Pergamon

Explor. Mining Geol., Vol. 4, No. 2, pp. 127-140, 1995

0964-1823/95 $9.50 + .00

0964-1823(95)00003-8

# Petrology and diamonds

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*Received October 27, 1994; accepted January 18, 1995.*

**Abstract** — Petrology and the necessary genetic terminology, or meaningful classification of rocks, may seem somewhat of an academic pursuit, but it is essential if the origin and relationships of different rocks are to be understood. Petrology, therefore, has an invaluable role to play in modern diamond exploration programs. These roles range from area selection to defining prospecting methods and priorities through to evaluation and mining. Group 1 and 2 kimberlites and lamproites, the only known primary sources of economic quantities of diamond, have been shown to be petrogenetically distinct rock types. Although the magmas forming these rocks only act as a transporting agent for diamond, the differences between these and other rock types have important implications for diamond exploration programs. Other petrographically similar, but petrogenetically distinct, rock types are often encountered during diamond exploration. These rocks appear to be of low potential for carrying economic quantities of diamonds and it is important to distinguish these rocks in order to limit the amount of follow-up work undertaken on them. Correctly classifying and interpreting the geology of such rocks, however, is not a straightforward task. The textural and mineralogical classification and the near surface emplacement of kimberlites and lamproites are also important factors in exploration and evaluation. The uses of petrology in exploration can now be illustrated using examples from the rapidly rising number of known kimberlites in Canada. Lamproites and Group 2 kimberlites are rare and have yet to be discovered in Canada.

## Introduction

The sparkle of diamonds seems to go far beyond diamond sales. It seems to affect all those who are involved with the many different facets of the diamond world. The mention of petrology generally has the reverse effect and its impression on people could perhaps be compared with a piece of coal, interestingly also known as black diamond (American Geological Institute Glossary of Geology, 1987). Coal, another type of carbonaceous material, however, has many valuable uses, often more basic than those of diamonds. Similarly petrology has many important uses in the geological aspects of the diamond industry.

Petrology deals with the origin, occurrence, structure and history of rocks (as defined in the American Geological Institute Glossary of Geology, 1987). Diamonds occur in a variety of natural rocks including those of sedimentary, metamorphic and igneous origins (e.g., review by Helmstaedt, 1994). The uses of petrology in relation to diamond investigations, therefore, are wide ranging. Each of these diamond host rocks requires the application of its own branch of petrology. Only rare examples of diamonds are known to occur in metamorphic rocks (e.g., Sobolev and Shatsky, 1990) but no economic deposits of diamonds are known in such rocks. The main host rocks to diamonds at surface are certain volcanic pipes (kimberlites and lamproites) and their mantle xenoliths as well as secondary sedimentary deposits derived from such pipes.

Economic secondary sources of diamonds, including both unconsolidated and consolidated sediments, have been known for over 2000 years being easier to find because they have larger areal extents than kimberlite or lamproite pipes. Since the discovery of primary deposits in the 1800s, the production of diamonds from secondary sources has now declined to some 25% of the total world diamond production (Levinson et al., 1992). Some of these deposits, however, are very significant diamond producers (e.g., Gurney et al., 1991). Each secondary deposit is unique and will require its own particular applications of sedimentary petrology.

The extensive petrological investigations of mantle-derived xenoliths and diamonds themselves (e.g., Nixon, 1987) have dramatically increased our understanding of the origin of diamonds, especially during the 1980s (reviewed by Kirkley et al., 1991; Helmstaedt, 1994). Kirkley et al. (1991) conclude that, as a generalization, most diamonds formed between 900 Ma and 3300 Ma at depths greater than 150 km in the mantle, either in peridotites or eclogites. These rocks must be stored under stable cratons at depths >110 km. The diamonds are then brought to surface as xenocrysts or in xenoliths in the rare magmas which originate deep enough in the mantle, namely kimberlites and lamproites. There is even recent petrological evidence which shows that the Wyoming sub-cratonic keel that stored the diamonds was destroyed after the emplacement at surface of some diamond-bearing kimberlites that derived from, or passed through, that keel (Eggler et al., 1988; Eggler and Furlong, 1991). All these conclusions have a considerable influence on the procedures used in the very important area selection for diamond exploration programs. Most economic diamond deposits occur within stable Archaean cratons or "archons" (e.g., Janse, 1994b; Helmstaedt, 1994; Helmstaedt and Gurney, 1994). The petrological studies of mantle rocks and diamond inclusions are also the basis for the interpretation of the origin and diamond potential of the 'indicator minerals' or mantle-derived xenocrysts, found during heavy mineral sampling. The latter is one of the two main methods used for locating primary diamondiferous deposits, together with remote sensing/geophysics. Recent reviews of the interpretations of indicator mineral data include Gurney et al. (1993) and Griffin and Ryan (1993).

The fact that diamonds occurring at surface are now known to be xenocrysts derived from the mantle prompts some geologists to refer to the volcanic host rocks as "only" (Kirkley et al., 1991; Grant 1994) the transporting agent of diamond from the mantle to the surface. Without these unique volcanic rocks, however, diamonds would rarely occur at the earth's surface. This paper discusses the classification of these volcanic rock types and the uses in exploration of the petrology of primary diamond deposits from which approximately 75% of the recent world diamond production is derived (Levinson et al., 1992). This is particularly relevant to Canada as most of the recent diamond discoveries here appear to be primary kimberlite pipes. Other discussions on the use of different aspects of the petrology of these rocks include Scott Smith (1992) and Mitchell (1991; in press - b).

## Petrological Investigations

Kimberlites, lamproites and similar rock types are complex, often hybrid, rocks. Meaningful conclusions on the nature of bodies investigated during exploration programs, therefore, are not always easily determined. Petrological investigations of any body should always start with the megascopic examination of all the available rocks, typically from outcrop and/or drillcore. If a suite of bodies are known, material from each of the bodies should be included in the investigation. These megascopic examinations should comprise relatively detailed descriptions of the rocks present. Preliminary interpretations can be made but must not replace the descriptions. These preliminary interpretations often change. Mitchell (in press - b) endorses this view by noting that "samples obtained during a grass-roots exploration program of a previously unstudied region cannot be correctly identified as being potentially diamond-bearing or diamond-free merely from macroscopic observations alone".

The results of the megascopic examination should provide the basis for sample selection, a critical part of any such investigation. A representative suite of samples should always be collected. Different types of sampling will often also be required to help solve each different aspect of an investigation, such as rock type classification, mineralogical classification, textural classification, internal geology, prospecting or evaluation priorities, mining problems, microdiamond and indicator mineral determinations, age determinations, matrix mineral chemistry, bulk rock chemistry etc. In complex bodies, any one sample is unlikely to contain all the features required to provide a meaningful interpretation. If a suite of samples is examined from one, or some related bodies, then the series of features derived from different samples is more likely to provide solutions. Examining a single thin section with no associated rock slab is likely to provide a reasonable insight into only the simplest of rock types or problems. The experience of the investigator(s) can be important. There is often an inclination to sample the harder and/or apparently fresher rocks and ignore the more altered material, but the latter may be different and sometimes more significant. For example, in investigations of lamproites the magmatic material is examined while the associated pyroclastics are often ignored although they are usually economically and texturally more important.

Further examination of these samples must include the macroscopic examination of a polished slab as well as the microscopic examination of thin sections. Additional matrix mineral and whole rock geochemistry may be required to augment the petrography. Any petrological investigation must begin with a rock type classification (see below). Subsequent interpretations are often dependent on this classification.

The problems already discussed are often made even more onerous as kimberlites and similar rock types are often very altered. The present mineralogy (often no primary minerals remain) and/or geochemistry can be of little value. Although not an easy task, with experience the petrography of altered rocks is potentially a very powerful tool for seeing through the alteration to allow a better assessment of the primary nature of the rock. The secondary minerals in these rock types often preferentially replace particular primary minerals and remnant textures can often be observed. These problems may be less extreme in Canada than in other more deeply weathered areas such as tropical Africa.

In these types of investigations sample preservation and preparation is often critical. Kimberlites, lamproites and similar rocks are often variable in nature, comprise a very wide range of grain sizes and are altered by both deuteric and surface processes. This makes them different from most other common rock types and special handling is often required (also discussed by Mitchell in press - b). For example the nature of the critical fine kimberlitic groundmass minerals cannot be assessed in many standard thin sections. Thinner sections are usually required.

## Rock Type Classification

The necessary genetic terminology, or meaningful pigeonholing of rocks, may seem somewhat of an academic pursuit but it is essential if the origin and relationships of different rocks are to be understood (e.g., Mitchell, 1994). Kimberlite was the term coined in the late 19th century to describe the newly discovered primary host rock of diamond (Lewis, 1887; 1888) and a later but informal definition of kimberlite was presented by Wagner (1914). Modern definitions started with Dawson (1971) followed by the contemporaneous work of Clement et al. (1977; 1984), Mitchell

(1979; 1986) and various Russian authors. This shows that, despite the continuous mining of kimberlite, it took 100 years to reach a modern, generally accepted, workable definition. More recent work is now succeeding in subdividing kimberlites rather than significantly improving on its definition (Skinner, 1989; Skinner et al., 1994; Mitchell, 1993; in preparation). Group 2 kimberlites have been shown to derive from different parental magmas to Group 1 kimberlites (Smith, 1983; Tainton and Browning, 1991; Mitchell, 1994; in preparation). Mitchell (1994) suggests that Group 2 kimberlites should be considered to be a separate rock type and that they should be given a different rock name; his proposal being orangeite.

Until the late 1970s lamproites were thought to be only academic curiosities with the term being introduced for some unusual rocks in Spain and Wyoming (Niggli, 1923). In the late 1970s diamonds were discovered at Ellendale and then at Argyle in Western Australia (e.g., Atkinson et al., 1984). These bodies have been shown to be lamproites (e.g., Scott Smith and Skinner, 1984; Jaques et al., 1986) and other previously known diamondiferous rocks have been subsequently recognized to be lamproites (e.g., Scott Smith and Skinner, 1984a; Scott Smith et al., 1989; Scott Smith, 1989). Excellent recent reviews of the petrology of kimberlites and lamproites have been given by Mitchell (1986) and Mitchell and Bergman (1991), respectively.

Differences in geographic distribution, near surface emplacement processes and resulting pipe geology, petrography and geochemistry have clearly shown that Group 1 and 2 kimberlites and lamproites have different petrogenetic histories and so warrant classification as separate rock types. Although these three types of magmas 'only' transport the diamonds from the upper mantle to the surface, these rock types must also be considered separately for practical exploration purposes. The differences between these rock types have important implications affecting such aspects as area selection for exploration programs (Janse, 1994b; Helmstaedt, 1994; Helmstaedt and Gurney, 1994), the interpretation of indicator mineral chemistry (GSC Open File, 1989) and the preservation and nature of potential ore reserves (Mitchell, 1991; Scott Smith, 1992).

Group 1 and 2 kimberlites and lamproites are relatively rare and form only a small part of the spectrum of intracratonic magmatism. Some of the other rock types may be petrographically similar to kimberlites and lamproites and contain comparable 'indicator' minerals. These other rock types include minettes, melilitites, alnoites, other ultramafic lamprophyres, katungites, kamafugites, leucitites and even carbonatites. To date such rock types are considered to have a low potential for carrying significant quantities of diamond. Diamonds have been reported from other rock types such as ultramafic and alkaline lamprophyres and alkali basalts but none of them has yielded economic quantities of diamonds (e.g., Nixon and Bergman, 1987; Janse, 1994a). These occurrences are usually poorly documented and have not always been substantiated. A wide range of rock types are encountered during diamond exploration programs and it is important to be able to distinguish potentially diamondiferous rocks that deserve further attention from those which should not require detailed follow-up work. The recognition of low interest volcanic rocks such as rhyolites, andesites and basalts is usually, but not always, relatively simple. Correctly classifying and determining the diamond potential of more kimberlite-like rocks, in particular alnoites and minettes, however, is often not straightforward.

The distinction of rock types is based on established petrological definitions. For these types of rocks the definitions are usually based on characteristic mineral assemblages which reflect the nature of the magma. In addition to the range of modal abundances, these definitions must include the compositions of the constituent minerals as they give further indications about the nature of the parental magmas and therefore the rock type. Kimberlites, and more recently lamproites, were challenging rocks to understand but they are now relatively well understood because considerable effort has been expended in investigating them as a result of their economic importance (see reviews of Mitchell, 1986; Mitchell and Bergman, 1991). Generally accepted working definitions have been developed (Woolley et al., in press) and meaningfully applied in exploration programs. Kimberlites, and to some extent lamproites, are complex hybrid rocks which are unusual in that xenocrystic and cryptogenic minerals comprise part of the diagnostic mineral assemblage. The definitions can very briefly be summarized as follows. Group 1 kimberlites are composed of essential xenocrysts and phenocrysts of olivine set in a matrix which can contain monticellite, phlogopite, carbonate, serpentine, spinel and perovskite. Group 2 kimberlites (or orangeites) are characterized by the presence of common phlogopite (macrocrysts, phenocrysts and groundmass), common xenocrysts and phenocrysts of olivine together with groundmass diopside and some spinel. Lamproites are characterized by Ti-phlogopite, leucite, glass, clinopyroxene, K-Ti-richterite, olivine, sanidine, perovskite, priderite and wadeite.

Other rock types are less well understood and the historic terminology among lamprophyric and alkaline rocks is confusing. There has yet to be some meaningful rationalization of the existing classifications. The plethora of rock terms for these rock types has resulted from: (1) the great petrographic diversity of rocks within a clan (clan, as defined by Mitchell, 1994, is a suite of comagmatic rocks that have been derived from a particular parental magma which has repeated itself in space and time); (2) the development of definitions based on single rocks or bodies which resulted in many locality-based rock names; and (3) the lack of recognition of petrogenetic suites of rocks. The recent rationalization of the lamproite terminology is a good example of overcoming these problems. This lamproite clan includes a wide array of petrographic types which, in the past, have generated many rock names. These rock names were not applied in a uniform way and the existing terms did not cater for the full spectrum of rocks. These features lead to a great deal of confusion. The range of rocks belonging to the lamproite clan have now been recognized and the old rock names are replaced by a mineralogical sub-division or classification (see below) which is based on the modal abundances of the main constituents (Fig. 1). For example a fitzroyite becomes a phlogopite leucite lamproite. Such an approach is less con-

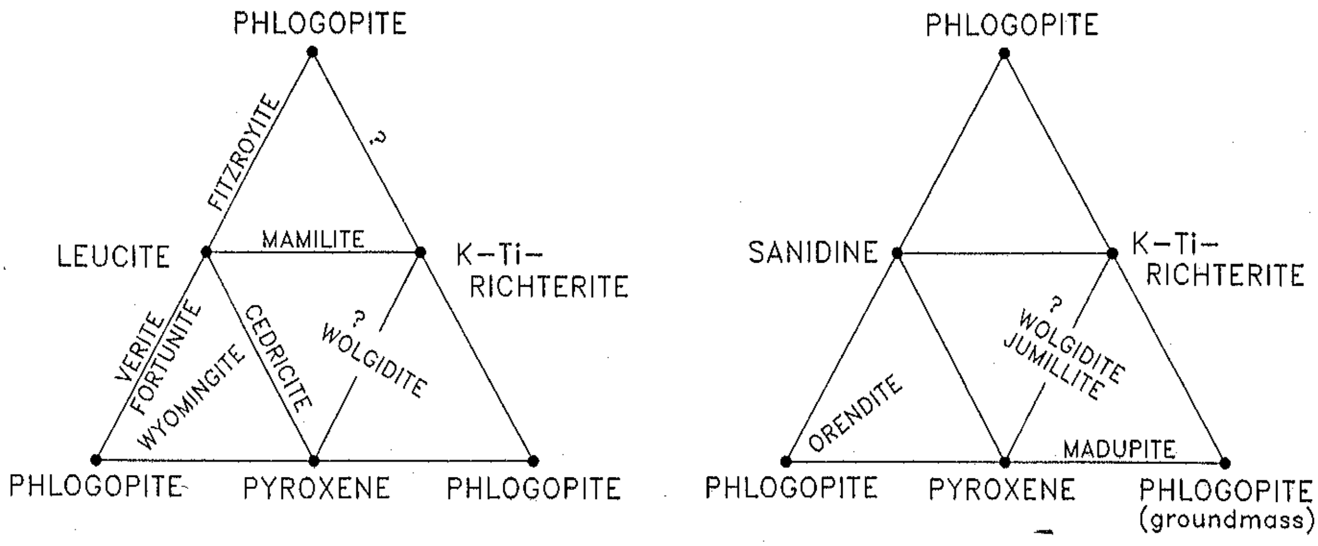


Fig. 1. Historic nomenclature of lamproitic rocks (from Mitchell, 1985).

fusing, more practical and caters for most possible petrographic variations.

Rock (1989) suggested that lamprophyres form a clan of rocks that have certain common characteristics (Fig. 2). This approach implies that Figure 2 is a hierarchical classification and that there is a petrogenetic relationship between the different branches. This clan included kimberlites and lamproites. There is no evidence to support any petrogenetic relationships between the different branches within Rock's proposed lamprophyre clan (Mitchell, 1994; in press; Woolley et al., in press). In fact Rock (1991) himself concluded that there are distinct magma types within this clan and that they have very varied associations and therefore different petrogeneses (Fig. 3). Mitchell (1994; in press - a) has suggested an excellent rationalization to this problem by use of the concept of a lamprophyre-facies which has no genetic significance. This facies is proposed as a means of conveying the concept that certain rocks have crystallized under different conditions from most of the rocks within any one clan. Hence, this term applies to a group of rocks derived from petrogenetically distinct clans which have common traits, mainly resulting from their volatile-rich nature reflected in hydrous mineral assemblages. No common petrogenetic processes, therefore, are implied for rocks termed lamprophyre-facies. Some of the mineralogical criteria which apply to the lamprophyre-facies are: phenocrysts of mica and/or amphibole with less clinopyroxene ± melilite set in a groundmass which may contain plagioclase, alkali feldspar, feldspathoid, carbonate, monticellite, mica, amphibole, pyroxene, perovskite, Fe-Ti oxides and glass (see Mitchell, 1994; and in press - a, for more details). Interestingly Mitchell (in press - a) did not include olivine in the definition as it is neither ubiquitous nor diagnostic of lamprophyres. Table 2 of Mitchell (1994) clearly illustrates the concept of the lamprophyre-facies. For example, within the alkali olivine basalt clan of rocks he notes three main facies, extrusive (basalt), hypabyssal and plutonic (gabbro). The hypabyssal-facies rocks are sub-divided into two groups depending on whether they are lamprophyric (sannaite, camptonite, monchiquite) or not (diabase). It should be noted that some of the rock types, such as leucite lamproites, included by Rock (1991) in Figure 3 should not be termed lamprophyres by either these or other criteria.

Rock (1991) describes the characteristics of different groups among rocks termed lamprophyres which can be used to aid further classification of unknown rocks. Hybridization and crystallization in magma chambers account for the petrological complexities of lamprophyres (Mitchell, 1994).

Further rationalization, however, is still required within this terminology. It is, therefore, often not easy to apply these terms and criteria both in general or for exploration programs. It is potentially easy to determine whether a rock or a suite of rocks can be classified as kimberlite or lamproite because these rock types have workable definitions. If the samples being examined fall outside these rocks types, it is often very difficult, or even impossible, to meaningfully apply a rock term to them. For example, as Mitchell (1994) notes, the term minette has such a broad definition that unrelated rocks from different petrogenetic associations, namely calc-alkaline volcanism, lamproites and mafic phonolites, are classified together. In an attempt to rationalize some of the terminological problems relating to diamond exploration programs for some other rock types the acronym 'melnoite' (for melilite and alnoite) was developed and successfully used by the Kimberlite Petrographic Unit (E.M.W. Skinner) of the Geology Department of De Beers Consolidated Mines Ltd. (unpublished data). This term has been introduced into the published literature by Mitchell (in press - a). This term is devoid of petrographic connotations so Mitchell (in press - a) supports the use of the term as an interim name until petrologists can agree on a stem name that conveys the nature of the parental magmas involved. The term caters to the lamprophyre-facies of the melilitite clan (some of the ultramafic lamprophyres in Fig. 2) which are typically associated with alkaline rock-carbonatite complexes. In such a scheme, alnoite would become melilite diopside phlogopite melnoite and aillikite, a phlogopite calcite melnoite

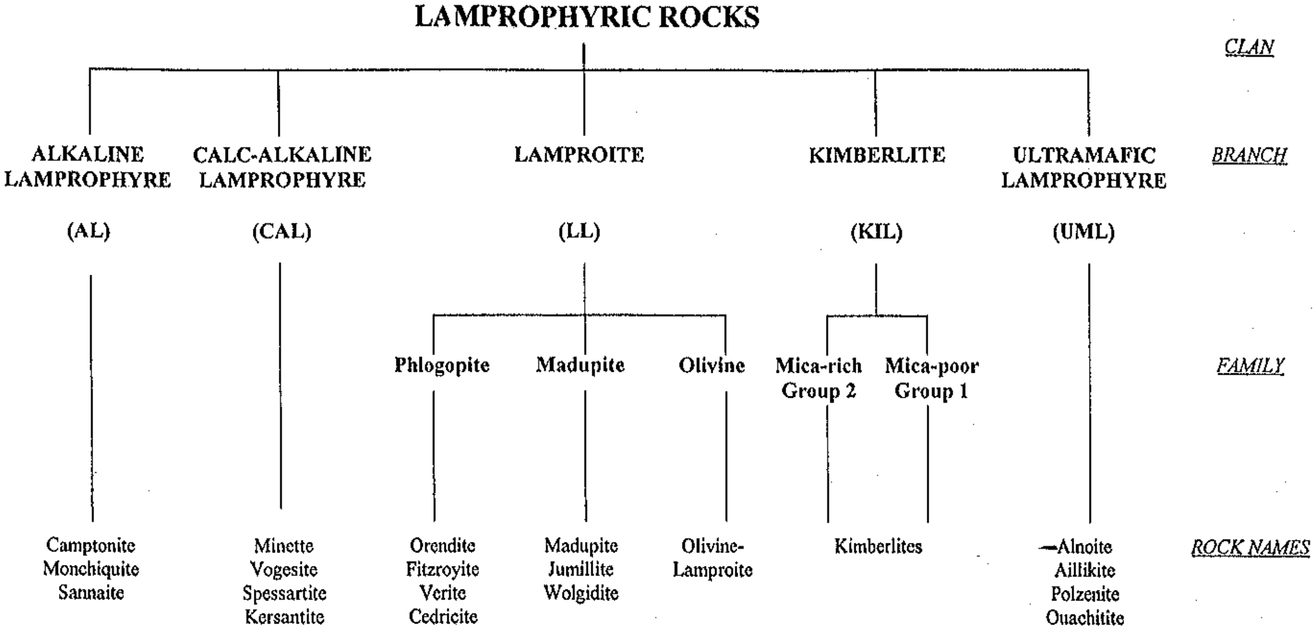


Fig. 2. The so-called lamprophyre "clan" after Rock (1989, 1991). It should be noted that in this work it is considered that the branches of this so-called clan do not have any petrogenetic relationships and that this figure does not represent a heirarchical classification scheme. Most of these rocks are better described as being of the lamprophyre-facies (after Mitchell 1994, in press - a).

(Mitchell, 1994). This approach is a considerable advance in the terminology of such rocks.

Many rocks encountered during diamond exploration can be considered to be of the lamprophyric-facies (Mitchell, 1994). Although small volume hypabyssal rocks are those most commonly encountered in diamond exploration programs, it should be noted that rocks with other modes of emplacement can be termed as lamprophyres, e.g., the vast minette province of the Christopher Island Formation in the NWT (Peterson, 1994).

Despite the drawbacks of Rock's (1989; 1991) lamprophyre clan concept, Figure 2 is a useful way of viewing many of the lamprophyre-facies and related rocks encountered during diamond exploration, but can only be used if the lack of petrogenetic relationships within the so-called clan is clearly understood. In Figure 2 the potentially diamondiferous rock types, Group 1 and 2 kimberlites and olivine lamproites, are clearly shown and separated from some of the other rock types which are found during exploration. Also the juxtaposition of the different rock types in Figure 2 gives an indication of some of the petrographic gradations between the different groups.

It is these petrographic gradations that typically provide many of the problems in classifying fresh hypabyssal rocks. This problem is illustrated in Figure 4 which considers the five main clans or rock types encountered during diamond exploration programs. Most single rocks or samples within one clan will display characteristic features which are used in the definition of that rock type (Fig. 4). The range or variety of petrographic types within each of the clans varies and is indicated by the width of the base of each curve in Figure 4. This variation in turn relates to the number of worldwide occurrences of each of these rock types. An indication of the relative abundances of these rock types is given by the height of each curve. For the rock types considered in Figure 4, melnoites are the most common and display the widest petrographic variation while Group 2 kimberlites are the least common and least variable. Some rocks derived from a single parental magma or rock type, usually the more extreme varieties, can fall outside the definition as well as overlap with another rock type, with respect to their petrographic features (Fig. 4). Classification of such gradational or intermediate rocks is often difficult or sometimes not possible. It can be seen from the schematic representation of this problem in Figure 4 that such overlaps form a considerable proportion of the total petrographic spectrum. As discussed above, petrological rock type classifications, therefore, should be undertaken on a suite of magmatic rock samples to attempt to eliminate the misleading examination of one atypical sample and to overcome the overlap problems illustrated in Figure 4.

Hypabyssal (or lamprophyre-facies) rocks are typically the most suitable samples on which to undertake rock classifications as these magmas have had more time to crystallize coarser groundmass minerals than extrusive rocks. The nature of the minerals in hypabyssal rocks are then a direct reflection of the parental magma or the clan from which they derived. In practice the main recognition of different rock types is based on their contrasting petrographic mineral assemblages and mineral compositions. Scott Smith (1992), Mitchell (1986; in press - b), Mitchell and Bergman (1991), Rock (1991) and Woolley et al. (in press) all discuss the criteria and present guidelines for the recognition of kimberlites, lamproites and other rock types so this aspect will not be discussed further here. Obtaining the compositions of the primary minerals in these rocks can often be extremely helpful, and sometimes essential. Mica compositions have been shown to be a particularly useful mineral in distinguishing

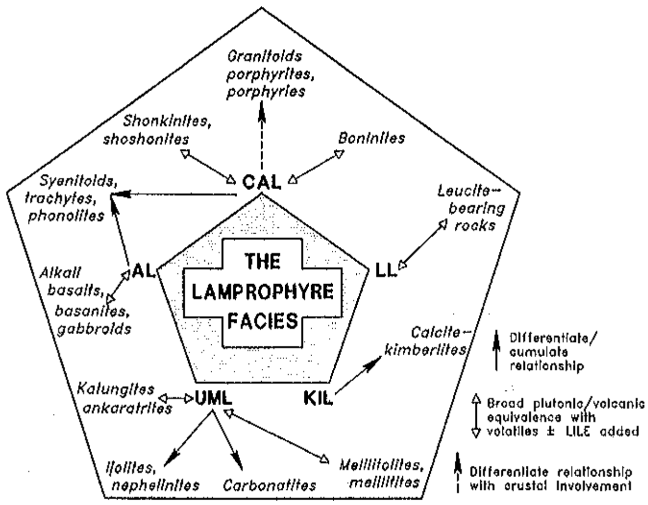


Fig. 3. Petrogenetic relationships between lamprophyres and some other igneous rock types (after Rock, 1989, 1991). Rock's term 'clan' has been replaced here by facies.

the overlapping rock types shown in Figure 4 such as Group 1 and 2 kimberlites from each other and from olivine lamproites or phlogopite lamproites from minettes (e.g., Scott Smith and Skinner, 1984a; Mitchell and Bergman, 1991; Mitchell, in press - b). Other minerals such as spinel and clinopyroxene, can also be used. It should be noted that the application of these well established definitions to fresh rocks may still not be straightforward. For example kimberlite magmas can be significantly contaminated by the digestion of crustal xenoliths (Scott Smith et al., 1983). These magmas can then crystallize minerals which appear to be fresh primary minerals that are atypical of kimberlites. A good example is the presence of clinopyroxene in Group 1 kimberlites.

The classification of other textural varieties of rocks is notoriously difficult. Crater-facies rocks are composed of rapidly quenched juvenile fragments, typically glassy lapilli, which usually have not had time to crystallize any groundmass minerals. The diagnostic features, therefore, are usually not present. A similar, but not quite so extreme, problem occurs in diatreme-facies kimberlites. Crater- and diatreme-facies rocks are fragmental rocks which are also very prone to alteration making them far from ideal for this type of investigation.

Whole rock geochemistry appears to be a much used tool in diamond exploration while it has not proved to be particularly successful in discriminating different rock types. As noted by Mitchell (in press - b) the bulk composition of the majority of diamondiferous rocks is a direct reflection of the modal mineralogy but the reverse does not hold because of the complex hybrid nature of most of these rocks. Hence, for fresh samples, the rock may be identified by direct observation of the primary minerals present without the use of bulk compositions. Bulk rock compositions can be used, with caution, to augment inconclusive investigations of altered or gradational rocks.

Unfortunately, no good discriminant plots have been published. Published and new bulk compositional data also must be interpreted with caution. Mitchell (in press - b) provides further discussion on this topic. Elphick et al. (1993) discuss the unreliability of whole rock geochemistry in their investigations of the James Bay Lowlands olivine melilitites. They believe that such results can be misleading "without intensive petrographic research".

## Sub-divisions within Different Rock Types

Once the petrological classification of a rock or body has been established, the geology of that rock or body can further be defined by sub-divisions based on mineralogical and textural classifications, not to be confused with the initial petrological classification.

## Mineralogical Classification

Kimberlites and lamproites can be meaningfully subdivided by using mineralogical classifications (Skinner and Clement, 1979; Scott Smith and Skinner, 1984a, 1984b; Mitchell, 1986, 1994; in press - a). These mineralogical classifications are best applied to hypabyssal or non-glassy magmatic rocks and are based on the modal proportions of the primary minerals in any rock. Most of these minerals crystallized from the magma and, therefore, are a direct reflection of the nature of that magma. This type of classification is, therefore, very useful in defining different batches of magma which have reached the surface and so distinguish different phases of intrusion within a body. In kimberlites olivine is excluded from the mineralogical classification because it is ubiquitous and, therefore, not useful in distinguishing most kimberlite magma types. A kimberlite may be described as a phlogopite monticellite kimberlite, for example, where monticellite is the dominant groundmass mineral and phlogopite is less abundant (defined as $< 2/3$ modal % of dominant mineral; Skinner and Clement,1979). In some situations olivine can have variable abundances, often as a result of flow differentiation etc., and, if such rocks need to be distinguished, the modal abundances of olivine can be used. Similar styles of mineralogical classifications can be applied to groups of rocks other than kimberlites and lamproites but no specific schemes have been established. The dominant minerals can still be used to differentiate between rocks such as a carbonate melnoite or a melilite melnoite. Mineralogical classifications are difficult to apply to other textural facies. For example extrusive rocks, in particular crater facies volcaniclastic rocks are rapidly quenched and, therefore, have not had the opportunity to crystallize any late stage minerals which are usually the main basis for the mineralogical classification.

Modal analyses are an extremely useful petrographic tool. However, there appears to be a reluctance to determine and use such analyses so the application of the mineralogical classifications are unfortunately often based on visual estimates. Modal analyses are an excellent way of presenting petrographic data. Examination of a modal analyses provides a reader with a quick and fairly accurate idea of a rock. Whereas in published petrographic descriptions, many of the pertinent features are often hidden, not included or even overlooked.

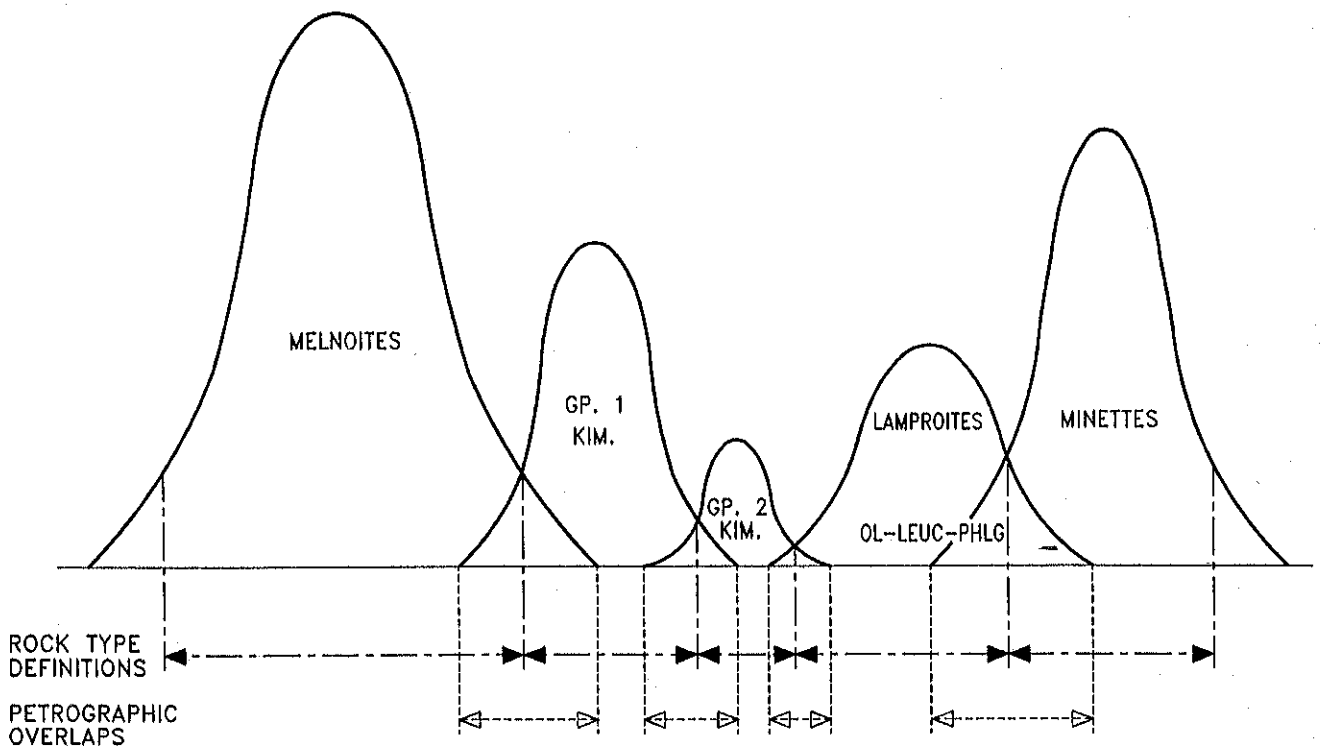


Fig. 4. Petrographic ranges for the rock types most commonly encountered during diamond exploration. The horizontal axis schematically represents the petrographic variation within each rock type. The heights of the curves indicate the relative worldwide abundances of each rock type (not to scale). The width of the base of each curve represents the relative ranges of petrographic types within one rock type (not to scale). The definition of each rock type caters for most, but not all, the petrographic variants in each rock type. The less common and more extreme varieties of each rock type may fall outside that catered for by the definition as well as show petrographic gradations or overlaps with the adjacent rock types.

## Textural Classification

The textures in a rock are a reflection of their emplacement processes. In many instances standard volcanological terminology can be applied (e.g., Fisher and Schmincke, 1984; Cas and Wright, 1987; McPhie et al., 1993) although there is no general acceptance of any one overall scheme. For example, currently there is extensive debate about the use of the term epiclastic (as discussed in recent newsletters of the IAVCEI Commission on Volcanogenic Sediments). Each use of this term, therefore, must be defined.

Magmatic rocks can be intrusive or effusive. Effusive rocks can be coherent or autoclastic (McPhie et al., 1993). For the rock types typically encountered during diamond exploration, the intrusive rocks are typically small hypabyssal intrusions many of which can be also termed lamprophyric-facies (after Mitchell, 1994; in press - a). Other textural types result from explosive emplacement processes. In most volcanic rocks these are primary pyroclastic rocks of different types (flow, surge, fall). These may, or may not, be reworked. Rocks resulting from sedimentological reworking are best termed resedimented volcaniclastics (after McPhie et al., 1993). Secondary processes can form other volcanogenic sediments which may, or may not, be associated with the pipe from which they erupted. These sediments are not related to any volcanic activity and the time of deposition of this material may be millions of years after the formation of the volcanic vents. Such sediments, which often incorporate extraneous material, can be preserved in depressions which need not be of volcanic origin. Rocks formed by these processes should not be confused with, or termed, primary or resedimented crater facies material. Mitchell (in preparation) has termed these pseudo-crater-facies deposits as metachronous volcanogenic sediments.

Different clans of rocks derive from different parental magmas. These magmas may not only have different compositions which are reflected in their mineralogy, but also may have different properties that affect their emplacement processes and hence textural classifications and pipe models (Fig. 5). Lamproite pipes typically comprise craters infilled with primary ash and lapilli tuffs and effusive magmatic rocks. Standard volcanological terminology can be applied to these and some other related rocks such as minettes. Many kimberlites have different styles of emplacement (Clement, 1982) to standard volcanic processes described in the literature (e.g., Fisher and Schmincke, 1984; Cas and Wright, 1987). The main reason for these differences appears to be the very abundant carbon dioxide which is still incorporated within many kimberlite magmas when they approach near surface. This difference has required kimberlite-specific pipe models (Hawthorne, 1975; modified by Mitchell, 1986) and textural-genetic classifications to be devised for kimberlites (Clement, 1982; Clement and Skinner, 1985; Clement and Reid, 1989; modified by Mitchell, 1986, 1989, in preparation). Kimberlites are different from many volcanic rocks in that extrusive magmatic or effusive rocks have not yet

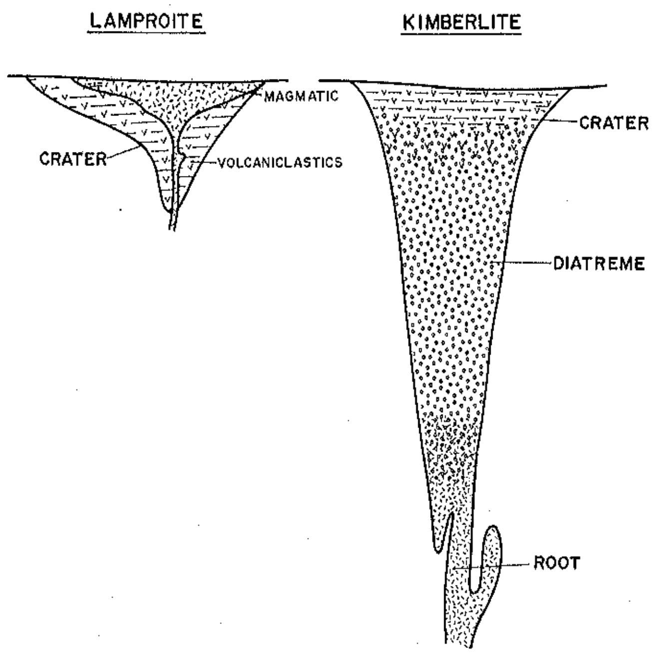


Fig. 5. A comparison of schematic geological models of lamproite and kimberlite pipes (modified after Scott Smith and Skinner, 1984a). Not to scale.

been found. Also, and more importantly, most kimberlites form deep carrot shaped pipes which have much larger depth to width ratios than most small volcanic bodies (Fig. 5). This feature results from the formation of the so-called diatreme-zone which is infilled mainly with structureless tuffisitic kimberlite breccia. These rocks are the end product of complex fluidized intrusive systems in which there is a rapid degassing of carbon dioxide from the host magma. The products of the development of this style of diatreme grade downward into non-fluidized hypabyssal kimberlite of the same phase of eruption. These rocks, together with other hypabyssal kimberlites that were emplaced during embryonic pipe development, form the root zone to the diatreme. In the upper parts of the pipes the diatreme-facies material grades into the crater zone. So far the investigation of the material occurring within many kimberlite craters has been hampered as most of the better investigated examples are extensively altered. For others there is little published information. These craters can be infilled with both primary and resedimented volcaniclastic kimberlite. The latter may include crater-lake sediments such as found at the Orapa Mine, Botswana. Crater-facies rocks have been described using standard terminology but crater deposits relating to a diatreme below may be somewhat different from standard pyroclastic material.

The kimberlite-specific textural classification, however, may be applicable to a few other rocks. For example, some melilititic-alnoitic (or melnoite) magmas which also contained abundant carbon dioxide appear to have formed similar intrusive diatremes. The alnoites or olivine melilitites of the James Bay Lowlands are a good example of kimberlite-like diatremes (Elphick et al., 1993). There are also some kimberlite pipes where there has been no diatreme development. The bodies deviate from the model (Fig. 5) and the kimberlite-specific classification may not be required except for comparison with other kimberlites. Examples of such kimberlites occur at Fort a la Corne in Saskatchewan and at Mbuji-Mayi in Zaire (Scott Smith et al., 1994).

## Some Applications of Petrology in Diamond Exploration

The emergence of lamproites in the late 1970s as a second known 'primary' source of economic quantities of diamond highlighted the importance of petrology in diamond exploration programs (GSC Open File, 1989). These rock types have been compared and contrasted elsewhere (Scott Smith, 1992; Mitchell, 1986, 1991; Mitchell and Bergman, 1991). The importance of this aspect of petrology in diamond exploration is also illustrated by the work of the staff of the De Beers Consolidated Mines Ltd. Geology Department who have written some of the classic papers in this field (Hawthorne, 1975; Clement et al., 1977, 1984; Skinner and Clement, 1979; Clement, 1982; Scott Smith and Skinner, 1984a, 1984b; Clement and Skinner, 1985; Clement and Reid, 1989; Skinner, 1989). Scott Smith (1992) discusses some of the implications of these differences in diamond exploration, with a particular emphasis on the use of petrography which now can be illustrated with Canadian examples.

The aim of any diamond exploration program is to find profitable diamond mines. Although Group 1 and 2 kimberlites and lamproites, as well as some secondary deposits, can all form successful mines, different exploration criteria must be used for their location. The proportion of current and past diamond production from each of these main sources may influence the implementation of an exploration program. As discussed by Scott Smith (1992), diamondiferous lamproites may be less common and/or more difficult to find than kimberlites. Most of the world's diamonds currently derive from kimberlite mines and, therefore, such bodies may be the best exploration targets. Once the aim of a program has been established, the apparently different tectonic settings of lamproites and kimberlites, as well as of secondary deposits, obviously strongly influence the next stage of any exploration program, which is the area selection. The many recent discoveries of diamondiferous kimberlites in the Archaean Slave craton in the Northwest Territories appear to be a good example of the application of Clifford's Rule (Janse, 1994b). This suggests that standard 'kimberlite' exploration criteria should be applicable to this area. There are no confirmed lamproites in Canada, but current exploration programs are operating on the margins of well established cratonic areas, for example in Alberta (Morton et al., 1993). This might suggest that lamproites are a more likely target in these exploration programs and, therefore, that different prospecting criteria may be required to facilitate their discovery. For example 'indicator minerals' in lamproites may be less abundant and their compositions require different interpretations (e.g., Atkinson, 1989; GSC Open File, 1989; Fipke and Nassichuk, 1991; Muggeridge,

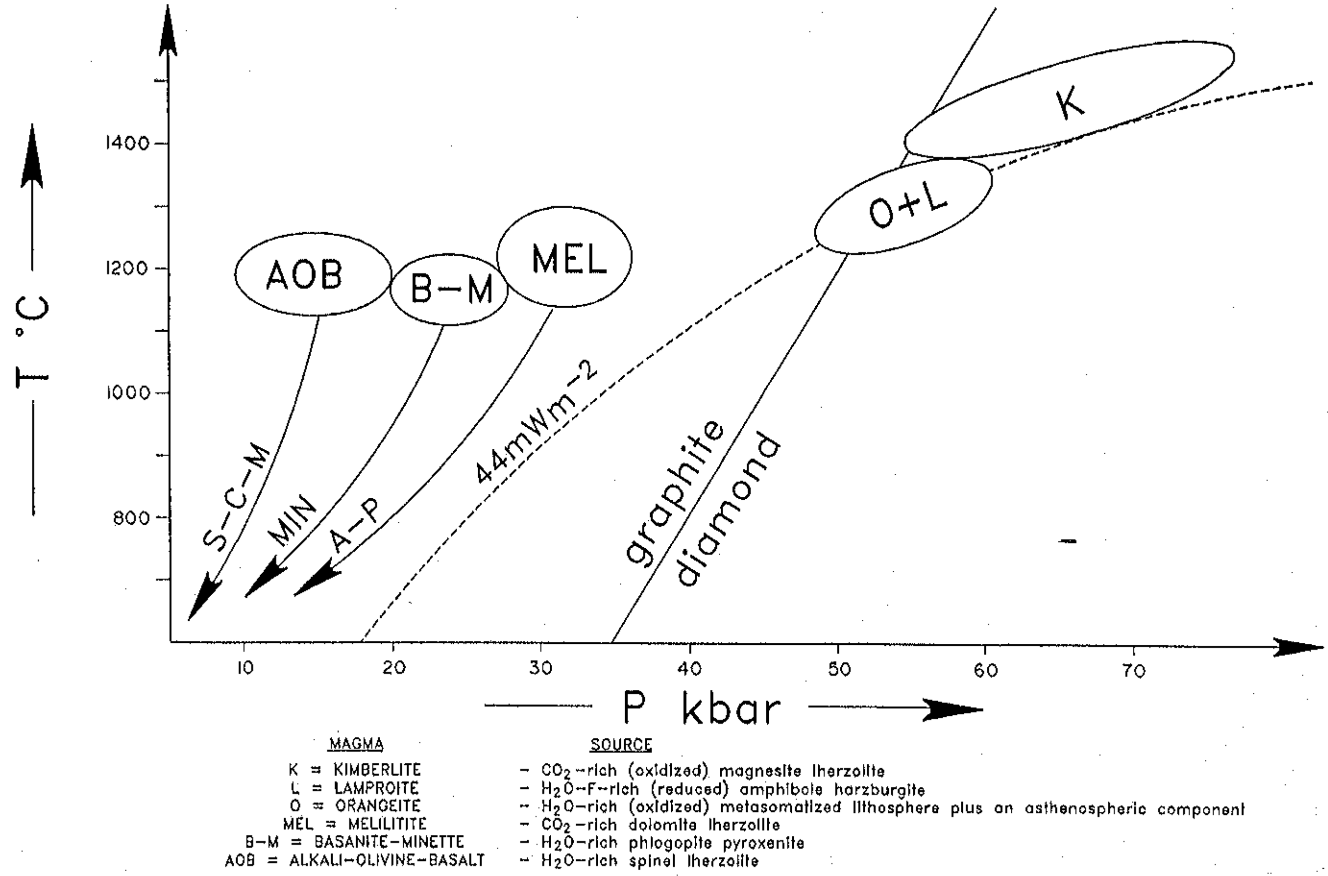


Fig. 6. Source regions, pressures and temperatures of formation of some mantle-derived magmas relative to a representative continental geotherm and the diamond-graphite transition (after Mitchell, 1994). All magmas are capable of crystallizing rocks of lamprophyric aspect under appropriate conditions at low pressures. S-C-M = sannaite-camptonite-monchiquite; MIN = minette; A-P = alnoite-polzenite.

1991; Scott Smith, 1992). Similar comments can be made for Group 2 kimberlites (Skinner, 1989; Tainton and Browning, 1991; Skinner at al., 1994; Mitchell, in preparation).

Group 2 kimberlites are so far mainly confined to the Cretaceous of South Africa and lamproites have yet to be found in Canada. It has been shown that metasomatized lithosphere has an important role to play in the petrogenetic histories of both Group 2 kimberlites and lamproites but not of Group 1 kimberlites (e.g., Mitchell and Bergman, 1991 and Mitchell, in preparation). The metasomatic histories and the resulting rocks within each cratonic lithosphere are different and may also be variable within one cratonic keel. The magmas at surface which either derived from, or were contaminated by, such variable metasomatized lithosphere must reflect these differences. The magmas derived from these variable source rocks must have different compositions and crystallize different minerals. A good example occurs among the lamproites. Each known province of lamproites is different and has its own unique characteristic. These characteristics must reflect the unique mantle history of the specific area of the metasomatized lithosphere involved in their formation. This feature is shown not only in the mineralogy of these rocks but also their geochemistry, notably the Sr-Nd isotopic signature for each area (e.g., Mitchell and Bergman, 1991). Group 2 kimberlites (orangeites) may be the reflection of lamproite-like petrogenetic processes in the Kaapvaal craton of South Africa which must have its unique metasomatic history. These rocks, therefore, may not form a separate clan of rocks but rather be a variation on the lamproite theme. All Metasomatized Mantle-derived Magmas could perhaps be considered as one broad group of rocks termed "MMM". Within the MMM group each province will display its own unique signature. In turn any MMMs derived from Canadian cratons would be expected to be different from any known examples. Group 2 kimberlites are the MMM produced in South Africa and similar rocks are, therefore, unlikely to occur in Canada.

Once igneous bodies are discovered during an exploration program, petrological classification becomes important. As noted above, petrological classification defines petrogenetically distinct groups of rocks. From a diamond exploration point of view it is important first to establish the relevant clans and second their origin. Those which originate in the diamond stability field (Fig. 6) within or below cratonic keels and have a diamond "friendly" (Helmstaedt, 1994) ascent to surface have the potential for yielding economic deposits. To date these rock types appear to include only Group 1 and 2 kimberlites (orangeites) and lamproites (Fig. 6). These rock types must be recognized otherwise unproductive follow-up work on other rocks that appear to have little economic potential may occur. Rocks which have derived from outside the diamond stability field obviously have no potential to carry diamonds, for example the minettes and melilitites (Fig. 6). Other associations are illustrated in Figure 3. Examples in Canada where the application of such classifications could have been prevented further exploration work include the alnoites or olivine melilitites and tuff breccias in the Hudson Bay Lowlands (Janse, 1989; Reed and Sinclair, 1991), the breccia pipes associated with the vast minette province in the area of Dubawnt Lake, Northwest Territories (Peterson, 1993, 1994; Petersen et al., 1993; Pell and Atkinson, 1993, Davis, 1994 and George Cross Newsletter, No. 28, 1994), the Ile Bizard alnoite intrusion which forms part of the Monteregian igneous province in Quebec (Raeside and Helmstaedt, 1982; Mitchell, 1979) and the Jack pipe in British Columbia (McCallum, 1994). The Hudson Bay and Ile Bizard occurrences are good examples of the overlap between alnoites and/or olivine melilitites or melnoites and kimberlites while Dubawnt Lake is an example of the overlap between phlogopite lamproites and minettes and the resulting difficulties in rock type classifications (Fig. 4). Other Canadian bodies have been correctly identified as kimberlites and follow-up work on most of these bodies has occurred. Examples include the Kirkland Lake kimberlites (Brummer et al., 1992a, 1992b; MacFadyen, 1993) and the Fort a la Corne kimberlites in Saskatchewan (Lehnert-Thiel et al., 1992). These examples are in addition to the recent discoveries in the Northwest Territories.

The potential for new rock types carrying significant quantities of diamonds must always be considered. Some authors comment that lamproites were relegated to the status of non-prospective rocks together with lamprophyres etc. prior to the discovery of the Ellendale bodies in Western Australia (e.g., Helmstaedt, 1994). It must be re-emphasized, however, that the lamproites which are now known to be significantly diamondiferous, namely olivine lamproites, form an extension to the group of rocks considered to be lamproites prior to the discovery of Ellendale. This is clearly illustrated by the absence of olivine from Figure 1 which caters to most of the historic terminology. In this respect it is also very pertinent to note that all the newly discovered and recognized diamondiferous olivine lamproites were all first termed kimberlites because they showed a greater superficial petrographic similarity to kimberlites than to leucite lamproites, although this classification was probably also influenced by the presence of diamonds. Calling these rocks kimberlites did not downgrade these rocks as non-prospective. Most of the previously known lamproites, i.e., leucite and phlogopite lamproites (as shown in Figs. 1 and 2) are still considered by most to have a low diamond potential. Such rocks, however, have the potential of being associated with diamondiferous olivine lamproites, with the Ellendale discoveries being one of the best examples. Here the diamondiferous olivine lamproites were discovered some 40 years after the leucite lamproites were relatively well known. Among other rock types which show greater similarities to kimberlites, the most likely candidates for carrying reasonable quantities of diamonds are probably a variety of the ultramafic lamprophyres, in particular alnoites. Features in known rocks of this type, however, do suggest a shallower depth of origin (Fig. 6; Mitchell, 1991, 1994) and, therefore, that they are truly non-prospective. As with the lamproites, unexpected diamondiferous rocks are likely not to fall within the recognized parts of established clans of rocks.

Petrology can be used to prioritize exploration work when more than one body is discovered. For example the application of mineralogical classifications among the wide range of rocks in the lamproite clan has shown that significant quantities of diamonds only occur in olivine lamproites. No lamproites (sensu stricto) are known in Canada but the only diamondiferous lamproite in North America, Prairie Creek, Arkansas is a good example of the economic implication of mineralogical classifications. The so-called "tuffs" that are barren of diamonds are composed of phlogopite lamproite while all the diamondiferous rocks are all olivine lamproites (Scott Smith and Skinner, 1984b). The Prairie Creek lamproite is also a good example of application of sub-divisions based on textural classifications. Economic diamond grades in lamproites so far appear to be confined to crater-facies volcaniclastic material. At Prairie Creek most of the diamonds are recovered from the olivine lamproite lapilli tuffs (so-called "breccias") while the magmatic olivine lamproite yields only a small quantity of diamonds. The olivine lamproite lapilli tuffs have been mined during the earlier part of this century and are currently being re-evaluated by a consortium of mining companies. Similar differences in grade with texture are shown by the new diamond grade data presented by Stachel et al. (1994) for some of the Ellendale Pipes in Western Australia. As a result of the application of these types of sub-divisions, prospecting priorities can, therefore, be placed on different parts of a single body, on different bodies or even on different provinces. Prairie Creek is also a good example of the influence the mineralogical and textural types of such rocks has on geophysics. Reed (1993) shows that the magmatic olivine lamproite at Prairie Creek has a magnetic response while both types of lapilli tuffs, including the diamondiferous material, are not magnetic.

The age of any bodies is important in prospecting programs. Occasionally stratigraphy and/or palynology techniques can be used to constrain the age of a body. Otherwise two of the best techniques for age determinations of these rock types appear to be the Rb-Sr isotopic investigation of primary mica and the U-Pb isotopic investigation of primary groundmass perovskite, either as mineral separates or in situ using an ion probe. These determinations can only be undertaken on suitable samples which should be selected by careful petrographic investigations. As found in other parts of the world, known kimberlites in Canada are Proterozoic to Cretaceous in age (e.g., Fig. 1 of Helmstaedt, 1994) and one expects economic deposits to be more common among the younger rocks. Limited information suggests that many of recently discovered bodies in Canada are Cretaceous (e.g., Fort a la Corne in Saskatchewan) to Eocene (e.g., NWT) in age (Lehnert-Thiel et al., 1992; Pell, 1994, respectively). Although no mines have yet opened, interestingly some of these bodies may prove to be the youngest economic kimberlites known in the world. Presumably as a result of their young age, crater-facies rocks are common among the newly discovered kimberlites in the Northwest Territories and Saskatchewan. A spectrum of ages, however, should be expected within the Slave craton. In the Northwest Territories, limited information suggests that hypabyssal, and diatreme-facies kimberlites are also present and that some of these bodies may have pipe shapes similar to those of the classic kimberlite model (Fig. 5). The combination of the age and the pipe models for these bodies obviously suggested that most of the pipes should be preserved and that significant potential ore reserves may be present. These implications apply not only to each body but also to each province. There are only poor examples in Canada of decreasing size with increasing age resulting from different degrees of erosion, as different aged kimberlites do not occur in the same areas. The Cretaceous kimberlites (95 Ma) in Saskatchewan include crater-facies pipes which range up to at least 100 ha (Scott Smith et al., 1994) while the Devonian aged Cross kimberlite in British Columbia is only 2 ha in size and is presently exposed within the root zone (cf. Fig. 5). The Kirkland Lake kimberlites at 150 Ma appear to include diatremes and hypabyssal material presumably associated with the root zone and range in size up to 6 ha (Brummer et al., 1992a, 1992b).

It should be noted that deviations from established pipe models (Fig. 5) should be expected. The Fort a la Corne kimberlites appear to be such an example. It appears that diatremes have not been developed in these bodies (Scott Smith et al., 1994) so reducing the potential ore reserves of any one body. There may be similarities between some of the kimberlites on Somerset Island to those in the Fort a la Corne area (Scott Smith et al., 1994) that deserve further attention.

Crater-facies rocks are complex and each volcanic center will be different with its own potential diamond distributions. Textural and mineralogical classifications leading to the determination of the internal geology of a body and the interpretation of the near surface mode of emplacement will be important in determining the diamond distribution, ore reserves and ultimately the mining methods of any such material. Scott Smith et al. (1994) is an example of the results of such an investigation. Some comments on the diamond distributions in the different facies of kimberlites and lamproites are reviewed by Scott Smith (1992) and Mitchell (1991). Detailed published information of contrasting grades in different facies within a kimberlite pipe are not yet available for Canada. The kimberlite processing undertaken by Kennecott Canada Ltd. on the DO-27 pipe in the Northwest Territories, however, suggests that two different phases which were termed diatreme and pyroclastic (presumably diatreme and crater-facies) had different grades of 1.3 and 35.9 carats/100 tonnes, respectively (e.g., George Cross Newsletter, No. 150, August 8, 1994).

A new avenue for the application of petrology in diamond exploration may be to define further the nature of the host magma or transporting agent of the diamond to the surface from the mantle. Detailed petrogenetic histories may allow further comment on the preservation of diamonds within that magma. This could supply an additional tool to predict the diamond potential of the rocks encountered during diamond exploration.

## Acknowledgments

The author would like to thank and acknowledge the staff of the De Beers Consolidated Mines Ltd. Geology Department for her initiation into the application of petrology in diamond exploration. Particular thanks go to Mike Skinner, Roger Clement, Barry Hawthorne and Jock Robey. The author is also grateful to Roger Mitchell for many discussions on these and other related topics and for making several preprints available. Jock Robey, Roger Mitchell, George Read and Adrian Smith are thanked for comments on the first draft of this manuscript. The first version of this paper was included in the unpublished Proceedings of the District 6 CIM Annual General Meeting held in Vancouver, British Columbia in October 1994.

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