that the explo-

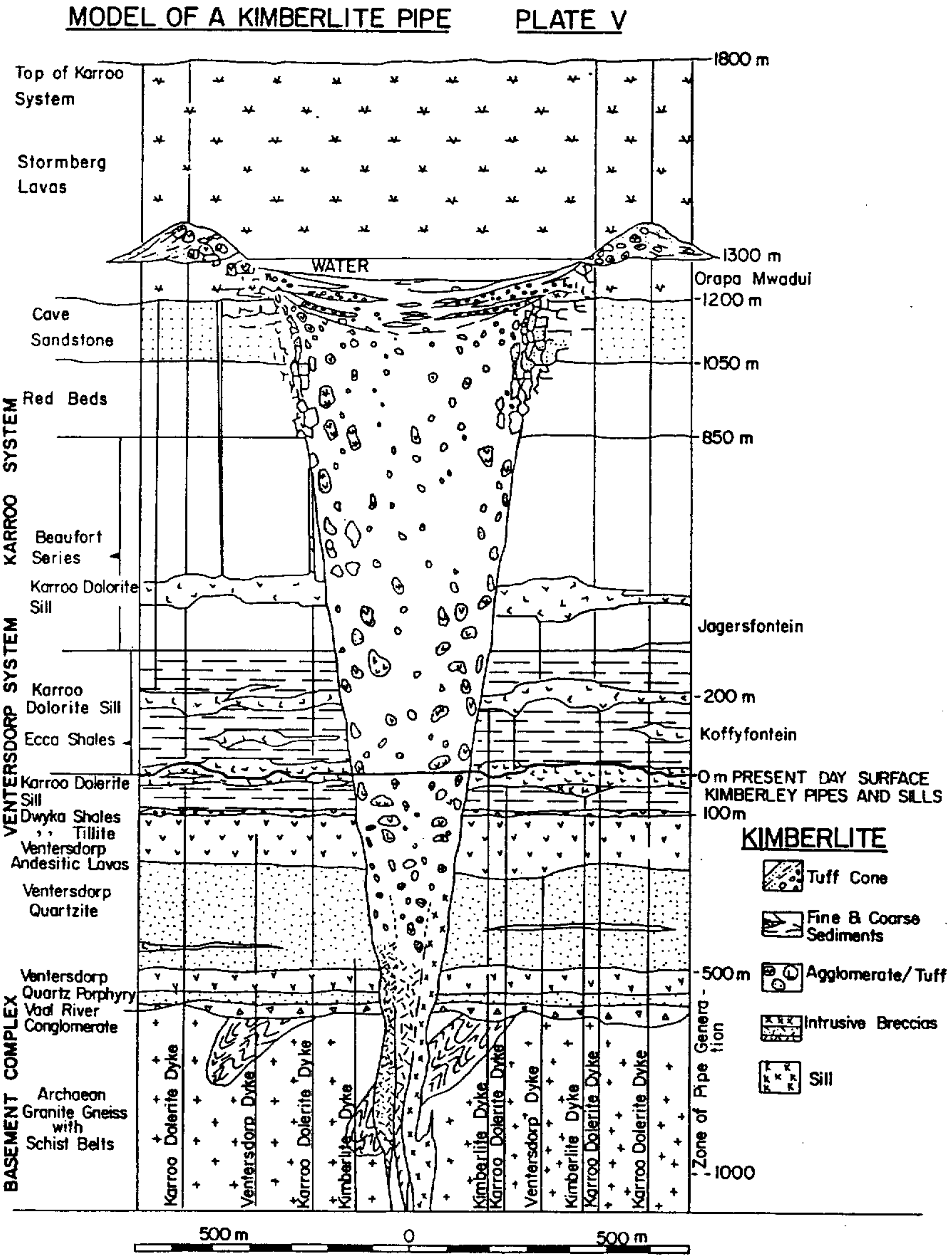


Figure 3.2.5 Model of a kimberlite pipe. From Hawthorne (1975).

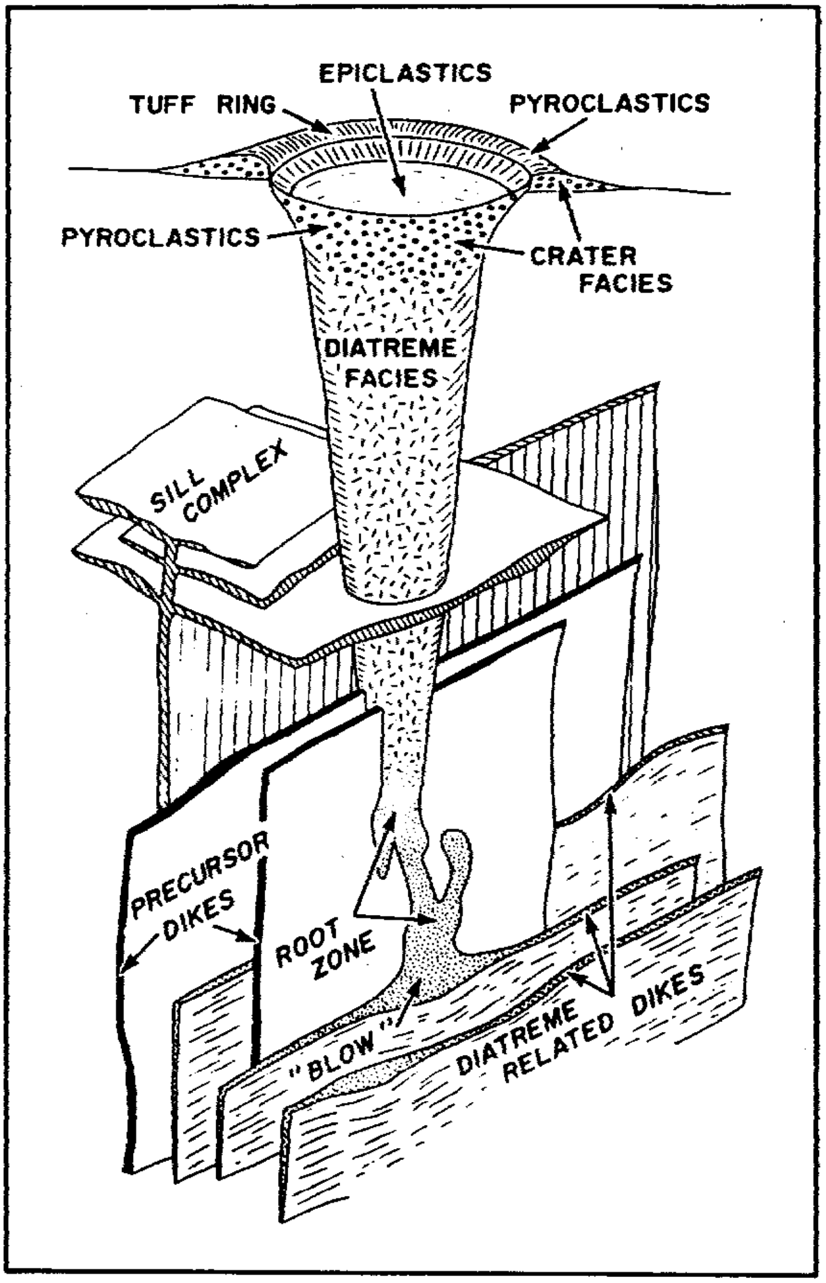


Figure 3.2.6 Idealized model of a kimberlite magmatic system (not to scale) based on kimberlites occurring in the Kimberley area. Hypabyssal-facies kimberlites include the *diatreme root zone*, dikes and sills. From Mitchell (1986).

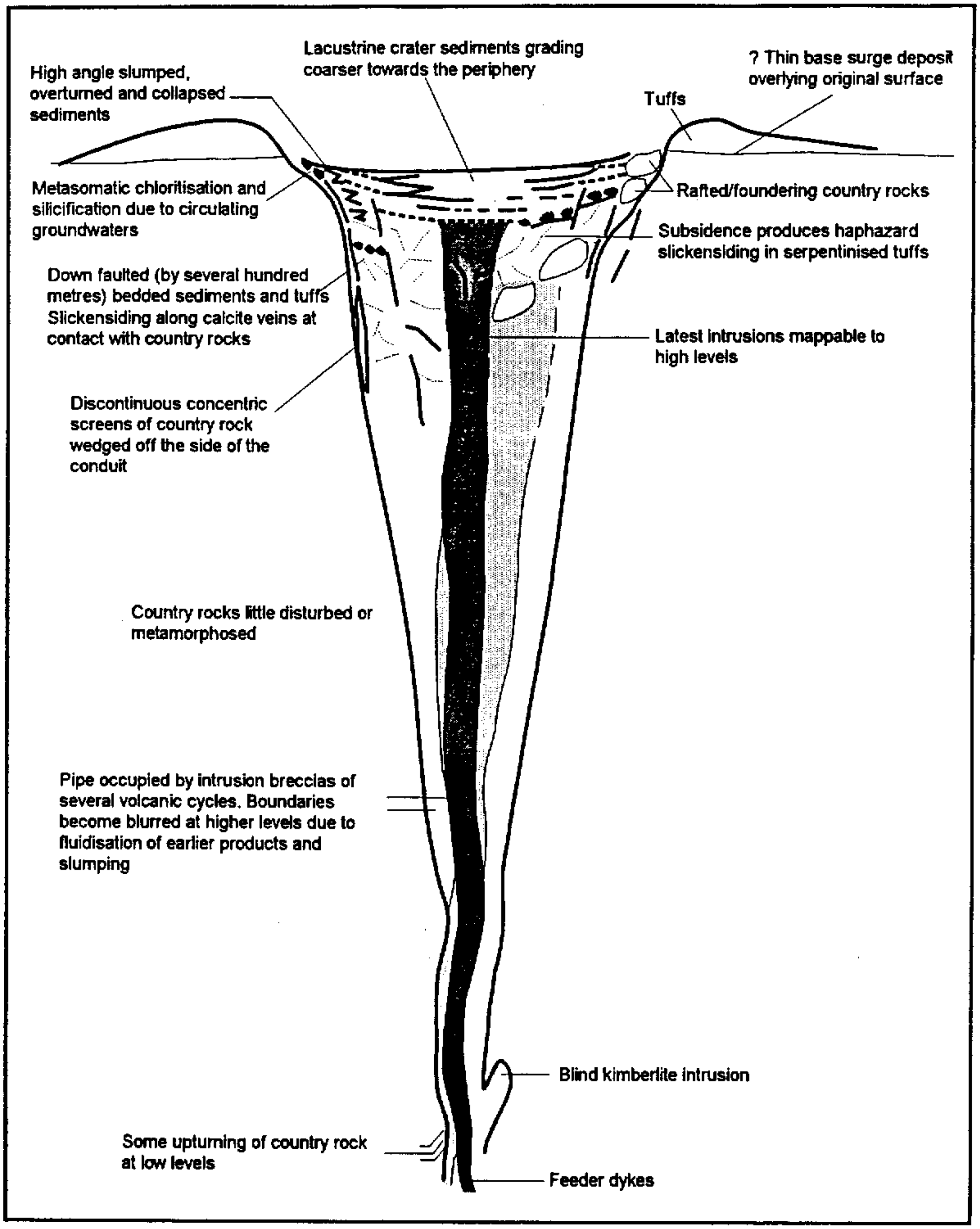


Figure 3.2.7 Schematic kimberlite diatreme (pipe) and maar. From Nixon, 1980.

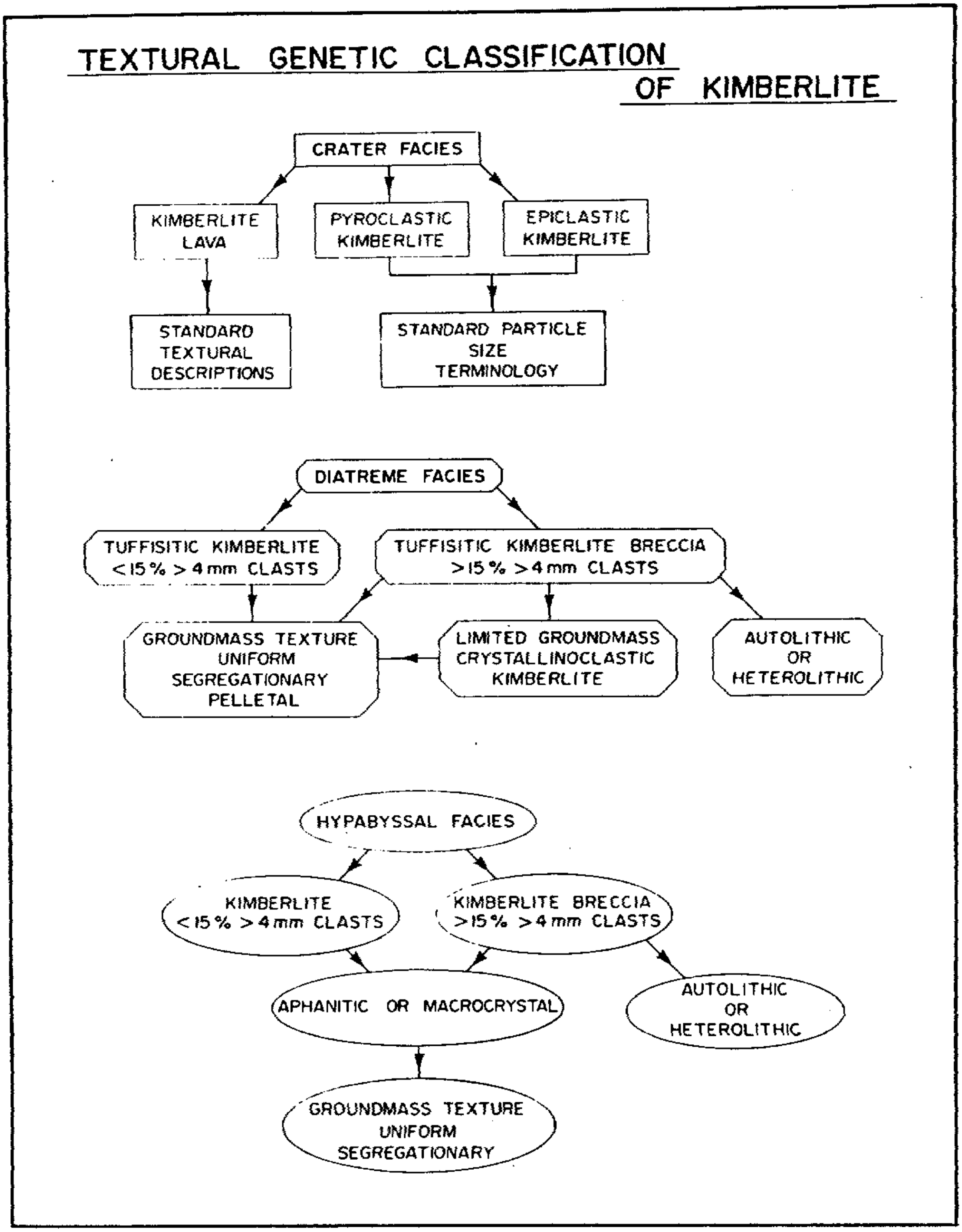


Figure 3.2.8 Textural genetic classification of kimberlite. From Mitchell (1991).

sion lifts debris no more than several hundred metres into the atmosphere, and the tuff ring is typically about 50 m high and is quickly eroded.

The cross-section area of pipes ranges from 0.4 ha to more than 200 ha (1 to more than 500 acres). Typical sizes and shapes are shown in Figures 3.2.3, 3.2.4, 3.2.5, 3.2.6 and 3.2.7. A textural classification of kimberlite matching the facies shown in Fig. 3.2.6 is given in Fig. 3.2.8.

3.3 Lamproites

Lamproites are ultrapotassic peralkaline rocks rich in Ba. They were little more than petrologic curiosities until 1979, when lamproite was found to host primary diamonds in economic quantities in Australia (Argyle and Ellendale pipes). Diamonds have also been found in olivine-bearing lamproite in Arkansas, India and the Ivory Coast. Lamproite is a grey, greenish grey or brownish grey hybrid rock rich in olivine both as phenocrysts and groundmass. Upper-mantle xenoliths and xenocrysts are the same as those found in kimberlites.

Table 3.3 Representative Ranges And Average Composition Of Lamproites (After Bergman, 1987)

	1	2	3	4
		Volatile Free (wt%)		
SiO_2	52.7 ± 3.8	51.3 ± 6.6	57.4 ± 5.2	52.5 ± 6.6
TiO_2	2.4 ± 0.3	5.1 ± 1.5	1.5 ± 0.2	3.0 ± 1.7
Al_2O_3	10.8 ± 1.4	7.4 ± 2.4	10.5 ± 0.2	9.0 ± 2.5
FeO*	5.1 ± 1.4	7.1 ± 1.1	5.3 ± 1.1	6.8 ± 2.2
MnO	0.9 ± 0.03	0.09 ± 0.03	0.08 ± 0.05	0.10 ± 0.05
MgO	8.4 ± 2.3	11.7 ± 7.5	10.5 ± 4.7	12.3 ± 6.6
CaO	6.7 ± 3.8	6.0 ± 8.0	4.9 ± 2.4	6.1 ± 4.4
Na_2O	1.3 ± 0.5	0.5 ± 0.3	2.0 ± 1.0	1.4 ± 1.0
K_2O	10.4 ± 2.4	8.3 ± 2.9	6.6 ± 2.2	6.9 ± 2.8
P_2O	1.5 ± 0.6	1.1 ± 0.6	1.1 ± 0.5	1.3 ± 0.7
BaO	0.67 ± 0.3	1.2 ± 0.8	0.3 ± 0.2	0.7 ± 0.6
ZrO_2	0.22 ± 0.7	0.15 ± 0.4	0.08 ± 0.04	0.13 ± 0.07
		Volatile Content (wt%)		
H_2O	2.6 ± 1.2	3.0 ± 1.8	2.8 ± 1.7	2.6 ± 1.8
CO_2	1.0 ± 1.0	1.9 ± 5.5	1.7 ± 2.3	2.7 ± 3.9
Number of samples	(24)	(51)	(98)	(309)

* Total Fe calculated as FeO

1 - Leucite Hills, U.S.A.

2 - Murcia-Almeira, Spain

3 - West Kimberley, Australia

4 - Average lamproite (worldwide)

Chemically, lamproite has K_2O typically 6%-8% and is magnesium-rich. Significant trace elements are Zr, Nb, Sr, Ba and Rb, as in kimberlite. Unlike kimberlite, CO_2 is low (less than 1%) but F (fluorine) is high. Si and Al are considerably higher than in kimberlite (Table 3.3).

Lamproites, like kimberlites, occur as pipes, dikes and sills. Both lamproite and kimberlite probably formed by partial melting of slightly different peridotite at greater depth than any other known volcanic rocks. Lamproites are easily distinguished from kimberlites and other alkaline ultramafic rocks on the basis of their bulk chemical composition and mineral chemistry. Lamproite petrology was recently reviewed by Mitchell and Bergman (1991).

3.4 Shape of lamproite pipes

In contrast to the carrot shape of kimberlite diatremes which are 2 to 3 km deep, lamproite pipes are usually more champagne-glass shaped bodies with less than 0.1 to 0.5 km of vertical extent (Figures 3.4.1, 3.4.2, 3.4.3, 3.4.4). This contrast has important implications for potential ore-volume calculations in diamondiferous pipes. The shape difference with kimberlite pipes results from the greater amounts of CO_2 and H_2O in kimberlite, which results in the final explosive emplacement phase being triggered at greater depth than for lamproite (Bergman, 1987). Lamproite volcanic vents have little or no topographic expression. Lamproite vents are not strictly diatremes, and possess four distinct facies: lava flow, crater or pyroclastic, hypabyssal, and plutonic (Mitchell and Bergman, 1991).

3.5 Age of kimberlites and lamproites

The age of kimberlite pipes ranges from Archean to Tertiary. Producing pipes are as old as 1,200 millions years (Ma) (Premier pipe, RSA), 1,100 Ma for Sierra Leone pipes, 342 Ma for the Mir pipe (Russian Republic), 150 Ma for Finsch (RSA), 90 Ma for Kimberley (RSA) to 41 Ma for Mwadui in Tanzania, with many intervening ages. Knowledge of the expected age of pipes is vital when exploring.

Although information on lamproites is less readily available, they are known to also cover a wide range from the Argyle pipe, which was intruded about 1,200 million years ago, to the Ellendale lamproites (about 50 separate bodies, located 400 km from the Argyle pipe), which were intruded in early Miocene time (20 million years ago). Some lamproites in Wyoming, Antarctica, and a few other localities may have been emplaced within the last one million years. From the large number of new age dates obtained on kimberlites and lamproites, it is also clear that kimberlite and/or lamproite intrusions can occur at several different times in the same area. Details of the implications of the age of pipes and their relation to the age of diamonds were discussed by Kirkland et al. (1991).

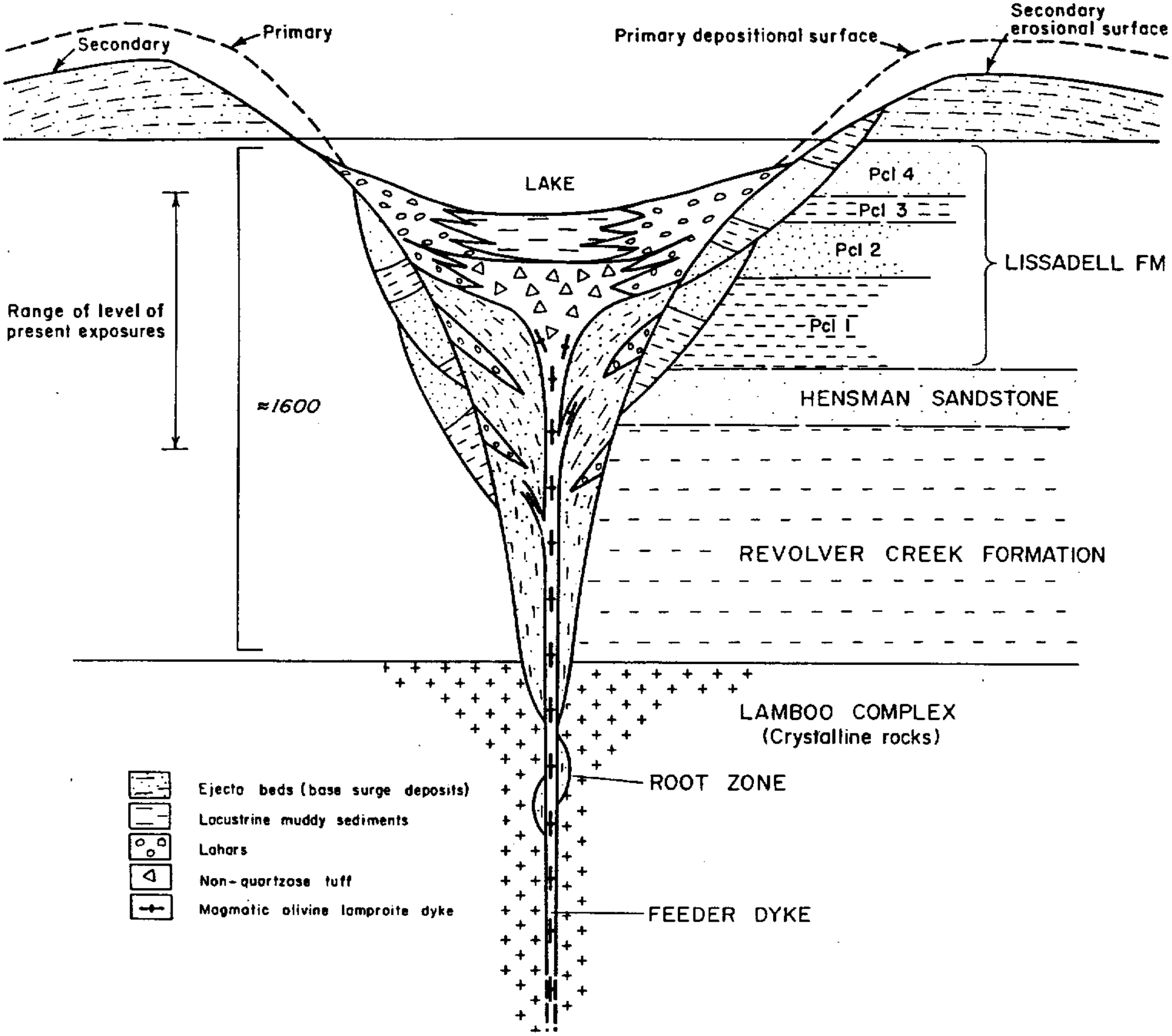
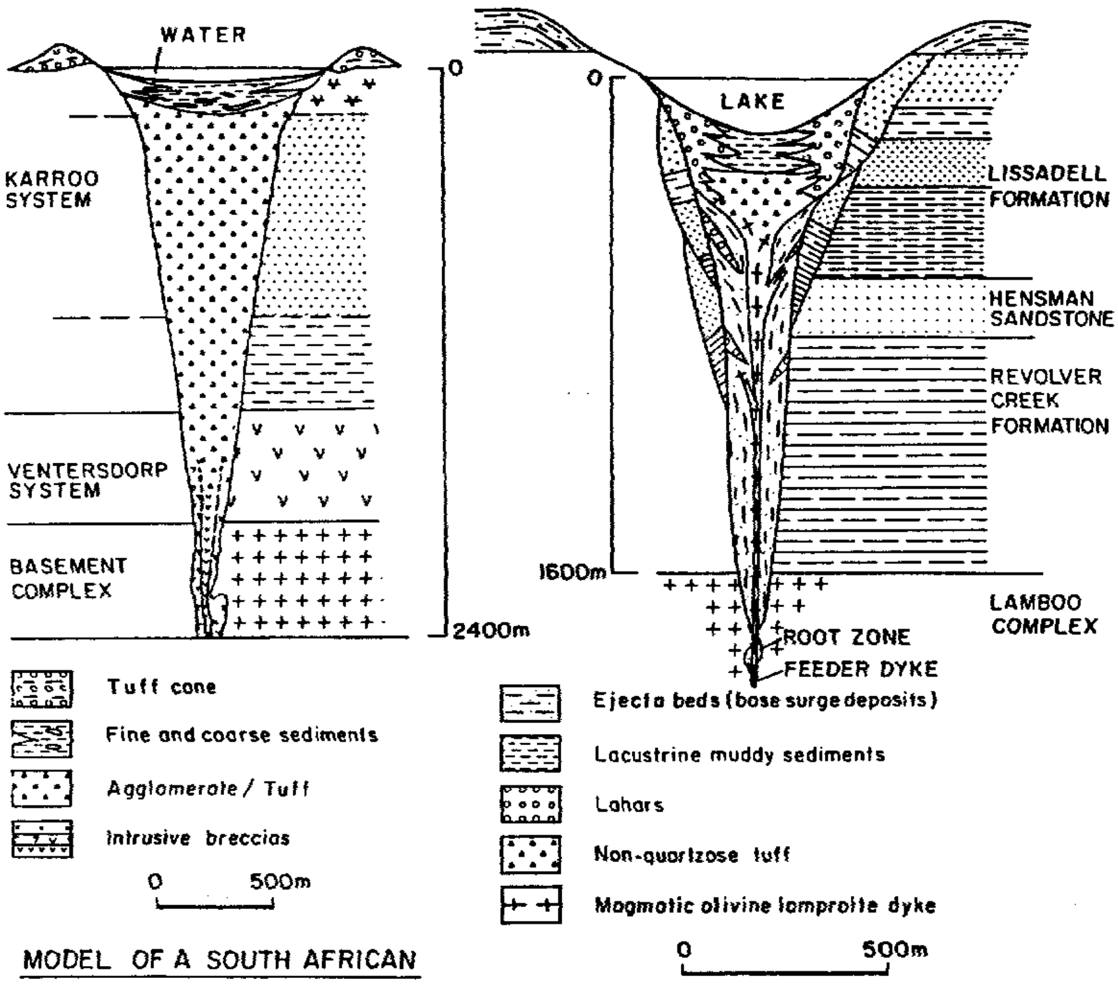
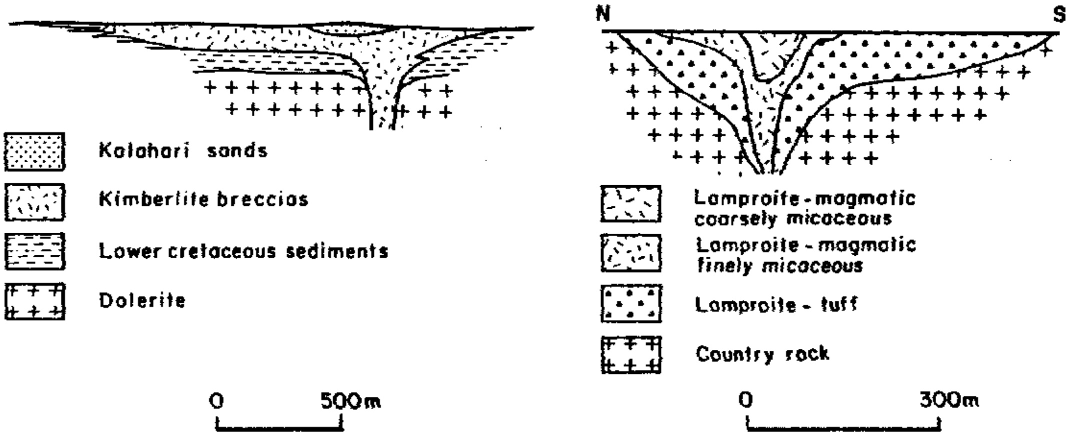


Figure 3.4.1 Schematic post-eruptive cross-section of the Argyle diatreme showing the diatreme, maar, feeder dike, ejecta beds on the crater rim and post-eruptive epiclastic sediments deposited in the maar crater lake. From Boxer *et al.* 1989).



MODEL OF A SOUTH AFRICAN KIMBERLITE PIPE
(after Hawthorne, 1975)

MODEL OF ARGYLE LAMPROITE PIPE
(modified from Boxer et.al., 1988)



CROSS SECTION OF TSHIBUA KIMBERLITE PIPE
(after Bardet, 1973)

CROSS SECTION OF ELLENDALE 9 LAMPROITE PIPE
(after Hall and Smith, 1984)

Figure 3.4.2 Comparative cross-sections of lamproite and kimberlite pipes. From Atkinson (1989).

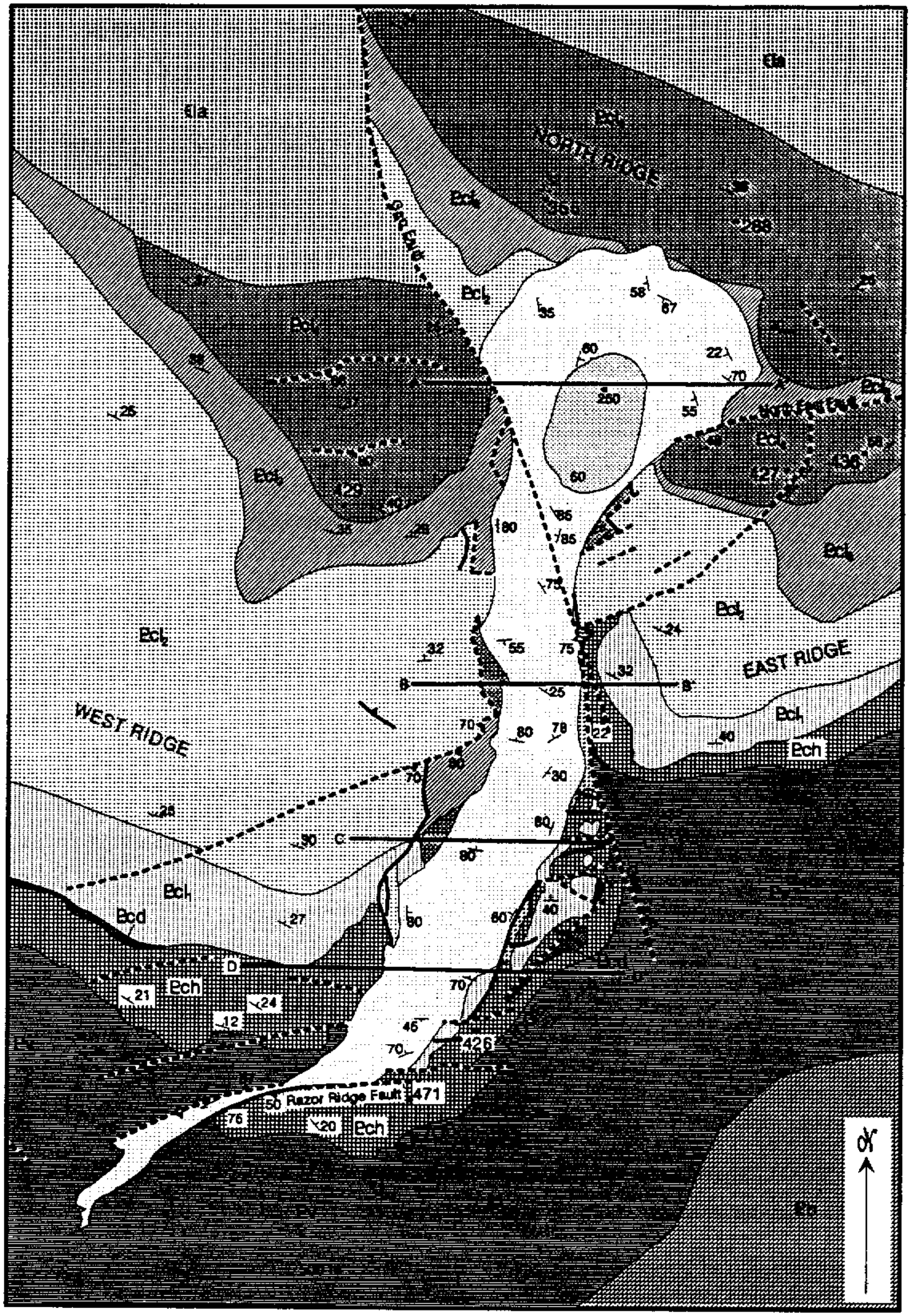


Figure 3.4.3 Geological map of the argyle diatreme. From Boxer et al., (1989).

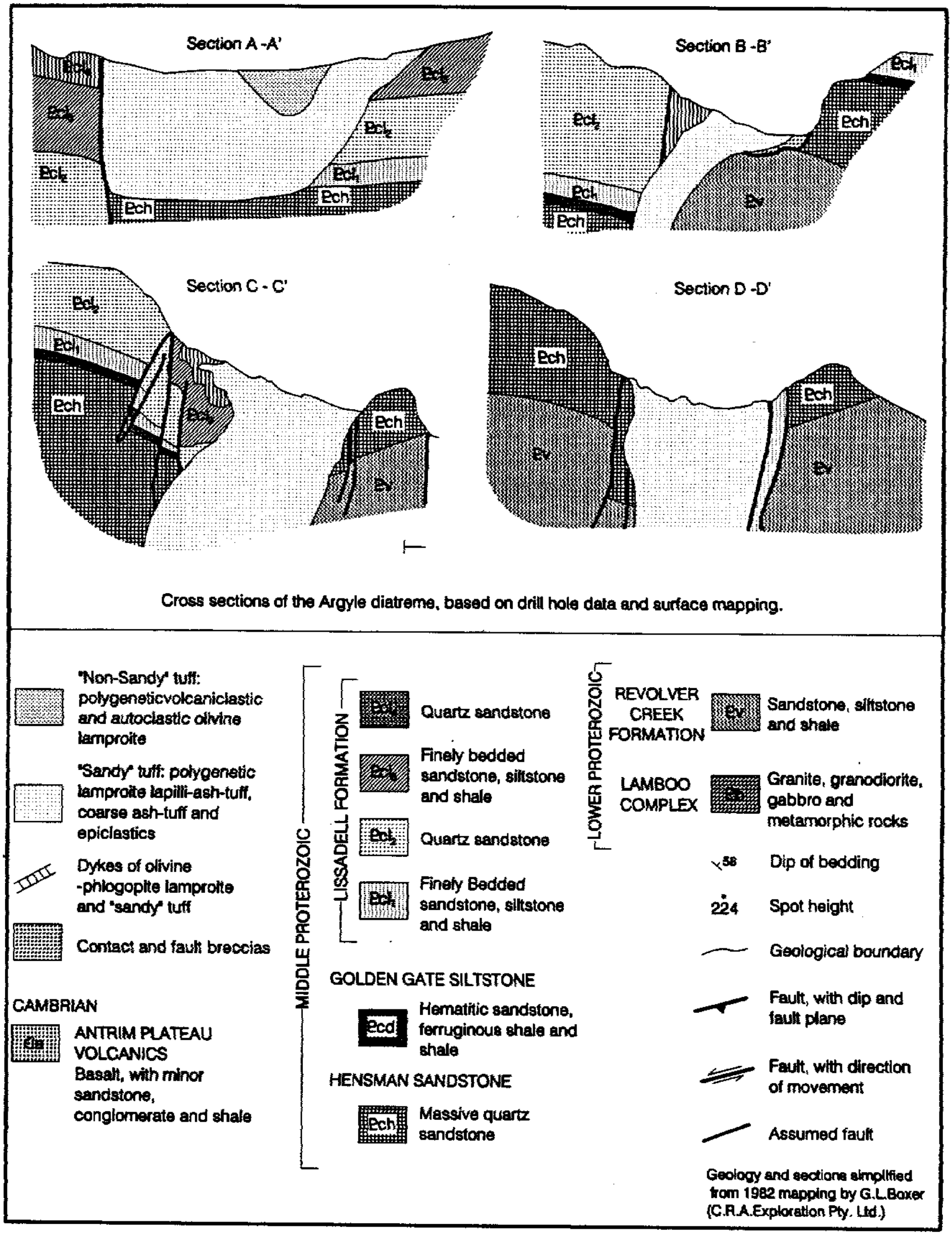


Figure 3.4.4 Cross-sections of the Argyle diatreme. From Boxer et al. (1989).

3.6 Rate of magma ascent and final emplacement

The rate of ascent of diamond-bearing kimberlites is determined fom the following evidence: diamonds are preserved during their ascent to the surface rather than reverting to graphite, or being converted to CO_2, or dissolving in the kimberlite magma; and the diamond-bearing kimberlites transport large xenoliths from as deep as 200 km below the surface. If the ascent was slow or with intermediate stops, diamond would react to graphite and the dense xenoliths would settle back through the magma. Estimates of the exact velocity depend on several assumptions, but there is general agreement that speeds of 10 to 30 km/hour are characteristic. Diamonds are thus brought to the surface from their storage areas at depths of at least 110 km (at the base of cratons) in 4 to 15 hours. As the surface is approached, within the last 2 to 3 km, the speed increases dramatically, probably to several hundred kilometres per hour. This is because within the kimberlite or lamproite magma there are large amounts of dissolved gases, mainly CO_2 and water, under great pressure. At about 3 km below the surface, explosions occur in the ascending magma as the gases come out of solution and expand enormously at the lower near-surface pressures, similarly to the foaming of a beer or pop bottle that is opened too rapidly. Because of these explosions, the rate of ascent increases rapidly (i.e. the magma accelerates) until the kimberlite breaks through the remaining crustal rocks. Because of the expansion of the gases, the kimberlite magma cools down rapidly, so that there is little thermal reaction with the wall rocks. With the temperature sufficiently low with respect to pressure, diamond resists conversion to graphite and survives metastably.

Lamproites appear to have somewhat different mechanisms of formation (see Mitchell and Bergman, 1991). Lamproite volatiles are dominated by H_2O and F, and are poorer in CO_2. During the ascent of volatile-rich lamproite, it is not until shallow depth (0.5 to 1 km) that significant exsolution of a fluid phase will occur. Expansion of these fluids at low pressure is thought to provide much of the energy required to form the funnel-shaped lamproite vents. Because kimberlite magmas exsolve volatiles (CO_2) at greater depths than lamproites, the deeper explosions initiate the formation of the root zone and the diatreme at depths 1 to 2 km below those at which lamproite vent formation takes place.

4. CONTROLS ON THE EMPLACEMENT OF DIAMONDIFEROUS ROCKS

Kimberlites and lamproites are restricted to continental intra-plate settings, and no occurrences are known in oceanic environments or young orogenic belts. It has been recognized for some time that kimberlite magmatism is largely confined to regions of continental crust underlain by old cratons (Fig. 4.1) These regions typically consist of an Archean craton (older than 2.5 billion years) surrounded by Proterozoic terranes, generally older than 1 billion years. Economically important kimberlites appear confined

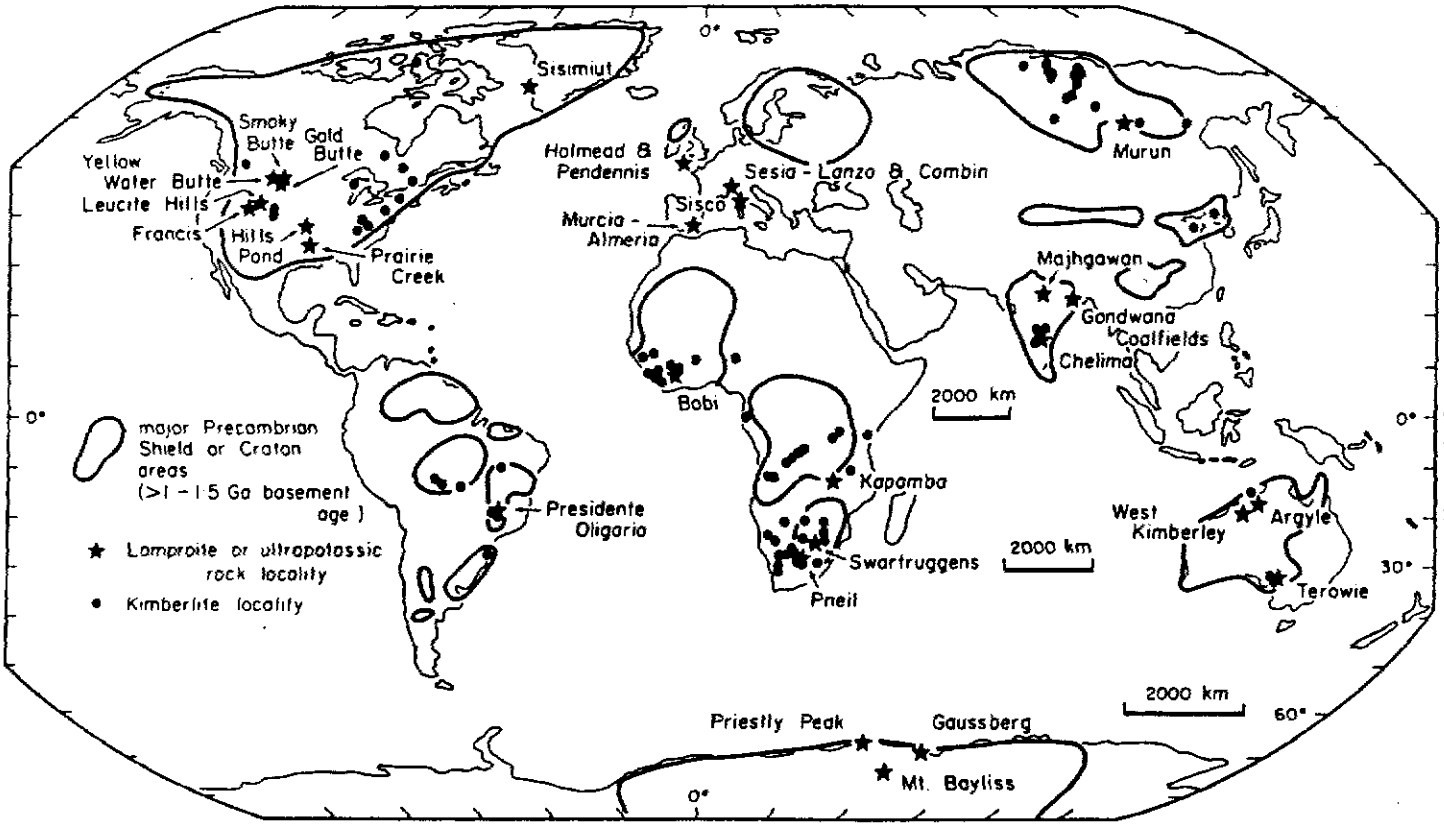


Figure 4.1 World map showing the distribution of lamproites relative to kimberlite fields and Precambrian shields (from Mitchell and Bergman, 1991)

to on-craton settings, and those occurring within the younger accreted terranes are not economic with respect to diamond content (Clifford, 1966; Dawson, 1980). However, this generalization is clearly contradicted by the location of the Argyle and other lamproites in Australia, within an 1,800 million year-old Proterozoic belt (Fig. 4.2).

The location of the Point Lake pipe in the NWT contradicts another assumption held in exploration until recently: the pipe occurs in the oldest part of the craton, on the exposed shield, a location thought not to be favourable for the preservation of kimberlite pipes because of inferred most extensive erosion.

The geographic and geologic aspects of kimberlite and lamproite occurrence have been reviewed by Clifford (1966), Janse (1984), Dawson (1989) and Kirkland et al. (1991). Kimberlites are widespread around the Earth, and more than 3,000 occur in southern Africa alone. There are more than 120 individual kimberlites (pipes, dikes or sills) in North America. Among these, about 60 are located in the Colorado-Wyoming State Line District. In Canada, pipe clusters are known in the NWT on Somerset Island (NWT) (19 pipes), and near the NWT-Yukon boundary (see below). More than 40 kimberlites/lamproites occur in the Rockies of southeastern British Columbia, at least 8 in Saskatchewan and at least 17 in the Lac de Gras area of the NWT which is undergoing intense exploration at present. A summary listing of kimberlites and related rocks of

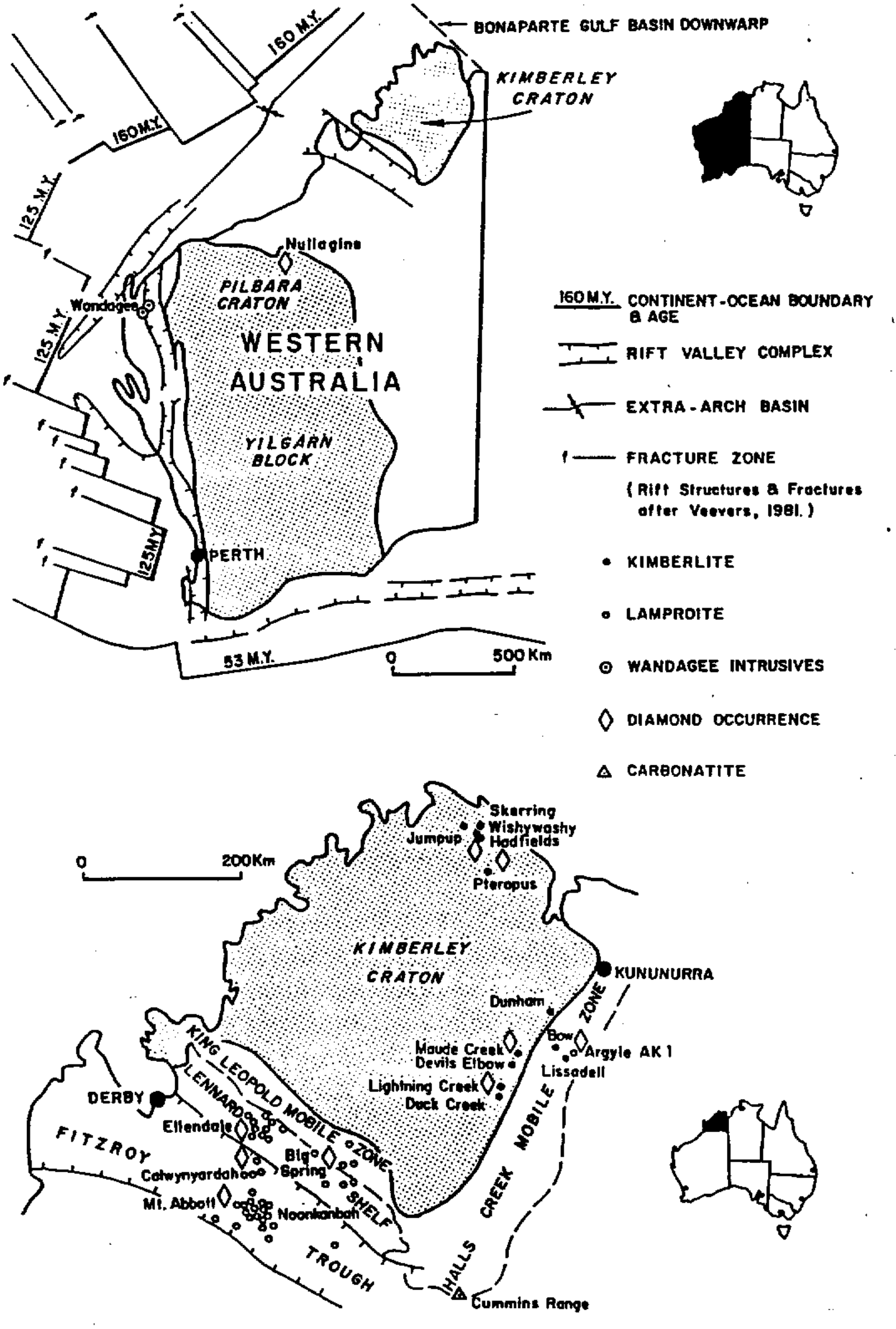


Figure 4.2 Location of kimberlites, lamproites and associated rocks in Western Australia. From Atkinson et al., (1984).

North America is given in Table 4.1, and a location map of known occurrences is given in Fig. 4.3.

Kimberlites occur world-wide in clusters of three to 50 or more pipes, in regions up to 50 km across. Individual clusters have one or more considerably larger pipes, which are more likely to be economic than small pipes. Certain areas, such as South Africa, Siberia, and northwestern Tanzania, contain many clusters. The five main pipes at Kimberley, South Africa, cover a circular area with a diameter of 10 km, but the entire cluster, including dikes, occupies an area about 40 km across. The ratio of economic to non-economic pipes in clusters varies considerably: Janse (1984) gives figures ranging from 5 out of 15 at Kimberley and 3 out of 29 at Orapa (Botswana), to 1 out of 30 at Alakit (Siberia). Some clusters have no economic pipes.

There are no similar statistics for lamproites. Not only is the discovery of the Argyle pipe in Western Australia relatively recent, but many of the rock types previously called lamproites, as well as related types, are presently being re-evaluated and reclassified. This has resulted, for example, in the reclassification of the diamond-bearing Prairie Creek pipe (at Murfreesboro, Arkansas) from a kimberlite to an olivine lamproite (see also Kidwell, 1990). Mitchell and Bergman (1991) estimated that the total volume of known intrusive kimberlite rocks is more than 5,000 km^3, while known lamproite rocks have a total volume of about 75 km^3. The large volume of extrusive lamproites, compared with intrusive varieties, may explain the paucity of recognized lamproites in the geological record. Once erupted, lamproite rocks are subjected to rapid erosion and are rarely preserved for times in excess of 30 million years.

Kimberlite exploration has been concentrated in areas of cratons whose roots contain diamond-bearing lherzolite or eclogite horizons. The xenoliths in kimberlite and lamproite can be used to define the paleogeotherm, which provides the data to determine whether the kimberlites are from an on-craton or off-craton source. Kimberlites are inferred to have deep-seated structural controls on their emplacement, but these structures are rarely apparent. The diatremes typically occur in areas where tensional stresses dominated, and a spatial relationship to diabase dike swarms or continental extensional volcanism (such as flood basalts) is common. This is the case in the Lac-de-Gras kimberlite field, which is cut by the Mackenzie dike swarm. As a result, many kimberlites occur on gentle, broad uplifts or regional warps, or on the periphery of structural basins. In Angola, kimberlites are emplaced along faults or at fault intersections. In Botswana, kimberlite emplacement appears to have been controlled by the intersection of two sets of regional anticlines. The Mesozoic intrusions in Liberia, Angola, South Africa, Botswana and Brazil seem to be related to the opening of the Atlantic Ocean and the breakup of Gondwanaland (Fig. 4.4).

A restricted scale of control is also evident in the form and distribution of kimberlite and lamproite intrusives. The initial emplacement of kimberlitic magma into the base of continental lithospheric plates is mainly controlled by lithospheric fractures, but the emplacement of kimberlite within the upper crust is frequently controlled by pre-existing

Table 4.1 Kimberlites And Related Rocks Of North America

#	Locality	Type	Reference
Canada			
1	Somerset Island, NWT	K	Fipke et al. (1990)
2	Mountain Diatreme, NWT	K	Fipke et al. (1990)
3	Saglek, Labrador	K?	Collerson (1976)
4	Aillik Bay, Labrador	La,K?	Hawkins (1976)
5	Castigon Lake, Quebec	C?	Dimroth (1970)
6	Chicoutimi, Quebec	La	Janse (1984)
7	Ile Bizzard, Quebec	A	Fipke et al. (1990)
8	Bachelor Lake, Quebec	K, La?	Dawson (1967); Watson (1967a)
9	Picton & Varty Lake, Ontario	K	Arima & Kerrich (1988)
10	Kirland Lake, Ontario	K	Fipke et al. (1990)
11	Michaud Township, Ontario	K	Watson (1973)
12	Coral Rapids, Ontario	La, K?	Brown et al. (1967)
13	Hearst, Ontario	K	Nixon (1987)
14	Keith Township, Ontario	K	Watson (1973)
15	Wawa, Ontario	La	Mitchell & Janse (1982)
16	McKellar Harbour, Ontario	A	Platt & Mitchell (1982)
17	Sturgeon Lake, Saskatchewan	K	Fipke et al. (1990)
18	Golden Cluster, B.C.	K,L,	Fipke et al. (1990)
19	Cranbrook Cluster, B.C.	K,B	Fipke et al. (1990)
20	Lac du Gras, NWT	K	This Report
United States Of America			
21	North Montana	K,L	Mitchell & Hawkesworth (1984); He & McGee (1984)
22	Iron Mountain, Wyoming	K	McCallum et al. (1975)
23	State Line, Colorado/Wyoming	K	Fipke et al. (1990)
24	Green Mountain, Colorado	K	Meyer & Kridelbaugh (1977)
25	Mule Ear, Moses Rock, Utah	K	McGetchin & Silver (1970); Stuart et al. (1972)
26	Garnet Ridge, Arizona	M	Watson (1967b)
27	Buell Park, Arizona	M	Roden & Smith (1979); Smith (1979)
28	Green Knobs, New Mexico	M,K	Smith (1979)
29	Riley County, Kansas	K	Brookins (1970 a,b); Berendson et al. (1985)
30	Murfreesboro, Arkansas	L	Fipke et al. (1990)
31	South Eastern Missouri	La?	Mansker (1973)
32	W.Kentucky & S.Illinois	La?	Koenig (1956)
33	Elliot County, Kentucky	K	Boliver (1972), Hunt & Boliver (1972); Garrison & Taylor (1980); Schulze (1984)
34	Norris Kimberlite, Tennesse	K	Meyer (1975)
35	Mt. Horeb, Virginia	K?	Young & Bailey (1955); Sears & Bilbert (1973)
36	Masontown, Virginia	K	Alibert & Albarede (1988); Hunter & Taylor (1984)
37	Dixonville, Pennsylvania	K	Hunter & Taylor (1984)
38	Syracuse, New York State	La?	Apfel et al. (1951)
39	Lake Ellen, Michigan	K	McGee & Hearn (1984)

Codes for Rock Types:
K = Kimberlite
L = Lamproite
La = Lamprophyric
A = Alnoite
B = Basaltic
C = Carbonatitic
M = Minette

(After Fipke et al., 1990)

Figure 4.3 Kimberlites and related rocks of North America. From Fipke, (1990).

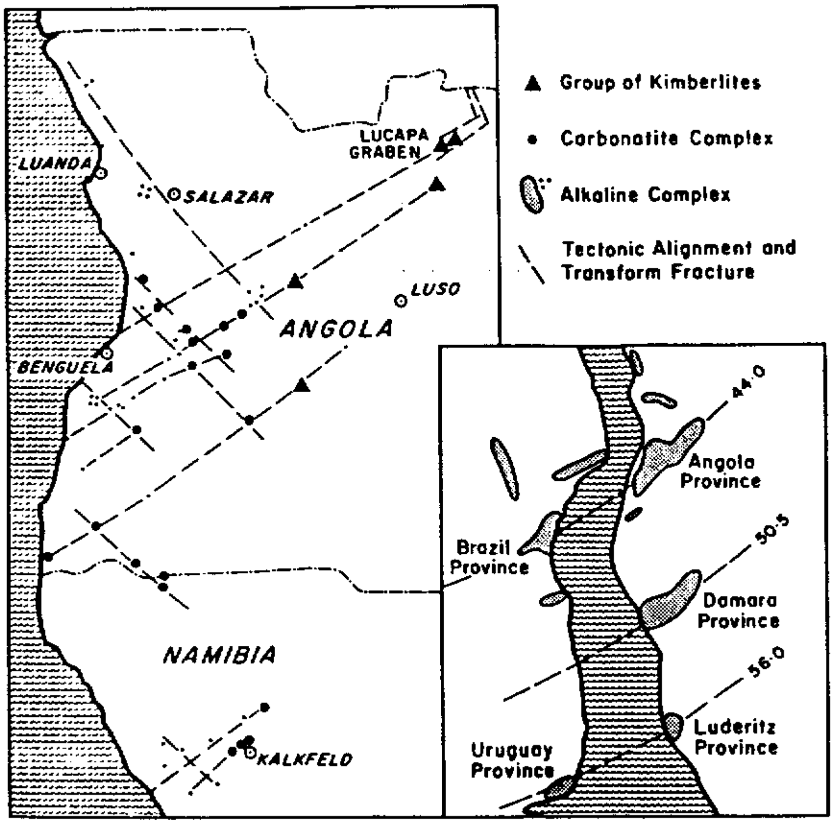


Figure 4.4 Association of kimberlites and related rocks with transform fractures. (From Atkinson, 1989)

joint and fracture patterns, which can mask the fundamental fractures. For example,in Saskatchewan, kimberlites occur near the intersection of northeast- and northwest-trending topographic lineaments and subtle aeromagnetic anomalies, and along the boundaries of subsurface basement terranes. Abrupt changes in the direction of river and lake channels occur near some of the pipes. The Saskatchewan kimberlite clusters appear to be on trend with the alkaline igneous province of central Montana, which is of Eocene age (44 to 64 million years old). An understanding of the basement tectonics along with the intrusive and deformation history of the sedimentary cover is the key to determining possible controls of kimberlite emplacement.

5. A REVIEW OF DIAMOND EXPLORATION METHODS

5.1 General guidelines

The following section is adapted from Fipke et al. (1990). Other summaries have been presented by Atkinson (1989), Fipke (1990), Jennings (1990), and Gibbins and Atkinson (1992).

Recent advances in knowledge about diamonds and their host rocks have focused attention on the extraordinary variability of diamond deposits. Kimberlite, historically the major source rock of diamonds since its discovery more than 100 years ago, is so extremely wide ranging in physical and chemical properties that there is still debate about a simple definition of the rock (see above). The recognition of a second important primary source of diamonds in olivine lamproite has expanded this diversity considerably. A lamproite such as Argyle, which produces one-third of the world diamond production by volume (but not by value: see below), is a demonstration of this diversity of source.

A variety of exploration techniques can be advantageously integrated into a diamond exploration program. These include the application of petrology, mineralogy, geochemistry, geophysics, geobotany and remote sensing. In terms of exploration for diamonds, several important points are (adapted from Fipke et al., 1990):

(1) The macro-diamonds in economic deposits are derived from occasionally highly diamondiferous peridotitic and eclogitic rocks formed in the lithospheric upper mantle.

(2) Both peridotitic and eclogitic diamonds occur in every known diamond deposit world-wide.

(3) Peridotitic diamonds, which are more common than eclogitic diamonds (see above), are interpreted to be Archean in age (> 2,500 Ma).

(4) Eclogitic diamonds are also old, but show a range of ages, all apparently younger than peridotitic diamonds (990 – 2,700 Ma).

(5) As diamonds are released into their new host volcanic rock by the disaggregation of pre-existing diamond-bearing rocks, other constituent minerals of those rocks will also be incorporated into the magma.

(6) Some of these minerals, notably garnet and chromite, have very distinctive compositions and their presence can be detected and used as a strong diamond indicator.

(7) In a single diatreme, it is reasonable to expect a roughly linear relationship between the amount of diamond present and the abundance of fragments of the host diamondiferous rocks from the mantle.

(8) Such comparisons can never be expected to be quantitative between different diatremes, because of variations in diamond grade of the eclogite and peridotite sources and the additional reductions in diamond content due to resorption and assimilation of the diamond source rock in the magma.

(9) Microdiamond counts in the kimberlite or lamproite may show correlation with macrodiamonds, but may not give good correlations with macro-grades in general, due to the decoupling effects of resorption followed by subsequent growth of microdiamonds.

(10) The heavy mineral (geo)chemistry approach gives the earliest possible signal about the diamond potential of the source in an exploration program (except for finding diamond itself).

(11) Macro-diamonds are likely to be found in regions of Earth with thick, cool lithospheric keels, where old rocks are preserved. Consequently, continental cratons may be prime targets if they are thick enough. Complex structural settings where overthrusting preserves old keels to survive underneath younger rocks are not ruled out.

5.2 Prospecting

Geological prospecting for float or bedrock kimberlite and lamproite, particularly in regions of varied rock types, and where other mantle rocks (peridotites, etc.) is exposed is important. Because of the relatively soft and friable nature of kimberlite and lamproite, it is likely that many will be found to underlie lakes or muskeg in northern Canada (Jennings, 1990). The setting of the Point Lake pipe in the NWT supports this generalization.

5.3 Heavy mineral tracing

The most widely used technique in exploration is heavy mineral sampling, and the resistant macrocrysts of garnet, chromite and ilmenite are sought in streams and gravels world-wide as evidence for the proximity of kimberlite. This has been the practice for more than 100 years, since kimberlite was first recognized as a host for diamond in South Africa. The targets should be the best G-10 garnets (harzburgitic) (Dawson and Stephens, 1975, 1976; Gurney, 1984), the highest-Cr chromites, the abundance of high-Na eclogitic garnets, the presence of Cr-diopside and the most Mg-rich ilmenites. Many case histories document the reliability and success of tracing these minerals to their bedrock source. The presence of diamond is the best indicator of all because of its extreme hardness and its known ability to be transported for more than 1,000 km; however, as the average grade of diamond in a commercial pipe is 200 times less than the average grade in a Canadian gold mine, ilmenite and garnet are more practical tracers as they are several orders of magnitude more abundant than diamond in kimberlite.

Garnet, ranging in colour from orange to red to dark purple, rarer varieties being green, is a common mineral in kimberlite. Two garnet groups are recognized, the peridotite group is characterized by Cr-rich garnets poor in Ca (Fig. 5.3 is a plot of G-10 garnets from worldwide localities) and the eclogite group is characterized by Ca-rich pyrope garnets with anomalous Na content. Ilmenite with low levels of Fe^{3+} and high levels of Mg and Cr is favourable for diamond association, although ilmenite is generally absent from lamproites. Spinel with high levels of Mg and Cr is favourably associated with diamonds. Chrome-diopside has a diagnostic emerald-green colour, and although it is a somewhat rare constituent of kimberlite, it is commonly used successfully in exploration. Olivine enriched in Cr has also been used successfully as a tracer in the cold climate of Yakutia to trace many kimberlites.

These minerals are sought in stream sediment, eskers, basal till, soil and other secondary deposits. In glaciated parts of Canada, the observed transfer of heavy

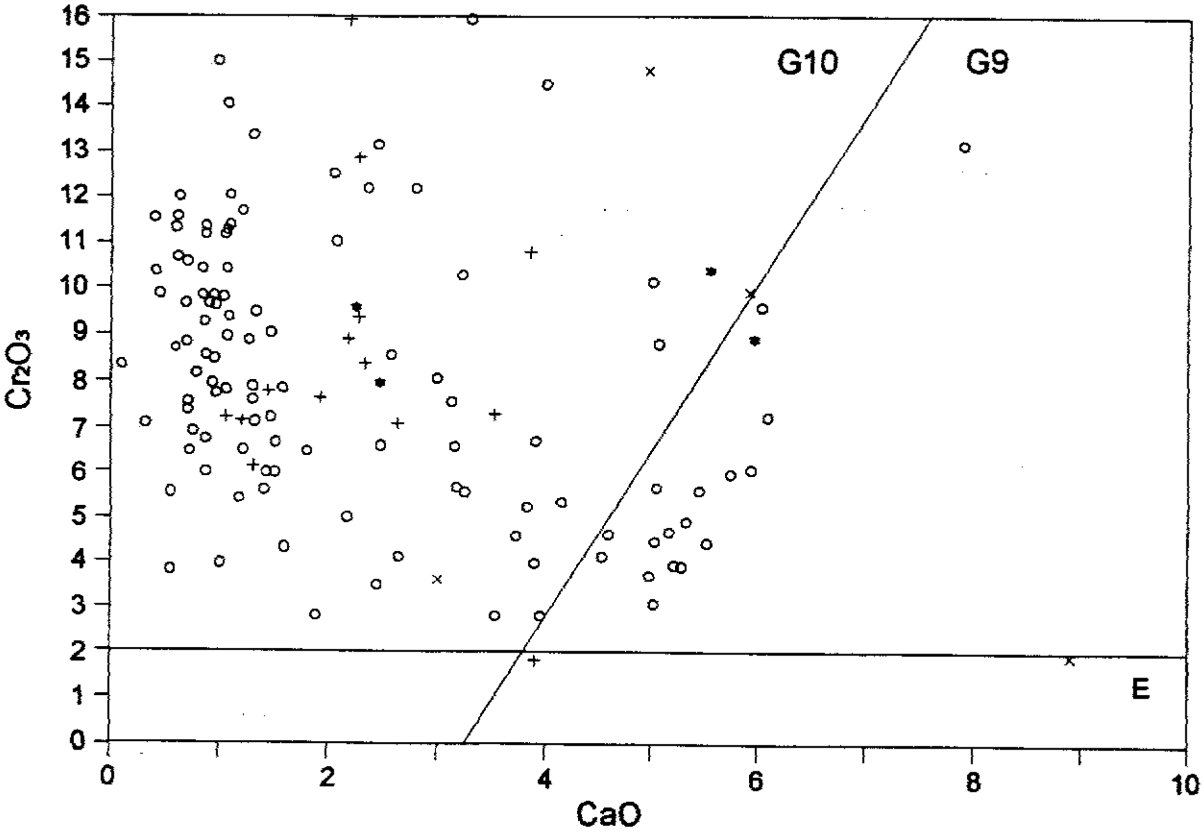


Figure 5.3 A plot of Cr_2O_3 against CaO for peridotitic diamond inclusion garnets from worldwide localities. About 85% of known inclusions fall on the CaO-poor side of the G10/G9 bounding line(Gurney, 1984) in the G10 garnet field. The 2% Cr_2O_3 line marks the boundary between eclogitic garnets (<2%) and peridotitic garnets. Symbols: ○ = South Africa; × = Australia; • = North America; + = Russia; (From Fipke at al. (1990).

minerals from one till to the next underlines the necessity of understanding the glacial history of the region. Placer diamonds have been found by placer miners in sands and gravels near the Yukon River in Alaska (Crooked Creek) and in the Klondike district (pers. comm. G. Dickson, 1992). Their primary sources are thought to be in eclogitic terrane, but have not been identified.

Field methods of processing samples involve gravity separation of the heavy minerals by panning or jigging, and visual observation of the concentrate to identify the tracer minerals. This is effective if the minerals are coarse-grained (greater than 1 mm) and abundant, but laboratory processing is more efficient at finer grain sizes, or if minerals are rare. Laboratory processing uses combinations of Wilfley tables, heavy liquid, electromagnetic and high-tension separations, fusion and acid digestion. A series of mineral concentrate fractions are produced and are searched visually under a binocular microscope for specific indicator minerals or diamonds.

The following is a case history of a heavy mineral survey conducted by Nixon (1980). Although glacial redistribution is cited as an impediment in Canada, the cold climate is an asset as it slows the chemical breakdown of eroded minerals:

"The dispersion of minerals from kimberlites and their disaggregated, deep-seated inclusions has given rise to this most widely used exploration method. In Lesotho, 4,180 duplicate samples (coarse and fine), heavy-mineral, stream-sand samples (plus geochemistry samples — see below) were taken by two teams in two field seasons, representing a sample density of 1.1 per km^2. The coarse samples were concentrates obtained by hand-gravitating circular sieves or screens (aperture 0.5 mm, determined by field experiments), and the fine samples were the panned fine fraction. Bulk sampling with a 4'6" (1.37 m) diameter rotary pan, which would normally be used at scattered major alluvial localities in a primary survey, was restricted to follow-up diamond evaluation work in kimberlites, and in gravels downstream from kimberlites.

Samples were examined under low-power binocular microscopes at the base laboratories, further concentration being unnecessary provided the fines had been panned down sufficiently. The field operators would often pick out indicator minerals themselves; training of personnel to recognize kimberlitic minerals was carried out with little difficulty. The main varieties (described by Nixon, 1980) are red-brown pyrope (discrete nodule suite), purple-red chromium pyrope (depleted lherzolite), ilmenite (coarse, rounded, a few grains with perovskite alteration or cream skin and distinct from the tabular basalt variety), chromium diopside (depleted lherzolite) found closer to source, and a few coarse chromite, enstatite and olivine grains (the latter distinguished from smaller, darker, more ferriferous, basaltic olivine grains which were locally abundant in traps or sills). Indicator minerals persist several miles downstream, even below a small dyke, with the ilmenite/garnet ratio usually increasing. Some 2.5% of the total samples examined proved positive with the identification of the following, in order of decreasing importance: gt, ilm, cpx (Cr diopside), opx, ol, chromite and phlogopite. The ratio of positive indicator minerals found in the two size fractions was:

Both coarse and fine fractions	Coarse fraction only	Fine fraction only
3	5	1

Considering the longer time necessary to examine the fine fractions, it is debatable whether these are worth collecting. This is certainly so where the background has a more complicated mineralogy, or where sedimentary rocks are shedding fine garnet and other grains.

The method was successful in Lesotho, where even small dykes were located, because of the clear mineralogical contrast with the basalts and sedimentary rocks, although small pyropes (probably kimberlitic) were found in some sandstones. The close drainage pattern aided the technique. In other drier areas, e.g. Botswana and East Africa, the sampling (except for large preliminary drainage samples) has to be based on sampling of surface soils along (for example) a 0.5 km grid. Samples of fixed size, e.g. 1 kg, and mesh range, e.g. -4/+16, can be washed in the field and/or separated in heavy liquids in the laboratory. By this method the heavy- mineral "haloes" around kimberlites can be contoured (Mannard, 1968).

The heavy-mineral method has been proved successful in a variety of environments including the Arctic USSR, but difficulties are encountered with glacial redistribution in parts of Canada. Aeolian and alluvial overburden cannot be found and limitations are imposed by some slightly eroded pipes (see below). Rock types which are related to kimberlite, e.g. alnoite, and which contain deep-seated xenoliths, produce a heavy wash of indicator minerals including zircon (but not diamond) which differs only in detail from those of kimberlites (Nixon and Boyd, 1979)."

An example of the treatment methods of diamond exploration samples was given by Gregory and White (1989). In Canada, laboratories which do heavy mineral separations include C.F. Mineral Research in Kelowna, B.C. (used by the Dia Met/BHP Minerals joint venture), OREX Laboratories in Surrey, B.C., Lakefield Research in Peterborough, Canamera Geological in Vancouver, the Saskatchewan Research Council in Saskatoon and the Techdel Laboratory in Thunder Bay. Once minerals such as pyrope garnet or chrome-diopside have been identified visually, they must be analyzed with a microprobe to determine their exact composition, e.g. Cr and Ca to identify G-9 or G-10 garnets.

5.4 Geophysical surveys

Diamond host rocks exhibit several features that are detectable by geophysical methods. Historically geophysical methods were employed in a secondary role in the search for kimbelite pipes. Geophysical surveys are now a primary exploration tool completely integrated with the other disciplines of diamond exploration.

The various geophysical tools have a multitude of applications throughout the exploration and development stages involved in discovering and evaluating diamond host bodies. The methods and tools employed vary from regional airborne surveys through ground based detailed follow-up to three dimensional modelling at the evaluation and development stages. The notes for this seminar focus on the methods employed at the early stages of exploration.

The Yukon presents a particular challenge in the skillful use of geophysics. The land is both glaciated and unglaciated, there is considerable topography and the territory does not have a generous history of diamond exploration providing the experience the exploration professional would typically draw upon.

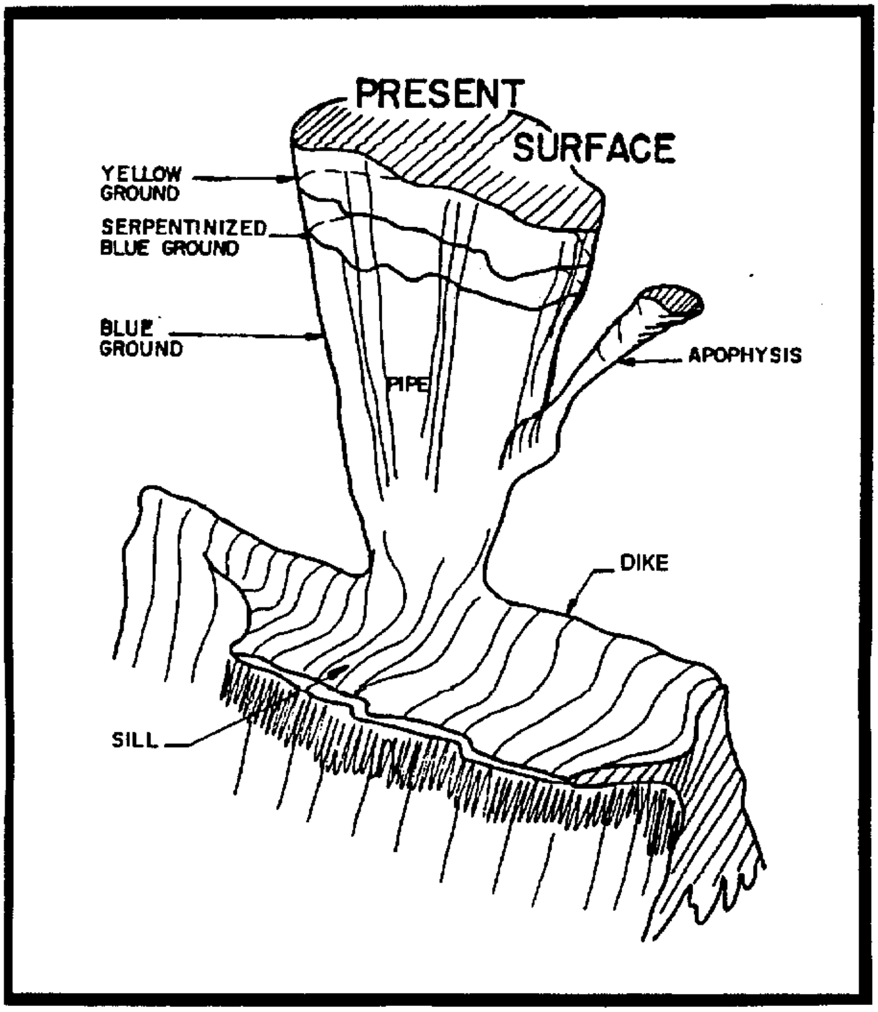


Figure 5.4.1 An idealized kimberlitic occurrence. Three main zones of composition are indicated. (from da Costa 1989)

The detection and mapping of kimberlite and lamproite intrusive bodies by means of their geophysical properties is dependent upon a sufficient contrast between the signal generated by the intrusion and the surrounding host material. The configuration, size and mineralogical composition of the body are all parameters that will derter-mine the response.

Figure 5.4.1, displays an idealized kimberlitic occurrence. Physical configuration and mineral composition are the two key elements governing the geophysical signature.

The roughly oval tapering shape and the possible presence of dikes and or sills provides the spacial model for response prediction to any geophysical method. The long axes may range from less than 30m to over 1500m. Sides of the plug are steep ranging from 50°-70° near the surface to plus 80° at depth. The presence of secondary bodies as illustrated is common and provides for an important geophysical target once a diatreme has been located on the ground.

Compositional differences within a pipe greatly vary its geophysical response. Below the surficial cover, assuming they have not been eroded, the following three zones are found:

> Yellow Ground (2m - >50m) - completely hydrated and oxidized kimberlite, consisting mainly of the clay mineral notronite and montmorillonite.
>
> Serpentinized Blue Ground (20m - >300m) - a transitional zone between fresh kimberlite and yellow ground. It comprises serpentinized kimberlite, which can contain masses of relatively fresh material.
>
> Fresh Blue Ground - fresh kimberlite also know as hardebank.

Yellow ground, being clay rich is more conductive than the underlying serpentinized blue ground, which in turn is less conductive than the deeper fresh kimberlite. Yellow ground has a relatively low specific gravity of about 2.5 as compared with fresh kimberlite with an S.G. of 2.6 - 3.0. It also features a low seismic velocity.

Fresh hard kimberlite typically contains 5 - 10 percent iron as ilmenite and magnetite. This feature often results in the pipe being more magnetically susceptible than the enclosing country rock. Magnetite is mostly converted to limonite in the altered yellow ground significantly lowering the magnetic susceptibility.

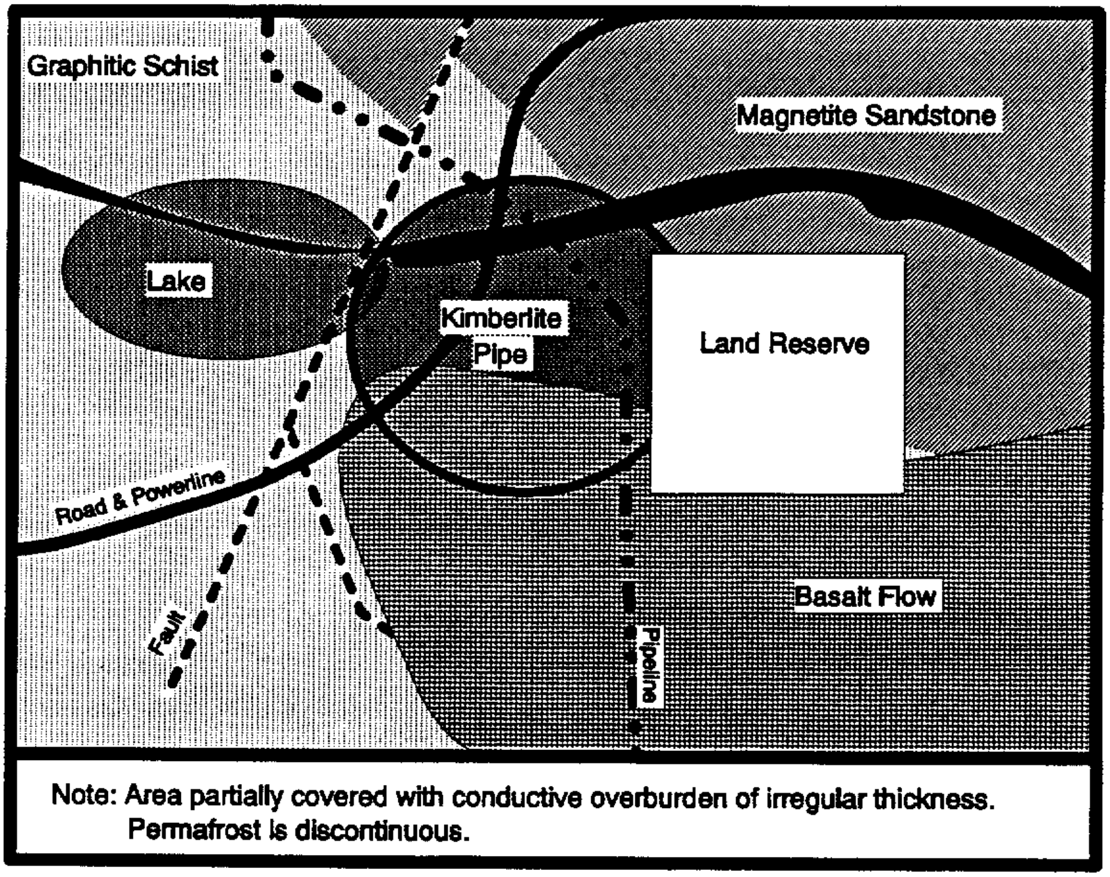
Table 5.4, presents typical values in kimberlite for some commonly employed geophysical properties. The data indicates that a kimberlite pipe should be detectable by gravity, magnetic, electrical, electromagnetic and seismic refraction. methods.

Table 5.4: Typical geophysical properties of kimberlite material and clay.

Material	Density (kg/m^3)	Magnetic Susceptibility (k x 10^6)	Resistivity (Ω·m)	Seismic Velocity (km/s)
Yellow kimberlite	2500	200 - 1000	10 - 20	1.5
Soft blue kimberlite	2620	10 - 20		
Fresh kimberlite	2640 - 2980	1000 - 3000	1000 - 200	
Clay	2000	50 - 630		1.8
Country rock (norite)				
- weathered			260	
- fresh	2930		1500 - 2500	5.6

It must however, be emphasized that diatremes are compositionally very heterogeneous. The variations are due to the emplacement process and nature of host rock ingested, the possible presence of epiclastic kimberlite, and the amount of subsequent erosion and weathering. Two or more intrusive plugs with differing composition can occupy the same body.

Figure 5.4.2, presents a plan view of a non-idealized kimberlite pipe. The real Canadian world seldom provides an ideal setting. This cartoon contains many of the



Note: Area partially covered with conductive overburden of irregular thickness.
Permafrost is discontinuous.

Figure 5.4.2 Plan of a non-idealized kimberlite pipe.

natural and man-made features that will conspire against the hard working diamond explorationist.

The plan view of the Premier Mine (Figure 5.4.3) is illustrated to demonstrate the complexity of actual diatreme geology. The pattern of re-intrusion, wall rock inclusions of large size, and typical inhomogeneity can be seen.

5.4.1 Magnetic Surveys

In unweathered kimberlite the iron oxides contained as magnetite exhibit the magnetic response we would expect, while the ilmenite can be variably magnetic. Ilmenite with a high titanium content has a magnetic susceptibility close to zero. Due to its high susceptibility, magnetite will dominate the magnetic response of the kimberlite. Therefore, the source of a magnetic anomaly over a pipe is located predominantly in the unweathered kimberlite and may be thought of as a vertical cylinder at some depth below the surface.

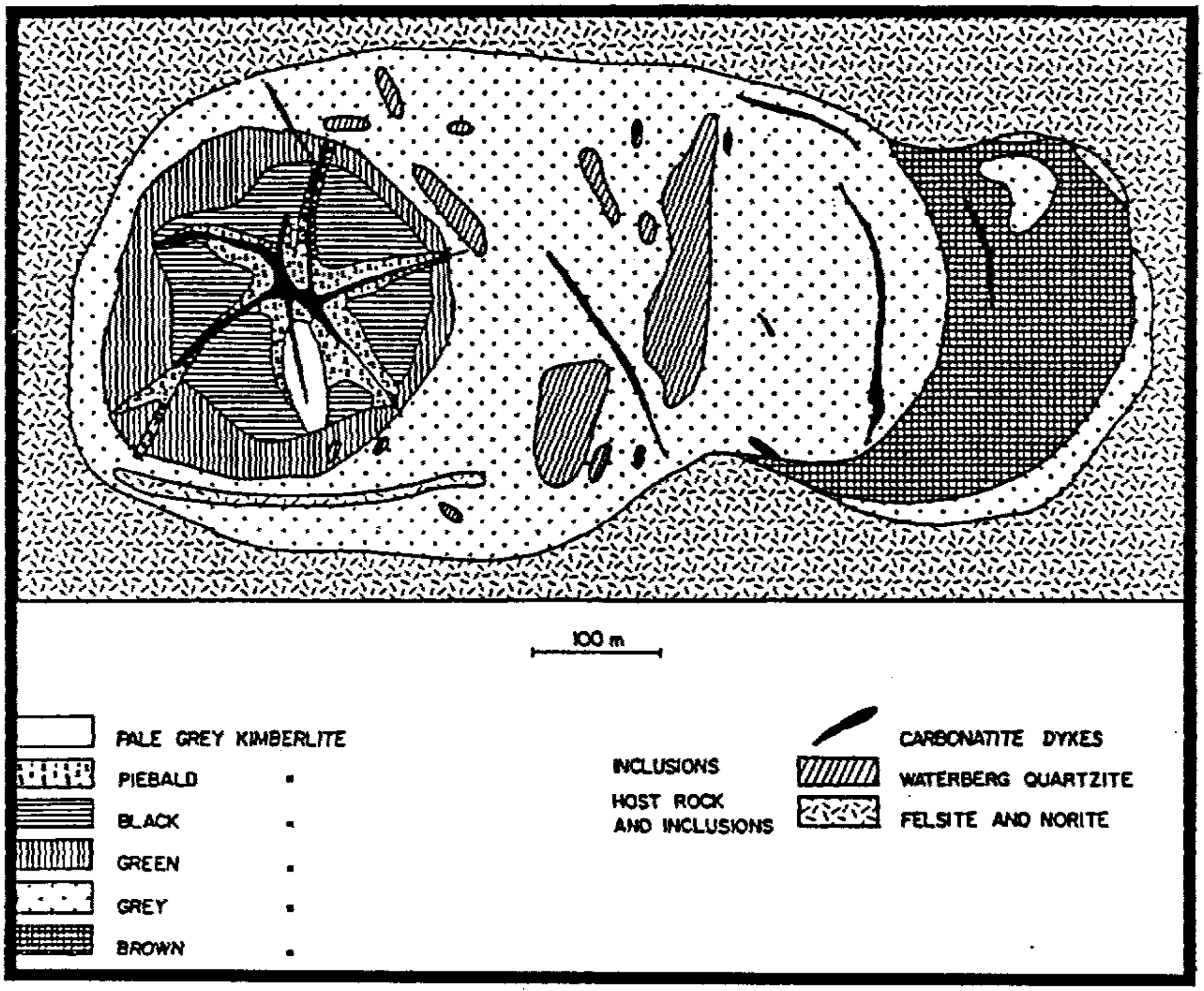


Figure 5.4.3 Plan view 330 m level of the Premier Mine, South Africa.

The clay-rich zone of yellow ground formed at the top of the pipe has the approximate geometrical form of a disc. The near-surface conductive body has a diameter slightly larger than that of the deeper magnetic source (Figure 5.4.4).

An example of the response from a ground magnetic survey over a pipe in Lesotho is shown as Figure 5.4.5. The pipe is intruded into a clean thick sandstone. Hard kimberlite at surface in a body that is in excess of 100m wide in a thick host of low magnetic susceptibility presents an almost ideal setting. Nonetheless, note the dipole type response. This survey was conducted in the late 1960's using a fluxgate magnetometer. A more recent survey with a tighter grid and new instrumentation shows a much more complex response.

Airborne magnetometer surveying provides a similar response to ground surveys. Figures 5.4.6 and 5.4.7 show contoured results over a kimberlite pipe at Lac du Sauvage, N.W.T. The figures are vertical magnetic gradient and total field magnetics respectively.

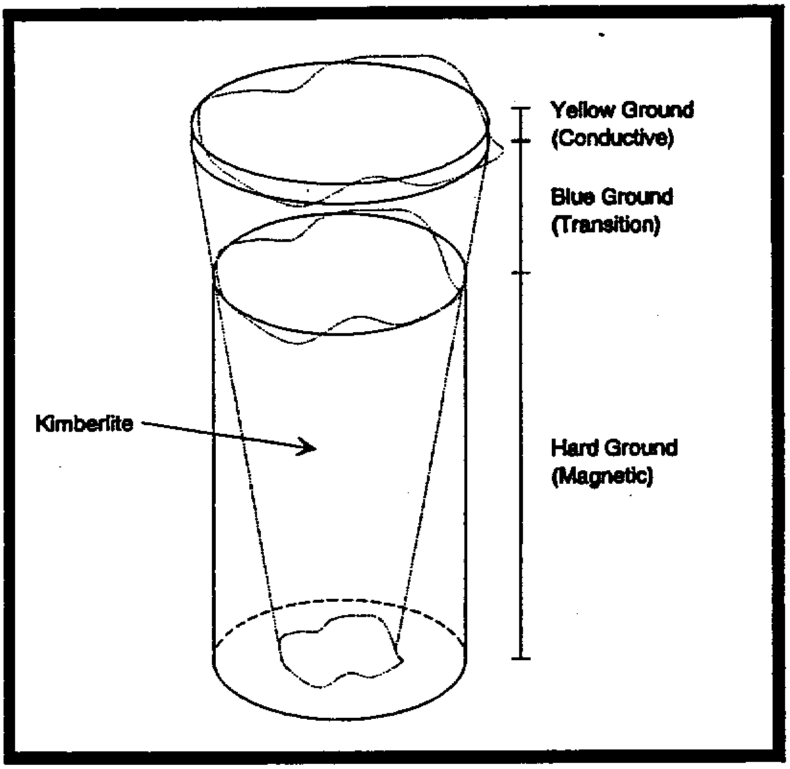


Figure 5.4.4 Model used to predict magnetic response of a nearly circular weathered kimberlite pipe. Note that because of typical tapering at depth, the conductive region is slightly larger in diameter than the deeper magnetic region.

5.4.3 Electrical Methods

Both EM and resistivity methods have application for diamond pipe exploration based upon the conductivity of the clays in the altered yellow ground. The conductive zone acts a a flat lying, thin-sheet or thick-disk conductor.

Figure 5.4.8, shows both EM and magnetic profiles across a pipe. Figure 5.4.9 presents contoured EM results for an adjacent area. The EM surveys show edge effects with the anomalies slightly offset from the magnetic anomalies. Typically a clear magnetic anomaly coincident with a low-amplitude (poor conductor) EM anomaly will be obtained over an exposed or shallow pipe provided yellow ground is present in sufficient thickness. EM can effectively be used to map yellow ground.

Yellow ground, due to its higher conductivity than most host rocks and hard kimberlite is suitable for delineation using resistivity techniques. In Figure 5.4.10, an apparent resistivity contour map over the small Kolo pipe in Lesotho, it can be seen that a resistivity low corresponds to the soft kimberlite, while a resistivity high is present over the less weathered hardebank. The magnetic survey over the same pipe shown in firgure 5.4.5 is more erratic exhibiting more rapid variations than the resistivity data.

Ground based IP techniques are effective in mapping pipe profiles. In kimberlite, yellow ground has a resistivity in the 2 to 5 Ω·m range, increasing to resistivities in the

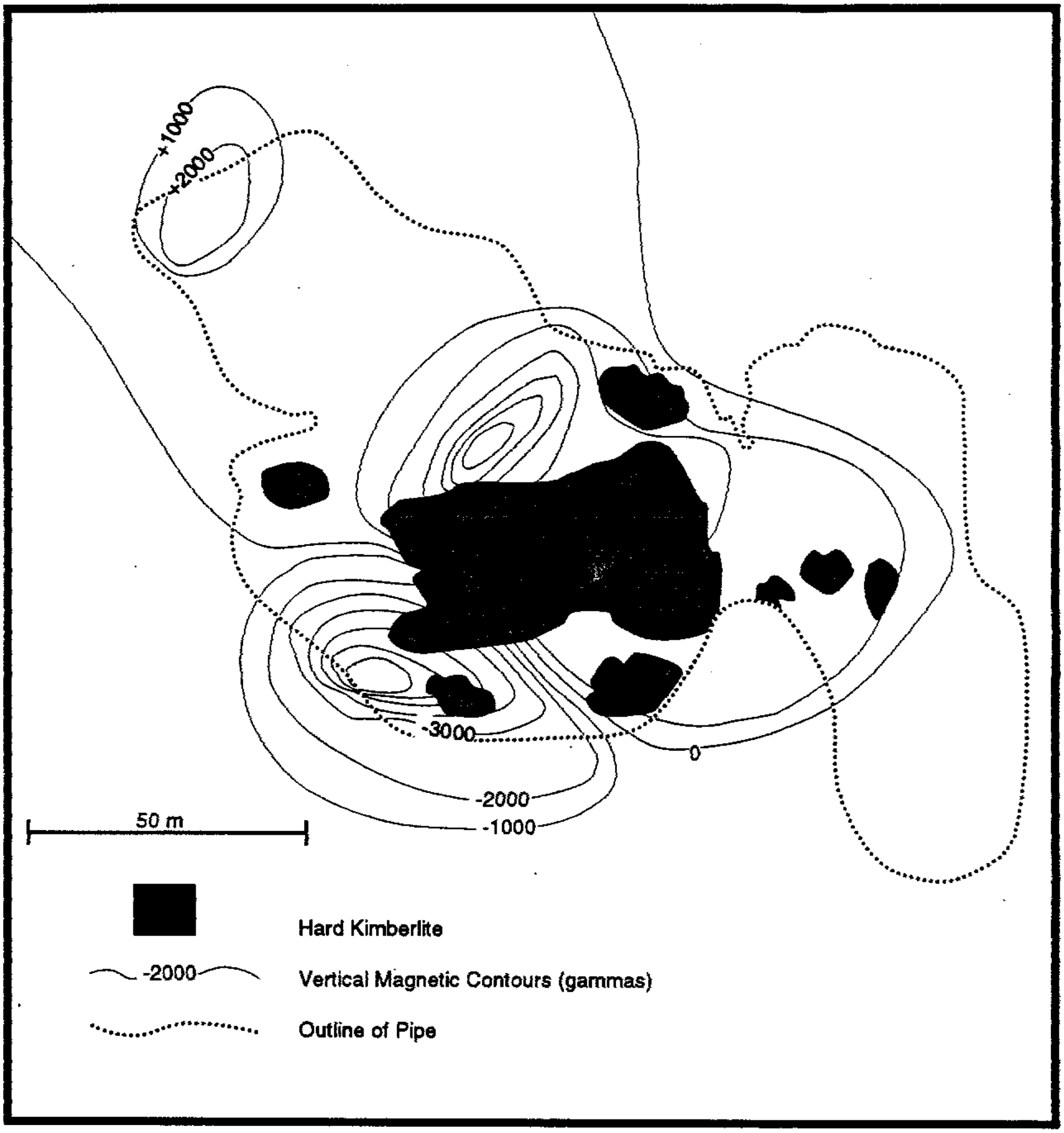
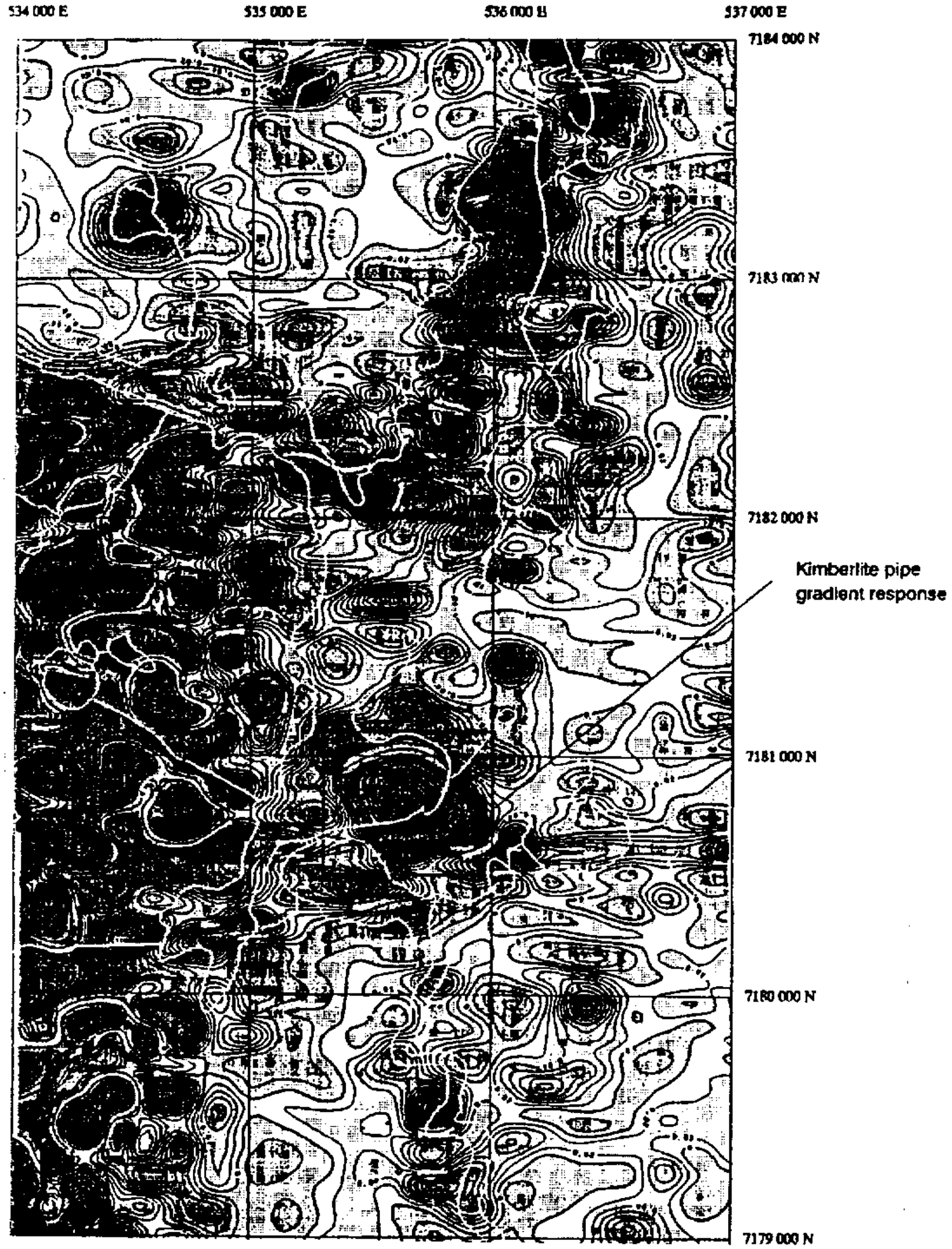


Figure 5.4.5 Vertical magnetic field over Kolo kimberlite pipe. Kimberlite intruded into a clean thick sandstone.

50 to 100 Ω·m range within blue ground, and a further increase to around 500 Ω·m in hard kimberlite. Since yellow ground, blue ground, hardebank weathering is a gradational process there are no sharp resistivity boundaries. Sharp vertical boundaries are visible at the edge of a pipe.

Figure 5.4.11, shows the resistivity response over a kimberlite pipe at Lac du Sauvage, N.W.T. from an airborne survey.



Kimberlite pipe gradient response

Figure 5.4.6 Vertical magnetic gradient, Lac du Sauvage kimberlite, NWT. Map contours are in nanoteslas/metre. White lines are topographic features. Grid squares are 1 km square.

Lines were flown north-south at a spacing of 150 m. Vertical magnetic gradient contour data, measured as the difference between two high sensitivity cesium magnetometers separated by a fixed vertical distance of 3 m, at an average sensor elevation of 30 m. (Compliments of Aerodat Limited)

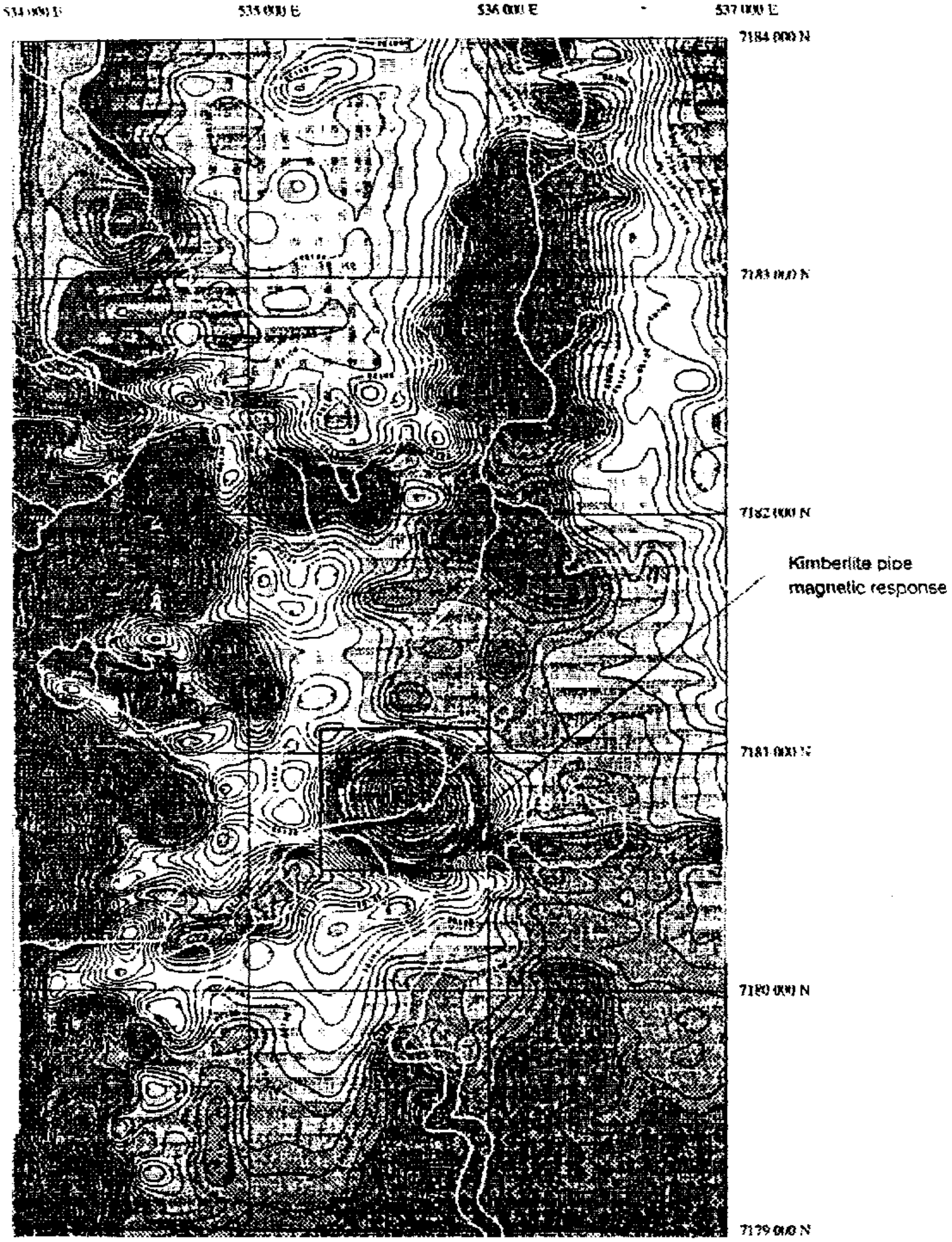


Figure 5.4.7 Total field magnetics, Lac du Sauvage, NWT. Map contours are in nanoTeslas. White lines are topographic features. Grid squares are 1 km square.

Lines were flown north-south at a spacing of 150 m. Total field magnetic intensity contour data collected by a high sensitivity cesium magnetometer at an average sensor elevation of 45 m. (Compliments of Aerodat Limited)

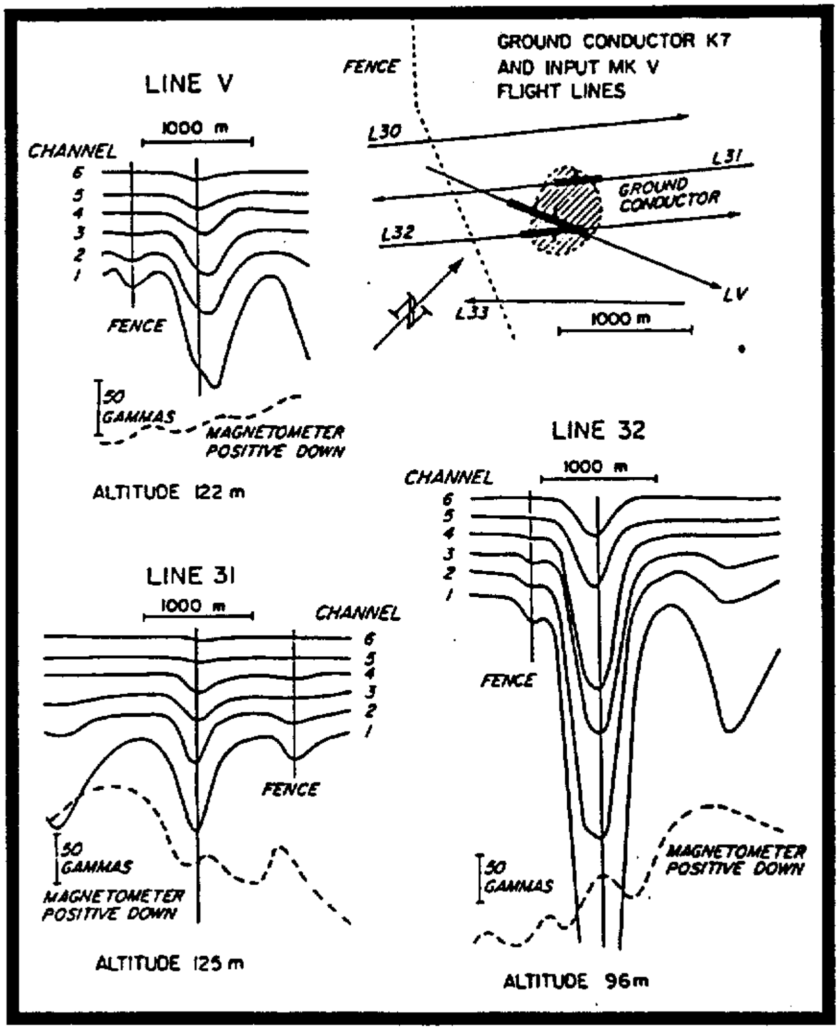


Figure 5.4.8
Airborne EM input and magnetic profiles across pipes K-11 and K-6, South Africa.

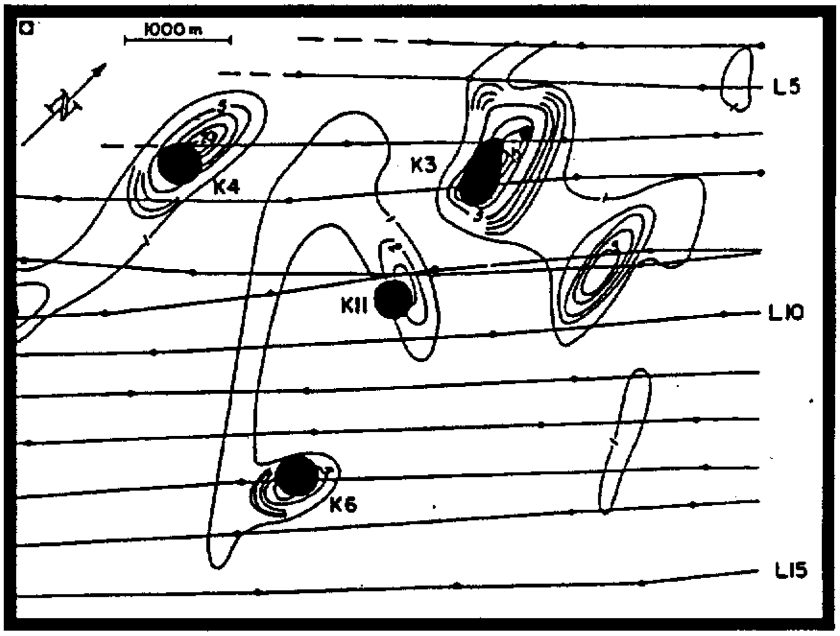


Figure 5.4.9
Input EM amplitude contours over pipes K-3, K-4, K-6 and K-11, South Africa.

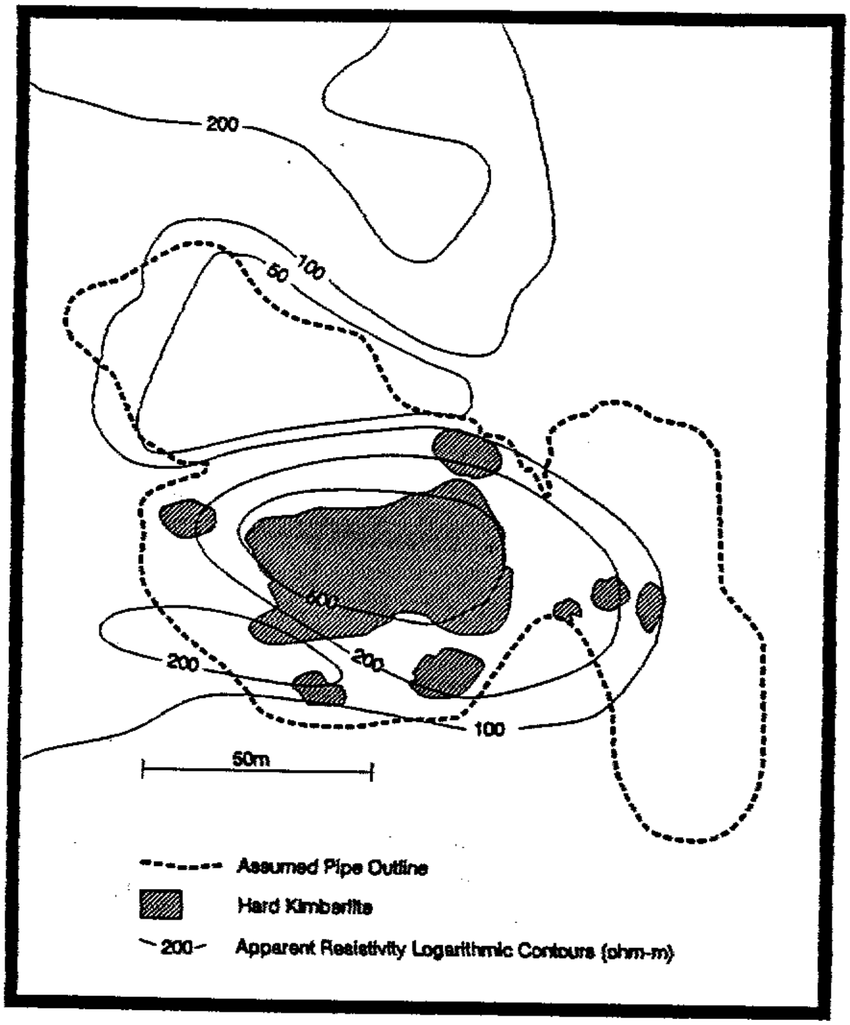


Figure 5.4.10 Logarithmic apparent resistivity contours over the Kolo pipe, Lesotho.

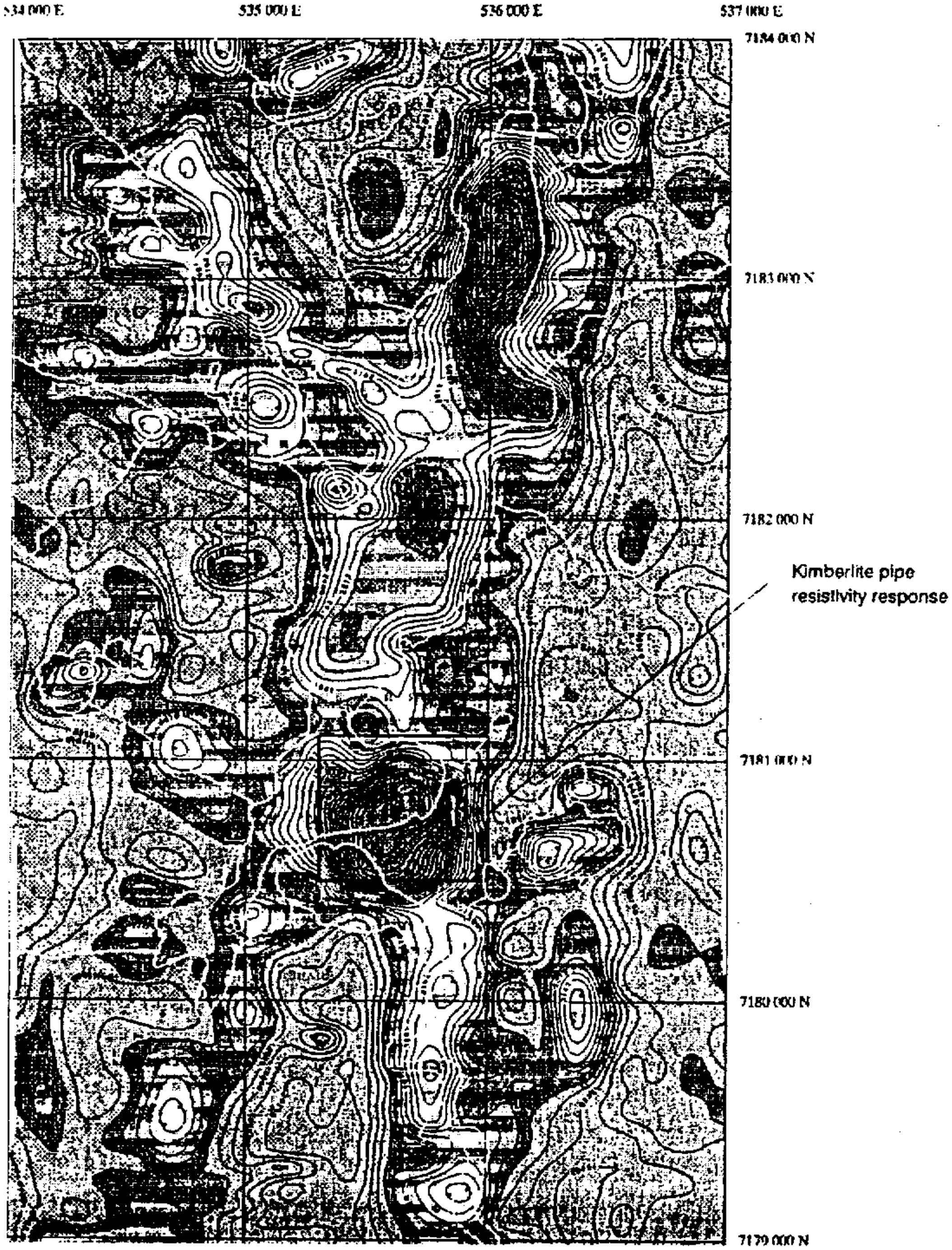


Figure 5.4.11 Apparent Resistivity (32 kHz Coplanar), Lac du Sauvage, N.W.T. Map contours are in Ω m. White lines are topographic features. Grid squares are 1km per side.

Lines were flown north-south at a spacing of 150m. Apparent resistivity calculated from the measured 32 kHz coplanar EM response, assuming a resistive half-space (200m) model. Average sensor elevation was 30m. (Compliments of Aerodat Limited)

5.4.3 Gravity

Weathering kimberlite reduces its density, resulting in negative gravity anomalies. A Bouger profile may be a characteristic negative superimposed on a large positive anomaly over weathered kimberlite pipes. Gravity is useful for detecting "blind" kimberlites or extensions of known bodies.

Figure 5.4.12, shows a gravity profile as compared with a plan view of a kimberlite pipe and its associated satellite pipe. This simplified gravity profile enhances the presence of a smaller intrusion within the main pipe and the presence of a buried kimberlite at the western boundary ot the satellite pipe.

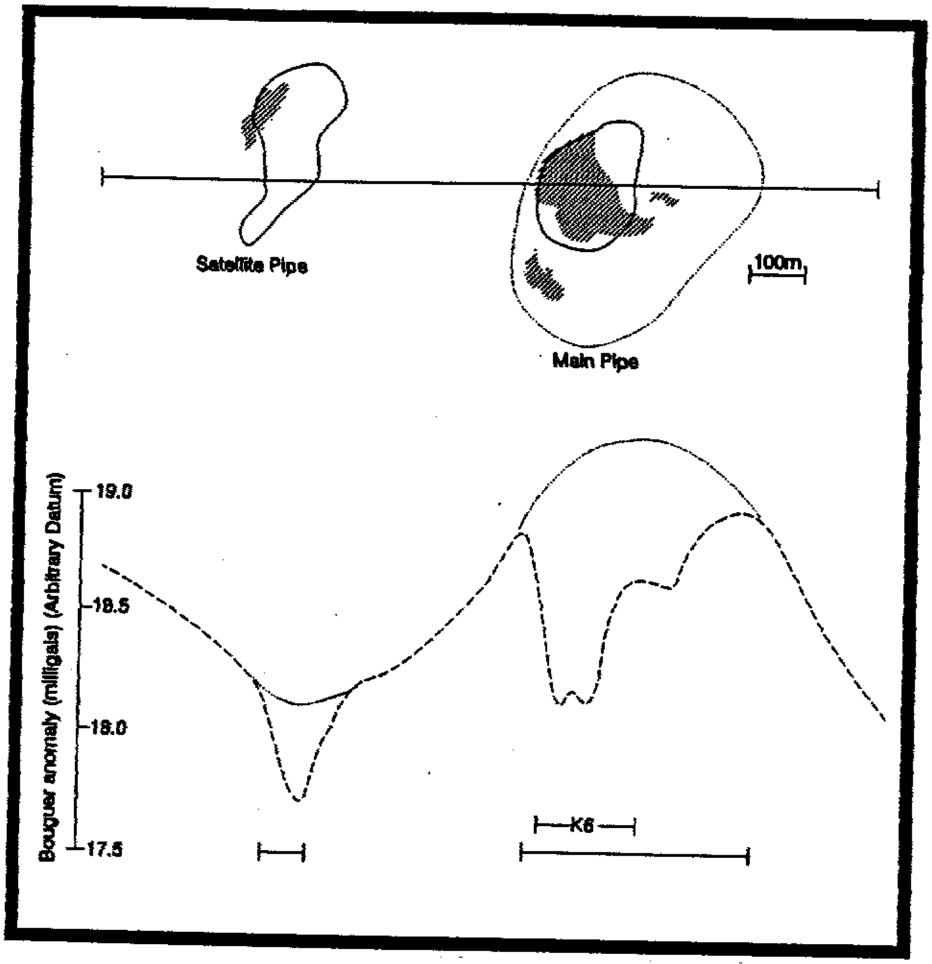


Figure 5.4.12 Simplified gravity profile of K-6 intrusion, South Africa

5.4.4 Seismic Surveys

Shallow seismic refraction has been employed with only limited success in profiling kimberlite bodies. Figure 5.4.13, compares a seismic refraction line over the Palmientfontein kimberlite pipe in South Africa with resistivity and magnetic profiles. The pipe boundary is detectable as a distinct velocity contrast. Velocities for yellow

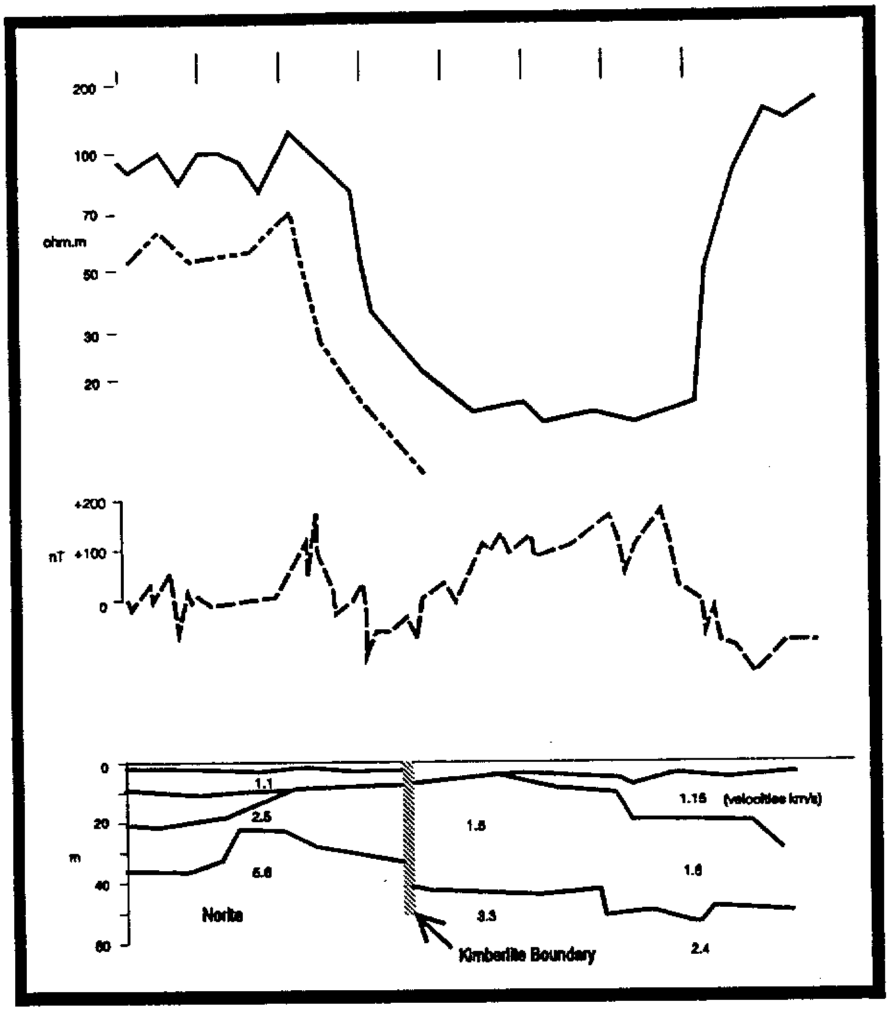


Figure 5.4.13 Resistivity, seismic and magnetic profiles across the Palmienfontein pipe, South Africa

ground and serpentinized kimberlite vary within the pipe, indicating differential weathering.

5.4.5 Ground Penetrating Radar

Ground penetrating radar techniques have the potential to recognize the velocity differences resulting from compositional differences in a fashion similar to seismic surveys. The radar energy is more effective at the shallow depths that are the focus of kimberlite and lamproite exploration. The application of radar to pipe evaluation should also prove more cost effective than seismic surveys.

5.5 Remote sensing

Remote sensing has a wide variety of applications in exploration for diamonds. Remote sensing refers to the science and art of obtaining useful information about an object, area or phenomenon through the analysis and interpretation of image data acquired by a device that is not in contact with the object, area or phenomenon under investigation. Such a definition includes geophysical surveying as described in the previous section. The term remote sensing is however, more generally applied to the study of images aquired by aircraft or satellite.

The basic element of remote sensing is the collection of the reflected energy from the earth's surface which is compiled to form an image. The image may be collected optically, such as standard aerial photography, or digitally. Energy sources can be passive (the sun) or active (generated from the aircraft or satellite).The reflected spectral energy may be collected for a wide range of wavelengths. The wavelengths typically collected for remote sensing purposes range from visible light through to microwave. Image analysis employs both visual and digital processing for interpretation.

The applications of remote sensing to diamond exploration depend upon: the nature of the geological problem, the scale of the target, the geological environment and the geomorphological environment. For all applications the resolution of data must be compared with the target size to determine the smallest target that can be recognized. For example using Landsat TM data bands 7,5,3, individual pixels are 30m per side. A circular target 100m in diameter will be represented by only 4-6 complete pixels.

The most obvious application of imaging is the direct detection of kimberlite or laproite. This technique can be successfully applied where the host outcrops at surface. Visual examination for prospective targets of the right size, shape, and texture is an excellent technique although somewhat painstaking. It is also possible to digitally search an image for the reflectance spectra of the target. When this is done for several bands and the prospective targets are visually reviewed by a geologist, the technique is effective at assessing large areas quickly for positive indications of either kimberlite or laproite.

In terrain where the target is obscured by glacial cover or water,indirect techniques may be applied depending upon the specific geological and geomorphogical parameters of the area. The indirect application of remote sensing techniques requires some ingenuity. For example, it has been suggested that the lakes overlying the kimbelites in the Lac de Gras area are deeper than other lakes in the area due to the recessive nature of kimberlite. The deeper lakes will be colder and thus recognizable using a thermal band. Limiting factors to this technique will be the generally poor resolution of thermal data and restricted windows for data collection.

In a Canadian setting, the widest area of application for remote sensing in the search for diamonds is the mapping of surfical geology. Satellite imagery has been succesfully used to map surficial sediments on a regional basis. The digital product has several advantages over convential surficial mapping. 1) It greatly reduces field costs and production times; 2) The digital product is easily and quickly revised; and 3) The digital map provides an excellent base for other digital data sets such as geophysical surveys and regional heavy mineral surveys.

Remote sensing has long been apposite to structural mapping and interpretation. In the search for diamonds and diamond hosting rocks, satellite images are useful at quickly depicting structual expression over a wide range of scales, from continental to regional. The recent addition of radar images to the geologist's remote sensing arsenal has enhanced this tool.

Little is published on the application of remote sensing to the exploration for diamonds and essentially nothing is published for the Canadian north that is applicable to the Yukon. In spite of the limited amount published remote sensing is employed on a world wide basis and has particular application to the Candian north with its large areas with limited infrastructure. With the present exploration "rush" in Canada, new remote sensing techniques applicable to diamond exploration will undoubtably emerge within the near future. The suitability of remotely sensed images for integration with other geoscience and geographic data sets is also increasing its general application to mineral exploration, diamond or otherwise.

5.6 Geochemical surveys

Kimberlites and lamproites characteristically have high Ti, Cr, Ni, Mg, Ba, Nb anomalies in overlying soils. Dispersion patterns can be complex, and dispersion areas can cover several hundreds of square kilometres. The following paragraphs are from an overview of geochemical surveys given by Nixon (1980):

"The ultrabasic nature of kimberlite, reflecting its mantle origin combined with a volatile component of incompatible elements, has produced a characteristic two-fold subdivision of elements which has been noted by Dawson (1967) and Harris & Middlemost (1970). The ultrabasic component includes Cr and Ni, and the incompatible element component: K, Rb, Sr, Cs, Ba, Nb, Ta, P, and LREE.

In Lesotho, pilot geochemical analyses for Rb, Cs, Be, Sr, Ba, Y, La, Zr, V, Nb, Ta, Cr, Co, Ni, Cu, Zn, Pb, B, Ga, Sn, P, Ce, Nd, Th and U were carried out on lowland sedimentary rocks and highland basalts to determine elements with a contrast. It was borne in mind that kimberlites could intersect and assimilate buried formations possibly high in elements not found at the surface. Nb was the most promising indicator (together with Ta if sensitive neutron activation analysis methods are used). Kimberlite values ranged from 80-250 ppm for Nb and 4-12 ppm for Ta. Although Cr and Ni are found in country-rock basalts, it was thought that the high levels found in stream sediments below kimberlites were sufficiently encouraging provided that total fusion methods were used. Further tests carried out in trial areas on 307 stream sediments split into 5 size fractions indicated that the optimum sieve size was 80 BSS. For further plotting purposes, threshold values T (median + 2 x standard deviation) were calculated from the results of a trial batch of 523 samples taken over the largest geological unit, the basalt area. Mean values in ppm were Ni, 73; Cr, 94 and Nb <10. These were plotted on 1:50,000 scale drainage maps as a worm diagram in terms of 1-1.5T, 1.5-2T, 2-4T, and >4T (T for Ni, Cr and Nb was taken as 90, 360 and 10 ppm). In case sulphide mineralization occurred in the area, base metals were also analyzed.

Collection of 17,100 samples (2.7 per km^2) was carried out at the same time as the heavy-mineral survey but the results were less useful. Cr and Ni, although indicating some kimberlites, also gave anomalies that were stratigraphically controlled and governed by "picritic" differentiation within the basalt pile and associated sills. Nb (and Ta) produced significant levels only close to the pipe, where heavy minerals were obvious in the stream sediments.

Although Gregory and Tooms (1969) obtained significant geochemical dispersion patterns near pipes in Colorado, the method has to be viewed in conjunction with the type of country-rock and the proven usefulness of indicator heavy-mineral surveys. Alkaline volcanic rocks such as carbonatites, alnoites and lamproites are rich in incompatible elements (although Cr and Ni are lower than in kimberlites) and hence may also give anomalies."

5.7 Lamproite exploration

Conventional kimberlite exploration techniques are only partially applicable to lamproites. A combination of aeromagnetic and heavy mineral methods was useful in the West Kimberley province of Australia (Argyle pipe) (see Atkinson et al., 1984). A few other case studies are available (e.g. Coopersmith & Mitchell, 1989).

6. DEPOSIT EVALUATION AND ECONOMICS OF DIAMONDS

The evaluation of diamond deposits differs from most other commodities because the return is not only dependent on the quantity of the discrete particles recovered, but is also related to the value of each particle (i.e. individual stones). Therefore, during deposit evaluation, three variables are assessed: the number of diamonds per unit of volume or weight (e.g., ct/tonne), the stone size, and the stone grade. Following the initial sampling, the probability distribution of the diamond frequency is calculated, allowing the determination of the minimum sample size required to obtain a given number of stones.

6.1 Microdiamonds, diamond deposit evaluation

Diamonds range in size from a few microns (1/1,000 of a millimetre) to the largest diamond found (the Cullinan) at 3100 carats. Although diamonds are known not to crystallize in kimberlite as a primary phase, nothing is known about the distribution of diamond-bearing eclogite and peridotite in the mantle, and it is therefore difficult to understand why some kimberlite pipes sample economic quantities of diamond and most do not. Grades of economically viable pipes range from less than 0.04 CM/tonne (0.04 metric carats/tonne, or 4 carats per 100 tonnes) to more than 7 CM/tonne.

Once a pipe has been found, relatively small samples (20-100 kg) can be tested for microdiamond (less than 0.5 mm) content using some form of dissolution or fusion of the kimberlite. This is the approximate size of samples reported on by Dia Met Minerals in their 8 December 1992 announcement (see Introduction). Deakin and Boxer (1989) have shown the use of micro-diamonds to predict commercial grade, by a method which depends on knowledge of the micro/macro-diamond relationship in a pipe. Plotting of either weight or numbers of stones against stone size can be used to predict size distribution of macrodiamond populations. In general, abundant microdiamonds are necessary for the likelihood of an economic deposit, but even low grade pipes can be economic because of occasional large, high-quality, high-value stones.

Because of the minute amount of diamond present in an economic pipe, and because of the random high diamond values present, it is difficult but important to know the true value of production in the current market. A highly efficient recovery process and sufficient tonnage must exist to evaluate grade. A sample parcel of 5,000 to 10,000 carats can be needed to give a good idea of the average value and grade of a pipe (Jennings, 1990). This is why bulk sample operations involving the treatment of several hundred to several thousand cubic metres are required during evaluation work.

At the Argyle pipe, where the mean stone size is 12 stones/carat, reconnaissance sampling was carried out by taking 16 m^3 (38 tonnes) samples on a 100 m grid to detect regional grade variations in a deposit grade greater than 1 ct/tonne (Atkinson et al 1984). Pit sizes were increased to 200-600 m^3 (500 to 1,500 tonnes) to confirm the surface grades. Ore reserves were then determined at the higher-grade southern end of the pipe by diamond-drilling 91 holes of 20 cm diameter on 50 m centres to an average depth of 120 m below ground surface, followed by crushing and processing 20 m-sections of core (about 1.5 tonne each) for recovery of diamonds. Six shafts 2 x 2.4 m in area were sunk to 43-64 m at sites of previously drilled large diameter drill holes to check grade in selected areas.

One of the best reviews of grade-tonnage and other models for diamond kimberlite pipes was presented by Bliss (1992). It offers methods of estimating average diamond size, largest diamond size, tonnage, percentage of industrial vs. gem diamonds, mineral deposit density and the probability that new discoveries can be mined profitably. It predicts, for example, that more than 70 kimberlite pipes will be discovered on the South American Precambrian shield. Once a kimberlite pipe has been discovered, the probability is approximately .005 that it can be worked for diamonds. If a newly discovered pipe is part of a cluster that contains a known diamondiferous kimberlite pipe, the probability that the new discovery can be mined for diamonds is 56 times that for a new discovery in a cluster without a diamondiferous pipe.

6.2 Prices of diamonds and grades of deposits

The following section is an overview of the world diamond situation in October 1992 (adapted from Credit Lyonnais Laing, 1992). The price of rough diamonds varies widely, from less than US$1.00 per carat for low-quality industrial diamonds to more than US$1,000 per carat for top-quality large gem stones. Overall, gems fetch an average price of US$250/carat, approximately 10 times the average price for near-gem stones, which in turn fetch approximately 10 times the average price for industrial diamonds (Table 6.2). Lamproite diamonds are of poorer quality than typical kimberlite diamonds, as the majority of lamproite stones are grey, yellow or brown industrial diamonds. However, gem-quality stones at Argyle are highly sought after; a review of the diamonds from the Argyle mine was presented by Grice and Boxer (1990).

Table 6.2 Current price of stones, from Johnson *et al.* (1989), updated for estimated price increases.

Category	Value (US$/ct)	
	Range	Typical
Large gems (> 2ct)	700+	850
Medium gems (0.45-2ct)	250-500	300
Small gems (< 0.45ct)	50-300	125
Near-gems	5-150	25
Industrial diamonds	1-150	21

The mix of stones is therefore critical in assessing the economics of any diamond deposit. The grades of diamond deposits are measured in terms of carats/tonne, but quality as well as quantity is important. Economic alluvial deposits tend to have low grades between 0.05 and 0.30 carats/tonne, but the overall quality of stones is better as the poorer stones have been broken down and worn away. The value per carat of alluvial deposits is relatively high at around US$225 to US$350/carat. In contrast, an economic kimberlite pipe will have a higher grade, generally around 0.4 to 1.0 carats/tonne, but the overall quality of the stones will be lower, probably around which has taken place. In many pipes, but not all, diamonds are concentrated more towards the top of the diatreme, and grade becomes more erratic at depth and commonly lower. A pipe which has suffered little erosion from rivers, glaciers and in-situ weathering is more likely to be economic than those which were subjected to erosion through millions of years; however, even this generalization is contradicted by the original Kimberley pipe, for which only 1/35 of the original kimberlite diatreme is estimated to have been preserved (see Gurney et al., 1992), and was mined for decades.

6.3 Known major deposits

A minority of the 5,000 known kimberlite or lamproite occurrences of many sizes in the world are diamondiferous, perhaps only 15% (this excludes alluvial diamond deposits). Only about 50 to 60 pipes can be classified as being or having been economic or nearly economic, i.e. about 1% of occurrences. Only about 12 major pipes are being mined today. During the past 50 years, only 5 pipes have been discovered which have been brought into production and yield more than 3 million carats/year. These are Udatchnaya in Siberia, Argyle in Australia, Orapa and Jwaneng in Botswana and Venetia in South Africa (which has just been put into production). An account of the Russian diamond exploration history was given by Strnad (1991). The 15 largest known pipes (by surface area) are listed in Table 6.3.

Table 6.3 Surface area of the 15 largest economic kimberlite pipes.

Deposit	Country	Surface Area (hectares)
Mwadui	Tanzania	146.0
Orapa	Botswana	106.0
Camafuca Camazombo	Angola	67.5
Catoca	Angola	66.2
Jwaneng	Botswana	54.0
Talala	Zaire	50.0
Argyle	Australia	45.0
Premier	South Africa	32.0
Zarnitsa	Yakutia	21.5
Udatchnyy	Yakutia	20.0
Massif I	Zaire	18.6
Finsch	South Africa	17.9
Latseng-la-Terai	Lesotho	15.9
Latlhakane	Botswana	11.6
Venetia	South Africa	11.4

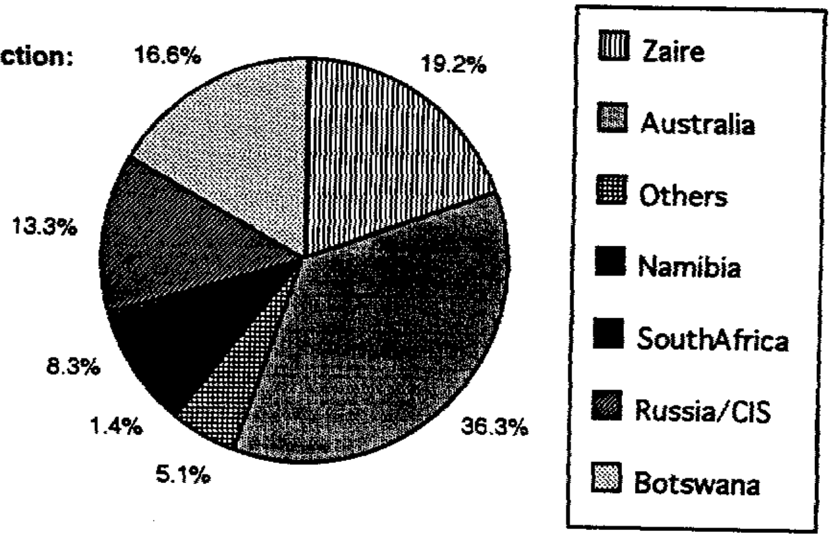
The Point Lake pipe has a surface area of around 20 hectares (50 acres). However, the area of a pipe is not necessarily a measure of reserves and production potential. The largest known pipe, Mwadui, produced just under 1 million carats/year at its peak. In contrast, the Argyle pipe, about 1/4 of the surface area, produces more diamonds in one year (35 million carats) than Mwadui yielded in its whole producing life of 50 years. Similarly, the new Venetia mine in South Africa is designed to produce almost 6 million carats/year from a pipe only 8% of the size of Mwadui.

6.4 World diamond production

Just 5 countries made up the bulk of production in 1991, namely Australia, Zaire, Botswana, Russia (through the Republic of Yakutia) and South Africa (Figure 6.4.1). In total, these accounted for more than 90% of total carats produced. The largest producer by far in terms of caratage was Australia with 36 Mct (million carats) from a world total of just under 100 MCt. Zaire, Bostwana and Russia produced 13 – 19 Mct each, and South Africa produced just over 8 Mct.

Figure. 6.4.1

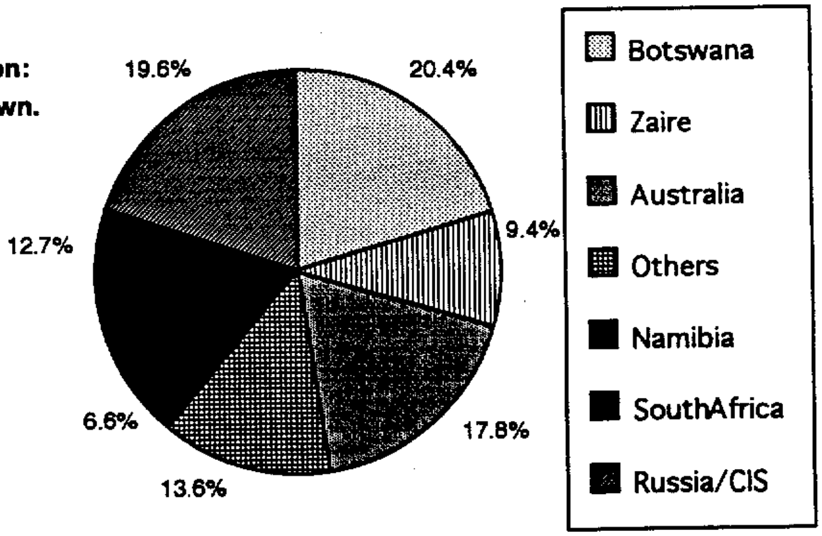
World Diamond Production: Main Producers.



The picture changes when the total value of production is considered (Figure 6.4.2). The current mix from world diamond production is around 15% gem, 40% near-gem, and 45% industrial. From estimated average prices of stones in each category, revenues were approximately 79% from gems, 19% from near-gems and only 2% from industrials. Using estimated average prices, the highest revenues were received by Botswana, closely followed by Russia. Both had total production worth approximately US$900 million, or 20% of world diamond production by value. Australia had approximately US$800M or 18% of production by value, as only 5% of the massive production output is of gem stones. South Africa had around US$600M or 13%, and Zaire had around US$400M or 9%. Although Zaire's production is mostly from alluvials, it is an exception in that the stones are not of good quality. In terms of value, Namibia is significant, with around US$300M or 7%, with a production that is 95% gem stones.

In the 1960's, world diamond production was around 40 to 45 Mct per year. This increased to 45-50 Mct/year in the 1970's before a major increase to more than 100 Mct

Figure. 6.4.2
World Diamond Production: Estimated Value Breakdown.



by 1990. The rapid growth in the 1980's was the result of the opening of major mines in Botswana, and particularly to the coming onstream of the Argyle mine in 1986.

The growth of the near-gem market has been a feature of the past 20 years. Before the 1970's, virtually all poorer-quality stones were sold for industrial use. But with the development of low-cost cutting and polishing in Bombay, the near-gem market has seen rapid growth. Near-gem production grew from around 1.5 Mct in 1970 to more than 40 Mct in 1990, and Bombay is now by far the largest cutting centre in the world in terms of volume, with more than 70% of the rough stones cut. In terms of value, the Bombay market is smaller, at just more than 20% (about US$1 billion) of the estimated total value of rough stones in 1990.

6.5 The marketing of diamonds

In 1991, the retail market for diamond jewellery had a total value of US$39 billion, from the sale of about 50 million individual pieces. The diamond value was about 18% of total retail value, the rest being precious metals used as setting, labour, and other value-adding costs. The diamond market is dominated by De Beers Consolidated Mines and the Central Selling Organization (CSO), who control approximately 80% of the rough diamond supply and thus have a major influence on the end market price. Australia, Botswana, Namibia, South Africa, Russia and Tanzania market their production through the CSO.

The CSO acts as a cartel for these diamond producers, with the stated aim of "maintaining price stability by matching supply with demand". This has generally been successful for the more than 60 years since the establishment of the CSO, as the price of diamonds has not been reduced in nominal terms during this period. Diamond prices in real terms have exceeded the retail price index by an average of 2.5% per year for the past 20 years (Fig. 6.5).

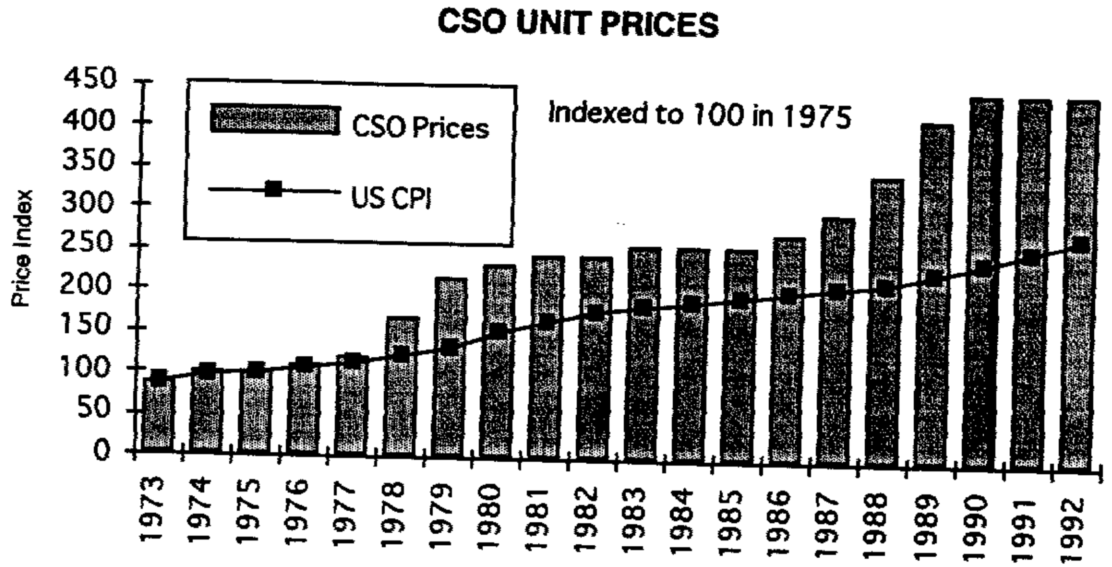


Fig. 6.5 CSO unit prices, indexed to 100 in 1975 (from Credit Lyonnais Lang, 1992).

In practice, the CSO and De Beers have bought surplus diamond production in periods of weak demand in the jewellery markets, and sold off the stockpile as demand picked up. The CSO and De Beers have come under financial pressure periodically because of their need to finance a large stockpile during weak diamond markets. This was the case in the mid-1970's after the first oil-price shock, which hit the demand for diamond jewellery. High inflation in the late 1970's saw diamonds being considered as hard assets, with consequent strong demand and rapid price increases. The situation changed in the 1980's as worldwide inflation subsided, and De Beers had difficulty controlling the diamond market as both demand fell and a greater supply of diamonds came from selling an increased stockpile. The mid-late 1980's saw a strong recovery of the diamond market. However, with the current weak state of western economies and a fall in demand for diamond jewellery, De Beers is now again under pressure. The cyclical problem is being added to by increased supply from "illicit" diamond production in Angola and the potentially huge supply of diamonds from Russia (Whitley, 1992).

7. YUKON GEOLOGY AND YUKON EXPLORATION POTENTIAL

Kimberlite occurs in the Mackenzie Mountains on the NWT side of the Yukon-NWT boundary, in at least two pipes, the Mountain diatreme, which contains diamonds (Godwin and Price, 1986) and the Coates Lake diatreme (Gibbins and Atkinson, 1992). The Mountain diatreme is the largest of a small cluster of 4 kimberlites of Silurian age that were emplaced into Cambrian to Early Ordovician shelf carbonates of the Mackenzie Platform, near the shelf edge. This setting is similar to that of the more than 40 diatremes known in southeastern British Columbia. Diamond exploration in the

Cordillera has been reviewed by Dummett et al. (1987). Alluvial diamonds have been recovered by placer operations in Alaska and in the Klondike district, and indicator minerals have been sporadically reported from several areas of Yukon.

The question of whether Yukon is a favourable prospecting region must be addressed by applying all of the usual criteria in diamond exploration. The first and most important control is the presence (or possible presence) of an Archean or Early Proterozoic lithospheric root, i.e. thick, cold continental basement. The buried Canadian Shield underlies more than 50% of Yukon, and little is known of its age and nature west of the Cordilleran orogenic front (see Figs. 7.1 and 7.2). The existence of cratonic basement which is sufficiently cool to have formed and stored diamonds cannot be ruled out from present knowledge, and the occurrence of kimberlite along the NWT boundary, well within the Cordillera, increases the potential for all of the autochthonous platform cover to host kimberlite pipes. This includes all of Yukon east of the Tintina fault, and that part of the ancient North America margin west of the fault in southern Yukon in the Pelly Mountains. The potential of this region is considered high.

To the west of the Tintina fault, the nature of the deep crust in the accreted portion of the Cordillera, mainly in western Yukon between the Tintina and Denali faults, is less clear. Some evidence exists that at least part of this area may be underlain by old crystalline basement of continental thickness: the Sr^{87}/Sr^{86} line crosses the Cordillera in this region (Armstrong, 1988; see also Fig. 7.2); other parts are likely thinner and younger crust of oceanic origin beneath which no mantle root has had time to become established. The terrane west of the Denali fault is the youngest-accreted part of Yukon, and as such would appear to hold the lowest potential for economic diamondiferous pipe emplacement.

The structural control of deep faults and other lineaments that can be linked to at least some diatremes world-wide is clearly potentially present in Yukon. The Tintina trench, a site of long-lived or repeated faulting on the scale of the entire crust or even the lithosphere, fits all the criteria noted in other lineaments associated with kimberlites world-wide. To a lesser extent, related parallel or splay faults, and faults intersecting the Tintina or splay faults at high angle may also have helped to let kimberlite magmas through. Finally, relatively little is known of the nature and affinity of many ultramafic rocks in Yukon, as in most of the northern Cordillera. The "Alpine" type ultramafics are assumed to be the main or only group present. However, because of their relative abundance, and the variety of their petrology, it is possible that some unusual occurrences may be misidentified and may include kimberlitic or lamproitic phases.

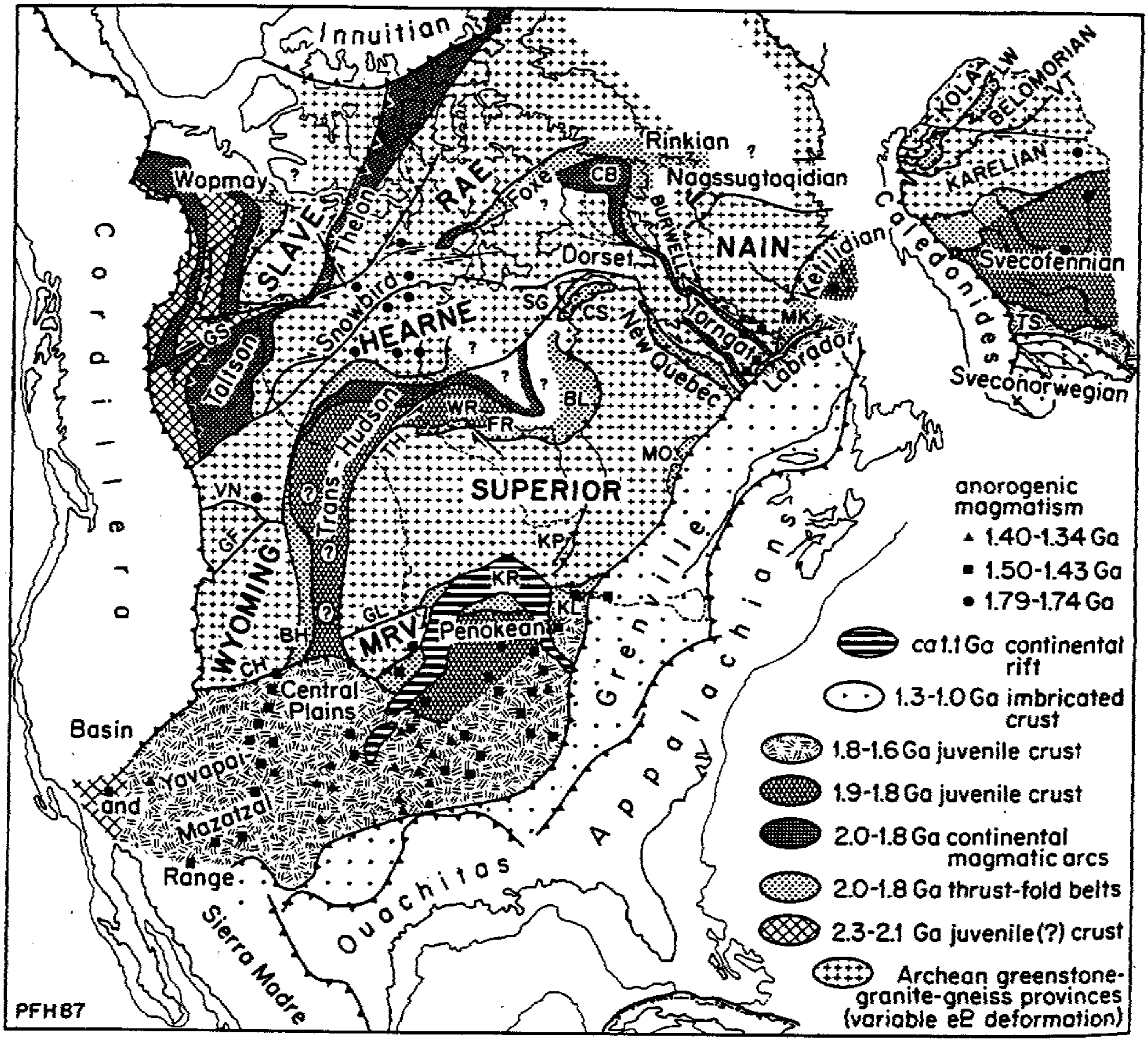


Figure 7.1 Map of the Precambrian elements of the North American craton (platform cover removed) and Baltic shield. Upper case names are Archean provinces; lower case names are Proterozoic and Phanerozoic orogens. BH, Black Hills inlier; BL, Belcher fold belt; CB, Cumberland batholith; CH, Cheyene belt; CS, Cape Smith belt; FR, Fox River belt; GF, Great Falls tectontic zone; GL, Great Lakes tectonic zones; GS, Great Slave Lake shear zone; KL, *Killarney magmatic zone*; KP, Kapuskawing uplift; KR, Keweenawan rift; LW, Lapland-White Sea tectonic zone; MK, Makkovik orogen; MO, Mistassinin and Otish basins; MRV, Minnesota foreland; SG,Sugluk terrane; TH, Thompson belt; TS, Trans-Scandinavian magmatic zone; VN, Vulcan tectonic zone; VT, Vetrenny tectonic zone; WR, Winisk River Fault. From Hoffman (1989).

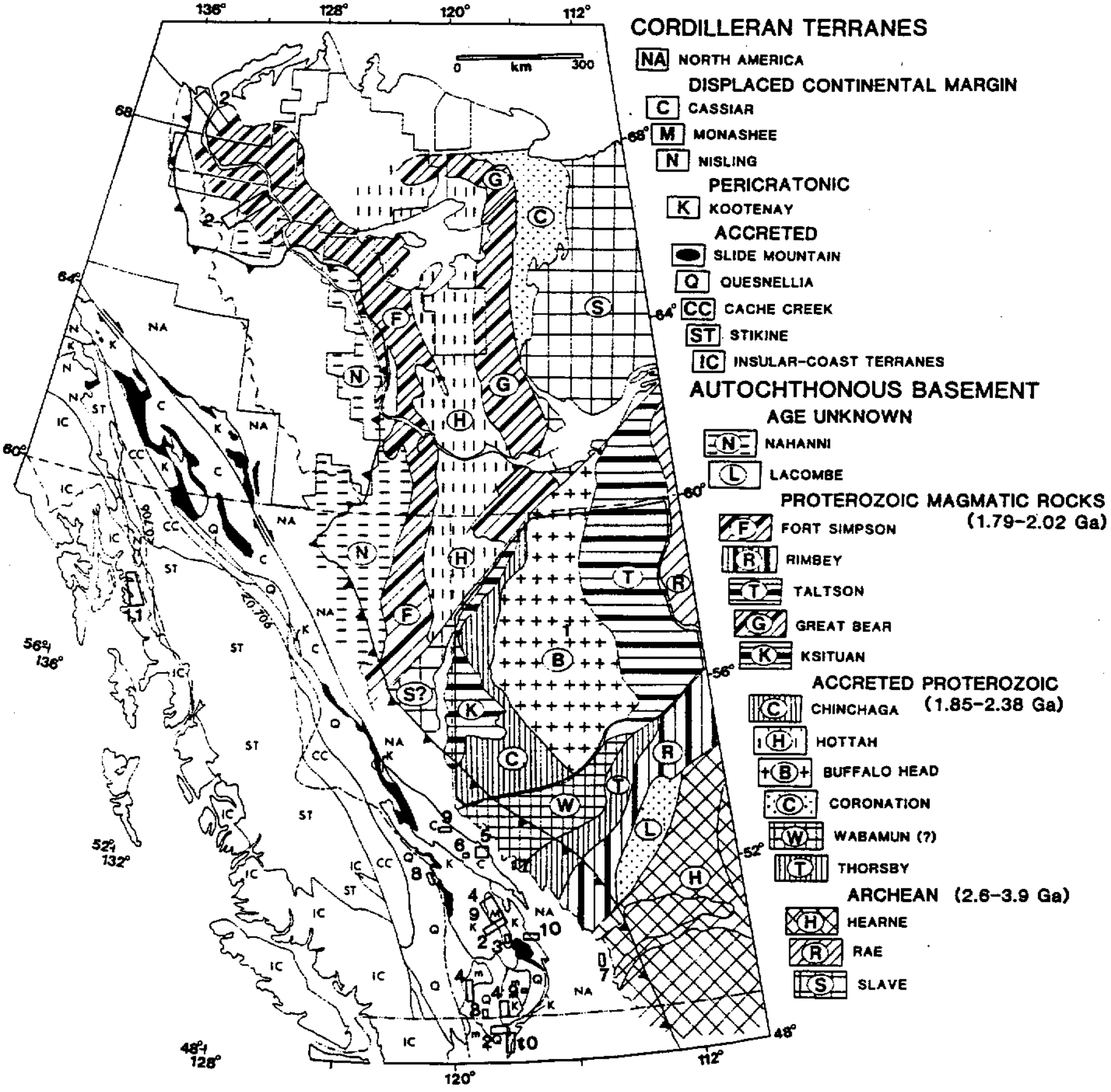


Figure 7.2 Compilation of autochthonous basement domains along the east margin of the Canadian Cordillera and simplified Cordilleran terrane map. The boxed areas north of 60° delineate the limits of aeromagnetic data used to define basement domains. m, undifferentiated high-grade metasedimentary gneisses, which may comprise displaced continental margin rocks, locally interleaved with rocks of pericratonic accreted terrane affinity. The Sr_i=0.706 is modified from the Cenozoic 0.705-0.707 "isopleth" of Armstrong (1988), (from Ross, 1991).

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